26

SÉANCES DE LA SOCIÉTÉ PRÉHISTORIQUE FRANÇAISE

DEWA 2023
FROM MINE TO OBJECT
Dialogues between Eastern and Western Archaeometallurgy (3rd-1st millennium BC)



ACTES DE LA SÉANCE CONJOINTE
DE LA SOCIÉTÉ PRÉHISTORIQUE FRANÇAISE
ET DE L'ASSOCIATION POUR LA PROMOTION DES RECHERCHES
SUR L'ÂGE DU BRONZE

MUSÉE D'ARCHÉOLOGIE NATIONALE
DOMAINE NATIONAL DE SAINT-GERMAIN-EN LAYE
22-24 NOVEMBRE 2023

Textes publiés sous la direction de
Zahra Hashemi, Marilou Nordez,
Martin Sauvage et Claude Mordant

Association pour la promotion des recherches sur l'âge du Bronze
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Foreword

Claude Mordant and Martin Sauvage

Archaeometallurgy (of non-ferrous alloys) is a discipline which encompasses the entire field of ancient metallurgy, from the extraction of metals from their ores to the present state of archaeological objects, and has been rapidly expanding over the last two decades. Considerable progress in advancing the field is enhancing our knowledge, whether about ore extraction and mining activities, production processes (from ore to metal) or artefact transformation (from metal to finished product), as well as the lifecycle of metallic products (from finished products to their current status and location).

This structuring of archaeometallurgical research has been accompanied by several bulkheads: researchers are often specialists in one step of the *chaîne opératoire*, a type of approach, a category of scientific analysis, a specific material or a particular geographic area or time period. It makes for research compartmentalized between different approaches such as mining archaeology, archaeometry, technology and archaeology on one hand, and, for example, between Europe and the Near East on the other. Although interdisciplinarity, which is now the norm, relativize this observation, the various specialists often have difficulty gathering and exchanging ideas due to their disparate methods, training, research traditions and questions.

Otherwise, it seems that archaeometallurgical research is developing in parallel in Europe and in the Near East, with relatively few bridges between these two regions, although some researchers navigate between these very different chrono-cultural, technical, environmental, and socio-political contexts.

This is why, in the framework of this conference, we wanted to create a dialogue between these two worlds. Our objective was to provoke a disciplinary, methodological, geographical, and chronological decompartmentalization to bring together researchers who are rarely in contact despite the complementarity of their approaches. We hope, in the long run, that this approach will allow us to strengthen ties, weave collaborations, and create an interdisciplinary research group on archaeometallurgy in the entire Old World.

The conference was organized around four axes, making four main sessions:

1. Mining and ore extraction activities

All evidence of ore exploitation and mining activities, whether they are direct or indirect, has been considered in this session.

2. Tools, actors and production loci: specialization and organization

This session was devoted to the organization of production and has questionned the notion of the 'workshop'. Who were the metalworkers? What was their degree of specialization? What was their socio-economic status? What was their symbolic position? What were their tools and their work environment? How were organized different stages of the metallurgical process? Can we distinguish different types of workplaces and/or activity areas according to geographical and chronological contexts?

3. The production process (chaînes opératoires)*, from metal to finished product*

What were the processes and methods of manufacturing metal objects? Here, direct or indirect clues that provide information on the gestures, techniques, skills and know-how of ancient craftworkers were used to propose reconstructions of the metallurgical production process. As metals are complex materials whose physico-chemical structures condition their reactions, approaches combining material sciences and technological studies have been favoured here.

4. Exchanges and uses of metallic objects: from archaeological contexts to the laboratory

All approaches that allow us to question the circulation of metals, whether in the form of ores, ingots, semi-products, finished objects, or fragments of objects, found their place here. From physico-chemical and isotopic analyses to typo-chronological studies, through use-wear analysis and tribological approaches or the detailed study of archaeological contexts, allowing us to address the

question of the use, functions and circulation of metal, were considered here.

This conference was part of a series of meetings organised by the Société préhistorique française (SPF), in conjunction with the Association pour la promotion des recherches sur l'âge du Bronze (Aprab).

The idea of focusing on Bronze Age archaeometalurgy arose from an informal discussion between Claude Mordant and Martin Sauvage following a meeting of the board of directors of the Société préhistorique française. The theme had come to the fore with the SPF's publication of Marilou Nordez's PhD[1] and, more recently, that of Zahra Hashemi (Peeters). [2] Archaeometallurgy interests a large community of scholars beyond Western Europe, particularly in the Near East even though few opportunities have been given to colleagues from these two geographical and cultural areas to meet and compare their work.

And this is why the SPF and the APRAB decided to organise this conference.

The Aprab and the Musée d'Archéologie Nationale (MAN) have been actively promoting research into the Bronze Age for many years now, and it was a natural step for them to enter into a partnership to host this international meeting.

Our thanks go to Rolande Simon-Millot and Christine Lorre for their enthusiastic reply to our proposal, and to Rose-Marie Mousseaux, Director of the MAN, for hosting the event.

Thank you to all the Museum staff for their commitment to the conference and to Sylvie Boulud, who is the APRABs treasurer.

This conference could not have taken place without the kind support (in particular financial support) from numerous partners and institutions.

Our thanks go to:

– the Musée d'Archéologie nationale - Domaine national de Saint-Germain-en-Laye ;

– the Société préhistorique française and the Association pour la promotion des recherches sur l'âge du Bronze;

– the Fondation Maison des Sciences de l'Homme;

– the Institut français du Proche-Orient in Beirut, and the French embassy in Iran;

– the "Archéologie et Sciences de l'Antiquité" joint research unit (UMR 7041 ArScAn) at Nanterre—including its team "Du Village à l'État au Proche et au Moyen Orient (VEPMO)"—and the "Travaux et recherches archéologiques sur les cultures, les espaces et les societies" joint research unit (UMR 5608 TRACES) at Toulouse;

– the Domaine de recherche d'intérêt majeur Patrimoines matériels – innovation, expérimentation, résilience (DIM Pamir) in the Île-de-France region;

– and the Research Commission of the University of Paris-Nanterre.

But the best institutional intentions must always be backed up by individual enthusiasm and effectiveness.... We would like here to thank again Zahra Hashemi and Marilou Nordez for all their help in organising this scientific event, this moment of discussion and debate and for their editorial work for its publication.

Concerning the editorial work, our warmest thanks go to the colleagues who kindly accept to participate in the reviewing of the present articles: Linda Boutoille, Florian Couderc, Léonard Dumont, Kristina Franke, Muriel Mélin, Emmanuelle Meunier, Pierre-Yves Milcent, Nima Nezafati, Omid Oudbashi, Véronique Pataï, Vincent Pigott, Bénédicte Quillec, Anna Sörman, Thomas Stöllner, Céline Tomczyk and Lloyd R. Weeks and also to Clare Gathercole who took charge of the English review of some articles.

We would like to thank all the participants very warmly for their positive response when asked to take part in the conference. Their enthusiasm has meant we have had to add on an extra half-day to the original schedule to accommodate everyone. Even with this prolonged conference, many colleagues who would have liked to take part or whom we would have liked to invite could not be included in the programme.

At the closing session of this first DEWA conference, we had already envisaged working towards a 'DEWA 2'. This idea has gained momentum, and we are delighted to announce here that this second session will be held in December 2027 at the Bergbau Museum in Bochum, Germany, thanks to the enthusiastic support of our colleague Thomas Stöllner. It is a great satisfaction to see that this desire to open up our specialities 'from East to West' has been accepted.

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1. M. Nordez, *La parure en métal de l'âge du Bronze moyen atlantique (XVe-XIVe siècle avant notre ère)*, Paris, SPF (Mémoires de la Société préhistorique française, 65), 2019.
2. Z. Hashemi et al., *Sangtarashan : l'âge du Fer au Pish Kuh du Luristan*, Leuven, Peeters (Acta Iranica, 62), 2023.

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Introduction: Between East and West – A state of the art

Marilou Nordez and Zahra Hashemi

METALLURGY: WHAT KIND OF REVOLUTION FOR ANCIENT SOCIETIES?

The strong dependence of modern industrial societies on metals invites us to revisit the long and complex history of human engagement with metals, which stretches back at least to the 9th-8th millennium BC: pendant of malachite from Shanidar, Iraq; native hammered copper beads from Çayönü, Anatolia or Ali Kosh, Iran (Pigott, 1999a). This millennia-long relationship with metals laid the foundation for the technological and cultural developments that followed, from the emergence of extractive metallurgy to the sophisticated alloying techniques of later periods. Over the last decades, research has highlighted the far-reaching consequences of metal technologies on social structures, craft production, agricultural systems, and exchange networks (Roberts and Thornton, 2014). Because metal artefacts rank among the most visible and durable archaeological evidence of protohistoric craftsmanship, societies of the Metal Ages have frequently been interpreted—often reductively—through the prism of their metallurgical production. This has given rise to narratives portraying metallurgy as a major metallurgical revolution or even as a vast process of premodern globalisation, a process that has even been conceptualised as "bronzization" (Vankilde, 2016).

Yet a fundamental question remains: what initially motivated ancient societies to adopt and develop metallurgy? The answer was almost certainly neither universal nor linear, but varied according to regional, chronological and cultural contexts. Early copper objects, for instance, did not offer clear functional advantages over implements made of wood, bone, stone or obsidian, which continued to be used alongside them for millennia. This observation prompts a reevaluation of the origins of metallurgy: what if metal was first worked not because it was indispensable, but because it was desired? The visual, symbolic, and perhaps even acoustic properties of metals may thus have played a key role in their early adoption, long before their practical utility became a defining factor (Lechtman, 1980).

Beyond technological innovation, metallurgy provides one of the richest archaeological proxies for investigating ancient societies. Owing to the generally excellent preservation of metal artefacts, archaeometallurgical evidence documents production systems (from domestic to palatial workshops), ritual practices (hoards, offerings, funerary assemblages), administrative organisation (standardisation, palace records), and exchange networks (from local circulation to long-distance trade). More broadly, metallurgy materialises economic organisation, social identities, political structures and systems of belief. Studying ancient metallurgy therefore involves examining not only how metals were produced, but also how they became embedded within the social, economic and symbolic worlds of past communities.

FROM ARTIFACT COLLECTION TO CONTEXTUAL ARCHAEOMETALLURGY: A PARADIGM SHIFT

From the 19th to the mid-20th century: an object-centred archaeology

In the 19th and early 20th centuries, archaeological approaches to metallurgy were largely shaped by antiquarian traditions, in which artefacts were collected, classified and compared primarily in order to establish chronological and cultural sequences. Metal objects, owing to their durability, visibility and aesthetic qualities, were among the first categories of archaeological material to be systematically inventoried and illustrated. Typological studies, such as those developed by Pitt-Rivers (1867–1869) and O. Montelius (1895), established artefact classification as a fundamental archaeological method, with metal objects serving as chronological markers for defining cultural groups and tracing patterns of interaction.

In the Near East, the development of modern archaeology at the end of the nineteenth and beginning of the twentieth centuries was closely associated with questions concerning the origins of civilisation and technological

innovation. Excavations in Mesopotamia, Anatolia and Iran revealed exceptional metal assemblages from sites such as Ur (Woolley, 1934), Mari (Parrot, 1936), Alaca Höyük (Arık, 1937) and Tepe Hissar (Schmidt, 1937). These discoveries contributed to the perception of the Near East as a primary centre of metallurgical innovation and reinforced diffusionist interpretations of technological development. Although subsequent archaeological discoveries and archaeometric approaches progressively challenged this model, early research remained largely focused on artefact classification, chronology and the circulation of technological innovations rather than on the social and economic systems underlying metal production.

The emergence of archaeometallurgy: from objects to technological systems

From the mid-twentieth century onwards, archaeometallurgy emerged as a distinct field of research at the intersection of archaeology, metallurgy and the Earth sciences. Early studies focused primarily on the classification, chronology and chemical characterisation of Bronze Age metal assemblages, particularly in Western and Central Europe (Coghlan, 1951; Coghlan and Case, 1957; Junghans et al., 1960, 1968, 1974). Large analytical programmes produced extensive datasets that transformed the study of ancient metals, allowing researchers to identify compositional patterns, technological choices and regional traditions (Bretagne: Giot et al., 1966, 1970, 1975; Scandinavia: Cullberg, 1968; gold studies: Hartmann, 1970; Switzerland: Rychner & Kläntschi, 1995; pan-Eurasian syntheses: Chernykh, 1992).

A major conceptual transformation occurred when research moved beyond finished objects to investigate the entire technological system behind them. The study of ores, slags, furnaces, production waste and manufacturing traces progressively expanded archaeometallurgical research from the analysis of objects to the reconstruction of entire production sequences. Important syntheses, such as those by Tylecote (1992), Craddock (1995), Morteani and Northover (1995), Mordant et al. (1998a to c) or Hauptmann (2007), demonstrated the importance of integrating mining archaeology, archaeometry and technological reconstruction in order to understand ancient metallurgy as a complex process extending from raw material acquisition to finished products.

The development of metallographic, chemical and isotopic approaches further transformed research questions. While early compositional studies aimed primarily at characterising metal groups, increasingly sophisticated analytical methods made it possible to investigate alloying practices, production technologies and patterns of circulation. Lead isotope analysis, introduced into archaeological research during the 1960s and widely developed in subsequent decades (Brill and Wampler, 1965; Gale and Stos-Gale, 1982, 1989), considerably expanded provenance studies, while also revealing the complexity of ancient metal circulation, including recycling, mixing and transformation.

Rather than seeking direct links between individual artefacts and specific ore sources, archaeometallurgy progressively shifted towards reconstructing broader systems of production, exchange and technological knowledge. By combining analytical results with archaeological contexts, researchers increasingly approached metals as dynamic materials embedded in economic networks, social practices, and cultural choices.

Beyond diffusionism: multiple trajectories of metallurgical innovation

Alongside methodological advances, interpretations of the origins and spread of metallurgy underwent a profound transformation. Early debates opposed diffusionist models, which postulated a single centre of metallurgical innovation, to hypotheses emphasising multiple independent trajectories. T. Wertime (1964, 1973), for example, argued that the complexity of extractive metallurgy implied one or a limited number of centres of invention, whereas C. Renfrew (1969) proposed that metallurgy could have emerged independently in different regions.

During the second half of the 20th century, archaeological discoveries increasingly challenged linear models of technological diffusion. Evidence from diverse regions demonstrated that early metallurgy had developed through a variety of local trajectories, shaped by distinct environmental, technological and social conditions rather than by a single process of transmission. At the same time, archaeometallurgy progressively shifted beyond the search for origins towards understanding metallurgy as a social, economic and cultural phenomenon. J. D. Muhly (1973) argued that metallurgy should be examined within the broader framework of ancient economies, emphasising its political, economic and social dimensions. This perspective was further developed by P. R. S. Moorey (1994), whose study of Mesopotamia deliberately moved beyond questions of invention or ore supply to explore the organisation of production, exchange and consumption within one of the ancient world's principal centres of craft activity. By demonstrating how a region poor in metal resources relied on long-distance procurement networks while becoming a major centre of technological innovation, Moorey highlighted the central role of trade, specialised craftsmanship and urban institutions in shaping metallurgical development.

Regional case studies reinforced this broader perspective. Research on the Iranian Plateau highlighted the diversity of metallurgical developments across Western Asia and the importance of regional technological traditions (Pigott, 1999b). In the Iberian Peninsula, archaeometallurgical studies increasingly emphasised local developments, resource exploitation and technological choices rather than simple external influences (Montero Ruiz, 1994; Ruiz Taboada & Montero Ruiz, 1999). Research in southern France likewise contributed to a more contextualised understanding of prehistoric metallurgy through

the investigation of early mining districts and production systems (Ambert, 1995). In Anatolia, the conference series *Anatolian Metal*, edited by Ünsal Yalçın, further contributed to this shift by bringing together archaeological, archaeometric and geological approaches to ancient metallurgy. These studies highlighted the diversity of Anatolian metallurgical traditions, the organisation of production systems, and the networks of exchange that connected Anatolia with neighbouring regions, from the Caucasus to the Eastern Mediterranean and the Iranian Plateau (Yalçın, 2000, 2005, 2011).

Beyond Europe and the Near East, archaeometallurgical research further demonstrated that metallurgical innovation followed diverse historical pathways shaped by local resources, social structures and cultural choices. In the Andes, H. Lechtman's work showed that metallurgical practices were inseparable from social values, political organisation and symbolic systems, fundamentally redefining the interpretation of pre-Columbian technologies (Lechtman, 1979, 1980). In North America, studies of native copper working in the Great Lakes region revealed an early and sophisticated tradition of metal use based on the extraction, shaping and circulation of native copper rather than extractive metallurgy, thereby challenging linear models of technological evolution (Ehrhardt, 2009). Research in Africa likewise undermined diffusionist interpretations by highlighting the diversity of metallurgical trajectories, the importance of local resource exploitation and the role of social organisation in technological development. Studies by Diop (1968), Trigger (1969) and Schmidt (1997), among others, demonstrated that African metallurgy cannot be understood simply as a consequence of external influences but rather as the outcome of locally embedded processes involving experimentation, knowledge transmission and specific relationships between communities and mineral resources. In Southeast Asia and China, archaeological research revealed distinct trajectories of copper and bronze production shaped by local experimentation, regional interactions and particular social contexts (Higham, 1989; White and Pigott, 1996; Bai, 2003; Linduff and Mei, 2009).

Together, these developments transformed archaeometallurgy from a discipline primarily concerned with the origins and diffusion of metallurgy into a field focused on the diversity of metallurgical practices and their integration within human societies. The central question was no longer where metallurgy began, but how different communities developed, transmitted, adapted and gave meaning to metallurgical knowledge within interconnected historical, economic and cultural landscapes.

ARCHAEOMETALLURGY TODAY: FROM MATERIAL CHARACTERISATION TO SOCIO-TECHNICAL SYSTEMS

Over the last decades, archaeometallurgy has increasingly developed as the study of metals as socio-technical systems, integrating technological processes, resource management, exchange networks and social practices. This evolution reflects a broader shift within the discipline, which has progressively moved beyond the study of metals as isolated materials or technical achievements. Rehren (2000) notably emphasised the need to avoid treating archaeometallurgy as an isolated field centred exclusively on analytical methods, arguing instead for a stronger integration of scientific approaches with archaeological, social and historical interpretations. Current research no longer focuses solely on the composition and manufacture of individual objects, but examines the multiple trajectories through which metals are acquired, transformed, circulated, used and deposited.

A major characteristic of contemporary archaeometallurgy is therefore a shift of scale: from the artefact to the chaîne opératoire, from workshops to production landscapes, and from regional assemblages to long-distance networks. This change has required the articulation of archaeological investigation with materials science, geology, anthropology, environmental studies and digital approaches. Scientific analyses are now increasingly interpreted within broader archaeological frameworks, aiming to reconstruct not only how metals were produced, but also how metallurgical knowledge, resources and practices were embedded within past societies.

This interdisciplinary perspective has been consolidated through a series of collective syntheses and methodological contributions that have highlighted both the global diversity of metallurgical traditions and the importance of integrating archaeological and materials science approaches (e.g. Roberts et al., 2009; Roberts and Thornton, 2014; Hauptmann, 2020). In parallel, the development of large collaborative research programmes and shared analytical infrastructures has enabled archaeometallurgy to address increasingly ambitious questions, combining extensive datasets, advanced analytical techniques and comparative approaches across broad geographical areas.

From provenance to metallurgical networks: resources, circulation and landscapes

The study of mineral resources and metal circulation has been one of the major fields of transformation in contemporary archaeometallurgy. While early provenance studies often aimed to establish direct relationships between artefacts and geological sources, research has progressively demonstrated that ancient metal circulation cannot be reduced to simple source attribution. Metallurgical processes, alloying, mixing of ores, recycling and the circulation of semi-finished products frequently modified the original signatures of raw materials. Current approaches therefore seek to reconstruct broader systems of production, circulation and transformation, in which metals are considered as materials embedded within technological, economic and social networks.

This evolution was made possible by the integration of mining archaeology, geological characterisation and

archaeometric analyses. Foundational studies demonstrated that ancient metallurgy could only be understood through the articulation of extraction, processing and manufacturing stages within complete technological sequences (Craddock, 1995; Hauptmann, 2007). The development of elemental and isotopic approaches considerably expanded these perspectives, while also highlighting the necessity of interpreting analytical results within their archaeological and technological contexts rather than as isolated chemical signatures (Mille and Bourgarit, 2000; Baron and Coustures, 2015).

One of the most significant conceptual shifts concerns the interpretation of mining activities themselves. Mines are no longer regarded solely as extraction sites, but as complex landscapes integrating technical practices, labour organisation, settlement patterns, mobility and environmental interactions. Research developed by T. Stöllner and collaborators has played a major role in this transformation, demonstrating how mining communities and production landscapes can be reconstructed through the combined study of archaeological remains, geology, landscape organisation and experimental approaches. Such perspectives have considerably broadened the understanding of ancient mining beyond the technical exploitation of ores (Stöllner, this volume).

At the European and Eurasian scale, recent research has increasingly combined large analytical datasets with archaeological contextualisation in order to reconstruct changing patterns of metal circulation. Studies of major mining districts illustrate the potential of this integrated approach: the distribution of copper from the Great Orme mine in Wales has been investigated through the combination of geological characterisation and artefact analyses (Williams, 2017), while recent research on north-western France has used thousands of elemental analyses and lead isotope measurements to reconstruct changing copper supply networks from the Middle Bronze Age onwards (Le Carlier de Veslud and Révillon, this volume). Similar approaches have been applied to the Iberian Peninsula, where archaeometallurgical investigations have explored the relationship between local copper resources, mining landscapes and broader exchange networks (Montero-Ruiz et al., this volume), and to western France, where recent research has reassessed prehistoric copper exploitation and circulation through combined archaeological and analytical approaches (Costa, 2023). At a wider continental scale, Tomczyk's research has contributed to modelling long-term relationships between ore exploitation, metal production and exchange networks across Europe through the integration of isotopic, archaeological and spatial data (Tomczyk, 2024).

Large collaborative projects have further accelerated this change of scale. The ERC BronzeAgeTin project (2013-2018, led by E. Pernicka) contributed to the development of tin isotope approaches and renewed discussions concerning tin supply during the Bronze Age, while the ERC FLAME project (*Flow of Ancient Metal across Eurasia*, 2016–2022, led by M. Pollard) created one of the largest comparative datasets of ancient metal analyses, providing new perspectives on circulation patterns across Eurasia. The Ancient Tin project (2020–2023, Leverhulme Trust, led by A. Williams; DEWA conference 2023, unpublished in this volume) has continued these discussions by investigating the role of British tin sources in Bronze Age European and Mediterranean exchange networks. Together, these programmes illustrate the transition from isolated provenance studies towards broader models of resource acquisition, mobility and economic organisation.

Beyond large-scale circulation networks, recent studies have also emphasised the importance of local mining traditions in the emergence and development of metallurgy. Research on the prehistoric copper mines of Roua in the southern Alps has demonstrated the significance of native copper exploitation during the 4th and 3rd millennia BC, combining field archaeology, mining studies and multi-method dating to reconstruct early extraction practices and their place within the emergence of metallurgy in Western Europe (Bussone, this volume). Such studies underline that metallurgical development resulted not only from long-distance exchanges but also from locally specific interactions between geological resources, technical knowledge and social organisation.

Overall, contemporary research has moved beyond the identification of metal sources towards the reconstruction of metallurgical landscapes and networks. From mining communities to interregional exchange systems, archaeometallurgy now investigates how geological resources were transformed into socially meaningful materials through interconnected processes involving technology, mobility, economic strategies and cultural choices.

Reconstructing technological systems: analytical methods, chaînes opératoires and craft organisation

The development of archaeometallurgy has been closely linked to the progressive integration of complementary analytical and archaeological approaches. Since its emergence as a research field, archaeometallurgy has combined the study of artefacts with investigations of technological processes, production remains and experimental reconstruction. Recent decades have nevertheless considerably expanded these approaches through the multiplication of analytical techniques, the development of large comparative datasets and the increasing integration of archaeological, geological and social perspectives. The objective is no longer only to characterise materials and reconstruct manufacturing processes, but also to understand how metallurgical knowledge, resources, technologies and practices were organised within broader social and economic systems.

Elemental and isotopic analyses have played a central role in this evolution. Advances in analytical precision have provided new opportunities to investigate alloying practices, raw material selection and patterns of circulation, while also reinforcing the importance of interpreting

scientific data within their archaeological and technological contexts. Portable X-ray fluorescence (pXRF) has become an important tool for non-destructive investigations in museums and field contexts, although its results require careful consideration of analytical limitations and surface alteration. Laboratory-based approaches, including LA-ICP-MS and ICP-OES, have provided increasingly detailed information on metal composition and technological choices (Mille and Bourgarit, 2000; Radivojević et al., 2019). Similarly, isotopic studies—particularly lead isotope analysis—have progressively developed from provenance-oriented approaches towards more complex interpretations integrating geological variability, metallurgical processes, recycling and patterns of mobility (Baron and Coustures, 2015).

Beyond composition, contemporary archaeometallurgy increasingly focuses on the reconstruction of *chaînes opératoires* and technological choices. Metallography and microstructural analyses provide access to manufacturing sequences, heat treatments and technical decisions that are invisible from macroscopic examination alone (Scott, 1991). Experimental archaeology has played a major role in this development by testing hypotheses concerning smelting, casting, forming and finishing techniques, while also providing insights into the skills and knowledge required for ancient metalworking. Combined with technological studies and archaeometric investigations, these approaches have contributed to a renewed understanding of craft practices as embodied knowledge rather than purely mechanical processes (Drescher, 1958; Armbruster, 2000). The recent reassessment of lost-wax casting process illustrates this renewed perspective by revealing the complexity and diversity of manufacturing sequences (Picod and Mordant, 2005), reconstructing its long-term development across Eurasia (Mille, 2017), and demonstrating the existence of advanced regional traditions, notably in Atlantic Europe during the Middle Bronze Age, thereby challenging earlier diffusionist interpretations (Nordez, 2024; DEWA Conference 2023, unpublished contribution).

This interest in technical gestures has also encouraged a broader reassessment of metallurgical tools and production equipment. Rather than being interpreted only as functional objects, hammers, anvils, moulds and stone tools are increasingly studied as evidence of specialised practices, workshop organisation and technical expertise. Recent research on metallurgical toolkits has combined typological analysis, use-wear studies, residue analysis and experimental approaches to identify the activities and skills involved in metal production (Boutoille and Peake, 2023; Boutoille, 2025; Hamon and Delgado-Raack, this volume).

At the same time, archaeometallurgy has progressively shifted from the study of isolated techniques towards the investigation of production contexts and the social dynamics of craft activities. Excavations of mines, workshops and settlements have demonstrated that metallurgy was embedded within broader economic, social and political structures. Earlier studies of mining districts and production areas showed how archaeological contexts could reveal labour organisation, craft specialisation, and the relationships between technological practices and broader social structures (Yener, 2000; Hauptmann, 2007; Roberts and Thornton, 2014). Recent research has further refined these perspectives by examining the diversity of production settings, from dedicated workshops to household-based activities.

Studies of production places increasingly combine spatial analysis, technological reconstruction and archaeometry to investigate how craft activities were organised. Research on Bronze Age metalworking in Scandinavia, for example, has demonstrated that production was not exclusively restricted to centralised elite-controlled workshops but occurred within a variety of settlements and social contexts, revealing a complex and multi-level organisation of craftsmanship (Sörman, this volume). Similar approaches have been applied to Near Eastern contexts, where archaeological and textual evidence contribute to reconstructing the status of metalworkers, the circulation of technical knowledge and the social framework of craft production (Joannès, this volume).

Technological studies have also shown that finished objects themselves can provide valuable insights into manufacturing systems. Through radiography, CT-scanning and technological classification, recent research has demonstrated that manufacturing choices can reveal production groups, changing degrees of standardisation and the evolution of manufacturing traditions. The study of Bronze Age swords in Europe by Dumont (2022; this volume) illustrates how large-scale technological datasets can be used to reconstruct changing production structures and the transmission of technical traditions. Likewise, investigations of exceptional metal assemblages, such as the Early Bronze Age gold and silver objects from the Maikop kurgan, reveal the complexity of ancient craft expertise through the study of tool marks, manufacturing techniques and functional choices (Armbruster, this volume). Analyses of copper-alloy artefacts from the Talysh region further demonstrate how imaging techniques and compositional analyses can illuminate technological practices within funerary contexts (Haze et al., this volume).

Together, these developments demonstrate that archaeometallurgy has moved from the identification of techniques towards the reconstruction of technological systems. Analytical methods remain essential, but their significance lies in their ability to reveal the organisation of knowledge, the choices made by craftspeople and the social contexts in which metallurgical practices were embedded.

From objects to biographies: circulation, value and deposition practices

The study of metal artefacts has progressively expanded beyond questions of production and typological classification to investigate the multiple stages of their existence after manufacture. Building on the concept of object biographies, increasingly used in archaeological research, met-

als are now approached as materials that underwent successive transformations through circulation, use, repair, recycling and deposition. This perspective has contributed to reconnecting technological studies with broader questions concerning value, exchange, identity and the social relationships established around material objects.

One important development has been the growing integration of technological, functional and contextual approaches to investigate how objects were used and transformed over time. Wear traces, repairs, modifications and recycling practices provide insights into interactions between objects and users, revealing that metal artefacts were not static products but materials continuously reshaped through human practices. Recent use-wear and techno-functional approaches, combining microscopic observations, experimental studies and contextual analysis, have considerably refined our understanding of the practical life of metal objects (Dolfini, DEWA conference 2023, unpublished contribution). Similarly, the integration of elemental analyses, geometric morphometrics and technological studies has opened new perspectives for investigating relationships between manufacture, use and deposition, as illustrated by recent work on Late Bronze Age axe blades (Enudde et al., this volume).

The circulation of metals has also increasingly been studied through the perspective of value, measurement and exchange systems. Beyond identifying trade routes, current research investigates how metals were measured, standardised, transformed into units of value and integrated into wider economic practices. Recent studies on Bronze Age metrology have demonstrated the importance of weight systems and measurement practices for understanding the organisation of exchange and the circulation of metal value across regions (Ialongo et al. 2021; Poigt, 2023). The ERC WEIGHT AND VALUE project (*Weight metrology and its economic and social impact on Bronze Age Europe, West and South Asia*, 2015–2022, coordinated by L. Rahmstorf) significantly contributed to this research agenda by exploring the relationship between weighing systems, standardisation practices and the economic organisation of Bronze Age societies.

Alongside these approaches focusing on measurement and value systems, recent research has also investigated standardisation and serial production as indicators of craft organisation and exchange networks. The SerialKey project (ANR Access ERC Starting Grant, 2024–2026, coordinated by L. Dumont) explores how the study of large series of metal objects, through technological, morphometric and spatial approaches, can provide new insights into production organisation, technical choices and the circulation of artefacts. These perspectives are further enriched by comparative approaches to ancient systems of value and circulation (Brandherm et al., 2017; Milcent, 2017), which highlight the close relationships between material culture, economic practices and social organisation.

This broader understanding of circulation has also transformed the interpretation of metal hoards. Long debated mainly through opposing economic and symbolic explanations, hoards are now analysed through their archaeological contexts, spatial organisation and relationships with surrounding structures. Rather than being considered isolated collections of objects, they are interpreted as deliberate actions embedded within landscapes, settlements and social practices. Recent research has shown that hoards could be associated with diverse situations, including storage, recycling, craft activities, household practices, communal gatherings or ritualised transformations of space (e.g. Tarbay, 2022; Nordez, 2023; Maciejewski et al., 2025; Hashemi et al., 2023; Milcent et al., 2023). Similar approaches in Southwest Asia have highlighted the diversity of practices underlying metal deposition, showing the importance of integrating object categories, archaeological contexts and social meanings rather than relying exclusively on typological classifications (Hashemi, this volume).

Together, these developments illustrate a broader transformation in archaeometallurgy: metal objects are no longer considered only as products of technical processes, but as materials whose meanings and functions evolved through successive interactions between resources, craftspeople, users and communities. By studying circulation, value, use and deposition, archaeometallurgy contributes to a more comprehensive understanding of how metals participated in the organisation of past societies.

Current challenges: data, environment and global collaboration

Despite these major advances, several challenges remain central to the future development of archaeometallurgy. The increasing production of large analytical datasets raises important questions concerning the harmonisation of protocols, reporting standards, reference materials and data accessibility. In this context, the implementation of FAIR data principles (Findable, Accessible, Interoperable and Reusable) has become a major objective for archaeological science, aiming to improve the transparency, long-term preservation and reuse of analytical datasets. The comparability of elemental, isotopic and spatial datasets depends not only on analytical precision but also on transparent documentation of sampling strategies, analytical procedures and interpretative frameworks. Discussions within archaeological science have emphasised the importance of reproducibility, open-access databases and sustainable research infrastructures as essential conditions for large-scale comparative approaches (Killick and Fenn, 2012; Kintigh et al., 2014; Pernicka, 2014; Marwick, 2017).

A second major challenge concerns the integration of metallurgy within broader environmental and landscape perspectives. Ancient mining and metal production are increasingly understood not only as technological activities but also as processes that transformed ecosystems, landscapes and human–environment relationships over the long term. Research on mining landscapes, particularly that developed by T. Stöllner and collaborators, has demonstrated that extraction sites must be studied together with associated settlements, infrastructures,

communication networks, resource management strategies and labour organisation. The combination of archaeological evidence with geological, geomorphological and palaeoenvironmental archives—including sediments, peat and ice-core records—offers new perspectives for assessing the environmental impact and long-term consequences of metallurgical activities (Knabb et al., 2016; Silva-Sánchez and Armada, 2023).

Finally, future developments in archaeometallurgy will depend on strengthening international and interdisciplinary collaborations. While analytical facilities, reference collections and digital infrastructures have expanded considerably, access to these resources remains uneven across regions and research communities. Addressing questions concerning the emergence, development and circulation of metallurgical technologies requires collaborative frameworks bringing together archaeologists, archaeometrists, geologists, historians, experimental specialists and digital researchers. Such cooperation is also essential for integrating diverse archaeological traditions into broader comparative perspectives while preserving the specificity of regional histories.

Finally, future developments in archaeometallurgy will depend on strengthening international and interdisciplinary collaborations. While analytical facilities, reference collections and digital infrastructures have expanded considerably, access to these resources remains uneven across regions and research communities. Addressing questions concerning the emergence, development and circulation of metallurgical technologies requires collaborative frameworks bringing together archaeologists, archaeometrists, geologists, historians, experimental specialists and digital researchers. A major example of this approach is provided by the Iranian-German research project *Ancient Mining and Metallurgy on the Western Central Iranian Plateau* (2000–2005). Focusing particularly on the prehistoric metallurgical centre of Arisman, the project combined archaeological excavation, mining archaeology, geological studies and archaeometric analyses to investigate the organisation of copper production from raw material procurement to processing and metal production. The resulting volume edited by A. Vatandoust and collaborators (2011) constitutes a comprehensive integrated studies of prehistoric metallurgy on the Iranian Plateau, demonstrating the complexity of early production systems and the importance of local resources, specialised activities and technological knowledge in the development of metallurgical communities. Such collaborative frameworks are also essential for integrating diverse archaeological traditions into broader comparative perspectives while preserving the specificity of regional histories.

More broadly, contemporary archaeometallurgy is increasingly moving towards the study of socio-technical systems in which materials, technologies, environments and communities are interconnected. By combining scientific analyses with archaeological, social and environmental approaches, the discipline provides new ways of understanding not only how metals were produced and exchanged, but also how they contributed to the organisation and transformation of past societies (Roberts and Thornton, 2014; Hauptmann, 2020).

CONTRIBUTION OF THE DEWA CONFERENCE

The contributions gathered in this volume reflect the major conceptual and methodological developments that currently characterise Metal Ages archaeometallurgy. Rather than considering metallurgy as a succession of isolated technical operations, they follow the trajectories of metals from resource acquisition to production, circulation, use and deposition. Through a combination of archaeological investigation, archaeometry, technological analysis, experimental approaches and historical sources, the volume explores how metals were embedded within economic systems, social practices and cultural traditions across a wide geographical area extending from Western Europe to Southwest Asia.

The first section focuses on mining and ore procurement, addressing one of the fundamental stages of the metallurgical chaîne opératoire: the relationship between mineral resources, extraction techniques and the emergence of metallurgical production. Several contributions examine ancient mining landscapes and the organisation of extraction activities, from early copper exploitation in the southern Alps (Bussone, this volume) to mining practices and fire-setting techniques across Europe, Eurasia and West Asia (Stöllner, this volume). Other contributions presented during the conference further expanded this perspective by addressing copper production in the Iranian Plateau (Nezafati and Stöllner, DEWA conference 2023, unpublished in this volume), copper mining in the Betic ranges (Montero-Ruiz et al., DEWA conference 2023, unpublished in this volume) and the role of tin sources and exchange networks in Bronze Age Europe (Williams et al., DEWA conference 2023, unpublished in this volume). Together, these studies illustrate the importance of integrating mining archaeology, geological characterisation and archaeometric analyses to reconstruct the first stages of metal trajectories.

The second section examines the places, tools and actors involved in metallurgical production. Moving beyond the identification of technical processes, the contributions investigate how craft activities were organised and how metallurgical knowledge was transmitted within different social contexts. Studies of workshops and production areas in France (Mélin and Néré, this volume; Blanchet and Mélin, DEWA conference 2023, unpublished in this volume), together with research on copper alloy production at Ayn Soukhna (Verly et al., DEWA conference 2023, unpublished in this volume) and precious-metal working at Saruq al-Hadid (Franke et al., this volume), demonstrate the diversity of archaeological evidence available for reconstructing metallurgical practices. Other contributions approach craft organisation

through tools, texts and spatial analyses, from the study of metallurgical stone tools and use-wear analysis (Hamon and Delgado-Raack, this volume) to the organisation of metalworking in Bronze Age Scandinavia (Sörman, this volume) and the social status of craftsmen in Mesopotamian contexts (Joannès, this volume).

The third section follows the transformation of raw metal into finished objects by focusing on manufacturing techniques, alloying practices and technological traditions. The contributions cover a broad geographical area, from the Caucasus and Iranian Plateau to Western Europe, illustrating the diversity of metallurgical choices and craft knowledge. Technological studies of exceptional assemblages, such as Early Bronze Age gold and silver objects from the Maikop kurgan (Armbruster, this volume), and analyses of copper-alloy artefacts from southern Azerbaijan and Iran (Haze et al., this volume), demonstrate the potential of combining technological reconstruction, imaging techniques and archaeometric analyses. Research on the long-term development of tin bronze metallurgy on the Iranian Plateau further illustrates how archaeometallurgical approaches can reveal changing alloying practices, technological choices and regional trajectories from the Bronze Age to the Iron Age (Oudbashi, this volume). Other contributions address the organisation of production and the transmission of technical knowledge through the study of bronze swords (Dumont, this volume) or ornaments (Nordez, DEWA conference 2023, unpublished in this volume), showing how manufacturing choices can reveal broader patterns of craft practice and innovation.

The final section considers the circulation, use and deposition of metal objects after production. These contributions emphasise that the life of metal artefacts continued far beyond their manufacture, involving exchange, transformation, use, repair and deposition. Studies combining chemical analyses, isotopic approaches and archaeological contexts investigate changing patterns of metal supply and circulation, including Bronze Age hoards from western France (Le Carlier de Veslud and Révillon, this volume) and object biographies reconstructed through technological and functional approaches (Enudde et al., this volume; Gorgues et al., this volume). Other contributions explore the social meanings of deposition practices, from metal artefact deposits in Southwest Asia (Hashemi, this volume) to the circulation and transformation of metal objects in Central Asian contexts (Luneau, DEWA conference 2023, unpublished in this volume).

Taken together, the contributions of the DEWA conference demonstrate the value of the chaîne opératoire as a framework for connecting different scales of analysis, from mineral resources and production techniques to exchange networks, object biographies and depositional practices. By bringing together case studies from Western Europe, the Mediterranean, the Caucasus, the Iranian Plateau, Central Asia and Southwest Asia, this volume highlights both the diversity of ancient metallurgical traditions and the methodological convergence that increasingly characterises archaeometallurgical research today.

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Session 1

Mining and ore extraction activities

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If Southwest Asia is a *Heartland of Metallurgy*, where are the mines?

Vincent C. Pigott and Vanessa Workman

Abstract: This paper examines early mining and metallurgy in Southwest Asia, a region often regarded as a heartland of metal production, yet lacking comprehensive archaeological documentation of its vast numbers of ancient mines. Focusing on copper and tin, the key components of tin-bronze, the study highlights the sparse, published evidence from some of the region's well documented mining sites, including Derekutugun (native copper) and Kestel/Göltepe (tin) in Anatolia, Vashnaveh (copper) and Deh Hosein (copper-tin) in Iran, and the Arabah Valley mining districts (copper) in the southern Levant. Here, we review the geological and technological contexts of these sites, detailing early mining techniques, ore extraction processes, and the role of metallurgy in regional economies from the Neolithic through the Iron Age of these two consequential metals. A brief discussion on future research directions is also included, focusing particularly on the isotopic analysis of metal sources and the trade networks that distributed these materials across the ancient Near East. Overall, the paper contributes a synthesis of available evidence and addresses the limitations and strides made in the study of early mining and its impact on the many forms of metallurgy in the ancient past.

Keywords: Mining, Metallurgy, Near East, Southwest Asia, Levant, Copper, Tin-bronze.

Résumé : Cet article examine les débuts de l'exploitation minière et de la métallurgie en Asie du sud-ouest, une région souvent considérée comme le cœur de la production métallurgique, mais qui manque de documentation archéologique complète sur ses nombreuses mines anciennes. En se concentrant sur le cuivre et l'étain, les composants clés du bronze à l'étain, l'étude met en évidence les rares preuves publiées provenant de certains des sites miniers bien documentés de la région, notamment Derekutugun (cuivre natif) et Kestel/Göltepe (étain) en Anatolie, Vashnaveh (cuivre) et Deh Hosein (cuivre-étain) en Iran, et les districts miniers de la vallée d'Arabah (cuivre) dans le sud du Levant. Nous passons ici en revue le contexte géologique et technologique de ces sites, en détaillant les techniques minières anciennes, les processus d'extraction du minerai et le rôle de la métallurgie dans les économies régionales, du Néolithique à l'âge du Fer, pour ces deux métaux importants. Une brève discussion sur les orientations futures de la recherche est également incluse, axée en particulier sur l'analyse isotopique des sources de métaux et les réseaux commerciaux qui distribuaient ces matériaux à travers le Proche-Orient ancien. Dans l'ensemble, cet article présente une synthèse des preuves disponibles et aborde les limites et les progrès réalisés dans l'étude de l'exploitation minière primitive et son impact sur les nombreuses formes de métallurgie dans l'Antiquité.

Mots clés : mines, métallurgie, Proche-Orient, Asie du sud-ouest, Levant, cuivre, étain-bronze

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Broadly speaking, the advent of settled village life in Southwest Asia ensued in the period circa 12,000–10,000 BCE. Importantly, within the following millennia two critical technological transitions, among many, were emerging, namely the advent of mining and metallurgy. It is the act of mining, a kind of landscape exploitation, that underpins many of the papers presented in this publication. Our paper has two main goals, first, to discuss succinctly what evidence does exist for the few, major, excavated and well documented Southwest Asian copper and tin mines and second, to succinctly overview the research problems that are most relevant to these mines.

REGIONAL TECTONICS AND ORE GEOLOGY OF SOUTHWEST ASIA

Early mining and metallurgy ensued in the extremely tectonically active, geologically tortured if you will, ore-rich regions of Southwest Asia, essentially the Fertile Crescent which for our purposes here includes the Anatolian and Iranian Plateau, then arcing across northern Mesopotamia and south into the Levant (figs. 1 and 2). The plate tectonics responsible for the complex geology of these regions generated significant metallogeny via plate contact and

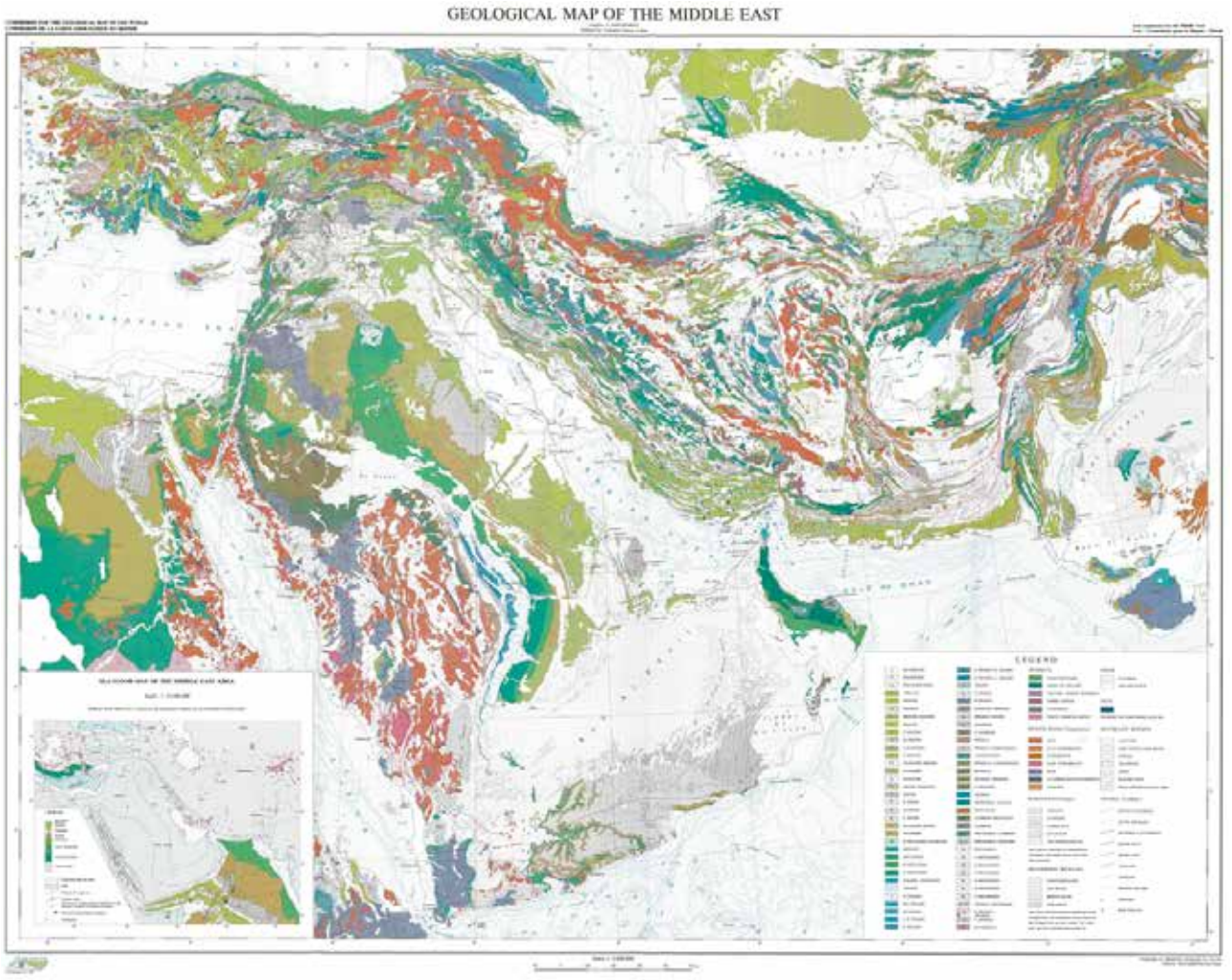


Fig. 1 – Geological map of the Middle East demonstrating its complex tectonic structure – (Map courtesy of the Geological Survey of Iran, 1986; Compiler Dr. Aghanabati).

subduction, vulcanism and metamorphism as well as myriad other powerful geological forces at play over the epochs. Over time, the ores exploited for the metals of antiquity were emplaced and weathered surficially often providing colorful, topographic clues to the presence of pigments/ochres, native copper and ultimately ores resting beneath. Here, we focus the following discussion on copper and tin, two metals that comprise the alloy tin-bronze and whose ancient mining played impactful roles in evolving societies and their economies in the greater region for millennia. The coming of tin-bronze in the late 4th/early 3rd millennium BCE is rivaled in terms of technological impact only by the later 2nd millennium BCE innovation of iron (e.g., Pigott, 2021; Erb-Satullo, 2019).

Figure 2, moving west from Afghanistan to Iran to Anatolia and southward to the Levant, presents some sense of the remarkable abundance of documented ore deposits, some with ancient mining, spread across Southwest Asia. Yet from this extraordinary multitude of known deposits, documented primarily by economic geologists, the number of archaeologically documented, i.e., those which have been excavated, chronometrically dated and subsequently published, currently remains strikingly small. Thus, we are significantly underinformed about the extractive processes that have allowed for the production of thousands upon thousands of artifacts in copper and its various alloys, used over millennia in Southwest Asia at many of the sites seen in Figure 2. The excavated mines our discussion will focus on are 3rd millennium BCE Derekutugun (native copper) and Kestel/Göltepe (tin) in Anatolia, ca. late 3rd/late 2nd millennium BCE Veshnaveh (copper) and 2nd millennium BCE Deh Hosein (copper-tin) in Iran, and the late 4th–1st millennium BCE mines of the Arabah, Timna (copper) in Israel and Faynan (copper) in Jordan.

LOCAL TECHNOLOGICAL DEVELOPMENTS: EXTRACTION FROM SEMI-PRECIOUS STONE TO METALLURGY

The Southwest Asian zone encompassing Anatolia, Iran, northern Mesopotamia, and the Levant, essen-

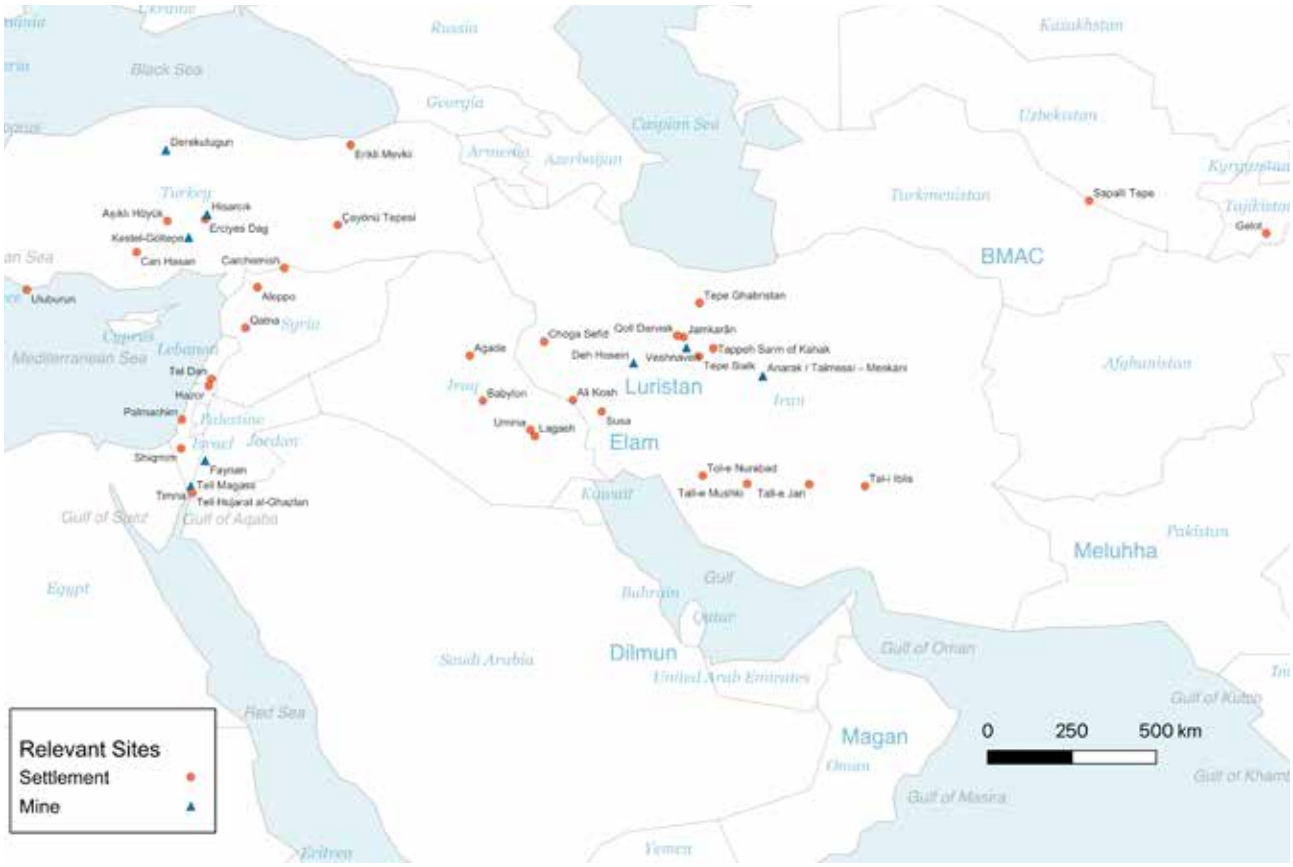


Fig. 2 – Mines and relevant sites in Southwest, Central and South Asia mentioned in the text (credit: J.B. Lowe)

tially the Fertile Crescent, can be considered the location of this region's metallurgical "heartland" in which the earliest known exploitation of copper-base ore minerals for pigments and beads began around the 11th millennium BCE (Roberts et al., 2009; Pernicka and Anthony, 2010, p. 164; see also Pigott, 2021, p. 828, fig. 29.1; Pigott: in press, fig. 1). Such mineral exploitation was followed by the use of native copper for beads and small implements from about the 8th millennium BCE. Well known examples of early (i.e., Neolithic) native copper use are: the folded bead from Ali Kosh in Iran (Smith, 1968; 1969); the multiple occurrences of beads at Aşıklı Höyük (Yalçin and Pernicka, 1999) and Çayönü Tepesi in Anatolia (e.g., Muhly, 1986, p. 5–7; Stech 1990). Less well known, but comparably early finds in this metal come from sites elsewhere, notably in Iran: Choga Sefid in Deh Luran, Tol-e Nurabad, Tall-e Mushki, Tall-e Jari in Fars, Tepe Sialk on the Iranian Plateau (Weeks, 2013, p. 278). The hammered, native copper mace head from Can Hasan can be considered anomalous based on its size, weight and that it was most probably used as a weapon (Yalçin, 1998). At 4th millennium BCE Tepe Yahya in Kerman in Iran, native copper use persisted here even as smelting emerged on the scene (Weeks, 2013, p. 278). Many of these finds comprise important examples of the initial (Neolithic) utilization of native metal for mostly decorative/aesthetic effect. Did these examples of experimenting with materials for such an effect pave the way for future metals-related innovations? Some would agree, others would not.

Millennia passed before the smelting of copper-base ores from ca. 5000 BCE and later can be documented (e.g., Roberts et al., 2009). The earliest dates for smelting and tin-bronze occurrences, ca. 5000 BCE are known currently from the Balkans/Serbia (Radivojević et al., 2021). Further east in the heartland, smelting is documented during the 5th/4th millennium BCE at sites including Tal-i Iblis (e.g., Pigott and Lechtman, 2003; Frame, 2012) and Tepe Ghabristan in Iran (e.g., Majidzadeh, 1979; Fazeli et al. 2005).

In the southern Levant, by the late 4th–early 3rd millennium BCE (Levantine Chalcolithic to Early Bronze Age), copper mining and smelting were active. This is concurrent with a broader appearance of copper-base objects, found in hoards and in settlement sites. The archeometallurgical record includes evidence for the exploitation of local ore sources in the Arabah Valley and small-scale production of copper artifacts at Chalcolithic period sites (Conrad and Rothenberg, 1990; Hauptmann, 2007; Levy et al., 2002). Simultaneously, the importation of a non-local copper metal—an arsenic-antimony-copper alloy—is evidenced by the analytical results from Chalcolithic metal finds at sites such as Nahal Mishmar, Shiqmim, and Palmachim (Tadmor et al., 1995; Shalev and Northover, 1993).

With regard to the exploitation of ores, when actual shaft and gallery mining began is a matter of some debate, but early on people were pitting into the surfaces of ore deposits in search of pigments. A progression from pits to shaft and gallery exploitation strategies is generally accepted along with alluvial and eluvial deposit mining occurring consistently across time (see fig. 3 for the mining chaîne opératoire). A significant number of the copper ore deposits noted in the maps above, with the exception of most of those in the Levant, are of the surface exposed, weathered copper sulfide type which means they have a reasonable likelihood of having ochreous pigments like hematite and also native copper accessible at or near their surfaces, often in the gossans that cap them (fig. 4). These gossans, the 'chapeaux du fer' or the 'Eisenhütten' are said to signal what lies beneath, but, until recently, it was very difficult to document the act of 'mining' native copper anywhere in the greater region. Well-known massive copper deposits, such as at Ergani Maden in central eastern Anatolia, and those in the Anarak (Talmessi/Meskani) mining district of central Iran, are native copper-bearing and are suggested to be among the important sources of this metal in early prehistory (e.g., Pernicka et al., 2011, p. 635–637, 643). Regrettably, modern mining has destroyed most indications of early exploitation at these and other mined ore deposits. It is also the case that native copper occurs in the upper zones, if not right at the surface of sulfidic orebodies, and therefore could have been easily collected and/or grubbed for by shallow surface pitting. An excellent and, in fact, the only exca-

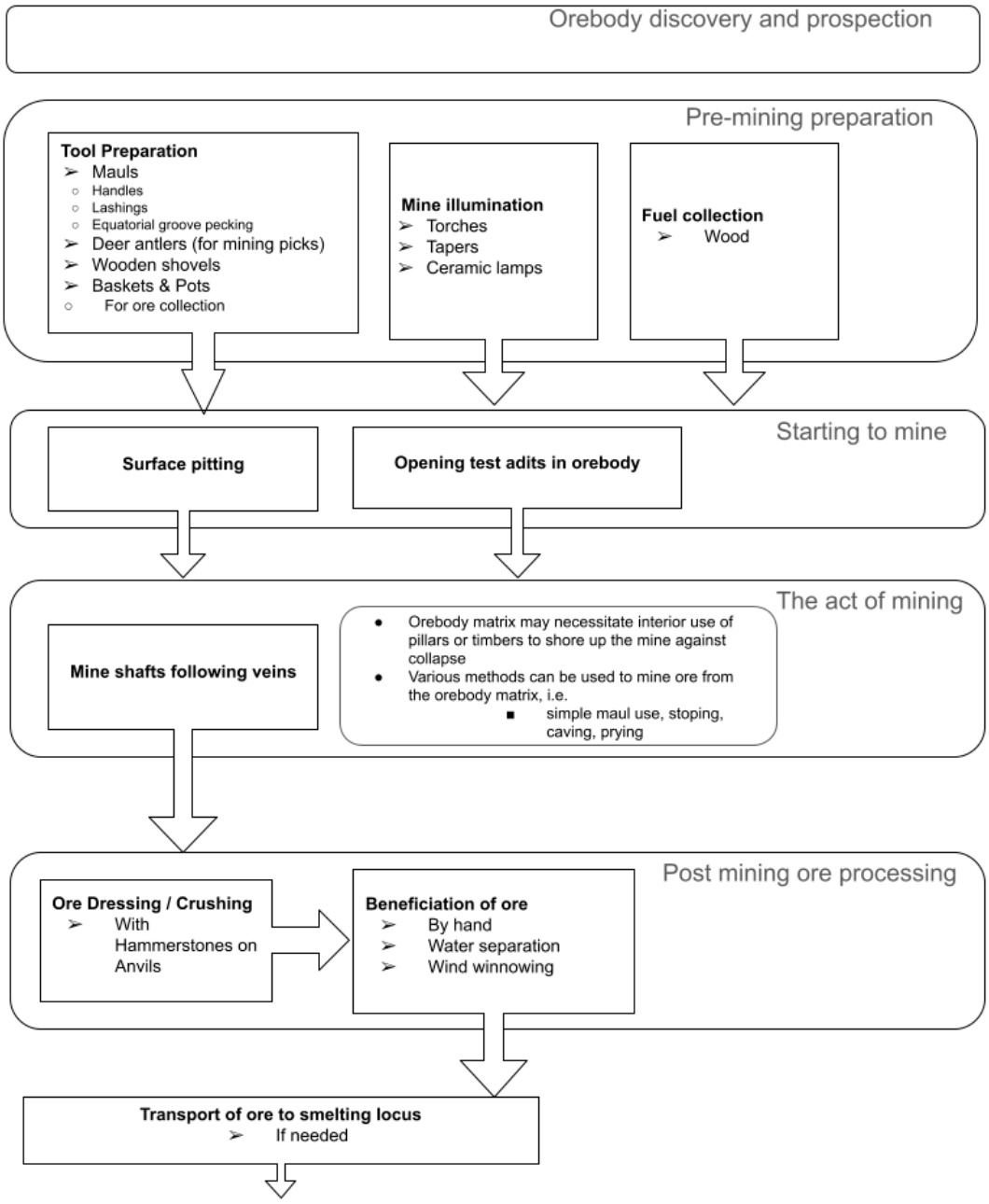


Fig. 3 – The *chaîne opératoire* for mining, from the discovery of a viable ore body to the transportation for reduction/smelting.

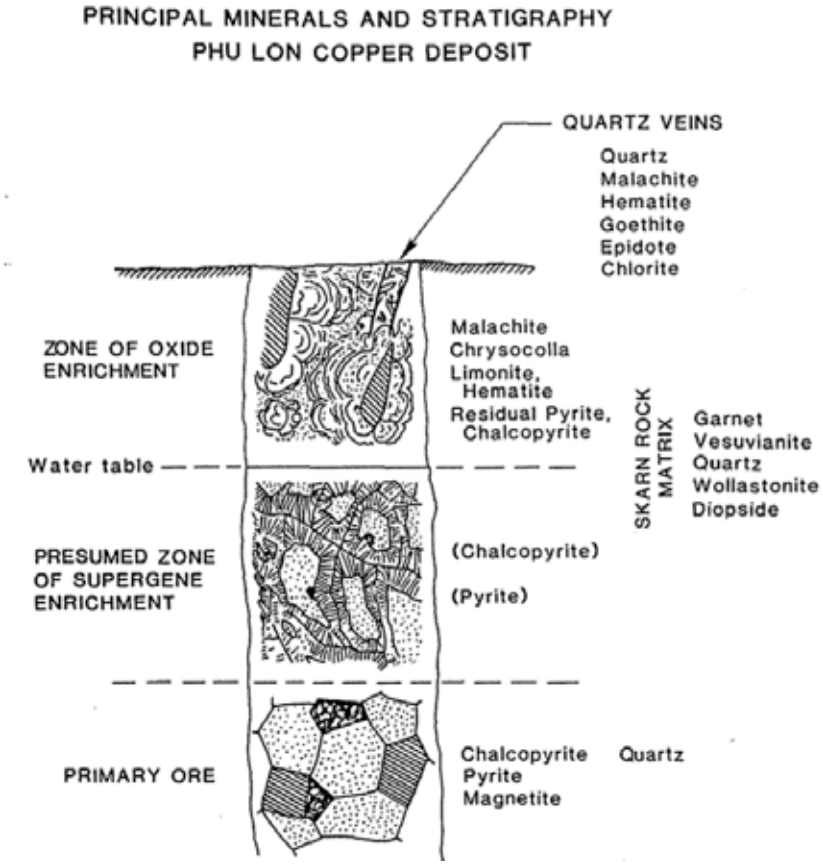


Fig. 4 – Schematic diagram of a weathered copper sulfide deposit capped by a gossan. Note the mineral changes from the primary ore layer to the oxide zone. Native copper is found in the surface gossan and in the Zone of Oxide Enrichment (diagram by W. W. Vernon in Rostoker et al., 1989, p. 71).

vated example, comes from the site of Derekutugun in north central Anatolia, where researchers collected pieces of native copper in stream beds close to the mine (e.g., Yalçin and Ipek, 2016, p. 19, Abb. 7)

COPPER AND TIN MINES OF SOUTHWEST ASIA

Derekutugun native copper mine (north central Anatolia)

The Derekutugun mine is located near a village of the same name in the Bayat district of Corum Province of north central Anatolia (Yalçin et al., 2019, p. 122, fig. 3) (fig. 5) It is the only well documented locus of prehistoric native copper mining in Southwest Asia. It was excavated by Dr. Ünsal Yalçin and team from the Deutsches Bergbau-Museum in Bochum, Germany between 2009–2011 and 2015–2017. Particular archaeological attention was paid by this project to the area known as the Maziönü locality. This mining locus has been dated to the first half of the 3rd millennium BCE, but there is every indication this native copper deposits was exploited much earlier according to its excavator. The basic geology of the deposit is described as follows:

> "a red bed deposit type that was formed in an arid basin margin. The native copper could have been enriched in the groundwater by leaching of surrounding copper-bearing rocks and impregnated into the loose sediments in a reducing environment. This process was probably promoted by the high sulfate content, or the high sulfate content of the groundwater was the prerequisite for the leaching and enrichment of the copper (Aral, 1990). The gray-green conglomerate series contain partially charred plant remains, which confirm a reducing environment (Yalçin and Maass, 2013, p. 4)."

Thus, the native copper was formed over epochs in "cracks and cavities of Miocene sediments" and as mentioned, by leaching by sulfate-rich groundwater. The metal often co-occurs with the oxidic ores of malachite and cuprite and the deposit has pockets of rock salt and combustible lignite. All of these minerals could have drawn local peoples to seek them for various purposes. We see in Figures 6a and b, the steep cliff faces into which numerous mine shafts were dug and the location of a small settlement, found by geophysical prospecting, where crucibles, slag, potsherds and mining tools were found. The mining sequence is reconstructed as follows (see mine plan, fig. 6):

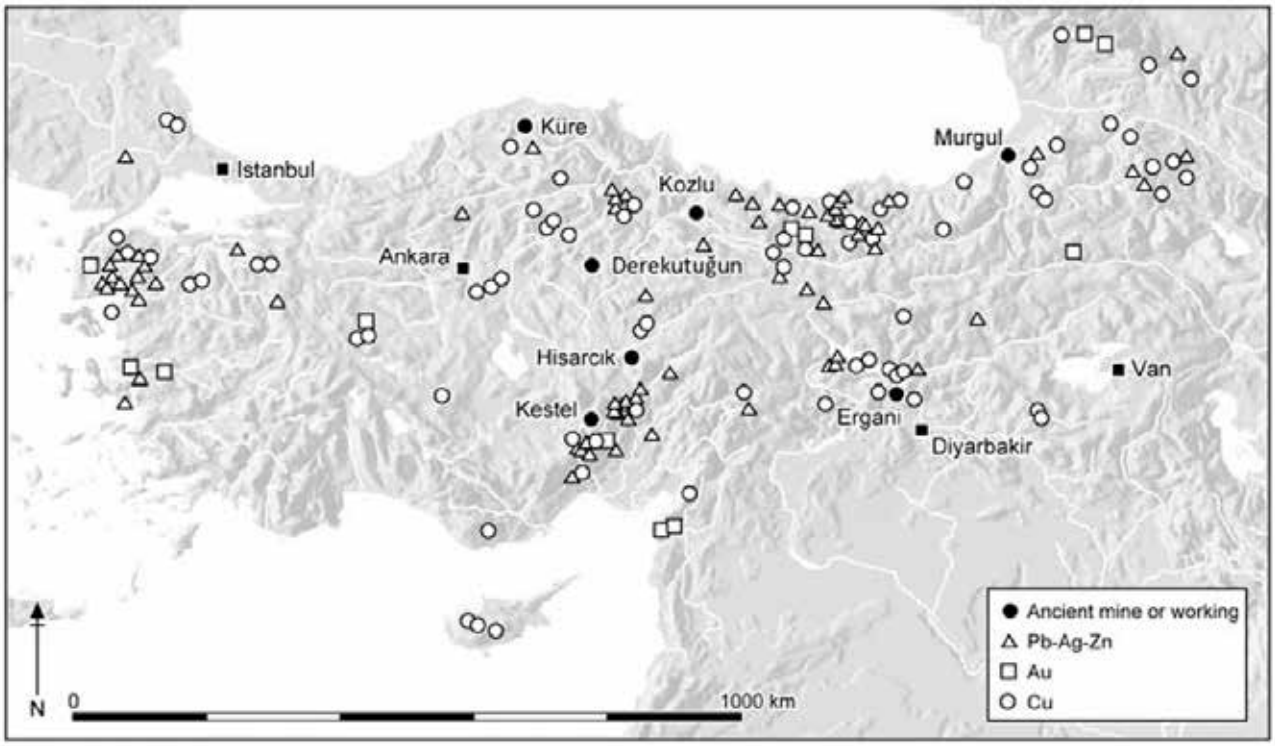


Fig. 5 – Known major ore deposits in Anatolia with important excavated pre-modern mines noted: Derekutugun: native copper; Kestel and Hisarcik: tin (after Lehner and Yener 2014, p. 532, fig. 20.1).

> "Following the copper-bearing cracks and layers, the Early Bronze Age miners entered the hill of Maziönü through a vertical shaft and then mined the metal in an east-west direction. So far, up to three floors have been identified in each of the four pits examined. Accordingly, the top floors would represent the older phases, and the bottom floors would represent the youngest phases. (Yalçin and Maass, 2013, p. 192, translated)."

The mine is best depicted through the maps and figures to follow. Figure 7a offers a wide view of the cliff face in which a multitude of mine shafts were dug in Prehistory in search of native copper. Given the steepness of the cliff-face one must wonder how the miners were able to negotiate the precipitous conglomerate cliff faces. The mining locus (Bergbaurevier) and the down slope mining settlement are indicated. Figure 7b shows the Maziönü

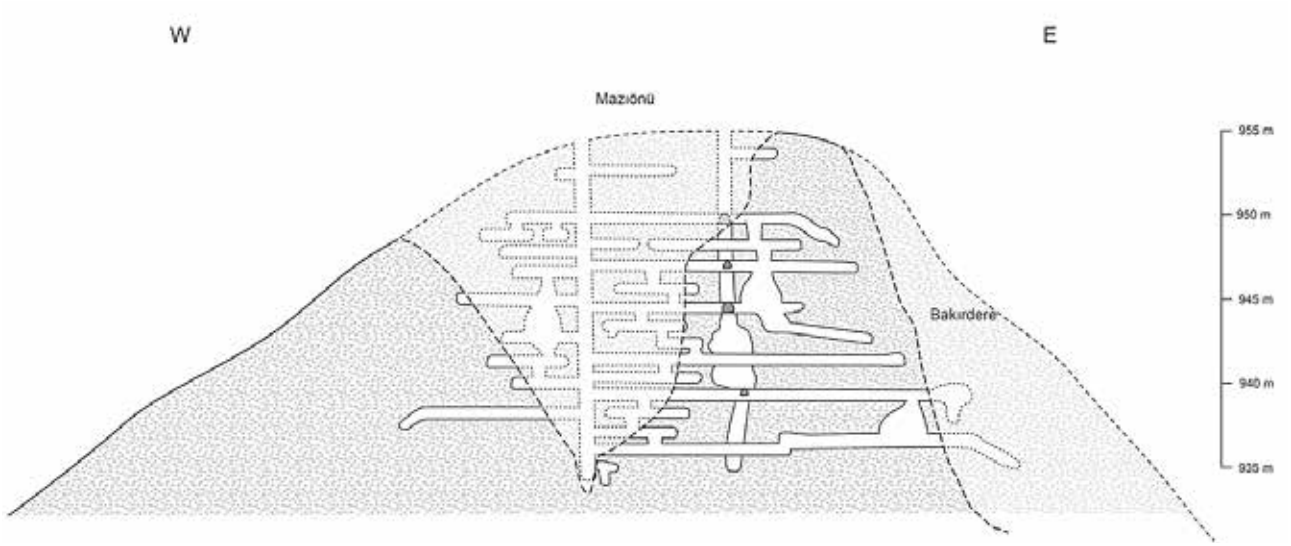


Fig. 6 – Derekutugun mine: diagram shows prehistoric mining works and their present morphology due to erosion (after Yalçin, and Ipek, 2016, p. 77, Abb. 92).



Fig. 7 – Ancient mining area, Bergbaurevier; a: located in the steep conglomerate wall at the Maziönü locus; the associated settlement (Siedlung) lies 300 m to the south (after Yalçin & Maass, 2013,p. 157, fig. 2); b: excavated ancient mining pits (G#'s) in the conglomerate wall of the Maziönü locus (after Yalçin & Maass, 2013, fig. 6).



Fig. 8 – Views of mine interiors at Derekutugun (after Yalçin & Maass, 2013, p. 162, Abb. 8, 172, Abb. 22).

area of the mine with its specific mining loci (G1, 2, 5, 5a, & 6). The mining complexes sit densely in this area, which emphasizes how intensive the mining activity was at Derekutugun. The sinuous profiles of the mine shafts are suggestive of the use of stone mining mauls to crush the orebody matrix containing the native copper in the slow, arduous process of hand mining (fig. 8). Numerous mining mauls and ore crushing tools did occur in the shafts and in vicinity of the pits, as well as near the mines (fig. 9a).[(1)] One so-called "pit" (Pit 1) had a length of ca. 20 m and an average height of 0.60m suggesting, in turn, prone miners working their way through the deposit. The shafts were probably initiated with the use of hand-held mauls which was in turn followed by, for example, the technique of prying off with wooden branch pry bars (see

1. Stone mining implements are discussed in greater detail in Yalçin and Ipek, 2016, p. 50–51, 53–54, 93–110).

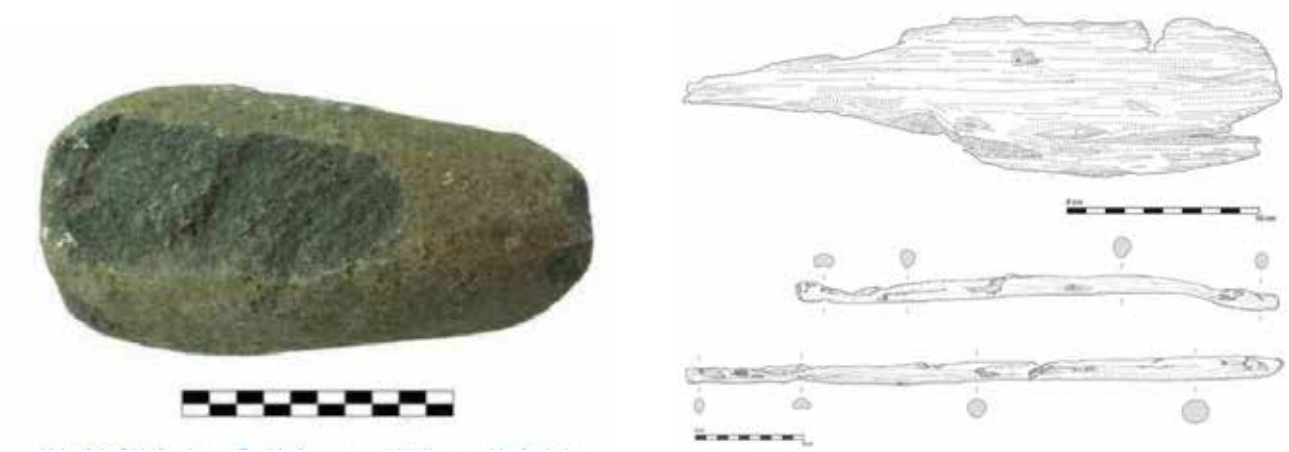


Fig. 9 – Mining tools of Derekutugun; a: peridotite mining maul from the immediate vicinity of the mining area; b: wooden (oak) mining shovel from mining locus 5a; c: two wooden (hazelnut) pry bars from mining locus 5a (Yalçin & Maass, 2013, p. 178, figs. 28, 29, 31).

fig. 9b) loose slabs of copper bearing wall rock. Some sort of 'picking' (holes 5 cm in size) with hardwood or horn (antler?) seems to be a common mining technique given the multitudinous marks seen in the mine walls. Also, apparently, some ore crushing with small stone hammers, did take place to some extent within the mine pits perhaps to make the mined material easier to remove.

Mined material was shoveled for removal using wooden shovels found in the mine into containers (ceramic?) (fig. 9b). Actual ore processing appears to have been carried out at the small, mining settlement about 300m down slope, where quite large hammerstones were found, one up to ca. 4 kg. Some, but not all, had been notched for hafting to a wooden handle. They were used to crush the host rock so the copper could be isolated for a final crushing using small hand-held, cylindrical to spherical hammers stones (ca. 600-700 g) against flat surfaced anvil stones (10–30 cm). Repetitive crushing produced round depressions in the anvil faces (4–10 cm in diameter and 0.5 cm in depth). The hand-held stone mining tools were mostly locally acquired peridotite, a hard coarse grained igneous rock ideally suited to ore crushing (fig. 9a). Other mostly hard stone cobbles in basalt, limestone, sandstone and andesite were also made modest use of. Some grinding stones were found, perhaps for fine crushing of ores, but not sure why this would be necessary for sorting the sizeable native copper fragments. They may have been used for food processing.

Figure 10 shows native copper from the mines, seen as nodules (10a) collected from stream beds near the mining area and native copper specimens (10b) from the mine which occurred in up to remarkably large 5 kg specimens. Specimens of this size presumably could have been cold worked into artefacts of some size or melted down for casting and perhaps even alloying with tin to make bronze. This alloy is known to appear initially during the



Fig. 10 – Native copper lumps from Derekutugun, found in a stream near the mines (left) and (right) in situ inside the mine [after Yalçin, and Ipek, 2016, p. 19, Abb. 7 (left) & 71, Abb. 87 (right)].

same period in which this deposit is being mined. The copper occurred in the conglomerates within the fissures as copper sheets or nodules (Yalçin and Ipek, 2016, p. 71, fig. 87). Most probably it was the process of the native copper eroding out of the conglomerate matrix and being re-deposited in the stream bed that led to the discovery of the deposit and its subsequent mining.

The copper itself bore noticeable traces of silver, gold and iron with silver characterizing Derekutugun copper. Various other elements were present as impurities at very low trace element levels (see fig. 41 and table 1 in Yalçin and Maass, 2013, p. 187–188). It should be noted that vanadium content can be 'quite high', but it appears to be associated with a higher gangue presence. A high vanadium presence was also noted in some slag from a looter's excavation at the Erikli Mevkii settlement locus and in the magnetite sands washed from the Bakredere stream near the mine.

Yalçin and colleagues' overall assessment of the lead isotope potential of Derekutugun is that it constitutes a 'closed isotope field' specific to the mine area such that it can be distinguished from various other ore-bearing loci in proximity to this mine and well beyond.[(2)] This has significant potential for linking copper from the mine to artifacts made from it and distributed throughout the greater region.

Potsherds and some complete vessels were also found in the mine shafts and pits with associations to other Anatolian sites (Yalçin and Maass, 2013, p. 14). Uniquely, wood (pine) 'kindling", a kind of long, thin taper it seems, for illumination were found on floors of some mine shafts II (Yalçin and Ipek, 2016, p. 52, Abb. 66, 67). There is no indication that fire-setting was used in this mine. Pits 5 and 5a yielded some 1650 traces of these thin tapers, ca. 4–18 cm long and often 4–6 cm in length and up to 10 cm long.

Initial ceramic finds in the vicinity of the mine indicated a prehistoric date and then with organic finds from within the mine itself, radiocarbon dating at the laboratory at ETH Zurich was performed on pieces of wood kindling, on 2 wood implements, a grain of grain and additional plant remains. The earliest dates for the Maziönü locus indicated a calibrated age of ca. 2900–2550 BCE, centered between ca. 2850–2700 BCE with a suggested periodization in the Anatolian Early Bronze Age II (Yalçin and Ipek, 2016, p. 185–186, Abb. 39). Suggested dating for mine ceramics supports an EBA date for the central and northern Anatolia region (Yalçin and Ipek, 2016, p. 17).[(3)] Mining in other loci at the mine dates as late as ca. 2000 BCE so it was exploited, perhaps intermittently, over the centuries.

Finally, this one-of-a-kind, all-important mining site must have yielded significant amounts of native copper over the centuries of the Anatolian EBA (see Aral, 1990, p. 67–71). The mined native copper in turn went into melting crucibles yielding substantial raw copper ingots(?) for local use as well as long distance trade for purposes of tin-bronze production early in the Bronze Age.

Kestel/Göltepe (south central Anatolia)

We turn now from the mining of native copper to tin mining at the highland Kestel/Göltepe tin mining complex in the ore-rich Bolkardağ district of Taurus Mountains of south-central Anatolia (fig. 11). The site was excavated in the 1980s and 1990s by Prof. K. Aslihan Yener of the Oriental Institute of the University Chicago and her team (Yener, 2000; 2021). The Kestel mining area is home to significant evidence of early tin mining and comprises the earliest known such mining in Eurasia ranging in date from late 4th well into the 3rd millennium BCE, but tin continued to be mined in the Bolkardağ at least until 2000 BCE (if not later). Calibrated ^{14}C dates range from ca. 3240–3100 BCE to 2870–2200 BCE (Yener, 2008, p. 58). EBA I-III ceramics were also found within the mine confirming its early mining activity.

In the ca. 2 km^2 area around the Kestel mines 1 and 2, substantial open pitting and ore processing is in evidence and probably represents early mining activity ca. 3000 BCE (Powell et al., 2021; Yener, 1996-7). Some evidence of crucible smelting of tin-bearing ore in this area was encountered and Yener suggests it may represent efforts to assay the ore "in order to make strategic decisions during mining" (Yener, 1996-7, p. 60). Estimates of ore extraction in the open-pitting zones around the mine entrances could range upwards of thousands of tons and that perhaps ten times as much ore was extracted in this manner than in the substantial underground workings. The mine's 4 km of tunnels produced ca. 4,600 m^3 of tin ore and it is possible, that even with working of a low-grade tin ore (1% Sn), ca. 115 tons of tin metal could have been produced from the Kestel mining locus over the span of a millennium (Yener, 2008, p. 58). This is certainly one of the largest ancient shaft and gallery mines known in Southwest Asia.

In the Kestel mine itself, there are two main episodes of mineralization, the first with a primary focus on cassiterite in the surface deposit. A second episode deposited a hematitic ore which was, within the mine, extracted for its albeit low tin content (fig. 12). This latter ore necessitated crushing and grinding by hand to a powder which was then smelted in ceramic crucibles. This was the main activity undertaken at the ore processing site of Göltepe some 2 km distant from the Kestel (Yener, 2021).

The tin-bearing, hematitic ore lumps from Kestel were hauled to this site to be beneficiated in pit workshops seen here (fig. 13). Surface survey yielded some 55,000 stone tools, 5,000 of which were excavated from the pit workshops. The tools were used to grind the ore to a powder rather than only crush it. The resulting powder (ca. 2% tin) was smelted in ceramic crucibles and

2. Lead isotope analysis of Derekutugun copper is discussed in greater detail in Yalçin and Maass, 2013, p. 188–191; Yalçin and Ipek, 2016, p. 74–76.
3. Mine ceramics are discussed in detail in Yalçin and Ipek 2016, p. 55–68, 111–194.

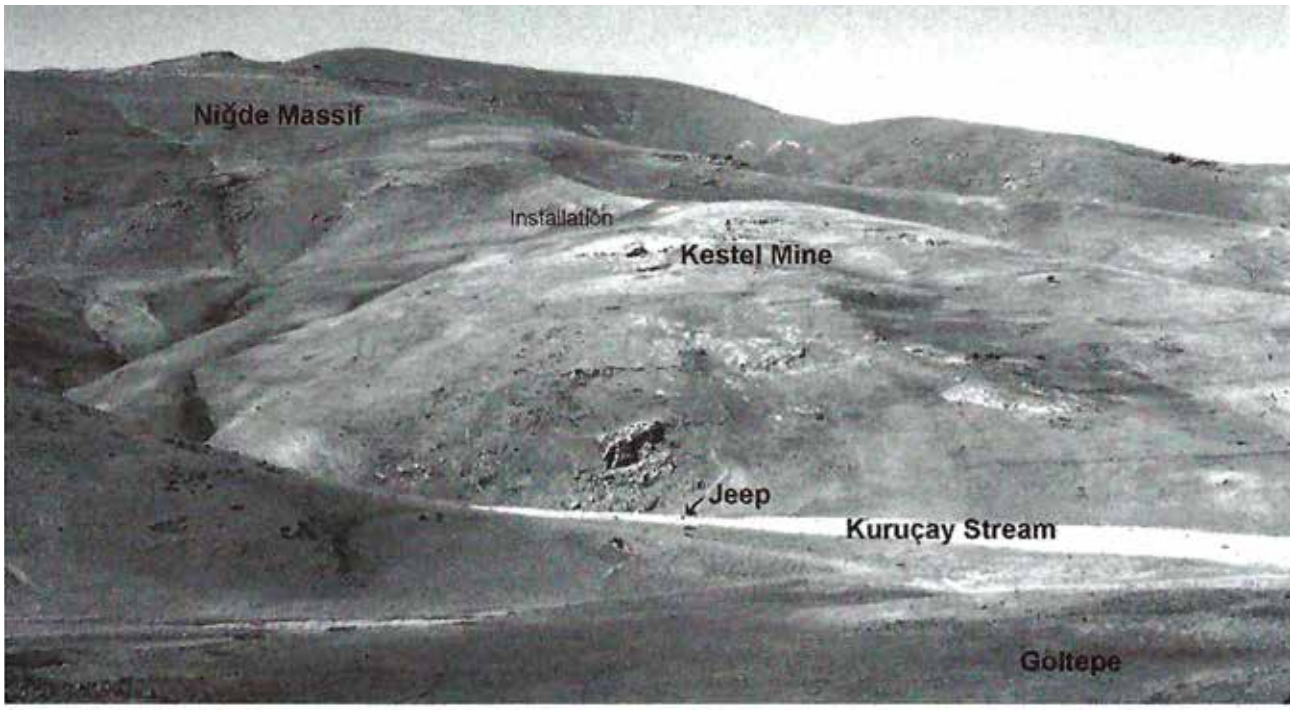


Fig. 11 – The 3rd millennium BCE Tin Mine at Kestel, Anatolia (Yener, 2021, plate 1A).



Fig. 12 – Dr. Mike Johnson sampling a quartz-hematite vein above the main entrance to the Kestel mine (Courtesy of Prof. Wayne Powell.)

probable bowl furnaces—1 ton of vitrified earthenware bowl furnace or crucible fragments were excavated at Göltepe. The tin-rich glassy slag layer in these fragments showed 30–90 wt % tin content and attest to the industrial-scale, high temperature processing of tin-bearing ores practiced at this remarkable site (Yener, 2021).

Lead isotope analysis (LIA) has linked tin-bronze artifacts from Bronze Age sites in Anatolia and Syria to the Bolkardağ mining district in the Taurus mountains where the Kestel-Göltepe complex is located (Yener et al., 1991; Sayre et al., 1992; 2001). By all indications the massive amount of tin produced at this complex was traded far and wide across the greater region. Subsequently, and despite recent arguments to the contrary (Berger et al., 2023a; 2023b) in the later 2nd millennium BCE, tin from the Bolkardağ mining district, it has been argued using LIA, was cast into some of the ingots found among a ton of tin ingots excavated from the Uluburun shipwreck—



Fig. 13 – Plan for Göltepe Building 1 (Area A) depicting ore processing, workshop stalls, thermal installations, ore grinders, and crucibles. This building dates to EBIII, Period 2. Some 5000 ore crushing tools were excavated from the workshops along with crucibles, powdered tin ore and ca. 1 ton of vitrified tin-rich material (Courtesy of Prof. K. A. Yener. Yener 2021).

about 1320 BCE—off the southern Turkish coast (Pulak, 2000; Powell et al., 2022; cf. Berger et al., 2022; cf. Williams et al., 2023; cf. Powell et al., 2024).

Interestingly, thus far in Southwest Asia, the Kestel mines are joined by only two other documented tin sources with mining evidence from later Prehistory. A second small Anatolian source is now known within the Erciyes Dag volcanic zone, at Hisarcik, Kayseri Province, central Anatolia. Here tin ores were emplaced via volcanic fumaroles (Yener et al., 2015).

Deh Hosein (western central Iran)

The third Southwest Asian source, one of particular importance, is located on the Iranian Plateau in the western central Zagros mountains in the mining district located at Deh Hosein (see fig. 2; Nezafati et al., 2011). Here sizable polymetallic deposits of copper, tin and mixed copper-tin ores, including stannite (Cu_2FeSnS_4), are found on the eastern border of Luristan Province in western Iran, renowned for its unique tradition of bronze casting. Additionally, Deh Hosein lies in relative proximity to sites in the Anatolian-Mesopotamian arc wherein some of the earliest tin-bronzes dated to the early 3rd millennium BCE have been documented (Rahmstorf, 2017, p. 188, fig. 16.3).

At Deh Hosein clusters of more than 75 open pit workings of deposits close to the surface with huge spoil heaps are spread across an expanse of 4.5 × 6 km^2 of this impressive mining landscape (fig. 14b). The presence of underground mine workings as well have been confirmed. The site was initially published by M. Momenzadeh (2004) and then by Nezafati and colleagues in 2011 following a season of research at the site. A single ^{14}C date inside an open pit mine yielded a calibrated date of ca. 1775–1552 BCE (Nezafati et al., 2011). No indications of smelting have been found at the site. If smelted, the stannite from Deh Hosein could have been used to produce, in a single stage process, tin-bronze of uncontrolled tin content.

Elemental analyses of bronzes held in Iranian Museums plus excavated bronzes from the Belgian Mission in Luristan all showed bronzes of uncontrolled tin content which could have been smelted from Deh Hosein ores (see also Haerinck and Overlaet, 2004; Fleming et al., 2005). In addition, Nezafati and colleagues conducted LIA on 18 Deh Hosein ore samples and 25 museum bronzes (Nezafati et al., 2011). These Luristan Bronzes dated stylistically to the 3rd millennium BCE and the Deh Hosein ores all shared LI signature compatibility as did a portion of the Luristan Bronzes dated to the 2nd and 1st millennium BCE. Significantly, ancient Near Eastern copper-base artifacts from the 3rd millennium BCE and later spread from western Anatolia to the southern Gulf also shared signature compatibility with the analyzed Deh Hosein ores—therefore, the research team suggested that Deh Hosein could well have served the greater Near East and beyond as important source of copper, tin and mixed copper-tin ores used to make EBA and later tin and tin-bronze artifacts (Nezafati et al., 2011).

In 2023 LIA published by Daniel Berger and colleagues in Frontiers in Earth Science suggests possible

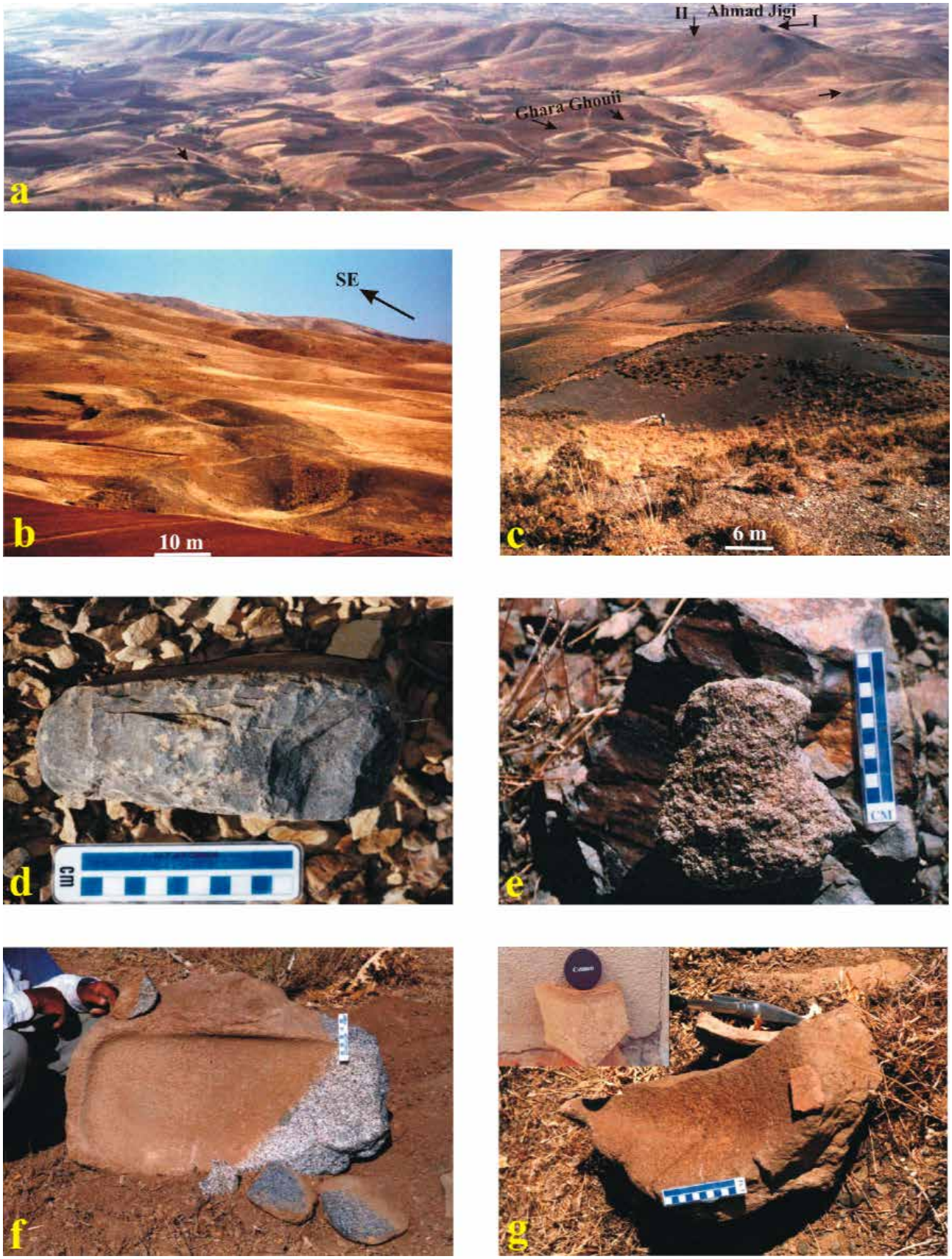


Fig. 14 – Deh Hosein mining landscape, open-pits, spoil heaps and mining and ore processing tools (after Nezafati et al. 2011).

signature compatibility between artifacts from three Central Asian sites, namely (Gelot, Gonur and Sapalli Tepe) and Deh Hosein ores. These sites date several centuries earlier than the single ^{14}C date for Deh Hosein. Thus, in sum, Deh Hosein can be seen as a prime example of an ore-rich, polymetallic deposit from which early on tin-bronze could have been chanced upon experimentally without the previous knowledge of, or conscious effort required to isolate copper and tin ores in order to smelt them to the two metals necessary to produce tin-bronze. Thus, Deh Hosein ranks as one of the most important copper, tin and copper-tin bearing deposits in Southwest Asia that, based on current indications, may well have been supplying tin metal across a sizeable expanse of the ancient Near East, if not across greater Southwest Asia.

Veshnaveh (north central Iran)

This large mining complex is situated in north central Iran as seen in fig. 2. The ore bodies are emplaced in middle-upper Eocene volcanics and sedimentary rocks in the larger Ormieh-Dokhtar volcanic belt spanning the length of western Iran (Nezafati and Stöllner, 2017, p. 68, figs. 1a and b). It was first documented by economic geologists in 1969 (Holzer and Momenzadeh, 1971, p. 2). Interestingly, this discovery is sandwiched between the American Theodore A. Wertime and his international team's pioneering "A Metallurgical Expedition through the Persian Desert" (Wertime, 1968), which did not visit Veshnaveh, and the fieldwork at Veshnaveh by the eminent German mining archaeologist Gerd Weisgerber from Bochum's Deutsches Bergbau-Museum in 1976 and 1978, and that of the French mission led by Thierry Berthoud and colleagues (Berthoud et al., 1976), whose teams did sample the Veshnaveh mines. This period can be seen as comprising the early beginnings of archaeometallurgy in Iran and in Southwest Asia generally. Subsequently, it was in the period 2000–2005 that Thomas Stöllner with Iranian-German teams undertook field work at the Veshnaveh mines (Chegini et al., 2001; Stöllner et al., 2004; Stöllner et al., 2011; Nezafati and Stöllner, 2017).

The Veshnaveh mines are comprised of three main loci, namely Mazrayeh, Lāghe Morād and Chāle Ghār, all within several kilometers of one another (see Nezafati and Stöllner, 2017, p. 70, fig. 3). Interestingly, these 3 mining loci share identical mineralizations (fig. 15). Some 60-plus mine workings of various sizes were recognized by the teams that have studied them, which are ^{14}C dated from the late 3rd to the mid-late 2nd millennium BCE. However, there are dates suggesting that copper mining may well have persisted into the early Iron Age in the late 2nd millennium BCE. The site's dating is supported by the presence of prehistoric, grooved mining mauls and the use of fire-setting as part of the mining process. The grooved mauls suggest they were hafted and, as Gerd Weisgerber once told me, the sinuous nature of prehistoric shaft mining, as seen in the Veshnaveh mines, reflects the use of such mauls (fig. 16c). It is suggested that the moderate copper ore yield during the period of exploitation is reflected in the unsophisticated mining techniques utilized in these mines (Nezafati and Stöllner, 2017, p. 68).

In terms of what ore was being mined, it appears to have been primarily chalcocite (Cu_2S; fig. 17). Other than chalcocite, the primary ore mineralization is described as comprised of bornite, hematite, digenite, chalcopyrite, native copper, and pyrite - hence deposits having a major sulfide component (Nezafati and Stöllner, 2017, p. 77). Copper in veinlets can range as high as 34.5% while hematite ranges as high as 17.5%. Veshnaveh copper is found only in the andesite-basalt unit occurring primarily in thin lenses, pockets, veins and veinlets, groundmass disseminations, amygdales and impregnations (Nezafati and Stöllner, 2017, p. 76). The veins and veinlets range from a few millimeters to several centimeters in width running several meters long and these were mostly mined out by Veshnaveh's ancient miners (Nezafati and Stöllner, 2017, see p. 77, fig. 6).

At the same time in the Veshnaveh deposits both malachite and atacamite, two oxidic minerals, are abundant in the secondary mineralization of copper that is present. The question arises here concerning the nature of the smelting activity used to reduce the deposits predominantly sulfidic ores to copper metal. Smelting copper sulfides generally requires that the ores be roasted prior to smelting to drive off the sulfur (Rostoker et al., 1989, p. 70, fig. 1; Koucky and Steinberg, 1982, p. 165, fig. 19). Regrettably neither evidence for roasting nor smelting Veshnaveh ores appears to have been identified. One possible solution to the difficulties that arise from smelting sulfides is the use of co-smelting in which a one-step direct reduction to copper is achieved by smelting a mixture of sulfidic and oxidic ores (Rostoker et al, 1989, p. 73, table 1). For example, Veshnaveh chalcocite and malachite may have co-occurred in the orebody, so that they were mined together without a conscious understanding that they were two distinct ores. Such an ore mixture was noted at the Lāghe Morād mine (Nezafati and Stöllner, 2017, p. 73, table 2). Co-smelting would have yielded copper metal in the smelting furnace in a single step. Or those smelting such ores could have intentionally mixed chalcocite with malachite to achieve one step smelting to copper metal. The reason that co-smelting as a solution to the presence of sulfur in the Veshnaveh mines is raised here is that the predominance of sulfides in these orebodies meant that those doing the smelting of these ores starting in the early 3rd millennium BCE had to have been able to deal with removing the sulfur and co-smelting would have been one solution to its presence.

In addition, no evidence was found of any sort of permanent settlement in the greater region surrounding the mines, nor was there evidence of the smelting of copper ore at these mines. It is possible that prehistoric pastoralist groups may have been exploiting the mines seasonally and were responsible for moving the ores to regional settlements conducting smelting to copper metal. It has been speculated that at the start of exploitation in the early 3rd millennium BCE Veshnaveh copper was being smelted

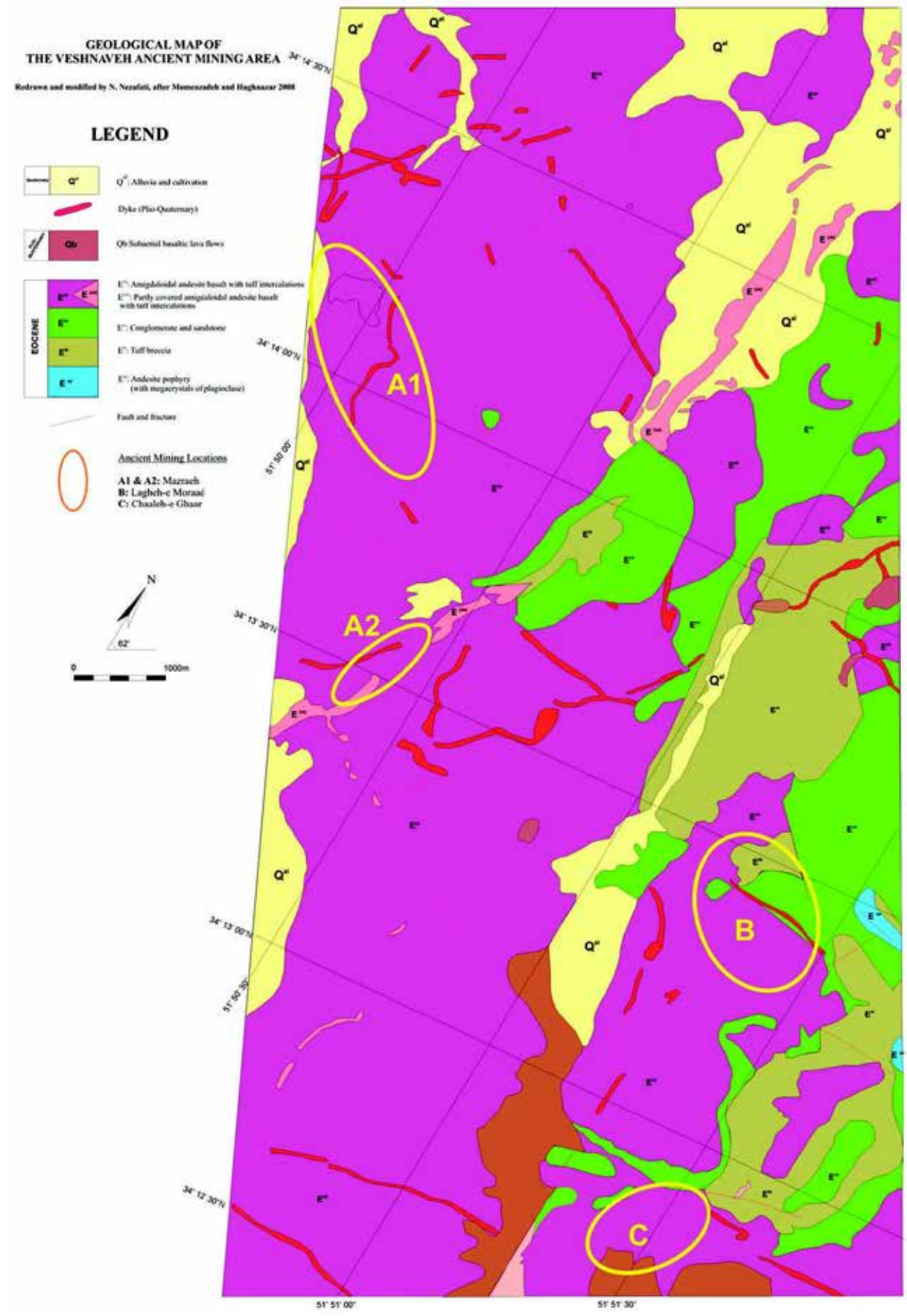


Fig. 15 – Geological map of the Veshnaveh Mining areas: A1 & A2: Mazrayeh, B: Lāghe Morād, C: Chāle Ghār (after Nezafati & Stöllner 2017, p. 70, fig. 3).



Fig. 16 – Veshnaveh copper mine, Iran (from Nezafati & Stöllner, 2017, p. 69, fig. 1 a-h).

at two major settlements in relative proximity to these mines, namely Tepe Sialk (e.g., Schreiner et al., 2003) and Arisman (Chegini et al., 2001; Vatandoost et al., 2011). Both of these sites yielded substantial evidence for copper smelting; however, lead isotope and trace element analyses of Veshnaveh ores eliminated these sites as possibilities (Nezafati and Stöllner, 2017, p. 71, 81).

At the same time, some level of isotopic signature compatibility was signaled at two other regional sites (near Qom), namely Tappeh Sarm of Kahak and Qolī Darvish, Jamkarān (Azarnoush and Helwing, 2005). Importantly, LIA of Veshnaveh ore and host rock provided an "indication of close genetic kinship" between the two. This in turn is of particular value in not only the analyses of samples from these two regional sites, but also it bodes quite well for the use of the isotopic signature of the Veshnaveh ores in future comparative studies of these ores and LIA results from other prehistoric sites on the Iranian Plateau. At Tappeh Sarm (Iron Age II/III) four artifacts shared similar isotopic ratio with the Veshnaveh samples, whereas only one sample from the workshop area at Qolī Darvish was isotopically compatible with the Veshnaveh samples (Nezafati and Stöllner, 2017, p. 79–84). The authors do suggest that chalcocite and bornite (both copper-sulfide ores) may have been transported from Veshnaveh to settlement workshops as at Qolī Darvish for smelting. This site dates from the Late Chalcolithic to the Early Bronze Age and has deposits dating to the 2nd millennium BCE as well.

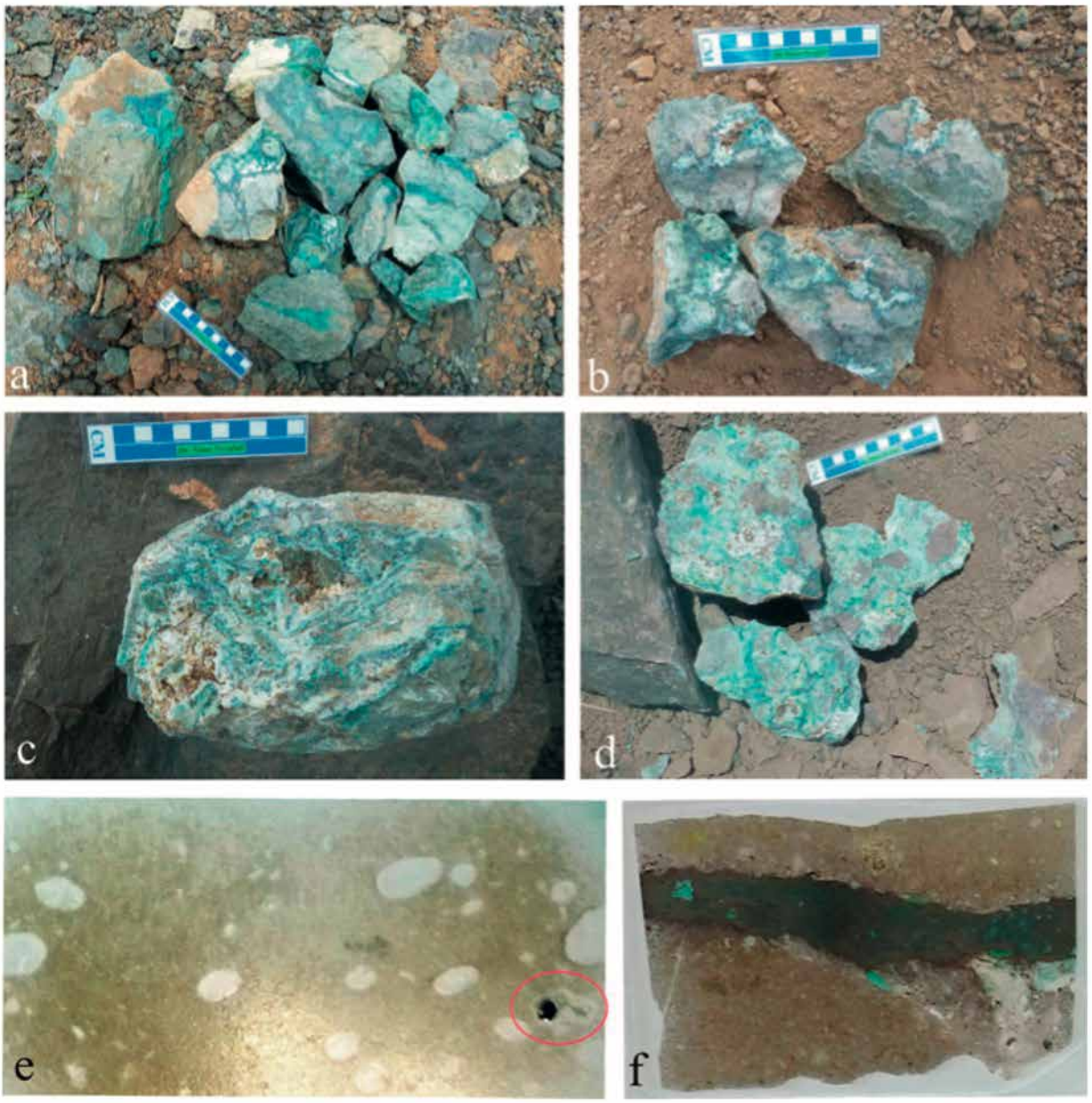


Fig. 17 – Examples of Chalcocite (Cu_2S) copper ores from Veshnaveh (Nezafati & Stöllner, 2017, p. 77, fig. 6).

The Arabah Valley (southern Levant)

Some of the best-preserved ancient mining landscapes in the broad region of Southwest Asia lie in the Arabah Valley. This metallogenic region is defined by the meeting of the African and Arabian tectonic plates creating a latitudinal (N-S) rift valley that runs from its convergence with the East Anatolian Fault in the north, through the Beqaa Valley in modern day Lebanon, and southward to the Red Sea. Activity along this fault system resulted in the formation and exposure of rich deposits of copper in the southern stretch along the Dead Sea Transform, known topographically as the Arabah Valley. Mining in the Arabah Valley contributed vast amounts of copper to the Levantine cultural and economic systems, with activity concentrated in the late Chalcolithic to Early Bronze Age and again in the Iron Age and Roman periods. The exploitation of these ore resources was distinct from those in central and northern Iran and across Anatolia, having principally served the metals markets immediate to their vicinity. In the Bronze and Iron Ages, the Arabah primarily supplied copper to Levantine settlements to the northwest and northeast of the mines (Genz, 2000; Hauptmann et al., 1992). From the late 4th to 1st millennium BCE, copper derived from the Arabah intermittently ventured into the greater eastern Mediterranean metals markets, interplaying with raw and scrap copper (among lead, silver, gold, and tin) supplies from Egypt, Cyprus, southern Anatolia, the Aegean, as well as points further east (Yahalom-Mack et al., 2014; Hauptmann et al., 2015; Kiderlen et al., 2016). There are periods of trade into Egypt; throughout time, the role of Egypt vacillated between that

of consumer (Rademakers et al. 2017; see a recent summary in Ben-Dor Evian et al., 2021) and exploiter of the copper resource.

Relevant to the periods addressed in this volume, archaeological remains of ancient mining and copper processing can be found in two main areas of the Arabah. On the eastern side of the rift valley, approximately 70 km from the Dead Sea, sits the Faynan mining district and on the western side, 25 km north of the Red Sea, sits the Timna Valley (see fig. 2).

Geology of the Deposits

The metallogenetic districts of Faynan and Timna are host to the richest copper ore deposits in the Levant. Once forming the same mineralization, the two mining regions now lie approximately 105 km apart due to the continued lateral displacement of the African and Arabian tectonic plates occurring on a geological timescale (i.e., hundreds of millions of years). The deposits are categorized as sedimentary stratified deposits "formed by the erosion of Precambrian veins and subsequent deposition in a lagoonal milieu at the borderline of the Cambrian sediments to the Precambrian basement" (Hauptmann, 2020, p. 39). The mineralizations are rich and multi-metallic; the ore minerals found there are chemical precipitates in sedimentary host rocks, to which large quantities of metal have been added in solution (Hauptmann, 2020, p. 54).

Copper occurs in several geological units at Faynan and Timna. If and when these were exploited on either side of the rift valley depended on characteristic traits like surface exposure, depth of deposit, and host rock, which, at times, mired accessibility for the ancient miners (Hauptmann, 2007, p. 63–65). The earliest exploited deposits were the copper minerals of the Massif Brown Sandstone (MBS; fig. 18). Many outcrops of green malachite in a soft sandstone host rock likely contributed to ease of accessibility for miners in the 4th–3rd millennia BCE. The richest deposits occur in the Cambrian dolostones and sandstones of the Dolomite-Limestone-Shale Unit (DLS; fig. 18). The DLS mineralization consists of secondary copper intergrown with manganese oxides (Hauptmann, 2020,p. 55–56), which was of significance to the increased efficiency of smelting operations in the 1st millennium BCE. The DLS deposit sits at a far greater depth to the southwest, where it is known as the Timna Formation. Having no surface exposure there, it was minimally, if ever, exploited in antiquity. At Timna, the Cambrian deposits are overlain with Cretaceous sandstones. The Amir formation, lying just beneath the MBS was the only deposit exploited there between the 5th–1st millennium BCE (Hauptmann and Horowitz, 1980; fig. 18). The ore minerals found in both deposits are secondary copper ores such as malachite and various copper silicates like chrysocolla, plancheite, and dioptase (Hauptmann, 2007) (see fig. 18).

Faynan

Faynan is a massive mining region divided into districts or areas by hills and valleys. While the industrial scale smelting debris was noted by earlier travels into

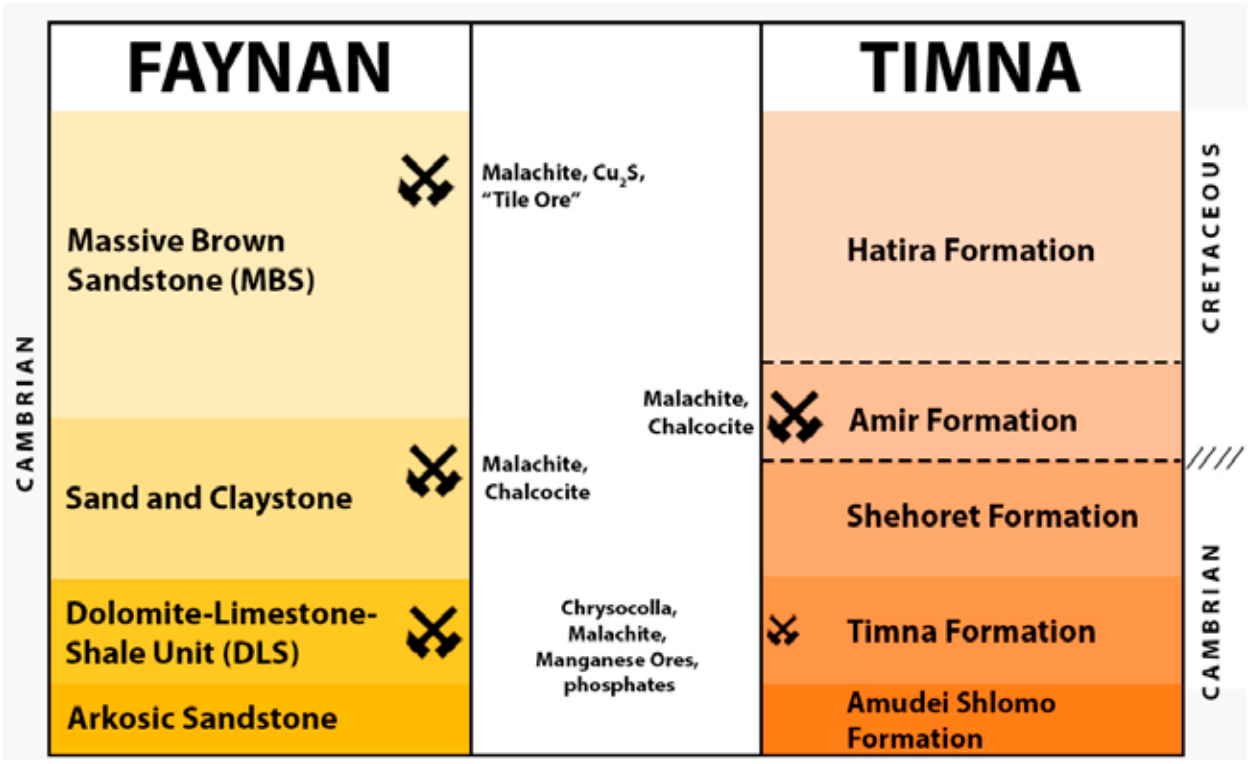


Fig. 18 – Lithostratigraphy of copper mineralization at Faynan and Timna (after Hauptmann, 2007, p. fig. 4.4).

the region, the first to recognize Faynan's historical significance was American archaeologist Nelson Glueck in the 1930s. Intensive research focused on past metallurgical activity in the Faynan Valley was initiated by Andreas Hauptmann and Gerd Weisgerber of the Bochum Mining Museum in the 1980s (Hauptmann, 2007). This was followed by successive research campaigns led by institutions in Jordan and worldwide. The latest of such endeavors began in 2002 with extensive surveys and excavations led by Thomas Levy and Mohammad Najjar of the University of California, San Diego (Levy et al., 2014). Throughout time, research has focused equally on Faynan's metallurgical and settlement history, with studies of landscape exploitation, and geological and environmental sciences.

Neolithic to Chalcolithic Periods

Earliest exploitation of copper mineral resources in the Arabah considerably pre-dates metallurgy. Prized green stones were collected from surface exposures in the area and traded or transported long distances to settlement sites in the Pre-Pottery Neolithic (11,500–10,500 years ago; Bar-Yosef et al., 2008). Hauptmann suspects that the utilization of copper ore from Faynan occurred on a modest scale with a likelihood that it was collected out of surface erosion rubble of the DLS (Hauptmann, 2007, p. 145). Working of malachite was discovered at Wadi Faynan 16, showing the use and value of the resource prior to the pyro-metallurgical revolution. Early indication for the use of Faynan ores for metals comes only in the late Chalcolithic. Adit mines at the mining areas Wadi al-Abiad, Wadi Ratiye, and Qalb Ratiye show efforts for ore removal that likely began prior to the 4th millennium BCE (Weisgerber, 2003, p. 79; Hauptmann, 2007).

Owing to challenges in accurately dating mining landscapes (esp. those that have seen millennia of reuse), chemical and LIA studies have been instrumental in connecting metal production documented at settlement sites with Arabah ore sources. LIA was carried out on copper metals and metal working production debris excavated at Chalcolithic Period sites in the Beer Sheba Basin such as Tell Abu Matar, Bir Safadi, and Shiqmim. Results were compatible with the Faynan ore body signature, providing evidence that ore was transported distances of up to 100–150 km to workshop settings where smelting, refining, and casting occurred (Shalev and Northover, 1987; Hauptmann, 1989; Shugar, 2000). This organization of production paradigm, smelting and copperworking activities occurring a great distance away from the Faynan mines, is unique to this early phase of metallurgy in the southern Levant (Levy et al., 2002; Hauptmann, 2007, p. 148).[4] LIA studies in this vein also provided substantial evidence that workshops and settlements consumed copper from multiple sources already in the Chalcolithic period – introducing new alloys and complex metals to Levantine metalworking (Tadmor et al., 1995; Hauptmann et al., 2015).[5]

Early Bronze Age

Prior traditions appear to have continued into the Early Bronze Age I (EB I), as minimal remains of mining or smelting can be archaeologically or radiometrically dated to the period between 3600–3100 BCE (recently confirmed by archaeometric work in Ben-Yosef et al., 2016). Smelting activity at Wadi Fidan 4 is dated to the early EB I but represents the only attestation of reduction activity in the mining district (Adams and Genz, 1995; Genz and Hauptmann, 2002). Mines at Wadi Dana, Qalb Ratiye and Wadi Kalib exploiting the Massive Brown Sandstone (MBS) formation are dated to the EB phase of occupation in the region (though, possibly already active in the Chalcolithic; fig. 19). Pit mining is attested, dug into the gravel conglomerate that overlays the MBS mineralization (Hauptmann, 2007, p. 112). Pit mines are positioned in a linear fashion, one after the other, showing clear evidence for continued exploitation of a single vein from above. Mines there are generally shallow and were exposed from the surface or from hillside adits, rather than creating extensive underground workings. Debris and tools from stone hammer production were also among the finds at WF 4 (Hauptmann, 2007, p. 114).

The picture changes in the EB II-III, during which time an expansion of both the Faynan population and their part in metal production is evidenced (Fritz, 1994; Adams et al., 2010; Levy et al., 2002; Ben-Yosef et al., 2016). Further developments in mining techniques are apparent in the Early Bronze Age when shafts were dug in connection with galleries to more precisely and efficiently target and exploit copper ore veins. Stone hammers and 'pock mark' impressions on the walls of the mines reveal the primary tool used for rock breaking from the mid-4th millennium BCE. Similar tools and evidence were discovered at the sites of Faynan, Madsus, and al-Jariya in the Faynan region, which are dated to the EB II-III based on pottery in mining backfill and tailing refuse (Hauptmann, 2007).

Early Bronze Age pottery found in spoil heaps (mining waste) supports the dating of a cluster of mines in Wadi Khalid (Hauptmann, 2007, p. 116). Some adit mines are dug 15–20 meters into the hill side. The 'chamber-and-pillar' approach to bedrock removal and stabilization is first documented at EB II-III at Wadi Khalid, Wadi Dana, and possibly at Umm ez-Zuhur where the DLS mineralization was exploited at increasing depths (Hauptmann, 2007, p. 251, see here fig. 19). Evidence in Wadi Kalib for both mining and smelting shows the relocation of initial ore processing activities to the mines and out of distant settlement sites. Wadi Fidan and Khirbat Hamra Ifdan (Site 14) also became key settlement sites for copper producing communities in the valley (fig. 19). Researchers estimate over a

4. Archaeointensity data from smelting site Timna 39b reported in Ben-Yosef et al., 2008 suggests the possibility of smelting also taking place next to the ore source in the Chalcolithic, though results were inconclusive.

5. Based on LIA compatibility, scholars have proposed Anatolia as the probable source for imported Sb-As-Cu metals in the Chalcolithic.

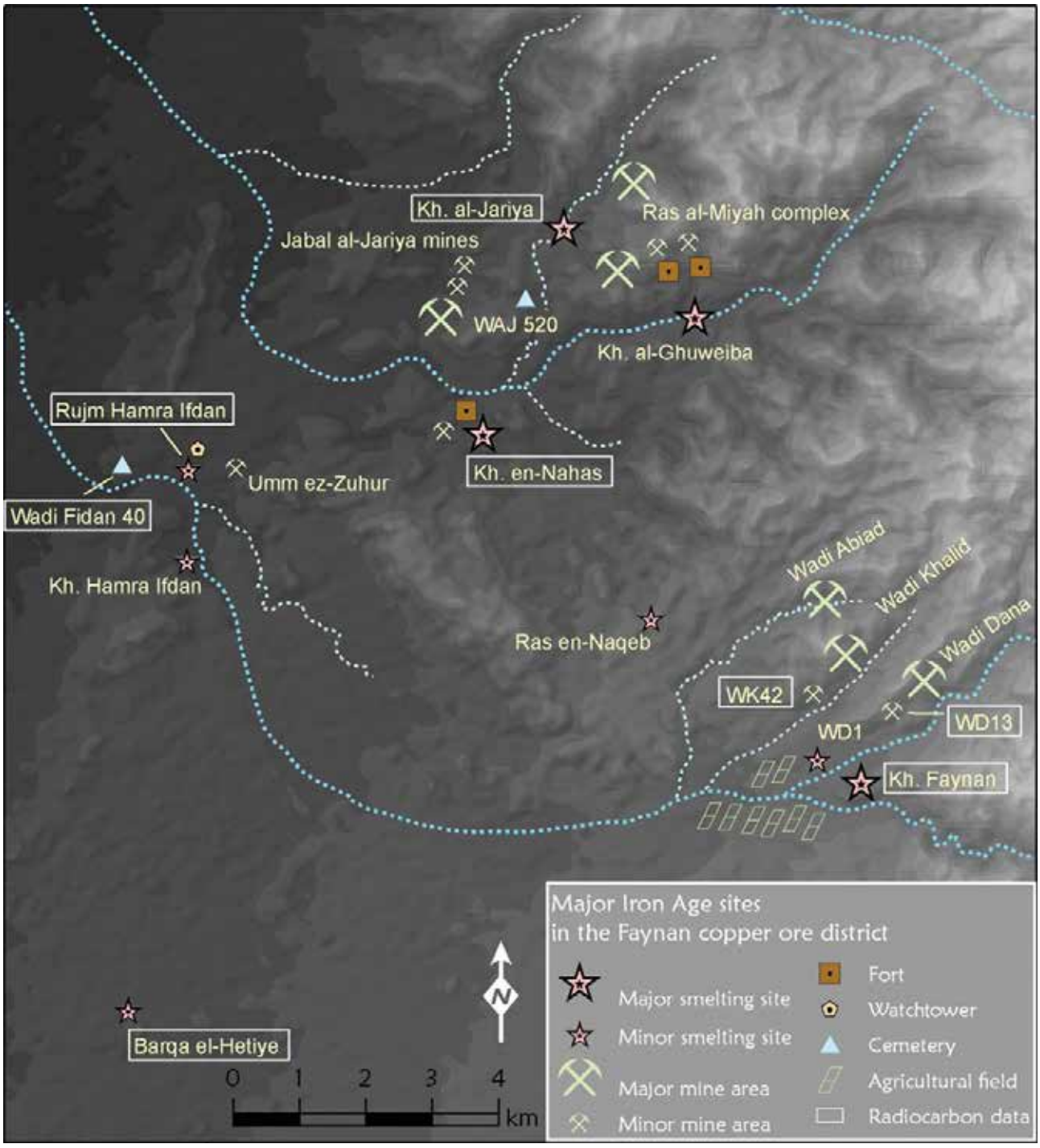


Fig. 19 – Mining and smelting sites in the Faynan copper ore district (from Ben-Yosef, Levy et al., 2010, fig. 1).

dozen smelting sites and several tons of slag at EB II-IV sites (Levy et al., 2002, p. 427; Hauptmann, 2007). This organizational revolution reduced the load of transport, allowing for an increase in efficiency and capacity for EB metal producers. Some consider this portion of the Bronze Age to be a golden age of Levantine copper production prior to the first millennium BCE. Isotopic compositions of small bar-shaped ingots found across the Cisjordan (west of the Jordan Valley) dated to the Intermediate Bronze Age are consistent with Faynan ores (Yahalom-Mack et al., 2014, p. 173). Despite noted decline in the urbanized systems of the EBA leading into the second half of the 3rd millennium, a sustained trade network of raw copper in Canaan is suggested (Yahalom-Mack et al., 2014).

Middle and Late Bronze Ages

Towards the end of the period, possibly already in the EB IV (note disagreements on periodization), decreased activity in Faynan was observed (Levy et al., 2002, p. 432). Far fewer mining and smelting sites were found

containing MB pottery. Some scholars attribute diminished endeavors to the rise in circulation of Cypriot copper with the enactment of newly formed trade routes in the Eastern Mediterranean. Between the early to mid- 2nd millennium BCE, the isotopic signature of Cypriot copper can be found increasingly in copper alloys of the southern Levant (Galili et al., 2012; Yahalom-Mack et al., 2014). A diminished quantity of dateable remains for mining and smelting pursuits is noted from the Middle to the later part of the Late Bronze Age. Juniper splits found in the Wadi Khalid mines, interpreted as torches to light the subsurface galleries, returned radiocarbon dates in the Late Bronze Age (Hauptmann, 2007, p. 120). This led Hauptmann to propose continued, though reduced, exploitation. A correlation drawn between the Cypriot copper supply dominating the Late Bronze Age Levantine (and Mediterranean) metals market (Muhly and Gale, 1991) from ca. the 14th to 12th c. BCE and the absence of significant copper industries at either Faynan or Timna is unopposed by scholars. The picture again changes dramatically at the termination of the Late Bronze Age, when trade networks were severely crippled by widespread political collapse throughout the Mediterranean world. The position of Cyprus weakened, both in metal production and [to a greater extent] in trade, and the copper-rich island ceased to serve as the Levant's copper source for the better part of the next four centuries.

Iron Age

Production and population resurgence is evident in the last centuries of the 2nd millennium, first on a small scale, escalating to a peak in the early 1st millennium BCE. In the wake of the Late Bronze collapse and the rise of new geopolitical entities in the Levant, Faynan again rose to the status of prime copper supplier for the southern Levant. Upon reactivation of mining efforts in Faynan, evolution in technological practice is observed from the mining and ore processing perspectives. Exploitation of the DLS mineralization took place on a grand scale. Born out of the need to dig deeper to reach the vein deposits of the DLS, miners began to integrate new techniques. A system was developed to ease ore and rock removal as well as the movement of the miners. Foot- and handholds were created in the walls of the shafts to aid in the haul of workers and rock. Double shafts were mined at a distance of 50 cm from one another: one shaft served miners to reach the depth of the copper minerals and the other for raising ore and rock waste to the surface (Weisgerber, 2003, p. 85; see here fig. 20). The double shafts also, importantly, served to increase ventilation and light for the gallery mines below. It is postulated that iron mining tools were used in these periods and would have greatly increased the miners' rock breaking capacities (Weisgerber, 2006).

As in the Early Bronze Age, Wadi Khalid served as a major mining area in the Iron Age. A comparison of the Early Bronze Age and Iron Age mining waste there shows an increased need to excavate deeper shafts to encounter the copper-bearing veins within the DLS. In the Iron Age, this resulted in mine tailings at the foot or slope of the mountains or valleys, much further away from the exposure or mine shaft themselves. Surveys of Umm ez-Zuhur and Madsus revealed 24 mine tailings dated to the Iron Age, along with a series of gallery and shaft mines. Iron Age miners frequently dug vertical shafts to depths of

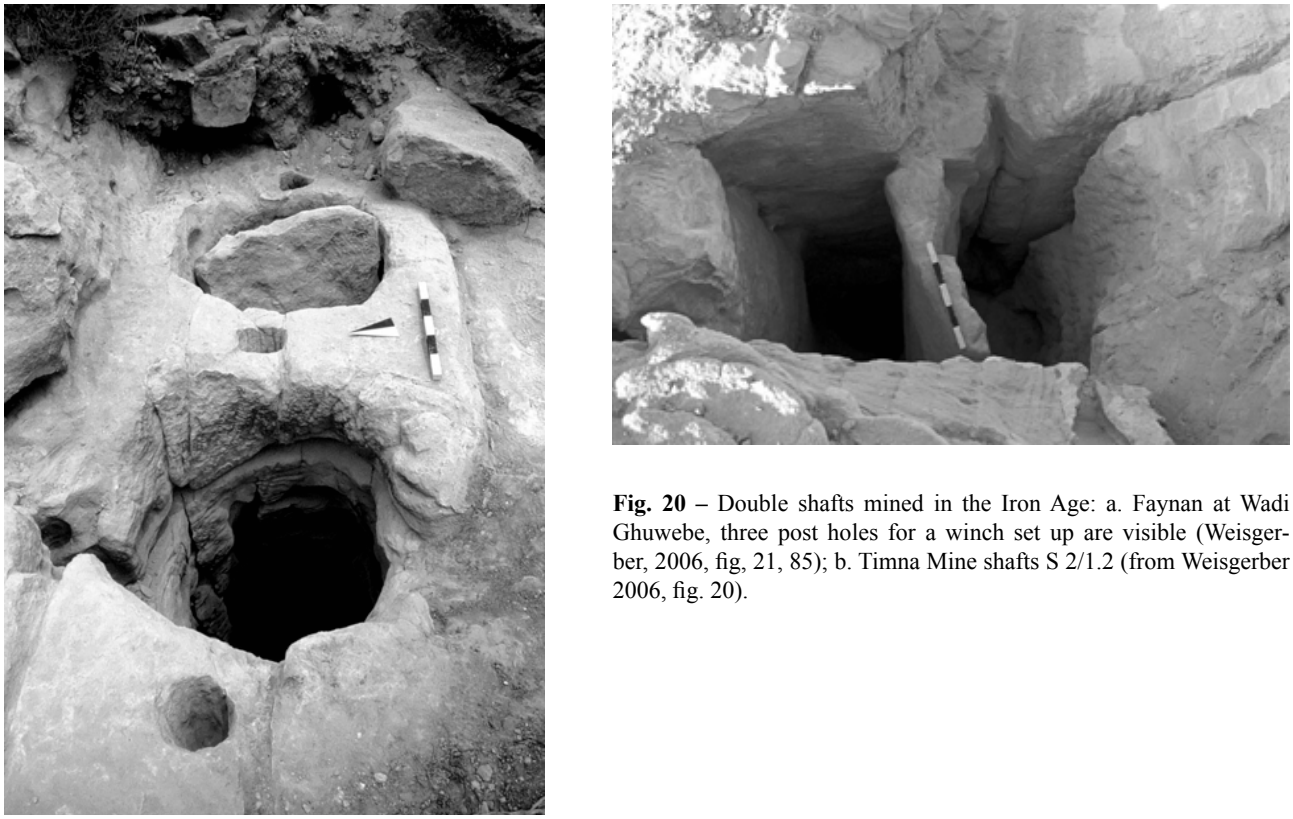


Fig. 20 – Double shafts mined in the Iron Age: a. Faynan at Wadi Ghuwebe, three post holes for a winch set up are visible (Weisgerber, 2006, fig, 21, 85); b. Timna Mine shafts S 2/1.2 (from Weisgerber 2006, fig. 20).

10–15 m below the surface. It is in Wadi Khalid that a single shaft mine dug up to 70 m deep was discovered (Weisgerber, 1989-1990). Hauptmann notes that this particular mine shows the upper limits of subsurface exploitation for the Iron Age miners (Hauptmann, 2020, p. 157–160), who operated within the confines of restricted air, light, and hauling abilities.

At Khirbat en-Nahas (KEN), enormous tailings near the mines and slag waste heaps at the settlement and copper production facilities (Strata M3–M1) to the northeast attest to the height of expansion of Iron Age exploitation efforts (Levy et al., 2014). Slag accumulations around KEN are estimated to measure somewhere between 50,000 to 80,000 tons. A similar, though smaller picture was found at nearby Khirbat al-Jariya, a smelting site sitting between the widely exploited Jabal al-Jariya mines and Ras al-Miya Complex (Ben-Yosef et al., 2010; Levy et al., 2014). The sites, along with 3 others, were occupied between the 13th to 9th centuries BCE according to radiocarbon dating and are considered the central locations of the early Iron Age industrial copper system controlled by local semi-nomadic peoples, predecessors to the Edomites (Ben-Yosef et al., 2010; Levy et al., 2014). As a proxy for understanding the magnitude of mining and smelting in the period, where only some shafts and galleries survive, Hauptmann estimated roughly a total of 100,000–130,000 tons of slag were generated at Faynan in the early 1st millennium BCE, resulting in ca. 6,500–13,000 tons of copper (Hauptmann, 2007, p. 147, table 5.3).

Timna

The Timna Valley forms a bowl off the western periphery of the southern Arabah Valley, 25 km north of the Gulf of Aqaba in the Red Sea. As at Faynan, travelers in the region were the first to document metal production activities in the valley. Upon visiting Timna, F. Frank (1934) and N. Glueck (1935) made connections between the mining works at Faynan (Weisgerber, 2006, p. 2). Glueck attributed the extensive remains of copper working to the early Iron Age, associating it with the period of the biblical Israelites. Formal research commenced at Timna in the late 1950's under the auspices of the Arabah Expedition led by Beno Rothenberg. The Arabah Expedition was a field defining endeavor, being the first archaeometallurgical-focused field project to ever be conducted. Over a nearly 40-year period, the Arabah Expedition surveyed and documented thousands of mine shafts, and hundreds of smelting and camp sites, tracking extensive occupation in the valley from the Chalcolithic to Islamic Periods (Conrad and Rothenberg, 1980; Rothenberg, 1990; 1999). Current research in the valley has been conducted since 2012 by the Central Timna Valley Project, directed by Erez Ben-Yosef.

Chalcolithic to Bronze Age

Indications for early mineral exploitation were found in settlement sites outside the Arabah, echoing the spatial organization of copper craft that was observed at Faynan.[6] Analysis of ore recovered from late 5th millennium BCE smelting contexts at Tell Magass and Tell Hujayrat al-Ghazlan (Khalil, 1988; Kalil and Eichmann, 1999) provided evidence for copper minerals originating from Timna in the period (Hauptmann, 2007, p. 290). Rothenberg and Conrad originally claimed an earlier Late Pottery Neolithic period of exploitation (Site F2) in the valley (Rothenberg, 1978; Conrad and Rothenberg, 1980), but this has been refuted, particularly in regard to reports of smelting in the period (Adams, 1997; Craddock, 2000, p. 156; Ben-Yosef et al., 2010). The Timna mines indicate multi-period exploitation characterized by increased mining depths and developments in mining tools and strategies over time. The upper level of the mine fields in Areas T and S show marks of rock breaking with stone tools, 'pock marks' considered to be Chalcolithic Period works (Conrad and Rothenberg, 1980; Shaw and Drenka, 2018; see here fig. 21). Large numbers of hammerstones of the grooved and pierced/drilled types found in the mines have long served as a means for "rough chronological classification into the Bronze Age or earlier periods" (Hauptmann, 2007, p. 16; Weisgerber, 2006). Early mines followed a two-step process: first digging a shaft, then following a vein outward in a radial fashion, which was repeated over and over in the area of the mine field. Several mines in Area S (Mine S28, S28/2) produced radiocarbon dates in the early 3rd millennium BCE (Ordentlich and Rothenberg, 1980; Weisgerber, 2006, p. 10, table 1). Levy et al. (2002) note, however, that surveys and excavations at Timna produced very little Early Bronze Age materials, giving credence to the possibility that Faynan played a more significant role during the late 4th–early 3rd millennium.

Mining works found at lower levels, as well as places where effort was made to widen tunnel and shaft entrances, bear longer and thinner marks made from pointed metal tools, such as hafted picks and chisels (fig. 21). In their exploration of Area T, complementing the work of the Arabah Expedition, Shaw and Drenka (2018) found that gallery mines dug in the Chalcolithic/Bronze Age had been extended and expanded. Later miners worked to connect previously dug galleries into larger subterranean complexes. 'Exploration winzes', vertical or shallow sloping shafts dug from one level to another, took advantage of the depth already achieved in past campaigns (Shaw and Drenka, 2018). It is presumed that these expansion efforts took place sometime in the Late Bronze or early Iron Age, now known to be the pinnacle of copper production in the valley.

Iron Age

The discovery of an Egyptian 'mining temple' (Site 200) in the center of the valley in 1969 led to a blanket relative dating approach to many of the largest mine fields and copper production sites. For a considerable period of scholarship, the two most significant smelting camps, Site 30 and 34, located centrally in the valley, were thought to

6. See footnote 4.

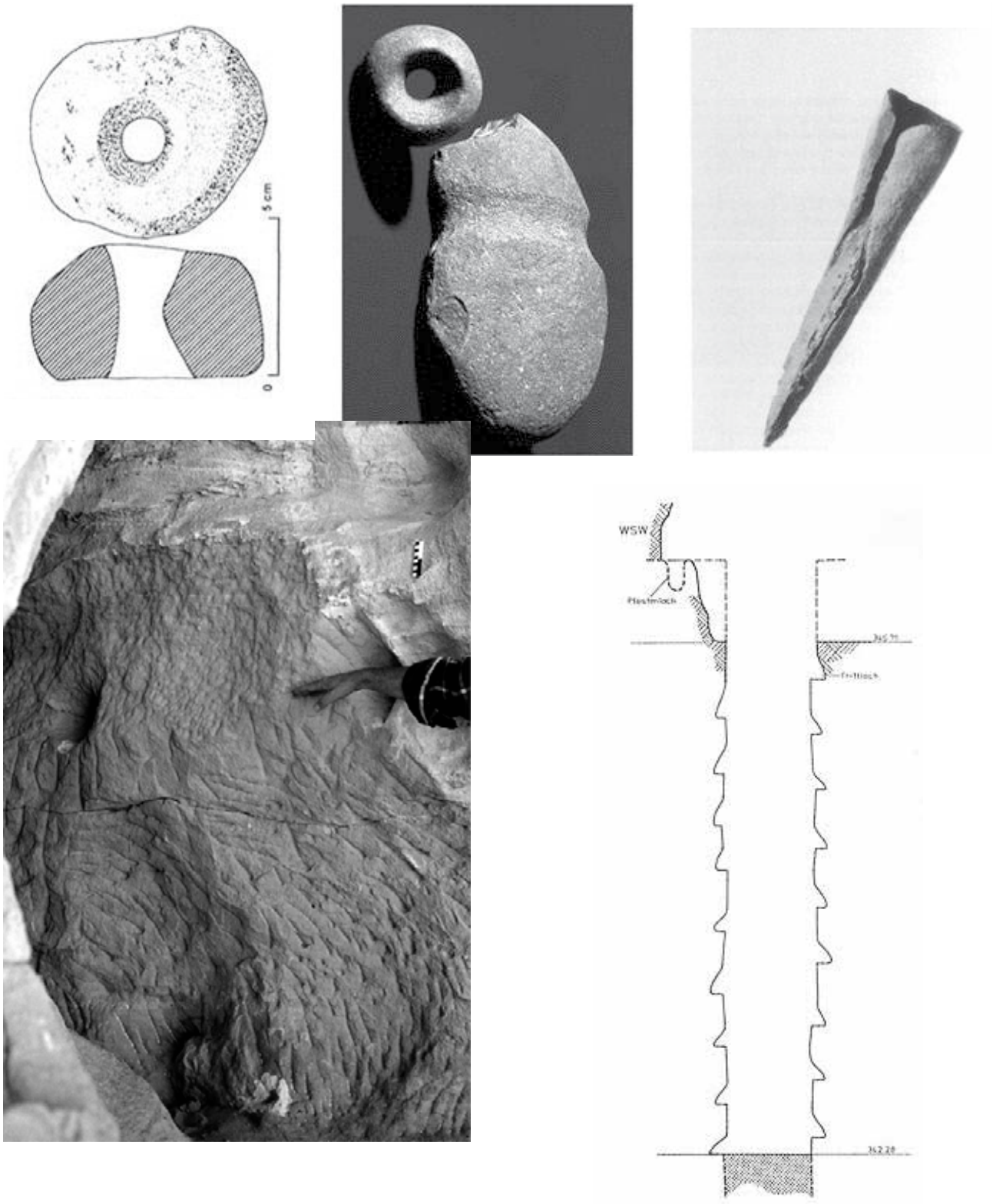


Fig. 21 – Characteristics of mining techniques at Timna: a. common tools and tool marks at the entrance of mine S 28/2. Peck or "pock" marks made from the percussion of hammerstones are visible above, while long thin depressions from mining with metal picks are seen marking the wall below (from Weisgerber, 2006: fig. 11); b. foot/hand holds carved into the wall of a deep shaft mine (from Conrad and Rothenberg, 1980, fig. 160).

be late 2nd millennium, coinciding with the years of Egyptian hegemony in the Levant (Rothenberg, 1988). Following extensive excavation and the archaeometric dating of Iron Age remains at Faynan (Hauptmann 2007; Levy et al. 2014), the previous chronological was called into question. Ben-Yosef and colleagues have used radiocarbon and geomagnetic-archaeointensity dating to establish an absolute chronological scheme for copper working sites at Timna (Ben-Yosef et al., 2008; Ben-Yosef et al., 2010; Ben-Yosef et al., 2012). Results (again) redated the prime period of exploitation at Timna to the early Iron Age, chronologically unifying the extensive copper industries in the eastern and western of the Arabah to the early first millennium. High resolution dating of slag deposits at Sites 30 and 34 have provided a range between the 11th–9th centuries BCE (Ben-Yosef et al., 2012; Ben-Yosef, 2016). Reattributing the mine fields and smelting camps, several thousand tons of smelting waste (Bachmann and Rothenberg, 1980) and ca. 900 mining shafts (Conrad and Rothenberg, 1980) to date to the Iron Age. Some of the most striking features in the Timna mining landscape are the thousands of 'plates' that dot the terrain. Excavations of select 'plates' showed that these are remains of pit mining in the conglomerate, alluvial/eluvial sediment containing copper ore nodules. Others found above bedrock are the remains of prospection mines, revealing a mass effort to identify and track ore veins. A recent archaeobotanical study on charcoal remains recovered from Iron Age Sites 30 and 34, found indications for abandonment due to the exhaustion of viable fuel resources in the local environment (Cavanagh et al., 2022).

CONCLUDING REMARKS

The above described five major published mining sites forms a rather sparse sample from which to draw much in the way of comparative conclusions concerning mining technology over time and over such a vast territory. In reviewing some of the best documented mining landscapes, basic trends in technological approach are evident. Most obvious is that mining and initial working stages (e.g., beneficiation, roasting, smelting) were determined by the available ore deposits—meaning humans adapted to the resources within their immediate environment, be that native copper, sulfidic or oxidic ores. Less predictable, naturally, are the trade routes and direction of exchange. Ore mineral or metal types could end up in circulation at great effort and under previously unforeseen circumstances.

Similar techniques for mining can be observed, potentially dictated by several parameters: (1) hardness and accessibility of the host geology, (2) availability of materials best suited for rock breaking (be that stone, bronze, or iron), and (3) the relative nature of ore richness to depth of deposit to sophistication of smelting technologies. These parameters, and more, have been summed under the umbrella of 'economic viability' of an ore deposit, a metric that can change minimally to substantially over time. It is obvious that open-pitting and shaft and gallery mining with sinuous tunneling through ore bodies are the common approaches used in early mining. The use of stone mining mauls and anvils of varying weights and sizes and fire-setting are also among the regular approaches to the act of mining as well as ore crushing/beneficiation. In mining regions with mineral wealth that was sustained over millennia, mining may follow temporal trends associated with technical innovation, resulting in increased mining and hauling capacities and ore acquisitions at increasing depths. A traditional view might assign causation, linked to a desire for more coupled with gradual technological sophistication related, for instance, to the availability of new utilitarian materials like tin bronze and iron. The impetuses behind these inclinations are more often found to be complex combinations of changes in societal organization resulting from regional cultural dynamics, along with fluctuating economic demands that together resulted in non-linear and non-cyclical phases of small-scale artisanal (or opportunistic) mining and mass resource exploitation (see Stöllner 2008; 2014). To this complex dynamic, we can introduce the possibility of exhausting a deposit or exhausting a particular resource within a deposit, say native copper from a gossan deposit or fuel resources from nearby smelting sites – all environmental limitations that invite another set of unique criteria with which to assess the use of a source.

All in all, a much larger sample is required before more can be said to adequately characterize technological and social trajectories in ore-related mining across antiquity, where persistent limitations arise from destructive long-term mining and absent datable remains. Regardless of restrictions imposed by preservation or access, in a region so large and culturally varied, at the end of the day each mining district within Southwest Asia deserves individualized study before being placed in dialogue. This work has vigorously continued throughout the last several decades, improving visibility of both the mining works and their chemical signature, which, when coupled together, contribute to a more coherent synthesis of exploitation, trade, and consumption systems.

Our discussion turns to focus on major research problems associated with the mining of native copper and copper and tin ores. As of late, in the study of the archaeometallurgy of Southwest Asia, finds of native copper and new evidence of this naturally occurring metal's geological availability have not received much scholarly attention. There is one recent exception, namely the remarkable discovery, excavation, and publication of the mines at Derekutugun in north central Anatolia. At present, this ca. 3rd millennium BCE mining site is unique in Eurasia first, because it is a native copper mine, and second because it has been excavated and presented in detail in a monograph (Yalçin and Ipek, 2016) and in various articles (e.g., Yalçin and Maass, 2013; Yalçin et al., 2019). For Southwest Asian copper and tin mining sites, this is indeed uncommon and, needless to say, we have so much more to learn.

The LIA of native copper from Derekutugun suggests isotopic signature compatibility with artifacts

from sites in relative proximity to it (Yalçin and Ipek, 2016, p. 71–76). Given the considerable amounts of native copper that must have been mined from Derekutugun and how much new LIA data has been published since that time for Southwest Asia, it may well be worth revisiting this mine's signature to see if it might be compatible at a number of settlement sites across a far wider region. It is hard to imagine that this large and rich deposit of native copper, signaled by pieces of the metal in the local stream bed, was not exploited earlier than the 3rd millennium BCE, as well as after, and a renewed LIA program just might reveal an earlier exploitation of the deposit.

Turning once again to Iranian native copper, it was mentioned above that the Anarak deposits had often been discussed as a major source of this metal in prehistory (e.g., Pigott, 1999, p. 78–79) and they have often been discounted (Pernicka, 2004). It is worth noting that these deposits are known for the co-occurrence of native copper and two, rare copper arsenides, algodonite (Cu_6As) and domeykite (Cu_3As), which if dropped into molten copper in a crucible would dissolve like sugar in water (W. Rostoker: pers. comm).

However, Weeks (2008) points out that potential examples of the Anarak deposits' exploitation, via LIA conducted on artifacts from Sialk I and at Tal-i Iblis, have been noted. Furthermore, he analyzed 16 artifacts from sites in Fars excavated by the Japanese mission: Tol-e Nurabad, Tall-e Mushki, Tall-e Jari in Fars - and 5 native copper samples from Talmessi. Analyses revealed that:

> "….the uncorroded copper-base artefacts from Fars are characterised by their high purity, with only trace levels of Ag. Corroded samples show more variability, although pure (oxidised) copper phases dominate and inclusions of metallic Ag are regularly seen. These silver inclusions commonly incorporate a few weight percent of copper and uranium. Arsenic-rich inclusions (Cu_3As-domeykite) were also occasionally seen in the archaeological samples. Interestingly, Talmessi native copper samples exhibit identical metallic Ag-Cu-U inclusions in a matrix of high-purity copper with common vein-like inclusions of arsenic-rich material (Cu_3As). These compositional characteristics serve to suggest that the metal used in Neolithic Fars may have come from Talmessi on the Iranian plateau, implying long-distance exchange of this material already by the late seventh millennium B.C. (Weeks, 2008, p. 341)."

At the same time, generally speaking, he also points out the caveats that not only are there countless numbers of copper ore bodies with 'old workings' on the Iranian Plateau and that the Anarak deposits have not been properly characterized compositionally or isotopically in terms relevant to the deposits' archaeometallurgical significance. However, in closing, it remains difficult to discount that these rich deposits were exploited in antiquity given the fact that in 1935 it was reported that native copper was being extracted from a depth of 80m at a rate of 300kg per meter (Pigott, 1999, p. 78).

One final thought regarding native copper, might there be some value in spending some research time, for comparative purposes, on the considerable literature devoted to the massive native copper occurrences known from the Lake Superior region of the US and their associated prehistoric exploitation over millennia (e.g., Martin, 1999; Ehrhardt, 2005, p. 61ff; Ehrhardt, 2014; Peterson 2024a, b).

This article concludes with some thoughts on the subject of tin-bronze. As was made clear early on, tin deposits are exceedingly rare in Southwest Asia. As noted above there are 3 known deposits: the massive Kestel-Göltepe complex, the small fumarole derived deposits at Hisarcik with some modest mining evidence, and lastly the extensive mining locus at Deh Hosein. Interestingly, both Kestel and Deh Hosein are stannite (Cu_2FeSnS_4) containing. This ore when smelted can produce a tin-bronze of uncontrolled tin content. Did the initial use of such a complex ore contribute to the early 'discovery' of tin-bronze? This remains an interesting speculation.

In addition, at least at Deh Hosein, the tight lead isotopic signature(s) of its ores makes it an ideal candidate for tracking this site's signature. Since the site's publication a substantial number of newly excavated and dated tin-bronze artifacts are known in greater Southwest Asia. Given how much time has passed since the comparisons of LIA results from the Deh Hosein ores with regional tin-bronzes, there must be new LIA results to which the DH ore signatures might be compared.[7] In the initial LIA of Deh Hosein ores, the researchers argued that these ores were used extensively across the greater Near East. New analyses comparing the Deh Hosein ores to the latest LIA results from tin-bronzes in the region may well add further weight to just how extensively this site's ores might have been used. It is clear that tons of complex copper ores were excavated at that site – where did it end up? Additionally, a renewed effort to use LIA to compare the isotopic signatures of the ores from the Kestel mine and the Bolkardağ district with the most recently analyzed tin-bronzes (other than the much-discussed Uluburun shipwreck tin ingots) may well prove quite rewarding as well.

The final discussion here will focus on questions concerning the movement, trade if you will, of tin metal and/or tin ores. The well-known and well-researched early 2nd millennium BCE Old Assyrian Period tin trade comprises one of the few textually documented accounts of actual tin being moved considerable distances from southern Mesopotamia north to the entrepôt of Karum Kanesh/Kültepe in central Anatolia (e.g., Yoffee and Barjamovic, 2018). The trade statistics are notable that "one may carefully suggest that some 1,500 donkeys made the journey to Anatolia each year during the best documented period carrying with them 15 tons of tin and 32,000 textiles" (Barjamovic, 2018, p. 141). But what did the donkeys carry, tin ore or tin ingots or both (see Larsen, 2015, p. 171–188)?

7. For recent LIA study of late third millennium BCE objects see Oudbashi et al., 2022; for Iron Age examples see and Oudbashi, Rademakers et al., 2021; Oudbashi, Renson et al., 2021).

In general, in Southwest Asia, tin ingots are quite rare as are, in fact, artifacts in tin until the later 2nd millennium BCE (e.g., Nessel et al., 2018, p. 69–71). Despite the recent flurry of LIA-based investigations of known tin ingots from the Eastern Mediterranean and their potential sources (e.g., Berger et al., 2023a, b; cf. Killick et al., 2020; Powell et al., 2022; 2024), the following facts remain and will be discussed briefly below. The texts discuss tin coming from the East, i.e., east of Mesopotamia; there is the early 2nd millennium BCE Old Assyrian Period tin trade that flows northward from unknown suppliers in southern Mesopotamia and that Dilmun was a known entrepot from which tin was obtainable.

However, as early as the later 3rd millennium BCE, texts speak of "tin from the east" presumably east of Mesopotamia (Muhly, 1973; 1976, p. 97). Levantine cultures, as well as Egypt, were late adopters by comparison. The Early Bronze to Middle Bronze shift, stretching the late 3rd to early 2nd millennia BCE, saw a change from the consumption of pure copper with the rare find of arsenical and tin alloys, to cultures increasingly reliant on tin bronze. Prior to ca. 2500 BCE, neither tin bronze nor arsenical copper artifacts appear with any frequency in the Levantine archaeological record (Greenberg, 2019, p. 116). By the mid-2nd millennium BCE, the demand for tin had doubled and that of arsenic halved (Kaufman, 2013, p. 663). Kaufman (2013) and others posit that the change coincides with a "cultural reorientation from the Egyptian to Mesopotamian sphere", corresponding with the weakening of Canaanite cities in the Beer Sheva basin and a strengthening of those in the north. Copper trade from the Arabah decreases and, along with an increase of other imports, copper metals with possible Cypriot or Anatolian origins begin to appear (Kaufman, 2013, p. 684). Interestingly, there is little chemical overlap between Middle Bronze arsenical copper and tin bronze artifacts, with tin rarely being added to an arsenic-containing object (Rosenfeld et al., 1997; El Morr and Pernot, 2011). Mari letters, discussed in more detail below, mention the importation of tin to the palace of King Zimri-Lim (18th c. BCE) and to the royal family in Aleppo, moving from Elam to Mari via Babylon. Letters specify some end points of these shipments as Carchemish, Qatna, Tel Dan, and Hazor (Sasson, 1966; Kaufman, 2013,p. 680).

Based on current evidence this leaves us with three choices: Deh Hosein, the vast, but archaeologically undocumented reserves of Afghanistan (e.g., Stech and Pigott, 1986; Thomalsky et al., 2013; Thomalsky, 2016), and the numerous excavated mines of southwestern Central Asia (e.g., Boroffka et al., 2002; Garner, 2015; Stöllner et al., 2011). For purposes of discussion here we will focus first on Deh Hosein and the environs of the Elam in southwestern Iran. In this regard, the still unanswered question remains as to where the tin that was being traded north to Karum Kanesh was originating.

Donkey caravans, it has been argued, moved south into southern Mesopotamia and to Elam and back (e.g., Reiter, 1999). Helwing (2009, p. 210) points out that texts support the idea of southwestern Iran, the lands of Anšan, as being tin bearing. Moreover, Joannès (1991) notes that the two, Elamite sister capitals of Susa and Anšan (Tal-e Malyan) were road stations for the donkey caravans enroute to points north and west, e.g., to Mari via Eshnuna and the Diyala Valley. Texts found at Mari indicate that agents with Elamite names were moving standard weight tin ingots (Helwing, 2009, p. 211). Thus, the strength of texts alone implicate Elamite (middlemen?) in carrying out a trade in tin moving into Mesopotamia and across it to major capitals like Mari. Additionally, Helwing's point above that the lands of Anšan were tin-bearing, of necessity brings into focus the major, mined tin source at Deh Hosein, positioned on the immediate northern periphery of Elam. Was this mining complex supplying tin in some form to the Elamite donkey caravans travelling north to sites in Mesopotamia (Pigott, 2021, p. 843, fig. 29.10)? Further complicating this picture is that scholars, as yet, have no idea where ores mined at Deh Hosein were being smelted to metal; perhaps in its hinterland or perhaps in major urban centers along the caravan routes north in Mesopotamia?

Speaking of further complications, we turn briefly to what we might call the 'Dilmun Conundrum'. There is little question that there is a considerable body of research devoted to Dilmun, centered on the island of Bahrain and its hinterland in the Gulf north of Oman and south of southern-most Mesopotamia. Dilmun had considerable involvement with Gulf polities, Mesopotamian urban centers as well as southwestern Iran (e.g., Crawford, 1989; Laursen and Steinkeller, 2017). In this regard, Ben Foster (Foster, 1997, p. 59; see also Helwing, 2009, p. 210) has stated that "Sumerian and Babylonian merchants went to Dilmun to buy copper and tin, while traders from Dilmun came to Mesopotamia, for example, to Sargonic Umma, Lagash, and Agade as well as to Susa when it was under Sargonic rule" (Pigott, in press). Helwing (2009, p. 214) makes the point that Elam obtained tin being traded from Dilmun. In addition, Helwing (2021, para. 67) argues that Elam's 2nd millennium BCE copper supply was coming from Gulf regional sources, thus involving Elam even deeper in interaction with Gulf traders. Once in the hands of the Elamites, tin could well have joined the trade networks headed north to various Mesopotamian urban centers located along the main routes. We end our discussion with this question, from where was Dilmun obtaining the tin which it was trading so actively? Two possibilities exist. Either Deh Hosein tin was traded by the Elamites to Dilmun in return for commodities not available in Elam or we must look east to across the Indian Ocean to the Indus Valley (Meluhha) known to be trading with Mesopotamian ports. Tin sources in the Hindu Kush and Afghanistan's reserves could well have been the Indus Valley traders' sources of this tin (e.g., Crawford, 1989; Thornton, 2013; Laursen and Steinkeller, 2017; Weeks, 2003; Pigott, in press).

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At the Dawn of Early Extractivism: Firesetting and Herding as practices of Early Mining Communities between Europe, Eurasia and West Asia

Thomas Stöllner, with a contribution of Erich Pucher

Abstract: The presentation aims at the dissemination of knowledge stocks within mining communities between Europe, West Asia and Central Asia between the 4th and 2nd millennium BC. Within this vast space, remarkable technical similarities in subsistence practices and ore extraction can be observed. They include ore extraction by means of firesetting, the extraction of ores with the help of special tool-sets and the subsequent ore dressing before the mines, as well as the regular transport of ore concentrates to settlements nearer or further away, where the ores were further smelted and cast into shape with the help of crucibles. These techniques required the appropriation of montane resource-scapes through more or less permanent, but mostly seasonal practices and a way of life equally tied to this rather extensive and mobile strategy at certain times during the year. It can be assumed that the management of grazing zones and animal herds had to adapt to these conditions in a specialised way and that other agricultural strategies were added in phases, when greater continuity in the year-round care of the fields was possible in the settlements. Climatic and subsistence conditions in the montane resource areas thus played an important basic prerequisite for the adaptation of technical practices in ore mining and further processing. Just as the basic geological conditions favoured the spread of certain techniques. The article compares some intensively studied ore mining sites (Georgia, Kazakhstan, Iran, Austria) of this period and sheds light on similarities, but also differences in a time before the development of first economized and extractivistic metal ore mining, which took place between the 3rd and 2nd millennium BC in different places in Eurasia and West Asia.

Keywords: Early Metal Age, Bronze Age, mining, firesetting, husbandry and pastoralism, food-supply, commercialisation

Résumé : L'exposé vise à montrer la diffusion des connaissances au sein des communautés minières entre l'Europe, l'Asie occidentale et l'Asie centrale entre le IV^e^ et le II^e^ millénaire avant notre ère. Au sein de cet immense espace, on observe des similitudes techniques remarquables dans les pratiques de subsistance et l'extraction du minerai. Elles comprennent l'extraction du minerai à l'aide de l'abattage par le feu et de maillets en pierre et le traitement ultérieur du minerai devant les mines, ainsi que le transport régulier des concentrés de minerai vers des villages plus ou moins éloignés, où il était fondu et mis en forme à l'aide de creusets. Ces techniques nécessitaient l'appropriation des espaces de ressources montagnards par des pratiques plus ou moins permanentes, mais le plus souvent saisonnières, et un mode de vie également lié à cette stratégie plutôt extensive et mobile à certaines périodes de l'année. On peut supposer que la gestion des zones de pâturage et des troupeaux de bétail a dû s'adapter de manière spécialisée à ces conditions et que d'autres stratégies agricoles ont dû être adoptées lors de certaines phases, lorsque les habitats permettaient une plus grande constance dans l'entretien des champs au cours d'une année. Les conditions climatiques et les conditions de subsistance dans les espaces de ressources montagnards ont donc joué un rôle important dans l'adaptation des pratiques techniques d'extraction du minerai. De même, les conditions géologiques de base ont favorisé la diffusion de certaines techniques. L'article compare certains sites d'extraction de minerais (Géorgie, Kazakhstan, Iran, Autriche) de cette période ayant fait l'objet de recherches approfondies et met en lumière les similitudes, mais aussi les différences à une époque précédant le développement de la première extraction de minerais métalliques économisée et extractiviste, qui a eu lieu entre le III^e^ et le II^e^ millénaire avant notre ère dans différents endroits d'Eurasie et d'Asie de l'Ouest.

Mots clés : Premier âge des Métaux, âge du Bronze, exploitation minière, abattage par le feu, élevage et pastoralisme, approvisionnement en nourriture, commercialisation

INTRODUCTION AND RESEARCH QUESTIONS

The spread of metallurgy since the invention of metallurgical pyrotechnics in the 5th millennium BC can be described as a spread of technical but also social practice bundles (generally Roberts et al., 2009; Hansen, 2013). Metal as a social innovation probably included further economic, social and technical innovations associated with the extraction of metal ores in mainly mountainous regions (Stöllner, 2023a). In addition to the more permanent use of

ecological marginal zones, developments from the 4th millennium BC onwards also led to the permanent expansion of mining regions. Ultimately, all of this points to a variety of knowledge complexes and innovation bundles that were absorbed, adapted and finally made into stable subsistence practices and their interrelation with social communities. Within this process, two sets of practices seem to be of central importance: the technique of setting fires and the development of distinct herding practices as an important source of meat and dairy products. Both practices depend on the climatic and subsistence conditions in the mountainous resource areas (wood, grassland) and thus played an important role in the adaptation of technical practices in ore mining. They provide the background to the question of what were the enabling and limiting factors when mining turned into a commercialised enterprise that also generated dependencies in various respects (food and supply regimes and ecological potentials). Even more, one could ask whether this period witnessed an 'economisation' of practices towards capacity-based mining (in the sense of an early extractivism).

The practice of firesetting is associated with a specific set of technical practices, including the subsequent processing of ore in front of the mines, as well as the regular transport of ore concentrates to settlements near or far, where the ore was further smelted and shaped using crucibles (e.g. Weisgerber and Willies, 2000; Strahm and Hauptmann, 2009; O'Brien 2015, p. 195–243; Hauptmann, 2020). Its oldest evidence is known for ore extraction at the end of the 6th and the beginning of the 5th millennium BC in the Middle Balkans and the Vinča culture (Jovanović, 1982; Radivojevic and Roberts, 2021). It is interesting to note that this technique, as well as the use of other techniques, such as the use of stone hammers and antlers, was initially used in the mining of jasper and green pigments in the 5th and 4th millennia BC (Schmid, 1999). It was not until the 4th millennium B.C. that the technique became the standard method over a wide area along the Tethyan Eurasian mountain belt and finally in the area of tin ore mining (from the 3rd millennium BC; Stöllner 2023a, p. 41–42; see here fig. 1). The connection with a deposit area with specific geological conditions of

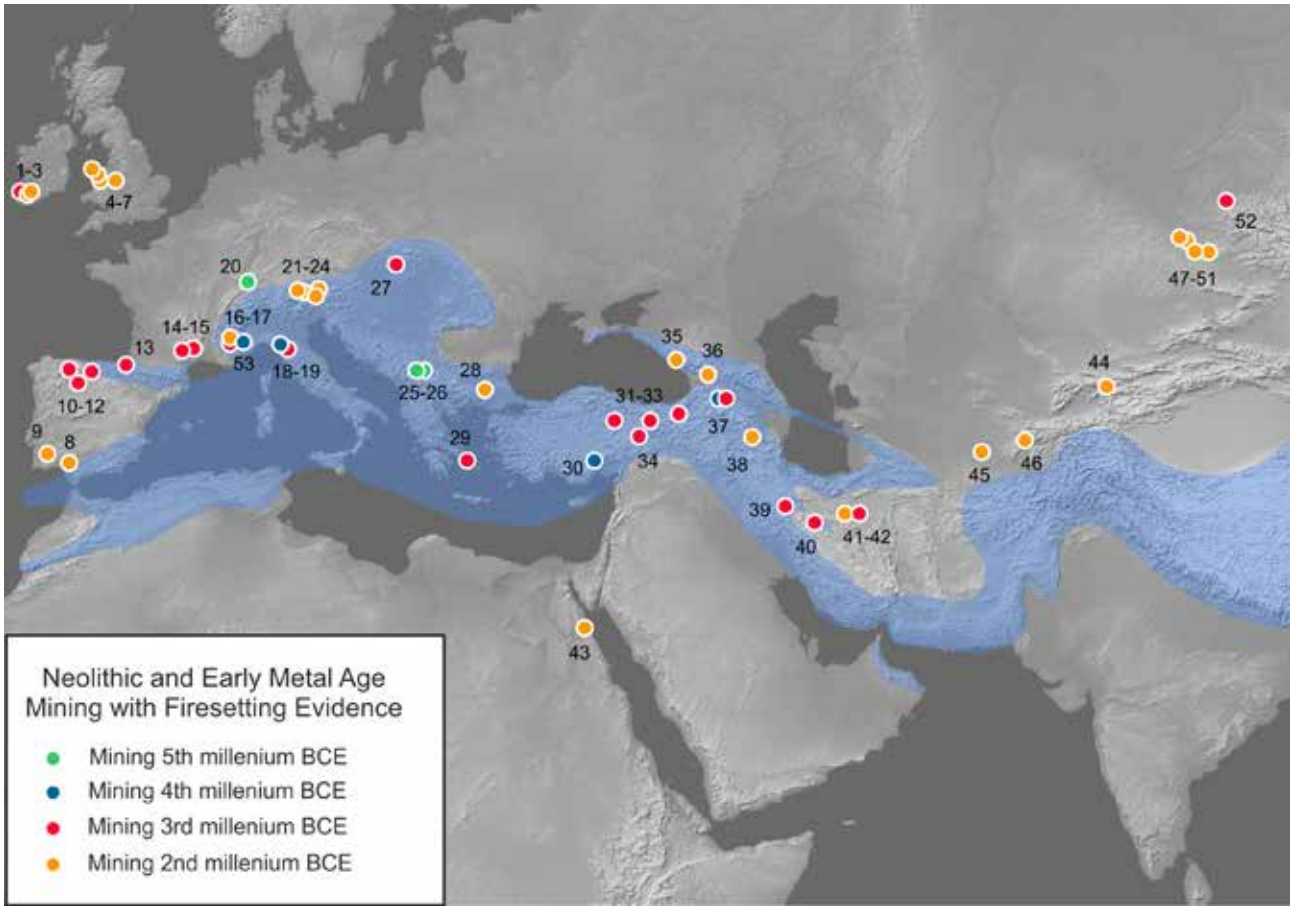


Fig. 1 – Firesetting in prehistoric mining (5th till 2nd millennium BC) and the TEMB-girdle (blue): 1: Ross Island; 2: Mount Gabriel; 3: Derrycarhoon; 4: Parys Mountain; 5: Great Orme; 6: Cwmystwyth; 7: Alderley Edge; 8: Chinflon; 9: Mocissos; 10: El Aramo; 11: El Milagro; 12: La Profunda; 13: Causiat; 14: Cabrière; 15: Bouco-Peyrol; 16: Saint-Vérant; 17: Les Rousses; 18: Libiola; 19: Monte Loreto; 20: Kleinkems; 21: Schwaz; 22: Brixlegg; 23: St: Veit; 24: Mitterberg; 25: Rudna glava; 26: Jarmovac; 27: Špania Dolina; 28: Adatepe; 29: Siphnos; 30: Kestel; 31: Gümuşhane; 32: Kozlu; 33: Murgul; 34: Zeytindağ/Keban; 35: Bashkazara; 36: Saarkasch; 37: Sakdrisi; 38: Mazrayeh; 39: Shakin; 40: Veshnaveh; 41: Kuh-e Zar, Anaru; 42: Kuh-e Baba Ahmad; 43: Jebel Zeit; 44: Aktaš; 45: Karnab; 46: Mushiston; 47: Karagoin; 48: Askaraly; 49: Kalai Topkan; 50: Urunchaj; 51: Čerdojak; 52: Vladimirovka; Altai (Map: DBM/RUB, Th. Stöllner).

hydrothermal deposit formations (veins and mass deposits), especially complex ores with quartz-rich, intergrown ores, indicates a connection with the application of the process (summary: Hauptmann, 2020). In addition, these more northerly and less arid regions (compared to the more southerly areas, for example) had better access to locally available fuels, which made the more extensive use of the techniques possible in the first place. The mining areas of the southern Levant (Egypt's Eastern Desert, Sinai, Wadi Arabah and Fenan), for example, have yielded little evidence of fire setting, suggesting ecologically unfavourable conditions for the use of the technique.

Firesetting and pastoralism as practice bundles therefore required the appropriation of mountain resource spaces through more or less permanent living and subsistence practices. This question became even more debated after A. Sherratt introduced 'secondary products' such as milk, cheese or wool as an important aspect of earlier prehistoric societies more than 40 years ago (Sherratt, 1981; 1983; critically: Vosteen, 1996; Craig et al., 2005).

M. Pearce speaks here of a metallurgy-pastoralism nexus (Pearce, 2025), but perhaps it is more appropriate to generalise it to a mining-metal-pastoralism nexus. The link in the appropriation of a mountainous landscape has already been demonstrated years ago by M. Pearce and R. Maggi (2005) in relation to the Ligurian Apennines. Other examples have since been discussed (Antipina and Morales, 2006; Berthon et al., 2021; Stöllner et al., 2022). In another context, I have called this a miner-herder strategy, which is linked to specific practices and can also lead to a certain tradition of action in specific landscape and climatic settings (Stöllner, 2023b). But also the vision of a (larger) meat supply, either in processed parts or in live animals, is discussed (Wijngaarden-Bakker, 2004; O'Brien, 2015, p. 264–265), as well as their reuse, mainly as working tools, as in the Great Orme (James, 2008; 2011). In many cases, however, the actual link to pastoral practices in the agricultural hinterland remains to be understood in order to understand the involvement of the mining communities themselves. The mobility patterns of domesticated animals, discussed later in this article, may provide a possible answer to this question.

For earlier periods, however, it remains to be seen whether the increasing appropriation and reorganisation of mountain areas actually led to a close economic symbiosis between herders and miners, or whether this was characterised more by coexistence (as has been suggested for the Kargaly mining complex in the southern Urals: Antipina and Morales, 2006). In the Alpine Arc, the development of hard cheese production may have become a similarly important aspect in later parts of prehistory. This required not only innovations in rennet management, but also a constant supply of table salt. Although current research in the Central Alpine Arc has only been able to establish a definite link between hard cheese production and alpine pastoralism in the Iron Age (Reitmaier, 2020), the production of fresh cheese (with a limited shelf life) and wool may have occurred even earlier.

The conspicuous linkage of the technique to certain ecological zones suggests that the spread of the technique occurred through the transfer of knowledge along similar ecological and economic lines. The central question may therefore be whether this spread (e.g. from south-eastern Europe to the west, east and south-east) took place through mobile mining groups passing on their knowledge of how to establish and adapt the technology to other communities related by metal consumption. But how was the division of labour organised within the mining groups? This certainly depended on the scale of production that was intended and that was to be achieved. A small labour force could certainly practise a different division of labour within kinship groups than larger enterprises. The gradual increase in the use of metal and raw materials probably changed the traditional strategies of direct access to other, more permanent strategies of managing ore deposits and subsistence conditions (as can be seen in large mining operations such as Mitterberg [Stöllner, 2015; Pernicka et al., 2016] or the Great Orme [Dutton et al., 1994; Williams and Le Carlier de Veslud, 2019]).

In the following, I will examine several intensively analysed ore mining sites from the 4th to 2nd millennium BC in Georgia, Kazakhstan, Iran and Austria, which the Bochum teams have been able to investigate for more than two decades. In particular, the question of the significance of different conditions for the connectivity of the montane deposits will be investigated. The question is whether certain technical and subsistence patterns can be compared in different ecological zones (Caucasus, Iranian highlands, Eurasian steppe zone, Alps). What kind of miner-herder practices can be observed? In contrast to the diffusion of metallurgy, the focus is more on the appropriation of peripheral environments and the application of knowledge practices in such ecologies.

FIRESETTING AS A TECHNICAL PRINCIPLE IN EARLY METAL AGE

Physical and chemical preconditions

Fire setting is not equally effective in all rocks because it relies on heat-induced expansion along the crystal lattice axes of certain minerals such as quartz, feldspar, calcite or iron carbonate (for physical requirements see Weisgerber and Willies, 2000, p. 135). This mineral association is common in igneous, sedimentary and metamorphic rock sequences. Quartz in particular has a high expansion behaviour, which is why quartz-rich rock sequences are particularly suitable for the application of this technology. The temperatures achievable in an open fire are typically between 600 and 800°C. Depending on the mineralogical composition, these temperatures have different effects: the heat capacity and density of the rock, together with the water chemically bound in the rock, determine the explosive effect of the heat applied to the rock: Sinock

(1984, p. 49–50) gives coefficients of thermal expansion for some important minerals. As already mentioned, quartz has the best expansion behaviour (4.42 at 800°C), followed by microcline, orthoclase and plagioclase. Not only do the minerals differ in their expansion behaviour, but also in their critical fracture temperature. Whereas basalt fractures at around 550°C, quartzite, granite and granodiorite fracture at temperatures between 200 and 300°C.

Ore-bearing rock formations are rarely so homogeneous that the effects of a fire can be accurately predicted. Other parameters must also be taken into account. The fuel available (in addition to logs, charcoal or brushwood can be used) must be considered, as must the influence of air currents (especially underground). The interaction of these and other parameters is crucial to the success of the technology. This is clearly demonstrated by the experience of various firesetting experiments (see below).

The early use of fire: basic techniques and evidence from the oldest metal ore mining

In addition to the use of fire itself, the technology is always associated with certain technical aids that are time-bound (Weisgerber and Willies, 2000). Within the prehistoric periods, an interaction with stone hammering can in principle be observed. There are also other components, such as certain bone and antler tools, which can vary in time and space. However, archaeological observations show that there are differences depending on the rock and the type of mineralisation. These can easily be understood as local adaptations from a basic repertoire of technical possibilities and experience. While the prehistoric firesetting technique developed from the 5th millennium BC onwards was mainly based on the interplay with stone hammering, metal tools (bronze, iron) were increasingly used to work the surfaces set on fire.

In this way, fire setting could be used as the main driving technique or in a supporting role. Bjørn Ivar Berg (1992, p. 55–76) therefore divides the driving work into three steps: hammering with fire setting, fire setting with hammering, or just fire setting.

The use of fire setting has to be implemented with varying degrees of efficiency in the driving work: the effect of the fire is more effective on the roof and walls than on the floor, making shaft sinking more difficult. On the other hand, sideways sinking at ground level is not a problem, provided that the working area is well ventilated. Under good ventilation conditions, sinking a vertical shaft is not too difficult and, in the case of this installation, could certainly be combined with lateral widening work, including the use of fire. However, the initial driving of a level area from a certain depth was always associated with ventilation difficulties, which is why laterally widened so-called tumble mines (for the term, see Weisgerber, 1989) were often preferred in early mining. Chimneys and ventilation shafts are also known. This principle can be clearly seen in the mines of Veshnaveh or Schwaz-Brixlegg (see Goldenberg and Rieser, 2004, p. 41, figs. 5–6; Stöllner et al., 2011a, p. 599).

The lighting of the fire was an important moment: not only did the sudden appearance of dangerous fumes have to be taken into account, but the direction of the fire also had to be supported. The construction of the woodpile was certainly of paramount importance, but in addition the fire could be steered in a certain direction by means of firesetting platforms or covers (stone slabs, 'muffles') (Gätzschmann, 1846, p. 697, p. 706; Weisgerber and Willies, 2000). In early modern mining there were detailed regulations on the development of flue gases (Agricola 1556, Book 6, p. 185; Weisgerber and Willies, 2000, p. 141).

The early use of fire: its manifestations in prehistoric copper, tin and gold mining

As mentioned at the beginning, the use of fire is one of the oldest and most important extraction techniques in ancient mining. Without being able to describe all the phenomena in detail, some examples of research carried out by the Deutsches Bergbau-Museum in Bochum in recent years will be discussed: They illustrate the application of the technology in various ore districts. In the Veshnaveh copper deposit (3rd/2nd millennium BC), driving was used throughout; since highly enriched copper ore nests in stratiform enrichment zones usually extend horizontally in basalt and andesite rocks, the advance was laid out to follow the rich ore parts (fig. 2, 1-3). Niches and linear drifts were driven up to 30 metres into the rock. In very rich ore zones, the drift was extended laterally. However, these were mostly driven adits, which in turn were laterally extended (Stöllner et al., 2011a, p. 598–600). One particular example is Mine 21 at Chale Ghar, where a panel with so-called exfoliation plates was discovered at the end of the adit.

These were probably left at the end of the last mining operation. Fire-set stopes developed differently in deposits with vein-like and subvertical ore bodies. Good examples are the tin mines of the Andronovo Culture in Central Asia: excavations at the mines of Karnab and Mushiston (Uzbekistan, Tajikistan) between 1997 and 2000, as well as the mines of Askaraly (Eastern Kazakhstan), have provided very good evidence for this technology (Stöllner et al., 2011b; Garner, 2014) (fig. 2, 8-11). At Askaraly, the highly enriched cassiterite veins and ore strings were mined in an enrichment zone. The individual firesetting domes became very high: this also necessitated the construction of firesetting platforms, as demonstrated in the fully investigated mine workings of Askaraly II, Western Mine (Stöllner et al., 2011b, p. 242–244). Such platforms have been documented by P. Pétrequin for the production of adze blades by the Yeleme in New Guinea: simple wooden scaffolds are leaned against the steep quarry wall and a fire is lit on them (Pétrequin and Pétrequin, 1993; Pétrequin et al., 2008). The wooden platform burns down with the fire before the



Fig. 2 – Firesetting traces in Bronze Age mines in West Asia and Eurasia. 1-3: Veshnaveh, Qom Province, Iran (Chale Ghar mine 21, Lagh-e Morad, mine 1); 4-7: Sakdrisi, Bolnisi district, Georgia (mines 1/2 north extension; mine 1/1; mine 1/2 north-extension, hammering traces; mine 2, southern drive mit Firesetting debris; 8-11: Askaraly II, Özkemen oblast, Kazakhstan, East mine 1, west drive with refilling, East mine 1, west drive lowest flour, West mine east lowest drive with burned wooden stage, West mine, east lowest drive wirth Firesetting debris, refilled; (photos: DBM/RUB, Th. Stöllner, J. Garner [9]).

desired piece of rock can be broken (fig. 2, 10). The granite dug mine at Askaraly is in many ways similar to the mines at Karnab, which were investigated in the 1990s as part of a large collaborative project (Pre-Islamic Tin Mining in Central Asia, 1995-1999; Garner, 2014). The mines were excavated to a depth of 17 m (pit 6/1: Garner, 2014, p. 95–98); similar depths were also reached in the Mushiston mine, while the Askaraly II mine stopped at a depth of almost 10 m. The almost shaft-like descents that could be reached by mining are interesting: examples of this type can be found at Askaraly II, West Mine (Stöllner et al., 2011b), at Karnab, Mine 6/1 (Garner 2014, p. 95–98), and in Georgia, Sakdrisi, Mine 1/1 (Stöllner et al., 2014).

A close analysis of the driving direction shows that the extractions were not aligned, but that very steep advances were made in short alternation in opposite directions. This is evidenced by short, flat steps that descend like stairs. This is particularly evident in mine 1/1 of the Sakdrisi gold mine: the steeply sloping part of the mine reached a depth of over 11 metres and could only be worked steeply upwards (fig. 2, 4-7). The use of firesetting allowed the Sakdrisi miners to reach depths of almost 30 m from the surface in extremely hard rock. The haematite-gold ore is embedded in a quartz-rich vein and silicified host rock of dacite and rhyolite: This required a great deal of hammering, as is clear from the thousands of hammer fragments found in the mining area (Stöllner et al., 2014; Tamazashvili, 2024).

The processing equipment found in Early Metal Age mines also follows a certain pattern, albeit with many variations. The tool most often found in connection with the use of firesetting is the stone hammer. At Karnab, the limestone used there (quartz-rich shell limestone: Garner, 2014) was only effective on the quarried granite in combination with firesetting: metamorphic rocks such as amphibolite, lamprophyre (Veshnaveh; Stöllner et al., 2011a) or andesitic rocks, porphyrites and granodiorites (Sakdrisi) were often used (Stöllner et al., 2014; Tamazashvili, 2024): As a rule, a certain section of rock types predominates. This is impressively demonstrated in Sakdrisi: the rock types found in Sakdrisi can be found as river pebbles in the nearby Mashavera River. However, it was found that the 100 formally suitable rocks collected did not match the spectrum of rocks found in the hammers found in the quarry. In particular, dense andesitic-basaltic rocks appeared to have been deliberately selected, followed apparently by granodiorites, which were collected a little more frequently.

The question of the method of hafting is more difficult because it has been demonstrated less frequently. Without going into all the evidence in detail, it should be noted that there is evidence of knotted hafting from Central Asia to Ireland, as discovered in the 19th century at Mitterberg in Salzburg (see, among others, Thomas 2018; for the example from Askaraly, cf. Stöllner et al., 2011b; fig. 3,7609). Thanks to the excellent excavation observations at Copa Hill (Timberlake, 2003a), there is also evidence for the so-called Chuquicamata shafting, a type that has proved particularly effective in experiments (Craddock, 1992; Timberlake and Craddock, 2005; Timberlake, 2017). In this case, the mallet is held in place by tied willow or hazel rods or hazel sticks. These are bent into a U-shape over a notch or shaft groove and the shaft is tied with rawhide.

In addition to the wide variety of hammers used in the mines described, other types of bone tools were also used (fig. 3). In addition to antler picks, such as those found at Sakdrisi, scrapers made from ox ribs and scrapers made from ox shoulder blades are common. They are known from all the sites described above, but ultimately from

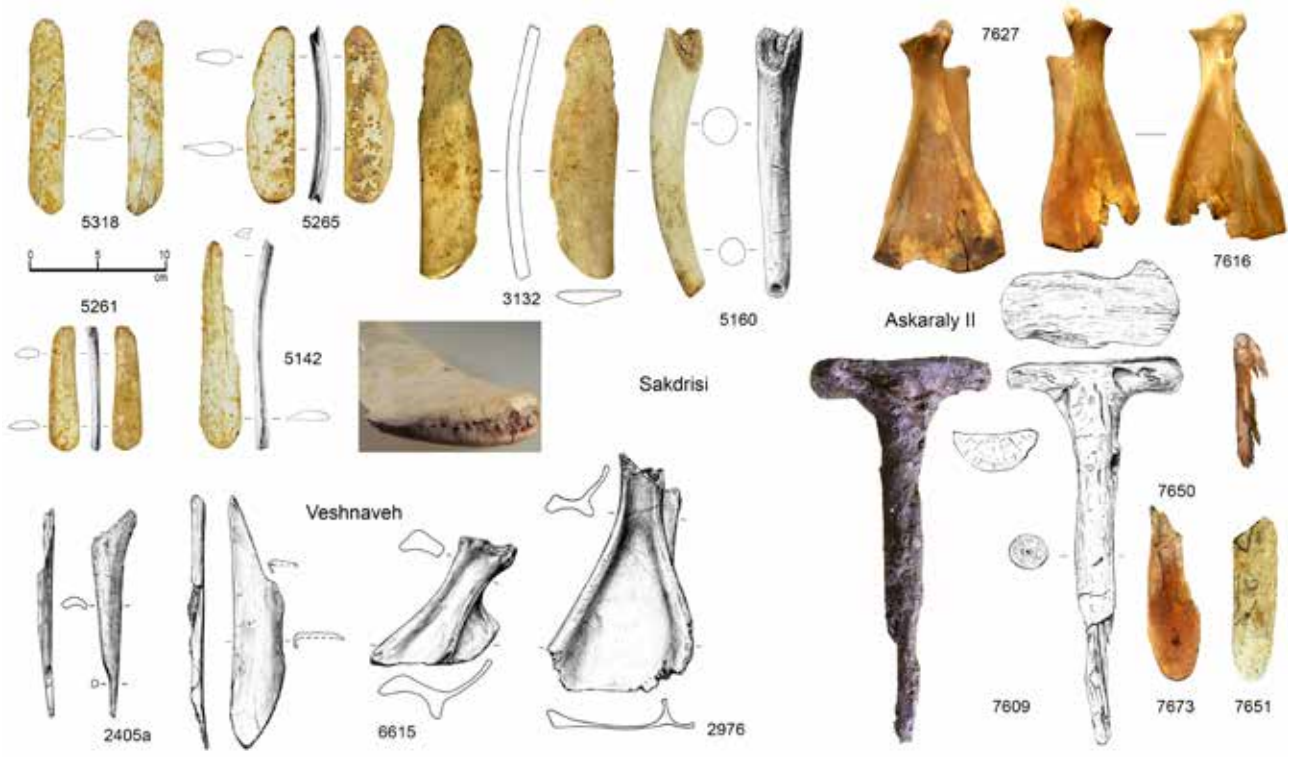


Fig. 3 – Bone tools from Bronze Age mining in Sakdrisi /Georgia, Veshnaveh/Iran, Askaraly II/Kazakhstan, antler, bone chisel, rib scrapers, shoulder blade scrapers, wooden handle (photos/drawings: Th. Rabsilber, K. Tamazashvili, J. Garner, Th. Stöllner).

all early metalworking sites, such as the Early to Middle Bronze Age examples in Wales and the Peak District (The Great Orme-Copa Hill, Cwmystwyth, Ecton, Derbyshire hire, Great Orme near Llandudno: Timberlake, 2003a; 2003b; unclear at Great Orme: Dutton et al., 1994; generally O'Brien, 2015).

Hammerstones and ore mills have often been found together. Particularly characteristic are 'dimple stones' with numerous cup-shaped depressions, which can be used effectively with stone hammers the size of a child's fist. Smaller and also widespread are small palm-sized underlays, often with a central depression (e.g. Garner, 2014). The case of Sakdrisi, in particular, has shown how diverse this working tool could be developed if the processing had to differentiate in detail (e.g. between gold-rich and gold-poor sands).

The wood needed for firesetting has been analysed in some cases: So far there is no evidence for the use of charcoal in the older prehistoric periods: in general, the natural supply of wood depends on the forests used, as shown by various archaeobotanical studies of ash and charcoal layers in early metal mining areas (fig. 4). In Sakdrisi, local oak was generally used as a heat-retaining wood (W. Schoch, in: Stöllner et al., 2021). In contrast, 10% consisted of a variety of brushwood, which was probably burned in the fire. In the tin mines of Askaraly in eastern Kazakhstan, on the other hand, juniper and conifer brushwood (*Juniperus*, *Abies* sp.) were used as brushwood, while poplar and birch were used as heat-retaining logs (det. W. Schoch, Stöllner et al., 2011b). This pattern of fuelwood use differs significantly from that found in the contemporary settlement and from the practice of cremation in the cemetery (fig. 5). In contrast, the

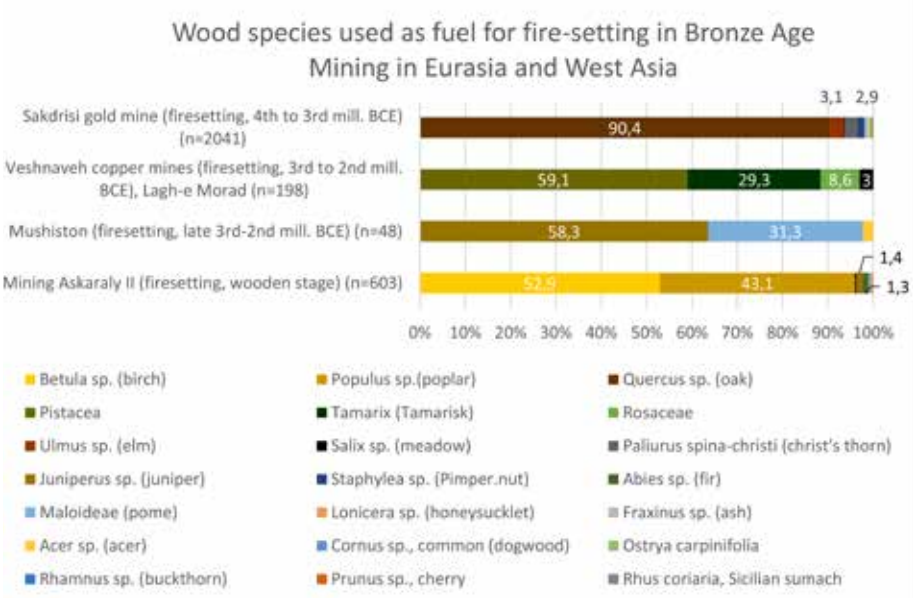


Fig. 4 – Wood-species used for Firesetting from Bronze Age mines in West Asia and Eurasia (data W. Schoch, Birmenstorf; R. Pasternak, Kiel).

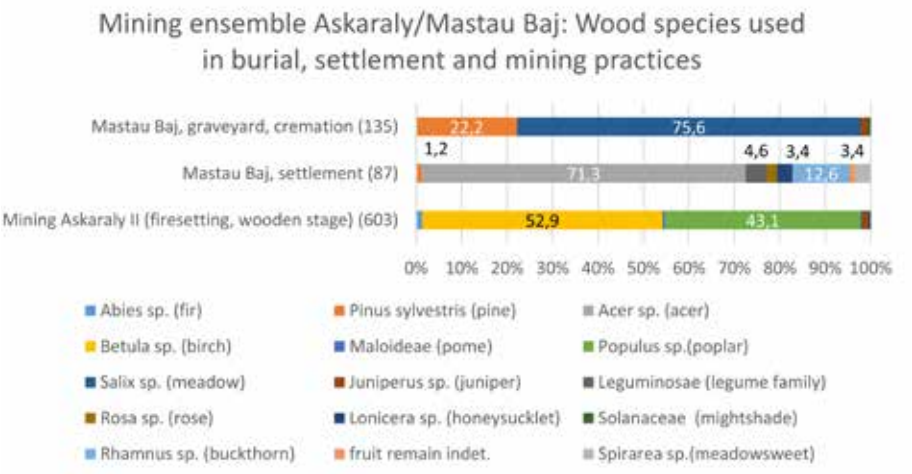


Fig. 5 – Wood consumption pattern of the Bronze Age mining community of Askaraly II/Mastau Baj in East Kazakhstan (data W. Schoch, Birmenstorf)..

very dry climate has affected the tree population in the copper mines of Veshnaveh: however, charcoal analyses have shown that in the 2nd millennium a combination of heartwood (pistachio) and tamarisk brushwood was used. R. Pasternak also assumes a denser forest cover than today, reduced probably due to intensive grazing since then rather than mining (R. Pasternak, in: Stöllner, et al. 2011; see here fig. 4). In the sparsely vegetated steppe around Karnab, wormwood shrubs seemed to be the only useful woody plants, but their suitability was demonstrated in a firesetting experiment (Garner, 2014).

Bronze Age mining in the Eastern Alps, where spruce and fir have been found (Zschocke and Preuschen, 1932; Rieser and Schrattenthaler, 1998–99, p. 175), whereas in the British Isles oak and beech heartwood were preferred (O'Brien, 1994, p. 166; O'Brien, 2004). It is unfortunate that we lack a modern investigation of the firesetting techniques proposed by Zschocke and Preuschen (1932) for the Mitterberg type of East Alpine deep mining. This is different for the copper ore mining in the carbonates of the Schwaz-Brixlegg district, where detailed modern observations are available (Pichler et al., 2013; Staudt et al., 2019). It is striking that, despite the wide variety of wood available, a combination of heat-bearing heartwood and heat-sparking brushwood was often chosen. This also proved to be a practical combination in the burning experiments.

Fire setting experiments of Bronze Age Mining

There is already a wide range of fire setting experiments to understand their use in prehistoric and historic mining (Rieser and Schrattenthaler, 1989/99; O'Brien, 1994; Schmid, 1999; Timberlake and Craddock, 2005; Py and Ancel, 2006; Timberlake, 2007 and 2017; Stöllner et al., 2012). Most of these experiments were based on historical accounts or archaeological observations of mining sites. This is different from the experiments of P. and A.-M. Pétrequin, which were designed on the basis of ethnographic observations in Papua (Pétrequin et al., 2008). E. Schmid in Kleinkems, who was one of the first to conduct experiments in 1952, tested water dousing (Schmid, 1999). Later experiments by Rieser and Schrattenthaler (1998/99), Timberlake and Craddock (2005), and Timberlake, Stöllner and Craddock (Stöllner et al., 2012; Timberlake, 2017) showed that this is not absolutely necessary. In the hard limestone of Kleinkems, however, it has proved helpful, as it did in the extraction of lapis in Badakhshan (Weisgerber, 2004, p. 133). It helps to cool the stone quickly, but does not increase the amount of stone.

The experiments conducted to date have also provided insights into the ratio of wood used to rock produced (the so-called wood-rock extract ratio), which ranged from 1:0.8 to 1:2.3 in the Welsh experiments and as low as 1:0.27 at Mount Gabriel, Ireland (O'Brien, 1994). In the Sakdrisi experiment, the ratio was strongly influenced by the amount of iron ore and weathered cracks, but generally an average of 1:0.7 was observed (Timberlake, 2017; here table 1 and fig. 6). Overall, smaller fires were shown to be more efficient. It was found to be important to stack stem wood (log-thick branches or logs) on the outside and brushwood on the inside. Stones were used to weight down the pile, making it easier to direct the fire in one direction. When stones were used, they proved to be very effective, especially in the parts that were exposed to the fire. However, in the parts that were not thermally treated, this efficiency decreased significantly.

The rock material and the preparation of the stone tools were also studied in detail, especially in the Brit-

	Fireset 1/2011	**Fireset 2/2011**	**Fireset 3/2011**	**Fireset 4/2013**	**Fireset 5/2013**	**Fireset 6/2013**	**Fireset 7/2013**	**Fireset 8/2013**	**Fireset 9/2013**	**Fireset 10/2013**	**Fireset 11/2013**
Wood (kg)	214	48	84	174	49	77	50	89	49	50	20
Wood sp.	oak	oak	oak	oak	oak	oak	oak	oak	oak	oak	oak
Wood size(m)	0.8-1.1	0.5-0.8	branch	0.3-0.8	branch	0.8	0.5	0.5–0.8	0.5	0.5	branch
Duration (min)	240	150	210	135	165	270	120	180	150	150	205
Firing time	180	120	180	105	135	240	60	150	120	120	175
Hammering time	60	30	30	30	30	30	30	30	30	30	30
Max temp. (°C)		796	500	577	746	762	746	666	826	472	577
Water douse (kg)	Y	N	N	Y	N	Y	N	Y	N	N	N
Exfol rock (kg)	78,09	14,7	12.2	4.3	2	5.6		3.26	0.66	6.3	0.3
Pick rock (kg)	35		6,8	9.4	7.7	7.5		22	6.6	5.1	1.4
Hammer rock (kg)	65,7		26	34.5	24.1	15.75		16	2.9	6.6	7.8
Hammer and pick rock (kg)		86,5					69				
Site	vein A-B, face	vein A	underground	vein B	vein B	vein B	vein C	Vein A-B, face	Feature 10135 Mine B2-3	NW rift, mine A	vein B
Mining time (hrs.)	1	0,5		1.5	1	1		1		0.5	0.5
TOTAL rock (kg)	186	101	45	48	34	29	69	40	10	18	10
Ratio wood: rock	**1: 0.87**	**1: 2.1**	**1: 0.54**	**1: 0.28**	**1: 0.69**	**1: 0.38**	**1: 1.38**	**1: 0.45**	**1: 0.2**	**1: 0.36**	**1: 0.5**

Table 1 – Experimental firesetting and mining experiments at Sakdrisi Mine (2011 and 2013).



Fig. 6 – Firesetting experiments in Sakdrisi 2011 and 2013. 1: preparing the hammer-stone tools with Chuqui-hafting; 2: underground fire-set with dense smoke; 3–4: hammer- and antler-work after the fire-set; 5–7: experimental tools with Mitterberg-, Chuqui-afting, antler-pick; 8: fire-set experiment with the tool-set used and driving cavity; 9: beneficiation experiment with ores and experimental tools (mallet, crushers and grinders); 10: beneficiation tools found in Sakdrisi, dimples-stones, grinding-plates, ginders and small anvils (photos: DBM/RUB, Klaus Stange, AVtention [1-7], T. Rabsilber [10], Th. Stöllner [8-9]).

ish experiments. This revealed the importance of the choice of stone used: the type of stone and its toughness must have been chosen empirically. For the mines at Cmwystwyth in mid-Wales, Timberlake suggests that beach pebbles were used because they would have been exposed to the selection pressure of the surf. It would therefore have been easier to recognise which pebbles were suitable for extraction. The preparation of the notches and stone hammers, i.e. the making of the necessary notches and grooves, could usually be done quickly: after a series of experiments, B. Craddock in particular was able to develop an efficient method for making notches of the Chuquicamata type (the Chuqui shafting). During a series of experiments in Sakdrisi, B. Craddock made various hammers with different possible hafting types to test their efficiency in hammer-

ing work (Stöllner, et al. 2012; Timberlake, 2017). The manufactured tools were to be made according to the knotted branch haft (Mitterberg type) and the so-called Chuqui haft (fig. 6, 1): both types were to be tested in direct comparison. For the Chuqui shafts, fresh hazelnut sticks were used, which had to be moistened, twisted at the bend and beaten open to allow optimal placement and fixation on the stone. Untreated, moistened raw goatskin was used to fix the handle of the hammer, which consists of two hazel rods. In addition, a glue made from boiled pig's ears was applied to the raw hide bindings for reinforcement. For the Mitterberg hafting, the rawhide binding was placed over the centre of the stone, which lay flat. An attempt was also made to match the stone to the contact surface of the knobbed hafting. The heaviest hammer weighed approximately 4 kg, while the lighter smaller hammers weighed between 0.5 and 1 kg. While the Chuqui hafting was more suitable for heavy hammers and proved effective for striking from below (underhand stopping), the Mitterberg hafting was best for smaller hammers and direct blows from above (fig. 6). Like a celt, it could also be used on the sole and ridge.

The Sakdrisi experiments also helped to understand the econometric parameters of free gold extraction at Sakdrisi (the so-called Paravani calculation). Firstly, in terms of the operational effort to extract gold from a deposit like Sakdrisi (according to the old enrichment in the veins), but secondly to understand the societal impact that the extraction once had (Stöllner et al., 2014; Stöllner et al., 2021). Reconstruction has allowed us to understand the work load and possible size of the work-groups, but also how continuous the exploitation may have been (year-round or seasonal).

INTERWOVEN MINING COMMUNITIES BETWEEN EURASIA AND WEST ASIA

If we look at the spread of mining practices and techniques as a whole, then it becomes clear that the attachment to certain ecological zones, whether they were arid or humid, may have been associated with certain adaptations in subsistence. Let me now analyse the examples of successful application of both the practice-bundle 'firesetting' and 'herding' in different geographical and deposit zones.

The southern Caucasus and the Dzedzvebi-Sakdrisi complex

We start with the South Caucasus in the 4th and early 3rd millennium BC: here, the extraction and further social embedding of gold production in the Sakdrisi and Dzedzvebi complex can be regarded as one of the best-studied examples of this period (Gambashidze and Stöllner, 2016; Stöllner et al., 2014; 2021; 2023: see here fig 7). Begun in 2004 by a Georgian-German team, the work has since been continued in nearly 14 campaigns and has focused on numerous aspects of gold and copper extraction, ore processing, and their economic and social embeddedness. A further look at Late Chalcolithic-Early Bronze Age developments in the wider Transcaucasian environment makes it clear that the Sakdrisi-Dzedzvebi process emerged during a phase of social and economic consolidation of the Kura-Araxes societies (Stöllner, 2021). This, in turn, was based on an earlier, Chalcolithic phase of extensive resource exploitation of the montane areas between the Kura and Araxes rivers, leading to an

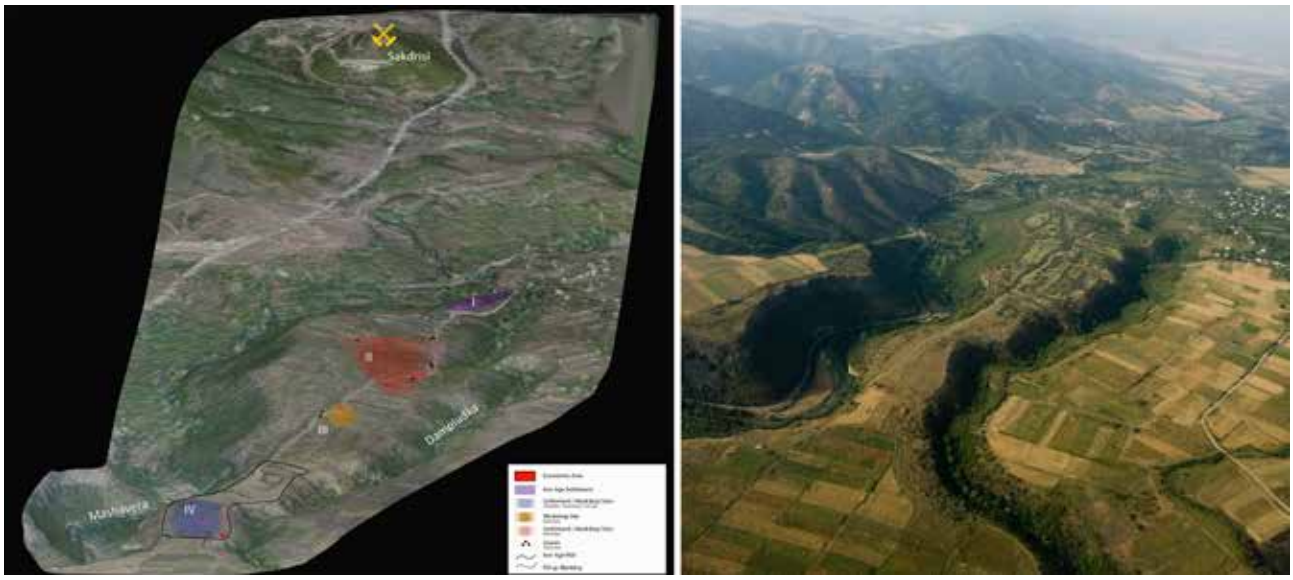


Fig. 7 – Left: The settlement plateau of Balichi-Dzedzvebi and its archaeological sites on the northern hilltop (I, Iron Age), northern slope (Dzedzvebi, area II, Early Bronze Age), on the northern part of the central plateau (Dzedzvebi, area III, Early Bronze Age) and on the southern plateau (Dzedzvebi, area IV, Chalcolithic, Early Bronze Age and Iron Age). Right: aerial photograph of the plateau (left: (plan processing/3D visualisation: DBM/RUB/GNM, A. Hornschuch/F. Klein; right: RUB/DBM, Th. Stöllner).

initial appropriation of metals and high pastures (Stöllner, 2024).

Recent results of studies on the mobility of domestic animals (Berthon et al. 2021; R. Bérthon and A. Vautrin in: Stöllner et al. 2023, p. 111–116; A. Vautrin in: Stöllner and Gambashidze 2024, p. 568–569; Vautrin 2024) show that pastoralism was initially oriented towards high-altitude summer pastures (figs. 8 and 9). With this seasonal mobility, mineral resources such as copper ores, but especially obsidian, were also appropriated and used more systematically (e.g. based on data from Dzedzvebi: Stöllner et al., 2023). In the Kura-Araxes communities, however, access changed again in the second half of the 4th millennium, as settlement landscapes and upland pastures were now used more intensively and permanently (generally Stöllner, 2021). There were now more permanent settlements at higher altitudes, and the mobility patterns of livestock also changed.

The corresponding results from the settlement phases of the Chalcolithic and Early Bronze Age settlement of Dzedzvebi clearly show this intensification, stabilisation, but also professionalisation of agropastoral practices (N. Boenke, in: Stöllner et al., 2023, esp. p. 106–111). Between the gold mines of Sakdrisi and the artisan settlement of Dzedzvebi, a permanent production process developed, which was accompanied by more stable subsistence conditions, probably due to a larger population living in the area for a longer time. The study of pottery finds also indicates that these groups came to the Mashavera valley from different parts of the Kura valley, possibly also via the Armenian plateau, to participate in the production process (Otchvani et al., 2021).

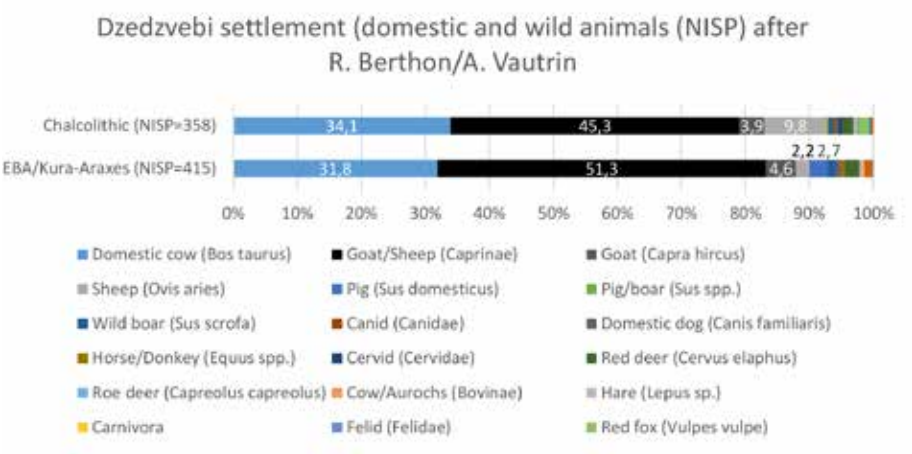


Fig. 8 – Relative representation of domestic mammals from Chalcolithic and EBA levels at Dzedzvebi (in % of the domestic mammals NISP) (draft/data: MNHN, A. Vautrin, R. Berthon).

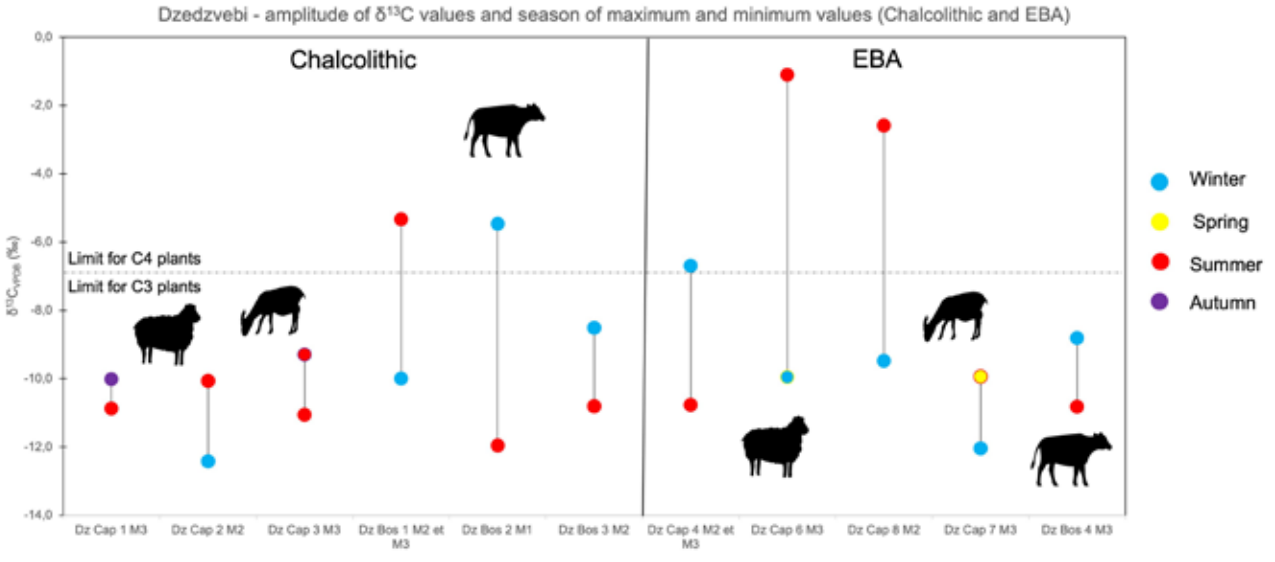


Fig. 9 – Amplitude of δ13C values during Chalcolithic and EBA. The colors designate the season for which the minimum/maximum of δ13C is reached (blue = winter, yellow = spring, red = summer, purple = autumn, when mixt colours = late season / early season, ex: red/purple = late summer-early autumn). The season was determined according to the δ18O value of the sample (draft/data: MNHN, A. Vautrin).

The process of gold production itself, which was clearly described, and by means of experiments and time calculations of the operation chain (based on the archaeological record) (Paravani calculation: Stöllner et al. 2021), clearly showed that different groups could have carried out the mining and processing. A small group of miners was probably able to extract enough gold in a few days to produce socially representative items such as golden earrings. It is likely that this type of mining was carried out in collaboration with the local population and local knowledge holders in order to exploit the rich gold deposit. The structures of the settlement show that larger groups may have stayed in Dzedzvebi at different times (of the year?; Stöllner et al., 2023, p. 121–124).

The high degree of ritualisation of gold mining reveals a multitude of negotiation processes (Stöllner et al., 2023, p. 127–128). Here, an interwoven resource landscape could develop that was effective for at least 500 years. The example of Dzedzvebi and Sakdrisi thus shows that the local connection between the settlement plateau and the mining zone led to the development of an intermediate resource landscape, which gradually became more stable in terms of location, but also enabled the integration of mobile groups through pastoralism and social practices around the gold-extraction and gold consumption.

Drought and mountains: The beginning of metal ore mining at the Central Iranian Plateau

The second example leads us to the Iranian plateau, and in particular its western part, a zone that experienced a strong dry phase and desiccation, especially in the middle Holocene (after more favourable conditions in the 6th and 5th millennia; Kehl et al., 2023; Rafiei-Alavi et al., 2023). The first metallisation of the plateau communities in the early 4th millennium probably led to a specialisation of metallurgical practices in the larger settlements (e.g. Helwing 2013; 2021). These were mostly located in water-rich areas, which may have been due to the climatic conditions of this zone. The intensification of copper and silver production at sites such as Arisman (Vatandoust et al., 2011, p. 11–530; Nezafati et al., 2021) and Sialk (Nezafati and Pernicka, 2005; 2012), which is particularly evident in the later 4th millennium, shows that the question of fuel resources already had a significant impact on the metal resource landscape at this time (fig. 10). The diverse ore supplies from a larger deposit area (Kahak, Baqoroq/Nakhlak, etc.) alone make this likely (e.g. E. Pernicka, K. Adam, M. Böhme, Z. Hezarkhani, N. Nezafati, M. Schreiner, B. Winterhöller, M. Momenzadeh, R. Vatandoost, in: Vatandoust et al., 2011, p. 675–679,

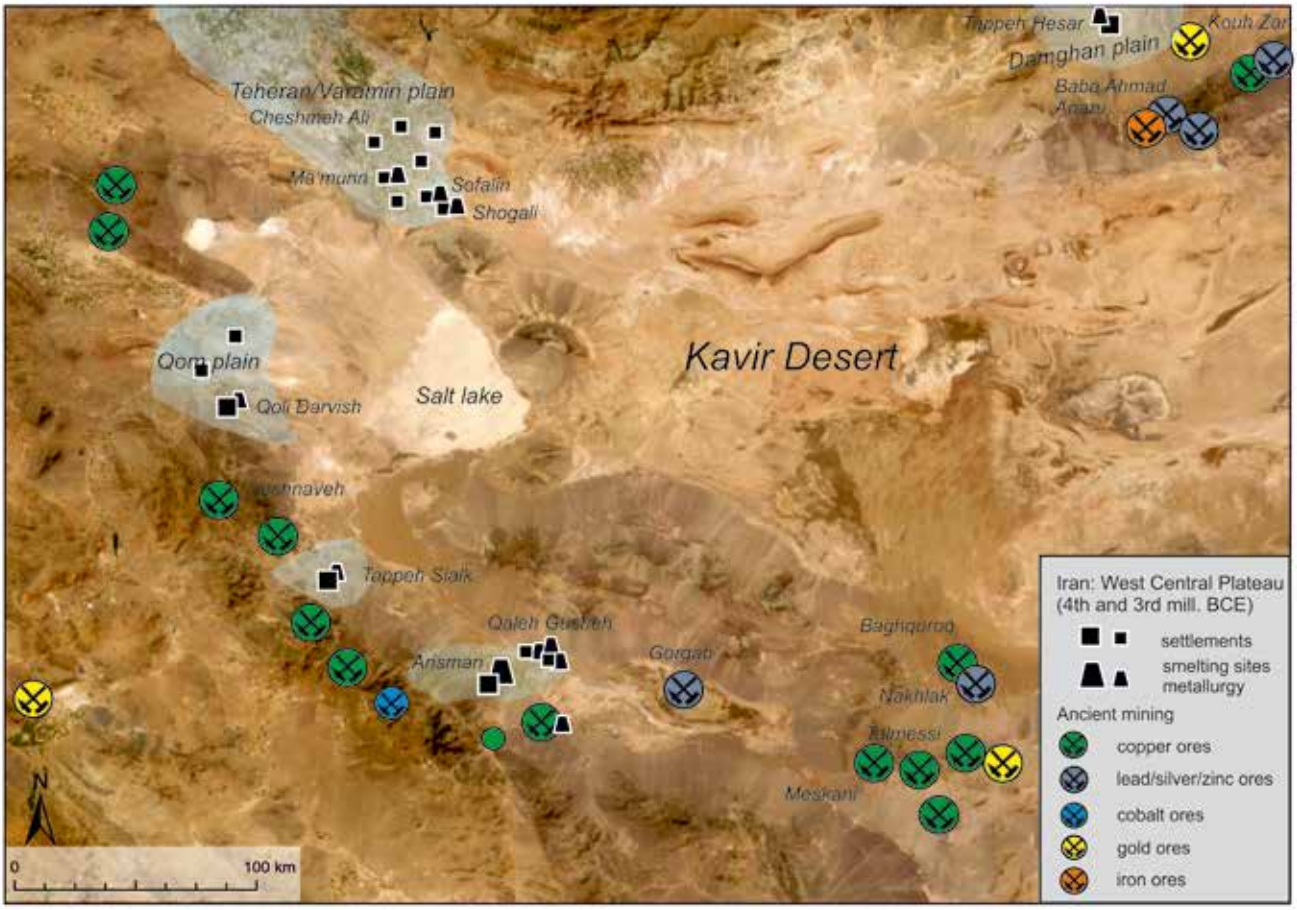


Fig. 10 – West Central Iran: Ore deposits, mining and metallurgical sites of the 4th to later 3rd millennium (after Vatandoust et al., 2011; Helwing, 2021; Fazeli-Nashli et al., 2013; draft DBM/RUB, Th, Stöllner).

figs. 45–46; for Nakhlak: Stöllner et al., 2004). This suggests sporadic and seasonal exploitation of the rich deposits in the surrounding area of west-central Iran (fig. 10). Unfortunately, hardly any mining from this period has been investigated. Currently, only the Veshnaveh deposit has been sufficiently investigated to provide answers about the character of ore exploitation (Stöllner et al., 2011; Nezafati and Stöllner, 2018; Stöllner et al., 2025).

In the Veshnaveh copper district, the earliest phase of near-surface ore mining can still be linked to the end of the Sialk IV period and the period just after. This is a period that is characterised by an extreme scarcity of evidence for settlement sites on the Western Central Plateau; recently, new sites have been discovered in the vicinity of Veshnaveh (near Fordu at the site of Yousef Khan: Sołtysiak et al., 2019; in general: Fazeli Nashli et al., 2022). This may indicate that mining at Veshnaveh was also active during this period. Most of the ^{14}C data from the mining come from a later period after the 4.2 event (fig. 11). The dating sequences and characteristics of the

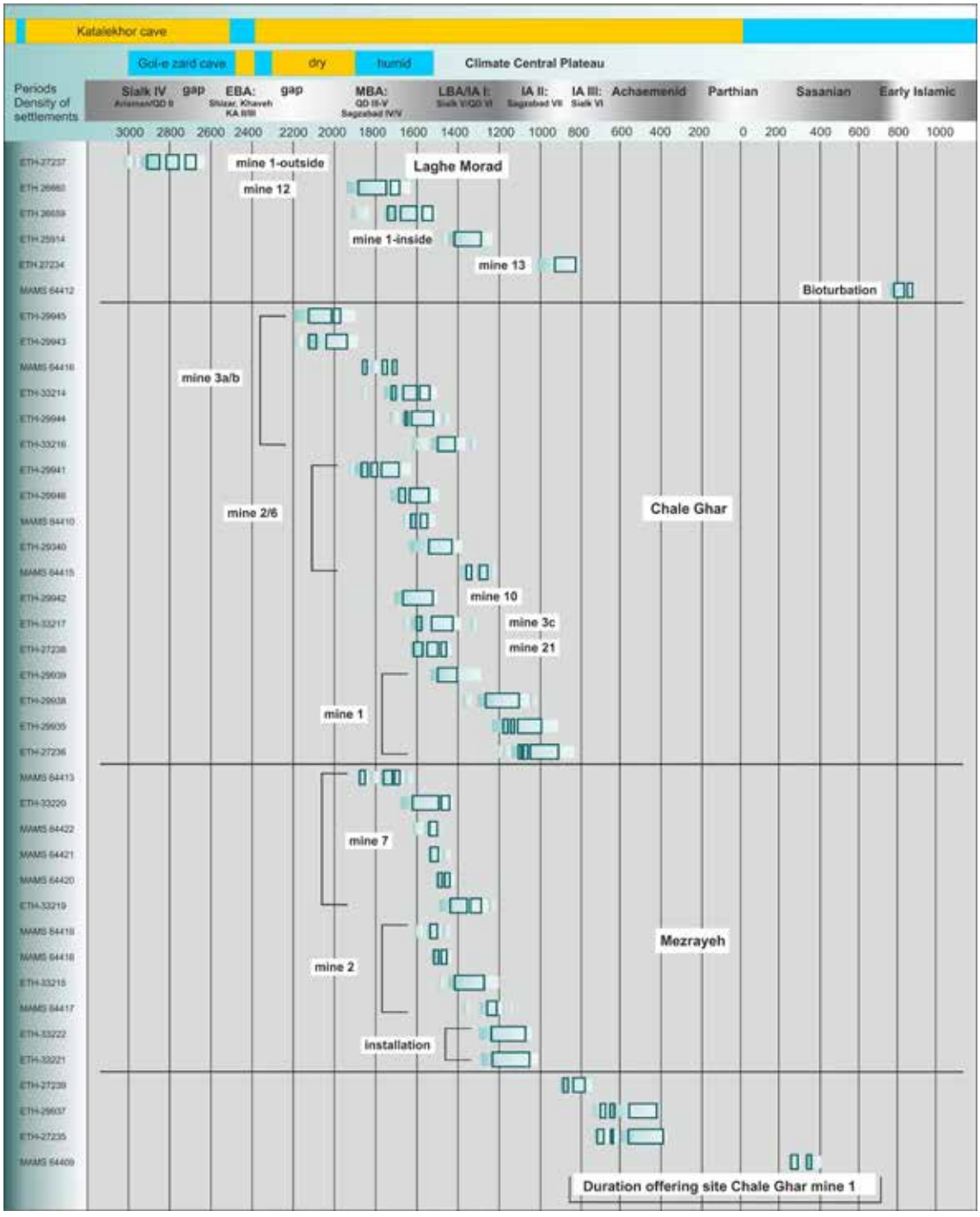


Fig. 11 – Veshnaveh, AMS-^{14}C-dates of mining and ritual activities in Veshnaveh and the climatic and settlement history of the Iranian Central Plateau (draft Th. Stöllner; climate and settlement data after Kehl et al. 2023; Rafiei-Alavi et al. 2023); calibration OxCal v4.4.4 Bronk Ramsey (2021).

Chale Ghar, Laghe Morad and Mezrayeh mining fields show that the pits were mined repeatedly over a period of time. In between, the mines were also used as shelters and campsites. This would also suggest that only small groups of miners worked outside the pits, extracting ore and processing it into concentrates. The use of woody plants (tamarisk and pistachio), especially during the Middle Bronze Age (phases 2 and 3) after the 4.2 climatic event, is important in terms of environmental and subsistence relationships. The archaeobotanical data (especially the charcoal, see above) suggest that the area was more heavily forested than it is today, especially in the stream valleys that drain to the east. However, as the natural fuel potential was not sufficient to produce fuel for the regularly used firesetting technique, this extraction must have been small-scale and gradual.

The analysis of domestic animal mobility by Monika Doll and Hande Özyarkent (figs. 12 and 13) shows that there was regional livestock mobility of caprides, which were reared in the mountainous zone of Kuhestan-e Qom, but were also driven to the summer pastures around the mining site (Doll, 2013; Özyarkent and Stöllner, 2025). The C3/4 ratio, however, indicates that the caprides were grazed in the halophyte area near the Central Plateau plains during the winter. This points to mining-herder communities, some of whom were engaged in (seasonal) mining activities, while others had to engage in animal husbandry (see also Stöllner, 2023b). Donkeys and cattle, on the other

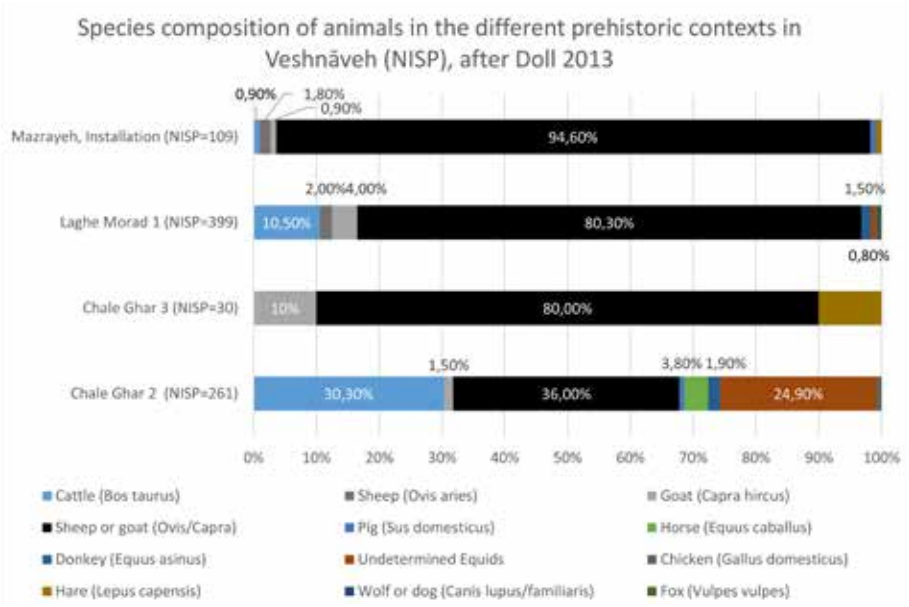


Fig. 12 – Relative representation of domestic mammals from EBA to MBA levels at Veshnaveh (in % of the domestic mammals NISP) (draft/data: DBM, M. Doll).

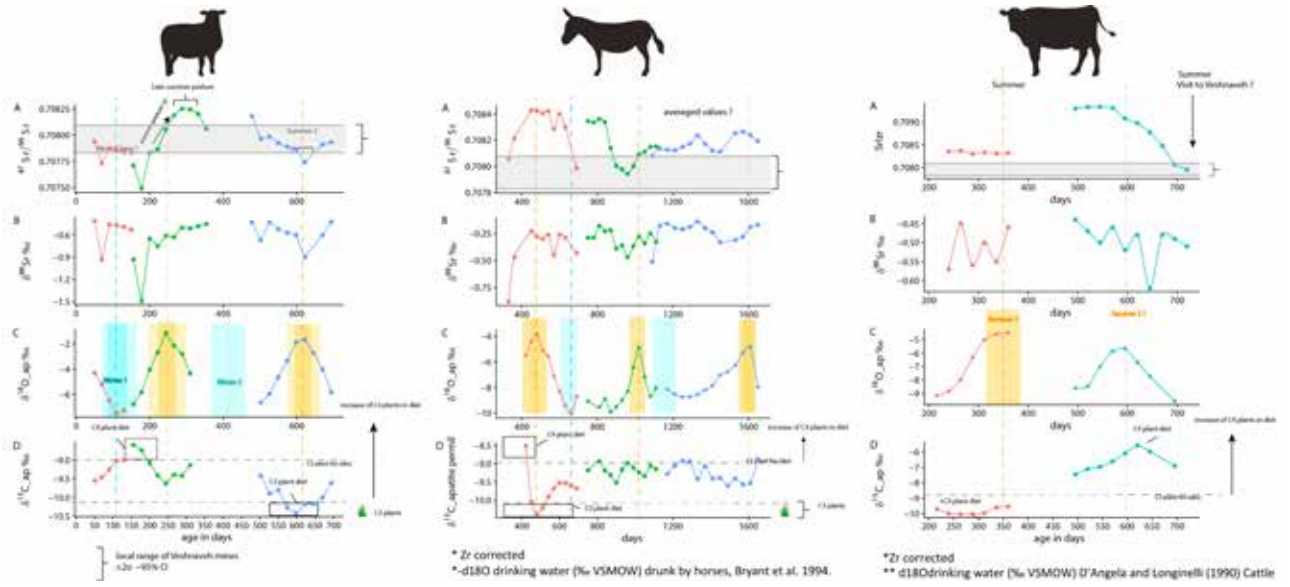


Fig. 13 – Veshnaveh, three domestic animals and indication of their mobility according to $^{87}Sr/^{86}Sr$, $\delta^{18}O$ and $\delta^{13}C$ apatite values; 1. Caprine 2, Molar 1/M2; 2. Donkey 1, Molar 1/2/3; 3. 3. Cow, Molar 2/3, draft: DBM, H. Özyarkent.

hand, were used for transport and to provide meat for the miners, who were probably only temporarily present. All this points to a highly adapted miner-herder economy, suggesting one or more permanent settlements at the end of the access valleys to the mountains. The mining groups probably came from there, and from there the herds were sent to the mountains (consumption of C3 plants) and to the plains to graze C4 plants, probably during the winter, when there was also enough water in the plains. It is also likely that the ore concentrates were transported from there to other metallurgical centres, if they were not further pyroprocessed in their settlement (which we have not yet discovered).

Central Asian herding and mining compounds: Tin mining in the Askaraly region

The importance of pastoral subsistence practices also played a central role in the mobility behaviour of Central Asian Andronovo societies, whose mining and especially metallurgical legacies are known from numerous settlements between the southern Ural foothills and southern and eastern Kazakhstan. One of the best known examples of mining activity based on a steppe economy is the mining area of Kargaly, investigated by an international team led by Evgenij Chernykh, where the mining settlement of Gorny in particular highlighted the great importance of domestic animal subsistence, especially cattle (Antipina, 2004). On a larger scale, the data from Gorny let us argue for extensive cooperation between different communities within a miner-herder complex (e.g. Antipina and Morales, 2006, esp. p. 79–80). The large quantity of animal bones found in numerous features not only indicates the great importance of meat consumption, but also of efficient herding, which in the first half of the 2nd millennium BC was probably much less nomadic and pastoral than previously assumed. The study of metals from the Early and especially the Middle Bronze Age in Central Asia also shows that there were numerous small-scale migrations. Such mobility patterns led to the exchange of metal products over large areas, but not necessarily to large-scale horizontal pastoralism (generally the broad concepts of Chernykh, 2017, p. 90–100; 190–210; on data from the Bochum Kazakhstan Project: Stöllner and Gontscharov, 2021; Stöllner et al., 2022).

Here, the Askaraly mining area, explored by the DBM and Kazakh colleagues between 2004 and 2008, shows the links between mining, settlement and burial activity. In the small mining settlement of Mastau Baj, the repeatedly mined tin ore cassiterite was processed (fig. 14). The Andronovo-Federovka style pottery found in all contexts

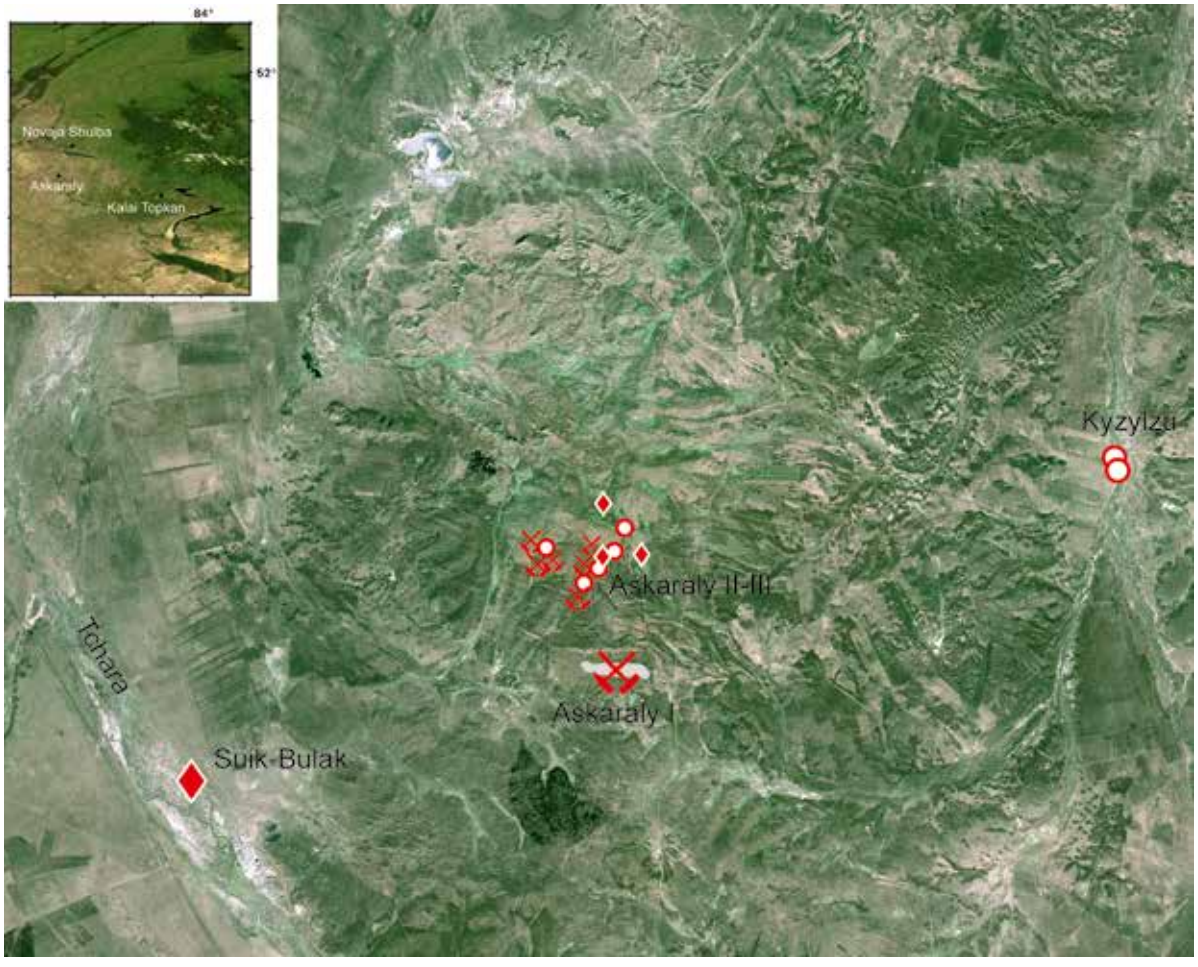


Fig. 14 – East Kazakhstan, Delgebetey (Askaraly)-Mountains, Bronze Age sites in the surroundings of tin-mines (pick/hammer symbols), rhomboids: graves; dots: settlements (mapping: DBM, A. Hornschuch, Th. Stöllner).

suggests that the Askaraly II sites were a contemporary ensemble. Around Askaraly II there were other Bronze Age mining zones (Askaraly I, III-V) (Stöllner et al., 2011b; 2022; Özyarkent and Stöllner, 2025).

The mobility of the caprids, which regularly moved between different ecological zones (C3/C4 plants), is again interesting. This aspect has been further investigated by M. Doll and H. Özyarkent in her PhD thesis (Doll, 2013; Özyarkent, 2019; Özyarkent and Stöllner, 2025). Nevertheless, most of the sheep, horses and goats moved within the regional framework, probably in the vicinity of the Delgebetej mountain zone (and the associated river valleys where the animals were driven, especially in the summer months; figs. 15 and 16). On the other hand, the cattle studied are striking: they show a very wide mobility to a winter pasture in the south (perhaps beyond the so-called Kazakh threshold). It is reasonable to assume that they were used as pack animals for transporting the tin, as is also assumed for the donkeys at Veshnaveh. Unlike other minerals, tin ore was reduced in the mining settlement. Whether it was then alloyed with copper to form raw bronze or cast into a finished product is unknown.

For the early 1st half of the 2nd millennium, it seems that finished products rather than raw metals were exchanged (see arguments in Stöllner and Gontscharov,

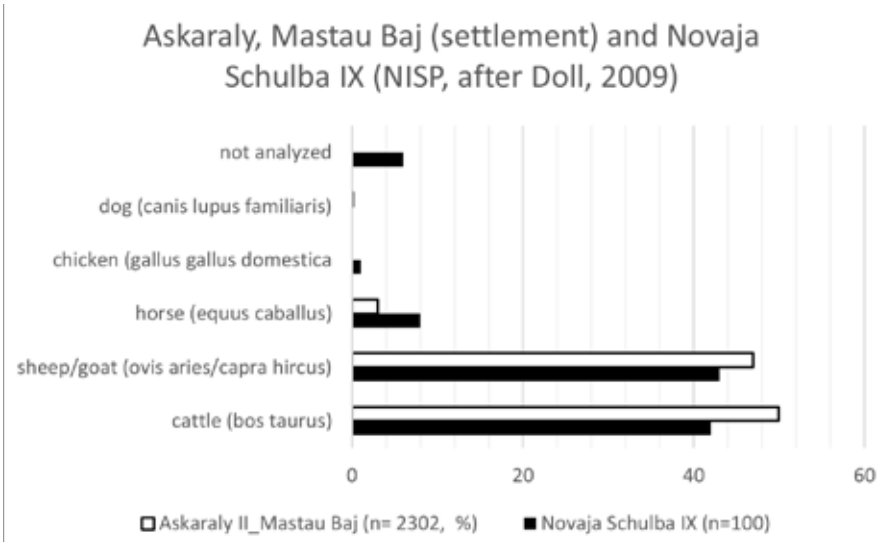


Fig. 15 – Relative representation of domestic mammals from Andronovo levels at Mastau Baj and Novaja Schulba (in % of the domestic mammals NISP) (draft/data: DBM/RUB, M. Doll, Th. Stöllner).

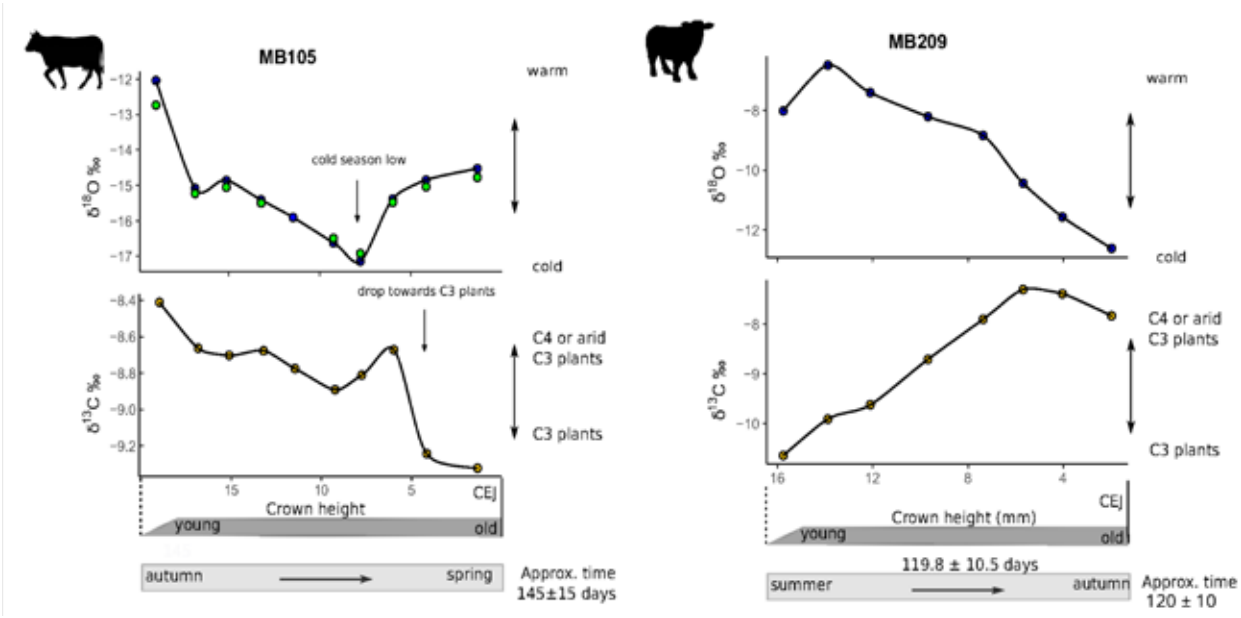


Fig. 16 –Askaraly II, Mastau Baj, Oxygen and Carbon isotope values from the cow sample MB105 (left) and the sheep sample MB209 (right); Oxygen isotope values are calculated to show the meteoric water values using equations water values using equations from D'Angela &Longinelli after Özyarkent, 2019).

2021). Ingots from this period are lacking, while they seem to have become more common in the later 2nd millennium (see also Stöllner et al., 2013; Gontscharov, 2019, p. 82-84). Metal objects, including those made of tin bronze, were used for numerous socially regulated transactions, which would have involved negotiation processes for mining and grazing rights (in general: Frachetti, 2012). A professionalised exchange of tin by the advanced 2nd millennium at the latest was ultimately based on already stabilised networks and mining landscapes since the earlier 2nd millennium BC: many of the metallurgical settlements known from the later Bronze Age already existed in the earlier Andronovo period (e.g. from central and eastern Kazakhstan: Kadyrbaev and Kurmankulov, 1992; Yermolayeva et al., 2024). The exchange of metals, but also their production, seems to have been based on a pastoral economy based on sheep/goats and cattle, organised according to seasonal cycles (see the arguments of Stöllner et al., 2022, p. 121–123).

An early industry evolved? The Alpine Arc and the Mitterberg

A different development of a subsistence-based mining economy is visible in one of the largest Bronze Age mining areas in Eurasia, the Central and Eastern Alpine Arc, where numerous mining communities with a fairly comparable technological concept and also stable subsistence conditions were established in the course of the second millennium (for a summary of the mining regions: Stöllner, 2009). The copper ore districts of the eastern and central Alps were gradually settled from the northern and southern Alpine foothills and then from the main valleys. The Inn and Salzach valleys, especially from the Early Bronze Age communities of southern Bavaria (Straubing culture: Kienlin and Stöllner, 2009; Töchterle, 2015; cf. Stöllner, 2019, p. 14–18). The following copper mining activities seem to have been based on stable supply networks (see already the arguments of Shennan, 1999; for food supply, cf. Pucher, 2009; Schibler et al., 2011; Marti-Grädel et al., 2012; Trebsche and Pucher, 2013). This also allowed the permanent use of alpine backwaters away from the main passage valleys. Our own research, which we have been conducting continuously since 2002 in the Alpine Salzach valley and in particular in the area of the well-known mining district on the Mitterberg (Zschocke and Preuschen, 1932; cf: Stöllner, 2015; Thomas, 2018), I focus mainly on this area (fig. 17).

In comparison with the other mining areas already presented, two aspects are particularly noteworthy for the Eastern Alps and the Mitterberg in particular. Firstly, even the earliest settlement of the later intensively exploited

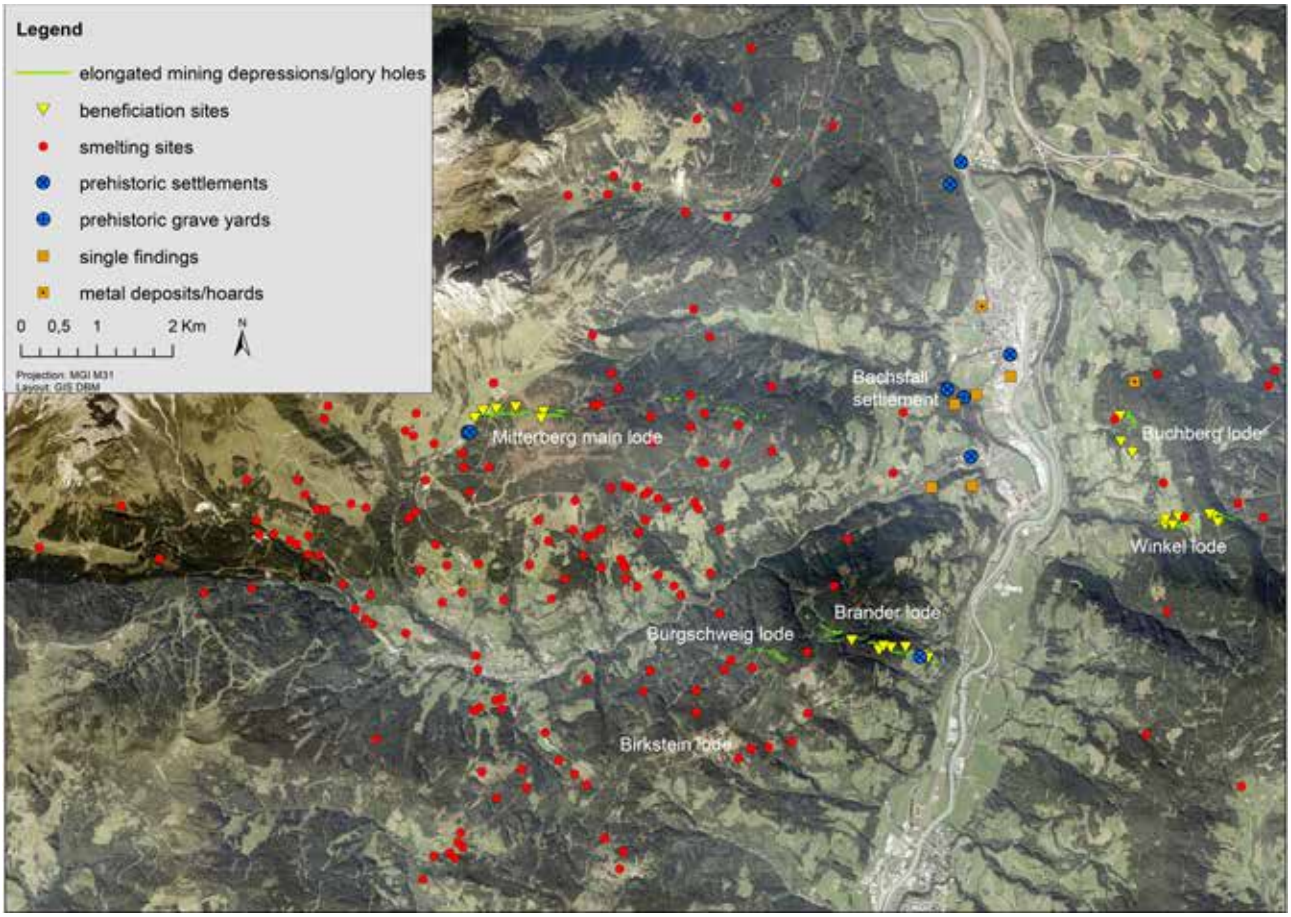


Fig. 17 – Mitterberg mining region, district of St. Johann, Salzburg (Austria), according to archaeological finds and sites (DBM/RUB, A. Hornschuch).

mining region seems to have followed a certain concept of settlement, supply and raw material exploitation. From the very beginning, the structures of the Bronze Age mining landscape in the Salzach-Pongau were subordinated to the needs of copper ore mining and smelting, initially via small village structures, from which the area was developed for mining (e.g. Shennan, 1995; 1999; Kienlin and Stöllner, 2009). In particular, the exploitation of the largest gangue ore deposit in the area around the main vein consisted of numerous contemporary smelting sites (more than 160 associated smelting sites can be identified), infrastructure (houses, mining camps) and evidence for the supply of pork and cooking pots. Such a structure is evidence of a mining community supplied from the valley, which was now even able to mine ore all year round, processing it in early summer and smelting it in autumn. A total of more than 24,000 tonnes of copper could be produced in the district and a total production cycle of more than 800 years could be achieved (Pernicka et al., 2016; Stöllner et al., 2011c). The intensive production required not only forest management (e.g. Breitenlechner, et al. 2014; Pichler et al., 2018), but also, as we assume today, a territorialisation of coniferous wood stocks between smelting and mining operations (on this argument: Stöllner et al., 2011c). Mining techniques also varied considerably, such as the use of firesetting techniques near the surface and wedge cutting with picks in deeper mine parts, which could reach depths of up to 200 metres.

Looking at the subsistence conditions of mining, we can assume that the regional subsistence was never sufficient, at least since the establishment of deep mining. In the Salzach Valley, the regional agricultural and pastoral economy was probably only able to provide sufficient subsistence during the late Early Bronze Age in the 18th/17th centuries BC. However, even this can be questioned by reference to purified cereals that may have been transported from the Alpine foothills (Klinglberg: Shennan, 1995). This aspect is clearest in the case of pork in the Mauken valley mining district, which was supplied from the valleys, possibly even from the Alpine foothills (Marti-Grädel et al., 2012; Schibler et al., 2011). For earlier times, one of the best evidences of meat procurement comes from the archaeozoological investigation of the Early to Middle Bronze Age settlement of Bachsfall near Bischofshofen in the Salzach Valley (fig. 18; Pucher, 2009). Meat animals such as cattle and sheep/goats may have been kept in the vicinity of the settlements. Cattle (especially females) were slaughtered after their best reproductive age and after their main use for milk production, indicating a high importance of dairy products in the agricultural zones around. The character of the use of sheep and goats is different. Their main age structure indicates that they were slaughtered in early adulthood, which in turn indicates a selection from local breeds. On the other hand, E. Pucher's study shows that pigs were supplied from abroad: The local pigs were rather large, as has been shown elsewhere in the copper districts. In particular, their age structure (surprisingly dominated by adults, which is not typical of domestic pigs, fig. 19) and the selection of a larger proportion of males indicate that they were supplied to the settlement. E. Pucher concluded that the community at the Bachsfall settlement was not primarily agricultural, but was supplied from an agricultural hinterland (wherever this was).

Later, the Late Bronze age/Hallstatt salt mines probably played an important role in the supply of pigs from abroad. There, pigs were processed into salt-pickled meat

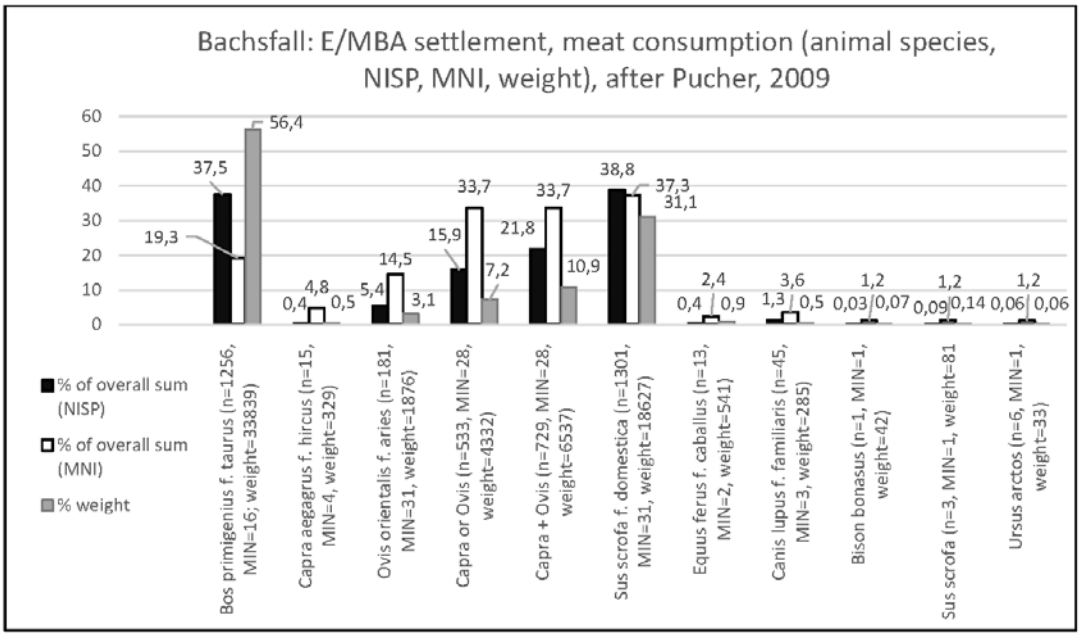


Fig. 18 – Relative representation of domestic mammals from, in % of the domestic mammals NISP, MNI and weight [g] (data: Pucher 2009).

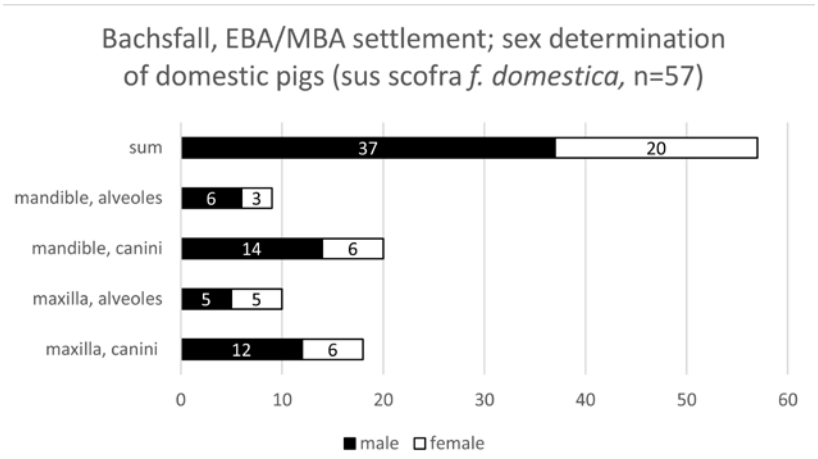


Fig. 19 – Early to Middle Bronze Age levels of Bachsfall settlement, domestic pig according to sex determination of maxillae and mandibulae (data: Pucher 2009).

portions (Pucher et al., 2013). This differs from the earlier evidence from Bachsfall, where pigs were delivered alive or as a whole (there is no evidence for the selection of body parts). This is striking in that a pastoral economy based on sheep and goats never developed in the central areas of the now large-scale mining industry, neither in Kitzbühel (Kelchalm: Amschler, 1937) nor on the Mitterberg (different in Grisons: e.g. Marti-Grädel et al., 2012). The progressive dichotomisation of economic practices is already evident here, which, with the large-scale production of copper, has now entered the realm of commerce and thus of mutual economic dependency.

Copper production not only attracted mining groups and ensured their economic advancement (and thus the valleys between the Inn, Salzach and Enns rivers), but also inevitably led to a now well-established division between subsistence and raw material extraction. This is a process that we have been able to observe in many parts of the ancient world since the second half of the 2nd millennium BC (see Cyprus, Feinan, among others; in general e.g. O'Brien, 2015; Stöllner, 2023a).

CONCLUSIONS

Returning to the questions posed at the beginning of this paper, it is clear that certain practices and a certain form of interwovenness with certain ecological niches emerged within the practice bundles of firesetting and herding within Early Metal Age mining. The close connection to the extraction of raw materials via presumably ritualised access in the form of 'direct access' still seems to have predominated in earlier forms of exploitation (e.g. the arguments in Stöllner, 2023a), but changed from the later 4th millennium BC onwards.

When comparing the examples outlined in this article, it is interesting to first understand the ecological embeddedness of the techniques and practices: in the case of fire setting, technology has not been the limiting factor: The West Asian and Eurasian examples are similar in technical aspects such as hammer and chisel work, ore processing and transport practices. The choice of fuel was more of a limiting factor, as forests were not abundant in the Iranian highlands or steppe zones. This may have forced sporadic or seasonal access by small-scale mining operations. At these zones a highly specialized use of fuel can also be observed, especially in the Askaraly ensemble. It may have been a consequence of this ecological background. This is certainly not the case for the Dzedzvebi-Sakdrisi complex or the Alpine Arc mining communities, which could make extensive use of local oak or spruce/larch and fir forests.

The annual cycles of pastoralism practised by mining communities (not necessarily by the miners themselves) were also influenced by environmental conditions. This is best seen in the regional mobility patterns of livestock. However, the use of cattle as a meat reserve and the donkey as a means of transport is also indicative: livestock played a varied role. While in Veshnaveh the grazing of sheep and goats seems to be linked to mining, the same seems to be true for sheep and cattle in the case of Askaraly. On the other hand, the case of Dzedzvebi already shows a different type of practice: Although herding is still involved, the supply of cattle from deeper parts of the valley seems to indicate organised supply patterns (R. Berthon, A. Vautrin in: Stöllner et al., 2023, p. 111–116). As mining and processing led to the involvement of different Kura-Araxes communities, animals could have been brought in by the groups themselves in the course of seasonal enterprises; such can also be suspected for the Ross Island evidence around the middle of the 3rd mill. BC (Wingaarden-Bakker, 2004). On the Dzedzvebi plateau, several kinship groups appear to have been involved in gold and copper production.

By the 4th millennium at the latest, permanent settlements arose around the mineral deposits, closely linked to pre-existing mobility networks, but also providing the first evidence of planning and more permanent management strategies for resource landscapes. Like Dzedzvebi,

but also many other examples (e.g. in Fenan: Wadi Fidan, Khirbet Hamra Ifdan: Levy et al., 2002; for Fenan in general: Hauptmann and Löffler, 2013) show that settlements moved close to the deposit zones as intermediate locations between subsistence practices and raw material extraction. However, the intensity of extraction itself depended on the available fuel resources and the social networks involved, which carried out extraction on a semi-permanent basis. However, the availability of grazing resources may also have been an important factor in the establishment of these semi-permanent mining areas. Pastoralism and, to a limited extent, other agricultural strategies were central to the establishment of these relay settlements, which also became stations for the various groups involved.

The elements presented here are ultimately the prerequisite for the development of stable, but now also more dichotomous social and technical practices of larger groups involved. The example of the 'Mitterberg' mining region (Pongau) allows some observations on the now permanent and large-scale enterprises. Even if the old figures of Zschocke and Preuschen (1932) for the number of people involved in the mining process are somewhat outdated, the number of workers must have been quite large. There is no doubt that permanent and more efficient mining strategies developed. First of all, a complex chain of practice bundles (e.g. the metallurgical chain of deep mining, wet and dry ore dressing, matte and black copper smelting, ingot and finished product casting) could be developed in the Pongau landscape since the 19th and 18th century BC. For reasons of ventilation, it was only possible to set fire to the upper parts of the elongated veins. Smelting and mining had to share forest areas in order to manage the availability of wood, which was used for timbering, ore beneficiation installations (puddles) and as a fuel for smelting and firesetting. The first practices of sustainable timber management are evidenced by a large statistical set of dendrological data (Stöllner et al. 2011b; Breitenlechner et al., 2014; Pichler et al., 2018).

The same applies to food supply (Pucher, 2009): already in the earlier phases, pigs in particular were supplied, as we can also prove a centralised production of cooking pots, which probably went hand in hand with the supply of grain to the mining communities. It is interesting to note that mountain pasturing (as in the central Alps) was not practised to any great extent in the mining landscapes themselves (see also Reitmaier, 2020, fig. 8). The extension of what we could call the Mitterberg process sensu lato (including the principles of the food supply regime: Stöllner, 2019) would therefore focus our perspective on even more complex knowledge bundles that had to be mastered by the inhabitants and copper producers of the Eastern Alps. Such examples open the windows for an economic mining and metallurgy from the late 3rd millennium onwards, which can also be observed step by step in trade and commercial practices. It resembles the principles of an early beginning of extractivistic and commercialiced access modes that 'accelerated' till today.

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Prehistoric native copper production at Roua (Southern Alps, France) from the 4th millennium BCE

Romain Bussone, Franck Sumera, Olivier Lemercier and Pierre Camps

Abstract: The native copper mines at Roua have yielded fire-setting workings and stone tools, evidence of ancient copper mining dating back to Prehistory. Located on a cliff, these works were partially damaged by black-powder workings conducted until the 19th century. An archaeological study conducted in the 1990s and 2000s already unscored the site's importance for prehistoric copper mining southern Alps. However, a comprehensive analysis was still needed to reconstruct the extent of the ancient works, date them and assess copper production in prehistoric times.
Two field campaigns (2019–2020) enabled systematic surveys to be carried out, revealing new galleries and identifying collapsed areas that were inaccessible due to the topography. The combination of several dating methods (radiocarbon, OSL, archaeomagnetism) applied to different sections of the cliff shows that native copper veins were mined as early as prehistoric times across all mining groups. Ancient copper production, estimated on the basis of dated galleries, reached several tonnes of copper during Prehistory.
Production at the Roua mines took place during the same period as that at Libiola and Monte Loreto in Italy (mid-4th–early 3rd millennium BCE), contributing to the spread of metallurgy from the Balkans. However, the specific nature of native copper mineralisation raises the question of how reduction techniques were acquired in the southern Alps, which have so far only been attested in Saint-Véran from the second half of the 3rd millennium BC. In any case, the native copper from Roua may have been used to manufacture small objects, such as those found in various contexts from the Late Neolithic period, particularly within Alpine and Chasséen cultures, possibly as early as the first half of the 4th millennium BCE.

Keywords: Neolithic, southern Alps, native copper, archaeomagnetic analyses

Résumé : Les mines de cuivre natif de Roua, situées dans les gorges de Daluis (Alpes-Maritimes, France), ont conduit à l'exploitation d'une minéralisation encaissée dans des formations permiennes très dures, sous forme de filons subverticaux millimétriques à gangue carbonatée. Le minerai est dominé par le cuivre natif, parfois associé à la cuprite, à des carbonates de cuivre ou encore, à de l'argent natif ; certains filons livrent des teneurs notables en arsenic. Ce type de minéralisation avec du cuivre natif abondant est rare en Europe. Il a suscité un intérêt dès la Préhistoire, le cuivre natif pouvant être extrait et mis en forme sans recourir à des procédés pyrométallurgiques. Des galeries creusées par le feu et des outils en pierre ont été rapportés dans les années 1990-2000, attestant d'une exploitation ancienne. Toutefois, l'absence de datations directes et d'études archéologiques approfondies ne permettait ni de dater ces travaux, ni d'estimer la production de cuivre aux périodes anciennes. Cet article, fruit d'un travail mené dans le cadre d'une thèse de doctorat (Bussone, 2023), vise à préciser l'extension des chantiers préhistoriques, à établir leur chronologie et à quantifier la production de cuivre aux périodes anciennes. Deux campagnes de terrain (2019–2020) ont permis d'établir des plans géoréférencés et de documenter les remplissages, l'état des parois, les traces d'outils et la morphologie des galeries. Ces observations ont permis de distinguer les creusements anciens, majoritairement réalisés par abattage par le feu, des reprises modernes et contemporaines, et d'identifier les secteurs propices aux datations.
La documentation d'un réseau de galeries jusqu'alors inexploré, le sous-groupe « Sud B » (S23-S28) a révélé des vestiges d'une activité préhistorique inédite, tant pour sa chronologie que pour la quantité de cuivre potentiellement extraite. Le réseau de galeries S24-S28 totalise environ 70 m de développement, 25 m de profondeur maximale et un volume d'environ 110 m³ documenté par photogrammétrie. Il conserve des indices nets d'une activité ancienne (fronts de taille liés à l'abattage au feu, remplissages cendreux, traces de suie) ainsi que 18 outils en pierre (17 maillets en roche encaissante et un outil en silex) attestant d'une activité préhistorique. Ces outils portent des stigmates compatibles avec l'extraction ou le dégagement du cuivre natif de la gangue ; un exemplaire présente des indices possibles d'emmanchement. Des microcharbons ont été identifiés dans des sédiments cendreux, vestiges d'anciens foyers d'abattage.

La chronologie des travaux a été établie par une approche croisée mobilisant radiocarbone, luminescence optiquement stimulée (OSL) et archéomagnétisme. Des charbons de petites branches prélevés dans les remplissages cendreux dans les parties profondes du réseau Sud B placent l'exploitation entre 3510 et 2900 (calBCE), soit du milieu du IV^e^ au début du III^e^ millénaire BCE. Des mesures OSL sur un bloc du même secteur fournissent un âge compatible avec des visites néolithiques (3165–2114 BCE à 95%, resserré à 2911–2379 BCE à 68%), le phénomène physique à l'origine de cet enregistrement doit être mieux compris (éclairage ancien ou chauffe). L'archéomagnétisme, appliqué à des prélèvements de parois chauffées dans d'autres secteurs, a livré des résultats qui convergent également vers le IV^e^ millénaire BCE. Cette méthode permet aussi, pour certains travaux (groupes Sud A, Nord), de proposer des attributions à d'autres périodes protohistoriques, notamment l'âge du Bronze. Ainsi, à Roua, l'ensemble des groupes miniers livre des indices d'exploitation préhistorique compatibles avec le IV^e^ millénaire et le début du III^e^ millénaire BCE, sans exclure la possibilité de reprises plus tardives.
L'estimation de la production de cuivre repose sur plusieurs simulations, rendues incertaines par le manque de données sur la teneur en métal et la variabilité de la minéralisation (épaisseur, continuité). Malgré une large fourchette, ces approches permettent de proposer un ordre de grandeur pour la production métallique. À partir du volume des travaux, les galeries datées du IV^e^ au début du III^e^ millénaire BCE auraient produit entre une et deux tonnes de cuivre. Pour l'ensemble des creusements attribués à l'abattage au feu, la limite haute n'excéderait pas cinq à dix tonnes. Bien que modestes comparées aux grandes exploitations alpines de l'âge du Bronze, ces quantités demeurent significatives au regard des premiers objets en cuivre, généralement de faible masse et peu nombreux, identifiés dans la région.
Roua se place ainsi parmi les plus anciens sites de production de cuivre d'Europe occidentale, contemporains des mines ligures (Libiola, Monte Loreto). Le site s'inscrit dans la dynamique de diffusion des premières métallurgies, tout en présentant une spécificité liée à l'exploitation du cuivre natif. Cette dernière interroge sur la place de ce site dans l'acquisition des techniques de production du cuivre dans le sud de la France, les autres sites de production néolithiques ayant impliqué l'utilisation de procédés pyrométallurgiques. Ces résultats soulignent également le décalage entre une production potentiellement non négligeable de petits objets en cuivre dès le IV^e^ millénaire BCE et leur faible représentation dans les découvertes néolithiques de la région, décalage qui pourrait s'expliquer par des problèmes de conservation du cuivre dans les sols, par des difficultés d'identification, et, très probablement dès cette période ancienne, par des pratiques de recyclage.

Mots clés : Néolithique, Alpes du sud, cuivre natif, analyses archéomagnétiques

The Southern Alps are rich in copper deposits (Rossi and Gasquet, 2014) that represent significant prehistoric mining potential. Although these deposits have been marginally exploited during historical periods (Ancel, 2010), some reveal limited evidence of prehistoric mining (Barge, 2006; see here fig. 1). To date, only the Saint-Véran mines have provided evidence of copper mining before the Bronze Age, supported by radiocarbon dating that places its beginning in the mid-3rd millennium BCE (Barge, 2003; Carozza et al., 2011).

The Roua native copper mines, located 70 km further south, had previously yielded evidence of prehistoric mining (Rostan and Mari, 2005). However, there was no chronometric data or quantification of the copper production to support this mining phase. This study, as part of a doctoral thesis (Bussone, 2023), aimed to fill these gaps and re-evaluate the significance of these deposits in prehistoric copper production within the Southern Alps.

A long-standing contrast exists between knowledge of early mines and the distribution of copper-based artefacts. Recent archaeological studies have confirmed the production of copper alloy objects specific to the Southern Alps and nearby areas such as Provence and northern Italy during the Metal Ages (e.g., Rubat Borel, 2009; Campolo, 2020; Girard, 2021; Mercurin and Lachenal, 2023). Although no prehistoric mines post-dating the Early Bronze Age have been documented locally, lead isotope analyses of some artefacts suggest compatibility with ores from the Southern Alps (Artioli et al., 2009; Bussone, 2023), hinting at possible regional mining.

The exploitation of regional mines during the early Late Neolithic is a hypothesis inferred from weapons engraved on rock art sites in the Southern Alps (Mohen and Eluère, 1990). Some of these engravings are morphologically like the daggers that were common in the Chalcolithic culture of Remedello (Müller et al., 2004; Morin et al., 2005; Bianchi, 2013a; Lumley, 2024; see here fig. 2). N. Bianchi has identified engravings, attributed to the even older Rinaldone culture, in the Vallée des Merveilles (Bianchi, 2013b). As a result, the study of Alpine engraved metal weapons attests to the circulation of copper objects in the Southern Alps between the first half of the 4th millennium BCE and the middle of the 3rd millennium BCE (Bianchi, 2013a; Huet, 2017), which potentially spurred regional copper mining.

Finally, as in other Alpine regions, copper objects and ore fragments from Late *Chasséen* settlements (Daurelle, Vernègues, Giribaldi, Arene Candide, Alba) attest to the circulation of copper production in the Southern Alps during the late Middle Neolithic and Late Neolithic (fig. 2). Indeed, awls or azurite fragments have been found at several of these sites, providing evidence of metal circulation from this early period (Giribaldi, Daurelle, Vernègues: Binder, 2004; Thiercelin et al., 2013; Moreau, 2017; Venturino et al., 2020). These discoveries, along with contemporary artefacts identified in northern Italy, Arene Candide, Alba (Maggi, 1997; Iaia and Dolfini, 2021), point to an early regional metallurgical development dedicated to the production of small copper artefacts (Van Willigen, 2017). The production of these objects predates known mining activities in the Southern Alps. However, they may be contemporary with the copper mines of Liguria (Maggi and Pearce, 2005). In fact, radiocarbon dating of the Libolia mines provides calibrated ages that fit with the first half of the 4th millennium BCE (Maggi et al., 2011). No contemporary mines had been identified in the Southern Alps prior to this study.

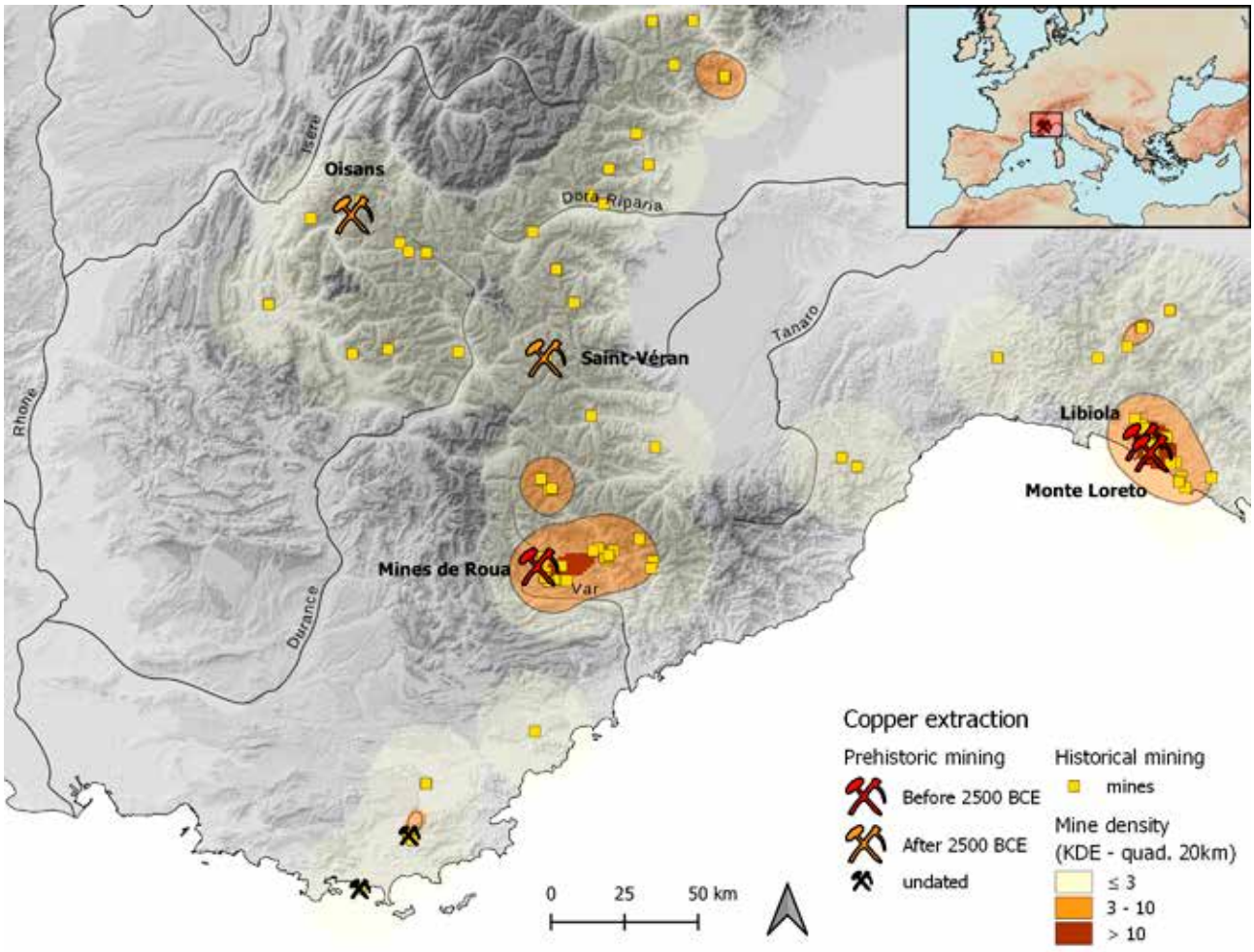


Fig. 1 – Copper deposits in the Southern Alps and prehistoric mining.

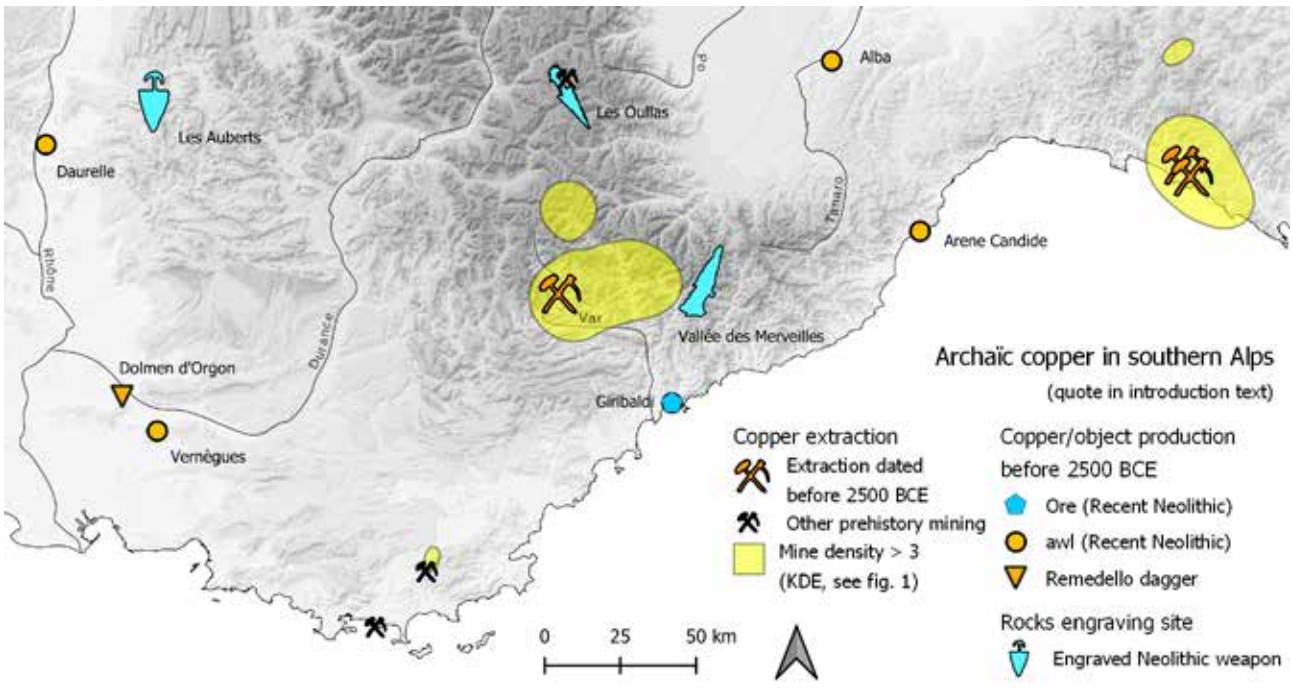


Fig. 2 – Copper mines and the location of copper artefacts dated to 4500 to 2500 BCE.

This paper presents the results of two archaeological survey campaigns at the Roua mine, incorporating chronometric analyses, material and artefact studies, and comprehensive mine surveys that enabled the 3D modelling of the mining volumes. The discovery of previously unknown galleries in 2020 has been a significant step forward for the study of prehistoric mining activities. Unlike other galleries that were damaged by more recent mining activities (17th-19th centuries), these newly discovered galleries are well-preserved and offer significant sections of prehistoric exploitation. They contained stone tools, fire-set workings, and backfill rich in ash and charcoal. These ecofacts, remnants of dismantled fire-setting pyres, allowed for the first reliable radiocarbon dating of Neolithic extraction activities through the analysis of charcoal from small branches. Additionally, we conducted Optically Stimulated Luminescence dating (OSL), which provided an age consistent with the prehistoric exploitation.

In galleries most affected by modern mining activities, the backfill remnants of pre-industrial fire-set mining were destroyed, making radiocarbon dating impossible. It was thus necessary to develop a specific methodology to date these ancient workings. Successful archaeomagnetic dating was carried out on several fire-set rocks. The study of mining remains from all periods enabled the reconstruction of the extent of the old galleries and the identification of sections most suitable for archaeomagnetic analysis. The dates obtained, combined with radiocarbon and OSL analyses, provide robust documentation of the prehistoric exploitation of native copper at Roua.

The 3D survey also facilitated the estimation of mining activity volumes and the quantification of copper production during prehistory. The results show that several tonnes of copper were produced at the Roua mines during the 4th millennium BCE, confirming the site's significant role in Neolithic metallurgy.

The dating and quantitative significance of this production prompt a reconsideration of the role of the Southern Alps in Neolithic copper production. Additionally, the importance of copper in the 4th millennium BCE in this region, as well as the question of its use in the production of regional artefacts, must be re-evaluated.

GEOLOGICAL AND HISTORICAL CONTEXT

Geology and Mineralogy

The Roua mines are in the heart of the geological Dôme de Barrot formation, within the Daluis gorges (Alpes-Maritimes, France). The mineralisation is hosted in Permian sedimentary rocks. Accessing the deposit is challenging, requiring a descent down a cliff that rises more than 300 m above the Var River. A layer of sandstone and carbonate-rich pelites outcrops on both sides of the gorges, 50 to 150 m below the summit ridge of the escarpment. The copper-bearing veins are controlled by this specific geological level, which has a maximum thickness of 5 m in the mining areas and consists of particularly hard rocks (Rostan and Mari, 2005). Although mineralisation outcrops on the western bank (e.g., observed in a road tunnel), ancient mine workings have only been identified on the eastern escarpment (fig. 3).

The mineralisation is trapped within subvertical veins, oriented between 60°N and 90°N, with thicknesses ranging from millimetres to centimetres. These veins rarely exceed two metres in height and are typically only recognised a few metres from the gallery entrances. Transverse faults observed in the field may have limited the depth extension of the mineralisation.

The veins are composed of a carbonate gangue (dolomite, aragonite) containing copper mineralisation. Two main types of veins have been identified: those hosted in pelite or sandstone, containing native copper with small amounts of cuprite and copper carbonates, and those hosted in sandstone, which contain more cuprite, along with native copper, millimetric geodes of arsenates, and copper carbonates. The latter vein has been the subject of mineralogical descriptions (Picot et al., 1966) and targeted for specific searches for micro-minerals near the geodes. Observations in the micro-geodes associated with cuprite have led to the description of nine new mineral types (Mari, 2023). The mineralogical composition of the veins is highly

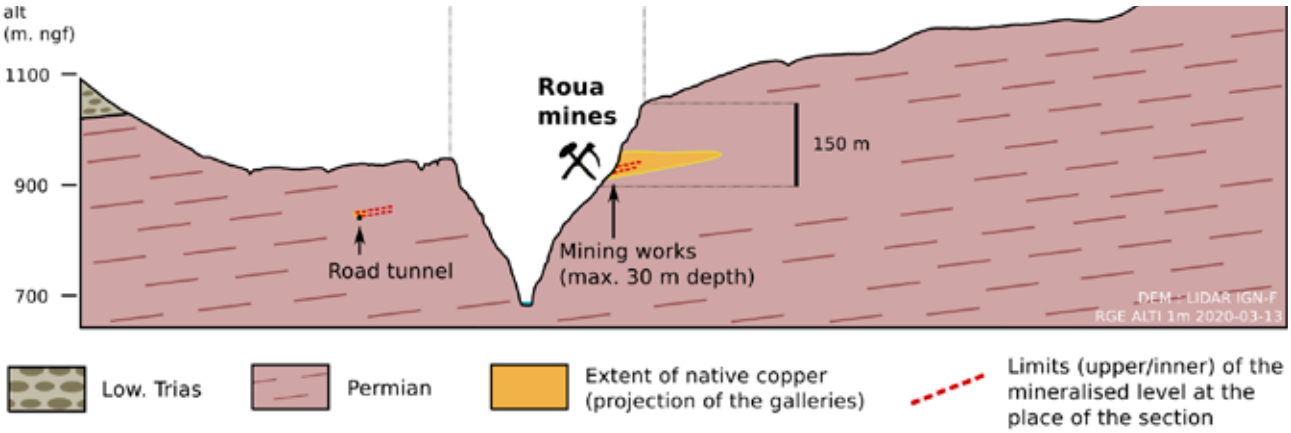


Fig. 3 – Topographic location of the Gorges de Daluis and the Roua native copper mines.

variable, with some veins lacking sulphides or arsenic, while others contain notable trace amounts. Native silver is present in several veins, and it appears to have been a significant component of the mineralisation in Gallery 1 of the Southern Roua group (Rostan and Mari, 2005).

Nonetheless, cuprite and native silver mineralisations are far less abundant than native copper (Mari, 2023), the primary ore extracted from this mine. It occurs as massive nodules or sheets a few millimetres thick within the carbonate gangue (fig. 4) and sometimes directly as small nodules in the Permian rock. The ore consists of nearly pure copper, making it usable by prehistoric societies without the need for pyrometallurgical processes.

Currently, the Roua deposit is exhausted. This makes it difficult to obtain mineralisation samples for geochemical analysis (lead and copper isotopes), which require only a few milligrams of ore at most.

Historical Mining (Industrial and Artisan)

The first mentions of ancient activities are found in contemporary archives of black-powder workings conducted between the 17th and 19th centuries CE (late 17th century; mid-18th century; 1863; 1883). In 1863, engineer Francfort documented the presence of ancient galleries filled with charcoal residues and human bones discovered during the clearing of the old underground workings (Francfort reports, cited in Mari and Mari, 2009). This ancient backfill, likely prehistoric, was discarded below the mines into the Var River. Between these exploration phases, small-scale black-powder artisanal mining was conducted in ancient mine workings around the 1840s (Juge, 1844). These artisanal workings, rediscovered in 2020 (Mari, 2021), had a lesser impact on prehistoric galleries and backfill.

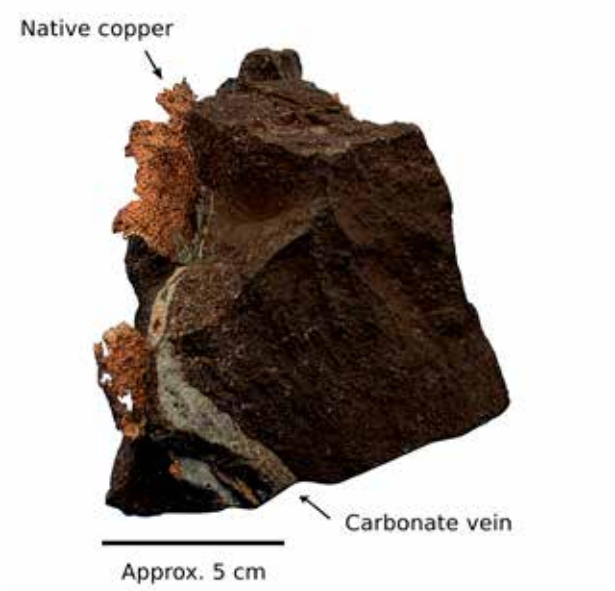


Fig. 4 – Roua native copper mineralisation (G. Mari collection).

First Archaeological Documentation: Evidence of Prehistoric Exploitations

The Roua mines have been the subject of archaeological studies to characterise the ore chemically (trace elements) and document the mining activities. Various extraction techniques were inventoried, and some of the remains were mapped (Rostan and Mari, 2005). The mine workings are divided into two geographical clusters, southern (S) and northern (N), numbered sequentially from south to north within each group. Several small or preliminary workings, too minor to be individually categorised, were sometimes included in the plan surveys (Rostan and Mari, 2005, fig. 2, 3 and 4). This initial study identified small-scale underground workings, rarely exceeding 5 m in depth. Most of these workings contain traces of later black-powder mining activities. The S1, S3, and N4 galleries revealed the most significant operations, conducted with powder, reaching depths of 30 m. Despite the extensive black-powder mining activities, remains of fire-set surfaces were observed near the gallery entrances in nearly all these mine workings. These remains indicate the existence of ancient exploitation phases that may have occurred from prehistory to modern periods. Stone hammers found in the northern group are the only evidence confirming a prehistoric mining phase.

First Steps in Tracing Prehistoric Metal Origins

Analyses of trace element concentration were conducted on native copper from Roua (Barge, 1995; Barge et al., 1998; Rostan and Mari, 2005) as the first step in studying the provenance of prehistoric metals. These analyses, performed on ore samples and experimental smelts (table 1), revealed mostly pure copper. However, it sometimes contained arsenic, in amounts of several percent by weight, and about 0.1 wt%. of silver. Arsenic content in the ore exceeded 10 wt%., while experimental productions yielded maximum concentrations of 2–3 wt%. Lead, antimony, nickel, iron, and zinc were present in low concentrations (less than 0.1 wt%.) in the ores and remained only as traces (less than 0.005 wt%.) in the experimental smelts. Other trace elements were found in very low concentrations in the ore, with some reaching up to 50–100 ppm (Hg, Mg, Bi) and others below 30 ppm (Au, Mn, Co, W, Te, Ti). Arsenic and silver are the main impurities likely to be present at low levels (approximately 2.5 wt% for arsenic and 0.1 wt%. for silver) in objects made from Roua's native copper.

The chemical composition of Roua's native copper, ranging from nearly pure to arsenical varieties, falls within the variability observed in prehistoric copper artefacts in Western Europe (Labaune, 2016). This does not imply direct evidence of native copper use, but rather shows that Roua ores are consistent with established compositional classes of prehistoric copper (e.g. arsenical and pure copper from the Stuttgart classification, Junghans et al., 1968). However, these observations

Summary of native copper analyses from Roua

Ore \ wt %.	Cu	Sn	Pb	As	Sb	Ag	Ni	Fe	Zn	Si
min	91.3	-	-	0.101	0.00011	0.013	0.00014	0.0021	-	0.1
max	99.9	0.04	0.098	12	0.0014	0.35	0.0038	0.0093	0.0032	0.4

Objects and experimental castings based on native copper from Roua (Barge *et al.*, 1998)

Obj. \ wt %.	Cu	Sn	Pb	As	Sb	Ag	Ni	Fe	Zn	Si
GLE	96.95	-	-	0.25	-	0.15	-	-	-	0.3
PA1	97.6	-	-	2.3	-	0.1	-	-	-	-
PA2	97.4	-	-	2.5	-	0.1	-	-	-	-
PA3	97.6	-	-	2.3	-	0.08	-	-	-	0.02
PRE	96.7	tr	0.005	3	-	0.15	tr	-	-	-

Summary of native copper analyses from Roua (next)

Ore \ ppm	Co	Au	Bi	Hg	Mg	Mn	Ti	V	W	Te
min	-	-	-	14	-	-	12	-	21	-
max	-	0.4	50	110	100	10	16	1.4	28	0.001

Objects and experimental castings based on native copper from Roua (next)

Obj. \ ppm	Co	Au	Bi	Hg	Mg	Mn	Ti	V	W	Te
GLE, PA1, PA2, PA3, PRE	-	*NA*	-	*NA*	*NA*	-	*NA*	*NA*	*NA*	*NA*

Table 1 – Summary of elemental analyses for Roua ore and experimental smelting products. Experimental smelts were not subjected to trace-level elemental characterisation. Data from C2RMF (1990s), Univ. Rennes (1990s), CINaM (SEM-EDX, 2010s), and DBM Bochum (before 2005) as reported in Rostan and Mari, 2005 and Mari, 2023. Ppm data reported for the C.2R.M.F series. Where not stated in the sources, analytical methods and instruments are unspecified. At Univ. Rennes: Cu by electrolytic determination, SiO_2 by gravimetry, impurities by spectrometry (Barge et al., 1998). Symbols: "–" undetected; "NA" not analysed; "tr" trace.

alone are not enough to determine the origin of copper in archaeological objects. Lead isotope analysis is needed to determine the geochemical fingerprint of Roua's copper ore. To date, some results have been obtained through doctoral research (Cattin, 2008; Bussone, 2023).

Characterising Prehistoric Exploitation: Chronology and Copper Production Quantification

The native copper from Roua constitutes a valuable resource for prehistoric societies. Fire-set workings are observable in many galleries of this mine. However, assessing the extent of prehistoric mining required the acquisition of chronological data on the exploitation. Finally, between 10 and 20 tonnes of metallic copper were extracted from the most extensive black-powder operations (Rostan and Mari, 2005). The prehistoric copper production also required estimation based on the ancient mine workings.

METHODOLOGY

We conducted two field campaigns in 2019 and 2020 to establish the chronology and quantify the volume of mining activities. Georeferenced surveys and plans were essential to determine the extent of the mining activities and to locate those attributed to different phases. This analysis included the study of mining techniques and the spatial distribution of archaeological artefacts to distinguish between different chronological phases. From these observations, fire-set surfaces were targeted for archaeomagnetic and OSL dating. Additionally, the few identified ecofacts were selected to obtain reliable radiocarbon dates for prehistoric activity.

Survey, Plan and Volume

The mine workings were surveyed by measuring azimuth, distance, and slopes between different stations using a DistoX. Topographic data and plans were produced using Therion software and a GIS. Georeferencing involved multiple stages: GPS point acquisition at select stations, targeting notable points from both banks, and finally controlling the position of the surveys using a high-precision (X-Y 1 metre) LiDAR model (IGN-F, 2020). The volume of mine workings was calculated from survey measurements by modelling simplified geometric shapes. Only the galleries in the South B group received complete photogrammetric coverage, allowing the generation of a high-resolution 3D model to estimate the volume of these underground workings. The volume and size of mine workings are used in the results section to estimate copper production during different phases of mining activities.

Chronological Phasing

Field observations allowed for the mapping of mining extraction methods, which were then recorded on plans to deduce the minimum extent of ancient mine workings. Relative chronological sequencing was determined based on the identification of mining techniques and signs of abandonment within the mine workings. The mining techniques were identified by the morphology of the gallery walls: thermal fracturing impacts and rounded profiles indicate fire-setting digging methods, while drill holes and blast damage are evidence of powder use. Tool marks

(from metal tools) and scraped walls and heavy picking in very localised areas to reach the mineralised vein on the working face also serve as indicators of the most recent phases. The backfill within galleries sometimes reveals the digging method used. The presence of tiny rock fragments and ashy or charcoal-rich sediment indicates an ancient phase of fire-setting activity. Archaeological artefacts are also linked to different phases of mining activities. Stone tools are linked to an ancient (prehistoric) phase, wood fragments to more recent phases, and bones may correspond to various phases of mining or periods of abandonment.

Abandonment markers also provide clues about the age of the workings. Various geomorphological phenomena were observed, such as gallery roof collapses, the filling of mine workings, or walls covered with carbonate deposits. These observations, combined with the identification of mining techniques, revealed the existence of ancient fire-set workings that have since collapsed and are now inaccessible or destroyed.

Dating

Archaeomagnetic, TL/OSL and radiocarbon analyses were obtained to date the ancient mining phase (see Bussone et al., 2026 for further details). The archaeomagnetic method, successfully applied to the fire-set rocks of the mine, relies on the ability of ferromagnetic (sensu lato) minerals to record elements of the Earth's magnetic field (declination D, inclination I, intensity F) after heating. Analysis of orientated samples from fire-set rocks in galleries N4, N12, N14, S2, and S9 through thermal demagnetisation revealed two components of magnetisations for each sampled wall, with directional data (D and I) in opposite directions. The first (retrieved from laboratory thermal treatment up to 500–650°C) corresponds to the archaeological magnetisation (due to the fire-setting), while the second (retrieved from the highest laboratory temperatures) is the natural remanent magnetisation of the Permian bedrock.

The dating of the mining activity is based on the comparison of the archaeological magnetisation directions with a regional curve for the late prehistoric Alpine region, constructed specifically for the Roua area during the Neolithic (Roua-6KBCE; Bussone et al., 2026), and for antiquity and historical periods with the French local curves (Hervé and Lanos, 2018; Gallet et al., 2002). This was achieved using archaeomagnetic data and high-resolution sedimentary data within a 1000 km radius around the mines. The correlation between calibrated solutions for inclination and declination may provide one or more age proposals for the fire-setting activities. We select the most probable chronological intervals that coincide with dates obtained from other dating methods and with the exploitation phases documented by archaeology and archival records (Prehistory, and possibly the modern period).

Two TL/OSL datings were tested on a Permian block from the South B network (junction S26-28), chosen for its calcite encrustation, which may have preserved the surface of recent lighting, increasing the chances of dating the fire-setting phase. Finally, the charcoal remains from the South B network, selected for radiocarbon analysis based on anatomical and taxonomic criteria, provided a reliable age for the prehistoric exploitation. However, bones were not included in these analyses due to uncertainty regarding their antiquity: they come from the surface of a backfill that has not yet been archaeologically excavated.

RESULTS

Survey of Prehistoric Workings

Most of the mining activities at the Roua site were documented during field campaigns (fig. 5). Some galleries mentioned in Rostan and Mari (2005) were not found. This is likely due to cliff collapses that affected galleries S11–12 and possibly S17-19. Small fire-set workings near known mine remains have been identified at N14 and S22. Previously undocumented workings were also recorded, including the partially collapsed gallery N15, and especially galleries S23-28. The geographic location and extent of these newly documented workings resulted in the creation of the 'South B' subgroup. Each of the North, South A, and South B groups requires a specific access path from the top of the cliff, as was likely the case during prehistoric periods. Moving between these groups along the cliff face is perilous today.

The galleries in the South B group (S23–28) and the North group (N12–15; N4) exhibit some of the most extensive fire-set workings. Archaeological artefacts associated with these mine workings indicate their prehistoric exploitation.

South B Group Workings

The galleries in the South B group represent the only mining network documented at Roua so far (fig. 6). The network, which comprises galleries S24 to S28, totals 70 m of underground workings with a maximum depth of 25 m and an approximate volume of 110 m³. Nearby is the smaller S23 gallery, which is 6 m deep and likely dug during the same phase. The study of these interconnected galleries was facilitated by a high-resolution 3D digital model acquired by photogrammetry. Preliminary investigations revealed the extent of fire-set workings. These were identifiable by the characteristic gallery profiles, soot marks, and the spread of ashy and charcoal-rich backfill. Archaeological artefacts found during field surveys indicate multiple phases of mining activity, one of which dates to prehistory.

Artefacts from the South B Galleries

The discovery of seventeen stone hammers (fig. 7) provides evidence of prehistoric activity within these

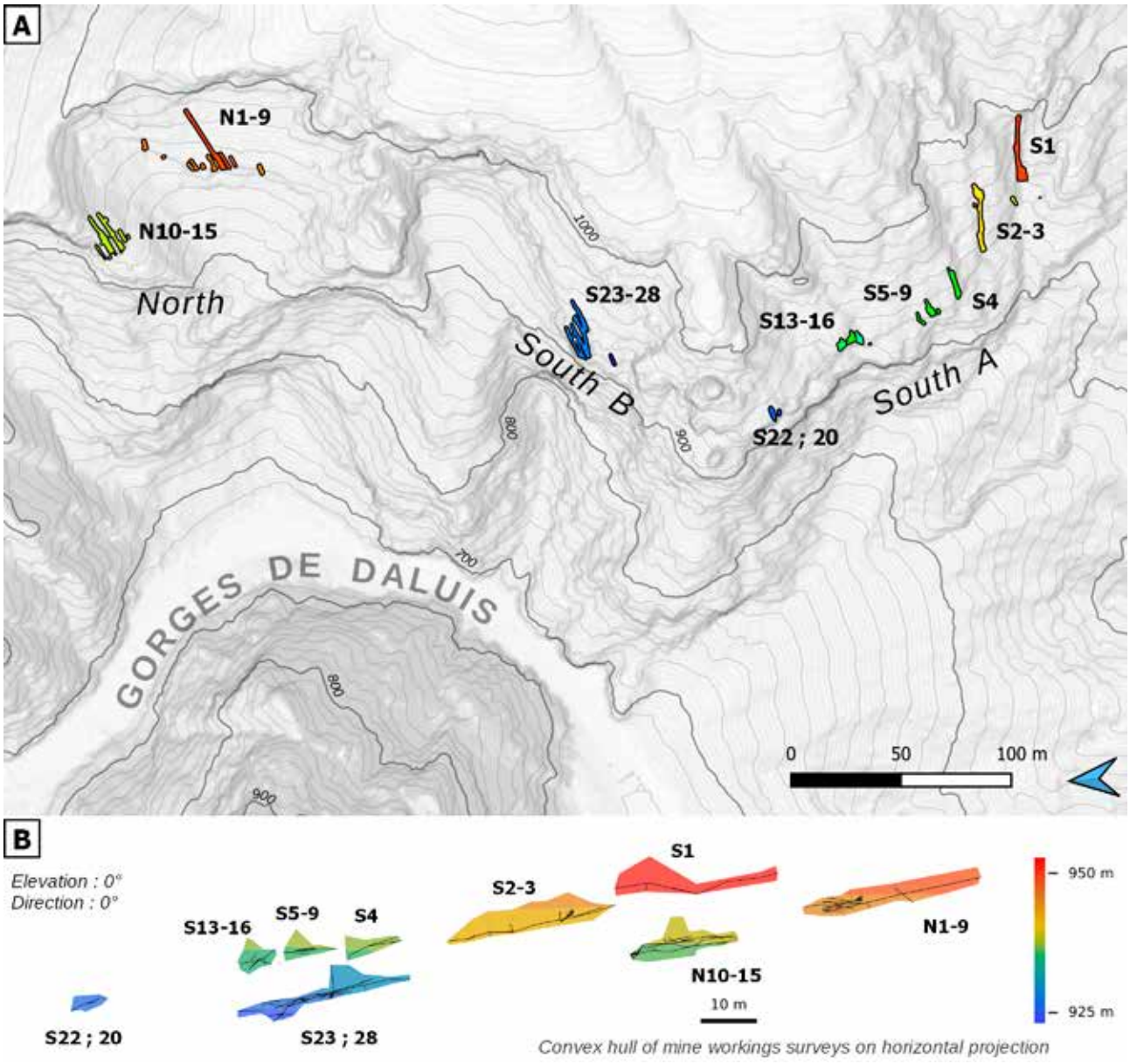


Fig. 5 – Plan (A) and section (B) surveys of the Roua mines. A: location of mining works in Gorges de Daluis; the colour indicates their average NGF altitude; B: projection of sections of all topographic surveys (underground workings are enclosed in a convex hull to distinguish them) with elevation and azimuth parameters sets at 0°.

workings. These artefacts were found on the ground at the southern entrance, within the stone blockages filling S26–28, and in the ashy sediment near the working face of S26. Crafted from the Permian host rock of the mine, these hammers vary in shape, from spherical to quadrangular, with weights ranging from approximately 400 to 960 g and diameters between 70 and 100 mm. Some show clear fractures and evidence of previous use (e.g. fig. 7, no. 11, no. 13). Only one hammer exhibits remnants of a possible hafting groove (fig. 7, no. 2). During preliminary observation, inclusions of native copper or secondary copper minerals were identified on two of the stone hammers recovered from Roua fig. 7, no. 11 and one found near N12 by G. Mari in the 2000s). One inclusion was located at a spall removal scar on maul no. 11 (fig. 7), well away from the striking surfaces observed for this tool, suggesting that it was initially used as a percussive implement and subsequently repurposed as an anvil. Most of the tools fit in the hand and could correspond to crushing tools; more rarely, the heavy ones and the one with remains of hafting (no. 2) possibly indicate a use for digging; Further examination would confirm these initial trends.

Additionally, a flint nodule with most of its surface still covered by cortex (fig. 7, no. 18) was found at the entrance of S23. It was used as a percussion tool, as indicated by erratic flake removals and the absence of cortex on one end.

Charcoal remains embedded in ashy sediment in galleries S24 and S26 testify to fire-setting activities. Prelim-

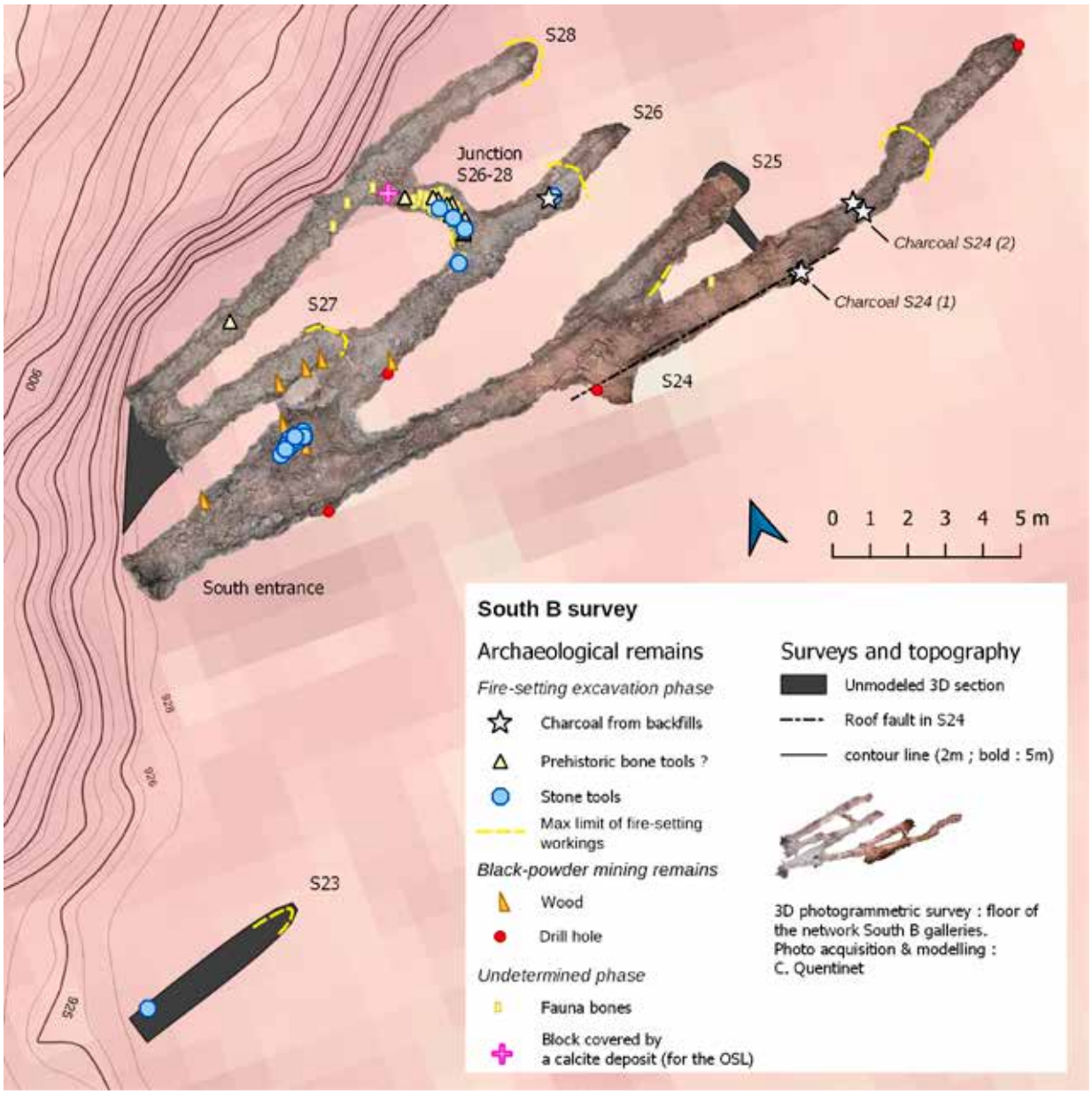


Fig. 6 – Fire-setting workings and prehistoric remains identified on the South B gallery surveys.

inary anthracological analysis identified wood remains of various sizes, including pine and oak logs, as well as small branches (Rosaceae, Ericaceae, Prunus, Acer, and juniper). These could have been used for the fire-setting process.

The bones were collected from the surface during the field campaign. A preliminary study was conducted to verify whether they were human bones, as identified by Francfort in the 19th century in old backfills of Roua mines (Mari and Mari, 2009). All those observed (NR = 35) are fauna remains, found dispersed across various sections of the network, although most (NR = 28) are concentrated in the S26–28 junction backfill. Among them, several bones exhibit characteristics that are incompatible with either recent mining remains or scavenger activities. This includes lower limb bones from a horse (one metacarpal) and cattle (one distal phalanx), which could date back to prehistoric times, possibly linked to the manufacture of miners' tools from long bones. Other bones belonging to ovicaprids (NR = 10) and a flat bone (scapula) of an ovino-caprine could also correspond to prehistoric tools. However, the antiquity of these remains is not guaranteed. Further studies, including excavation of the backfill, detailed archaeozoological analysis with use-wear traces examination and radiocarbon dating, are required to accurately identify the prehistoric faunal remains.

Finally, wooden remains were found near the entrances of the South B network. Torches stuck into the walls, burnt fragments on the ground, as well as unburned boards and tool handles, resulted from more recent visits. These items, including a long rosebush stick found near a drill hole at the entrance of S26, date to the black-powder workings phase, likely from the second half of the 19th century CE.



Fig. 7 – Stone tools found in the South B galleries.

The Extent of Prehistoric Workings

The fills and extraction marks on the walls of the South B group galleries reveal a complex mining history. Small-scale black-powder workings were located at the southern entrance, in the first few metres of S26, and inside S24, where these activities were most significant. The continued digging of S24 to a depth of 3–4 m, the clearing of a roof fault, and the installation of a platform midway through the gallery testify to this activity. Despite these modern interventions, prehistoric backfill remains have persisted. These remains, consisting of ashy/charcoal-rich sediments and tiny rock fragments, are found on the ground and in wall niches up to 20 cm above the current floor level. Coarser sediments cover these ancient fills in some areas, resulting from a partial roof collapse in S24 and S25, caused by the fault (the working face of S25 is nowadays still inaccessible). Traces of this collapse remain under the gallery roofs, suggesting that the original workings were cleared during later black-powder workings. This sequence of events is a highly significant indicator of the antiquity of the first diggings. While other galleries in the network show no signs of collapse, a calcite deposit covering the fire-set workings further indicates the antiquity of these mine workings.

The South B network was shaped by fire-setting. The working face of S28 retains the complete, characteristic smooth shape, while S27 has only preserved part of it. In galleries S24 and S26, remnants of the original working face are observed at 1 and 4 metres from the current face, respectively. In S25, the impact of fire-setting is visible at least in the first half of the gallery, and in the S26-28 junction, it is identifiable in the first half extending from S26.

The direction of diggings in different sections of the network also indicates relative chronology. The working face of S27 was dug before the opening of S26, the S26-28 junction was dug from S26 toward S28, and galleries S25 and S24 were once a single gallery before S24 was extended with a new section. Thus, S27 and the southern entrance are likely the oldest mine workings in the South B network.

The North Group Workings

The North group provided the first evidence of prehistoric activity with the discovery of stone hammers and four-

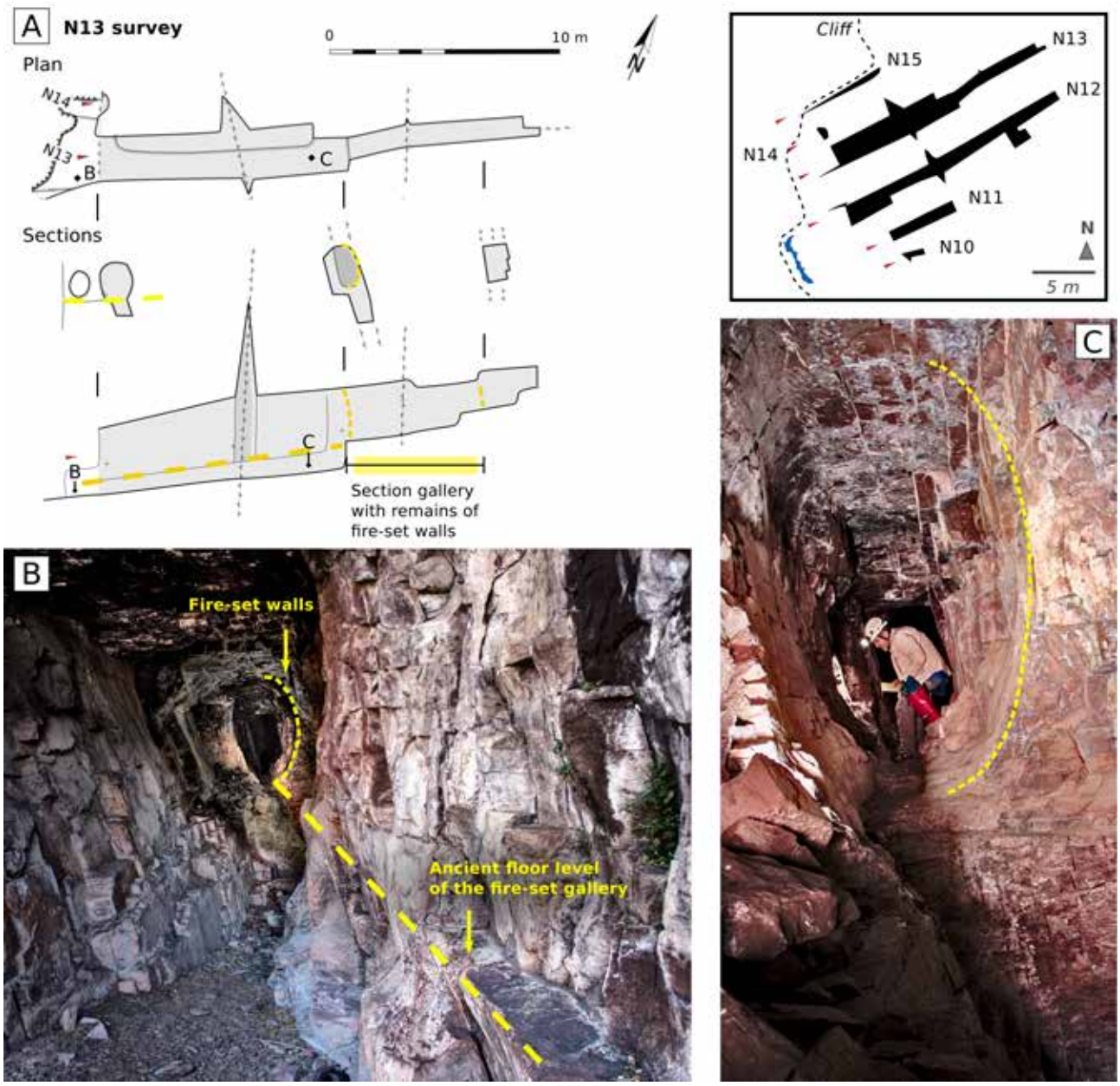


Fig. 8 – Plan and cross-section surveys (A) of the fire-setting evidence in N13. Photos of the entrance (B) and the mid-gallery (C) showing the scale of the ancient fire-setting workings (highlighted in yellow dotted lines).

teen native copper sheets (Rostan and Mari, 2005; Mari and Mari, 2009). These were located near the entrance of gallery N12. The extent of fire-set workings in galleries N12–15 and N4 was reassessed based on geomorphological observations and identifying the minimum extent of ancient workings.

Reassessment of fire-set workings (N12–15)

Galleries N12 to N15 have undergone significant destruction due to later mining activities and natural collapses. In N13, black-powder activities nearly obliterated the original fire-set galleries, leaving only a 5-metre section, partially destroyed by a trench dug from the cliff to the middle of the underground workings (fig. 8). Despite this, remnants of the original gallery level can still be seen on the right wall, up to approximately 4 metres from the current entrance, indicating that part of the original gallery entrance has disappeared (fig. 8; fig. 9; N13).

Observations of the surrounding mine workings lead to the conclusion that the original entrances of galleries N12, N14, and N15 were further out on the cliff face (fig. 9). The south wall of gallery N15, visible only from the west Gorges de Daluis bank, shows a typical fire-set gallery profile that contrasts sharply with the steep edges of the cliff (fig. 9; N15). The working face of this gallery is marked by a white deposit, likely calcium carbonates. These remains, which show no indication of black-powder reworking, likely collapsed during an ancient phase. The floor limits of this gallery can be observed at the base

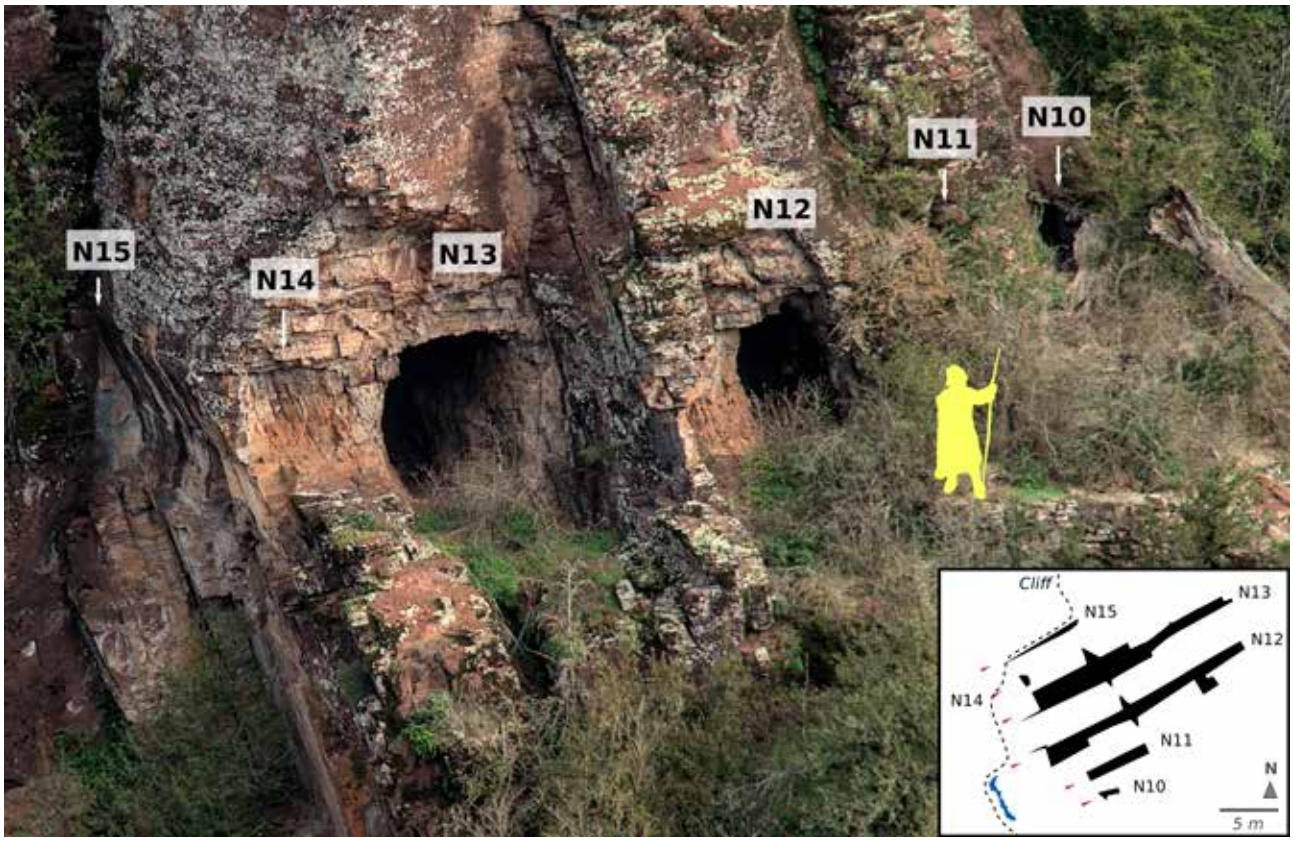


Fig. 9 – Photo of galleries N15–12, showing the collapse of the entrances to the old galleries.

of the right wall and might extend a few metres above the remains of N14. These observations led to a reassessment of the nature of the workings in N14. What initially appeared to be a small fire-set working is now understood to be the working face of a small gallery a few metres deep, now collapsed (fig. 9; N14).

Near the entrance of N12, magnetic susceptibility surveys revealed the presence of a heated wall, confirmed by archaeomagnetic analysis (Bussone et al., 2026). From the west bank, the limits of these workings are visible at the junction between N13 and N12 (fig. 9; N12). This too is a small gallery section, potentially connected to N12, which collapsed in ancient times.

Extent of fire-set workings

The estimation of the extent of collapsed fire-set sections represents a minimum for these workings. The depth of N15 was estimated at 9 m based on surveys of N13 (helped by the location of a transverse fault opening onto the cliff) and LiDAR data.

The minimum extent of fire-set surfaces in galleries N13, N12, and N4 was determined by observing profile interruptions. The combined extent of fire-set workings in N12-15 and N4 totals approximately 60 m.

Across the entire North mines, the cumulative depth of ancient workings reaches 93 m, making it the group with the most extensive fire-set workings. In comparison, the South B group reaches 76 m, and the South A group, heavily affected by destructive power-blast workings, totals 43 m.

Chronological Phasing and Dating

Four main phases of activity have been documented (fig. 10). The first phase corresponds to the initial fire-set workings. The second phase is characterised by the abandonment and deterioration (collapses) of these remains. The third phase involves powder-blast workings, while the fourth phase is marked by more recent abandonment and further collapses.

Evidence of the third phase includes numerous drill holes, the sub-rectangular profile of the workings, pick marks on the older working faces, surveyor inscriptions, and work platforms that facilitated mining operations between the 17th and 19th centuries CE.

Simultaneously, remnants from the first phase are still visible in most galleries. These include rounded sections of the workings and artefacts associated with earlier periods. Among these are stone hammers found in the North and South B groups, which attest to prehistoric activity. A grinding stone (see Rostan and Mari, 2005, fig. 5) found in the South A group might also be linked to this early phase of exploitation.

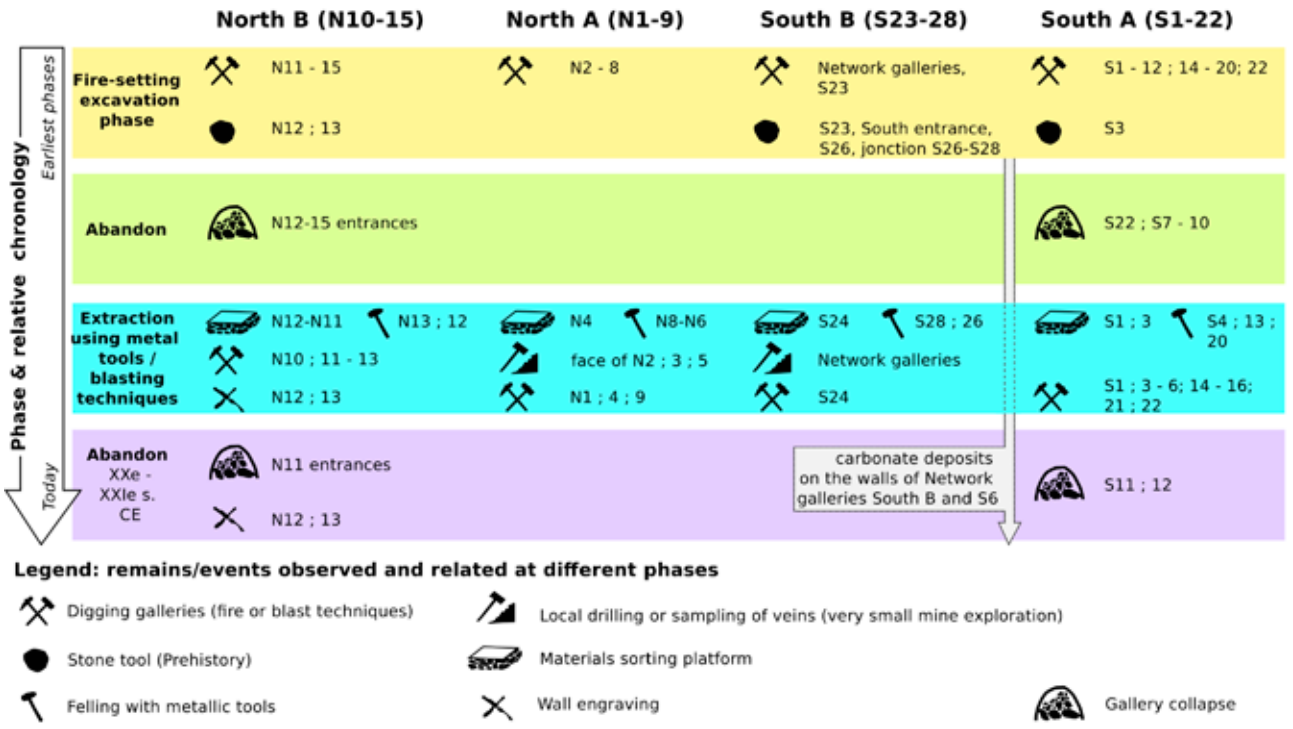


Fig. 10 – Relative chronology by mining techniques: main phases for Roua copper exploitation.

The first-phase workings have been dated by means of chronometric analyses (fig. 11, table 2). Radiocarbon dating was performed on charcoal samples extracted from ashy backfill layers located in the deepest parts of the South B network (S24 and S26). These radiocarbon ages, with a negligible old wood effect, were calibrated with the IntCal20 curve (Reimer et al., 2020). The exploitation of the South B network is thus situated between the mid-4th millennium and the early 3rd millennium BCE (3510–2900 cal. BCE).

Two OSL analyses from a block taken at the section between junction S26-28 and S28 provided an age range of 3165–2114 BCE (95 %), narrowing to 2911–2379 BCE at a 68 % confidence interval. The origin of the recorded signal (light from lighting or fire-setting) is unknown. This age confirms that different parts of the southern network were visited during the Neolithic period. Future in situ dosimetry measurements and analysis of the Permian rock mineralogy (to distinguish quartz from feldspar) will further refine the OSL analysis.

Archaeomagnetic calibration over a wide working range (4500 BCE–1950 CE) can yield multimodal HPD intervals for a single direction (D, I) due to secular variation. The Roua-6KBCE regional calibration curves, while less constrained for older periods because of the lack of archaeomagnetic data, perform better than global models (Bussone et al., 2026). The interpretation for age in this paper privileges posterior modes and the largest parts of the probability mass. Where independent constraints exist (^{14}C/OSL, stratigraphy, archives), they are used to arbitrate among competing modes. Finally, we assume that intervals recurring across independently sampled directions are more probable. Under these rules, the fire-set rocks analysed converge on the 4th millennium BCE. N12 reduces to two credible windows, late 5th or late 4th millennium, with a clearly dominant 4th millennium solution (3254–2999 cal BCE; 89 % of the probability mass). S9 yields a solution in the second half of the 4th millennium (e.g., 3286–3040 cal BCE, 12 % of the probability mass; while a large share of its mass and posterior modes lies in the later 5th millennium, that mode is not supported by regional context). N4 retains several credible intervals, most in the 4th millennium and together 48 % of its probability mass and S2 admits an early 4th millennium solution (3958–3528 BCE; 17 %). It should be noted that N4 and S2 also deliver regions compatible with the end of the Neolithic period (2326–2039 12 % and 2309–2129 BCE 5 % respectively) or with the Bronze Age (1796–1598 10 % and 1733–1153 BCE 23 % respectively). Finally, S2 yield HPD regions between 500 BCE and 500 CE (one corresponding to its posterior mode), but these calibrated ages do not overlap and are less consistent with archaeomagnetism, ^{14}C, and OSL elsewhere on the site. N14 is atypical: a Late Bronze Age interval (1219–1001 cal BCE; 34 %) is plausible, whereas a 16th century CE alternative is unlikely given the historical record.

Chronometric data from the three mining groups (North: N1–15, South B: S23–28, South A: S1–22) indicates a main phase in the 4th and early 3rd millennia BCE (fig. 11: ^{14}C and OSL data and N12/S9 archaeomagne-

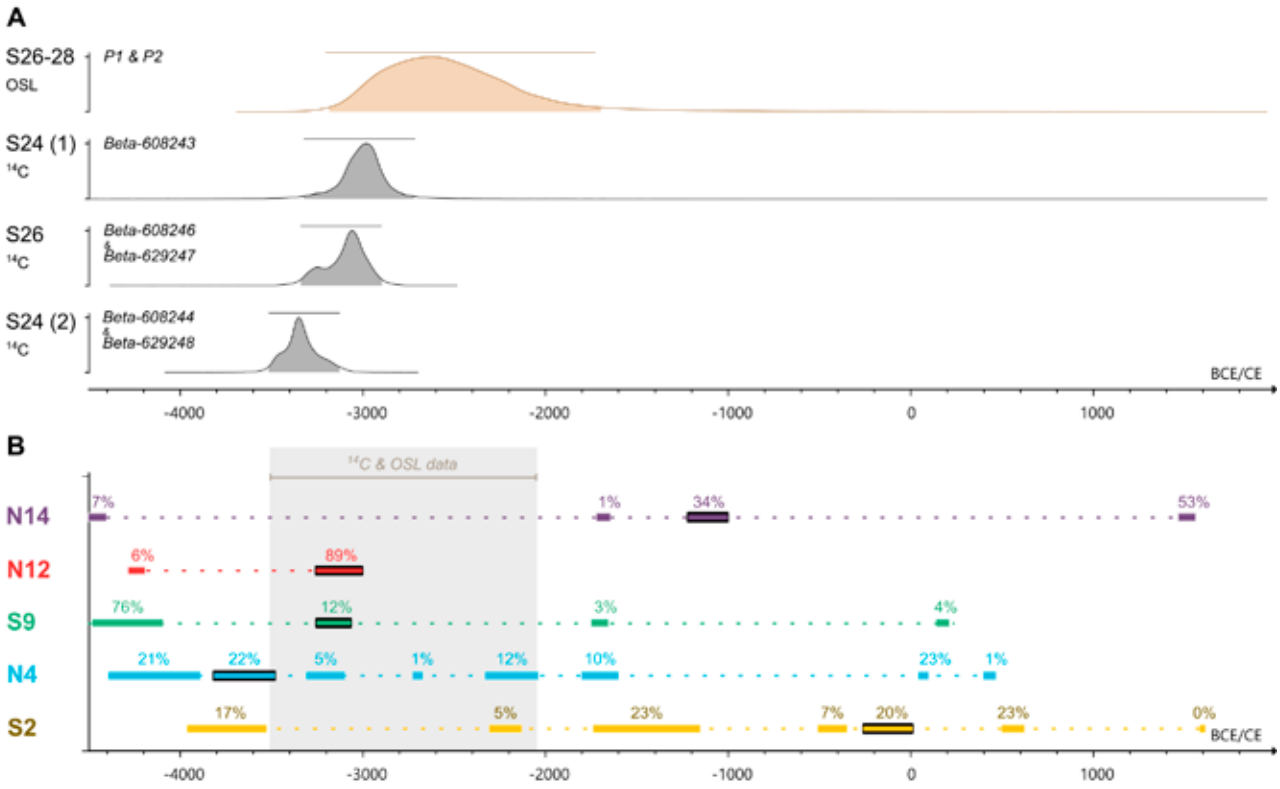


Fig. 11 – Chronology of the fire-settings (^{14}C and archaeomagnetism) and of ancient lightings (OSL) in the Roua mines (4500–1950 CE). A: bayesian a posteriori age (95 % of the HPD is represented, table 2 for raw data) for location S26–28, S24 (1), S24 (2), and S26 (see fig. 12) ordered from most recent to oldest (ChronoModel 3.2.9; Lanos and Dufresne, 2024; calibration curve: IntCal20; Event modelling); B: scatter plot of archaeomagnetic dating (see fig. 12 for sample location), credible intervals (95 %) obtained by combined inclination and declination calibrated data. Percentages indicate probability mass within each HPD. Black-outlined region indicates the posterior mode of the HPD (the region of highest posterior density) for prehistoric times post 4000 BCE. Grey square in the background delineates the prior time range defined by ^{14}C and OSL data (ChronoModel 3.2.9; calibration curves: Roua-6KBCE and French local curves post 300 BCE; Hervé and Lanos, 2018; Gallet et al., 2002).

Feuille1

Sample location*	Method	Remain	More details	Lab. Code	Lab. Data		Calibration curves	Age BCE** 95 % HPD
S24 (1)	14C	Charcoal	Verification of taxa and anatomical criteria on charcoal to date those without old wood effects; palaeotemperature and sedimentary context (ash) to avoid lighting remains	Beta-608243	4390 ± 30	*BP (1950)*	IntCal20	3093–2914
S24 (2)				Beta-608246	4620 ± 30			3511–3347
				Beta-629247	4510 ± 30			3354–3098
S26				Beta-608244	4420 ± 30			3319–2920
				Beta-629248	4440 ± 30			3330–2929
26-28	OSL	Permian rock	Sampled under a post-mining calcium carbonate deposit	P1-OSL	4480 ± 380	*BP (2020)*		3165–2114
				P2-OSL	4830 ± 360			
N4	ArchMag	Permian rock	Sampled on archaeological identified fire-set walls and field magnetic susceptibility	N4	D: -2.9°; I: 59.7°; α95: 0.5°			4000–1596
N12				N12	D: -9.9°; I: 41.4°; α95: 2.3°			3237–3019
N14				N14	D: 7.9°; I: 59.0°; α95: 2.1°		Roua-6KBCE	3642–997
S2				S2	D: 1.9°; I: 63.7°; α95: 1.4°			3958–1
S9				S9	D: 0.8°; I: 54.3°; α95: 0.9°			3686–1626

Table 2 – Chronometric data obtained for the fire-setting phases (^{14}C and archaeomagnetism) and ancient lightings (OSL). See Bussone et al., 2026, for more details on the methodology and data relating to the selected remains, analysed to obtain an age, as well as their interpretation. *The column refers to a specific location and not to the entire gallery (see fig. 6 or fig. 12 for sampling location). ** TPQ and TAQ are 95 % HPD computed between 4000 and 1 BCE. Credibility intervals for archaeomagnetic ages between 4500 BCE and 1950 CE are detailed in fig. 11.

tism). However, the possibility of later mining during prehistory or antiquity cannot be ruled out, particularly for the Late Neolithic or Early Bronze Age for N4 and S2, and especially for the Late Bronze Age with N14.

Radiocarbon ages from the deepest South B galleries imply that the earliest openings (e.g., South entrance, S27) predate these dates, likely falling within the 4th millennium BCE. The N4 and S2 calibrations also provide solutions for the first half of the 4th millennium BCE that we cannot exclude, despite later alternatives.

The frequency of ancient workings remains unknown. However, fire-setting is known to have been a slow and demanding process. These mining operations sometimes required numerous fires, particularly when dealing with hard rock. Larger pyres were necessary in such cases (Weisgerber and Willies, 2000). For instance, according to experiments by Py et al., 2012, approximately 200 fires were needed to dig a 2 m gallery in Triassic quartzite (Fournel, French Alps). The small size of the ancient galleries at Roua, combined with the site's topography (steep cliffs), highlights the considerable effort required for fire-setting on Permian rock. This rock is one of the hardest encountered in prehistoric mines in southern France, according to mechanical resistance analyses (Rostan and Mari, 2005).

PREHISTORIC COPPER PRODUCTION, THE QUESTION ABOUT THE AMOUNT OF METAL EXTRACTED

The absence of direct data on the grade and continuity of the veins makes any attempt to assess the quantity of copper extracted difficult, both in prehistoric times and in the modern period. The volume of the galleries does provide an estimate of the amount of material removed, but the proportion of copper in relation to the host rock remains unknown. This can vary greatly, with the thickness of native copper ranging from a few millimetres to more than three centimetres, as indicated by millimetric veinlets, now exhausted, still visible in the galleries which contrast with the very rich specimens preserved in private collections.

Three independent calculation methods (M1, M2, M3) are applied to estimate production from the mined volume, each defined by a set of parameters. To reflect uncertainty, we treat parameters and gallery volumes as variable and generate many plausible realisations via Monte-Carlo sampling. This yields distributions of copper production (rather than single figures) for each method and mining context, from which we report central estimates and uncertainty ranges; we also verified that results are stable at the chosen iteration count (30,000 iterations were run). The first approach (M1), based on the void volume, evaluates the mass of host rock using its density (2,400–2,650 $kg \cdot m^{-3}$), the fraction of ore within that volume (0,1–2 %), the copper grade (90–97 %), the proportion of ore gathered (85–95 %), and a dilution factor capturing gangue inclusion for ore gathered (1.03–1.07). The second approach (M2) models the mineralised portions of the veins directly, assigning each gallery a thickness (0.001–0.02 m) and assuming that a substantial share of this volume corresponds to metallic copper extracted (30–80 %). Finally, a third estimate (M3) generalises the results obtained for the most productive galleries (N13, N12, N4, S3), following P. Rostan's evaluation, about 10–20 t (Rostan and Mari, 2005), although the details of that calculation are not documented. These models are produced for distinct parts of the mine: the volume of the present underground workings (approx. 1.061 m^3); the sections attributed to fire-setting (including estimates for parts collapsed or destroyed by blasting; approx. 331 m^3); and, lastly, the segments upstream of dated sampling points (location in fig. 12; approx. 118 m^3), in order to assess prehistoric production (N14: 2 m; N12: 4 m; N4: 4 m; S9: 2 m; S2: 2 m; and the South B network, except parts of S24, S25, S28, and S26–28). 80 % of the volume corresponds to sections dated to the second half of the 4th millennium BCE (N12, S9, parts of the South B network). For all three mining contexts considered (table 3), M1 systematically yields the lowest estimates, whereas M3 provides the highest. M2 displays the greatest dispersion (largest standard deviation), while M3 is the most tightly constrained. Although the three models differ, their results remain within the same order of magnitude for any given volumetric context.

Aggregated over all periods, total copper production does not exceed a few tens of tonnes (table 3), with an upper bound of 37.9 t under M3; fire-set workings account for several tonnes, peaking at 9.7 t under M2; lower bounds for M1 and M2 are on the order of a few hundred kilograms. For the prehistoric segments upstream of the dated points, production amounts to a few tonnes overall (approximately 1–3 t), with a maximum of 4.8 t under M2 and minima between 200 and 300 kg under M1 and M2. The credible upper limit for extraction in prehistoric times is given by the tonnage obtained from fire-based mining, i.e., between 5 and 10 t of copper at most. All things considered, we can deduce that production in the galleries dating from the 4th millennium BCE produced around one or two tonnes of copper.

Also, at the end of prehistoric exploitation and for the fire-setting exploitation phase, the Roua deposit remained rich in copper resources, as evidenced by specimens extracted during modern and contemporary black-powder workings (Mari and Mari, 2009). The abandonment of mining during prehistory may have been more related to social or economic factors than to resource depletion.

Finally, compared to the 1400 tonnes of copper produced at Saint-Véran between 2400 and 1600 BCE (Carozza et al., 2011), the Roua mines are considered small. However, this production may have played an important role in the spread of metallurgy beyond the Southern Alps.

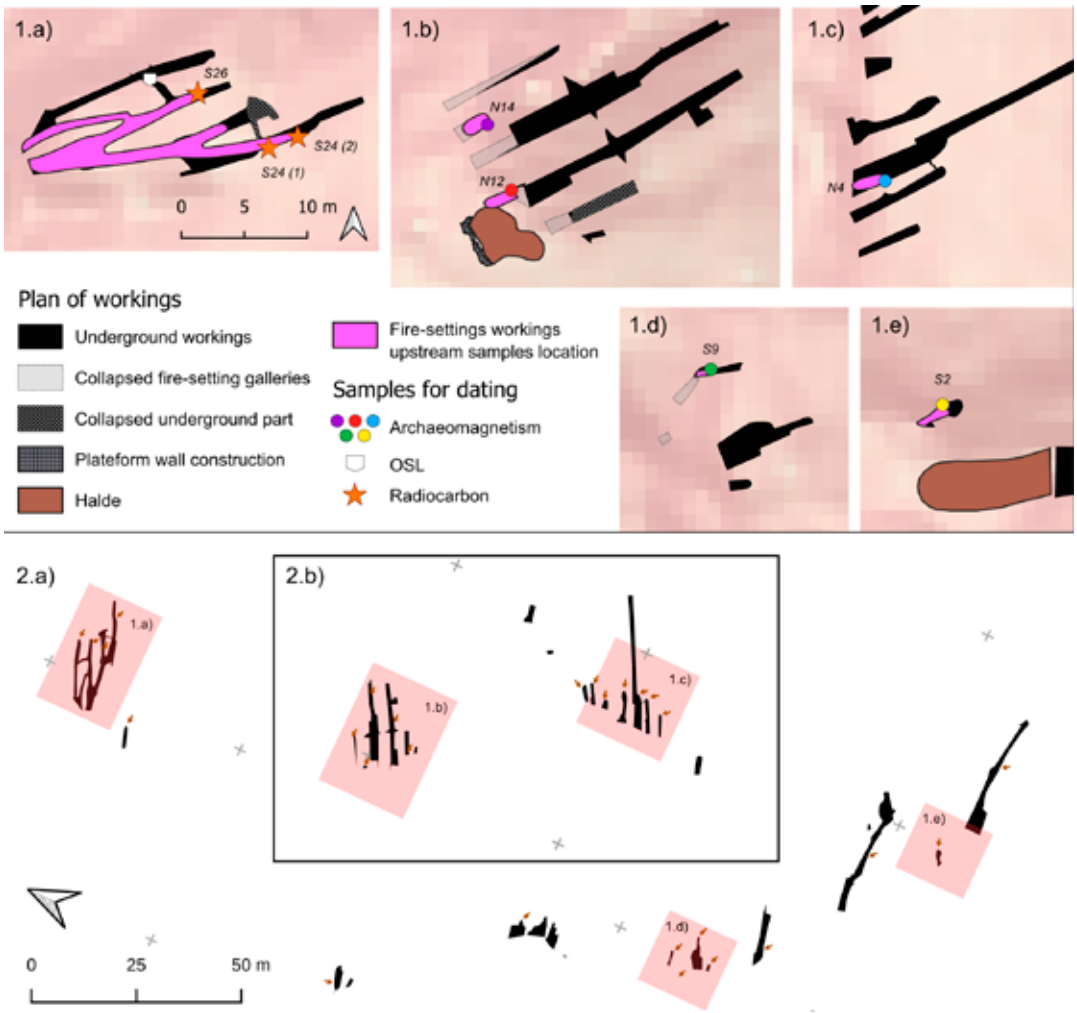


Fig 12 – Locations of sampling points and of fire-setting workings upstream of the dated samples, used for tonnage estimation. 1: maps of sampling locations, all at the same orientation and scale, with the parts of the dated works used for tonnage estimation coloured in pink; 1a: OSL and radiocarbon sampling (South B); 1b-1e: archaeomagnetic sampling at N14 (violet circle) and N12 (red circle), N4 (blue circle), S9 (green circle) and S2 (yellow circle), respectively. 2: maps situating the locations in (1) within the survey of the mine workings, at the same orientation and scale; 2a: South A and South B groups; 2b: North group. Little brown arrows indicate the deepest fire-setting workings observed. See fig. 5 for the position of these different groups in the local topographical and geographical environment.

		Quantity of copper metal extracted (tonnes)		
Methode		All underground work preserved	Prehistoric mines	Firesetting
M1	mean ± sd min – max (HDI 95 %)	**11.8** ± 6.6 *[2.2–24.6]*	**1.2** ± 0.7 *[0.2–2.4]*	**2.2** ± 1.2 *[0.4–4.6]*
M2	mean ± sd min – max (HDI 95 %)	**17.4** ± 10.4 *[2.6–37.6]*	**2.2** ± 1.3 *[0.3–4.8]*	**4.5** ± 2.7 *[0.7–9.7]*
M3	mean ± sd min – max (HDI 95 %)	**29.4** ± 4.39 *[21.2–37.9]*	**2.9** ± 0.4 *[2.1–3.8]*	**5.5** ± 0.8 *[4–7.1]*

M1 — Void-volume model: Estimates copper from excavated void, combining host-rock density, ore fraction, copper grade, gathered ores, and dilution (part of gangue in collected ore).

M2 — Vein-thickness model: Models mineralised vein volume per gallery (thickness/width) and converts it to copper via metal fraction and copper density.

M3 — Reference-scaling model: Scales Rostan and Mari's 10–20 t estimate from key galleries to the whole mine in proportion to gallery volumes.

Table 3 – Copper metal produced (t) by method (M1–M3, see text) and mining context (all galleries preserved, prehistoric mines, fire-setting work). Values are Monte-Carlo summaries (mean ± sd; 95 % Highest Density Interval min–max).

DISCUSSION

The renewed documentation of the Roua mines and the successful application of archaeomagnetism to fire-set rocks provide concrete insights for the study of early metallurgy in Western Europe. The ages obtained for fire-set workings, through various chronometric tools (radiocarbon, archaeomagnetism, OSL), indicate that mining took place during the 4th millennium and into the early part of the 3rd millennium BCE. Up to a few tonnes of copper were produced from Roua in prehistoric times. Although the rhythm of mining is unknown, this production stands out in comparison to the quantity of artefacts identified in the region for the period.

Pioneering Copper Production Sites in Europe: 6th–4th millennium BCE

The chronology of prehistoric exploitation at Roua places these mines among the earliest copper production sites in Europe (fig. 13). The Balkans provide the earliest evidence of mining activities, along with sites like Ai Bunar in Bulgaria, Rudna Glava, and Jarmovac in Serbia (Radivojević et al., 2021). Copper pyrometallurgy activity is also documented at Akladi Cheiri in Bulgaria (Rehren et al., 2016), dating from the second half of the 6th millennium BCE to the first half of the 5th millennium BCE. In Spain, evidence of contemporary copper production was found at the Cerro Virtud settlement (Montero-Ruiz, 2005). A crucible fragment containing copper residues was dated between 4900 and 4460 BCE (Ruiz-Taboada and Montero-Ruiz, 1999).

In Western Europe, the earliest known mine workings are found in the Southern Alps, in Liguria and in Spain. Mining activities are confirmed at Roua, Monte Loreto, and Libiola for the 4th millennium BCE, where copper production likely began during the early stages of this millennium (this study; Maggi et al., 2011). By the end of the 4th millennium BCE, other mining sites in Europe emerged, such as Spanie Pole in Slovakia (Tocík and Žebrák, 1989) and Mocissos in Spain (Goldenberg et al., 2021), whereas copper from Alpine mines was only widely used from the middle of the 3rd millennium BCE in the production of Central Mediterranean artefacts (Artioli et al., 2020). Other archaeological sites provide evidence of copper production around the Alps in the 4th millennium BCE. Copper reduction sites from this period include Mariahilfberg in the Austrian Alps (3950–3650 BCE; Bartelheim et al., 2002), where the ore

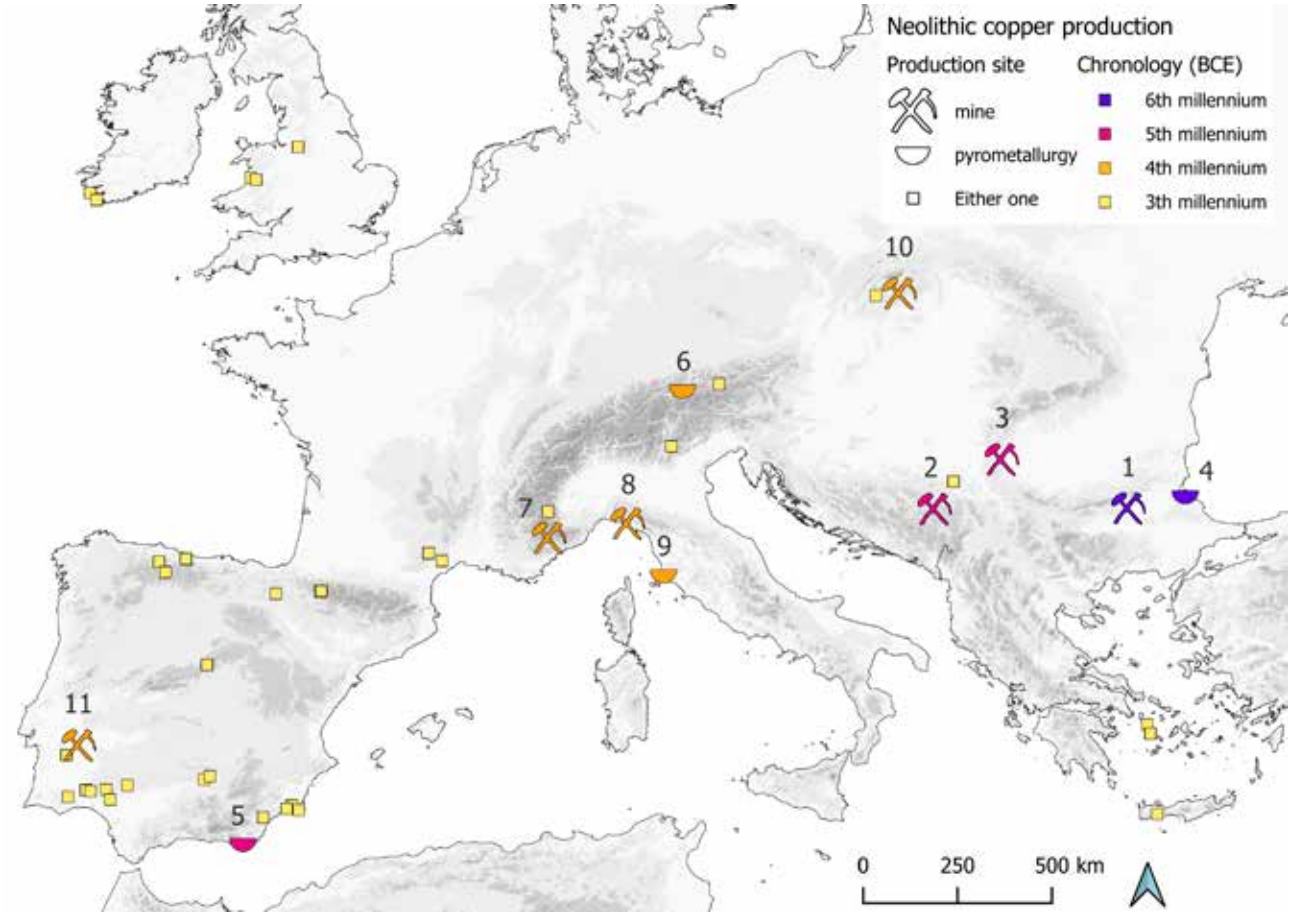


Fig 13 – Europe's earliest copper production sites, mines and pyrometallurgical workshops (6th–3rd c. BCE). 1: Ai Bunar; 2: Jarmovac; 3: Rudna Glava; 4: Akladi Cheiri; 5: Cerro Virtud; 6: Mariahilfberg; 7: Roua; 8: Libiola – Monte Loreto; 9: Cava Solvay di San Carlo; 10: Spanie Pole; 11: Mocissos.

may have been imported (Höppner et al., 2005), and Cava Solvay di San Carlo in central Italy (Fedeli and Galiberti, 2016), a production site processing ore that is probably the source of the copper used in Otzi's axe (Artioli et al., 2017), one of the rare demonstrations of artefact production based on Italian ores for these ages.

The dating of mining activities at Roua (and, by extension, in Liguria) during the 4th millennium BCE does not contradict existing hypotheses about the diffusion of metallurgy from the Balkans to Western Europe. In the Central Mediterranean Basin, exchanges of objects and copper with the Balkans are well-documented through typological studies (Van Willigen, 2017; Iaia and Dolfini, 2021) and geochemical analyses using lead isotope analyses (Artioli et al., 2020). These studies indicate the importation of Balkan objects and probably copper raw materials from this region. Nonetheless, the results of our study provide an indication that the temporal gap between the introduction of copper artefacts and the exploitation of local mines may be smaller than previously assumed. However, the use of copper from Southern Alpine mines is rarely confirmed by isotopic tracers (Artioli et al., 2020; Dolfini et al., 2020) in artefacts dated to the 5th–4th millennia BCE. Few objects from this period have been analysed to date. Consequently, the impact of local copper ore exploitation and the production of metal objects in these regions require further in-depth investigation.

Regarding copper production volumes, Roua's output before the beginning of the 3rd millennium BCE, estimated at 1–2 t, appears modest compared to other pioneering mines, such as Ai Bunar in Bulgaria (6th–5th millennium BCE) and Monte Loreto in Italy (4th–3rd millennium BCE), which have been estimated to have produced several hundred tonnes of copper (approximately 725–800 t, and 454–500 t respectively; Pearce, 2009; Chernykh, 1998). Although these early estimates should be treated with caution, as they rely on limited and sometimes uncertain data, they nonetheless suggest that the Roua mines were considerably less productive than these other European copper sources throughout prehistory. If the total Roua production is considered over several centuries of continuous activity, it would represent only a few kilograms of copper extracted per year during the second half of the 4th millennium BCE. Even if this low annual output appears modest in absolute terms, it remains remarkable in the broader context of early metallurgy, when the first copper artefacts in Western Europe, mainly small beads and awls, rarely exceeded a few tens of grams each. The quantities potentially extracted at Roua could therefore account for the production of a considerable number of such small objects. This observation strengthens the hypothesis that copper mined in the Southern Alps may have supplied local or regional copper object production (as suggested by Van Willigen, 2017). Although most of these early artefacts currently escape archaeological discovery, this discrepancy suggests that the amount of circulating copper during these periods is likely to have been significantly underestimated (Pearce, 2009).

More broadly, the production of copper objects in Eastern France during the transition from the 5th to the 4th millennium BCE is highly likely, as evidenced by recent discoveries in the Paris Basin and Alsace (Lefranc et al., 2012; B. Milles in Cottiaux et al., 2014). These early objects are comparable to Swiss Alpine and Central European artefact production. In the vicinity of the Western Alps, some artefacts may also originate from regional production (Van Willigen, 2017). The local manufacture of objects raises questions about the origin of the copper used. Based on current evidence, we can hypothesise that small-scale copper mining in Alpine deposits was probably already practised at the beginning of the 4th millennium BCE.

Copper Objects Contemporary with Roua's Copper Production West of the Alps

Copper artefacts in the vicinity of the Western Alps, dating to the later 5th and first part of the 4th millennium BCE, may have been produced using regional copper. This includes several copper awls found in *Chasséen* contexts, particularly in Provence: at Daurelle in Montélimar, Drôme, France (Thiercelin-Ferber, 2013) and Cazan Clos du Moulin in Vernègue, Bouches-du-Rhône, France (Moreau et al., 2017). In northwestern Italy, similar artefacts have been unearthed from *Chasséen* levels in the Arene Candide cave in Finale Ligure, Liguria, Italy (Maggi, 1997) and at a *Chasséen* settlement excavated at the 'G. Rodari' primary school in Alba, Piedmont, Italy (Venturino et al., 2020). Lead isotope analyses of the awl from Alba revealed compatibility with copper from the Balkans, like contemporary artefacts and ores from that region (Artioli et al., 2020). Technical and elemental analyses of that from Arene Candide indicate that it was made from pure copper, probably native copper (Campana et al., 1997). Unlike the few objects from the 4th millennium in Italy that match Balkan ores, the Arene Candide value (Campana et al., 1996 for the isotopic analyses) lies outside the Balkan fields. G. Artioli notes that this old analysis was obtained with a TIMS instrument on a Pb poor artefact, so lead isotopes ratios calculated on ^{204}Pb are uncertain. In his review (Artioli et al., 2020) the value does not fit the Balkan ores, except perhaps in areas absent from the reference sources, and has only a weak affinity with Catalonia. The western regions of the Alps remain plausible, but in the absence of precision on the isotopic ratios calculated for ^{204}Pb for the awl, it is difficult to compare them with a specific deposit in these regions, especially since most of the mine coppers are absent from the references. Therefore, a regional native copper source such as Roua remains a plausible hypothesis. Additionally, two azurite fragments from the same period were found at the *Chasséen* site of Villa de Giribaldi in Nice, Alpes-Maritimes, France (Binder, 2004). These finds indicate active prospection of copper-bearing materials at the 5th–4th millennium BCE transition and suggest that regional deposits likely supplied copper, for pigments, and plausibly for early copper objects (Pradeau, 2015, p. 114, p. 250; Van Willigen, 2017).

Other copper objects discovered earlier in Provence could also be contemporary with Roua's prehistoric exploitation and might incorporate copper produced from regional mines. However, the chronological and cultural attribution of Neolithic metallic objects presents a significant challenge due to poor discovery contexts (see, for example, the case of ones attributed to the Bell Beaker culture in eastern Provence and Southern Alps: Lemercier, 2004; or more generally for Western Europe: Labaune, 2016). When the chrono-cultural context is lacking, the dating of these objects primarily relies on typological comparisons, which can lead to divergent chronological interpretations. A notable example for the Southern Alps is the double-spiral copper pendant found in Grotte de la Sarrée (also known as Magagnosc) in the Alpes-Maritimes. Proposals for dating this object range from the late 5th millennium BCE to the Early Bronze Age (Mercurin, 2017, p. 582–585). Some authors suggest a connection with examples found in Pfyn cultural contexts (Strahm, 1994; Binder et al., 2008). Quantitative elemental analyses revealed nickel (0.03 wt%) and bismuth (0.022 wt%) levels too high to correspond to copper directly produced from Roua's mines (Courtin, 1974, analyses by S. Junghans at the Stuttgart Laboratory).

In Provence, rolled sheet metal beads have been inventoried (Barge, 1995). These objects could be among the earliest copper items produced in the Southern Alps, as well as in other regions of eastern France and the Northern Alps. In these areas, some have been dated to the late Middle Neolithic and Recent Neolithic (Ottaway and Strahm, 1975; Lefranc et al., 2012; B. Cottiaux et al., 2014). However, in Provence, the age of most of these objects is uncertain due to early, clandestine excavations or the disturbed nature of their burial contexts from ancient reoccupations (multiple burials, natural cavities). Sometimes, the mere presence of a copper bead has led archaeologists to date a site to the end of the Late Neolithic. These contexts should be re-examined, considering the possibility of an earlier date for these copper artefacts.

Flat axes can also be counted among the oldest copper objects in Europe, with examples found in Italy in contexts dating from the second half of the 5th and 4th millennium BCE (Van Willigen, 2017; Iaia and Dolfini, 2021). Between the Southern Alps and the western Rhône Valley, several flat axes, either whole or fragmentary, have been inventoried, all found out of context: on the La Gaude plateau, Alpes-Maritimes (Barge, 1995), in the Grotte de Déboussadou, Bouches-du-Rhône; Courtin, 1978), in the Grotte des Conchettes, or Déroc, Ardèche (Montjardin, 1991), at Puyméras and Brémonde, Vaucluse (Lermercier et al., 2004), as well as a fragment preserved in the Saint-Jurson museum collection, Alpes-de-Haute-Provence (Barge, 1995). According to the classification used by Iaia and Dolfini (2021), the example of La Gaude is of the trapezoidal type with a plain biconvex side profile, and is therefore similar to axes found in peninsular Italy and central Europe, dated to the 4th millennium BCE, or even the 5th millennium BCE.

The Orgon dagger of the Remedello type can be compared to Italian examples dated to the first half of the 3rd millennium BCE. Although belonging to an Italic culture, this object may have incorporated copper produced in the Southern Alps, Provence, or Liguria. However, the use of copper directly produced from Roua's mines is excluded due to impurities in bismuth (0.2 wt%., analyses by J.-R. Bourhis, CNRS, Laboratory of Prehistoric Anthropology, Rennes, according to Courtin and Sauzade, 1975).

Fragments of copper (rods, sheets, wires, broken objects, or unidentified fragments) from throughout the Neolithic have been unearthed from sites in Provence or the Lower and Middle Rhône Valley. These metallic remains, sometimes only briefly mentioned, indicate the circulation of raw metallic copper materials that could have been used locally to manufacture objects. Some of them are dated from the early Late Neolithic, like the two copper sheets from the Abri Sanguinouse, Roque-sur-Pernes, Vaucluse (Lemercier et al., 2004), and the origin of the metal in this type of object could be regional. It is noteworthy that a very small number of Neolithic sites in the Southern Alps also yield raw copper ore (e.g. Giribaldi, Dolmen des Arboins, Alpes-Maritimes, France: Binder, 2004; Mercurin, 2017) and, more rarely, remnants related to evidence of practices of local metallurgy. These observations do not seem to concern the direct use of native copper (with the possible exception of the piece of copper found at the Dolmen des Arboins; Mercurin, 2017, vol. II.1, p. 440–441, unfortunately now lost) and indicate the use of other types of copper ore (azurite for Giribaldi, assuming that it is indeed the original mineral collected in prehistoric times and not a neo-formed oxidation). Other remains provide direct evidence of Neolithic pyrometallurgical activities in Provence; the Late Neolithic site of Fortin du Saut, Bouches-du-Rhône, yielded a stone crushing tool made from a Permian material similar to the host rock of the Roua mines (which could also correspond to several Provençal copper mines) and casting waste (Furestier et al., 2007; Labaune, 2016), which probably dates from between 2550 and 2350 BCE according to the pottery. This leads us to believe that the metallurgy at Fortin du Saut may have relied on regional ore exploitations, now confirmed in the Southern Alps for the 4th and 3rd millennia BCE (Roua, Saint-Véran).

CONCLUSION

The copper deposits of the Southern Alps and Provence, despite only modest historical exploitation, reveal significant prehistoric mining potential. Up to several tonnes of copper were produced during prehistoric times from Roua mines. The scarcity of prehistoric mining data is mainly due to the destruction of ancient remains during historical mining activities. Using archaeomagnetism to date fire-set surfaces is a novel approach with the potential to uncover the earliest mining activities.

The chronology established for the exploitation of the Roua mines challenges traditionally accepted timelines for the spread of metallurgy in Western Europe, particularly in southern France. While the influence of Balkan metallurgy in the spread of Neolithic copper artefacts remains unquestioned, especially in Italy, in terms of both cultural context and material provenance, this study demonstrates that by at least the mid-4th millennium BCE, the copper deposits of the Southern Alps were sought after. The dates obtained for Roua's fire-setting extraction method are contemporary with those of Ligurian mines. It is plausible that other copper deposits, notably those in Permian host rock from Provence, may also have been exploited during this period, although there are currently no dates available for these mines. Recent awl finds from late Middle Neolithic contexts in the Southern Alps may point to early regional use of copper, as for other Alpine culture (Pfyn or Cortaillod). Accordingly, the production of local copper artefacts, potentially based on regional mining as early as the transition between the 5th and 4th millennium BCE, should be considered plausible but remains to be demonstrated pending further geochemical (Pb isotopes) and ancient mining investigations.

Copper production at Roua during prehistory is estimated at several tonnes, which may seem modest compared to other European Neolithic mines. However, the exploitation of these small copper mines likely played a crucial role in the spread of metallurgy across Europe. The copper mined at Roua was a valuable resource for the Neolithic societies of the Southern Alps. This production far exceeds the mass of copper artefacts found in the region and dated to the 4th and 3rd millennium BCE. This indicates a period when metal was more abundant than previously thought. The current scarcity of copper objects attributed to the Recent Neolithic is largely due to recycling practices. It is important to note that in the Southern Alps, the chronology of Neolithic copper artefacts is often uncertain due to the nature of the archaeological documentation and site contexts. This uncertainty may have led to the overlooking of chronological hypotheses predating the end of the Late Neolithic.

Given the nature of the ore (native copper), copper production at Roua did not require pyrometallurgical treatment. To date, the earliest evidence of ore processing areas in the Western Alps is for those at Saint-Véran, dated to the mid-3rd millennium BCE. These observations raise questions when considering the Balkan metallurgy, which was based on the exploitation of copper oxides and sulphides. Integrating Roua's mining activities into the diffusionist model of Balkan metallurgy, particularly in terms of technical transfers and the adoption of pyrometallurgical practices in the Southern Alps, needs further investigation.

Finally, the geographical location of the Roua mines, at the crossroads between the Alps and the Mediterranean and at the junction of Piedmont, Provence, and the Rhône corridor, suggests new avenues for investigating potential connections with early metallurgies observed in Switzerland, northeastern France, and the western Mediterranean Basin. A re-evaluation of the role of smaller regional mining areas in the development of prehistoric metallurgy in Western Europe is necessary.

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Chalcolithic and Bronze Age Copper Mining at the Internal Betic Ranges (South-East of the Iberian Peninsula):

Ignacio Montero-Ruiz, Mercedes Murillo-Barroso, Aaron Lackinger and Daniel Pérez-L'Huillier

Abstract: This paper reviews the early development of metallurgy in the south-eastern Iberian Peninsula, focusing on Chalcolithic and Bronze Age copper mining within the Internal Betic Ranges. Archaeological evidence documents metallurgical production during the Los Millares and El Argar cultures, despite the elusive identification of prehistoric copper mines in this region. Several surveys have been conducted from the 19th century to the present, uncovering limited yet significant archaeological evidence, such as stone tools and pottery around the mines, suggesting prehistoric mining activities. These studies usually include geological background, identifying copper mineralisation across three tectonic complexes: Nevado-Filábride, Alpujárride, and Maláguide. Recent investigations employ modern analytical methods, including trace element characterisation and lead isotope analysis (LIA), to connect archaeological finds with local copper sources. Key findings indicate that copper ores were processed at settlements rather than mines, highlighting the small-scale nature of early metallurgy in the region, in contrast to other mining regions such as Sierra Morena. Continued research is essential to fully understand the extent and chronology of copper mining activities throughout different historical periods in the Betic Ranges.

Keywords: Metallurgy, Survey, Recent Prehistory, Trace Element Compositions, Lead Isotope Analysis, Mining hammers, Stone Tools

Résumé : Cet article passe en revue les premiers développements de la métallurgie dans le sud-est de la péninsule Ibérique, en se concentrant sur l'exploitation minière du cuivre au Chalcolithique et à l'âge du Bronze dans les cordillères Bétiques internes. Si la production métallurgique au cours des cultures de Los Millares et d'El Argar, les mines de cuivre préhistoriques restent difficilement saisissables dans cette région. Plusieurs études ont été menées du XIXe siècle à nos jours, mettant au jour des preuves archéologiques limitées mais significatives telles que des outils en pierre et des poteries autour des mines, suggérant des activités minières préhistoriques. Ces études incluent généralement le contexte géologique, identifiant la minéralisation du cuivre dans trois complexes tectoniques : Nevado-Filábride, Alpujárride et Maláguide, et les prospections récentes emploient des méthodes analytiques modernes, notamment la caractérisation des éléments traces et l'analyse isotopique du plomb (LIA), pour relier les découvertes archéologiques aux sources de cuivre locales. Les principales conclusions indiquent que les minerais de cuivre étaient traités dans les villages plutôt que dans les mines. Cela souligne la faible envergure des premières productions métallurgiques dans la région, contrairement à d'autres régions minières telles que la Sierra Morena, et en particulier sa partie centrale, comme le démontrent les prospections et sondages en cours dans la vallée du Alto Guadiato et Los Pedroches. La poursuite des recherches est essentielle pour saisir l'ampleur et la chronologie des activités minières de cuivre au cours des différentes périodes historiques dans les cordillères Bétiques.

Mots clés : métallurgie, prospection, Préhistoire récente, compositions d'éléments traces, analyse isotopique du plomb, marteaux miniers, outils en pierre

The south-east of the Iberian Peninsula is a key region in the development of early metallurgy. Besides the debate on the possible independent invention of metallurgy during the 5th millennium BC based on the early chronology of Cerro Virtud, Almería (Ruiz Taboada and Montero-Ruiz, 1999; Montero-Ruiz et al., 2021), clear metallurgical production is documented during the Los Millares culture (Chalcolithic) and the El Argar culture (Early Bronze Age). Copper ores have been found in many Chalcolithic sites together with smelting crucibles, prills and fragments of slag. On the contrary, few melting crucibles or moulds from this period have been identified

in the archaeological record (Montero-Ruiz, 1992). A significant number of metal objects are documented, mainly in the Bell Beaker period, with simple shapes (awl, dagger, axe, arrowhead) but personal ornaments made of copper are absent in this area and in the whole Iberian Peninsula (Murillo-Barroso and Montero-Ruiz, 2012). The technology of this metallurgy based on secondary copper ores has been described in detail in some papers (Rovira-Llorens and Montero-Ruiz, 2013, Murillo-Barroso et al., 2017; 2025b). The main features are:

– direct reduction of ores without the addition of fluxes, using ceramic vessels (smelting crucibles) as containers for both the ores and the fuel required for the smelting process;

– use of polymetallic ores, especially those containing arsenic, which naturally produced arsenical copper;

– the small amount of slag produced is immature, with very heterogeneous mineralogical and chemical compositions and high viscosity, therefore resulting in an inefficient separation of metallic copper, with substantial copper losses in the slag;

– thermodynamic equilibrium and atmosphere stability were not consistently maintained, with variable $_pO_2$ and redox conditions both locally and temporarily, with better reducing conditions in some areas of the crucible at certain moments and more oxidising conditions at some others.

During the Early Bronze Age (El Argar culture), there were no substantial technological changes, although evidence of smelting activities and copper ores is sparser in the main settlements, with a better record of moulds and crucibles (Montero-Ruiz and Murillo-Barroso, 2010). Metal production seems to have increased, as evidenced by the higher number of metal objects, with some typological changes: the use of rivets in daggers instead of tangs, the presence of wings in arrowheads, the first appearance of weapons (halberds and swords) as well as the proliferation of personal ornaments (spiral rings, earrings, bracelets, ear dilators and exceptionally, silver diadems), which were almost absent from the archaeological record during the Copper Age.

Although some evidence suggests local or regional production, the identification of the copper mines worked at this time is very elusive. This contrasts sharply with other regions of Iberia where prehistoric copper mines are well documented (Blas Cortina and Suárez Fernández, 2022; Rovira Llorens and Montero-Ruiz, 2022). However, in these areas, smelting and melting activities, along with the related materials, are nearly unknown, for example in the astur-leones region in the north of Iberia. The exception is the Iberian southwest, where both mines and metallurgical-related materials have been found (Hunt Ortiz, 2003).

GEOLOGICAL BACKGROUND

The Betic Cordillera constitutes the westernmost end of the Mediterranean Alpine Orogen and consists of two major domains: the External and Internal Zones (fig. 1).

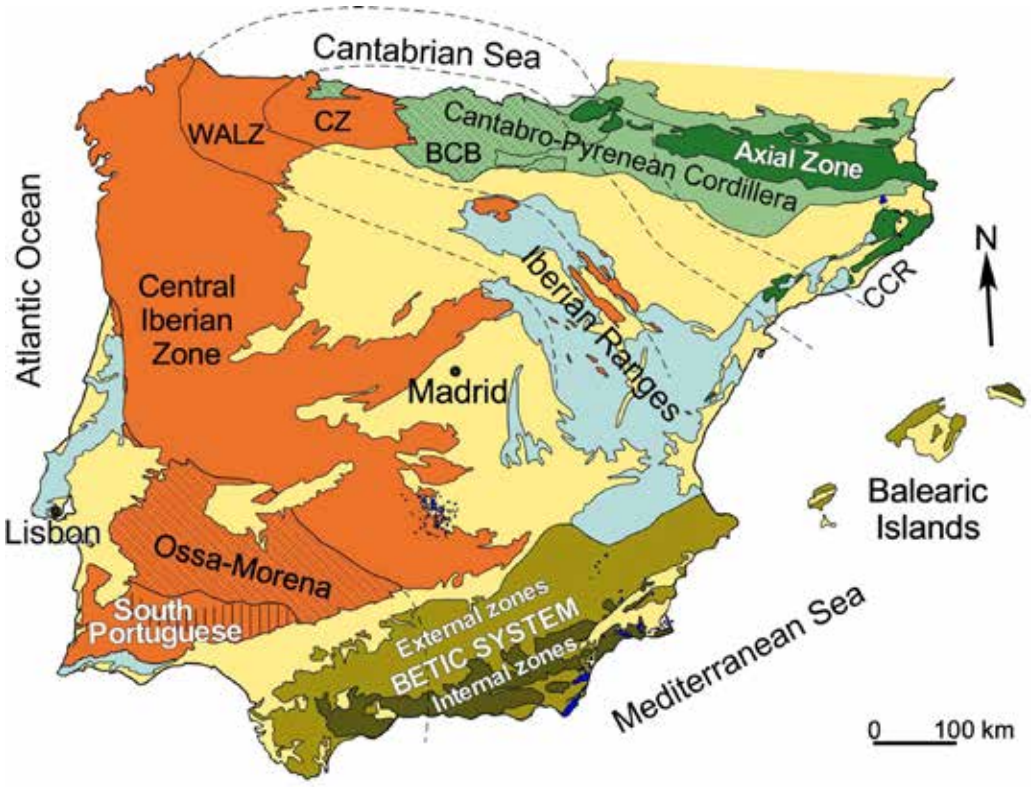


Fig. 1 – Geological map sketch of the Iberian Peninsula.

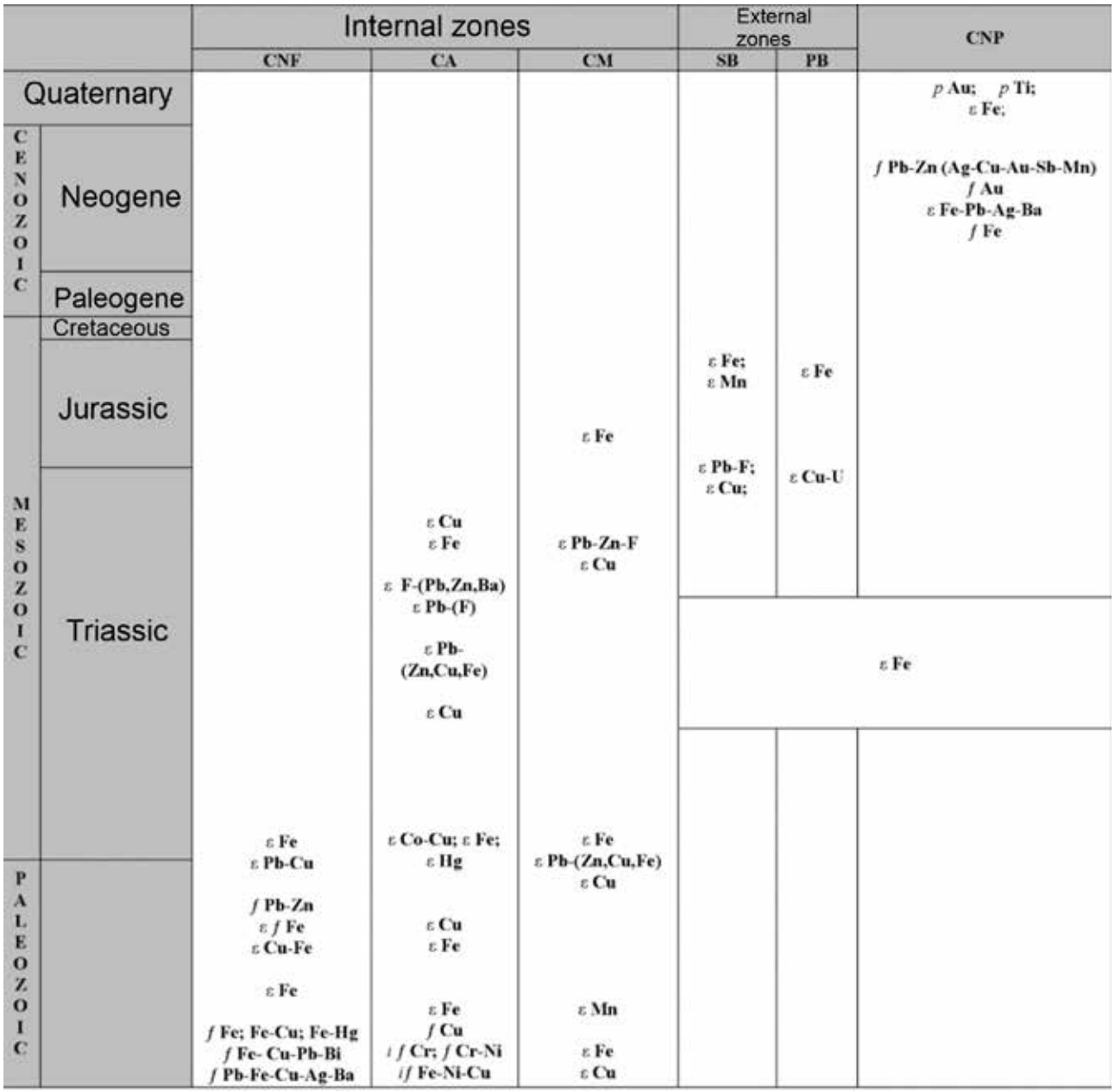


Fig. 2 – Main mineralization zones in the units of the Betic Chain (modified from García-Cortés, 2011). CNF = Nevado-Filábride Complex; CA = Alpujárride Complex; CM = Maláguide Complex; SB = Subbetic; PB = Prebetic; CNP = Postorogenic Neogene Basins.

The External Zones are mainly composed of Mesozoic and Tertiary sedimentary rocks, deposited along the southern paleomargin of the Variscan Iberian Massif. The Internal Zones are mainly made up of metamorphic Paleozoic and Mesozoic rocks, distributed across three superposed tectonic complexes: from bottom to top, the Nevado-Filábride, Alpujárride and Maláguide complexes. These Internal Zones extend over more than 600 km from the Málaga province to the south of Alicante, covering the provinces of Almería and Granada, with several mountain ranges in both the coastal and inland areas. Copper is present in all three domains, as described by J. Sánchez-Valverde et al. (2013) and A. García Cortes (2011; see fig. 2):

– *Nevado-Filábride Complex.* Copper mineralisations are found within the so-called Mulhacén section, in low-temperature, hydrothermal veins and fractures. The main primary ores include siderite, with disseminations of galena, pyrite, chalcopyrite, sphalerite, cinnabar, stibnite, tetrahedrite and arsenopyrite.

– *Alpujárride Complex.* Two types of copper mineralisation appear within the metasedimentary formations of this complex: stratiform-stratabound Fe-Pb-Zn-Cu deposits of probable sedimentary origin, and subvolcanic deposits with a similar chemistry, filling faults and/or fractures, probably remobilising the former stratiform mineralisation. The copper minerals are predominantly sulphides, and minor copper carbonates as secondary

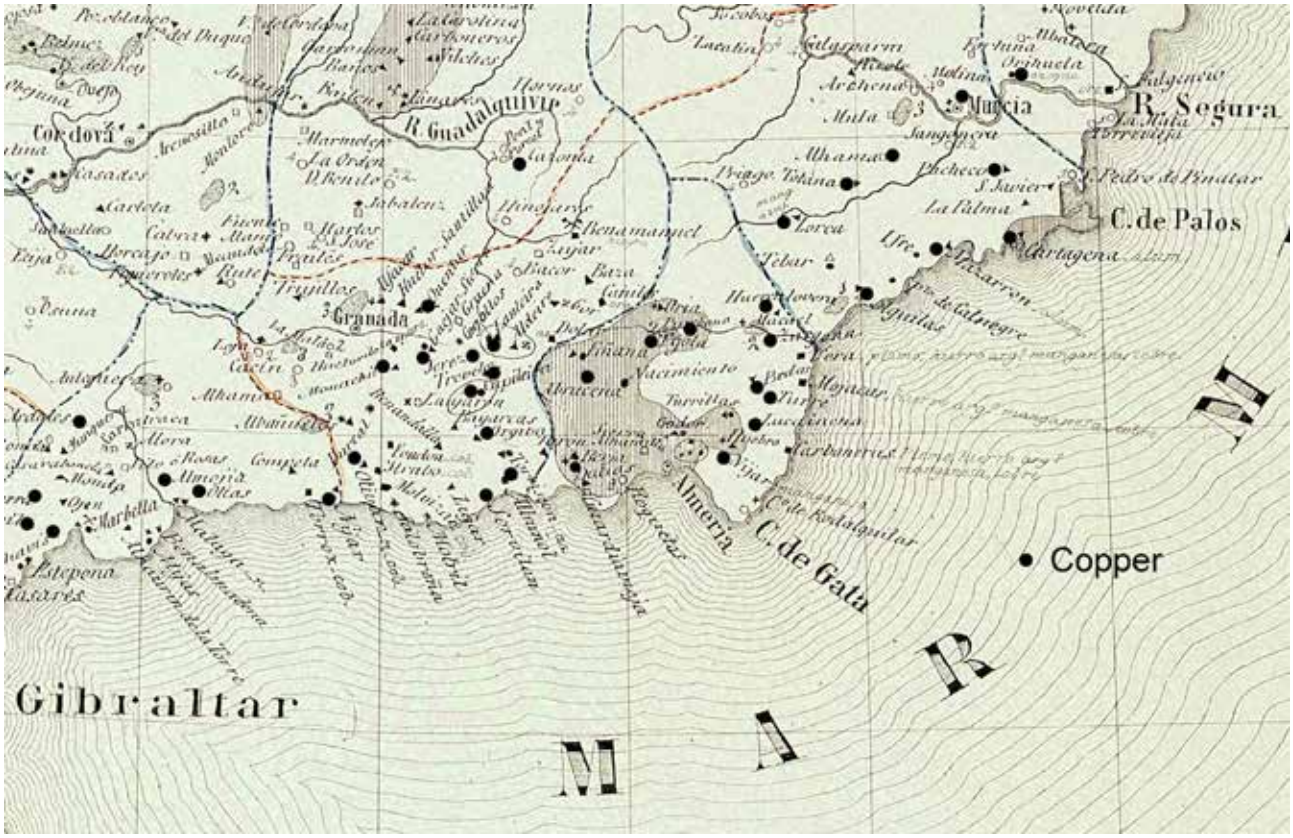


Fig 3 – Fragment of the "mapa minero" of Miguel Avellana (1860) showing the distribution of copper mines in the Betic Ranges (https://www.ign.es/web/catalogo-cartoteca/resources/html/003492.html).

mineral associations, alongside tyrolite, annabergite, cinnabar, goethite, magnetite, proustite and pyrargyrite.

– *Maláguide Complex.* Located in the western part of the region, near the city of Málaga and in the Montes de Málaga, with some outcrops also located north of Granada and in the Sierra de las Estancias. In this complex, copper mineralisation mainly occurs in the Saladilla Formation, which consists of conglomerates, sandstones, pelites, grey dolomites and Permian-Triassic gypsum. Copper minerals in the Maláguide Complex are mostly sulphides. Minor secondary copper carbonates, likely associated with basic volcanism, appear particularly in the Sierra Arana. In the Sierra de las Estancias area, the copper mineralisation appears to be of sedimentary origin, although recent tectonics activity has played an important role in its final concentration (Carrasco Cantos et al., 1979).

Historical studies mention the use of some copper mines since the 16th century (González, 1832) and geological and mineralogical studies have documented various types of copper ores and associated mineral species (Calderón, 1910; Calvo, 2015). Copper mines are also represented on historical maps (fig. 3).

Modern and interactive resources, such as MINDAT website (https://www.mindat.org/loc-3102.html), provide precise information on mines, including descriptions and locations for each province. Other valuable tools include the layer with mines location launched by the Spanish Mining Institute (Instituto Geológico y Minero de España, IGME-CSIC), the maps available through the Spanish Infrastructure of Spatial Data Geoportal (IDEE), which can be downloaded for use in GIS software, or the official app developed by the National Geographic Institute (Instituto Geofráfico Nacional, IGN). These resources are useful when planning field surveys.

LOOKING FOR PREHISTORIC MINES

The archaeological research in the 19th century began with the Siret brothers (Siret and Siret, 1890), mining engineers working in the mining districts of Almería and Murcia. Luis Siret, who lived in Herrerías (Almería) until his death in 1934, documented the archaeological discoveries made in these mines and had access to materials found during the mining operations. However, this modern mining was mostly focused on lead and iron. Only a few references to Roman or medieval materials were published (Siret, 1906), but general comments on the use of copper in the early metallurgical stages can be found in their first book (Siret and Siret, 1890, p. 65, 271). They proposed the local exploitation of some ore deposits close to archaeological sites, such as Parazuelos (Murcia), based on the similar elemental composition of slag fragments recovered at the site and the copper ores collected from the surrounding mines (fig. 4).

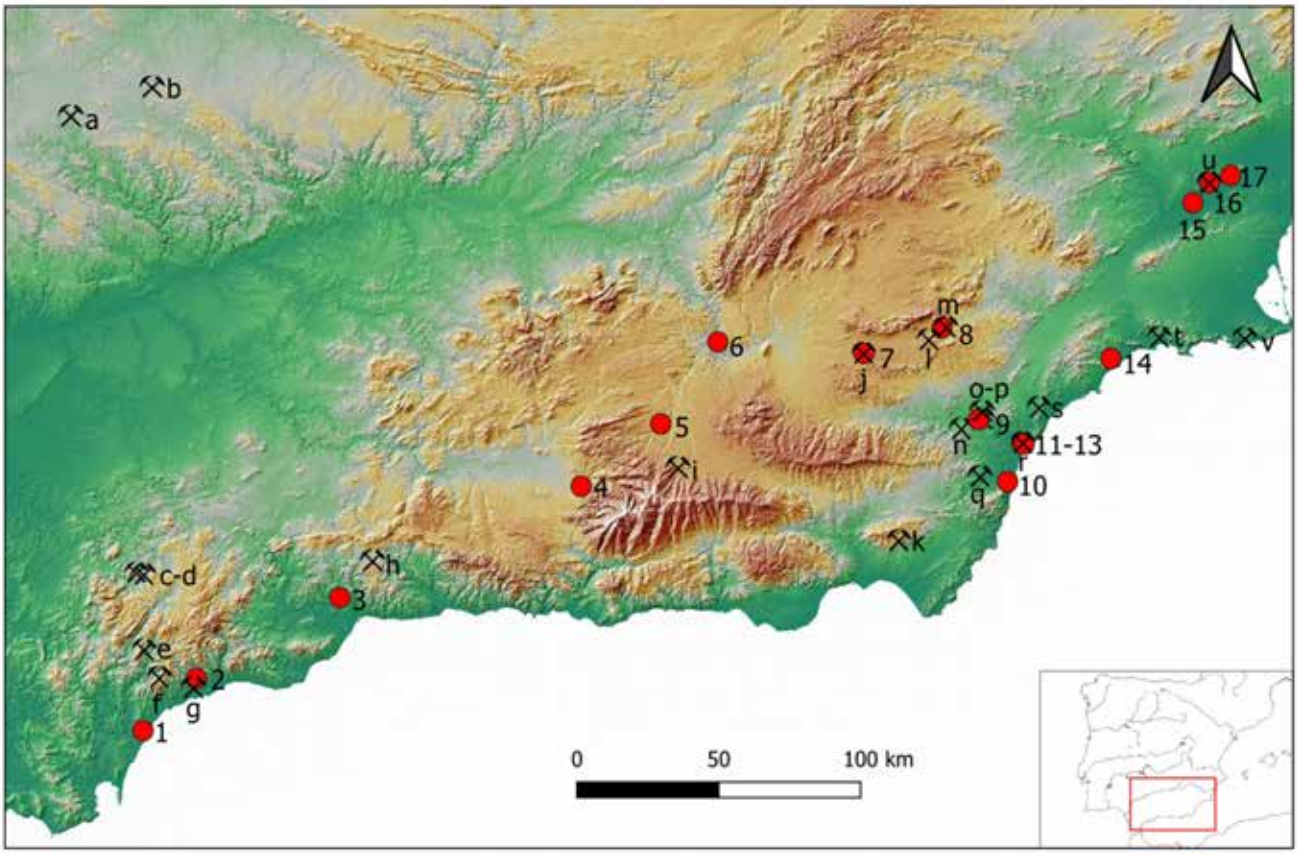


Fig. 4 – Location of archaeological sites and mines mentioned in the text. Settlements – 1: Castillejos de Alcorrín; 2: Montemayor; 3: Cerro de la Peluca; 4: Cerro de la Encina; 5: Cuesta del Negro; 6: Terrera del Reloj; 7: El Malagón; 8: Cerro de los López; 9: Santa Bárbara; 10: Las Pilas; 11: Cerro Virtud; 12: Herrerías; 13: Almizaraque; 14: Parazuelos ; 15: Monteagudo; 16: Cerro de la Mina; 17: San Antón. Mines – a : Las Minillas; b: Los Perules;, c: Escaurías; d: Montecortillo; e: La Horadada; f : San Pedro; g: Cadernillo; h: Mina Casacara; i: Santa Constanza; j: El Malagón; k: ALS 2; l: Peñón Colorado; m: Cerro de las Minas; n: Zurgena ; o: Cerro Minado; p: Molino del Judío; q: Pinar de Bédar; r: Herrerías ; s: Pulpí; t: Balsicas ; u: Cerro de la Mina; v: Filón Consuelo.

Despite L. Siret's knowledge of the mining activity in the region, only one hammerstone is found in the Siret collection at the Museo Arqueológico Nacional (MAN) in Madrid. It is a rectangular-shaped, partially grooved cobble stone found at the 'Niño' mining concession (fig. 5), located near the Herrerias hill (Murillo-Barroso et al., 2020, p. 94, fig. 6). While it is not the typical grooved hammerstone found in many other prehistoric mines in Iberia or Europe, S. Timberlake (2023) notes that such cobbles with minimal modifications are very common in many sites in Britain, but are difficult to identify in the field and are occasionally not recognized as such.

Surveys in the 1980s and 1990s

In the 1980s, surveys linked to the Millares project identified some copper deposits (20 mines) around the archaeological site, but no archaeological materials (such as stone tools or pottery) were associated with any of these mineralisations, which were potentially the most suitable for exploitation (Keesman et al., 1991–1992, p. 290). However, a brief note on a possible Chalcolithic copper mine in Sierra Alhamilla (Site ALS2) was published (Rothemberg et al., 1988).

The archaeological record (handmade pottery fragments with some copper ores and slags) was not diagnostic, and no further references to this site have been published since then, except for the presence of arsenic in the copper ores that could be related with the arsenical copper production (Rothemberg, 1989). Also, near the El Malagón site (Granada), a small copper vein was identified, leading to the suggestion that the location of the Chalcolithic site was determined by this resource. However, no tools or data on the composition of the copper ore were published to confirm the similarity with the mineral found in the settlement (Arribas et al., 1989).

Cl. Domergue (1987; 1990) made brief references in the 'Corpus of Roman mines in the Iberian Peninsula' to prehistoric tools found at Filón Consuelo and Cerro Minado (a single hammer, though without a precise description or documentation).

The Vera Basin (Almería) was selected by Montero-Ruiz for his PhD on prehistoric mining and metallurgy (Montero-Ruiz, 1992). Some copper mines were sampled, including Cerro Minado and Pinar de Bedar, with ores characterised by XRF. No evidence of prehistoric tools was found. The copper ores usually contained high levels of arsenic and some other minor elements in proportions similar to the archaeological ores found in the Almizaraque metallurgical site (Montero-Ruiz, 1992). This suggested that arsenic might have been a natural

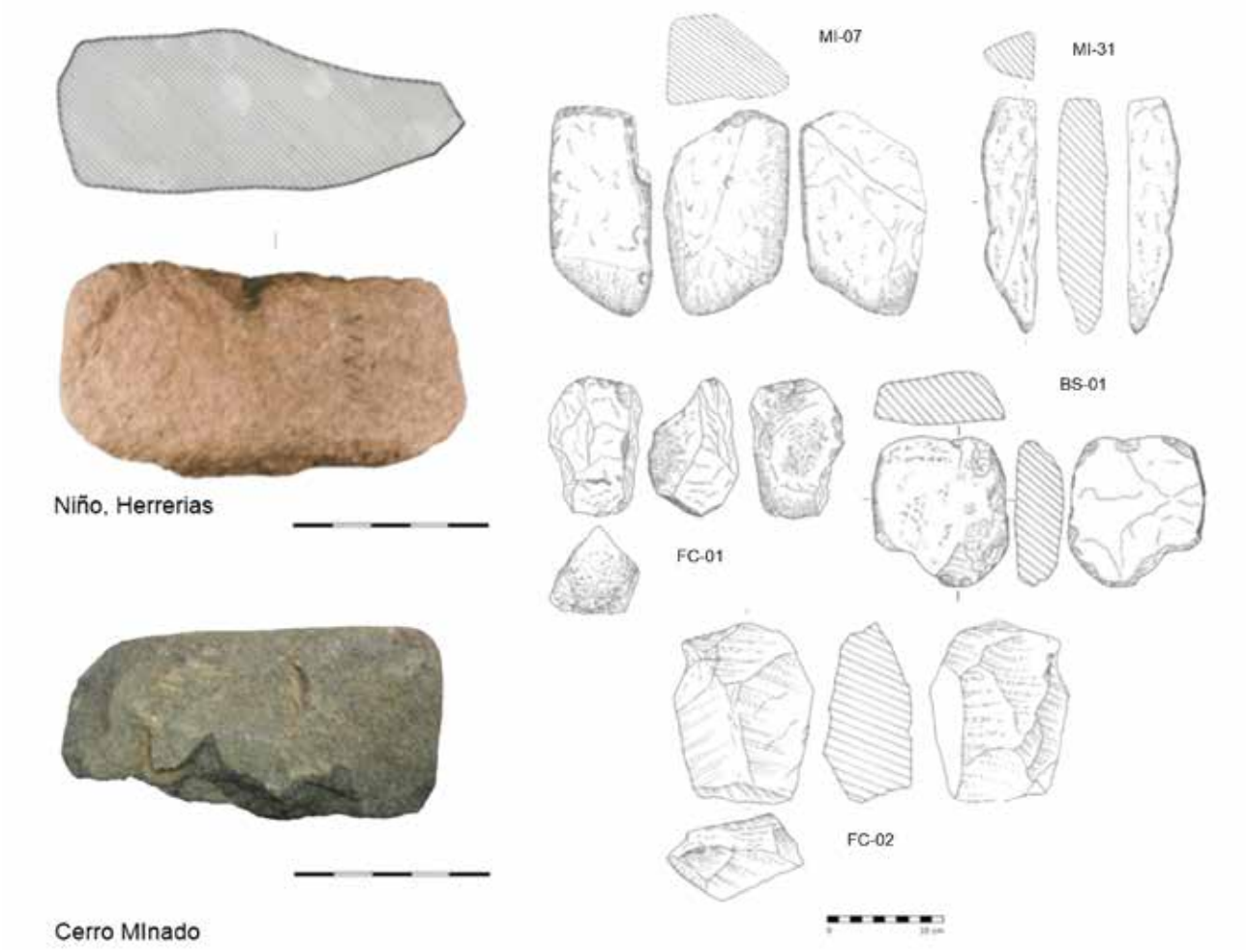


Fig.5 – Stone tools from Niño, Herrerías (after Murillo-Barroso et al., 2020) and Cerro Minado, Balsicas, and Filón Consuelo (after Escanilla, 2016).

alloy, and its presence in the metal would have depended on the original ore smelted.

At the same time, Rodríguez Vinceiro started a survey in Málaga Province, visiting copper mines and sampling ores (Rodríguez Vinceiro et al., 1992). This research highlighted the absence of mines from this province in Domergue's Roman mines catalogue (Domergue, 1987). Rodríguez Vinceiro's paper compiled several references to stone hammers and provided information about three copper mines near Chalcolithic sites with metallurgical evidence. Stone tools or prehistoric pottery suggesting prehistoric mining activities were not found at these mines; instead, the proximity to archaeological sites was the main argument used to suggest their exploitation during this period.

Years later, F. Rodríguez Vinceiro published new information on the mines in Málaga province, with elemental composition analyses of ores and a few lead isotope data (Rodríguez Vinceiro et al., 2018). The absence of modern works in the likely ancient small trenches and the recovery of lithic tools related to ore crushing at the Casacara mine are significant. Fragments of stone hammers and prehistoric pottery were also mentioned at the La Peluca mine, located very close to the Cerro de La Peluca settlement. The paper also includes new references to mines with stone tools made of diabase, although the original information and tool descriptions remain unpublished (Rodríguez Vinceiro et al., 2018, p. 95). The limited number of lead isotope analysis (LIA) of local ores could only suggest the use of the Casacara mine, but this evidence requires further reinforcement through more comprehensive isotopic characterisation.

Prehistoric Mining in coastal areas of Murcia and Almería

The next survey was conducted in the province of Murcia by N. Escanilla as part of his PhD (Escanilla, 2016). Several units were visited to identify the mining works and sample the copper ores, including: Sierra de Orihuela, Sierra Espuña, Sierra de la Tercia, Sierra de la Torrecilla, Sierra de En Medio, Sierra de Almagro, Sierra Almenara, Sierra del Águila, Sierra de la Carrasquilla, Sierra del Aguilón, Loma de Bas, Sierra de las Moreras, Sierra del Algarrobo, Sierra de Cartagena and Sierra de Carrascoy.

For the first time, a direct radiocarbon date from a copper mine was published (Cerro Minado, MAMS-18508: 3905 ± 21; 2500–2300 cal. BC) with information on two other prehistoric mines (Filón Consuelo and Balsicas) in the area (Escanilla and Delgado-Raack, 2015). The few stone tools from Cerro Minado confirmed the references made by Cl. Domergue (1987) and other early 20th century sources regarding the discovery of antler tools (Escanilla, 2016, p. 208–209). All the stone tools from the three mines are similar (fig. 5), consisting of unmodified or minimally modified gabbro or amphibolite cobbles, without clear grooves to facilitate handling. However, grooved stones were found among the stone hammers in the Bronze Age sites of El Argar and Peñalosa. Therefore, the absence of grooves in the Cerro Minado mining tools, combined with the radiocarbon date obtained, is the main evidence supporting the classification of all of Cerro Minado's stone tools as belonging to the Chalcolithic period (Escanilla and Delgado-Raack, 2015, p. 94).

The survey provided mineralogical and trace element data using pXRF, PIXE and XRD from several mines, distinguishing some rich polymetallic mines with arsenic and other pure copper-iron ores.

German Survey around Castillejos de Alcorrín (Málaga)

This survey focused on the raw materials found in the hinterland of the Phoenician site of Castillejos de Alcorrín. Iron, copper and lead mines were visited and sampled (Renzi et al., 2016). Analyses by XRD and ICP-SFMS identified copper minerals in five mines:

1. San Pedro (chalcopyrite and brochantite, with significative detection of Co, Ni, Zn, As and Cr)
2. Cardenillo (chalcopyrite and brochantite, with Co and As as minor elements)
3. Montecortillo (malachite, atacamite and brochantite, with As, Pb and Co)
4. Las Escaurias (azurite, bornite and brochantite, Pb, Sb, W, As and Ag)
5. La Horadada (chalcopyrite)

Historical references suggest that mining activities began between the 16th and 18th centuries, and it is difficult to confirm earlier exploitation, except during Roman times. The lead isotope analysis (LIA) of archaeological material from the site of Los Castillejos does not match any of the LIA results obtained from geological samples. The proximity of some archaeological remains to the mines is insufficient to confirm the prehistoric use of these copper sources. Due to their visual proximity, the Bronze Age site of Montemayor is related to the Cardenillo mine. Furthermore, a stone hammer was discovered at Montemayor, although no prehistoric evidence comes from Cardenillo mine (Renzi et al., 2016, p. 169).

Lower Segura valley (Santomera, Murcia)

The Lower Segura Valley has received limited scholarly attention concerning prehistoric mining activities. There is, however, longstanding tentative evidence for the early exploitation of local copper resources. A survey conducted in 2010 and 2011 by D. Brandherm et al. (2014) at the Cerro de la Mina settlement identified a significant number of potential prehistoric ore-crushing tools in the form of metabasite cobbles. Natural erosion and modern mining activities have likely destroyed parts of the archaeological site. Cerro de la Mina is notable for its deposits of copper oxide ore, primarily malachite. Modern extraction activities are evidenced by spoil heaps scattered along the lower slopes of the hill.

More than 500 metabasite cobbles were found, most of them weighing between 800 and 2000 g. Experimental research, along with 3D scanning and morphometric analysis (Ingram and Brandherm, 2023) sought to link these cobbles to prehistoric mining practices. The study argued that the crushing and pitting damage observed on the archaeological samples resulted from their use as tools.

Like the stone tools previously described in the region, these are unmodified cobbles; however, in this case, they are related with a Bronze Age context (fig. 6).

The investigation was complemented by elemental characterisation and LIA of copper ores from the mine, as well as archaeological objects from nearby Argaric sites of San Antón and Monteagudo. The LIA suggests that only one of the analysed objects (a bronze dagger blade without inventory number from the Orihuela Museum) could be related to the ores of the Segura Valley. Another bronze dagger, from grave 21 of Cerro de la Encina (Granada), could also match with this provenance (Brandherm et al., 2022).

Both the metabasite cobbles and the LIA results support the existence of small-scale mining activity in the Cerro de la Mina. This is an exceptional case due to the proximity between the mine and the Bronze Age settlement, similar to the Cerro de la Peluca in the Málaga province.

Survey in the eastern part of the Internal Zone of the Betic

This survey was aimed to improve the characterisation of trace element compositions and lead isotope analyses using MC-ICP-MS from the Cerro Minado, Pinar de Bédar, Sierra Cabrera and Sierra Almagrera/Herrerías (Murillo-Barroso et al., 2019; here, fig. 7). Although previous studies by I. Montero-Ruiz (1992) and N. Escanilla (2016) had already published composition analyses of these mines, neither trace element analyses nor LIA had been conducted.

The scarcity of archaeological evidence for prehistoric mining activities in the area, partly due to extensive modern landscape alteration, means that these works can only be confirmed through indirect evidence. In a subsequent publication, Murillo-Barroso et al. (2020) confirmed, through LIA of metallurgical remains and artefacts from Chalcolithic sites, the local exploitation of these mines. Specifically, evidence pointed to the

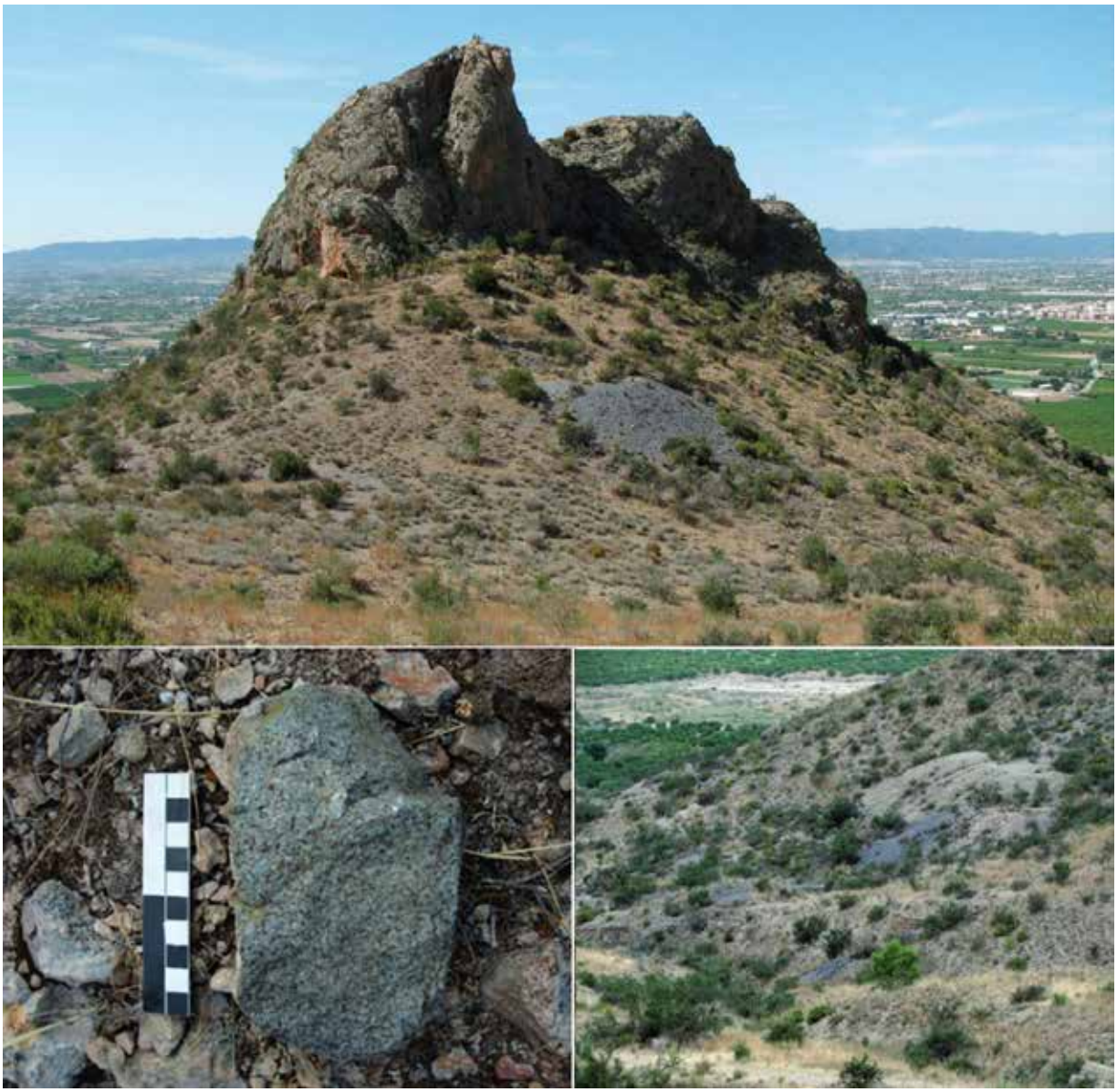


Fig. 6 – Cerro de la Mina (view from the south of Sierra de Orihuela), metabasite tool found in the site and view of the modern dumps at the base of the hill (after Brandherm et al., 2014).



Fig. 7 – Left: Mina Aprovechado, Pinar de Bédar. Right: Detail of the mineralisation and some samples collected.

exploitation of Pinar de Bédar by the inhabitants of Las Pilas, while Cerro Minado was identified as the source for sites such as Santa Bárbara and Almizaraque. The possibility that Almizaraque and Las Pilas also exploited ore from Herrerías, albeit to a lesser extent, remains open.

This study reveals the possibility of the simultaneous use of different resources within a relatively small area, which reinforces the interpretation of metallurgy in the region as a small-scale activity. This directly reduces the archaeological visibility of mining activities, as the simultaneous exploitation of multiple ore sources results in lower extraction intensity at each individual site. Furthermore, the transport of copper ores to settlements for smelting significantly reduces the chances of preserving archaeological evidence within the mines themselves.



Fig. 8 – Left: Zurgena Mine. Right: Some copper ore samples and a prehistoric sherd recovered from Zurgena mine.

In 2023, another survey was conducted in an inner area of this region covering the mines of Zurgena (fig. 8), Huércal Overa and Pulpí. Eight copper deposits were documented, but archaeological evidence of possible prehistoric works (limited to a few pottery sherds) was only recovered in two of them. Trace element and LI characterisation of these outcrops is still ongoing, although pXRF screening of ore samples revealed that these are polymetallic deposits containing arsenic (up to 6 %), antimony, lead and zinc (table 1).

Survey in the inner parts of the Betic Cordillera

A survey carried out between 2015 and 2018 focused on sampling copper mines located in the inland areas of the Argaric territory (provinces of Granada and Almería). The aim was to characterise them through lead isotope analysis (LIA) using MC-ICP-MS, and trace element analysis via Q-ICP-MS (Murillo-Barroso et al., 2025a). This study examined copper mines situated along the northern fringes of the Sierra Nevada, Sierra Arana, Sierra de Baza, Sierra de los Filabres and Sierra de las Estancias, all part of the Betic Cordillera and distributed in the three superposed tectonic complexes. From bottom to top: the Nevado-Filábride, Alpujárride and Maláguide complexes.

The main copper deposits at the Nevado-Filábride Complex are those located at the northern edge of the Sierra Nevada. Among the six mines visited, only one - Santa Constanza – yielded archaeological evidence of prehistoric exploitation, in the form of stone hammers and pottery (fig. 9).

In the Alpujárride Complex, copper ores were sampled from Filón Violeta, De La Cruz, San José, Don Jacobo and José Miguel-1 and -2 mines. No direct evidence of prehistoric exploitation was found at these mines, although prehistoric occupation dating back to the Neolithic has been documented in the surrounding areas.

Copper minerals in the Maláguide Complex were sampled at Venta del Molinillo, Peñón Colorado and Cerro de la Mina mines, the latter being just a few hundreds of meters from the Neolithic settlement of Cerro de Los López (Martínez García et al., 1988). Both Peñón Colorado and Cerro de la Mina yielded prehistoric pottery and stone hammers, suggesting a probable prehistoric exploitation.

Nº	Mine	PROV.	As	Sb	Pb	Zn	Ni	Ag	Co	Stone Tools	LIA
1	Las Escaurias	MA	×	×	×			×			
2	Montecortillo	MA	×		×						
3	Horadada	MA					×		×		
4	San Pedro	MA	×			×	×		×		3
5	Cardenillo	MA	×						×		3
6	Lagar de los Huescas	MA									
7	Lagar de las Animas	MA									2
8	Cerro Coronado	MA				×					
9	Los Bravos	MA									
10	El Ángel	MA	×								
11	Santopitar	MA				×			×		
12	Casacara	MA	×		×	×			×	×	1
13	La Peluca	MA								×	
14	Caserón de las Palomeras	MA				×					
15	Venta del Molinillo	GR	×	×	×	×		×			5
16	La Estrella	GR									
17	Probadora	GR	×	(×)							1
18	Santa Constanza	GR								×	3
19	Filón Violeta	GR	×	×	×						1
20	De La Cruz	GR	×	×	×	×		×			3
21	San José	GR	×		×	×					
22	Hernán Cortés	GR	(×)								1
23	Previsión	GR	×								3
24	Peñoncillo	GR	(×)								2
25	José Miguel 1	AL									
26	José Miguel 2	AL	×				×				1
27	Don Jacobo	AL	×	(×)	×			(×)			4
28	Peñón Colorado	AL								×	2
29	Cerro de la Mina	AL	×		×					×	3
30	Zurgena	AL									
31	Cerro Minado	AL	×			×	×	(×)	×	×	20
32	Pinar de Bédar	AL	×			×					13
33	Cortijo Grande	AL									1
34	Mojacar	AL	(×)	(×)							
35	Herrerías	AL	×	(×)	×			×		×	6
36	La Estrella	AL			×						2
37	Cala de Oro	AL	×		×						
38	Pulpí	AL	×								
39	Alcolea	AL	×	×	×	×	(×)	(×)			4
40	Filón Consuelo	MU	×	×		×				×	
41	Balsicas	MU		×						×	
42	La Diosa S. de Enmedio	MU	×	×	×	×					
43	Santa Isabel S. de Enmedio	MU		(×)	×						
44	Castillarejos (S. Tercia)	MU	×								
45	Zarzicos	MU	×								

Table 1 – General composition patterns of copper ores from the Southeast. PROV = Province. MA = Málaga, GR = Granada, AL = Almería, MU = Murcia.

46	Minas de Merzu (S. de Torrecilla)	MU									
47	Rambla Roja	MU			(×)						
48	Cortijo de Los Tostones	MU		×	×		×				
49	Mina Adela	MU									
50	Santomera C. de la Mina	MU	×							×	10
51	La Francesa-Zurgena	AL				×					
52	Las Minas-Zurgena	AL			×	×					
53	Fuente del Pino-Zurgena	AL				×					
54	Castillo de Santa Bárbara	AL									
55	Molino del Judío	AL	×		×	×					
56	Rambla del Saltador	AL									
57	Diputación Fuente	AL	×								
58	El Zurdo	AL	×	×	×	×					

Table 1 (continued) – General composition patterns of copper ores from the Southeast. PROV = Province. MA = Málaga, GR = Granada, AL = Almería, MU = Murcia.



Fig. 9 – Left: Mina Previsión (Sierra de Baza, Granada). Right: copper ore fragments and a stone hammer from Mina de Santa Constanza (Sierra Nevada, Granada).

At the same time, the study publishes new trace element and LIA results from the argaric settlements of Cuesta del Negro and Terrera del Reloj, located in Granada province, just 10 to 50 km from the sampled mines. The comparative LIA study including previous data from two other Bronze Age sites in the area, Cerro de la Encina and Cerro de San Cristóbal (Murillo-Barroso et al., 2015) suggests that copper from mines across all three tectonic complexes may have been used in Bronze Age metallurgy. The study also confirms the presence of metal originating from Cerro Minado, further supporting its exploitation during the Bronze Age.

A GENERAL PERSPECTIVE

In recent years, some field surveys in several parts of the internal Betic ranges have significantly increased our knowledge of the copper resources available in this extensive area.

Most of the recent researchers visited the mines, looked for evidence of prehistoric works, and sampled ores to be characterised by trace elements and LIA. Table 1 compiles data on the elemental composition of copper ores, the identification of stone tools and the number of LIA results obtained from each mine.

Copper ores are widely distributed throughout the Betic Ranges, but in general they consist of small mines or outcrops. Surface copper ores are oxides and carbonates, with iron and arsenic as the main impurities. However, diverse polymetallic combinations with elements such as Sb, Ag, Ni, Co, Zn or Pb have also been identified.

Elemental data is now available for ores from 58 mines, but stone tools have only been found at 10 of these sites. Most of these tools are unmodified cobbles made of metabasites or other hard rocks. The absence of clearly grooved stone hammers, which are common in other Iberian mines, along with the limited number of lithic tools found in each mine, contrasts with the more abundant and clearer prehistoric mining evidence from areas such as the Sierra Morena (north of the Guadalquivir Valley: Domergue, 1987, Hunt Ortiz, 2003). For example, L. Arboledas Martínez et al. (2023) compiled data on 116 copper mines in the provinces of Badajoz, Jaén, Sevilla, Huelva and Córdoba, most of which presented grooved stone hammers as the main archaeological indicator. Recent surveys in Badajoz (Hunt-Ortiz et al., 2025) and Córdoba have documented hundreds of these tools.

In our own surveys in the Alto Guadiato valley and the southern part of Los Pedroches (Córdoba), an area where over 40 copper deposits had been listed in geological documentation; we were only able to relocate 26, probably due to modern landscape alteration (Pérez-L'Huillier et al. 2022). This clearly suggests that copper resources accessible to prehistoric communities were far more abundant than what is visible today. Evidence of prehistoric mining (stone hammers and pottery sherds) was documented in five of these deposits—previously unknown as prehistoric sites. At the intensively surveyed Los Perules mine (Hinojosa del Duque), 174 stone hammers and 52 fragments of prehistoric pottery were recovered. Characterization of the tools is still ongoing, but most are grooved boulders, while 79 % of the pottery can be attributed to the Copper Age. Trace element compositions and LIA are still ongoing, but preliminary pXRF analyses revealed a high-purity copper ore with only minor impurities.

A similar situation was documented at Las Minillas mine (Granja de Torrehermosa, Badajoz), where prehistoric mining and on-site smelting evidence have been documented (Hunt Ortiz et al., 2017; Hunt Ortiz and Ling, 2023). Although with a later chronology (Late Bronze Age), more than 900 stone hammers have been documented up to now in that single mine (Hunt Ortiz et al., 2025).

This clearly contrasts with the ten mines in the Betic ranges where only fragments of possible tools have been identified, with the exception of Cerro de la Mina de Santomera, which provides more substantial archaeological evidence.

Copper mines in the Betic Cordillera were clearly exploited during the Chalcolithic period, as confirmed by M. Murillo-Barroso et al. (2020). The case of Pinar de Bédar is particularly relevant: although no lithic tools have been recovered from the mine, LIA and trace elements composition conclusively shows that these ores were used at the Chalcolithic settlement of Las Pilas.

Cerro Minado remains the only mine dated to the second half of the 3rd millennium BC based on radiocarbon dating. However, its exploitation seems to have continued into the El Argar Bronze Age, as indicated by LIA matches with Argaric artefacts. Nevertheless, the scale of mining activity appears to have been relatively limited, suggesting a small-scale production.

Most copper mines in the region are located within 10 km of Chalcolithic or Bronze Age settlements. Ore processing, however, typically occurred within the settlements rather than directly at the mines.

Sites such as Cerro de la Mina de Santomera (Murcia) and Cerro de la Peluca (Málaga) are particularly noteworthy, as both settlements are located on the same hill as the copper mines. This spatial proximity complicates the task of demonstrating the simultaneity of mining and habitation without more detailed archaeological investigation (Ingram and Brandherm, 2023).

Copper resource exploitation in the Betic region has a long and significant history, though the Late Bronze Age remains less well defined. During the first millennium BC, Phoenician, Iberian, and Roman interests predominantly focused on lead/silver and iron resources. Cl. Domergue (1987) and L. Arboledas Martínez (2010) mentioned only a single copper mine, La Paloma (Bayarque, Almería), which provides definitive evidence of Roman exploitation. The main phase of Roman mining activity in this region occurred during the Late Republic and the 1st century AD.

Overall, the research conducted, highlights the complexity and variability of copper mining practices in the Betic region. It also underscores the importance of continued archaeological investigation to better understand the scale, chronology, and organisation of mining activities across different historical periods.

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Session 2

Tools, actors and production loci: specialization and organization

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Economy and Status of the Metallurgist According to Babylonian Texts of the 1st millennium BC

Francis Joannès

Abstract: In Mesopotamia during the 6th century BC, the social status of metalworkers (ironsmiths, bronzesmiths and goldsmiths) varied considerably. Often, they were part of the permanent temple staff and were paid in the form of maintenance rations or, less commonly, silver. The technologies used were not particularly sophisticated, and skills were passed on within the family. However, we must take into account the fact that almost all of our sources come from temples.

Keywords: Neo-Babylonian, metallurgy, blacksmith, bronze smith, goldsmith, temples, craftsmanship.

Résumé : En Mésopotamie, au VI^e^ siècle avant J.-C., le statut social des métallurgistes (forgerons, bronziers et orfèvres) est loin d'être uniforme. Ils font souvent partie du personnel permanent des temples et sont rémunérés sous forme de rations d'entretien ou, plus rarement, d'argent. Les technologies utilisées ne sont pas particulièrement sophistiquées et c'est au sein de la famille que se transmettent les compétences. Cependant, il faut tenir compte du fait que presque toutes nos sources proviennent des temples.

Mots clés : néo-babylonien, métallurgie, forgeron, bronzier, orfèvre, temples, artisanat.

This presentation of the activities and status of metalworking craftsmen in Babylonia during the 1st millennium BC is the result of a collaborative research. It was carried out within the framework of a Franco-Austrian research project on the material culture *(Material Culture of Babylonia in the 1st millennium BCE)*, which ran from 2018 to 2022, and for which I was assisted, as far as metal is concerned, by M. Djabellaoui and B. Gombert, doctoral students at Paris 1 – Panthéon-Sorbonne University. In particular, B. Gombert (2018) provided a substantial amount of data, collected as part of his doctoral thesis on the army and military structure in Babylonia during the Neo-Babylonian (626–539 BC) and Achaemenid (539–330 BC) periods.

The aim of this paper, therefore, is to draw on the wealth of data provided by Babylonian cuneiform tablets on metalworking, especially during the so-called long 6th century BC, in order to present some information on the activities and status of metalworkers in this period. Several studies[1] have already been carried out on this corpus, but they are not very well known, either because they have been published within the rather narrow field of Assyriological literature, or because a part of they have remained unpublished. On the neo-babylonian metallurgy in general, see especially: Zawadzki 1985; Joannès, 1993; Jursa, 2010; Kleber, 2016; on the metallurgy in Sippar: Zawadzki,1991; Joannès, 1992; Bongenaar, 1997; Jursa and Zawadzki, 2001; on the metallurgy in Uruk: Beaulieu, 2003, Payne, 2007; on the metallurgy of weapons: Gombert, 2018.

The two main sources for our subject are the cuneiform archives of the temple of the Babylonian Sun god, Šamaš, in the city of Sippar, known by the Sumerian name of Ebabbar 'the Shining House', and the cuneiform archives of the temple of the famous goddess Ištar, in the city of Uruk, called Eanna 'the House of Heaven'. The study of these archives, which consist mainly of administrative and accounting documents, has made it possible to reconstruct the prosopography of metalworkers between 650 and 500 BC (Zawadzki, 1985; 1991; Bongenaar, 1997; Payne, 2007) or to evaluate the use of certain metals (Joannès, 1992; 1993; Beaulieu, 2003; Kleber 2016; Gomb-

1. The bibliographical abbreviations used here are those of the *Chicago Assyrian Dictionary* (CAD), volume 20 (U and W), p. VII–XXIX (= Roth, 2010).

ert, 2018). Many comments on the socio-professional environment of metalworkers can also be found in the large synthesis edited by M. Jursa and published in 2010.

In Babylonia, craftsmen working with metal can be divided into three distinct categories, corresponding to three different designations expressed in Akkadian by the terms *nappāḫ parzilli* ('iron smith'), *nappāḫ siparri* ('bronze smith'), and *kutimmu* ('goldsmith', which replaced an earlier designation *nappāḫ ḫurāṣi* 'smith for gold'). For convenience, I will use the terms 'ironsmith', 'bronzesmith' and 'goldsmith' to refer to these craftsmen, although I am aware that these global equivalents are not exact translations. The Akkadian word *nappāḫu* 'the smith' is related to both the homonymous object *nappaḫu*, denoting the leather bellows used by the smith in the furnace, and the verb *napāḫu*, meaning 'to blow, to light (the fire)'; this akkadian name of profession is also often written, according to the rule of cuneiform writing, by an ideogram (i.e. a sign with the value of a whole word), which is of Sumerian origin and is read SIMUG to designate the smith. But this same ideogram can also have the value DE_2 which means 'to melt'. The sumerian smith is therefore the person who melts metal while using the heat of fire.

During the first millennium BC, and more specifically in the 6th century BC, the craftsman who worked with gold was no longer a smith for gold (*nappāḫ ḫurāṣi*) but a goldsmith (KU_3-DIM_2: The person who works (DIM_2) the precious metal (KU_3)', which in Akkadian became *kutimmu*), and the *nappāḫu* themselves were thus divided into only two categories: bronze smiths and ironsmiths. Each category was usually impermeable to the other. Prosopography confirms that, with very few exceptions, a bronze smith never worked with iron, and vice versa.

However, some boundaries are not entirely clear and a certain degree of overlap remains, not between bronze and iron, but between bronze and precious metals: some bronze smiths are recorded as working silver or refining precious metals. However, this is never the case for ironsmiths. So there exist differences not only in vocabulary (ironsmith, bronze smith, goldsmith), but also in practice: those who worked bronze could also work silver, but not iron.

Finally, there were also social distinctions that cut across all three categories: some craftsmen were independent or even members of what might be called the Babylonian urban elite. This membership of the social elite is reflected in their civil status by the mention of an ancestor's name used as a family name, after the father's name: 'PN_1, son of PN_2, descendant of PN_3'. In contrast, other craftsmen were members of the temple's dependent-class: they were legally free (not slaves), but the temple administration exercised a kind of legal authority over them. They are called *širku*, 'those who are vowed (to the divinity)', which is generally translated as 'oblates'. While, as might be expected, the number of rich peoples among the independent craftsmen was higher among goldsmiths than among ironsmiths, there were goldsmith oblates among the temple staff, which is more unexpected.

As was said earlier, the textual corpus documenting the activities of smiths during the 6th century BC comes overwhelmingly from the archives of two great temples of Babylonia. It is therefore in institutional archives, rather than private ones, that we will find most of the information concerning the metallurgical activities.

It is true that in the non-institutional field we find an ancestor's name linked to metalworking *(nappāḫu)*, which is borne by at least one Babylonian family during the 6th century BC: its members are known as the 'descendants of the Smith' in Babylon, but a study of their archives (Baker, 2004) has shown that metallurgy was completely outside the professional field of these people. The people documented by this group of texts should therefore be considered equivalent to the Smith, Fabre, Lefebvre, Schmied and Schmitt of our contemporary European societies.

To return to the temples, they were not only places of worship, but also important economic entities, providing for their own needs, whether for worship or for the management of their agricultural estates or flocks. They therefore needed a specialised workforce capable of making and repairing the jewellery that adorned the statues of the gods, the worship equipment used to prepare and present offerings, as well as tools of all kinds and sometimes even weapons.

According to A. Bongenaar (1997, p. 355–356), although the metalworkers were organised in small groups, probably corresponding to individual workshops, the temple of the god Šamaš in the city of Sippar seems to have established an administrative structure in which a *nappāḫu* called Bēl-uballiṭ acted as a link between the temple administration and the individual metalworkers. This Bēl-uballiṭ was therefore the person to whom the temple entrusted the responsibility of transferring the raw material to the craftsmen: generally gold, and at least once iron, but not bronze: the bronze smiths had their own allocation structure.

All in all, the system seems to have been poorly structured and very much based on individual relationships between the temple and the craftsmen. Only in the case of the goldsmiths was there any sort of regulation, and even then only because the goldsmiths worked on objects that came into contact with the divine statues and therefore had to enter inside the holy area of the temple.

One last point should be emphasized: despite its wealth (several hundred texts documenting metallurgical activities), temple documentation reveals only a part of the chain of operations. In other words, the extraction and processing of raw ore took place outside Babylonia. The Babylonian temples mention only metal in the form of ingots to be worked, or scrap metal. Similarly, very little is said about the technology used to work the metal, so this must be often deduced. However, there is enough data to allow us to attempt an overview based on three types of metallurgy: 1) iron, 2) bronze, 3) precious metals.

THE IRON SMITHS *(NAPPĀḪ PARZILLI)*

Social and professional status

The records of the temples at Sippar and Uruk tell us that the ironsmiths working for the temple were initially, at the beginning of the period covered by the temple archives, at the end of the 7th century, few in number, usually a group of two or three in each of these temples. From the middle of the 6th century their number increased to six or seven ironsmiths. The social status of these ironsmiths was not very high: most of the *nappāḫ parzilli* in the temple of Uruk were oblates. They also owed certain obligations to the temple, such as taking part in the major digging or construction work. They were remunerated by food rations in kind, except in the case of one file from Uruk dating from 591 to 587 (years 15-18 of Nebukadnezzar's reign), where the temple used outside ironsmiths against payment of a salary in money.(2) This file is linked to the obligation of the temple of Ištar to provide labour for major royal works (digging canals or building large edifices) and it also shows that, in addition to the temple staff, there were 'freelance' metalworkers, i.e. private craftsmen who worked on their own account, in the city or countryside, with whom the temple occasionally concluded work contracts under certain circumstances. The same system can be found in Sippar, where, according to S. Zawadzki, the temple of the god Šamaš sometimes employed ironsmiths on a casual basis, as and when required.(3)

Place of work

Ironsmiths' workshops are never mentioned in temple archives. However, we do know that these craftsmen used charcoal for their furnaces and that they were able to produce it themselves (see below BM 75517). Their mastery of the charcoal-making technique meant that they may also have been responsible for supplying the temple with charcoal for another purpose like the sacred offerings.

BM 75517 (Bongenaar 1997, p. 360–361, pl. 6.)

Adarru, the smith (and) oblate of Šamaš, spoke to Bēl-uballiṭ, the Temple Administrator of Sippar, as follows: "I will give 6 ½ *mašīḫu* (= about 234 litres) of charcoal *(bulû)* monthly to Ebabbar as (my) work assignment".Bēl-uballiṭ, the temple administrator of Sippar, heard him and decided: "6 ½ *mašīḫu* will be delivered to the storehouse (of Ebabbar) as the obligation of Adarru". Adarru said the following: "There will be no other obligation upon me".
(Written) in the presence of Bēl-uballiṭ, the temple administrator of Sippar. (3 witnesses and the scribe).
Sippar, 26-xi of year 1 of Cambyses, king of Babylon, king of the Lands (02/26/528 BC)
From the first day of the month Addaru, (this allocation of charcoal) will be his duty.

Adarru is known as an ironsmith. This ironsmith undertook to supply the temple with charcoal every month, in addition to the charcoal needed for his own metalwork. As noted by A. Bongenaar, the product to be delivered according to the contract, *bulû*,(4) is quite often attested in combination with the smiths. In CT 55, 202, silver is given to Bunene-ibni, the ironsmith, for "two *kor* (= 360 l.) of *bulû*-charcoal", and in CT 55, 250, Arad-Gula, the ironsmith, also received silver for (the production of) *bulû*-charcoal.

Activities

According to E. Payne (2007, p. 287), 75% of the Uruk texts mentioning the *nappāḫ parzilli* record the delivery of raw or worked raw material to a ironsmith or the delivery of iron tools to the temple by the ironsmith. The iron 'raw material' was supplied in the form of ingots *(kušru)* or plates known as 'turtles' *(šeleppūtu)*:

CT 55 222

5 iron bars, 1 iron ingot *(šeleppūtu)*; total: 57 ½ minas of iron (28.75 kg) were taken from the *bīt miḫṣi*-workshop to the storehouse

———————

14-xii of year 20 of Kandalânu (month 03 or 04/628 BC)

P. R. S. Moorey (1994, p. 291) mentions also fish-shaped plates at Khorsabad in Assyria (8th Century BC). Broken pieces of iron tools and iron scraps *(ḫušê)* are also sometimes found.

The objects produced by the ironsmiths fall into four main categories:

– blades (knives) and cutting tools (axes);

– iron rings (for prisoners) and metal parts for closing doors (bars, rings);

– tools for livestock farming (shearing scissors, branding irons);

– agricultural tools such as hoes, spades and pickaxes. Ploughshares were also made of iron. We can also find fasteners (nails, pegs) and sickles, which were generally very light in weight.

Examples of ironsmith's work: the *marru* spades:

2. Cf. the study by E. Payne, in Jursa, 2010, p. 688–694.
3. Zawadzki, 1991, p. 37: "Silver is mentioned as payment for finished objects only in a few texts. In these texts the term *idū* is used, which denotes payment to hired men. (…) On the ground of documents available so far, we can conclude that the Ebabbar temple in Sippar employed smiths only occasionally."
4. Bongenaar 1997, p. 361: "G. van Driel suggested the translation 'charcoal' for *bulû*, which may have been measured in *kor*s, but more importantly, charcoal is an absolute necessity for melting scrap metal (Joannès, 1993, p. 102). Burning wood does not produce enough heat."

Oberhuber Florenz1960 no. 1

13 minas 10 shekels [= 6.5 kg] of iron, work completed, the weight of 9 iron *marru* spades:[5] that is what Nabû-lē'i delivered to the warehouse
15-iv of year 8 of Nabonidus, king of Babylon (07/24/548 BC)

YOS 6 81

[x] iron spades brought by [.....]a, Ištar-šum-ēreš and Šamaš-zēr-ibni are in the hands of Nanaia-karābi, son of Ina-ṣilli-Nanaia. 2 broken iron *marru* spades to be reattached (the blade to the handle): the iron *marru* spades were given to the ironsmith, and (another) iron *marru* spade was given to the Treasury.
Received (from) Ištar-zēr-ibni, son of Šamaš-zēr-ibni.
15-vii of year [o] of Nabonidus, king of Babylon (september or october, between 556 and 539 BC)

The main task of the ironsmiths was therefore the production of agricultural tools and their repair. This means that the pattern of use of metal agricultural implements was the same for iron in the first millennium as it was for bronze in the early second millennium BC: agricultural implements were the property of the temple. The temple distributed them to the workers according to the work they had to do, then took them back and had them repaired if necessary. We can assume that the smiths had real practical know-how, but this was limited to hammering and shaping iron, which did not make them high-level craftsmen. This fact has already been noted by Moorey (1994, p. 281, quoting Curtis, 1979, p. 381) for the Neo-Assyrian period: "Neo-Assyrian smiths did not know how to manipulate in the most effective ways the operations in which iron attains the greatest strength".[6]

Moreover, the *nappāḫ parzilli* usually worked on non-cultic objects, which unmistakably belonged to the profane sphere of the temple. It is evident that in Mesopotamia, the fabrication of cultic objects from iron was virtually non-existent, with the exception of certain ceremonial weapons that were part of the equipment of divine statues; in CT 55 235, they are said to be made of iron. But they may contain also elements of gold and silver as in YOS 24 51:

CT 55 235: (payment in silver for work completed by the *nappāḫ parzilli* Arad-Gula on the weapons of the goddess Annunītu in Sippar)

3 shekels of silver for the iron dagger of the Annunītu's quiver (and) 2 shekels of silver for 60 arrowheads. In all, 5 shekels of silver were paid into the hands of Arad-Gula the ironsmith.
22-x-of year 11 of Nabonid, king of Babylon (01/21/544 BC)

YOS 24, 51 ll. 12-16 (Inventory of cult objects from the Temple of Ištar in Uruk, no date)

(…) two iron daggers with silver and gold (ornaments), one iron throwing-stick with silver and gold (ornaments), four *mēṭu*-maces of iron and gold, two silver *tuḫullu*?, one iron sickle (…)

Among the objects made by ironsmiths, we find finally weights for weighing, which can be considered an elaborate handicraft. However, the form of these iron weights, which weighed 1 mina (= 500 g.) and its subdivisions into shekels, is not known, unlike the bronze weights, and they may have been produced in specialised workshops outside the Temple.

In conclusion, the temples employed ironsmiths, who were primarily drawn from their permanent dependent labour force, the oblates. When necessary, the services of independent ironsmiths were used, a sign that this craft was also present in the rest of society.

Oblate ironsmiths are not part of the temple's 'high-tech workforce'. They have a certain amount of know-how, which can be defined as the mastery of the furnace and its supplies, as well as simple technical skills such as hammering and shaping certain tools. However, it should be noted that they are neither steelworkers nor manufacturers of high-performance weapons. The primary function of these individuals is the maintenance and restoration of the fundamental tools required by the temple for its agricultural operations.

THE BRONZESMITHS *(NAPPĀḪ SIPPARI)*

Social and occupational status

In 6th-century Babylonia, bronze metallurgy is a much more experienced craft than iron metallurgy, with some 18 centuries of tradition, three times longer than that for iron. The bronzesmiths were also more closely involved in the cultic life of the temple and were more skilled in a wider range of techniques than the ironsmiths: in particular, they practised copper-tin alloying, metal casting, object shaping and probably damascening.

While the *nappāḫ parzilli* worked on agricultural tools, the *nappāḫ siparri* worked on cult objects. They could work with raw metal: bronze, silver, tin, or make repairs to extant bronze objects. They mainly made pots and vessels of various shapes and sizes, but were also involved in casting and testing. A *nappāḫ siparri* could therefore be called upon to make silver bowls, implying that it was technical skill rather than the type of metal that counted. Some evidence suggests that the *nappāḫ siparri* knew how to mould objects with the lost-wax casting technic. Finally, some *nappāḫ siparri* also knew how to assay silver and gold (by melting and removing impurities). The boundary between the *nappāḫ siparri* and the goldsmiths was therefore permeable, especially as the lat-

5. 1 *marru*-spade = 730 g. on average
6. Moorey, 1994. The same author points out that there are no studies of Neo-Babylonian data.

ter tended to specialise in working with gold, often leaving silver to their colleagues in bronze.

Activities: objects produced

The bronzesmiths produced and repaired bronze and silver objects[7] mainly for cultic purposes. Among the objects supplied by the bronzesmiths we find:

– cultic vessels for preparing and serving food offerings: incense burners *(nignakku)*, bowls and vessels *(makkasu*, *sūtu* and *kirru)*, basins for ablutions *(ša mê qātē)*, cooking pots *(mušaḫḫīnu)*;

– musical instruments, like kettledrums and part of a harps *(balaggu)*;

– weapons: spears *(azmarû)*, arrowheads;

– parts of doors and parts of carts (mainly the wheels), such as a cart for the 'house of the brewers' *(attaru* ša *bīt sirāšê)*. Bronze plates or strips, decorated or not, could be applied to wooden supports: this was the case for monumental doors and ceremonial chariots.

– measuring vessels like a bronze *sūtu* capacity-measure[8] or bronze lion weights.[9]

Technical aspects

Among the objects cited, we can distinguish between bronze objects made in moulds (spearheads, arrowheads, grids), sheets or plates modelled upon a shape, then riveted or brazed to form vessels (bowls, pots, cauldron-*mušaḫḫīnu*), and more elaborate objects, probably made by lost-wax casting, such as bronze weights in the shape of a lion, examples of which have been found in Assyria.

To produce the objects ordered, the *nappāḫ siparri* had at his disposal either ready-made bronze in the form of *kušru*-ingots,[10] or copper and tin, or even bronze and tin which he mixed himself, according to a standard ratio which had been known for several centuries: in the 2nd millennium BC the ratio between tin and copper was 1 to 6 (Joannès, 1993, p. 104, §9). In the Neo-babylonian documentation (6th century BC), however, it seems that tin was not only used to make an alloy, but also sometimes to strengthen an existing bronze, or to make a solder between bronze elements.

Bronze and tin at Sippar during the reign of Nabonidus (556-539 BC):

Nbn 471 (tin/bronze ratio: 1 to 8 ⅔)

½ talent 5 minas 20 shekels of bronze (= 17.6 kg); 4 minas and 5 shekels of tin (2.04 kg) from the (temple)store, on the occasion of the entry of the sheep (?) to the Bunene temple were given to Libluṭ and to Iqūpu, the bronze workers.
6-xi-of year 10 of Nabonidus, King of Babylon (02/15/545 BC)

Nbn 924 (tin/bronze ratio: : 1 to 5)

10 minas of bronze (= 5 kg) and 2 minas of tin (= 1 kg), the first part of ½ talent and 5 minas of bronze (= 17.5 kg) for the plates(?) of the bronze cauldron (used to prepare the *tabnitu*-offerings), were given to Libluṭ, the bronzemaker, 23-x of year 15 of Nabonidus, king of Babylon (01/08/540 BC).

The problem is that we have no evidence of any technical handbook in cuneiform describing the art of bronze metallurgy during this period. The approach favoured by the temple administration in its written archives was a purely arithmetical one, taking into account the numerical standards for the production of an alloy or the loss that occurred in the refining and alloying process and was considered acceptable, and then comparing the weight of the raw metal supplied with the weight of the object produced. It is therefore by reference to the type of object produced that we can suggest the use of a particular technique, with a degree of uncertainty of course. However, if we compare the type of work carried out by the ironsmiths with that of the bronzers, it seems clear that the latter's technical baggage was superior and that the range of their creations was wider.

THE GOLDSMITHS *(KUTIMMU)*

As E. Payne writes (2007, p. 203): "The goldsmiths were responsible, first, for fashioning and maintaining the jewelry and other gold objects that ornemented the cultic statuary of the temple. They were also responsible for cleaning jewelry. Second, the goldsmith, together with the bronze smiths were responsible for smelting gold and silver and assaying gold."

Social status

Goldsmiths had a special status among the staff of temple craftsmen: some of them were part of the staff authorised to enter the sacred space of the temple where the statues of the deities resided, the so-called 'entrants' *(ērib bīti)*. In this capacity, goldsmiths had a specialised function in texts from the 3rd and 2nd centuries BC, which was called "the prebend of goldsmith and entrant into the room of secrecy": *isiq kutimmūtu u* ērib *bīt pirištūtu* (Doty, 1977, p. 126).

But this function did not exist before the Hellenistic period. Prior to that time, goldsmiths were scattered

7. Nbn 159 (making of *makkasu*-bowl of the temple of the Lady of Sippar); CT 55 284 (making a plate for the *šalām bīti* ritual)
8. YOS 24 66.
9. Weighing 10 minas (5 kg), 5 minas (2.5 kg), 3 minas (1.5 kg), 2 minas (1 kg); 1 mina (0.5 kg), etc.
10. Cf. TCL 12 112: "2 talents 14 minas of bronze (= 67 kg) in 10 ingots-*kušru*, to work, were given to Bazuzu the bronze smith (…) 21-x of year 15 of Nabonidus, king of Babylon" (01/06/540 BC).

throughout the strata of the babylonian society, some were prominent, others were simple oblates, i.e. they were dependent of the temple and belonged to what could be called the group of its specialised workers.

Independent goldsmiths, i.e. those who were not oblates, generally worked in workshops of one or two people, but were much more subject to the control and supervision of the temple administration than were the bronzesmiths or the ironsmiths. They have rights, such as a form of exclusivity in the service of the temple (i.e. the temple gives them priority), but they have also duties: the raw materials supplied to them by the temple may only be used for orders from the sanctuary, and these always take priority.

E. Payne has observed a change in the relationship between the temple of the goddess Ištar at Uruk and its goldsmiths: until about 600 BC, the responsibility for working the gold was more or less evenly distributed among all known goldsmiths. Then this responsibility was reduced to two individuals, working as a team, who were responsible for almost all the gold worked.[11]

Goldsmiths' activities.

Kutimmu worked mainly with gold and silver, but could also combine them with precious or semi-precious stones. As we have seen, some precious metal forms can be worked by *nappāḫ siparri*. So what was the specific contribution of the goldsmith *kutimmu*? According to S. Zawadzki (1991, p. 45), in Sippar they worked only with gold, while silver remained in the hands of bronzesmiths.

The *kutimmu* were first and foremost experts in judging the purity of metal: they knew how to carry out a precision weighing operation and how to purify gold and silver by removing impurities. They were sent by the temple outside to buy gold, and they knew how to assess its quality and set its price.

In the protocol for judging the purity of gold, the precious metal is first refined by passing it through a furnace, which removes most of the impurities. This is followed by an operation known as *pīdānu* (var. *pādunu*), which is currently recorded from twelve references.[12] This word has been interpreted as meaning 'to test' and would therefore imply the use of a touchstone.

Refining gold by firing and *pīdānu* assay:

Nbn 489

(Regarding) 2 minas 2 shekels (= 1,016.26 g) of gold, which were put into the furnace: on this 10 ½ shekels (= 87,46 g) of gold disappeared during the firing, and 1 mina and 51 ½ shekels of red gold (= 928.8 g) came out of the furnace. And 1 mina and 8 ½ shekels (= 570.6 g) of red gold, on the gold that was bought for silver, (given) from the workshop.
In all, 3 minas of red gold (= 1,500 g), which were sent to Babylon by Marduk-šum-uṣur, son of Bēlšunu, Šamaš-erība, son of Balīḫu, and Bēl-uballiṭ, the metallurgist, for the sceptre of Anunnītu.
In the presence of Bēl-ahhe-eriba, *qipu* of the Ebabbar (and) Mušēzib-Marduk, priest of Sippar
2-i of year 11 of Nabonidus, king of Babylon (04/10/545 BC)

To obtain 180 shekels of 'red' gold, 68 ½ shekels of red gold already available in the goldsmith's workshop were added to the 111 ½ shekels of gold resulting from the refining of 122 shekels that had been put into the furnace. The refining loss was 10 ½ shekels, or 8.6%.

YOS 6, 121[13]

5 minas of gold, (weight) of 5 plates, a royal donation, which were placed in the furnace: in the first firing, 45 shekels of gold disappeared; the gold was reduced to 4 mines 15 shekels; at the second time through the furnace, 32 shekels of gold disappeared during the firing; the gold was reduced to 3 mines 43 shekels;
To be checked *(ana pīdāni)* by the silversmiths Bēl-ibni and Širiktu.
(Weighed) with weights of 2 minas and 1 mina, in bronze, ½ mina, 10 shekels, (and) a unit of 5 shekels in iron,
15-ii of year 8 of Nabonidus, king of Babylon (05/26/548 BC)

The first loss is 15%, the second 12.5%. The total loss is 25% of the initial weight: the gold has lost about ¼ of its initial weight.

EPHE No. 609 (Kandalanu's reign 648-626 BC)

1 mina and 56 shekels of gold (= 966.5 g) to be verified (*ana pīdāni)* are at the disposal of [PN].
20 minas and 10 shekels of silver (= 10.083 kg) for [(.....)] the silver fermenting vat (placed before) the god [DN] were put at the disposal of Nabû-zêr-ibni, the *nappāḫ siparri*; (the vat) was placed in the bronze balance, and it was weighed (with a weight of) 10 minas of bronze (and a weight of) 10 minas of polished stone *(galala)*.

If we follow K. Kleber (Kleber, 2016, p. 131–132), this term, used in Akkadian from the 6th century onwards, can be related to the Arabic root *ftn* meaning 'to test, probe, try, examine', from which the Arabic term for touchstone *(fatīn)*, is derived.

11. Payne, 2007, p. 228: "This shared responsibility added a layer of accountability and protected both the craftsmen and the temple from theft or the accusation of theft. For the next fifty years, two pairs of individuals—a pair of fathers and a pair of sons from each family—are responsible for nearly three-quarters of the total gold worked during this period."
12. BM 63883 (= Bertin, 1883, no. 1431); EPHE 609 (= Durand, 1982, p. 34 and pl. 115); CT 55 294; GC 2 39, 277, 372; Nbn 394, 431; UCP 9 43; YOS 6 54, 112, 121.
13. See the study of this text in Joannes, 1987.

Goldsmith activities: production

The *kutimmu* mastered the techniques of sophisticated goldsmithing in order to produce the jewellery *(šukuttu)* that adorned the statues of the gods and was beyond the reach of the *nappāḫ siparri*. Again, however, there is no textual information about the way they practised goldsmithing, the tools they used or the equipment they had in their workshops. The texts tell us what they make, not how they make it. We need to be able to compare the names of jewels and parts of jewels given in the texts with what has been found in archaeological finds from this period in Mesopotamia, and to draw up an exhaustive list of the types of objects made from precious metal in order to know what techniques were used.

The divine patronage

Finally, it is worth mentioning an interesting phenomenon: the activities of temple metalworkers were linked to the patronage of the Mesopotamian god of technology and knowledge, Ea. When it came to the making of divine statues and cult artefacts in general, Mesopotamian scholars likened human craftsmen to a series of gods who personified the art being created. For example, the well-known *Sun Tablet of Sippar* (Woods, 2004) recounts the making of the cult statue of the god Šamaš in Sippar:

> "To the fashioning of that image his (= the priest Nabû-nadin-šumi) attention was directed and so, by the skill of Ea, by the craft of Ninildu, Kusibanda, Ninkurra (and) Ninzadim, with reddish gold (and) lustrous lapis-lazuli, he properly prepared the image of Šamaš, the great lord" (Woods, 2004, p. 85–86, col. iv ll. 12–21).

These are the patron gods of craftsmen: Kusibanda god of the goldwork, Ninildu, the god of carpentry, Ninkurra, a sculptor goddess, Ninzadim, a lapidary god, to whom we can add Ninagal, the divine smith, specialized in the work of copper, bronze and silverwork.

We find, then the god Kusibanda being the 'holy protector' of the goldsmiths as Ninagal is the one for the bronzers. But there seems to be no place for the ironsmiths, both because these equivalences were established at an early date, i.e. before the widespread use of iron, and because in the 1st millennium iron was not one of the noble raw materials used in worship.

CONCLUSION

What can we conclude from this brief review of the status and activities of craftsmen in Mesopotamia during the Neo-Babylonian period, based on textual documentation and in the specific context of temple archives?

Firstly, all categories of metalworkers taken together were more diverse in status than might be expected. The majority of goldsmiths, for example, were undoubtedly members of the upper classes, but there were also oblates among them who were dependent of the temples.

Secondly, metalworkers were part of the permanent staff of the temples. Whether for religious or utilitarian purposes, the temples used these craftsmen and paid them either in maintenance rations or, more rarely, in wages. By specialising some of their oblates in these activities, the temples also ensured the stability of this workforce.

The technologies used were not necessarily very sophisticated: goldsmiths and bronzesmiths seem to have mastered a number of technical aspects of their craft, but this is probably not the case for ironsmiths, who made and repaired tools with relatively simple shapes. In all cases, skills were passed on within the family. The prosopography of the craftsmen of Sippar and Uruk reveals many cases of metalworkers passing the trade from father to son.

We must therefore take into account the nature of the sources, almost all of which come from the temples: the data produced at the same time by the royal palace should be studied to see whether, in the field of weapons in particular, the palace employed ironsmiths with more sophisticated techniques than their temple counterparts. Excavations at Khorsabad and Nineveh have yielded pieces of military equipment made of iron, testifying to its importance to the Neo-Assyrian kings, and the same was undoubtedly true of the Neo-Babylonian royal arsenals. Clearly, there are still many avenues to explore in this area.

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From mould to object... The metallurgists' workshops of the Late Bronze Age in Montélimar and Aubervilliers (France)

Muriel Mélin and Éric Néré

Abstract: Places dedicated to bronze casting are mostly revealed indirectly, through material that is often very discrete, such as fragments of moulds, crucibles or tuyères, as well as rare metal waste. These objects are generally found where they were discarded. Direct traces that would indicate the precise location where the casting took place, and the work spaces related to it, remain extremely rare.
This paper highlights two particular sites from the Late Bronze Age, "Rue Saint-Denis" at Aubervilliers in Seine-Saint-Denis and "Rue du Bouquet" at Montélimar in the Drôme. Those two sites have yielded remains related to important metallurgical activities, one thanks to the exceptional preservation of cultural layers, the other through a significant quantity of clay mould remains.
At Aubervilliers, no space dedicated to casting has been located, but evidence of casting was found in a secondary position; at Montélimar, at least one casting area has been identified through concentrations of droplets of cuprous material thanks to very well-preserved layers. At Aubervilliers, the evidence of casting consists of numerous well-preserved clay moulds, a few fragments of crucibles and of a tuyère, and small metal residues. In contrast, at Montélimar, the remains of moulds are very degraded (mostly millimetre-sized fragments). The site has yielded an interesting number of copper-alloy items, among which are numerous finished objects. Some of them were destined for remelting; some may have been used on post-casting activities (punches, a chisel…). At Montélimar, the post-casting phase is also well attested by macrolithic tools. At Aubervilliers, up to three thousand fragments of clay moulds were found; it can be established that a minimum of 120 objects were produced on site, showing a certain variety (weapons, ornaments, tools) with a specialisation in pins and chapes. On both sites, the bronzesmith's workshop was probably part of a settlement.
Finally, the comparison of these two sites accentuates how the difference in the data acquired is directly linked to the differences in preservation conditions.

Keywords: craftsmanship, metallurgy, bronze workshop, copper alloy, Late Bronze Age.

Résumé : Les sites dédiés à la fonte du bronze sont le plus souvent mis en évidence de manière indirecte, grâce à des vestiges souvent très discrets, tels que des fragments de moules, de creusets ou de tuyères, ainsi que de rares déchets métalliques. Ces objets sont généralement retrouvés là où ils ont été jetés. Les traces directes permettant de localiser précisément le lieu où la fonte a eu lieu, ainsi que les espaces de travail qui y sont liés, restent extrêmement rares.
Cet article met en lumière deux sites particuliers du Bronze final, Aubervilliers, « rue Saint-Denis », Seine-Saint-Denis, et Montélimar « rue du Bouquet », Drôme, France. Ces deux sites ont livré des vestiges liés à d'importantes activités métallurgiques, l'un grâce à la conservation exceptionnelle des niveaux archéologiques, l'autre grâce à une quantité significative de vestiges de moules en argile.
À Aubervilliers, aucun espace dédié à la fonte n'a été localisé, mais des traces ont été découvertes en position secondaire ; à Montélimar, au moins une zone de fonderie a été identifiée grâce à la concentration de gouttelettes de matière cuivreuse, identification rendue possible par des couches très bien conservées. À Aubervilliers, les témoins en lien avec la fonte consistent en de nombreux moules en argile bien conservés, quelques fragments de creusets et d'une tuyère, ainsi que de petits résidus métalliques. En revanche, à Montélimar, les restes de moules sont très dégradés (principalement des fragments de l'ordre du millimètre). Le site a livré un nombre intéressant d'objets en alliage cuivreux, parmi lesquels figurent de nombreux objets finis. Certains d'entre eux étaient destinés à la refonte ; d'autres ont peut-être été utilisés pour des activités post-fonderie (poinçons, ciseaux…). À Montélimar, la phase post-coulée est également bien attestée par des outils macrolithiques. À Aubervilliers, jusqu'à trois mille fragments de moules en argile ont été trouvés ; on peut établir qu'au moins 120 objets ont été produits sur place, présentant une certaine variété (armes, parure, outils) avec une spécialisation dans les épingles et les bouterolles. Sur les deux sites, l'atelier du bronzier faisait probablement partie d'un habitat.
Enfin, la comparaison de ces deux sites met en évidence le fait que les différences observées dans les données recueillies sont directement liées aux différences de conditions de conservation.

Mots-clés : artisanat, métallurgie, atelier de bronze, alliage de cuivre, Bronze final.

Bronze Age metallurgy is mainly approached indirectly, through the study of objects which, thanks in particular to the quantities of metal diverted to become part of hoards, allow us to understand manufacturing processes. Much less is known about the actual places of production, the metal-casting areas or the post-casting areas and their links to other archaeological structures, including settlements.

While there has been a significant increase in discoveries in France relating to Bronze Age settlements over the last twenty years, linked to development-led archaeology (Lemercier et al., 2018), the same cannot be said for metallurgical production: it appears that those remains are particularly difficult to apprehend in the field.

CURRENT STATE OF KNOWLEDGE IN FRANCE

For a long time, the site of Fort Harrouard at Sorel-Moussel, Eure, has been the main reference site for Bronze Age metallurgy in France, as it provided numerous elements related to metallurgy: moulds, crucibles, tuyères, metal residues and even furnaces (Mohen and Bailloud, 1987). Over the last two decades the corpus of remains linked with metallurgy has grown, mainly for the Late Bronze Age period, although it is still very sporadic on each site, with remains often few in number and small in size. Apart from the sites of Montélimar and Aubervilliers presented here, other recent discoveries can be mentioned, in particular the sites of Ifs, Calvados, which have yielded a considerable number of clay mould fragments dating from the Late Bronze Age: from two pits at 'Object'Ifs Sud' come 593 fragments of moulds, weighing 4.4 kg (Besnard-Vauterin, 2020). Moulds used to make swords, spearheads, bracelets, among other things, were identified, representing a minimum number of individuals (MNI) of 86 objects cast on the site (Gomez de Soto in Besnard-Vauterin, 2020). In addition to those mould remains, crucible fragments (MNI = 6) and metal residues, numbering 26 including semi-finished products, were also discovered.

From slightly earlier in the Late Bronze Age than the sites of Ifs, the site of Mathieu, a BFIIIa-IIIb enclosed settlement located a dozen kilometres further north in Calvados, yielded 172 fragments of clay moulds (1.4 kg). These were used to cast weapons (swords, spearheads) and maybe tools. Other traces of metallurgy include four crucible fragments, a few metal scraps and a possible tuyère, complemented by lithic tools. These remains come from several pits and ditches (Giazzon et al., forthcoming).

While archaeological indicators of metal casting are recurrent, they remain erratic on each site and unstructured: they are essentially movable (moulds, crucibles, etc.), tenuous (even when fragments of moulds are numerous, this rarely if ever allows the restitution of complete valves) and often poorly preserved (subject to weathering). As for metal remains like casting jets or miscasts, they could be easily remelted and are less frequent. Thus, if fragments of moulds, of crucibles, metal residues or tuyères are regularly discovered, excavations more rarely provide a combination of all. Moreover, these are often the only clues to metalworking activity on the sites and they are mainly recovered dispersed in refuse pits, and not in a structured way. As with many other crafting activities, related archaeological structures, impacts in the ground, are extremely rare. On the other hand, lithic studies and analyses can sometimes help to determine whether casting and/or metalworking was carried out on a site, or even bring it to light where there is no mould or crucible to do so (Hamon et al. 2021; Hamon and Delgado-Raack, this volume).

Evidence of furnaces or melting hearths, and thus precise locations of the casting works, are virtually non-existent. A very recent discovery is worth mentioning: the site of Saint-Avé (Morbihan), where the remains of a furnace have been unearthed, in association with a construction on posts. The few, rare associated remains (tuyère fragments, a mould fragment) suggest that this was a bronzesmith's furnace, as does the presence nearby of 12 copper-alloy objects grouped together in a small pit, as a hoard, which can, in this context, be considered a metal reserve (Blanchet, 2026).

The bronzesmith's workshop therefore remains difficult to grasp in France. These observations are also valid on a wider scale, as can be seen from the European overview recently produced by B. Molloy and M. Mödlinger (2020).

Two recent discoveries, which are exceptional in terms of their degree of preservation, help to explain why this production remains so elusive (Mélin and Néré, 2021). These are two Late Bronze Age sites (fig. 1): one in the Paris region, at Aubervilliers, Seine-Saint-Denis, dated to the second stage of LBA or BF IIb–IIIa (Ha A2–B1), and the other in the Rhône valley at Montélimar, Drôme, dated to BF IIa (Ha A1).

AUBERVILLIERS

Context

The site of "Rue Saint-Denis" in Aubervilliers was first revealed in 2008 by an evaluation/*diagnostic* (Caparros et al., 2010). The subsequent excavation was then carried out in 2014 over an area of around 8,000 m² by Arkemine (Mélin, 2016). Two distinct loci comprising traces of metallurgical activity were identified (Mélin et al., 2017): the one we present here is attributed to the second stage of the Late Bronze Age (ca. 1150–950 BC), possibly more precisely to the BF IIIa (Ha B1) considering the associated ceramics, while the second includes structures dated to the Late Bronze Age/Early Iron Age transition (fig. 2). These two loci with metallurgical installations seem to be directly linked to the presence in the subsoil of pockets

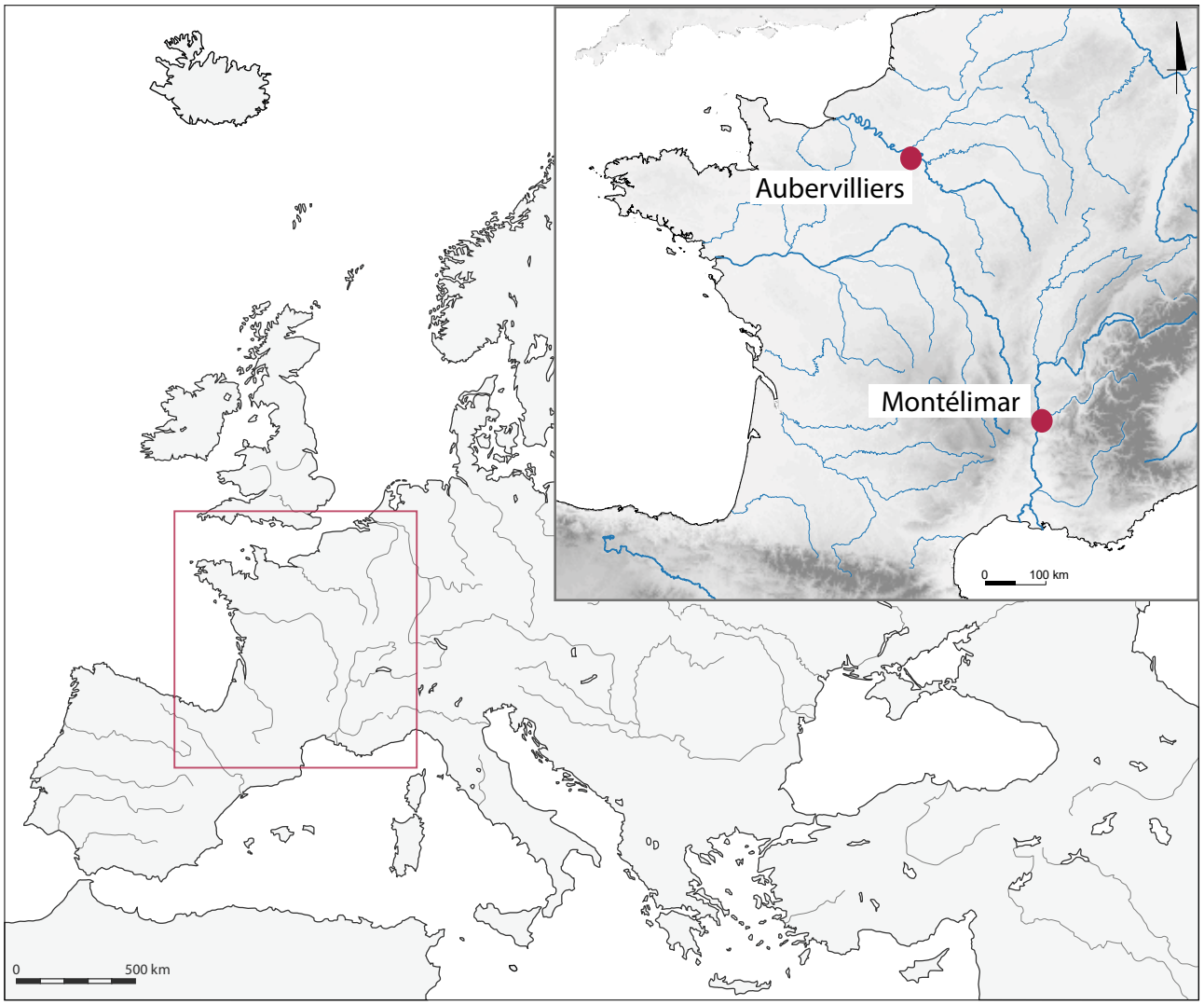


Fig. 1 – Location of the sites of Aubervilliers, "Rue Saint-Denis", Seine-Saint-Denis, France, and Montélimar, "Rue du Bouquet", Drôme, France (CAD M. Mélin).

of sand and clay, two constituents necessary for the manufacture of clay moulds. Tests on raw materials present on the site and petrographic analyses carried out on the moulds and crucibles point in this direction (Mélin et al., 2020).

The features

The first locus saw a great deal of metallurgical activity, as evidenced by the abundant and relatively well-preserved clay moulds, which were found discarded into pits. The typology of the metal artefacts cast on site is typical of the second stage of the Late Bronze Age.

There are no features directly linked to casting, no soil levels and no hearths or furnaces. The structures associated with the metallurgical remains are extraction pits and/or silos that have been reused as dumping grounds. Close to these are two or three small buildings on posts (one of which has been truncated by recent excavation: see fig. 2). The contemporaneity of these with the workshop, if possible, is not certain (Mélin et al., 2020).

The pits in which the evidence of metallurgical activity was found also included ceramic sherds, faunal remains common to settlement sites, fragments of lithic macro-tools and loom weights; the assemblage thus bears witness to activities other than the production of metal objects alone. The presence of four bronze objects, only one of which seems to be linked to the castings made on site (see below), a fragment of glass bead and a fragment of a lignite bracelet also illustrate other aspects of daily life and a certain status for the site.

Although the actual location of the casting place(s) is not known, the nature and concentration of the remains suggest its presence in the immediate vicinity. Traces of hearths can be particularly fleeting; at Aubervilliers, numerous modern disturbances in several places on the site easily obliterated them. The Aubervilliers workshop can therefore only be seen through the remains it left behind. These remains, linked to the foundry work carried out on the site, consist of a large number of clay mould fragments, crucibles, tuyères and metal residues.

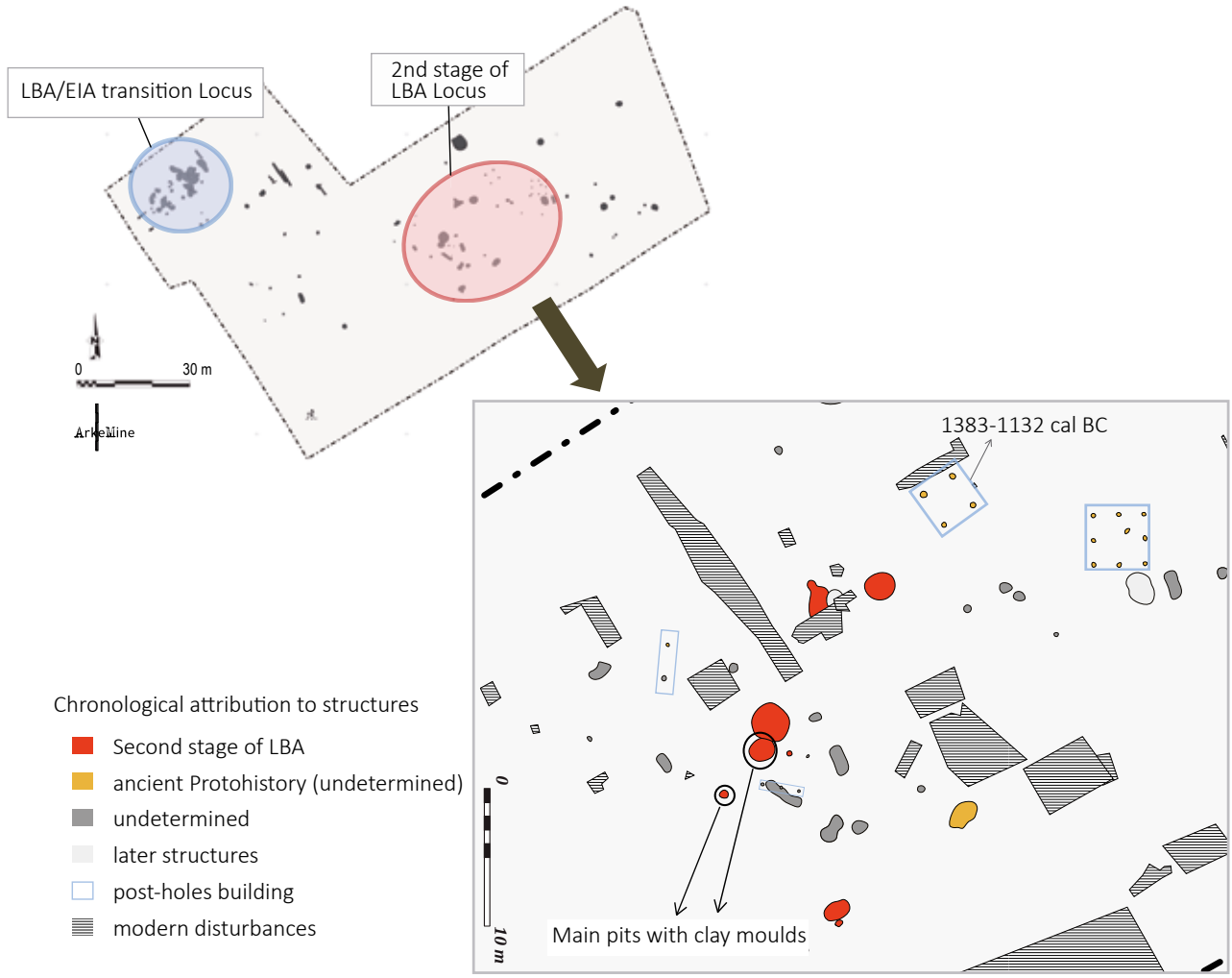


Fig. 2 – Aubervilliers, "Rue Saint-Denis". Plan of the excavation with the two protohistoric bronze metallurgy loci. Focus on the workshop area dated to the second stage of the Late Bronze Age: French BF IIb-IIIa (CAD Arkemine and M. Mélin).

Ceramic remains

Numerous clay moulds

Almost 3,000 fragments of moulds made exclusively of clay, weighing over 10 kg, were found, scattered across 7 structures, including one in particular, a large silo-type structure whose stratified filling included heaps of moulds (Mélin et al., 2020, fig. 3). These figures are particularly significant compared with what is known elsewhere in France, such as at Fort Harrouard in Sorel-Moussel or at the site of Ifs mentioned above. The preservation environment has enabled these elements to be preserved in such a way that a fairly large number of objects produced on the site can be identified (around 30 % identified). This also makes it easier to establish the minimum number of objects cast on the site: over 120 objects were made in the Aubervilliers workshop (table 1).
A variety of artefacts were produced (fig. 3), but two in particular were made several times, some in series (Mélin et al., 2020): at least 80 nail-headed pins (pins of the same type were produced at Fort Harrouard), at least 16 lozenge-section chapes, small hemispherical-headed nails, two spearheads, one or two swords, a possible sickle, as well as many other items not precisely identified. The objects produced here are of typically Atlantic affinities (Mélin et al., 2020).

Other ceramic remains

The other clay remains, which are much less numerous, consist of highly fragmented remains of crucibles, recognisable by their scorified appearance and their coarser paste than that of the moulds (NR = 21, for a weight of 99 g). Unfortunately, it is not possible to estimate the volume of metal originally contained in those crucibles from these small preserved parts. Fragments of a *tuyère* were also discovered in the same levels (fig. 4).

Copper-alloy remains

Metal waste

The residues, droplets and other shapeless metal waste, are few in number, 19 elements, and very small in size and weight: around 8 g, to which must be added a few

Aubervilliers « Rue Saint-Denis » clay moulds	Number of rest	Minimal number of individuals
Ornaments		
Pins	422	**80**
Weapons		
Chapes	299	**16**
Spearheads	30	**2**
Swords	9 ?	**2 ?**
Tools		
Sickle ?	1	**1**
Other		
Small nails	13	**18**
Object decorated with concentric circles	10	**1**
Others (funnel…) and undetermined	2214	**-**
Total	**2998**	**120**

Table 1 – Aubervilliers, "Rue Saint-Denis". Determination, number of remains and minimum number of individuals of the clay moulds found at locus 2 (M. Mélin).

miscast pieces still caught in moulds (fig. 4). No casting jets were found.

Compositional analyses[1] carried out on 13 samples (metal waste and objects) at the Laboratoire Iramat d'Orléans (Arles in Mélin, 2016; Mélin et al. 2020) show that the metal used at Aubervilliers was a ternary alloy, a lead bronze, which began to circulate from this second stage of the Late Bronze Age in Atlantic metallurgy (Northover, 1982; Briard, 1988, fig. 5). Similar alloys were used at the contemporary site of Fort Harrouard (Queixalos et al., 1987). Interestingly, in Aubervilliers, there are differences between the recipes for the alloys used at the BF IIIa locus and the Late Bronze Age/Early Iron Age locus (much lower level of impurities, no deliberate addition of lead for the latter), potentially indicating different raw materials. One particularly interesting small metal residue from the BF IIIa locus is a centimetre-sized piece of a Pb/Sn alloy, with over 70 % lead (fig. 5). Such lead-tin alloys were also found at the Late Bronze Age Swiss site of Hauterive-Champréveyre, in the form of rings and wires (Rychner-Faraggi, 1993, p. 21 and 57); tin was dominant in this case. It is difficult to know the nature and role of this residue, but it is consistent with the alloy used on the site at this time, which included an addition of lead. It could be a clue to the form in which the metals used in the alloy were transported (in small, pre-alloyed pieces) and to the way in which these alloys were made.

1. Analyses were carried out at Orléans, Centre Ernest Babelon by Laser ablation inductively coupled plasma mass spectrometry (LA-HR-ICP-MS).

Bronze objects

Four copper-alloy objects were collected during the excavation, a pendant, a gouge and two pins; three of them were found in a large pit and one pin was found in another pit among remains of moulds. Only the latter is directly linked to the workshop: a pin with a nail head, the type of which corresponds to that cast on numerous occasions on the site and the alloy of which is similar to that found in the metal remains from the workshop, unlike the other three objects. In the case of those other three objects, no moulds were found that could correspond to these products. The second pin does not belong to the type with a nail head melted on the site; its different alloy (without added lead, and containing different trace elements) also suggests that it should not be linked to the production at Aubervilliers, but rather to the domestic occupation of the site.

MONTÉLIMAR

Located in the Rhône Valley, commune of Montélimar, the "Rue du Bouquet" excavation was carried out between April and November 2015, covering an area of 8,000 m². The site, largely stratified, corresponds to different levels of a multi-phase settlement with occupations ranging from the Middle Neolithic to Antiquity. A number of areas were selected for detailed excavation, covering a total surface area of 800 m², and yielding over 16,000 finds (ceramics, fauna, macro-lithics, flint, bronze). Two particular

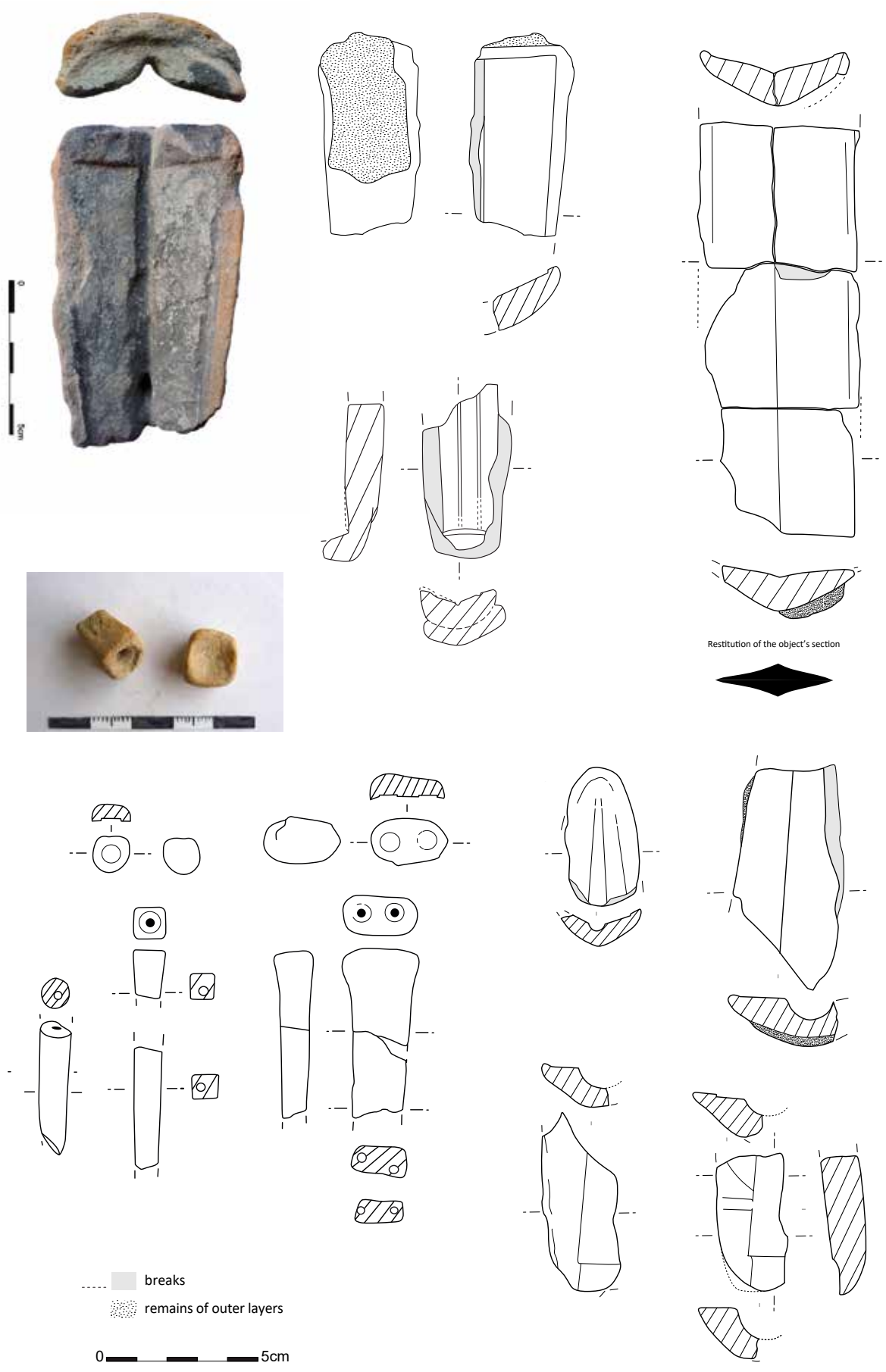


Fig. 3 – Aubervilliers, "Rue Saint-Denis". Selection of fragments of clay moulds used to cast chapes, pins, swords and spearheads (photos and CAD M. Mélin).

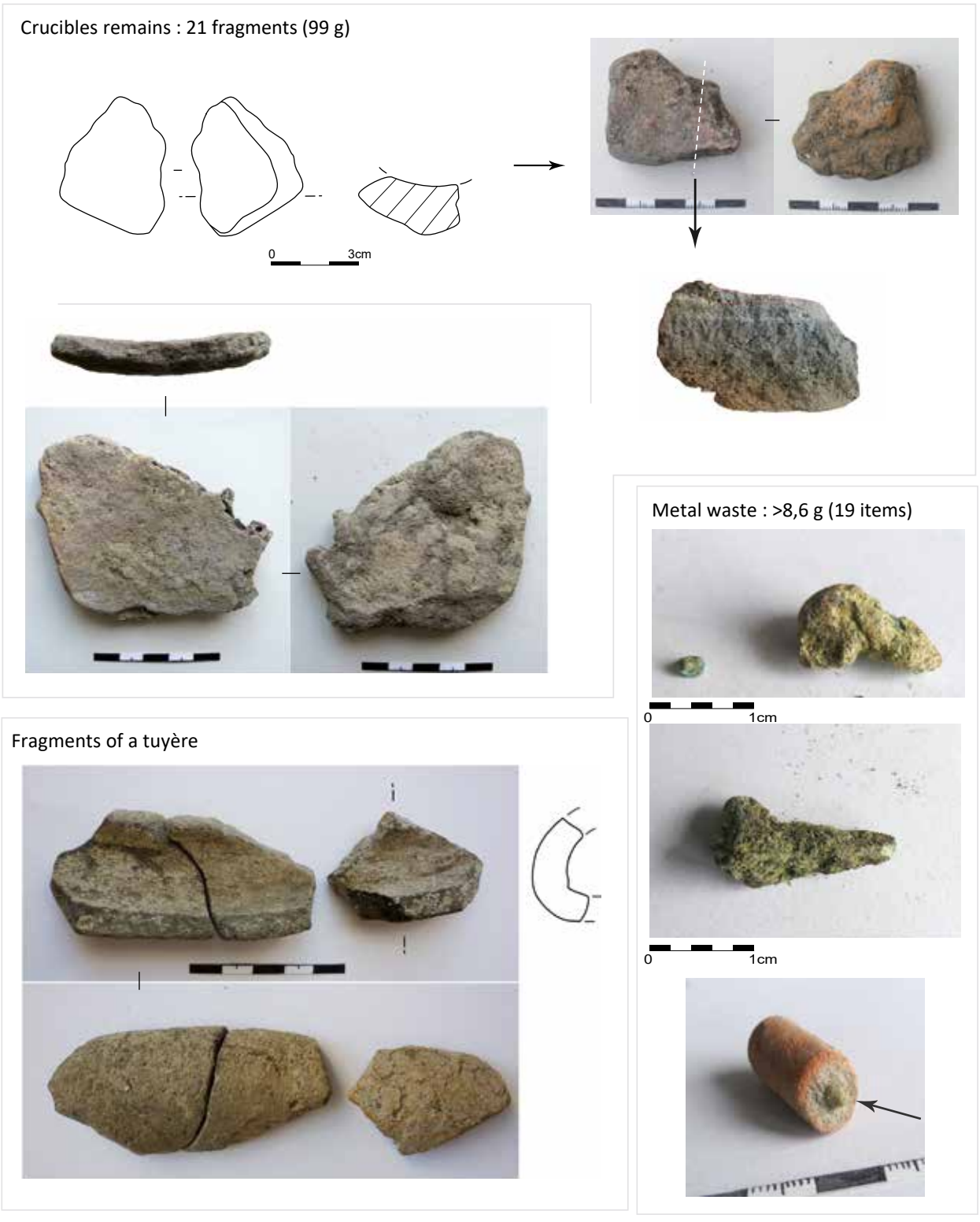


Fig. 4 (up) – Aubervilliers, "Rue Saint-Denis". Fragments of crucibles, copper-alloy remains and fragments of a *tuyère* (photos and CAD M. Mélin).



Fig. 5 (left) – Aubervilliers, "Rue Saint-Denis". Small metallic piece composed of a lead-tin alloy (photo M. Mélin).

areas illustrate the site's remarkable degree of preservation, one of which contained a bronzesmith's workshop. To the south-west of the site (fig. 6), a floor level dated by ceramics and bronze artefacts to Hallstatt A1 yielded numerous objects that reveal a work area devoted to the production of copper-alloy objects (fig. 6). This in situ discovery of identifiable evidence of a "bronzesmith's workshop" is exceptional. However, without careful conservation of these levels and an extensive and appropriate excavation protocol, this workshop could not have been studied.

General excavation protocol

In order to fully understand how this workshop was studied, we felt it important to return to an overview of the excavation protocol we implemented, without going into detail as we have already done (Néré et al., 2016). Three levels of survey were defined in order to preserve as much information as possible within the time constraints imposed by preventive archaeology.

1) Once mechanical stripping had been completed, the entire area was manually cleaned in 5 to 10 cm layers to reach the highest soil level densities. Each find thus identified was recorded, labelled, sampled and topographed. In all, just under 16,500 artefacts (notated PI for « Pièces Isolées ») were georeferenced, covering an area of 750 m², or more than 9 % of the total right-of-way. The workshop area alone accounts for almost 500 m² of this total.

The presence of numerous copper-alloy objects and remains, as well as the discovery of a large ceramic frag-

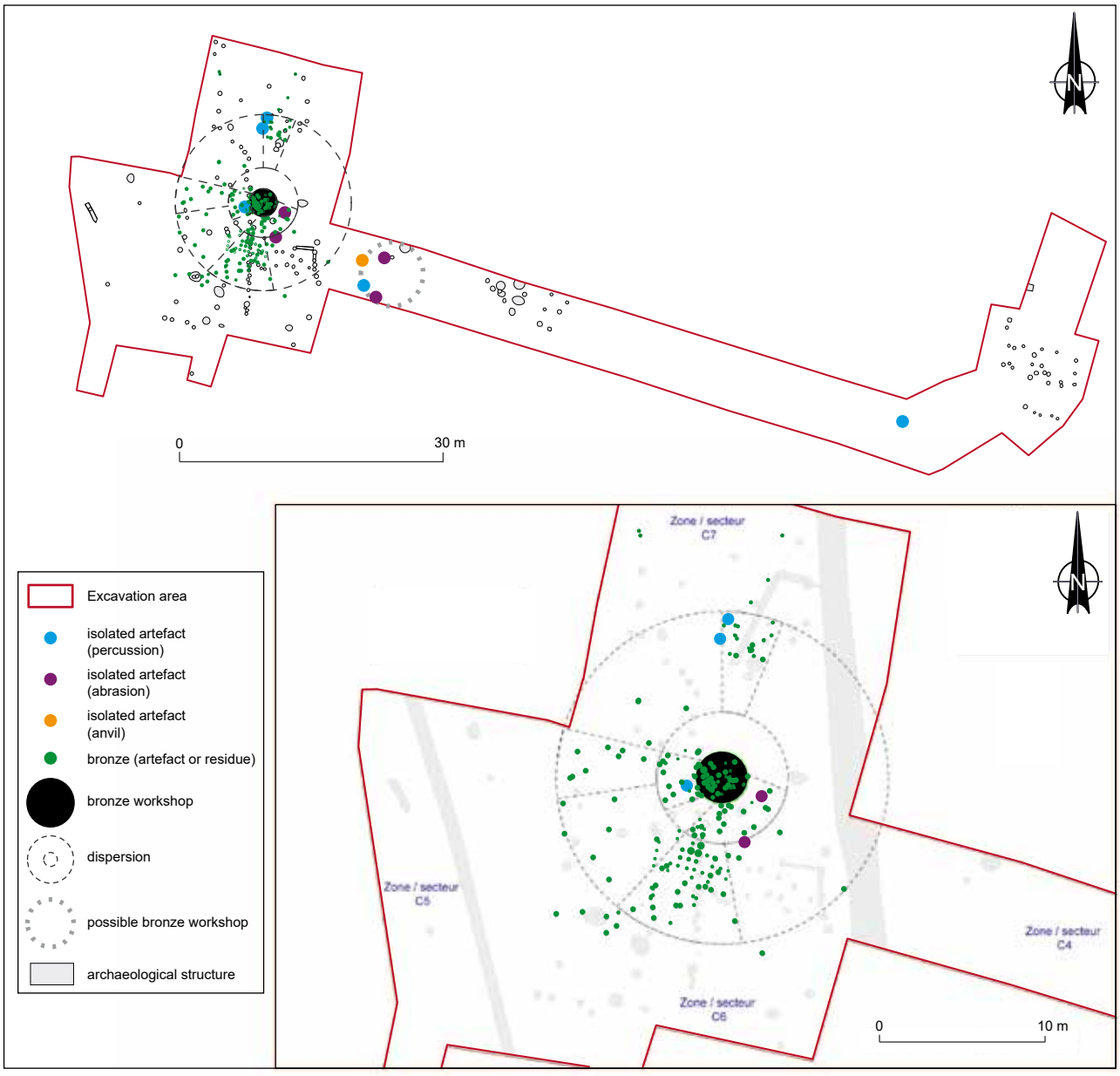


Fig. 6 – Montélimar, "Rue du Bouquet". Plan of the area and detail plan of the Late Bronze Age (Bronze final IIa) bronze workshop (CAD F. Notier, Inrap).

ment with traces of copper (PI 1246 and 1247, Néré, 2017), were the first indications of the presence of a bronze-related metallurgical workshop. The over-representation of wood charcoal compared with other sectors gave further weight to this hypothesis. It was then decided to reinforce the basic protocol. For this reason, a grid was set up in this sector.

2) An orthophotographic survey was carried out using a gantry crane, using the grid to correct for distortion due to the focal length of the lens. Soil levels were then drawn from this survey.

3) A flotation/sieving station was set up next to the area during excavation: sediment samples were taken in quarter-m² increments, based on this grid, over the equivalent of layers 2 and 3 (from 5 to 20 cm amplitude), notably around PI 1246 and 1247. They were processed in the field by flotation (to obtain charcoal for anthracological analysis) and sieving (to obtain rejects linked to metallurgical activity and to collect snails for malacological study and seeds for carpological analysis).

4) Additional surveys were attempted, such as an archaeomagnetic survey, but the results proved negative, as the methods used detected nothing, which in itself is an important result: the workshop is not detectable by archaeomagnetism (Hulin in Néré, 2017).

Copper-alloy remains

Of the 9,000 objects recovered from the area, 119 copper-alloy remains were found, with 217 casting elements for a total mass of around 460 grams (Nordez in Néré, 2017). Table 2 shows the distribution of copper-alloy elements within the various object categories identified. 79 fragments were identified, excluding shapeless residues, foundry waste and unidentified fragments. The Minimum number of individuals (MNI) is 65 items.

	Montélimar "Rue du Bouquet"		
	Number of rest	**Minimal number of individuals**	**Weight (g)**
Ornament and clothing	40	33	232
Pins	21	11	206
Annular ornaments	9	6	14
Pendant	3	3	3
Pearl	1	1	4
Belt buckle	1	1	3
Buttons	2	2	2
Toiletries	1	1	2
Razors	1	1	2
Tools	15	11	61
Sickles	3	1	31
Chisels/ Punches	12	10	30
Weapons	2	2	5
Arrowheads	2	2	5
Rings	21	18	36
Others	42		25
Foundery	215		92
Cast residues	2		3
Total	**335**	**65**	**451**

Table 2 – Montélimar, "Rue du Bouquet". Inventory of metal remains by functional category according to number of remains (NR), minimum number of individuals (MNI) and mass in grams (M. Nordez, CNRS).

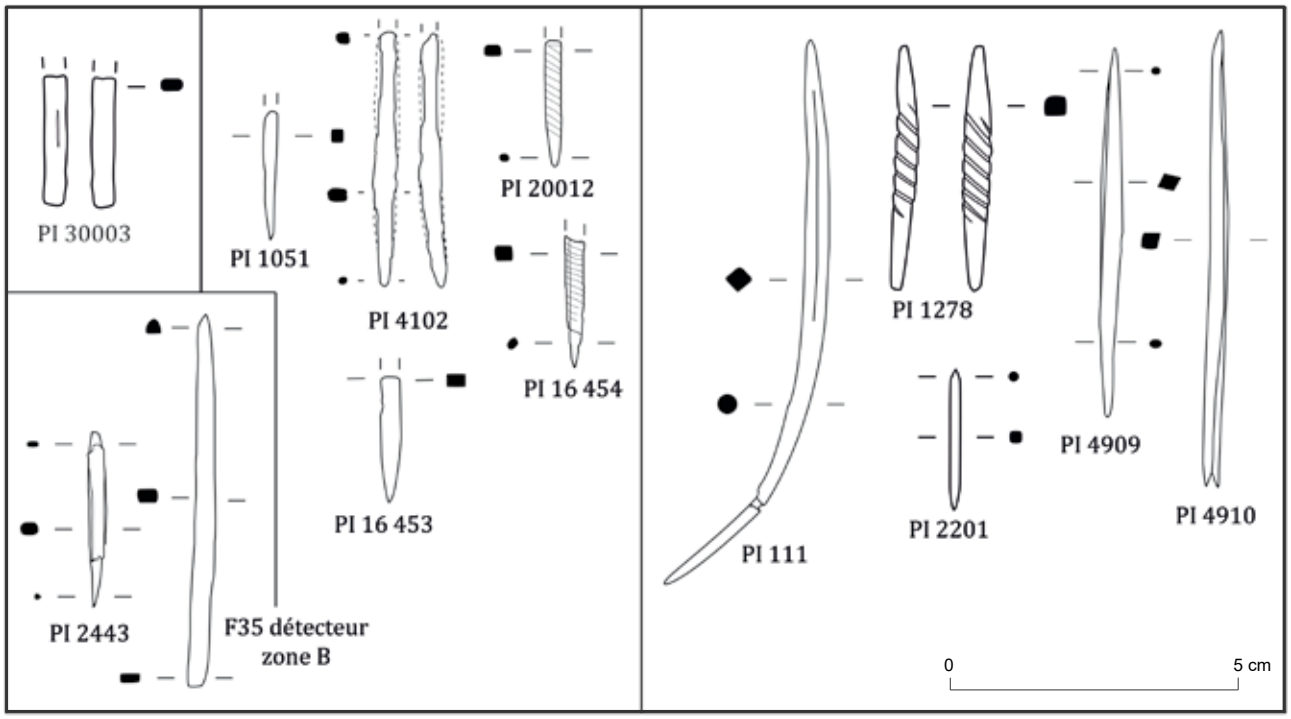


Fig. 7 – Montélimar, "Rue du Bouquet". Drawings of part of the workshop's copper-alloy tools (Drawings M. Nordez, CNRS).

Tools

Many of the bronze tools are related to metallurgical activity, but we cannot exclude wood, textile, bone and ceramic crafts either. Ten punches and chisels (NR = 12) of various shapes and sizes may have been used in the workshop (fig. 7). The active ends of these tools are badly weathered, severely limiting traceological observations.

Three sickle fragments, which may initially have belonged to the same object though this cannot be confirmed, were scattered around the site: one is a point, another is a blade with a rib but no preserved edges, and the third is a handle and knob.

Rings

Rings (fig. 8), which are also well represented (21 fragments for an MNI of 18 individuals), are considered here as a category in their own right: they may be suspension or belt elements, but also semi-finished products used in exchange or raw material reserves. These last two hypotheses are quite attractive at Montélimar: in fact, the rings are on the whole quite irregular, sometimes unfinished, or even found in the form of half-rings (incomplete rings on which no break is visible). At the contemporary site of Hauterive-Champréveyres, Switzerland, seven rings were made not of bronze but of copper or pure tin, or a tin-lead alloy with tin predominating (Rychner-Faraggi, 1993, p. 57). While there are many possible explanations for these particular alloys, the possibility of raw material reserves is quite tempting. However, as analyses are still in progress on the objects and foundry residues from Montélimar, we cannot go any further into these considerations.

Ceramic fragments

The locations of ceramic fragments do not form a visible concentration around a single point, but rather a heterogeneous coating over the entire area. However, given the density of metal finds, we have studied in detail the ceramic fragments that may relate to metallurgy, and more specifically to casting. A few fragments of objects bear direct witness to this activity. Firstly, there is a ceramic conglomerate mixed with evidence of copper castings located in the centre of the workshop. Secondly, at least one fragment of a crucible handle has been identified. It is made of fairly fine ceramic and was manufactured for



Fig. 8 – Montélimar, "Rue du Bouquet". Pre-study photograph of part of the rings in the bronze workshop area (photo F. Notier, Inrap).



Fig. 9 – Montélimar, "Rue du Bouquet". Photograph of a *tuyère* (photo F. Notier, Inrap).

this activity alone. Next, the longitudinal half of a *tuyère* (7 cm long and 4 cm in diameter) was found (fig. 9). One of these ends is badly altered by the object's close proximity to the fire. It must have been moulded directly on the rod into which the founder blew. Finally, several ceramic objects show traces of overheating with regular shapes showing that they are crucible fragments. Several of these small fragments have trapped droplets of copper alloys. The ceramic is partly vitrified, due to the very violent temperature rises. A possible fragment of mould can be added, on which three fine, elongated parallel hollows can be discerned (fig. 10). The nature of the object produced remains difficult to determine given the modest size of the fragment (a sickle?).



Fig. 10 – Montélimar, "Rue du Bouquet". Fragment of a clay mould (photo F. Notier, Inrap).

The stone tools of a bronze maker

Tools from outside the workshop

Stone tools clearly distinguish the two types of contemporary occupations within the site (Cousseran-Néré in Néré, 2017): for example, there are numerous finds related to milling associated with domestic areas. Thanks to the preserved ground level, it can be seen that milling elements are systematically close to buildings. In one case, the mill is located close to a building, but also in a work area, perhaps a courtyard associated with numerous seeds and fragments of charred flatbreads.

Workshop tools

Other objects amongst the lithic tools highlight specific metallurgy-related equipment (Cousseran-Néré et al., 2020), outside the settlement but only a few dozen metres from it. Whether it's the different types of percussion tools, striking supports or abrasive tools, we can see that the objects studied are specific and that they are concentrated around the observed combustion zone, in association with objects made of copper alloys, and that they enable us to trace a real *chaîne opératoire*.

We also note that, more than the raw material, it is the specific granulometry of the various elements that distinguishes this corpus and seems to have guided the choice of Bronze Age craftsmen.

As far as shapes are concerned, the tools used for percussion are completely different from those used for the plastic deformation of metals (brasswork or goldsmithery), as they appear in the Génelard hoard (Cousseran-Néré et al., 2020), for example. This is not very surprising, since plastic deformation of sheet metal seems to have been fairly limited, if not non-existent, in Montélimar: several striking supports of different sizes have been identified, but they are small.

Polishing tools

Use-wear analysis shows that seven tools may have been used for post-casting abrasion or abrasive finishing of bronze objects. Their shape varies from quadrangular to triangular to circular (fig. 11).

Three groups of abrasive tools can be distinguished. This classification is independent of part morphometry. It takes into account only the granulometry of the rocks used to support the objects. All rocks have a grainy texture, ranging from very fine to coarse. A fine-grained rock is more likely to be used to finish the object at the end of the casting process, or to maintain metal blades, while a coarser rock is more likely to be used for deburring at the end of the mould. Abrasive tools are quite common on Bronze Age sites (Hamon and Blanchet, 2015) and are therefore directly linked to the development of metallurgy and the use of metal objects.

Striking supports (anvils)

Probably linked to this activity, two striking supports were found in the workshop floor level, along with a limestone chip, probably detached from another striking support. The first is a small, whole tool fashioned from a block of white limestone (fig. 12), marked by sparse,

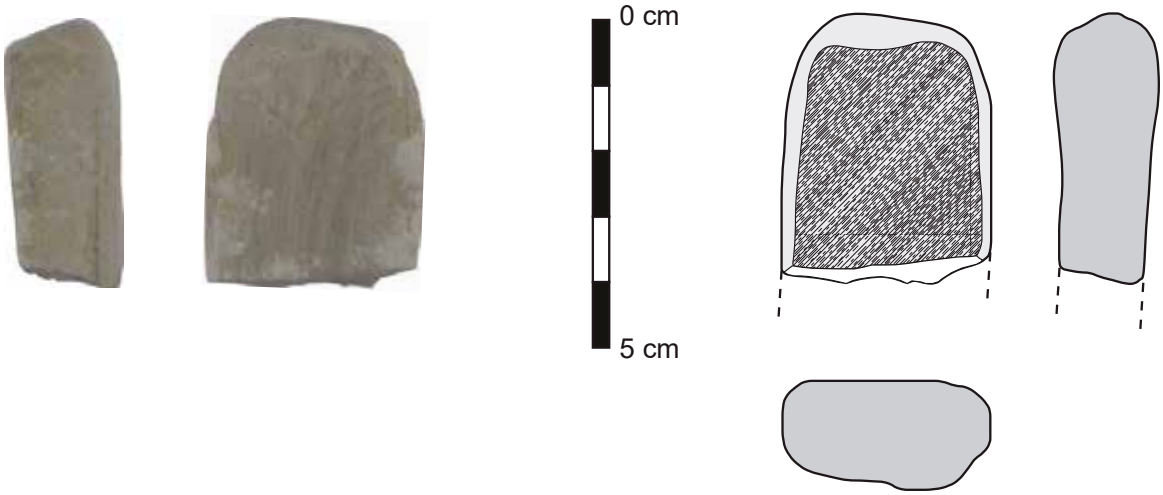


Fig. 11 – Montélimar, "Rue du Bouquet". Photograph and drawing of a polisher from the workshop (photos S. Cousseran-Néré, drawings L. Boutoille and S. Cousseran-Néré, Inrap).



Fig. 12 – Montélimar, "Rue du Bouquet". Photograph of an anvil from the workshop (photo S. Cousseran-Néré, Inrap).



Fig. 13 – Montélimar, "Rue du Bouquet". Hammerstone from the workshop (photo S. Cousseran-Néré, Inrap).

random micro-percussion marks characteristic of a striking support. This small artefact was probably used as a striking support for two small bronze objects (e.g. rods or pins) shaped with a percussion tool (see above). The second is a fine sandstone striking support angle, larger than the first. Quadrangular in shape, it is concave on one side. This working surface has a uniformly smooth surface. Lastly, a small chip probably produced by hitting a striker on an anvil, from which it would have originated, was found in the area of the bronzesmith's workshop.

Hammers

Hammers from Montélimar can be divided into 4 defined types (Cousseran-Néré et al., 2020). Type III (fig. 13), in particular, may be characteristic of these bronze workshops. It stands out from the other hammerstones observed to date in this geographical area. Three Type III firing pins were found in the workshop and four more in the rest of the excavation (table 3). Their loca-

Montélimar "Rue du Bouquet"	
Lithic artefacts	
Percussive tools	14
Anvils	2
Abrasive tools	7
Undetermined	1

Table 3 – Montélimar, "Rue du Bouquet". Inventory of lithic tools by functional category (S. Cousseran-Néré, Inrap).

tion—outside the workshop identified in a soil level also attributed to Hallstatt A1, and found near several larger bronze drops and casting elements, or, in another area, near well-dated bronze objects—suggests that the metalworker's workshop extended beyond the area originally identified, marking several work zones. This not only supports the hypothesis of discriminating tools with a specific function in one of the stages of the bronze production chain, but also demonstrates that the site certainly included several bronze workshops outside the prescription zone.

Several workshops in one area

As we have suggested, it is highly probable that the workshop excavated in detail was not isolated, but belonged to a group of small workshops located in the midst of settlements (several houses were identified—fig. 6). At least two other workshops in the excavation area are more than likely. But others seem to be possible in the area, as suggested by nearby archaeological operations, evaluations not followed by excavations as here. These include the large evaluation operation directly to the west (Vermeuleen et al., 2006), which yielded traces of bronze castings and fragments of objects in two areas, and the operation 100 m to the northwest, which once again uncovered a fragment of a cut-out pin (Néré, 2017). In all, this represents 5 locations outside the excavated workshop, at least 3 of which make it easy to imagine other work areas.

COMPARISON OF THE TWO SITES

Due to their different preservation conditions, these two Late Bronze Age sites show a number of differences (table 4).

Soils

At Aubervilliers, no stratigraphy was preserved, unlike at Montélimar. At Montélimar, in the absence of the preserved occupational floor it would not have been possible to identify the workshop at all, as there are virtually no excavated structures apart from postholes: all the remains were found on the ground level (Néré, 2017). The site would have been recognised as a Late Bronze Age settlement, but the metal production aspect would have been impossible to see. This finding is extremely important to emphasise because generally none of the sites with metallurgical remains have preserved occupational floors, and only a few significant remains are found in hollow structures mixed with domestic material, as is the case at Aubervilliers. This clearly demonstrates the fleeting nature of the structures left behind by the bronze workshops.

Casting hearths

At Aubervilliers, no space dedicated to casting has been found; at Montélimar, at least one casting area has been identified. In the very well-preserved soils, concentrations of droplets of cuprous material have made it possible to locate the work 'centre' from very discrete traces. In the case of Montélimar, contrary to the proposals of Michel Pernot (1998), this space dedicated to the foundry was not located inside a building, but outside, albeit well sheltered along a palisade. Similarly, no pit was dug to install the hearth, which must have been on the ground, and most of the remains of this work area have disappeared, easily washed away by the weather.
Experiments show that a simple flat hearth is sufficient to bring the alloy up to the required temperature and, if it is not used many times, it will leave very little mark on the ground. The hearth could be more 'constructed' and delimited by stones, as proposed at Fort Harrouard (Mohen and Bailloud, 1987, p. 128, fig. 70). The case of Montélimar confirms that the probability of finding the actual location of the casting remains low, even under favourable conditions.

Evidence of casting

At Aubervilliers, evidence of casting predominates, although found in a secondary position. It can be presupposed that the casting was located in the immediate vicinity, in a place destroyed by modern excavations noticed on site. The finds consist mainly of fragments of clay moulds, together with a few small fragments of crucibles and a tuyère. The very small metal residues are also undeniable evidence of casting activity. However, of the four bronze artefacts found on site, three do not seem to be linked to casting activity per se, as seen through composition analysis of the metal and the differences observed with the moulds.

At Montélimar, these casting indicators are elusive; several hundred fragments of clay have been discovered, but they are usually millimetre-sized and only one large crucible fragment has been found. Slag (as in vitrified

Type of remains	Aubervilliers	Montélimar
Furnaces	-	-
Workshop floor	-	+
Moulds	+++	+
Crucibles	+	+
Tuyères	+	+
Metal residue	+	+++
Lithic tools	-	++

Table 4 – Comparison of metallurgical remains between the sites of Aubervilliers and Montélimar (M. Mélin and E. Néré).

clay), which is more abundant, is associated with several hundred droplets. A fragment of a tuyère was found in the immediate vicinity of the workshop. Many of the bronze rings and fragments of rings found in the same area may have been used as raw material for remelting, and the conglomerate of clay and mixed copper droplets found in the centre of the area may correspond to the heart of the melting zone.

Evidence of post-casting working

At Montélimar, the post-casting phase is well attested and is mainly represented by macrolithic tools: polishers, hammers and anvils make up a whole range of stone objects used for plastic deformation work. The corpus of tools from Montélimar contrasts with that found at Génelard, and there are very few tools in common between the two groups. The famous Late Bronze Age hoard find of Génelard contains numerous bronze and stone tools for fine metalwork. Being a collection of objects selected for their symbolic aspects, no doubt, but also for their preciousness, their specificity, these are not objects abandoned or deposited at random (Thevenot, 1998). One could almost say the opposite of the Montélimar objects, because even if the technical investment is certain, for example in the case of the hammers, most of the objects (the polishers, for example) are little invested, they come from simple pickings. These are undoubtedly the 'everyday' objects used by the craftsmen, providing evidence of part of the bronze-making process, but it is certain that the more sophisticated tools were not abandoned on site. The only objects in common with Génelard are punches and other small finishing tools made of copper alloys. Those from Montélimar, which are very worn, are abandoned objects that are of little or no use. It is still difficult to confirm that all the stages of bronze working were carried out here; that of removal of the excess of metal (flashing and casting jets) and that of primary hammering were carried out on site, as shown by the lithic tools, but also by the fragments of casting jets, and other casting elements made of copper materials. Anvils also confirm the existence of this phase.

Finished objects are present on the site, sometimes fragmented (which suggests remelting), but sometimes whole, although it is difficult to know, with rare exceptions, which objects were made on site.

At Aubervilliers, anvils and polishers are missing, but some lithic tools could have been used as hammers; post-casting work may have been carried out on the site, following the opening of the moulds. No finished objects have been found: the pin that was potentially produced on site is whole and does not appear to be in a finished state. However, it is difficult to be certain given the preservation of the metal.

Artefacts from the workshop

At Montélimar, there are many finished objects, but the lack of unity makes it impossible to know whether they all came from the on-site workshops or whether they were destined for remelting. Apart from the large number of rings, there are few identifiable objects, and for the former, there is a strong probability that they were indeed there as raw material: their cutting into halves or quarters suggests this.

The only well-identified objects that may have been cast in Montélimar are the alpine-type sickles. In addition to three parts of their blade, a casting jet and two fragments of clay moulds (very degraded) relating to this type of object were discovered. A large whole pin with a flat conical head, found in another area, combined with numerous traces of a probable other workshop, seems to indicate that pins of this type may have been cast here. Shortly after the excavation, an identical pin was found a few kilometres further north, in Loriol, Drôme, in a cremation burial, confirming their probable local origin (Gaillard, 2020). As well as objects made from copper-based materials, it seems that gold objects were also cast in the same workshop, as evidenced by a fragment of a small plate found in the same area.

Unlike Montélimar, production at Aubervilliers was identified mainly on negatives of clay moulds. This production shows a certain variety (weapons, ornaments, tools), even if a specialisation in pins and chapes can be established (Mélin et al., 2020). There are objects of various sizes (from swords to nails), as well as a variety of casting techniques (cluster casting, for example). It has been noticed that for the same nail-headed pin shape, several types of moulds have been implemented. Analyses of the composition of residue alloys and castings have also revealed that a similar recipe (a ternary alloy) was used to cast these objects.

Context of the workshop

At Aubervilliers, as at Montélimar, the bronzesmith's workshop was probably part of a settlement. The domestic nature of the associated remains and the possible presence of two or even three buildings support this view. The site of Aubervilliers is neither fortified nor in a high position, contrary to the models proposed on the basis of the rare sites that provided such evidence in northern France: Fort Harrouard (Mohen and Bailloud, 1987), Caesar's Camp at Catenoy, Oise (Blanchet and Talon, 1987) or Saint-Pierre-en-Chastre, Oise (Blanchet, 1984) in particular. The 'exclusive role that has often been attributed to fortified hilltop sites in the production and distribution of bronze objects during the Late Bronze Age' (Delrieu, 2013, p. 144) therefore needs to be nuanced.

Despite the lack of ore in the Paris Basin, the Aubervilliers site was able to acquire metals (copper, tin and lead) through its trading network. In Montélimar, there were many regional sources of supply: there were numerous copper mines in the Alps, and the Rhône Valley traffic routes made it easy to obtain supplies. Initial physico-chemical analyses (study by C. Le Carlier in Néré, 2017) have shown that some of the copper came from the mines at Saint-Véran in the Queyras (Hautes-Alpes), which is almost 200 km away

but easily accessible via the valleys leading into the Rhône valley, directly to Montélimar.

CONCLUSION

The information on the bronze workshops identified from the two sites presented is varied. Firstly, the data acquired is directly linked to the differences in preservation conditions between the two sites: the site of Aubervilliers benefits from very good preservation of the moulds, making it possible to estimate production in detail and determine an MNI, an essential element for subsequent inter-site comparisons. This is rarely possible due to the rapid deterioration of fragments after unmoulding, as is the case at Montélimar. On the other hand, the preservation of the occupational level at the Montélimar site made it possible to spatialise various elements linked to metallurgy, and thus to estimate the location of a casting place, which is rarely recognised.

On any excavation, the archaeologist is extremely dependent on the conditions in which the remains are preserved, and the recognition of metallurgical activity is particularly subject to this. Such activity remains truly fleeting in the Bronze Age, no doubt because it is not yet structured in the way that will be seen in the historical periods (at Autun or Bibracte, for example: Chardron-Picault and Pernot, 1999; Duval et al., 1991). It is common for a single element to be indicative of metallurgical activity (a fragment of a crucible, a tuyère, a fragment of a mould valve, etc.), the quantity of metal remains being generally very small. The casting sites themselves are remarkably rare, as are the post-casting sites, which are mainly revealed by the presence of lithic tools.

At the same time, technological studies carried out on the metal objects themselves (traceology, metallography, etc.) have made it possible to make significant progress on the question of the manufacturing process, but these studies are still mostly disconnected from the production sites. Studies of the lithic macro-tools used in metallurgy have also expanded considerably in recent years (Hamon and Delgado-Raack, this volume). Experiments have provided a wealth of information too on technical issues, organisation and the traces left by bronze castings. All these studies, whether or not they are directly linked to a workshop, are therefore complementary to what can be found in excavations and together contribute to our understanding of the production chains for bronze objects.

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Stones in the toolkit

Contribution of use-wear and residues analysis to the identification of Copper and Bronze Age metal object production in Europe between the 3rd and 1st millennium BC

Caroline Hamon and Selina Delgado-Raack

Abstract: The emergence and development of copper and bronze metallurgies, but also of those of precious metals such as gold and silver, are major issues in addressing the cultural and economic dynamics of prehistoric Europe. However, since research has focused on typologies and distribution of metal objects, the documentation on the structures of ore extraction and metal production workshops remains disparate, and only partially enlightens the stages of production.
The identification of the stone tools involved in these technical processes makes it possible to partially fill this gap in continental Europe. Thus, recent work in use-wear and residue analysis (e.g. XRF, SEM-EDX) on different categories of stone tools (picks, crushers, grinders, casting moulds, anvils, abraders, hammers, whetstones, etc.) have made it possible to specify the technical processes used for extracting ores, transforming them into metal, shaping metal objects and maintaining them.
This paper discusses the contribution of functional analyses to the identification of these tools, and of the contexts of metal production during Metal Ages. The presence of such tools in settlements, in workshops, as well as in particular funerary contexts, allows us to better understand the organisation of production and the degree of specialisation of metalworkers within the societies of the 3rd to 1st millennium BC.
Keywords: Metallurgy; Lithic tools; Bronze Age; Use-wear analysis; XRF; SEM-EDX.

Résumé : L'émergence et le développement des métallurgies du cuivre et du bronze, mais aussi des métaux précieux comme l'or et l'argent, constituent des questions majeures pour aborder les dynamiques culturelles et économiques de l'Europe préhistorique récente. Cependant, si les recherches se sont concentrées sur les typologies et la distribution des objets métalliques, la documentation sur les structures des ateliers d'extraction des minerais et de production des métaux reste disparate et n'éclaire que partiellement les étapes de la production. Depuis le III^e^ millénaire avant J.-C., la contribution des outils en pierre aux processus métallurgiques est évidente dans les contextes miniers, où des centaines de marteaux ont été utilisés pour l'extraction des minerais, en particulier du cuivre et de l'étain. Associés au phénomène campaniforme, des outils en pierre retrouvés dans les tombes dites « de métallurgistes », accompagnant les défunts, constituent la première preuve de leur participation possible à des activités de métallurgie du cuivre au cours de leur vie. Au début de l'âge du Bronze, les habitats ont livré des outils de métallurgistes, preuve de l'existence d'ateliers dédiés soit à la production de cuivre et d'alliages de cuivre, soit à la fabrication d'objets. Compte tenu des stratégies intensives de recyclage du métal, ces outils en pierre constituent les rares éléments, avec les foyers et les déchets métalliques, capables d'indiquer l'existence d'anciennes zones de production de métal. À ce titre, l'identification de ces ateliers de production élargit le champ des investigations sur les métallurgies, et contribue à éclairer leur organisation au sein des territoires de la fin du Néolithique et du début de l'âge du Bronze, de l'échelle intrasite à l'échelle macro-régionale. L'identification des outils en pierre impliqués dans les processus métallurgiques permet de combler partiellement notre perception de l'organisation de cette activité en Europe continentale. Au-delà de l'évidente adaptation morphologique aux gestes et aux actions, le haut degré de sélection des matières premières est un point commun à tous les outils en pierre impliqués dans des processus métallurgiques. Les roches utilisées pour la fabrication des outils métallurgiques doivent répondre à un large éventail d'exigences physiques, incluant une résistance aux chocs, aux fluctuations thermiques et une certaine abrasivité, variant d'une étape à l'autre de la chaine opératoire.
De récents travaux menés sur les traces d'utilisation et l'analyse des résidus (par ex. XRF, SEM-EDX) de différentes catégories d'outils en pierre (pics, broyeurs, meules, moules, enclumes, polissoirs, marteaux, pierres à aiguiser, etc.) ont permis de préciser les procédés techniques utilisés pour l'extraction des minerais, leur transformation en métal, la mise en forme des objets métalliques et leur entretien. Ils reposent sur quelques référentiels expérimentaux, qui ne couvrent qu'une partie de la diversité lithologique employée pour les outils en pierre et celle tout aussi large de la composition des métaux transformés. Les principaux référentiels tracéologiques portent sur les outils d'extraction minière,

sur les outils de concassage du minerai, sur le façonnage des objets métalliques par déformation plastique et leur finition par polissage.
Comme cela a été constaté expérimentalement, le façonnage des objets métalliques ainsi que le polissage laissent des résidus (cuivre, argent, or) adhérer à la surface de la pierre. Cependant, ils ne sont pas toujours préservés sur les surfaces des outils archéologiques. L'une des raisons de la préservation différentielle des résidus semble liée à la texture et à l'état dans lequel le métal a été travaillé, ce qui renforce ou diminue les liens entre les deux matières en contact. Un autre facteur est lié à la porosité et/ou à la rugosité de la surface de la roche de l'outil, qui offre plus ou moins de possibilités de capturer les résidus dans les parties inférieures du microrelief. Un dernier facteur renvoie à la préservation des micropolis, qui peuvent piéger des résidus métalliques en très faibles quantités. Une stratégie analytique « étape par étape » se révèle ainsi la plus pertinente. Il semble donc préférable de commencer par une détection qualitative de l'absence/présence de ces résidus (par pXRF, par exemple), avant de soumettre les échantillons à des mesures plus quantitatives (XRD ou SEM-EDX). En outre, en fonction de la question archéologique, une cartographie de ces résidus peut être pertinente pour préciser la fonction et la cinétique d'un outil.
A travers différents exemples issus de la littérature archéologique, il apparaît évident que la combinaison d'analyses tracéologiques et de résidus semble la plus à même de préciser la fonction des outils en pierre en contexte de métallurgie. Les analyses fonctionnelles contribuent ainsi notablement à l'identification des outils de métallurgistes et des contextes de production du métal pendant les âges des Métaux. La présence de tels outils dans les habitats, les ateliers, ainsi que dans des contextes funéraires particuliers, nous permet de mieux comprendre l'organisation de la production et le degré de spécialisation des métallurgistes au sein des sociétés du IIIe au Ier millénaire avant notre ère.

Mots clés : métallurgie ; outils lithiques ; âge du Bronze ; tracéologie ; XRF ; SEM-EDX.

European recent Prehistory offers a scenario of deep socio-political changes, in which the rise of institutional power and the development of ruling classes was one of the milestones. In this process of transformation, the rise and spread of metallurgy represented a crucial economic aspect propelling innovative technology and new social and economic relations, mainly from the 3rd millennium BC onwards (Rovira, 2001; Nicolas, 2015; Roberts and Frieman, 2015). Some of the main questions to be addressed in the study of the prehistoric metallurgical *chaîne opératoire* are what kind of ore was exploited (mainly copper, gold, silver, tin), who performed the work, with the aid of which working means and, finally, for what purpose. By answering these questions, research provides critical data about access to natural resources (nature, composition, origin and circulation, control), the organisation of work (communal vs. individual), the technology applied in each stage of the process, and the products derived from it (ingots, ornaments, tools and weapons for elites or more widespread diffusion).

From the 3rd millennium BC onwards, the contribution of stone tools to metallurgical processes is obvious in mining contexts, where hundreds of hammers were used for the extraction of ores, especially copper and tin (Ambert et al., 2011; O' Brien, 2015). Associated with the Bell Beaker phenomenon, stone tools were found also accompanying the deceased in the so called 'metallurgist graves', and constitute the first evidence that points to their possible participation during life in copper metallurgy tasks (Bátora, 2002). With the Early Bronze Age, settlements have provided metallurgists' tools, as evidence of workshops dedicated either to copper and copper alloy production or to object manufacturing (Pernot, 1998; Armbruster, 2010; Drenth et al., 2013; Delgado-Raack et al., 2015; Nicolas et al., 2015; Hamon et al., 2020). Considering the complex and intensive recycling strategies of metal, such stone tools appear to be among the rare elements, together with fireplaces or metal wastes, able to point to the existence of past metal production areas. As such, their identification enlarges the scope of investigations of metallurgies to more unexpected or discrete contexts, and contributes to shedding light on metallurgical organisation within the Copper and Bronze Age territories, from an intrasite to a macroregional scale.

The study of macrolithic material allows insight into metallurgical production, at different stages of the *chaîne opératoire* (Delgado-Raack and Risch, 2008), and into the degree of specialisation of this activity (fig. 1). In prehistoric mining activities, stone is, together with antler, the most important raw material used for dismantling the rock for ore extraction (picks, slings and other percussing tools) as well as for the crushing and first mechanical cleaning of the ore (hammerstones, crushing platforms). From the beginning of copper and gold metallurgy and before the introduction of casting processes, the main metal transformation mechanism was cold plastic shaping through hammering for which the only imperishable tools available were stone hammers and anvils.[1] Some time later, with the introduction of alloys, crucibles and casting moulds became indispensable means of work for which stone was again one of the main raw materials. Stone tools were also needed for the polishing and sharpening of metal objects in the last stages of the metal manufacturing processes.

From another perspective, when metallic objects themselves are not always preserved in the archaeological deposit due to alteration processes and their constant recycling, stone moulds can provide additional data about

1. In these contexts, evidence of metallurgical structures (e.g. kilns) and waste (slag, casting drops) is non-existent and the only elements for an analysis of metallurgical work processes are represented by macrolithic tools or the metal objects themselves, given that the latter have been preserved in the archaeological deposit.

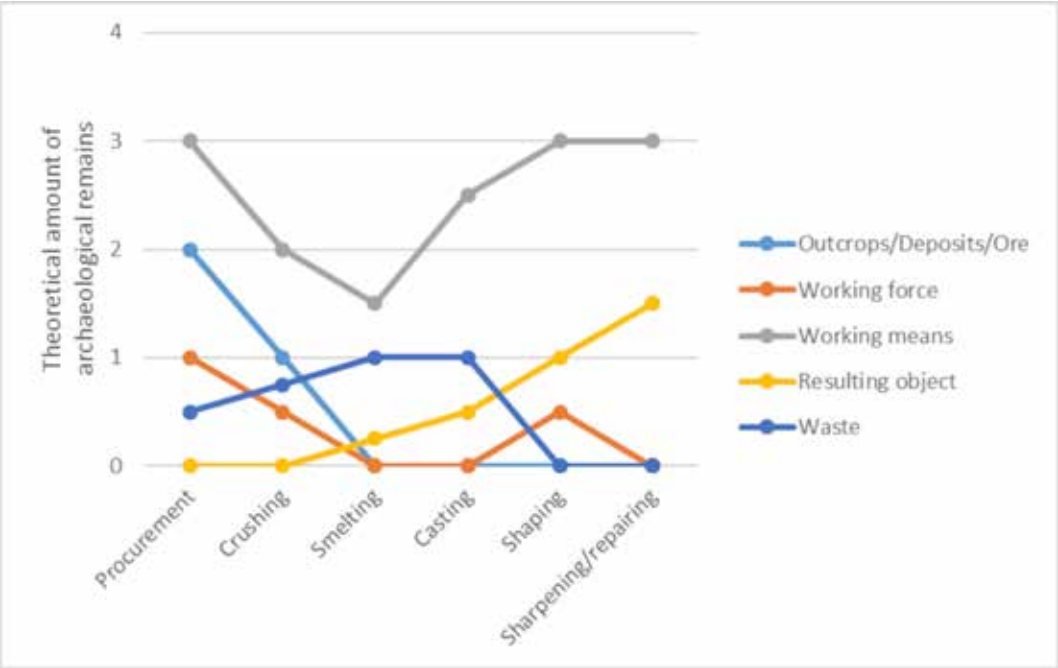


Fig. 1 – Schematic representation of the theoretical quantity of archaeological remains produced in each of the stages along the metallurgical *chaîne opératoire*.

the type of objects cast, as well as their composition (if residues are compositionally analysed). Similarly, although stone crucibles are not as abundant as pottery crucibles (Soriano and Escanilla, 2016), they are generally better preserved than the latter (Contreras et al., 2000).

As a result, macrolithic assemblages offer directly or indirectly valuable information about the development of metallurgical work processes in Prehistory. The heuristic potential of stone tools in the transformation of metal comes from their good preservation in the archaeological record and their ubiquity in the metallurgical work process, from procurement of metallic raw material to the maintenance of metal objects (Delgado-Raack and Risch, 2008).

Throughout this paper, we will offer some insights for the recognition and functional interpretation of macrolithic tools used for metallurgical work processes. Based on several recent case studies, we will discuss the methodological issues for the application of use-wear and metal residues analysis of stone tools from Copper and Bronze Age contexts. The goal is here to contribute as efficiently as possible to the debate on the social and economic background at the base of metal production development.

CONTEXT OF DISCOVERY OF STONE TOOLS, A BIBLIOGRAPHIC REVIEW

Due to the interest devoted in the history of research to funerary contexts, more than half of the evidence available in the literature for metallurgical macrolithic tools comes from graves (74/145, i.e. 51 %; fig. 2). From the 1960s onwards, some authors drew attention to the so called 'metallurgist graves' scattered across Europe, including characteristic grave goods that were directly linked to the manufacturing of metal ornaments, tools and weapons (Butler and Van der Waals, 1966; Semenov, 1969). The study of their content and their mapping allowed the definition of an exclusive phenomenon of primarily adult male graves (with a few exceptions, e.g. Chernych, 2003, Ernée et al., 2020) from the 4th to the 2nd millennia BC, distributed from the Caucasus to the European Atlantic coast and from northern to Mediterranean Europe. The differentiated emphasis put in each region of the continent on some types of grave goods has already been highlighted elsewhere. While in the burials of eastern Europe the first part of the metallurgical *chaîne opératoire*, that is casting (moulds, crucibles, tuyères), is predominantly represented, the second part of the work process, namely plastic shaping (anvils, hammers, sharpeners, polishers), stands out for western Europe (e.g. Delgado-Raack and Risch, 2006). Especially in this region, metallurgist graves reached their critical point during the Bell Beaker and Early Bronze Age i, in a context of an incipient metallurgy. Research recently published with additional graves from central and northern Europe has considerably enlarged the empirical basis for the study of this paneuropean phenomenon (Nessel, 2019). Not only the deposition in graves of specific metallurgical stone tools, metal objects and pottery vessels related to socially outstanding individuals, but also the location of these graves far away from potential ore resources causes them to highlight the social relevance of plastic shaping, finishing and maintaining of metal objects, over smelting and casting operations.



Fig. 2 – Distribution of archaeological contexts with presence of metal plastic shaping stone tools Europe-wide during the 3rd–2nd millennia BC, according to the context of discovery. Data taken from Occhi, 1997, p 520–523; Bátora 2002; Delgado-Raack and Risch, 2006, fig. 6; Freudenberg, 2006, fig. 5; Brandherm, 2009, fig. 1; Freudenberg, 2010, fig. 7; Soriano, 2011, fig. 8; Boutoille, 2019b, with additions after Delgado-Raack et al., 2015; Hamon et al., 2020; Delgado-Raack et al., 2020; Hamon et al., 2021 and Müller et al. ,2023. This map shows a general and not exhaustive review of archaeological contexts in which stone anvils and metallurgical hammers were found. It is based on the publications cited, which provided information about the type of contexts. The two rectangles show the areas studied by Boutoille (2019a) with > 130 sites for France and adjacent countries (A) and Nessel (2019) with > 80 sites for Central and Northern Europe (B). The data from both publications have not been included in the map due to their high density and the absence of systematic information regarding the type of contexts in the first publication.

The publication of these collections helped with the recognition of two concomitant artefact types which participated in the plastic shaping of metal objects through hammering: the stationary piece, represented by the anvils, also known as *cushion stones*, such as were found in Lunteren or Leubingen (Butler and Van der Waals, 1967-1968; Freudenberg, 2006; Boutoille, 2019), and axe-shaped hammers with blunted edge, such as the specimen found in grave 9 at Künzig (Bertemes et al., 2000; Lynch, 2001; Bertemes, 2004; Boutoille, 2012). Moreover, small stone plaques (Muñoz, 2017) and larger slabs (Delgado-Raack and Risch, 2006) have been identified as sharpening tools in graves. Unlike sharpeners, a few specimens have been interpreted as touchstones for the checking of gold quality (Eluère, 1985; Crellin *et al.,* 2022, and for more recent periods in Moravia, see Ježek and Zavřel, 2013).

In contrast to the abundant data coming from funerary contexts, stone tools recovered in settlement contexts including metallurgical workshops (31/145, i.e. 21%), unknown contexts (36/145, i.e. 25%) or hoards (4/145, i.e. 3%) are scarcer.[2] Reasons for this could be difficulties in the recognition of such artefacts, which can appear isolated from other discrete metallurgical evidence like kilns, melting waste, etc. Nonetheless, in recent years the systematic application of use-wear and residues analysis has enhanced the visibility of these kinds of tools. In addition, new findings in mines and settlements have enabled new ideas about how the work process for mineral procurement and first cleaning, as well as that for metal plastic shaping, could have functioned (Hamon et al., 2009; 2020; Delgado-Raack et al., 2015; Caricola et al., 2020; Delgado-Raack et al., 2020; Müller et al., 2023; Eguíluz et al., in press).

2. In some regions of Central and Northern Europe isolated findings from unknown contexts seem to be more frequent than funerary contexts (Nessel, 2019). In this case the percentage of unknown contexts in which such tools were found (41/83, i.e. 49%) surpasses the quantity of graves (39/83, i.e. 47%), hoards (2/83, i.e. 3%) and settlements (1/83, i.e. 1%) with such findings.

MECHANICAL PROPERTIES OF STONE TOOLS AND METALLURGICAL PROCESSES

Beyond their obvious morphological adaptation to gestures and actions, the high degree of raw materials selection is a common point shared by all stone tools involved in metallurgical processes.

Recent research addressing the definition and evaluation of the mechanical properties of rocks participating in percussion and cutting mechanisms show that rock behaviour is determinant in raw material selection (Delgado-Raack and Gómez-Gras, 2017; Delgado-Raack et al., 2019; Monik et al., 2021). Even so, the metallurgical *chaîne opératoire* introduces additional complexity in the technological process. The technology of metal is critically subject to the state in which it is being worked. Depending on the transformation phase, metal working tools will enter into contact with hard rocks (ore mining and mechanical cleaning), minerals in liquid state under high temperatures (casting) and pre-heated or cold metal of different hardness (plastic shaping). Moreover, kinetic environments also change throughout the metallurgical *chaîne opératoire*, from blowing to frictional mechanisms through thermal impact. Following these processes, the raw materials which metallurgical tools are made of must fulfil a wide range of physical requirements for them to achieve the expected results under the best conditions.

Consequently, each category of tool involved in the metallurgical process is subject to rigorous selection. In mining contexts, ore procurement is done with the aid of rather large, massive and tough tools that are highly cohesive and have a hard mineral composition (fig. 3). These tools are usually made of igneous rocks (including volcanic ones), such as granites, gabbros or andesites (Delgado-Raack and Gómez-Gras, 2017, p. 58; Delgado-Raack et al., 2019, table 3; Caricola et al., 2020, p. 7), although especially resistant metamorphic rocks are also sometimes represented in the assemblages (secondarily metamorphosed hornfels). Raw material chosen for casting moulds must be both resistant to high temperatures and easily workable to a casting matrix. In this case, the most used rock types are detritic sedimentary rocks such as sandstones and calcarenites, which are mechanically softer than the previous examples. However, their grainy structure and clay content withstands heating much better than do igneous rocks, avoiding the spread of cracks along the mineral faces. At the same time, they are more easily workable than metamorphic rocks such as slate

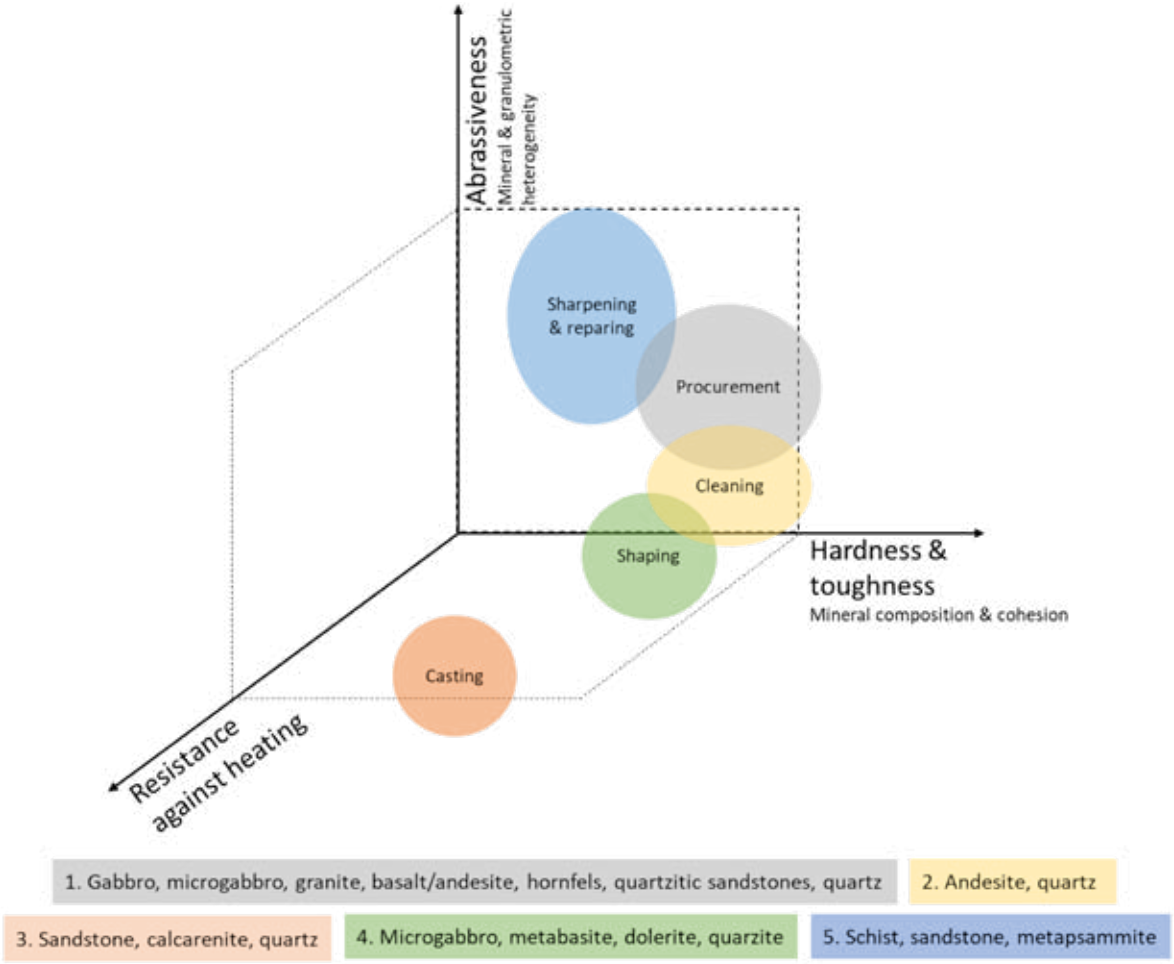


Fig. 3 – Mechanical properties of rocks involved in each stage of the metallurgical process and types of rocks used for them.

or schist. These rocks, although being resistant to high temperatures, include oriented structure or schistosity, which makes the manufacturing process more difficult to control. Tough and cohesive rocks (gabbro, metabasite, quartzite) come into use again for the hammering of metal, though in this case rather fine-grained variants are predominantly used which, opposite to coarser-grained rocks, allow the preparation of smooth working surfaces for the treatment of dainty metal sheets. For the final sharpening and repairing working stages, qualitatively different rocks can be implemented. The roughness of sandstones, metapsammites and schists is used for abrasive purposes, while other more compact materials as mentioned before (fine-grained gabbro, quartzite) can be used for polishing metallic surfaces.

These criteria for raw material choices are of course partly dependant on existing supply strategies and on material availability in a more or less local or regional area around the archaeological sites, implying adaptations towards the better option, and balance between procurement investment and required qualities. One must also note that these raw material choices encompass the use-wear formation process (Adams, 2002; Dubreuil et al., 2015), with consequences for the possibility of conducting functional analysis.

USE-WEAR AND RESIDUES ANALYSIS, A STEP FORWARD

Functional analysis, including use-wear and residues analysis, offers insights complementary to the typological approach to shed light on the contribution of stone tools to metallurgical processes. Based on experimental tests, these approaches are essential to identify a wider range of tools that cannot be isolated within large series solely on the basis of morphological criteria, and thus improve our knowledge of the metallurgist's toolkit. They also help refine the interpretation of tools' function at different steps of the *chaîne opératoire* of metal object production.

Building experimental collections for archaeological use-wear analysis

Reference collections are essential for the interpretation of use-wear traces and the functional interpretation of tools. As a matter of fact, use-wear analysis on metallic objects has faced several obstacles to its development, including plasticity of the metal matter, logistics required for metal production and marked alteration of the surfaces. Consequently, the few pioneer works on metal objects use-wear analysis (Gutiérrez and Soriano, 2008; Gutiérrez and Lerma, 2015; Dolfini and Crellin, 2016) did not pay particular attention to the role of stone tools in metallurgical work processes, including for smelting and casting procedures.

Considering the emerging nature of the recent research on the topic, only a few experimental works, including ours, have been conducted, thus opening the door to a wide field of research to be developed. Functional considerations were first discussed based on ethnographic (Armbruster, 2006) and iconographic data (Boutoille, 2012), in which metallurgical artefacts, their specific morphology, their role in the *chaîne opératoire* and the movements performed with them were defined. On this basis and to go further through experimental works, attention was especially paid to mining and first cleaning of ore (Timberlake *et al.,* 2007; Caricola et al., 2020), metal plastic shaping (Delgado-Raack, 2008; Müller et al., 2023; Hamon *et al.,* 2024) and polishing/sharpening (Delgado-Raack, 2008; Muñoz, 2017; Hamon, et al., 2024). The main lines of each experimental procedure are summarised in table 1.

These experiments faced several challenging issues:

– First, the diversity of stone tool raw materials selected in the different archaeological contexts demands the development of adapted experimental collections, as the nature and properties of the rock have direct consequences on use-wear formation. Macrolithic tools present the challenge of being coarser-grained materials than flint, with a higher mineral heterogeneity in grain size and composition. This implies that mineral particles included in the rock will react differently against wear, developing variable trace patterns in each case. In addition to the grain scale, there are specific aspects of use-wear (e.g., incidence or extension) that can only be observed at the general level. As a result, several observation scales are needed for the analysis of stone surfaces, including low and high magnification approaches according to Adams *et al.,* 2009.

– A second fundamental issue is the variability of metal compositions and their respective mechanical reactions, that also strongly influences use-wear formations. Each group of alloys should be tested separately within experimental protocols, in order to refine the functional interpretation of stone tools that may be used for different metals and alloys, and different steps of their production.

Considering mining activities, experimental protocols did stress different use-wear signatures depending on the nature, composition and texture of the ore extracted. The high level of tool fracture during use engendered longitudinal split fractures, oblique damage or microflake removals that left only part of the active surface preserved (Caricola et al., 2020). For copper carbonate extraction, macropits and macrocracks were the most frequent range of traces, while grains were mostly affected by deep step macrofractures. Micropolishes were accompanied by long and oriented striations, and the traces extended along the top of the grains with smooth texture and flat topography. Copper ore crushing generates fine and random percussion impacts, for which morphology, depth and concentration depends on the texture, size and hardness of the ore (Hamon et al., 2023). Impacts are generally associated with copper residues. A concentrated smooth levelling of the topography is visible. Minerals display fine and dense microfractures. A compact and rough micropolish develops on spots or larger zones.

	Type of activity	Tool type	Raw material	Contact material	Kinetics	Working time (min)	References
COPPER	Copper ore Mining	Percussor, Pic	Igneous and metamorphic rocks	Wall of copper carbonates ores (malachite and azurite)	Perpendicular blows and leverage	90 to 180	Caricola et al. 2020
	Copper ore crushing /grinding	Hammer, anvil	Dolerite, granite	Ore fragments	Perpendicular blows	15 to 60	Hamon et al. 2024
	Copper shaping	Hammer and anvil (shafted in oak trunk)	Gabbro	Copper tube with 1 mm th. wall (pre-heated)	Perpendicular blows	150	Delgado-Raack 2008
	Copper shaping	Hammers	Dolerite, quartz	Dagger, flat axe, palmela point	Deburring (lateral blows), flattenting (perpendicular to oblic blows)	30	Hamon et al. 2024
	Copper polishing	Polisher	Quartzitic and mica schist	Copper sheet	Back and forth friction	120	Delgado-Raack 2008
	Copper polishing	Abraders, polishers	Sandtone, Schist	Dagger, flat axe, palmela point	Back and forth friction	30	Hamon et al. 2024
BRONZE	Bronze shaping	Hammer	Dolerite, quartz	Flat axe, palstave, dagger	Deburring (lateral blows), flattening (perpendicular blows)	30	Hamon et al. 2024
	Bronze polishing	Abraders, Polisher	Sandstone, Schist	Flat axe, palstave, dagger	Back and forth friction	30	Hamon et al. 2024
SILVER	Silver shaping	Hammer and anvil (shafted in wooden block)	Dolerite?	Circular 40 mm diameter sheet of 26.1 g sterling silver (“annealed”)	Perpendicular blows	270	Freudenberg 2009
GOLD	Gold shaping	Hammer and anvil (shafted in pine trunk)	Gabbro	Gold nugget (24 carats) of 3 g (cold)	Perpendicular blows	30	Müller et al. 2023
	Gold polishing	Polisher	Gabbro	Gold sheet	Back and forth friction	10	Müller et al. 2023
	Metal sharpening	Sharpener	Sandstone, Slate, schist	Copper and bronze daggers	_	15	Muñoz 2017

Table 1 – Summary of experiments conducted on different working stages of metal manufacturing in which macrolithic tools are involved, after bibliographic review.

As for metal shaping, experiments highlighted the necessity of rounded and smooth surfaces to avoid any damage to the metal surfaces. For this reason, cobbles are particularly suitable blanks, as they avoid sharp edges that could both break the stone and damage the metal surface. These particular morphologies can be obtained by accurate selection of naturally rounded and weathered pebbles as well as by manufacturing. The manufacturing process of intensively transformed cushion stones has been experimentally reproduced and lasted a total of 80 hours (Freudenberg, 2006). Advantages of such a work inversion in the case of cushion stones could be linked to a longer durability in terms of work intensity or use-life, but this is an issue still to explore.

Experimental stone surfaces used for gold, silver and copper plastic shaping are characterised by highly homogenised and levelled reliefs, due to the pressure created by the perpendicular blows wearing down the most exposed topography to rounded forms (including the edges of previous striations and pits, which are progressively obliterated; Delgado-Raack and Risch, 2008; here fig. 4). Metal particles attached to the stone surface are pushed into anfractuosities. This process provides a shiny reflective surface, often extensively covered by residues, which can partly make it difficult to observe the stone surface directly. These patterns have been recorded on both tools, the anvil and the hammer (Müller, et al., 2023). In all experiments, metal residues stayed attached to the stone surface regardless of the metal object being worked in pre-heated or cold state. Nonetheless, the penetration capacity of residues coming from pre-heated metal is higher, reaching even deeper points of the low topography and enhancing them to cover the relief more intensively. At higher magnification, the surface is covered by a smooth to rough micropitted and microstriated micropolish (Hamon et al., 2023).

Polishing can be clearly distinguished from hammering on both stone and metal surfaces (Müller et al., 2023). The wear mechanism based on horizontal friction favours the development of linear traces on metal and/or stone, shown by fine and dense striations reproducing the direction of motion. Metal particles adhere to high topogra-

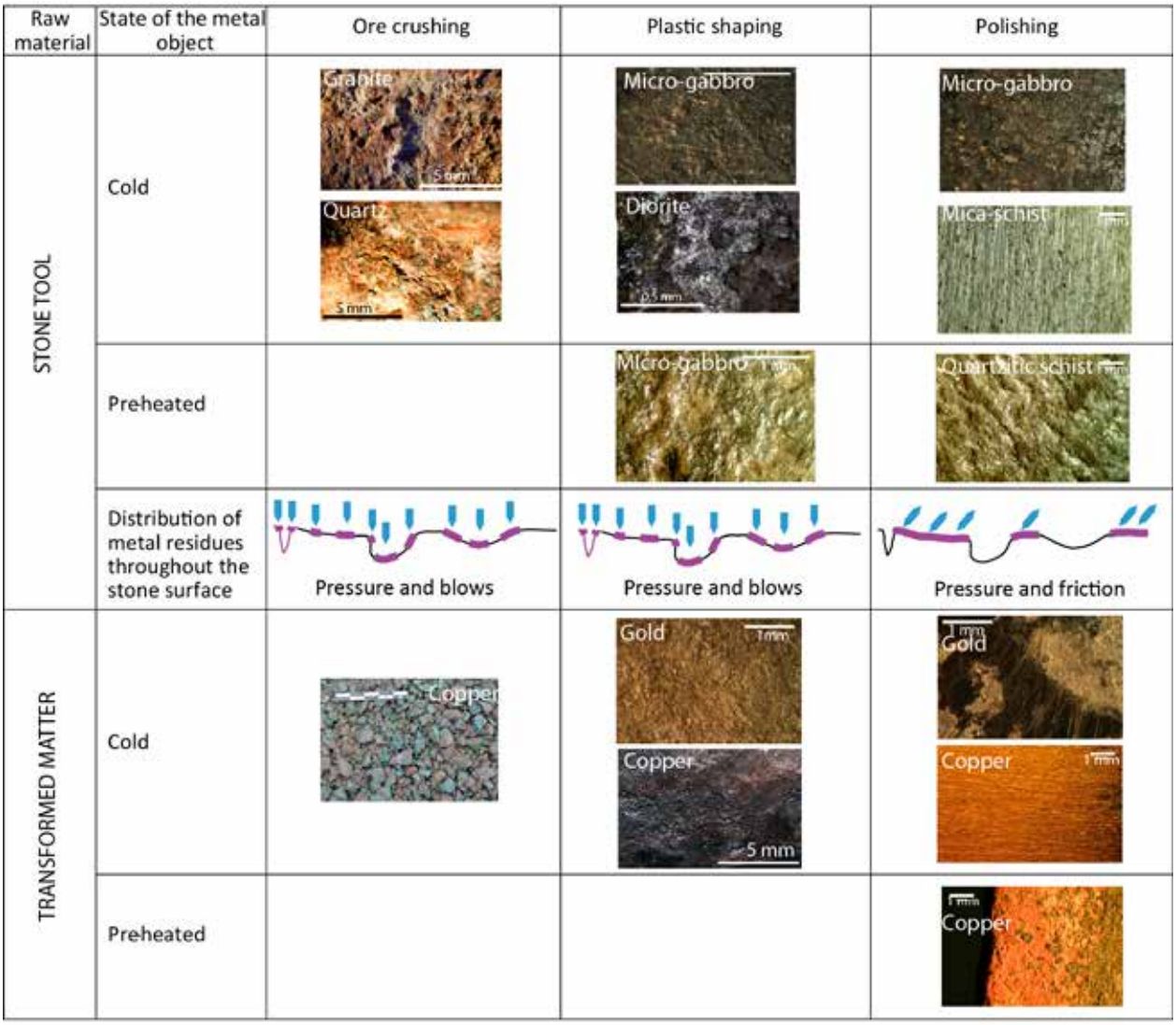


Fig. 4 – Stone and metal surfaces reproduced in experimental metallurgical tasks during copper ore crushing (after Hamon *et al.,* 2024), plastic shaping and polishing (after Delgado-Raack, 2008; Müller et al., 2023).

phy of the stone, although mineralogically heterogeneous rocks (e.g., schistose rocks) tend to slow down this process. On metallic surfaces polished in a cold state, striation patterns appear as a dense weft of fine linear traces providing a smooth and shiny appearance. This effect grows, the finer the grain size and more homogeneous the mineral content of the polisher is. Deeper areas of the metallic surface are left intact as they were hammered. This shows the importance of the previous work step of plastic shaping, as preparatory work to flatten the relief as much as possible. Polishing of metal in pre-heated state does not achieve the same effect at all, although it could help with the flattening of the metal surface in concomitance with plastic shaping.

First results of experiments done on mining/crushing of ore and plastic shaping/polishing of metal need to be expanded in the future in order to test, for example, the same mechanisms with other rock types or other contact materials (mainly varied bronze alloys) or in longer experimentation sequences. In addition, new ways have to be explored that could shed light on specific questions related to the recognition of plastic shaping tools. Especially in the case of highly symmetric tools intensively prepared for use (i.e., the so called *cushion stones*), it remains sometimes unclear whether they were used as anvils or as hammerstones, or even as both. In this sense, we hope a deeper analysis of the qualitative aspects of use-wear and residue analysis will enable researchers to distinguish stationary and mobile tools.

Another major issue is, in certain contexts, the good preservation of residues (Carey et al., 2023). In certain cases, they cover the surfaces below, and all use-wear traces appear inaccessible for analysis. In addition, some residues show intriguing patterns, such as shiny levelled surfaces with micropitting and fine linear striations of variable orientations, that make them occasionally difficult to distinguish from spotted micropolishes (fig. 5a). In this sense, residues can also be informative of the kinetics (percussion, friction, etc.) and nature of contact material of the tools.

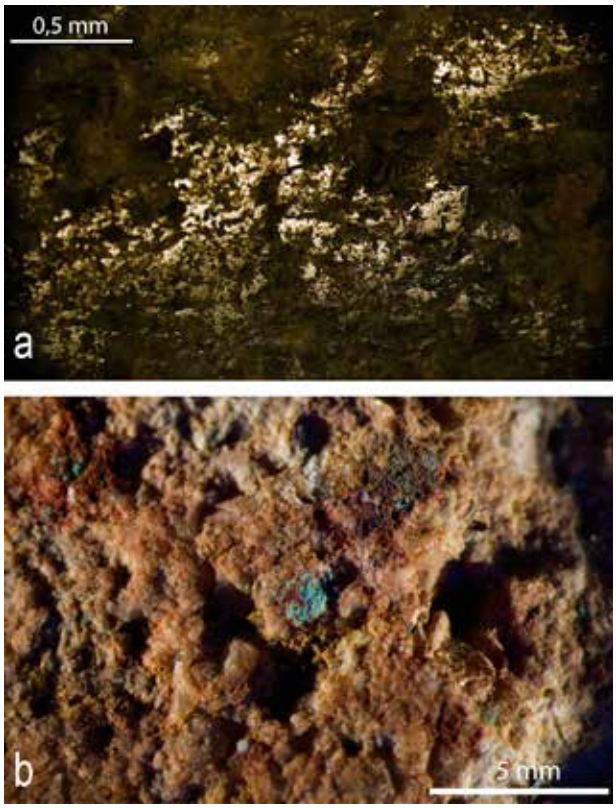


Fig. 5 – Examples for experimental use-wear; a: typical micro-pitted micropolish of copper alloy object shaping on a tool made out of eclogite, including copper residues (after Hamon *et al*., 2020); b: Red and green residues of copper ore on a crushing tool, filling the interstices of the upper and lower part of the microrelief (photo: C. Hamon).

Residues analysis

As was experimentally recorded, metal plastic shaping as well as polishing leaves metal particles (copper, silver, gold) adhered to the stone surface. However, they do not always remain preserved on the archaeological working surfaces. One reason for the differential preservation of residues seems related to the texture and state of the metal being worked, enhancing or diminishing the bonds between the two materials. For example, one is much more likely to find metal residues on casting moulds than on other metallurgical stone artefacts, as melted metal easily enters surface anfractuosities and porosities before cooling down.[3] The manipulation of metal in liquid or viscous state can even lead to contamination of surfaces other than the active one (casting matrix).

Another reason is linked to the porosity and/or surface roughness of the tool's rock, that offers more or less opportunity to catch residues in the lowest parts of the microrelief. This is particularly true for mining and crushing tools, which although being made of highly compact rocks, include rugged active surfaces: first because they are in contact with significant quantities of mineral matter, and second because their use in throwing percussion may create a strong bond between ore and tool's surface.

A third reason is linked to the development and preservation of micropolishes. Some works have demonstrated that a well-developed micropolish can trap metal residues in very low quantities (Hamon et al., 2020). Metal plastic shaping using the tools can be done via cold hammering or via the working of slightly pre-heated metal objects and can therefore provide residues in different quantities and extents restricted to their active surface(s). Definitely, intense or regular retouching processes for the maintenance of the working surface can contribute to the removal of residues, while a low intensity of use can lead to an absence of them.

Additional reasons for the absence of metal residues in archaeological specimens could include the soil conditions in the archaeological deposit. But these mechanisms are not well understood and investigated, and are subject to particular local conditions. On the other hand, metallic elements making up the soil can adhere randomly on the tools' surface. For this reason, it is important to make a thorough record of the location of adherences on broken or natural *versus* anthropic surfaces and on passive *versus* active surfaces. In addition, the recovery of suspected artefacts should always be accompanied by a sampling of the surrounding sediment, in order to evaluate the possible origin of the residues preserved on the stone tool. In this context, it could also make sense to scrape the adhered dust/sediment from the uncleaned surface. Nonetheless, our experience has shown that a bath with neutral soap by fingertip washing and a subsequent rinse with running tap water is not enough to detach or damage the adherences from the stone surface, i.e. does not affect their preservation. Overall, it is convenient to wash the artefact's surface for a proper observation of (a) manufacturing and use-wear traces and (b) possible particles alien to the rock. In fact, the best conditions for use-wear and residues analysis have been provided on clean surfaces, as the detection of the majority of metallic residues has been done until now first optically on previously cleaned surfaces (Delgado-Raack et al., 2015; Crellin et al., 2022; Carey et al., 2023; Müller et al., 2023; here fig. 5b).

One of the main concerns of researchers when approaching residues analysis is the balance between expenses and output. Our proposal, suitable for optimising further analytic investment for compositional characterisation, is to start with the optical tracking of suspected particles adhered to the stone surface. Given that results are positive, throughout the procedure, cheaper, qualitative and non-destructive techniques will be replaced by more accurate ones, including quantitative and maybe destructive measurements (fig. 6). This 'step-by-step' analytical strategy is all the more relevant, as the residues preserved may be very low in quantities. It seems then relevant to start with qualitative detection of absence/ presence of such res-

3. This is also the reason why at compositional level, some more or less volatile metallic elements could appear over-represented in relation to others and *vice versa*.

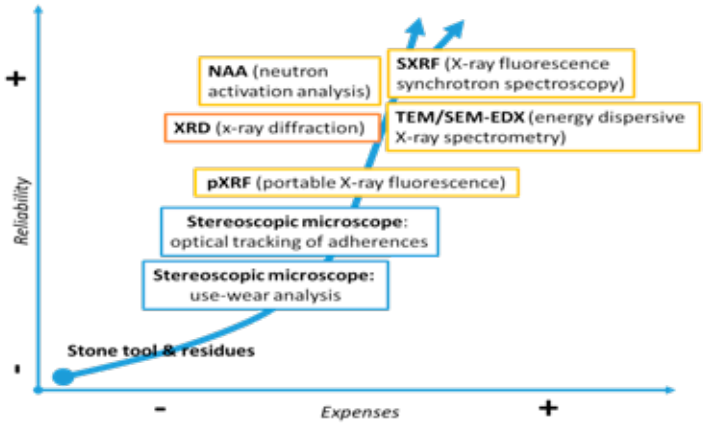


Fig. 6 – Proposed work-flow for residue analysis on stone tools. Blue rectangles stand for optical technique; yellow ones for elemental composition techniques; orange ones for phase composition technique.

idues (such as pXRF analysis), prior to submitting the samples to more quantitative measurements (such as XRD or SEM-EDX analysis). Besides, depending on the archaeological question, a mapping of these residues may be relevant to the precise function of a tool, and its kinetic.

CONTRIBUTION OF STONE TOOLS TO THE *CHAÎNE OPÉRATOIRE* OF METALLURGICAL PROCESS

On the basis of extensive literature on the topic, it is now possible to draw a quite precise panorama of the role of stone tools in the *chaîne opératoire* of metallurgical processes, from ore procurement to tool sharpening.

General pattern

Striking is the existence of relatively specialised categories of tools at each stage of the production, that appear non-interchangeable (table 2). As a matter of fact, the hammers used to process ore and reduce it into small fractions do definitely not offer the same characteristics as the hammers used to flatten, thin and regularise the metal objects' surface. Moreover, different sets of tools can be chosen for better efficiency in the processing of ore, or in the finishing action on metal tools, mainly by considering the results expected. The know-how associated with the forging or with the finishing stage implies a relatively high diversity of tool types, that ensure accuracy of the gesture, as well as reliable results. This diversity of tools with characteristic morphologies also expresses different ways

Task within metallurgical *chaîne opératoire*	**Mechanism involved**	**Macrolithic artefacts involved**
Procurement (mining, collecting)	Mechanical dismantling of rock	**Maces** **Picks** **Slings**
Processing, Cleaning (crushing)	Mechanical break up of ore carrying rock	**Maces** **Pestles** **Crushing tools** **Mortars** **Stone slabs** **Grinders**
(Roasting / Smelting)	(Heating ore)	**(Ovens; burned plaster)** **(Reduction vessels)**
Casting or melting	Heating ore	**Crucibles** **Molds**
Plastic shaping	Mechanical shaping of cold/hot metal blank through pressure/blows	**Anvils** **Hammers**
(Tempering / annealing)	(Heating & cooling up metal object)	_
Finishing	Sharpening Polishing Decorating	**Sharpeners (whetstones & slabs)** **Abraders** **Polishers** **Touch stones**
Maintenance	Re-sharpening Repairing	**Sharpeners (whetstones & slabs)** **Abraders** **Polishers** **Touch stones**

Table 2 –Schematic role of the main category of stone tools employed at each stage of the metallurgical process.

of doing things amongst the workshops and groups of producers, following a chronological or regional pattern.

Procurement: mining, collecting and crushing ore

Most of the stone tools involved in ore extraction during the Copper and Bronze Age reflect not only direct adaptation to the rock available locally to obtain tools resistant to throwing percussion, but also adapted morphologies of the active surfaces as well as systems of handling, to extract ore. Most of these adaptations and characteristics of stone tools depend on the type of outcrop and on the organisation of the extraction system (open-air, subterranean, shaft etc.) and of the mining communities (size of the groups, rate of control, frequency and seasonality, volume extracted, transportation, etc.). The example of the copper carbonate extraction in Grotta della Monaca, Southern Italy (Caricola et al., 2020) illustrates perfectly how the weight and morphology of the tools' active surface was deliberately adapted to the specific configuration of each mineral outcrop, as confirmed by use-wear analysis. Use-wear analysis demonstrated that tools were used for the exploitation of different outcrops and types of minerals: heavy tools for the excavation of calcite planes and middle-size tools employed in the excavation of mixed deposits, while the active surface in contact with copper ores was significantly reduced.

Copper crushing and cleaning operations

Throughout Copper and Bronze Age contexts, the processing of ore and its reduction into smaller fractions prior to smelting generally requires stone tools.[4] They require blocks of dense and non-contaminant rocks, resistant enough to ensure efficient crushing of sometimes very hard mineral matter. They also generally show an association of percussion impacts and of strongly smoothed surface due to an association of crushing (throwing percussion), pounding (throwing and resting percussion) or grinding actions (resting percussion), that can alternate through the process while the size of ore fragments is getting more and more reduced. Most tools involved in ore crushing and grinding share common points with the processing of semi-hard mineral matter, such as step fractures and grain levelling (Carey et al., 2023). Analysis of such numerous crushing tools on the Chalcolithic exploitation of Cabrières, Hérault, France (Hamon et al., 2009) pointed to them probably being pre-shaped by pecking, prior to being used for crushing and then grinding. They attest to the presence of a workshop, close to the extraction mines, in order to produce copper metal. Their functional analysis points to possible use for ore reduction but also the sorting and cleaning of small particles of smelted copper considering the presence of heating traces on the active surfaces (fig. 7). Though use-wear analysis pointed optically to the random presence of copper residues in the anfractuosities of some tools' active surfaces, the XRF analysis did not manage to detect the presence of 'greenish' and altered copper elements. As suggested, this may be due to the too low quantities of copper residues preserved, and their high rate of dissolution in the superficial water. This lack of copper residue detection on crushing tools can be more problematic, especially in regular settlement contexts where crushing tools and anvils could have been used for other purposes. There, their identification as metallurgists' tools is crucial, as they allow identification of discrete metal production that is barely visible through other remains, as in the case of the Early Bronze Age sites in Brittany (Hamon and Blanchet, 2015; Hamon et al., 2020; 2021).

Casting

Moulds have been frequently deposited in the so called metallurgists' graves throughout Europe (Bátora, 2002), and are frequently found in hoards (Boutoille, 20090; 2012) or settlement contexts throughout Europe. But very few works have combined use-wear and residues analysis to get more into the details of their use, considering the small group of challenging issues related to the function of this type of objects. Consequently, archaeometric analyses have generally been conducted to determine the composition of clay moulds. However, some works have been carried out on the metallic surface residues, to explore their composition and thus the origin of the ores entering production. As an example, we will cite here two recent works illustrating the potential of different archaeometric methods to analyse residues on moulds. The chemical composition of preserved layers of metal on two moulds from Late Bronze Age graves in Poland was investigated using ED-XRF and SEM-EDS analysis. This work highlighted that several metal objects with different compositions were cast in the same moulds (Nowak et al., 2022). Another archaeometric analysis combining XRF, SEM-EDS, Micro-FTIR and Micro-Raman has explored the nature of some black residues on a Late Bronze Age mould surface from Galicia, NW Spain (Figueiredo et al., 2021). It allowed determination of the nature of the alloy and the type of object cast as well as showing some preparation of the surface of the mould with carbonised bone deposits in order to smooth the surface during casting.

Plastic shaping

Hammers and anvils are concomitant tools needed for the plastic shaping of metal objects (Armbruster et al., 2003).[5] The anvil is the stationary element, which had to be often fixed in a wooden stump, especially the smaller specimens (Armbruster et al., 2019). The blows

4. The typical crushing tools, with their central 'cupule' for throwing percussion impacts, can be either the upper or lower part of the crushing system, though this is generally difficult to determine on archaeological tools.

5. It cannot be ruled out either that tools of other raw materials, such as wood, could have acted in concomitance with them.

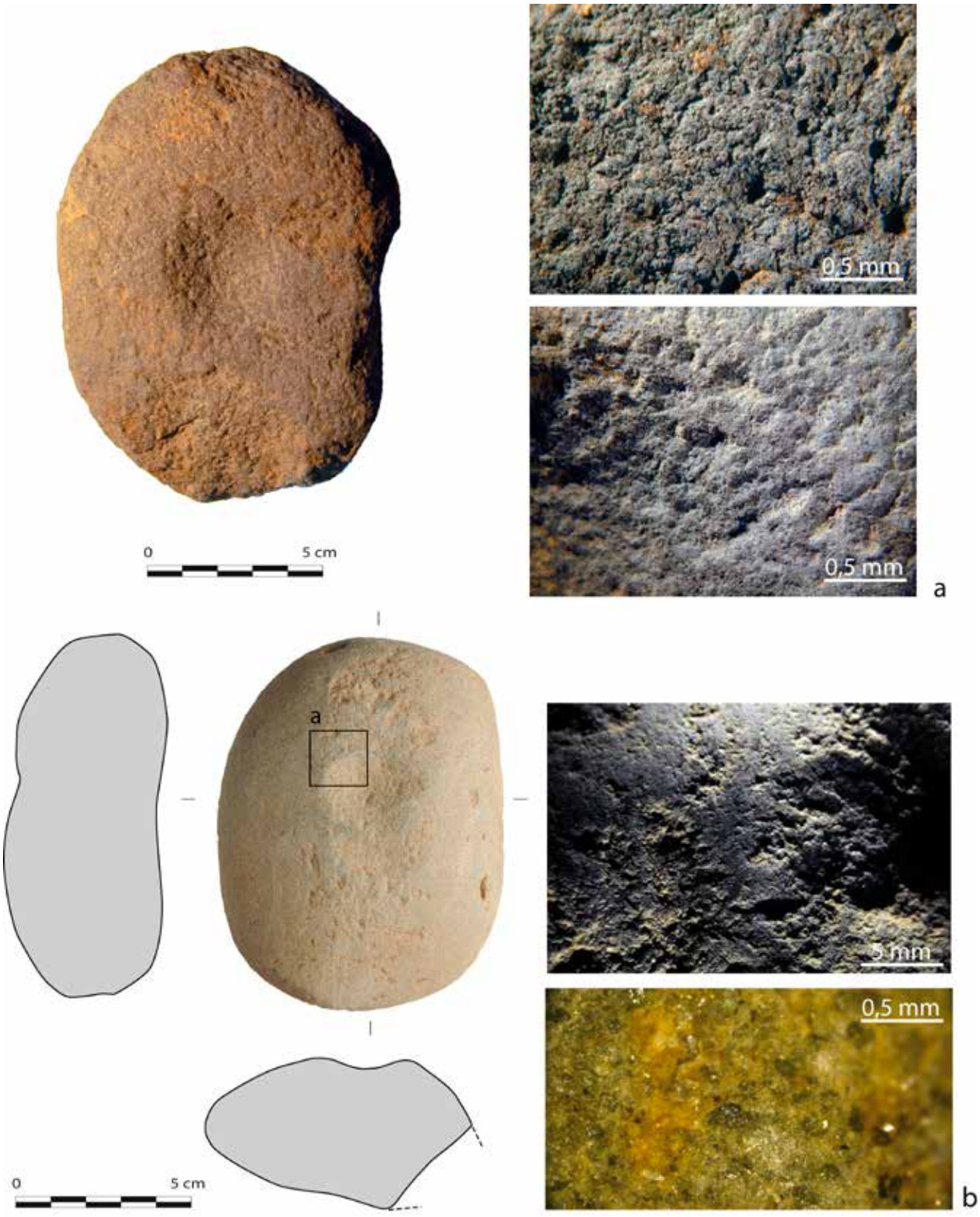


Fig. 7 – Examples of crushing tools and use-wear; a: basalt crushing tools from Cabrières (Hérault, France), detail of macroscopic use-wear face and cupule side (after Hamon *et al.,* 2009); b: diorite crushing tools from Plonéour-Lanvern (Finistère, France; after Hamon *et al*., 2021).

performed with the hammer as the mobile part of the equipment were aimed at morphologically modifying the metal, through drawing, bending, edging, cutting, punching, flattening, etc. Pressure processes acting in this mechanism lead to changes in the interior structure of metal, which is recognisable through metallography in the specific oriented appearance of the dendrites inside metal objects (Rovira Llorens and Gómez Ramos, 2003; Montero and Rovira, 2013). Such data suggest that during the Copper Age and the first part of the Bronze Age

manufacturing of metal objects was mainly based on cold hammering, combined sometimes with annealing.

The density of the rock selected as well as the morphology of the active surface of the tool are directly adapted to the different hammering actions, considering the diversity of actions and gestures associated with this stage for different kinds of objects (Armbruster, 2000, p. 49). In general terms, straight surfaces will accomplish the flattening of the contact surface, displacing the metal laterally, while a convex morphology will favour the curving or bending of the surface (Boutoille, 2015). Active surfaces of anvils tend to be located on the widest sides of the tools (obverse or reverse) and are straight or slightly convex. Hammering fronts include a higher morphological variability between straight and very pronounced convexity; they are usually narrower and can appear installed on different sides of the contour. Nonetheless, it is not always possible to discern between passive and active tools based on morphometrical parameters, as anvils and hammers constitute two closely related artefacts, some of which could have functioned in both ways.

All metal shaping tools fulfil at least two requisites: (1) their physical properties make them mechanically resistant against blows and (2) their highly smooth surfaces ensure the integrity of the metallic objects to be shaped without damaging them. Following these technological parameters, different types of tools can be distinguished. One of the most widely known types is represented by so called *cushion stones* (Butler and Van der Waals, 1967; Freudenberg, 2010), the name being highly expressive of their most important characteristic, namely their regular 'padded' appearance. All their surfaces were intensively prepared before use and more than one (or even all of them) could have been used for metal plastic shaping. Acute as well as right angles were erased through friction and converted to facets (fig. 8). Although they appear in earlier contexts such as the Bell Beaker (Fitzpatrick, 2011) they are typically associated with Early Bronze Age richly equipped graves such as Leubingen or Lunteren, central Europe (Butler and Van der Waals, 1967) or Los Cipreses, southwestern Europe (Delgado-Raack and Risch, 2006). The second type of tool has been frequently addressed as 'axe-shaped hammer with blunted edge' (Bertemes et al., 2000; Lynch, 2001). These hammers are equipped with a smooth active front instead of a cutting edge and were unequivocally used as the mobile part of the metal plastic shaping equipment. Such specimens have been frequently recorded from the Copper Age onward in Bell Beaker grave contexts (e.g. Künzig-Bruck, Bavaria; Bertemes, 2004) as well as in settlements (e.g. Cerro de la Virgen, Iberian Peninsula; Delgado-Raack, 2013), and also at other European Bronze Age sites (Boutoille, 2015; Hamon et al., 2020; Eguíluz et al., in press). Further types of tools are clearly

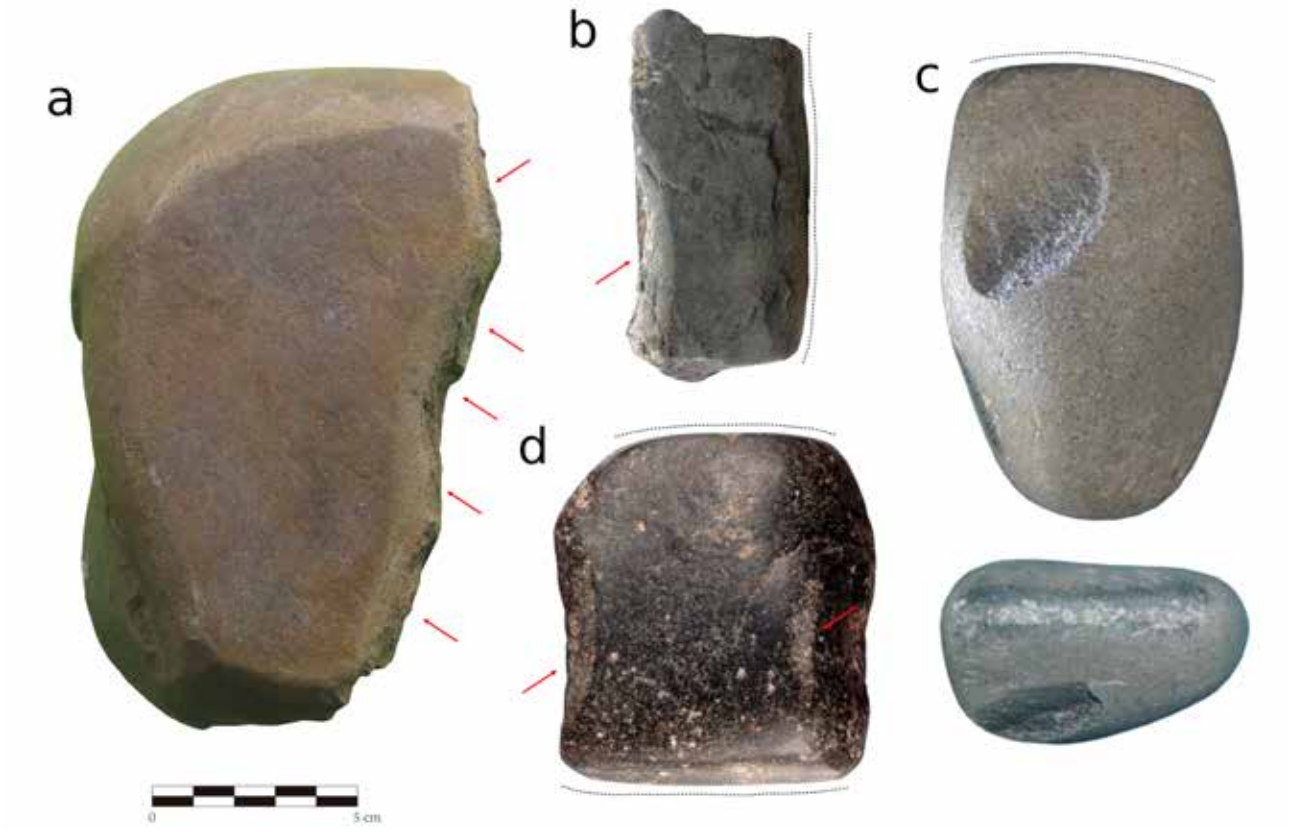


Fig. 8 – Metal plastic shaping stone tools from Bruszczewo (Poland; Delgado-Raack et al., 2020); Tira del Lienzo (Murcia, Spain), lateral view of the tool (Delgado-Raack et al., 2015); Los Cipreses (Murcia, Spain) (photo: Jesús Gómez Carrasco, 2005, Photographic Archive of the Archaeological Museum of Lorca); and Gatas (Almería, Spain; Delgado-Raack, 2008). Arrows indicate manufacturing facets; dotted lines indicate hammering surfaces.

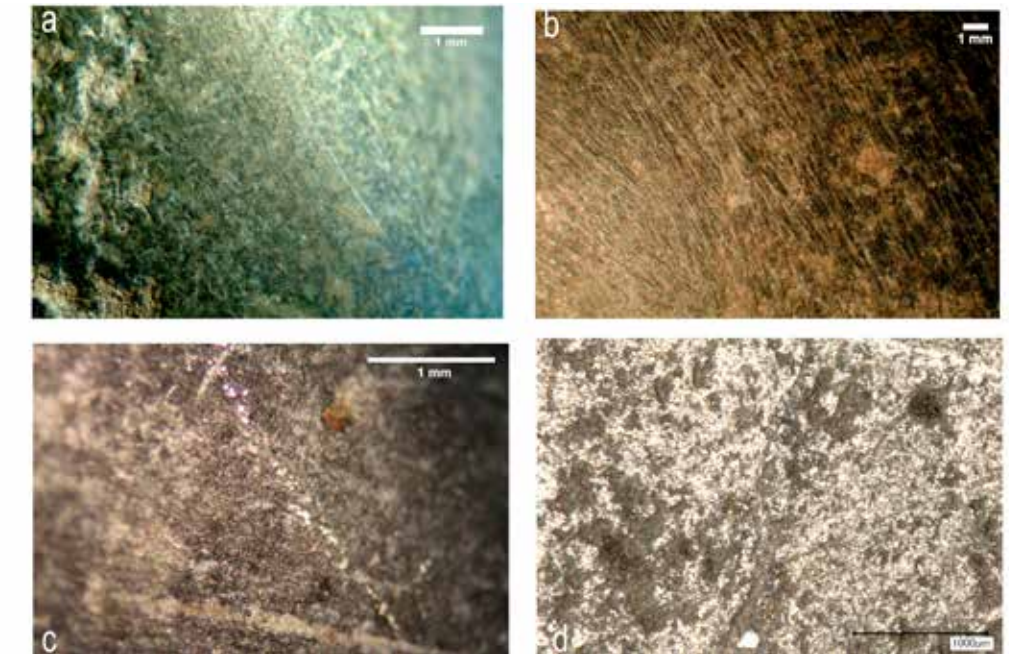


Fig. 9 – a: Hammer with blunted edge showing on its active front fine oblique striations (manufacturing traces) cut by pitting (use-wear traces; Delgado-Raack, 2008, fig. 4.1.66); b: Cushion stone covered by fine and dense striations (Delgado-Raack and Risch 2006, fig. 2); c: Silver linear trace located on a hammering surface (Delgado-Raack et al., 2015, fig. 5e); d: Gold remains filling up anfractuosities on anvil (Müller et al. 2023, fig. 7d).

more irregular in shape. This is the case of former stone battle axe heads which were reworked into metallurgists' tools in the Wessex culture in Great Britain (Crellin et al., 2022) and other broken pieces of artefacts, which were reused as anvils in the Únětice culture of Central Europe (Eguíluz et al., in press). Finally, thanks to use-wear and residue analysis, a series of plastic shaping tools have started to appear in the archaeological record that, contrary to the previously mentioned artefacts, were made of naturally rounded cobbles. Examples of this kind of tools have been documented, for example, in Bell Beaker graves from Hulín – Pravčice 2 (Peška, 2016, fig. 13), in the Bronze Age grave of Upton Lovell G2a (Crellin et al., 2022) and at the Iberian site of Gatas (Delgado-Raack 2008, fig. 4.1.66). Moreover, experiments have shown that the use of unmodified cobbles in metal plastic shaping is viable as they ensure a high degree of homogeneity of the rock (Müller et al., 2023).

Although metrical and use-wear analysis[6] have not been developed systematically, the available data include a wide metrical variability among the cushion stones ranging between 50 and 200 mm (Risch, 1995; Delgado-Raack et al., 2015; Ache, 2019). According to this, the active surfaces of some *cushion stones* are much larger than hammers while others fall in the same metrical group as the latter, offering only narrow or reduced surfaces for work. This means that they were probably embedded in a wooden stump as a stationary element, and were often extracted, rotated and inserted again or even used as a mobile tool. It is likely that metrical variability of the tools was linked to (a) the type of metal (gold, silver, copper, bronze) and (b) the type and/or size of the object to be transformed (ornament, weapon/tool). In this sense, lighter artefacts would be suitable for soft, precious metals such as gold (Boutoille, 2019), while larger surfaces corresponding to heavier tools would be needed for metal tools or weapons.

Besides the mentioned technological variability, all specimens analysed under the scope of use-wear seem to have common trace patterns regardless of whether they have wide or narrow fronts (facets). According to the recording system published by Adams et al., 2009, active surfaces display sinuous to flat topographies and regular microreliefs, in which abrupt slopes are absent. The most frequent use-wear pattern includes linear traces, strong levelling of minerals, polish, adherences and pitting. Following the chronological order of appearance, dense and shallow linear traces are still recognisable as remains of preparation of the surface before use (fig. 9b). Their distribution can be concentrated or covering and their borders have been gradually worn and smoothened due to the regular pressure of hammering with a softer material (metal) in between (Delgado-Raack and Risch, 2008, fig. 4). In the case of narrow active fronts of the axe-shaped hammers with blunted edge, these striations are oriented parallel to the longitudinal axis of the facet. The process of plastic deformation of metal objects itself provides the active surface with a homogeneously levelled aspect and a covering and highly reflexive polish with a close or even connected density (Delgado-Raack et al.,

6. Many publications refer to the general metrics of the tools, but few include the dimensions of the actual active surface involved in work. In a similar way, systematic descriptions of use-wear are still scarce for metal plastic shaping tools. This makes comparison of large data sets still difficult.

Site/Grave	Chronology	Artefact type	Residues	Bibliography
Groß Sarau (Northern Germany) – Dredging finds	Late Neolithikum (LNI)	2 anvils	Cu, Fe	Freudenberg 2009
Künzing-Bruck (Bavaria, Germany) – Grave 9	Bell Beaker	1 hammers	Au (75%), Cu	Bertemes et al. 2000; Bertemes 2004; 2010
Těšetice, Turovice (Moravia, Czech Republic) – Graves	Bell Beaker	2 anvils	Cu, Au alloy	Batora 2002: 199, 205 (cited in Peška 2016)
Hulín 1, Hulín-Pravčice 2, Opatovice (Moravia, Czech Republic) – Graves	Bell Beaker	2 anvils Several anvils	Cu, Au, Ag	Peška 2016
Hengelo – Elderinkweg (Netherlands) – Hoard	Bell Beaker	2 anvils and 1 whetstone	Cu, Au	Drenth et al. 2013; 2016
Zwenkau (Central Germany) – Cremation burial 1	Bell Beaker	1 hammers (nr. 32)	Au (42%) Ag (41%) Cu (16%)	Hänisch & Schneider 2005 (cited in Conrad 2009/10)
Hulín 1, Hulín- Pravčice 2 and Opatovic (Moravia, Czech Republic) – Graves	Bell Beaker	Several anvils and hammers	Au, Ag, Cu	Peška 2016
Milukovice 12/10, 13/8, 36/204, 60/6 (Bohemia, Czecj Republic) – Graves	Bell Beaker	4 pebbles / hammers	Au, Ag, Cu, Sn, Pb, Zn	Ernée et al. 2020: Tab. 40b
Franzhausen (Austria) – Graves	EBA	Several tools	Cu	Martin 2014
Upton Lovell G2a (England) – Grave	EBA	1 anvil and 1 hammer	Au, Cu	Shell 2000; Crellin et al. 2022
Tira del Lienzo (Iberian Peninsula) –Workshop	EBA	1 anvil/hammer	Ag (mainly), Cu	Delgado-Raack et al. 2015
Ploneour-Lanvern (Brittany) – Settlement	EBA	1 hammering and polishing tool (nr. 15)	Cu, Zn	Hamon et al. 2020
Tremuson la Colignière (Brittany) – Settlement	EBA	2 hammering tools	Cu	Hamon et al. 2021
Lannion Bel Air (Brittany) – Settlement	EBA	2 anvil, 2 abraders 2 hammering tools	Cu	Hamon et al. 2021
Bruszczewo (Poland) – Settlement	EBA	1 anvil	Au, Ag, Cu	Müller et al. 2023
Humanejos (Iberian Peninsula) - Grave	Bell Beaker	1 sharpener / whetstone	Cu	Muñoz 2017

Table 3 –Summary of cases in which metal plastic shaping stone tools have provided metallic residues.

2015). This glossy polish affects the most exposed points of the relief without reaching the deepest anfractuosities. Small impacts of percussion and isolated striations can appear scattered along the surface. Their interior is not as dark as the former preparation traces, and they clearly cut into the polished relief, evidencing occasional and accidental direct contact between both stone tools during work (fig. 9a).

Residue analysis can provide complementary data to use-wear analysis on gesture, angle, orientation and contact surface between the stone tool and the metallic object and is additionally relevant for the definition of the kind of metal worked. According to the published works (table 3), the quantity and nature of the preserved residues are diverse, and their comparison difficult to establish considering the numerous taphonomic biases involved in their preservation. Nonetheless, their preservation on the stone surface stands for a direct contact between stone and metal (hammering), opposite to the indirect contact (sheeting), which uses a layer of a flexible and thin material such as for example leather interposed between stone and metal (Perea, 1995). Given that they have been optically recognised and described at mesoscopic level, at the present state of the research two kinds of adherences can be noted. On the one hand, and most frequently, metallic residues appear as a bright and glossy linear trace of continuous or intermittent distribution overlapping former use-wear traces (fig. 9c). Their formation should be understood as an effect of accidentally scratching the metal object against the stone, similarly to the isolated striations mentioned above. On the other hand, residues stay adhered to the stone as tiny particles of plastic appearance loosely scattered or concentrated in certain areas. Examples of residues recorded up to now exhibit a matte green colour when they have a carbonatic composition (malachite) or are shiny (gold and silver).

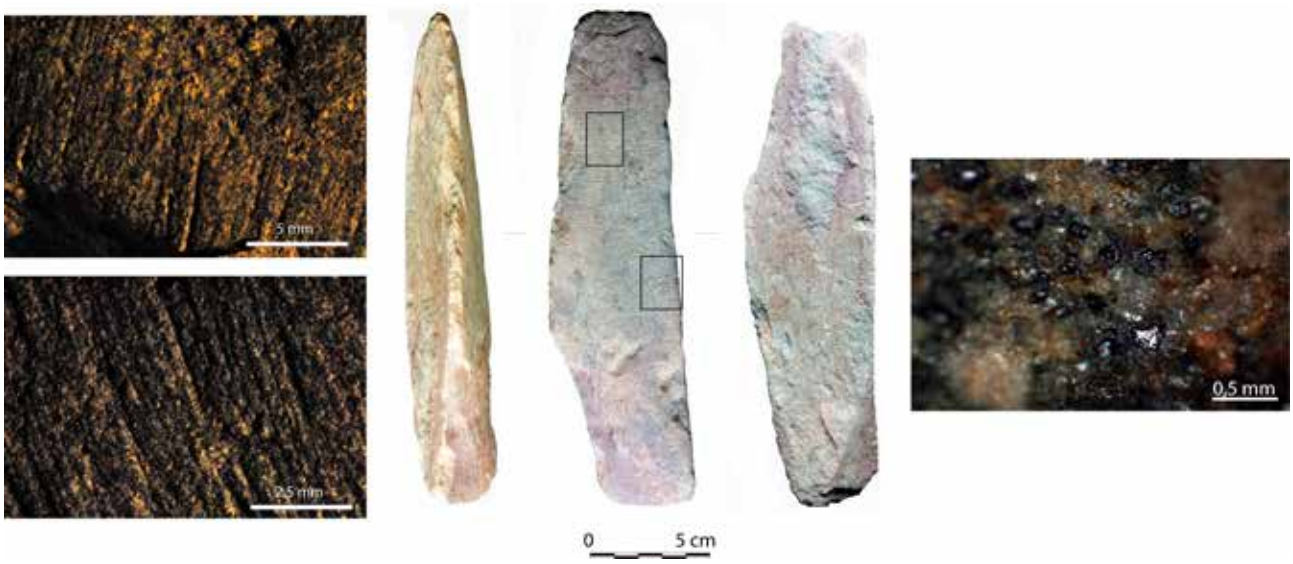


Fig. 10 – Example of finishing tool: sharpener on schist sandstone from Lannion (Côtes-d'Armor, France; after Hamon et al., 2021).

When they are sufficiently developed, residues can additionally suggest the gesture, as most of them remain in the anfractuosities of the topography after being pushed through hammering pressure (fig. 9d). Both distribution patterns of residues can be clearly distinguished from other patterns involving regular friction on metal (Müller et al., 2023). It is important to highlight that distribution and density of residues is not necessarily coincident with the distribution and density of the glossy polish mentioned above.

From the technical point of view, the position of metal plastic shaping in the metallurgical *chaîne opératoire* must have accumulated a high production value, judged from the final stages of metal manufacturing. At this stage metalworkers managed already transformed raw materials in society (mined, cleaned, smelted) and applied their technical knowledge and expertise, which was limited to a reduced part of the population. This included, among other things, controlling the mechanical properties of gold, copper and silver and, later on, bronze, under hammering mechanisms and especially when annealing was involved. In fact, the non-linearity of the plastic shaping constitutes the main difficulty of the task when it comes to conferring the desirable proportions, resistance and hardness on the metal object (Mohen, 1992, fig. 53; Coghlan, 1975, p. 90).

As research in the European continent on plastic deformation of metal goes on, this picture starts to diversify. Some data available for Copper Age Iberian settlements could suggest the existence of workshops managed at collective community level (Delgado-Raack, 2013). The most frequent types in this period are the axe heads with blunted edge. Although Bell Beaker graves equipped with anvils and/or hammers tend to include prominent grave goods, for specific regions such as Moravia it has been stated that the figure of the craftsman could have been subjected to a 'popularisation' process (Peška, 2016, p. 15). Some examples of stone tools with metal residues suggest that they were actually used before being included among the grave goods. The production devoted to metallurgical stone tools reached its climax during the Early Bronze Age, when they were most accurately manufactured, as several prominent graves show (Leubingen, Lunteren and Los Cipreses). Whether the buried individuals took an active part in metal plastic transformation or symbolically took over this role should be addressed in the future through (a) the enrichment of the empirical basis on systematic use-wear and residues studies of stone tools, and (b) other approaches such as anthropological ones (e.g. enthesopathies). For Early Bronze Age settlements, a dichotomy arises based on the coexistence of both workshops specialised in certain manufactures addressed to the elite (e.g., metallurgical and textile production; Delgado-Raack et al., 2015) and small workshops in which plastic deformation of metal took place at small scale (Hamon et al., 2020; 2021).

Finishing

For finishing operations, abraders, polishers, smoothers and sharpeners can be diversely used to shape, regularise or homogenise the surface of metal objects. Depending on the expected surface effect, the rocks selected can be abrasive and granular, to take off matter, or on the contrary very dense and regular, to smoothen the metal object's surface. The tools used are generally of elongated shapes, used in a transversal or longitudinal motion as suggested by the numerous striations covering the surface of these stone tools (fig. 10). In some cases, longitudinal grooves in the centre of tools or transversal incisions on their lateral edges can be visible and suggest the complementary use of different parts of the objects to shape their sides and edges.

The category of sharpener, used rather during the metal tools' life than during their shaping stage, is a little apart: their presence within assemblages and settlements should be more frequent, considering the regularity of their everyday use. In contrast to other types of tool, metal

polishers and sharpeners offer less probability of finding residues on their active fronts. In a functional study on perforated stone plaques from Bell Beaker funerary contexts found at the Iberian site of Humanejos, the author reports the observation of copper residues on sharpeners made of sandstone, slate and schist before cleaning and after 15 minutes experimentation, while only one out of 10 archaeological specimens analysed bear metal residues (Muñoz, 2017, p. 22 and 28-29).[7] One out of three whetstones analysed from a hoard context in the Bell Beaker site of Hengelo provided metallic residues (Drenth et al., 2013).

DISCUSSION AND PERSPECTIVES

The development of such investigations on the role of stone tools in metal object production should follow some guidelines in the future.

We cannot stress strongly enough the necessity of combining use-wear and residues analysis to obtain a complete overview of the tool's functioning. Another key point relies on the use-wear analysis of large series of tools, as the only reliable analytical strategy to detect possible candidates for metallurgists' tools. This use-wear approach combined with experiments can help detect ways of doing things specific to certain groups of craftsmen and workshops. Combined experiments and use-wear analysis of stone and metal objects would together be essential to refine the observations and test their plausibility and their relevance in regard to the characteristics of the finished products (Dolfini, 2011; Gutiérrez-Saez and Lerma, 2015). Then, on the basis of the identification of macroscopic residues or of best preserved micropolished surfaces, compositional analysis can be conducted by SEM-EDX, XRF or XRD, to refine the type of metal processed, and possibly determine the elements entering into its composition. The results could contribute to the discussions on possible small-scale exploitation of ores, in regions where they are suspected though their presence is not fully demonstrated (Le Carlier de Veslud et al., 2017).

To avoid interpretative bias, and enlarge our panorama of the contexts of production of the first metallurgies, such analysis should not only focus on mines or graves, but also consider stone tools found in settlement contexts. This should help track contexts of small-scale metallurgical production, linked or not to domestic units, and that are generally neglected or simply not clearly highlighted within the archaeological record, especially for the first copper production (Gandois et al., 2019; Obon, 2020). This observation is particularly true in the eventually frequent case of spatial segmentation of the metallic production. The smelting and casting operations have a particular connotation, due to the fireworks required, and their transformative value from rock to metal, and from metal to object. In contrast, sharpening and repairing should not be considered relevant clues, considering their daily use. Nonetheless, among shaping tools, a series of findings in certain European regions point towards a domestic development of some of the metallurgical tasks, which opens the door to a scenario of more widespread activities among Bronze Age communities than initially suspected.

To open new perspectives, a series of still pending questions can be listed.

First, the question of the arrival of metal on sites is key to understanding better the exchange routes and their structuration: detecting if ore or metal was circulating, and in which format it arrived at the sites, is of crucial importance in discussing the control of the resource and its exchange routes. By the time metallurgy was starting to expand in Europe, there are some examples that suggest ore was travelling long distances from the raw material source to the final context of use (e.g. silver in Tira del Lienzo: Delgado-Raack et al., 2015; gold in Bruszczewo: Müller et al., 2023). Whether metal circulated as ore, ingots or even half-finished products is also a matter of a wide analytical scope that should be carried out at superregional level.

Then, the shaping of objects in cold or pre-heated state is still not completely solved, and the choice of such or such technique is still under debate. The organisation of workshops and the transmission of the craftsmen's know-how is also still to be explored, to better understand the networks of mastering of these technologies, especially for the late Neolithic/early Chalcolithic periods. With the Bronze Age, the metal progressively replaced stone as a major mineral matter to exchange. The stone tools involved in metallurgical production are in the end a minor part of the general stone assemblages, but these particular implements are specifically selected to be buried in graves, to materialise the particular function or status of the deceased. The function of perforated stone plaques as possible sharpeners should also be subjected to systematic use-wear analysis, as they constitute emblematic objects, in Bell Beaker and Bronze Age graves (Butler and Van Der Waals, 1966-1967; Bátora, 2002; Turek, 2004; Fitzpatrick, 2011; etc.). As such, the tools may be considered as signature-objects, and the deceased as possible specialists.

From the point of view of the social role played by craftsmen, the mere fact that metallurgy was performed in regions where metallic ore was non-existent, must have implied that the artisans of this exotic raw material were special individuals in society. The so called 'metallurgist graves' are almost all related to adult males, who could have gained a long apprenticeship and enough expertise during their lives in order to directly perform such work processes. Taking for granted the direct participation of such individuals in the metallurgical work process and the remote distances existing between natural metal sources and some of the 'metallurgist graves', the possibility cannot be ruled out that these men moved within the wide system of exchange networks offering their know-how

7. This sharpener was recovered from a burial in direct contact with a metal dagger, although metal remains were preserved not only on the contact surface but also on the back of the tool. This should stand for a functional origin of the residues.

and services to the population of different countries (e.g. Amesbury: Fitzpatrick, 2011).

Finally, the reconstruction of the detailed *chaîne opératoire* of production along with a systematic study of skeletal remains (enthesopathies) should help clarify the relationship between metallurgical work and the most prominent figures buried in rich graves with abundant metal objects and the labour means needed for their manufacture. If they were not the direct executors of the metallurgical work, they were at least able to remove from the productive process not only a whole series of specialised work instruments but also weapons, tools and metallic ornaments, and keep them out of circulation, in a certain form of control.

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The spatial, social and political organisation of metalworking in southern Scandinavia during the Bronze Age (c. 1700–500 BCE)

Anna Sörman

Abstract: Production and use of metalwork in southern Scandinavia during the Bronze Age (1700–500 BCE) has above all been attributed to emerging elites. Bronze crafting is often assumed to have been organised at two levels: elite-controlled prestige goods production at centralised workshop sites, set against widespread (controlled or independent) production of utility objects in common households. However, this model is inferred from a functionalist view of finished goods (utility versus prestige) and inspired by anthropological theories, rather than from the material remains of production itself. With evidence of casting increasing due to large-scale contract archaeology, this paper presents an analysis of the craft organisation in the Nordic Bronze Age through the physical casting sites. Mould and crucible fragments, and their spatial relation to contemporary buildings and other activities, form the main focus of the analysis. These data demonstrate that bronzes were cast at most, if not all, settlements during the Late Bronze Age. Metalworking also occurred at small single farms; a production argued to be dependent on visiting specialists. The results thus confirm the idea of a hierarchical organisation of production from Period III onwards, but also reveal a complex, user-oriented and multi-tiered craft organisation. Prestige objects were manufactured in both longhouses and cult-houses within larger settlement complexes, seemingly in settings related to the status and gender of their intended users. Furthermore, casting often appeared in central and highly visible locations, suggesting it had the character of a performance. Considering the motifs behind the making of new objects, castings were probably linked to transformations such as initiations, inaugurations or establishment of new households. Thus, metalworking played an active and conspicuous role in social reproduction at various levels and arenas in Nordic Bronze Age societies.

Keywords: Nordic Bronze Age, southern Scandinavia, bronze casting, copper-alloys, metalworking, craft production, craft organisation, workshops, social organisation, elite, hierarchy, heterarchy, prestige goods, social reproduction.

Résumé : Dans le sud de la Scandinavie, la production et l'utilisation du métal durant l'âge du Bronze (1700–500 av. J.-C.) ont surtout été attribuées à des élites émergentes. Accumuler, porter, offrir et sacrifier des objets en bronze pour acquérir et maintenir le pouvoir social est considéré comme un trait essentiel de l'économie politique de l'époque. Ainsi, l'influence politique exercée sur la production du métal constitue un thème récurrent des recherches antérieures. Depuis les années 1950, on suppose une organisation du travail du bronze en deux niveaux : une production centralisée de biens de prestige contrôlée par l'élite, associée à une forme de production domestique plus basique et plus répandue (contrôlée ou indépendante). Cet archétype à deux niveaux repose sur une classification fonctionnelle des objets en bronze, combinée à des modèles anthropologiques d'artisanat spécialisé dans des sociétés hiérarchisées ou des chefferies. Cependant, les données archéologiques provenant de véritables sites de production ont rarement été consultées ou analysées de manière systématique pour confirmer ou remettre en cause cette vision. Avec l'augmentation rapide des découvertes liées au travail du métal grâce à l'archéologie préventive à grande échelle, il est devenu évident que ces concepts et interprétations doivent être réévalués.
Cet article présente les principaux résultats de la thèse de doctorat de l'auteure, soutenue à l'Université de Stockholm en 2018, dans laquelle l'organisation artisanale de l'âge du Bronze scandinave a été analysée à travers l'étude de sites de fonderie. L'analyse spatiale s'est appuyée sur trois échelles contextuelles : le type de site (par ex. un habitat), le type d'espace dans lequel avait lieu la coulée (par ex. une maison longue, une structure funéraire), et l'emplacement précis de la coulée (par ex. un foyer particulier et la zone d'activité autour). Les fragments de moules et de creusets, ainsi que leur relation spatiale avec les bâtiments contemporains et avec d'autres activités, ont constitué le cœur de l'analyse.
Le bronze était fondu et allié dans des foyers ouverts où la température nécessaire était obtenue grâce à un système de ventilation, dirigé vers le creuset placé dans le foyer. Les preuves de cette méthode résident d'abord dans la forme et les indices de vitrification des creusets de l'âge du Bronze, puis dans la présence de tuyères coudées en forme de L. Les fourneaux n'étaient pas utilisés pour le travail du bronze, contrairement à ce que supposaient de nombreuses recherches antérieures. Les foyers de fusion du bronze ne peuvent être identifiés que

par la présence de déchets liés à la fusion et à la coulée, et sont rarement détectables. Les vestiges les plus manifestes de la production métallurgique sont donc les débris céramiques provenant des creusets et des moules de coulée. Il est ici admis que les creusets et les moules représentent principalement des déchets secondaires, déposés à proximité immédiate des lieux originels de coulée.
Les données issues des sites scandinaves montrent que le bronze était coulé dans la plupart - voire la quasi-totalité - des établissements durant le Bronze final (c. 1100-500 av. n. è). L'enquête menée confirme l'hypothèse selon laquelle le travail du bronze était une pratique largement répandue, et non limitée à quelques sites exceptionnels. Contrairement à la Suède et au sud de la Norvège, on trouve des preuves substantielles de métallurgie dès le Bronze ancien au Danemark. Les vestiges des périodes I–III (c. 1700-1100 av. n. è) montrent que le bronze était coulé dans les sites d'habitat, à l'intérieur de maisons longues qui sont en général légèrement plus grandes que la moyenne. Cette concentration du travail du bronze dans ces maisons plus vastes pourrait indiquer un degré plus élevé de monopolisation spatiale – et sans doute politique – qu'aux périodes ultérieures.
Au Bronze final, le bronze était produit dans les habitations et sur les sites funéraires ou rituels, au sein du paysage habité. Le travail du métal avait également lieu dans de petites fermes isolées ; on suppose que cette production dépendait d'artisans itinérants. Les résultats confirment donc l'idée d'une organisation hiérarchisée de la production, tout en révélant une organisation artisanale complexe, axée sur les utilisateurs et à plusieurs niveaux. La distinction entre objets prestigieux et objets utilitaires ne structurait pas la production. L'organisation et la mise en scène des coulées dépendaient du rôle social des objets fabriqués. Les coulées semblent avoir eu lieu dans deux grands-types de structures : les maisons longues, où les gens vivaient et travaillaient, et les maisons cultuelles, davantage réservées aux enterrements et aux activités rituelles spécifiques. Des objets prestigieux étaient produits aussi bien dans les habitations que dans les maisons cultuelles. La production était mise en scène dans une variété d'espaces intérieurs et extérieurs, entre des tombes, près des maisons cultuelles, dans les maisons longues, dans les cours de ferme ou dans d'autres espaces communautaires. Cela montre que la production avancée de biens de prestige n'était pas organisée dans des ateliers spécialisés, isolés spatialement ou centralisés. Au contraire, des bronzes de grande valeur étaient fabriqués dans plusieurs types d'espaces et dans des circonstances variées.
À partir des empreintes identifiées dans les moules de coulée issus de maisons longues et de maisons cultuelles, l'auteure suggère que des types d'objets différentes étaient produits dans ces deux catégories d'espaces. Une séparation entre les armes associées aux hommes et les grands éléments de ceinture destinés aux élites féminines semble se dessiner. Cela signifierait que l'organisation artisanale était structurée par différentes institutions sociales. Plutôt que des ateliers spécialisés organisés pour le forgeron, les coulées étaient organisées spatialement en fonction de leurs futurs propriétaires. Les objets prestigieux étaient fabriqués à la fois dans les maisons longues et dans les maisons cultuelles, au sein de grands complexes d'habitat, dans des cadres liés au statut et au genre de leurs futurs utilisateurs. Enfin, le travail du métal se déroulait souvent dans des lieux centraux et très visibles, ce qui suggère qu'il revêtait parfois un caractère performatif. L'auteure discute donc de la manière dont la coulée – l'événement le plus spectaculaire du processus de fabrication du bronze – pouvait être exploitée dans des rituels publics ou semi-publics. Compte tenu des projets sociaux et des motivations derrière les nouveaux objets, les coulées étaient probablement liées à des transformations telles que des initiations, des inaugurations ou la fondation de nouveaux foyers. Ainsi, le travail du métal jouait un rôle actif et visible dans la reproduction sociale, qui prenait place dans différents lieux et à plusieurs niveaux dans les sociétés nordiques de l'âge du Bronze..

Mots-clés : âge du Bronze nordique, Scandinavie du sud, fonte du bronze, alliages cuivreux, métallurgie, production artisanale, organisation artisanale, ateliers, organisation sociale, élite, hiérarchie, hétérarchie, biens de prestige, reproduction sociale.

This study investigates the role of bronze casting in societies of the Nordic Bronze Age in the second and first millennium BCE. Instead of turning to the rich and often extravagant bronze objects, we will here turn our attention towards the subtle debris left over from this production process; fragments of crucibles and moulds.

Similar to many other regions and periods, studies of craft organisation in the Nordic Bronze Age have been preoccupied with the question of the link between metalworking and the elite. Accumulating, wearing, gifting, and sacrificing bronzes to gain and maintain social power is considered a key feature of Bronze Age political economy. Hence political influence over the production of the metal is a prevalent theme in previous research. The dominating interpretative model since the 1950s is that of a hierarchically organised production, with a domestic small-scale production at farms on the one hand, and a specialised crafting perhaps tied to workshops or elite residents, on the other (e.g. Oldeberg, 1960, p. 50; Rønne, 1987; Levy, 1991; Björhem and Säfvestad, 1993, p. 80; Jensen, 2002, p. 365; Kristiansen and Larsson, 2005, p. 225–227; Björk, 2007, p. 55; Goldhahn, 2007; Karlenby, 2011, p. 168; Nilsson, 2011; Ängeby and Lindman, 2017, p. 133).

The link between the elite and the production of bronze objects has been envisioned in different ways; for example, as a centralised production for redistribution (e.g. Weiler, 1994, p. 120–121; Carlie, 2004, p. 169), as an elite-attached craft worker producing on commission in a larger area (e.g. Björhem and Magnusson Staaf, 2006, p. 166), or metalworkers as ritual specialists in a wider sense (e.g. Goldhahn, 2007). These interpretations have mainly been based on the products (where a significant part is indeed made up of items such as weapons and personal adornments), or from selected sites in the data. These questions have never been systematically studied and rarely demonstrated through the production debris from crafting activities.

This paper is based on my doctoral dissertation, which aimed to study the metalwork production through the actual remains from bronze casting (Sörman, 2018). Traces of bronze casting have increased over the last few years, thanks to data emerging from contract archaeology. Apart from revealing more casting debris, large-scale excavations have also dramatically advanced our understanding of Bronze Age landscape-use, settlement organisation, the relation between funerary and domestic sites etc., at least for more well-excavated regions (e.g. Arturs-

son, 2009; Karlenby, 2011; Boddum et al., eds., 2012). These new insights, and the accumulated data from more than 100 years of archaeological excavations can now provide important windows into the whereabouts of bronze artefact production in this period.

This study demonstrates that the organisation of metalworking was indeed structured in a hierarchical way. The most interesting insights, however, emerge when we approach the bronze casting at a human scale, and explore the variation *within* sites at various scales of the 'settlement hierarchy'. Casting appeared in the midst of almost all social arenas of the later part of this period, and I suggest that bronze casting events were sometimes used to manifest the social order, where this part of the production sequence could take the form of public rituals.

AIM, SCOPE AND QUESTIONS

This study investigates the spatial organisation of bronze working in the Nordic region during the second and first millennium before the current era (c. 1700–500 BCE). The aim is to reconstruct how casting was organised in space, and what this spatial organisation and contexts, in turn, indicate regarding its role in society. The study investigates three sets of questions:

1) What does the casting debris found in excavated Bronze Age contexts represent, and how does it relate to the original production loci?

2) Where was casting carried out in relation to the settled landscape, at what spatial and social arenas were different bronze objects manufactured, and which factors can explain the choice of casting locus?

3) How may these new observations regarding spatial and social organisation of production illuminate the role bronze casting played in Bronze Age societies, and in particular the relationship between metalworking and the social elite?

Finally, some remarks on the theoretical points of departure. It should be emphasised that bronze metalworking in the Nordic Bronze Age is here regarded as a specialised or skilled craft, meaning that parts of the procedures in its *chaîne opératoire* demanded skills (relying on training and know-how) only attained by a minority of the society's members (but not presuming a specialised, full-time activity, see e.g. Nørgaard, 2018; Molloy and Mödlinger, 2020, p. 174).

In small-scale societies, crafts demanding exceptional skills were often regarded as depending on exceptional, supernatural powers (Helms, 1993, p. 53). The process of making objects with advanced technologies is therefore often central for the meaning and value of an object (Costin 2001, p. 27) and often stood in special relation to institutions of power (e.g. Helms, 1993; Hayden, 1998). The connection between such skilled crafts and political elites is well-established in ethnographic studies, but is known to have taken many different forms (e.g. Helms, 1993, p. 69). Models of attached, independent and embedded craft production in relation to the elite have been discussed (e.g. Earle, 1981). Such models have later been criticised for theorizing the connections between elites and specialised craft production in a too restrictive way (Costin, 2001, p. 300; DeMarrais, 2013). For the Nordic Bronze Age, with its many skilfully produced ritual and prestigious bronze objects, this aspect of bronze casting organisation and understanding the relations between bronze crafting and power is therefore crucial.

Ultimately, the aim is to better understand the socio-political role and cultural form of this craft, drawing inspiration from the scholarly discussion on technology as social action (e.g. Gell, 1998; Dobres, 2000). My primary interest thus lies in the socio-political aspects of production, rather than technological or archaeometallurgical issues.

BACKGROUND

To set the stage for the study, this background first introduces the Bronze Age of southern Scandinavia, with its metalworking tradition, society and archaeological remains. The second part discusses important trends and ideas in the previous scholarship about bronze metalworking and craft organisation in the Nordic Bronze Age.

The Nordic Bronze Age – an introduction

The Nordic Bronze Age is a loosely defined region, characterised by similar cultural expressions and joint influences in the period 1700–500 BCE (commonly divided into an early (c. 1700–1100 BCE, period I-III) and a late (c. 1100–500 BCE, period IV-VI) part). The 'Nordic' or 'south Scandinavian' Bronze Age encompasses Denmark with northernmost Germany, and the southern parts of the Scandinavian peninsula, within today's Norway and Sweden (Thrane, 2013; here: fig. 1). This area in northern temperate Europe is geologically and topographically varied; the south is part of the North European lowlands, while areas further north are marked by joint valley landscapes and mountainous areas. Populated zones during the Nordic Bronze Age were concentrated to the arable lands, primarily in low-laying valleys and plains, often in direct connection to bays, lakes and waterways. In this article this region is interchangeably named the 'Nordic area' and 'southern Scandinavia'.

The archaeological definition of the Nordic Bronze Age is primarily based on stylistic and functional similarities in the bronze metalwork (e.g. Montelius, 1885; Baudou, 1960; Sørensen, 1989, p. 458), but also on similarities in subsistence patterns and domestic architecture (e.g. Jensen, 2002; Thrane, 2013). It is important to note, however, that this region was far from uniform; there are regional and local variations in burial customs, the size and organisation of social formations, access to various exchange networks as well as in the production and use of material culture and metalwork.

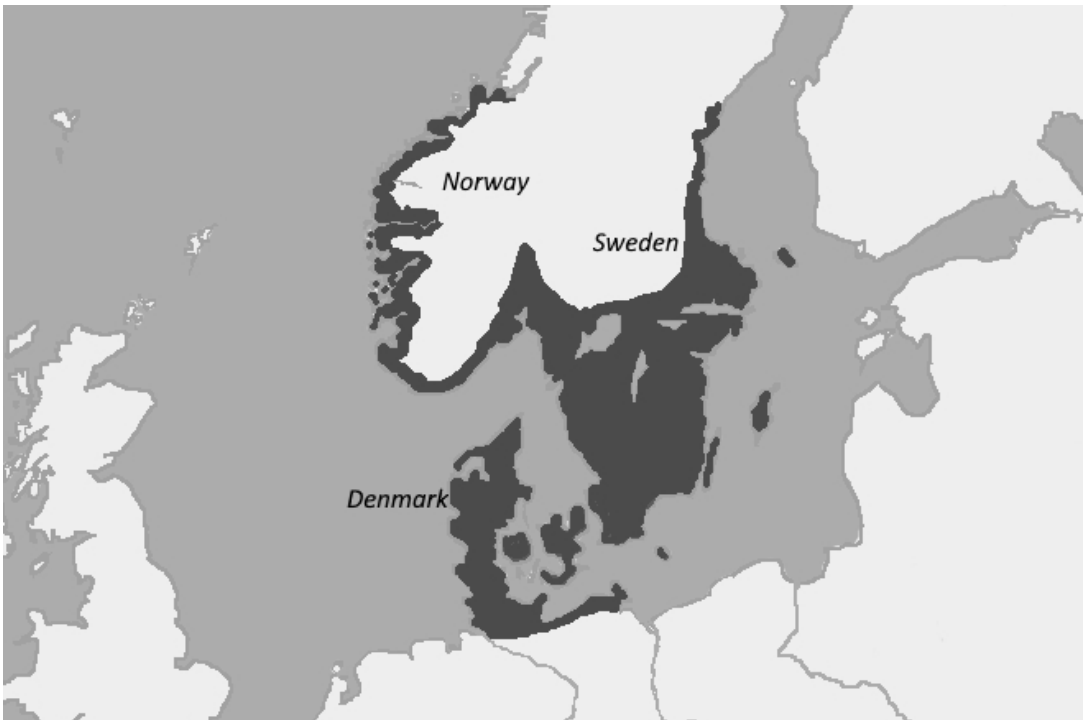


Fig. 1 – Map of Northern Europe with illustration of the approximate extension for the Nordic Bronze Age area in southern Scandinavia (illustration: Wikimedia commons, public domain, with edits).



Fig. 2 – Examples of bronze metalwork from the Nordic Late Bronze Age Period V, c. 900–700 BCE (illustration: Montelius, 1885).

Metals and metalworking

Bronze was used for making a variety of objects, notably in the Late Bronze Age when the repertoire of metalwork became more diversified (fig. 2). Throughout the period, local bronze objects have a strong element of prestige goods; with items such as cult and ritual props (including the famous curved bronze lure instruments, and the richly decorated horse tack and wagon ornaments), exclusive weaponry, and high-status adornments, signalling the bearers gender and social position in the politico-religious hierarchy (e.g. Levy, 1982; Sørensen, 1997; Jensen, 1997 and 2002). Common tools of bronze were socketed axes, socketed chisels, punches, awls and various sickles, however a large part of the tools used in the Bronze Age daily life were made from stone, horn and flint.

Copper was brought in to Scandinavia from other areas of Europe, as confirmed by compositional and isotopic studies of Nordic bronze objects over the last decade (Ling et al., 2013 and 2014; Melheim et al., 2018; Nørgaard et al., 2021). Local copper ore from the Scandinavian peninsula was thus not exploited in this period, at least not to any significant or detectable extent. External exchange networks and alliances for trade where Nordic communities participated in this 'bronzization' and long-distance connections is well-established (Vandkilde, 2016). Finds of unalloyed copper and ingots of tin and lead show that metals were also acquired in their pure forms (Oldeberg, 1942; Ling et al., 2014). Gold (from foreign sources) is also present, especially up until Period V, circa 800 BCE (Sørensen 1989, p. 464). Iron production was gradually introduced during the final stages of the Bronze Age, in some areas already in Period V (c. 900–700 BCE; Hjärthner-Holdar, 1993).

Nordic metalwork has a strong emphasis on casting —large, thin-walled objects were cast with lost-wax technique rather than produced via hammering and annealing (e.g. Oldeberg, 1942; Nørgaard, 2015, p. 125 and 2018). Melting bronze was accomplished in open hearths, where the necessary temperatures were achieved through forced draught as testified both by the flat, open shape of the crucibles, which are often heavily sintered along the rim, and by finds of L-shaped ceramic *tuyères* (Jantzen, 2008, p. 299; Sörman, 2018, p. 49–51; here: fig. 3). As we will see, this direct melting technique left very few traces in the ground, and the fire-places used for melting bronze can rarely be identified. Instead, the main body of Bronze Age casting remains in southern Scandinavia are indirect evidence from the production, the pear-shaped ceramic crucibles and pieces of the fragile ceramic moulds (bivalve or lost-wax). In some regions of the Nordic Bronze Age sphere stone casting moulds were also in use, however these were rarely left discarded at the production sites.

Bronze Age society and remains

The Nordic Bronze Age is characterised by small-scale agro-pastoral communities without defensive architecture or fortified central sites. The level of social hierarchisation probably varied between communities, but might have taken the form of small, unstable chiefdoms where power structures shifted over time (e.g. Levy, 1995; Artursson, 2009; Earle and Kristiansen eds, 2010). Habitations were loosely organised in multi-household settlements and single farms with longhouses for living and storage, complemented with smaller buildings and surrounding activity areas (Jensen, 2002; Artursson, 2009). The settlements, often covering several hectares, might be short-lived, or have long continuity throughout and beyond the Bronze Age. Settlement hierarchy is indicated both by size difference of longhouses, as well as multi-household settlements versus single farms (e.g. Artursson, 2009). Ritual sites and burial grounds are often located close to the settlements, sometimes on slightly (or dramatically, depending on the local topography) higher ground. Ritual depositions, mostly pieces or assemblages of metalwork intentionally placed at various points in the landscape, were abundant throughout the period (e.g. Levy, 1982).

In terms of geopolitical dynamics there are variations within southern Scandinavia. The southernmost areas and notably the Danish peninsula of Jutland is often seen as a bottleneck for access to the Continent; both via the landway, via Rhine, and via the North Sea and onwards to the Atlantic sea-bord. This privileged access to southern networks can be seen, for example, in the early influences and establishment of local bronze production (e.g. Karlenby, 2008a, see below).

This study is focusing on the north-eastern parts of southern Scandinavia, a less densely populated area where some of the most extravagant elite expressions of

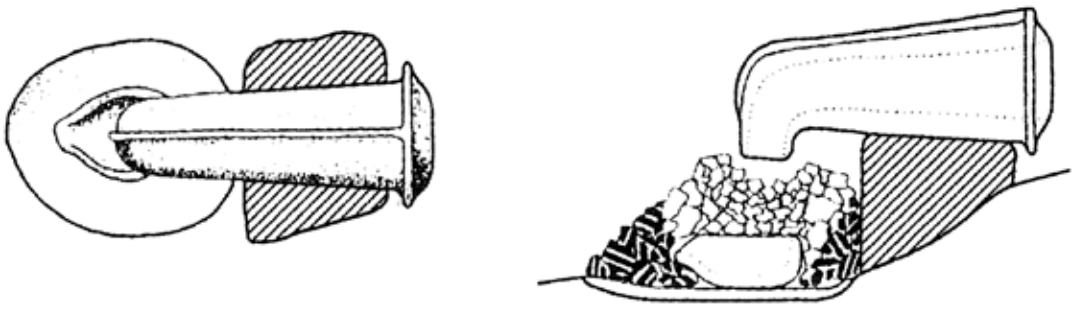


Fig. 3 – Principle for Nordic Bronze Age melting technique in simple hearth with L-shaped tuyère (drawing after D. Jantzen, 2008, fig. 5).

Nordic Bronze Age culture are not as pronounced as further south, and where local bronze casting seems to have made its appearance somewhat later.

The organisation of metalworking in southern Scandinavia – previous research

Surprisingly little research has specifically addressed the question of the organisation of bronze metalworking in southern Scandinavia (however see Levy, 1991; Jantzen, 2008). The interpretations and assumptions about this craft are numerous, but mostly occur in studies concerning other issues, such as political economy, settlement organisation or ritual specialists, or, in excavation reports for individual sites. In the following, I will highlight the theoretical and empirical underpinnings of current understandings of how bronze artefact production was organised.

1890–1950: The first 'bronze casters' workshops'

Local production of bronze metalwork in the Nordic area was suspected already by 19th century scholars, based on the indigenous design of Bronze Age metalwork (e.g. Worsaae, 1843). With time, more concrete evidence of this production emerged through finds of stone casting moulds and metallic casting debris, such as casting sprues in hoards. From the turn of the century 1800–1900 the first 'bronze casting workshops' were excavated in Scandinavia. These 'workshops' consisted of cultural layers containing ceramic crucible and mould fragments, found under presumed 'grave mounds'—mounds that turned out to be middens of fire-cracked stones dating to the Bronze Age (e.g. Neergaard, 1908; Sarauw and Alin, 1923; Svensson, 1940; Oldeberg, 1942, p. 165–171). The primary interest at the time was the technical issues of Bronze Age casting.

In the accounts of these excavations, and in the wider archaeological literature, the Bronze Age metalworkers were mentioned as highly skilled professionals, performing their specialised activity in workshops (e.g. Neergaard, 1908, p. 273; Oldeberg, 1933, p. 189 and 1942; Svensson, 1940; Jensen, 1956; Vestergaard Nielsen, 1956). There was also some debate as to whether these workshops had been integrated in the settlements, or rather had formed specialised crafting places, for example based on the absence of post-holes in the miniscule trenches (e.g. Neergaard, 1908, p. 282ff; Sarauw and Alin, 1923; Oldeberg, 1942, p. 171). This debate was somewhat premature, since settlements themselves were not yet known. The concept of the workshop used from this point has strongly influenced Bronze Age archaeology in Scandinavia throughout the 20th century.

1950–1990: Domestic production versus prestige goods

In 1960, when Andreas Oldeberg published the material from Skälby—a 'bronze casting workshop' in eastern Sweden that he had excavated in the 1930s—he expressed what had come to be the dominant understanding of Bronze Age metalworking organisation in Scandinavia up until today. Places like Skälby, with rich and numerous finds of ceramic casting residue (the site had yielded over 200 crucible fragments and over 400 mould fragments) were, according to Oldeberg, to be understood as 'workshop sites in proper meaning', while sites with only a few such finds probably represented small-scale domestic production (Oldeberg, 1960, p. 50). Two levels of production were thus envisioned for metalworking in Bronze Age Scandinavia—the specialists with their workshops, versus the domestic, small-scale production on farms.

With intensified construction projects in the 1960s and 1970s, leading to larger develop-led excavations, the first Bronze Age settlements were identified in Scandinavia. Questions about economic systems, subsistence strategies and economic specialisation were often main themes of interests during this period of processual archaeology. The presence and extent of bronze working was seen as an indication of the settlement's relative economic status; intensive workshop production or small-scale household production (e.g. Jaanusson and Vahlne, 1975; Björhem and Säfvestad, 1993). The market economist and industrial terminology in older literature is striking; workshop production at larger sites was assumed to aim at clients in a larger region and sometimes portrayed as mass production (e.g. Jaanusson and Vahlne, 1975; Coles and Harding, 1979, p. 497; Jaanusson, 1981, p. 21–22; Herner, 1987).

During this period, there was also a strong interest in the social structure and political economy, inspired by neo-evolutionary anthropological models for chiefdoms. The political control of the production of bronze objects became seen as a key factor in social hierarchisation (Levy, 1982; Kristiansen, 1987; Kristiansen and Larsson, 2005, p. 52; Vandkilde, 2016). Regional expressions in style and manufacture were considered as mirroring political units, territories or 'workshop spheres' [Swe. *verkstadskrestar*] (e.g. Levy, 1982; Larsson, 1986; Rønne, 1987; Kristiansen, 1987, p. 33–34; Herner, 1987; Kristiansen and Larsson, 2005, p. 35–37, 58). Such workshop spheres were regarded as distribution areas for centralised, chiefly controlled workshops/crafters (Levy, 1982, p. 93–100; Herner, 1987; Rønne, 1987; see also Costin, 2001, p. 306)—workshops defined based on the distribution of finished goods, rather than the workshops themselves.

This era also marked the discovery of the Hallunda workshop in eastern Sweden; a site which came to be a standard of reference in Swedish and Scandinavian research and to some degree also in northern Europe (Jaanusson and Vahlne, 1975; Vahlne, 1989). The Hallunda Bronze Age settlement, partially excavated in the 1960s and 1970s, featured extensive casting debris and a particularly large concentration of crucible and mould fragments, structures interpreted as bronze melting furnaces, and remains of a peculiar-looking building interpreted as a workshop (Vahlne, 1989; here: fig. 4). Hallunda, with its 'furnaces', strongly influenced the expectations of a Scandinavian Bronze Age bronze casting workshops in the coming decades.

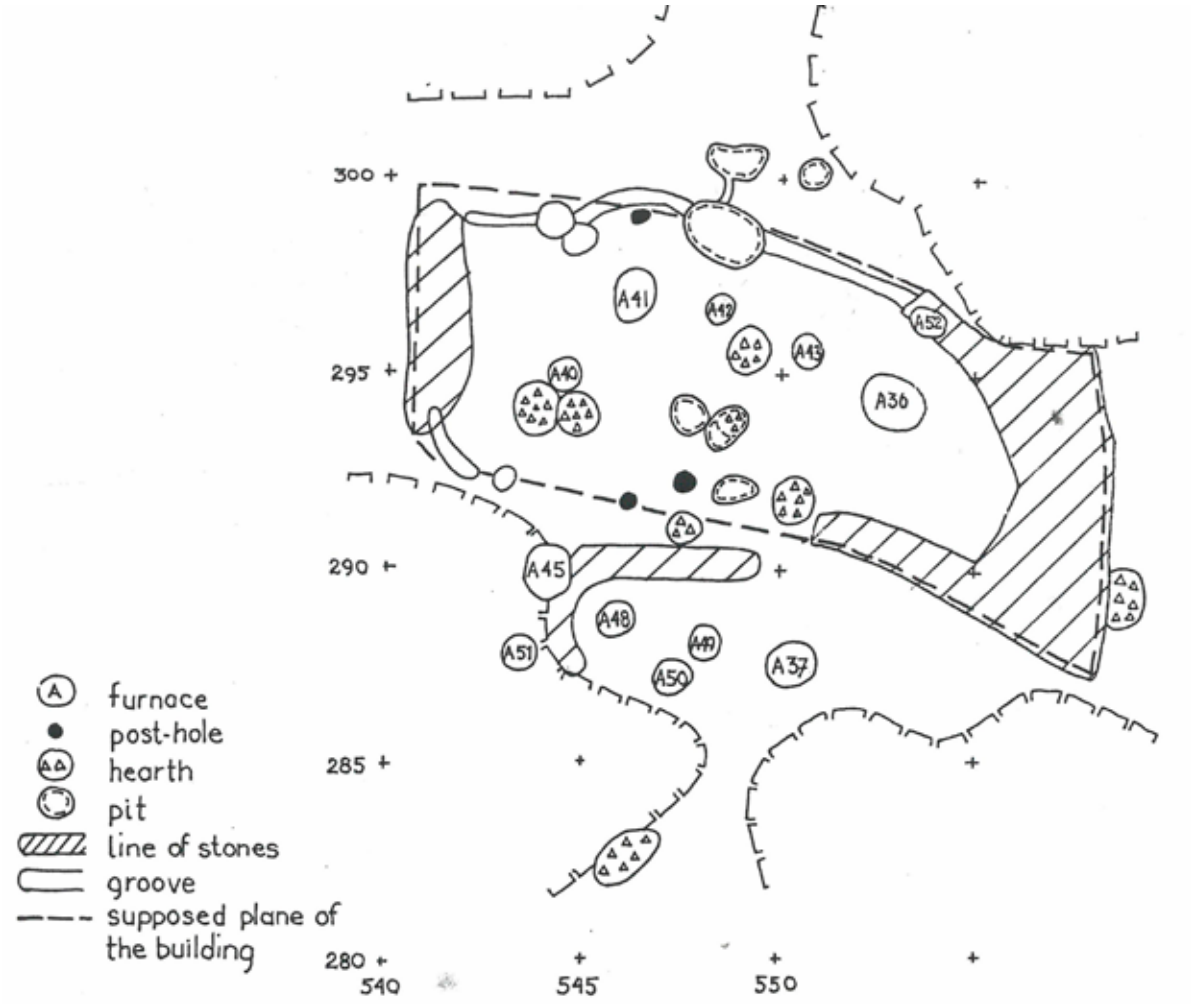


Fig. 4 – The bronze casting workshop with 'furnaces' at the Bronze Age settlement in Hallunda, Södermanland, Sweden (iustration: reworked after G. Vahlne, 1989, fig. 2).

1990–2010: Casting at cultic buildings and the bronze smith as ritual specialist

From the 1990s onwards, two new currents of thought can be observed in the research about bronze working. One of these currents was a critique against the idea of centralisation in craft where several texts pointed at the lack of empirical evidence supporting chiefly monopoly of bronze casting (e.g. Levy, 1991; Kuijpers, 2008 and 2013, p. 140). However, the link between craft and social power remained rather unexplored, as this critique did not result in clear counterproposals or new interpretative models.

Secondly, this period saw a growing interest in the ritual dimensions of prehistoric crafts, which also influenced the view on bronze casting in the Nordic Bronze Age (e.g. Budd and Taylor, 1995; Prescott, 2000). More attention was now given to the contextual evidence of casting remains at excavated sites. The find in 1986 of a cult-house with remains from casting activities at Sandagergård on the Danish island of Zealand was an important turning point. This stone-built, rectangular structure was associated with several urn burials, menhirs and rocks engraved with hand-signs, but also featured crucible and mould fragments (Kaul, 1987; here: fig. 5). Flemming Kaul, who published the site, argued that the casting debris should not be seen as signs of a 'profane' use of the building, but instead pointed out that "many of the bronze objects of the period may be seen in a prestige or ritual context, so there is no reason why bronze casting might not in certain circumstances have involved particular rituals" (Kaul, 1987, p. 43; see also Levy, 1991, p. 70). Kaul later suggested that cult-houses like Sandagergård might have been the place where young men were initiated and got to cast their own razor as a symbol of adulthood (Kaul, 1998, p. 44–45). However, as no mould fragments allowed for the identification of the objects cast at the Sandagergård this was a purely speculative proposal.

The contextual link between cult houses, burials and bronze casting in Scandinavia was later thoroughly explored by Joakim Goldhahn in his essay *Dödens hand* [Eng. The Hand of Death] (Goldhahn, 2007). Goldhahn pointed out that bronze casting debris is often found in connection to burials, not only at Sandagergård, but also at many other sites in Scandinavia, and that these contexts had previously been overlooked as a consequence

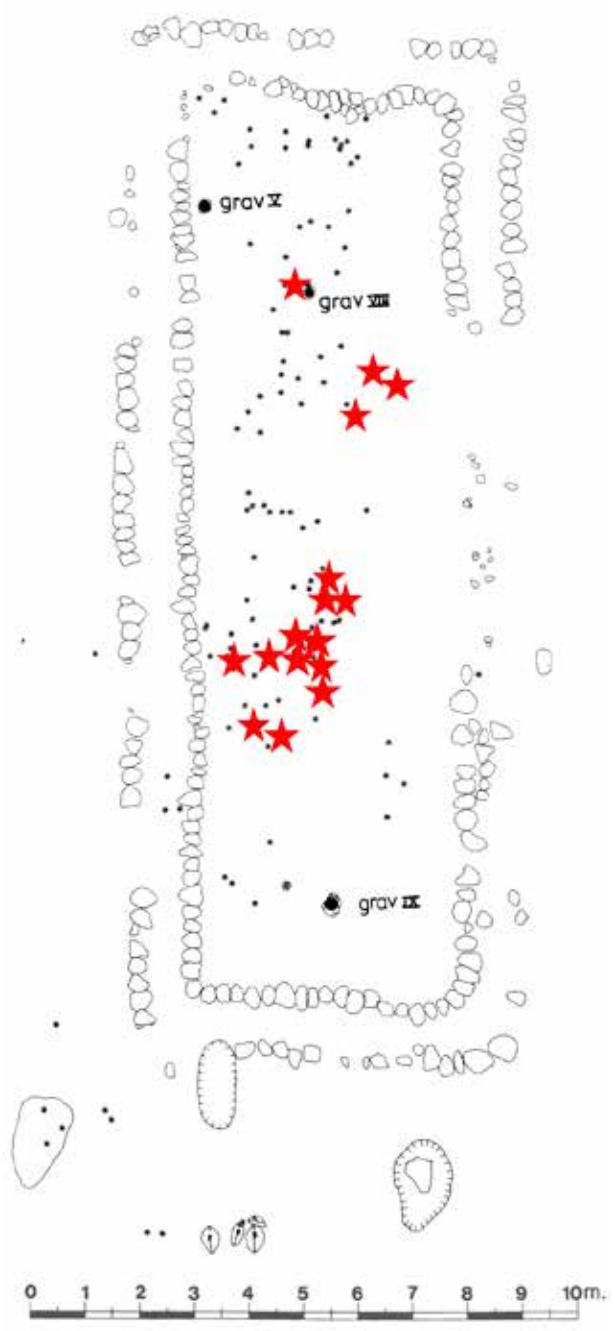


Fig. 5 – The cult-house at Sandagergård, Zealand, Denmark, excavated in 1985. The small black stars illustrate the general distribution of Bronze Age finds. The red stars represent fragments of crucibles and ceramic moulds. Three urn burials recovered inside the structure are also marked on the plan (drawing by Stig Grummesgaard Nielsen and Flemming Kaul, edited by the author).

of functionalist thinking and inability to appreciate the ritual aspects of specialised crafts in prehistory. He re-interpreted the previously mentioned Hallunda workshop as a cultic building, where the bronze casting had been carried out in parallel to cremations and funerary rituals, contemporaneous to the surrounding burials (Goldhahn, 2007 and 2013).

Inspired by post-processual thinking, Goldhahn and others discussed the role of bronze casting as cultural metaphor used to mark social transformations, notably linking metallurgy with the process of cremation and transformation of the dead through fire (Goldhahn, 2007 and, 2013; Melheim 2012; see also Brück, 2001). Goldhahn argued that bronze smiths functioned as ritual specialists, mastering several overlapping technologies, and that bronze casting and death rituals were technologically, spatially and metaphorically linked in the Scandinavian Bronze Age. One of his overarching arguments was that bronze casting was esoteric, often carried out in secret, in hidden or closed-off spaces, away from view. In parallel, he still envisioned a 'simple household production' at Bronze Age farms (Goldhahn, 2007, p. 323). What emerged was thus the same two-tiered organisational model as before, but where the smith in service of the elites was now seen in a new, cultic and ritually charged light.

2010–today: Large-scale excavations and widespread evidence of casting

Since the beginning of the 2000s, the number of larger contract-led excavations have increased in several regions of southern Scandinavia. This has also led to increasing amount of casting finds, evoking a discussion about the spread and degree of centralised control in production, and appeals to study this material closer (Sørensen, 2015). Sites with casting generally continue to be seen as either workshop sites or small-scale domestic production. One interpretation which goes beyond this traditional view was presented by Anne Lene Melheim and colleagues 2016, discussing the important 'workshop site' at the large burial ground at Hunn in southern Norway. This large burial and cultic site is suggested to have functioned as a seasonal trade and crafting site, where larger assemblies were initiated by chiefs, for honouring the dead, trading and for producing bronze objects for redistribution (Melheim et al., 2016). This perspective is interesting because it proposes new angles on the character of production through studies of the context at the site —hypothesizing about the social realities that might hide behind terms like 'central workshop site'.

During the last fifteen years there have also been efforts to synthesise the finds from bronze metalworking in southern Scandinavia, or parts of the region (Jantzen, 2008; Boddum et al. eds., 2015). The most ambitious study so far is the *Quellen zur Metallverarbeitung im Nordischen Kreis der Bronzezeit*, by Detlef Janzen. While published in 2008, the study was finished already in 1993, and it therefore does not include more recent, large-scale excavations of Bronze Age settlements and casting sites (Jantzen, 2008). Nevertheless, the detailed studies of refractory debris, casting techniques and find contexts led Jantzen to draw many important conclusions. Several of these conclusions are interesting stepping-stones for this study. In terms of

the social organisation, Jantzen broadly follows the traditional model, of workshop production versus small-scale household production (Jantzen, 2008, p. 300ff). Jantzen's most important result, in my opinion, is how he defines the character of production, based on a synthesising view of casting debris and casting sites, where the flexible and spatially wide-spread craft production is emphasised:

> Nach diesen Beobachtungen läβt sich überall dort, wo das einfache Schmelzverfahren im Tiegel praktiziert wurde, der typische Arbeitsplatz eines bronzezeitlichen Gieβers durch eine ebenerdige oderleicht eingetiefte Feuerstelle („Schmelzplatz") definieren, die in einigen Fällen um eine Grube oder eine mit Steinen umgebene Fläche zum Vorheizen von Gieβformen erweitert sein kann. Die Einfachheit des Verfahrens ermöglicht es sogar, bestehende Feuerstellen kurzfristig zum Bronzeschmelzen zu benutzen; vielfalch dürften Fundstücke wie Bronzetropfen, Tiegel- und Formfragmente dann die einzige Möglichkeit bieten, diese Nutzung überhaupt nachzuweisen. Umgekehrt folgt daraus, daβ ein derart einfaches Verfahren auch eine hohe Mobilität zuläβt und an nahezu jedem Ort betrieben werden kann, ohne daβ zuvor besondere Anlagen errichtet werden müssen. (Jantzen, 2008, p. 299)

Summary

In the previous research, two central ideas regarding the organisation of bronze casting in the Nordic Bronze Age have been particularly influential. First, the notion of workshops as the prominent place for specialised metalwork. The idea was established early, with the discovery of the first 'bronze casters' workshops' around 1900, and with time enhanced by theories promoting centralised and specialised forms of production. The idea of casting workshops became further established with the discovery of the Hallunda workshop in Sweden, published in the 1970s. As I have discussed elsewhere (Sörman, 2017), this steered expectations of what to find in the archaeological record, and might partly explain the low interest in the somewhat underwhelming casting finds that followed.

A second key idea is the concept of a two-tiered, hierarchical organisation of bronze artefact production in Nordic Bronze Age society. A specialised workshop production (more explicitly tied to the elite) on the one hand, and small-scale household production on the other. This idea was established in the mid-20th century, based on an observation of the difference in quantity of casting remains between sites. This is problematic, as the quantity of debris often reflect preservation conditions rather than original intensity of production. I argue that we, besides quantity, must give more attention to the quality, content and context of production within sites to better understand the organisation of the craft.

ANALYSING CASTING SITES IN SOUTHERN SCANDINAVIA

Introduction

Analytical approach

To study the spatial organisation of bronze working, three different levels of scale are considered in this analysis: the type of site (e.g. settlement), the type of arena where casting took place (e.g. longhouse, burial ground), and the precise setting of the casting (e.g. a particular fireplace and the immediately surrounding activity area). The contexts of casting debris and their distribution inside and outside houses and between activity areas are thus key. While the first level concerns the production in relation to the larger settlement pattern, the second and third levels concern the human scale, and let us hypothesize about aspects such as visibility, placement, and perception of the casting event.

Source criticism

Throughout this analysis, we must be aware of the source critical limitations of casting debris (principally crucible and mould fragments). I want to draw attention to three points in particular. Firstly, casting debris do not represent the full *chaîne opératoire* of making a bronze object, but only the process of casting the object into shape. Other steps in the manufacturing process, for example preparing ceramic moulds or making the finish on the object, possibly happened elsewhere, and are generally much more difficult to trace archaeologically.

Secondly, it must also be considered that casting debris is fragile and easily exposed to weathering processes. Sometimes mould fragments are observed during excavation, but too degraded to be collected (Eriksson, 2003, p. 129, 133). Experimental casting with lost-wax moulds has demonstrated that fragmented ceramic moulds, left on the ground and exposed to the elements and human passage, degrade quickly and can disappear completely within a few days (Nordez, 2019, p. 216). The preservation of cultural layers and ancient ground levels is another key factor. Therefore, ceramic casting debris in archaeological contexts is generally underrepresented, and this debris does not represent the original production or totality of debris once present.

Thirdly, this material is a bi-product from production, meaning indirect evidence in the form of waste. It raises questions about the relation between the find contexts for the debris and the context of the casting. The link between fragmented crucibles and ceramic moulds, and rare cases of metallic debris, and the original casting activity must be deduced from the location, context and conditions of deposition. In this exercise, a differentiation between production deposition (in primary, *in situ* position at the casting site), waste deposition (in secondary position, for example in waste pits or swept aside) and intentional

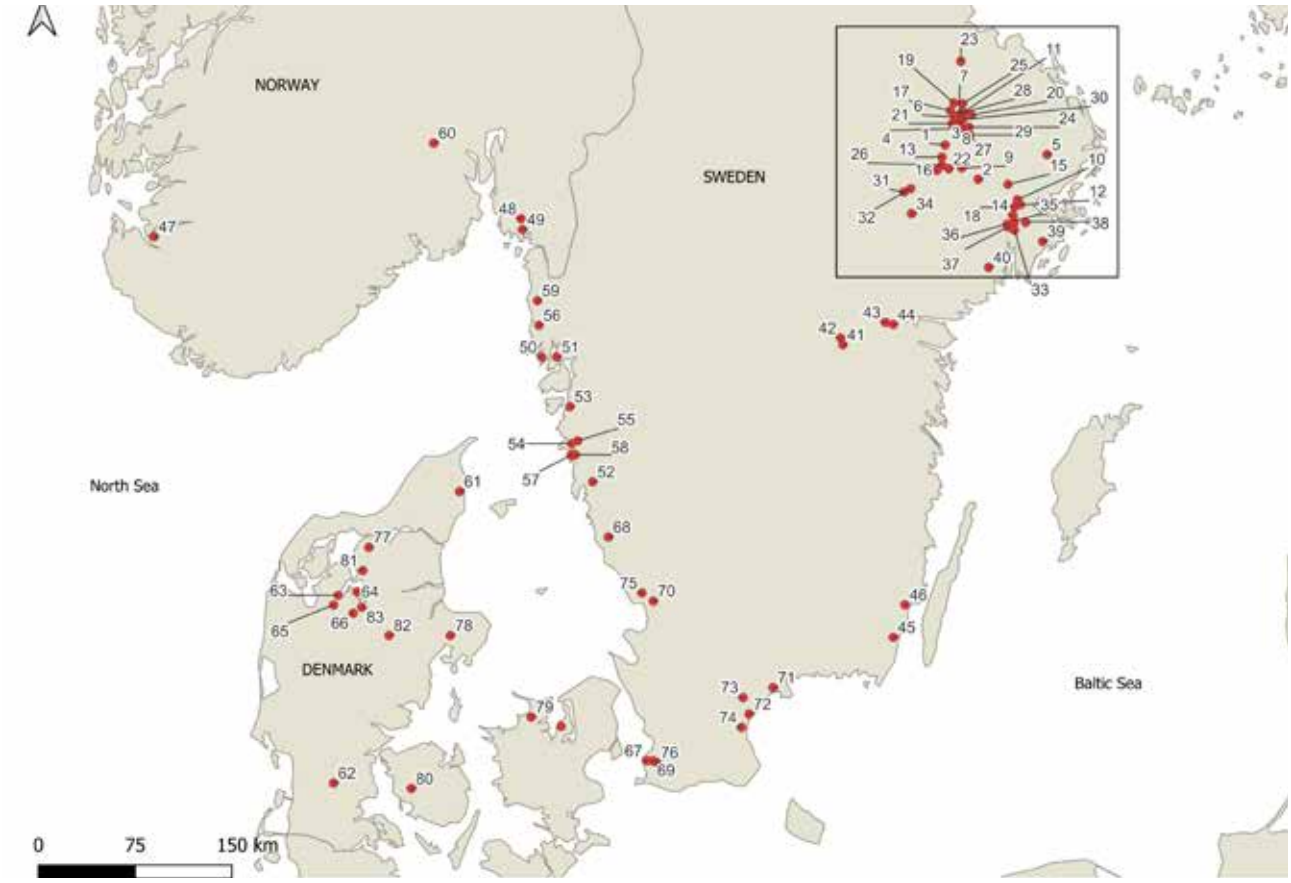


Fig. 6 – Map of southern Scandinavia with excavated sites featuring Bronze Age crucible and/or mould fragments included in this study. The case study area in southeastern Sweden is marked out with a rectangle. Numbers refer to the site list presented in table 1. For more detailed information and references, see Sörman (2018).

deposition (secondary or tertiary position where objects have been reused or buried as part of rituals etc.) is useful to distinguish the quality of the data (Sahlén, 2011, p. 150). Since intentional, ritual use of casting debris has been argued for find material in cult-houses and burial grounds (e.g. Melheim, 2012, p. 257; Ängeby and Lindman, 2017, p. 129, 133; as well as for British finds see discussion in Molloy and Mödlinger, 2020, p. 183), this question must also be evaluated in this study.

Introducing the dataset

A case study area in south-eastern Sweden, including the counties of Södermanland, Närke, Uppland and Västmanland (fig. 6) was chosen for a more thorough investigation. In this area, a full overview of excavated Bronze Age sites was sought for, and the presence and absence of casting finds was comprehensively evaluated against the full dataset of all excavated Bronze Age sites (Sörman, 2018, appendix 1 and 2). Other areas of southern Scandinavia, here including Denmark, Norway and the rest of southern Sweden, have also been included but treated more summarily (fig. 6). Studying the whole area in equal detail would have been far too time consuming, especially as the primary data (in the form of excavation reports) are still largely analogue and difficult to access. For these areas, the aim has been to contribute to overview, based on accessible reports and previously published finds. More sites certainly await discovery in the 'grey literature'. However, the sites presented here; 40 in the case study area and an additional 44 sites in the rest of Scandinavia (see infra table 1), are numerous enough to create a representative overview of the phenomenon.

Results: What does the casting debris found in excavated Bronze Age contexts represent?

Production deposition

The clearest example of a melting hearth observed in the material included in this study, was found during a settlement excavation in Bredåker, eastern Sweden in the beginning of the year 2000s. Ceramic mould and crucible fragments were recovered from several locations within a partially excavated Late Bronze Age settlement (Frölund and Schütz eds., 2007). An area with a dense concentration of crucible fragments, mould fragments and small bronze droplets, was interpreted as a workshop area for bronze casting (Schütz, 2007). Small, pea-shaped bronze droplets were found around the hearth A1516 (one droplet was also found in the hearth-fill), revealing that this fireplace had been used for melting bronze (Schütz, 2007, p. 36; here: fig. 7). Experimental castings with ancient methods carried out by Anders

Söderberg have demonstrated that such metallic droplets and small melts, that occur when manipulating the crucible with molten bronze, is a strong archaeological indication of areas and fire-places used for bronze casting (Söderberg, 2002). Such metallic debris might not always be preserved, and might also be too corroded for identification with metal detectors. These preservation issues, and the fact that most spill-bronze is likely to have been collected for recycling, explains why such finds remain extremely rare.

Another possible example of a melting hearth where droplets were found close to a fire-place with casting debris, was found at the Late Bronze Age settlement at Fragtrup on Danish Jutland (Draiby, 1985). In Fragtrup, a charbon-rich layer deposited in the yard between two (partly contemporary) longhouses from Period V-VI (c. 900–500 BCE) contained ceramic mould fragments and two small bronze droplets, together with other waste (Draiby, 1985, p. 162-163; here: fig. 8).

Hearths or hearth pits with indirect evidence for bronze melting in the form of ceramic casting debris around and in certain features show the variety in both hearth construction and context of casting; from simple hearth pits at the yard of a longhouse: Tallboda (Äijä et al., 1996), to a stone-lined rectangular hearth on a terrace in front of a cult-house: Åbrunna (Strucke and Holback, 2006), large, stone-lined oblong hearths with casting debris and bronze melts at a burial ground: Bromölla (Petré, 1959), but also from indoor hearths in longhouses, like at Early Bronze Age Store Thyrrestrup (Nilsson, 1996) and Late Bronze Age Apalle (Ullén ed., 2003; Sörman, 2019; here: fig. 9). What characterises a hearth or hearth pit used for melting bronze, as pointed out by Thomas Eriksson (2003, p. 145), is not special construction details, but the addition of a forced air-flow.

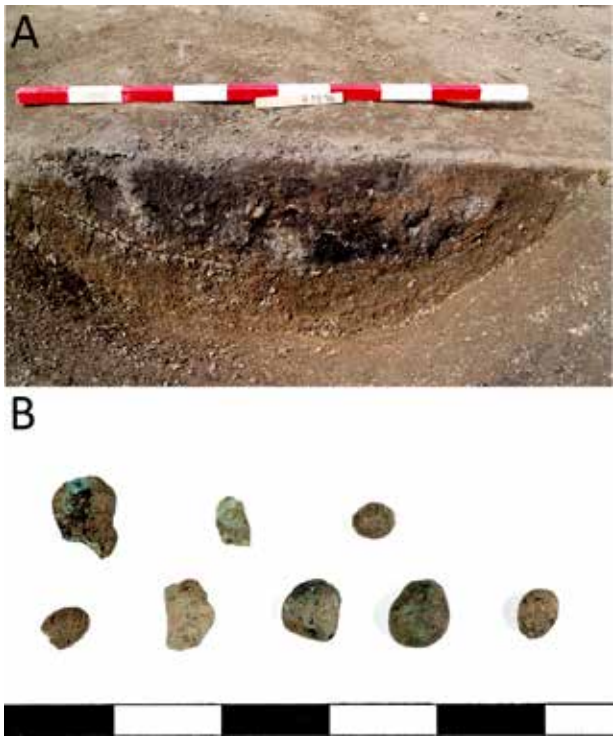


Fig. 7 – Melting hearth and bronze droplets from a Late Bronze Age settlement at Bredåker, Uppland, Sweden. A: Hearth identified as used for melting bronze, based on finds of bronze droplets and casting debris found in and around the feature (photo: Berit Schütz, Upplandsmuseet); B: Spill from bronze casting, in the form of small pea-shaped melts found at the casting loci (photo: Bengt Backlund, Upplandsmuseet).

Casting debris which can clearly be identified as production deposition—within or around particular fire-places—remains rare in the dataset over all. This rarity is due to the recycling of metallic debris and the limited preservation of crucible and mould fragments as ancient ground levels are generally heavily eroded or completely ploughed out.

Waste deposition

Most crucible and mould fragments have been recovered from cultural layers, and can be categorised as waste deposition (Sörman, 2018, appendix 2). The second most common find-contexts are secondary fills in features such as pits, pit-systems or post-holes. When found in burial structures, casting debris are part of fill-material rather than included in burial depositions or special deposits, indicating that they are re-deposited waste from earlier/contemporary activities at the site, rather than intentionally placed (Sörman, 2018, p. 133). Casting debris in cultural layers seems to be waste discarded near of where the casting took place, similarly to other waste material found within settlements, cultic sites or on burial grounds.

Intentional deposition

In a few cases, casting moulds have been subjected to intentional deposition as house offerings in Late Bronze Age longhouses. In two cases, complete bivalve moulds for socketed tools have been deposited intact (with both halves) in post-holes: one ceramic mould for a socketed chisel deposited in a house in Degeberga in Scania, southern Sweden, and one stone mould for a socketed axe from a longhouse at Forsandmoen, Rogaland in southern Norway (fig. 10). In these cases, the production of a tool for the household seems to have been associated to a protective or founding deposition in the house (Sörman, 2018, p. 190–191).

Conclusion – melting hearths and waste deposition

Production deposition of casting debris *in situ* in or around specific melting heaths is rare. Instead, fragments of moulds and crucibles are commonly found as secondary deposits in cultural layers, pits or mounds of fire cracked stones. Exceptions are a few cases of intact moulds for socketed tools, ritually deposited as house offerings during the Late Bronze Age. I therefore argue that most crucible and mould fragments found at excavated Bronze Age sites represent waste depositions, deposited in close vicinity to the original casting loci. This evidence can therefore often provide good indications about the spatial organisation of casting.

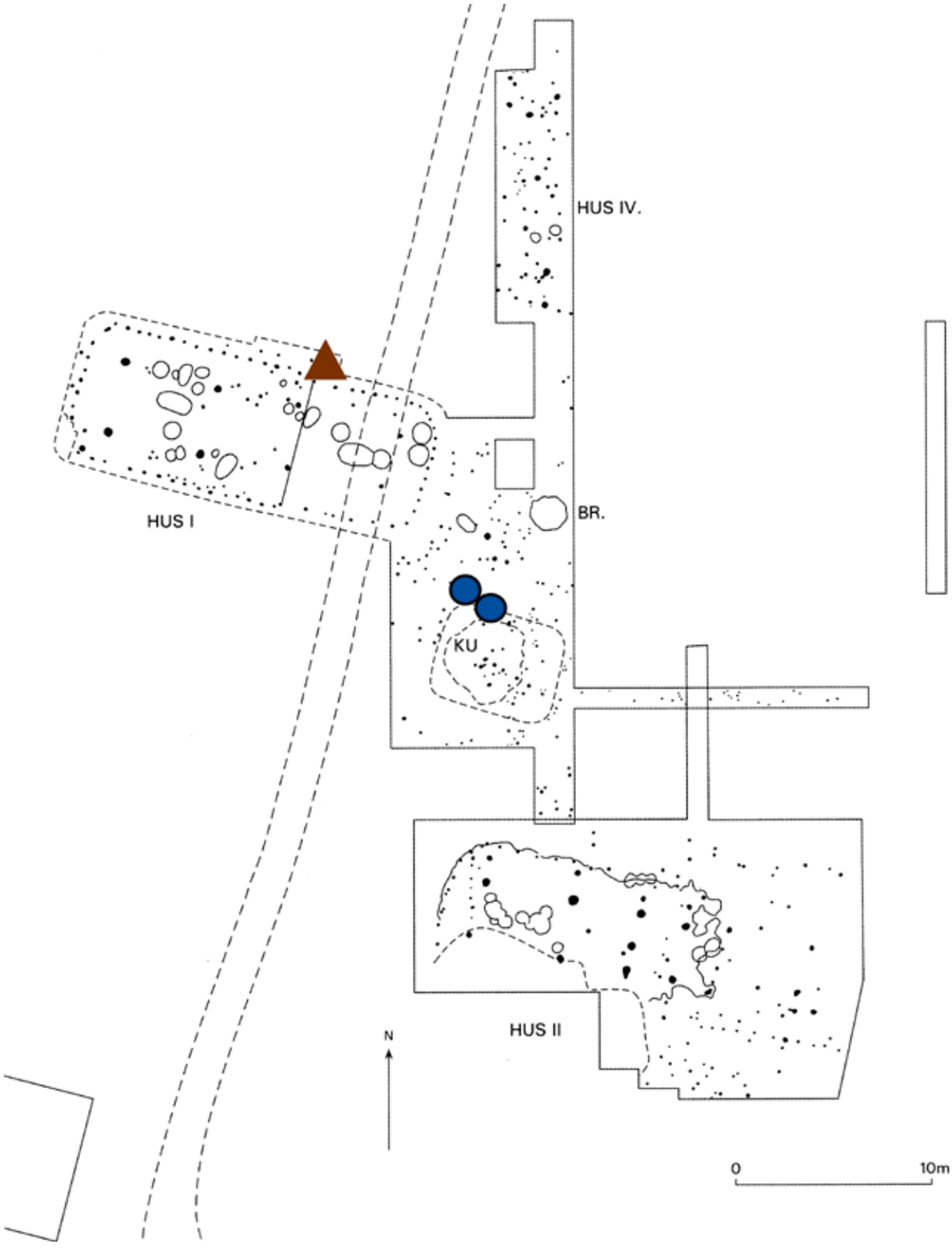


Fig. 8 – The Fragtrup settlement at northern Jutland, Denmark. Between the longhouse remains mould fragments (blue circles) and small metal droplets were found. Next to house 1 a crucible fragment (brown triangle) was also recovered. BR = well, KU = cultural layer with sand, coal and fire-cracked stones (reworked after B. Draiby, 1985, fig. 3, and D. Jantzen, 2008, plate 77).

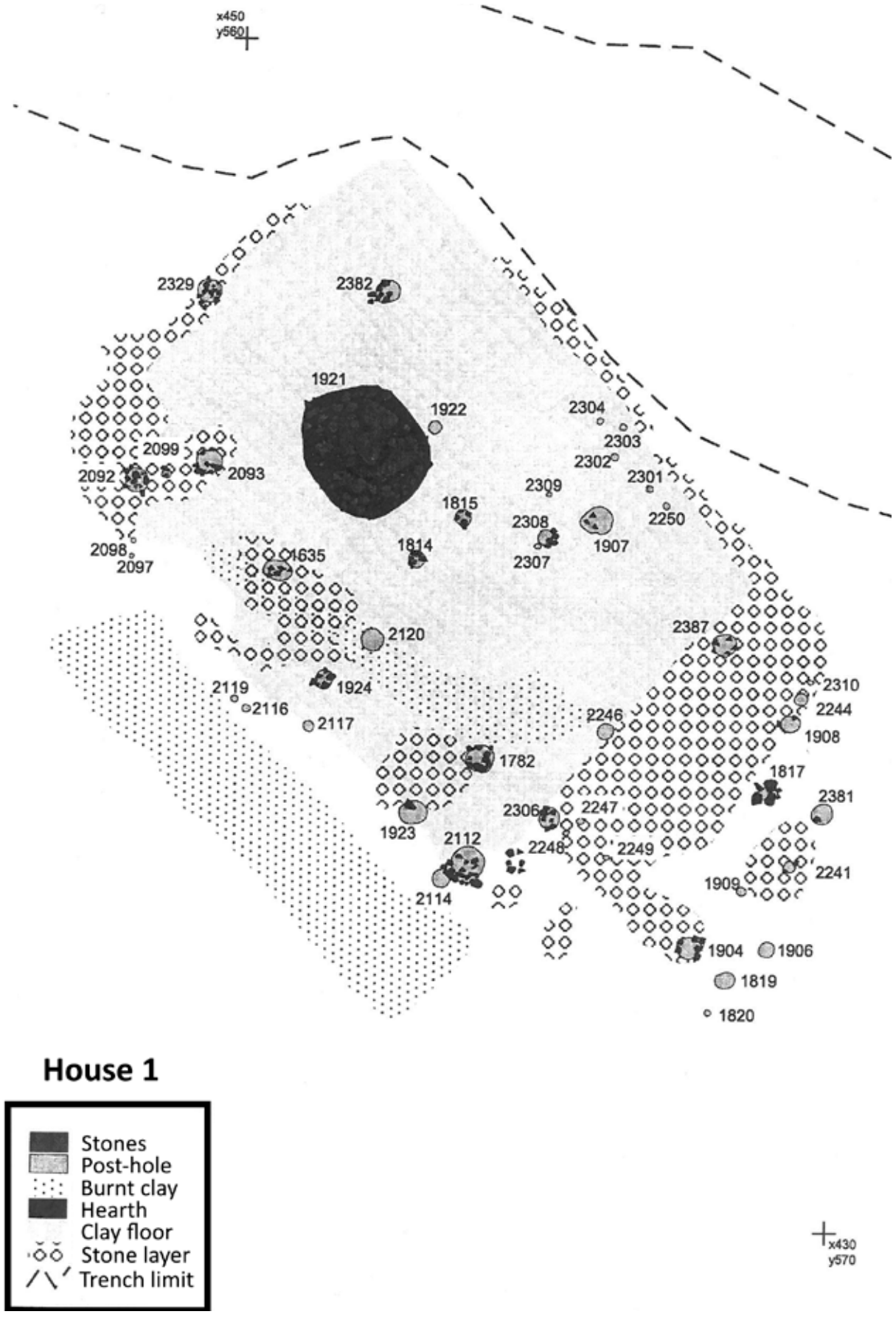


Fig. 9 – Longhouse (K2) from the Late Bronze Age at the Apalle settlement in eastern Sweden. The house is dated to settlement phase 5, roughly corresponding to Montelius Period V (c. 900–700 BCE). Recovered from the hearth (A1921) was a fragment of a casting mould, possibly for a hanging vessel (reworked after I. Ullén, ed., 2003, house catalogue).



Fig. 10 – Stone mould for socketed axe, intentionally deposited in post-hole of a Late Bronze Age longhouse at the Forsandmoen settlement in Rogaland, southwestern Norway. (photo: Olle Hemdorff & Trond Løken. Arkeologisk museum, UiS).

Results: In what spatial and social arenas were different bronze objects manufactured?

The following section presents an overview of the spatial organisation of bronze casting in southern Scandinavia, illuminated by a few representative examples. We will begin by the sparse evidence from Early Bronze Age. Thereafter, the two primary social arenas for bronze casting in the Late Bronze Age; longhouse milieus and cult-house milieus will be discussed. Finally, we will look at the rare cases where bronze metalworking is indicated at small, single farms, before ending this section with a summary and interpretation of the findings.

Early Bronze Age – casting at settlements and large longhouses

Casting debris that can be confidently dated (through context/stratigraphy or preserved mould imprints) to the Early Nordic Bronze Age (c. 1700–1100 BCE, Montelius Period I–III) is rare, compared to the evidence from the later part of the period (Jensen, 2002, p. 118; Jantzen, 2008; Sörman, 2018, p. 162–164). Most Early Bronze Age finds known so far are from Danish settlements (e.g. Kristensen, 2015; here: table 1). In several cases, settlements with bronze casting feature unusually long longhouses, with a length approaching 50 meters and with an inner surface of almost 500 m^2 (Jensen, 2002, p. 109ff).

One such example is the **Store Thyrrestrup** settlement at Jutland, with a 48-meter-long longhouse from Period II, dated to c. 1400 BCE (Nilsson, 1996 and 1997; Jensen, 2002, p. 115). In the house's westernmost room were traces of bronze casting, in the form of mould fragments by the hearth (fig. 11). The room also featured a pit with deposited metalwork (3.2 kg, including for example palstave axes and a bronze melt). This impressive house, with its casting debris and its hoard, has been interpreted as a chiefly household, indicating monopolisation of the early bronze crafting (Nilsson, 1996). At **Skudsrup**, also on Jutland, a settlement dating to Period II-III featured several houses of which the longest measured 50 meters (Ethelberg, 1995 and 2000; Jensen, 2002, p. 117). In the western room there were traces of both bronze casting and weaving. Several Early Bronze Age sites with casting are also known from northern Jutland, recently synthesised by Inge Kjær Kristensen, who has drawn attention to casting debris at the settlements of **Lundbro II**, **Virksund**, **Rosgårde** and **Kluborg** (Kristensen, 2015).

Looking further north, no excavated Early Bronze Age sites with casting are so far known from Norway (an Early Bronze Age settlement with 'furnaces', but no finds of casting debris was considered unconvincing and therefore excluded, see Sörman, 2018, p. 151). In southern Sweden finds occur, but are rare. In a longhouse of 23 meter from Period III at **Elinelund**, Scania, in southern Sweden, a crucible fragment was found in a post-hole in its western room (Sarnäs and Nord Paulsson, 2001). Another potential case is the 50-meter-long Period II longhouse at **Bruatorp** in Småland (Dutra Leivas, 2001), however as only bronze melts were found and there were no crucible or mould fragments, on-site casting is more uncertain. Finally, the large Bronze Age settlement at **Apalle** in central Sweden also bears traces of bronze casting in Period

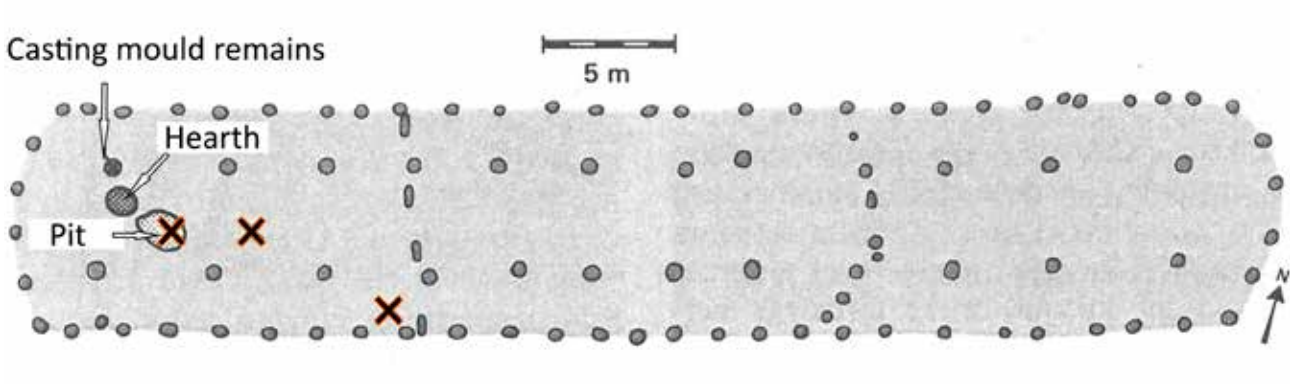


Fig. 11 – Period II longhouse from Store Tyrrestrup, Jutland in Denmark. The western room featured a pit with a metalwork hoard, and mould fragments from bronze casting close to the hearth. The crosses mark bronze items found in the plough soil (redrawn after T. Nilsson, 1997, p. 12).

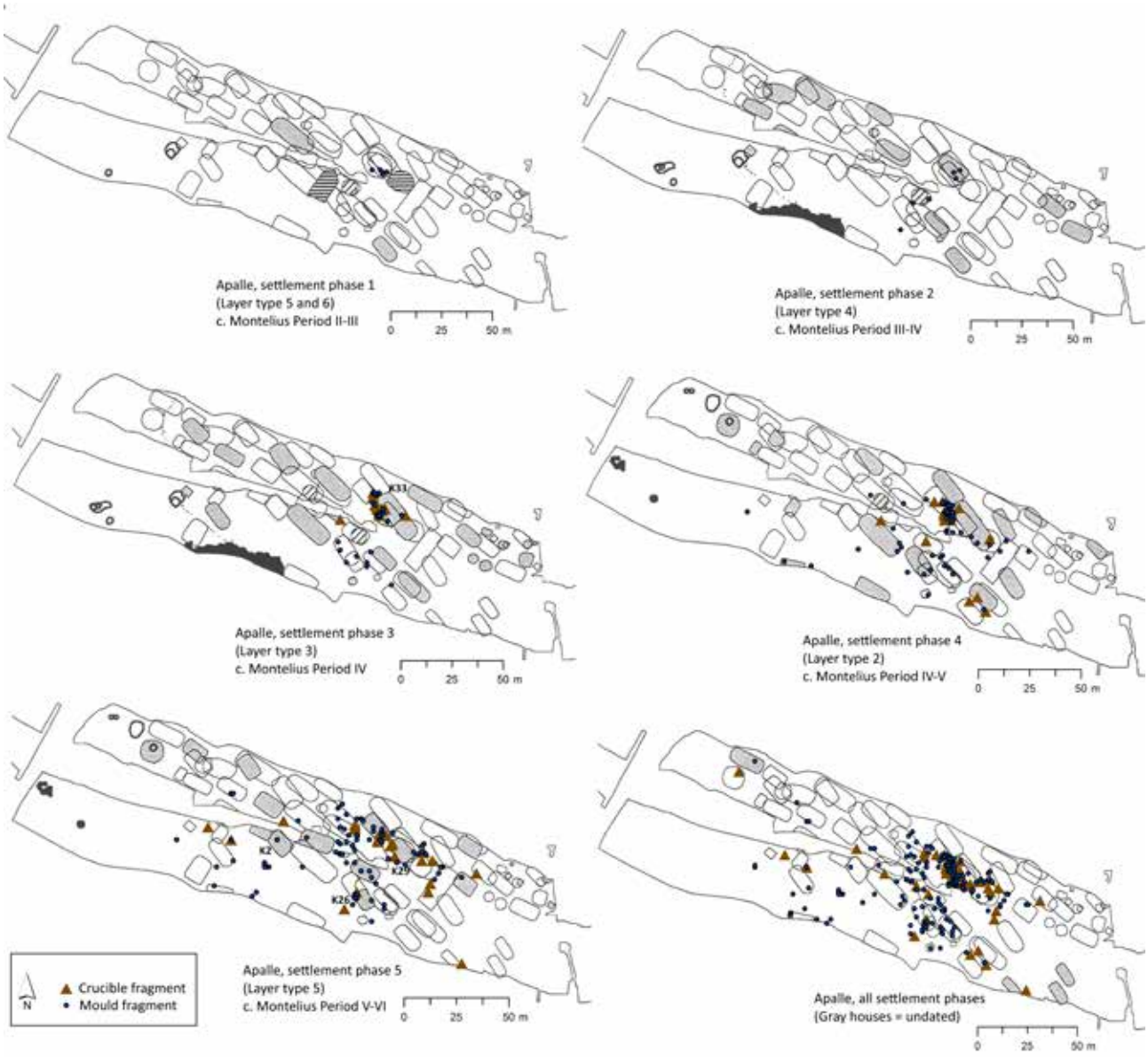


Fig. 12 – Major settlement phases at the Bronze Age settlement at Apalle, Uppland in eastern Sweden. Plans showing the distribution of fragments of casting moulds (blue circles) and crucible fragments (brown triangles), in settlement phases 1-5, and in total (reworked after I. Ullén, 2003, ed., figs. 34–38, with data from T. Eriksson, 2003).

II/III (settlement layer 5 and 6, here: fig. 12), where some casting mould fragments were recovered from a centrally located cultural layer, between the house, the farming plot and the midden of fire-cracked stones (Ullén ed., 2003; Sörman, 2018, fig. 32). To sum up, we have certain indications of Early Bronze Age bronze casting outside Denmark, but the examples are still too few to reconstruct its spatial organisation.

Late Bronze Age – casting at larger settlement complexes (longhouse milieus and cult-house milieus) and at small single farms

The find-contexts for casting debris from mid-late Bronze Age southern Scandinavia indicate that bronze casting was carried out in two main social milieus. On the one hand, in connection to longhouses, in various settings within settlements. On the other hand, in connection to cult-houses and/or burials, within ritual activity areas. These two milieus are often located in close proximity to each other, forming integrated parts of vast grave and settlement areas. This pattern is particularly clear in the case study area in eastern Sweden, and the presentation below will have an emphasis on sites from this region.

Longhouse milieus

The longhouse milieus are contexts characterised by domestic buildings—longhouses—with surrounding yards and activity areas, often featuring pits, hearths, and cultural layers, sometimes also other forms of buildings such as small storage houses and, in some regions also middens or

mounds of fire-cracked stones. These milieus have several common traits; their topographic location, their composition and certain elements in the find material.

Topographically, longhouse milieus are often located on clay or sand in flat, or gently sloping or terraced terrain. Lower areas, below the longhouse milieus (often wetter before modern drainage for agriculture) were generally used for pasture in the Bronze Age. Higher grounds —whether the subtle, flat hills or eskers like in Denmark and southernmost Sweden, or rocky moraine hills, ridges or mountain areas like in the Swedish and Norwegian fissure valley terrain—feature monumental structures such as cairns and tumuli, as well as burial grounds which are thus often located on topographic elevations. In term of composition, the key feature in longhouse milieus are the longhouses for dwelling. The find material often has a lower percentage of fine ceramic vessels and higher rate of crude storage and cooking pots compared to cultic sites; another difference is the absence of burials and only occasional finds of human bones (Sörman, 2018, p. 131–141).

The bronze casting remains in longhouse milieus are found in a wide variety of contexts, both within buildings and in outdoor areas (Sörman, 2019; here: table 1). This demonstrates that casting was not concentrated to special workshop buildings. Although it is often difficult to pinpoint the duration, intensity and chronological time-span of the casting based on the debris, it is not unusual, at least when excavations have covered larger parts of a settlement, with casting debris occurring at several different places within the settlement (e.g. Eriksson, 2003; Frölund and Schütz eds., 2007). To exemplify bronze casting in the south Scandinavian longhouse milieus, a few sites will be briefly described.

At **Apalle**, eastern Sweden, a uniquely well-preserved dwelling with intact stratigraphy allowed for the identification of several settlement phases, which included multiple longhouses and other buildings (Ullén ed., 2003). The distribution of casting debris indicates metalworking at the settlement throughout period II/III to period VI (fig. 12). A concentration of mould and crucible fragments at a centrally located circular building, previously suggested to be the main crafting hut/enclosure, seems to have been only one of several casting loci within the settlement during Period IV (c. 1100–900 BCE, settlement phase 3; Ullén ed., 2003). Over time, bronze-working featured at central courtyards, inside longhouses (fig. 9) and other buildings, as well as in a large, communal area in the southern part of the settlement (Sörman, 2018, p. 68–80). The production at Apalle included a wide range of objects, from simple neck-rings, dress pins and axes, to complex lost-wax-castings of prestigious objects such as belt ornaments and fibulas (Eriksson, 2003). Apalle, being one of the region's largest grave and settlement complexes, with its production of prestigious bronze objects and ornaments for local leaders, indicates the presence of social elite.

Other large Bronze Age settlement with extensive longhouse milieus such as **Pryssgården, Brogård** and **Vrå**, all in Sweden, are much less informative as relatively little casting debris was recovered from these sites, probably due to the poor preservation of cultural layers which characterise these sites (see Sörman, 2018, p. 93–94, 147–148, 164–165). Only few, scattered crucible and mould fragments were found, and its chronological as well as temporal distribution within the settlements are harder to estimate.

There are also settlements complexes which are only partially excavated, providing insights into the casting activities at parts of the site. At the yard in front of a Period V (c. 900–700 BCE) longhouse in **Tallboda**, eastern Sweden, the production of an exclusive spectacle fibula (also Period V) was indicated through the finds of mould and crucible fragments in a sooty pit a few meters south of the building (Äijä et al., 1996; Sörman, 2019, p. 162–163; here: fig. 13 and 20) At the **Skuttunge kyrka** settlement in eastern Sweden, mould fragments, probably for a spectacle fibula, were recovered from the floor layer of a longhouse that appears to be from the Late Bronze Age (Sörman, 2018, p. 100–102). At the previously mentioned **Bredåker** settlement, the large spatial distribution of debris indicates more than one casting loci within the site (Schütz, 2007, p. 246; Sörman, 2018, p. 98). The well-preserved casting loci with melting hearth, discussed above, was part of a longhouse milieu, but the exact surroundings and its relation to other features and buildings are unsure due to the limited extent of the excavation (Schütz, 2007).

Cult-house milieus

Cult-house milieus include both large, complex burial grounds and smaller groups of graves, and sites with ritual activity areas and cult-houses. Many of the burial grounds where bronze casting debris have been found also have cult-houses and other activity areas among the graves. Like for the longhouse milieus, these sites can be characterised by their type of constructions, their find material and their topographical location.

Constructions under the umbrella term 'cult-house' refer to particular-looking buildings or building-like constructions related to funerary contexts (Victor, 2002). The term cult-house, when used for the Nordic Bronze Age, thus refers to several non-domestic buildings which differ by construction, location and find material compared to the longhouses on settlements (Victor, 2002; Goldhahn, 2007; Mattes, 2008). As demonstrated by Helena Victor (2002), they can be divided into two main groups; stone-frame cult-houses which are low, rectangular enclosures of cold-walled stones, and post-built cult-houses either with a simple four-post quadratic structure, or post-built D-shaped small buildings or huts. Whether some of these structures, notably the stone-foundation type cult-houses were foundations for actual buildings, or enclosures or platforms of some kind (or even burial monuments in themselves) is unclear (e.g. Kaul, 1987 and 2006; Svanberg, 2006). They generally have a connection to burials or appear in the vicinity of graves (Victor, 2002). In terms of find-material, they sometimes feature a higher concen-

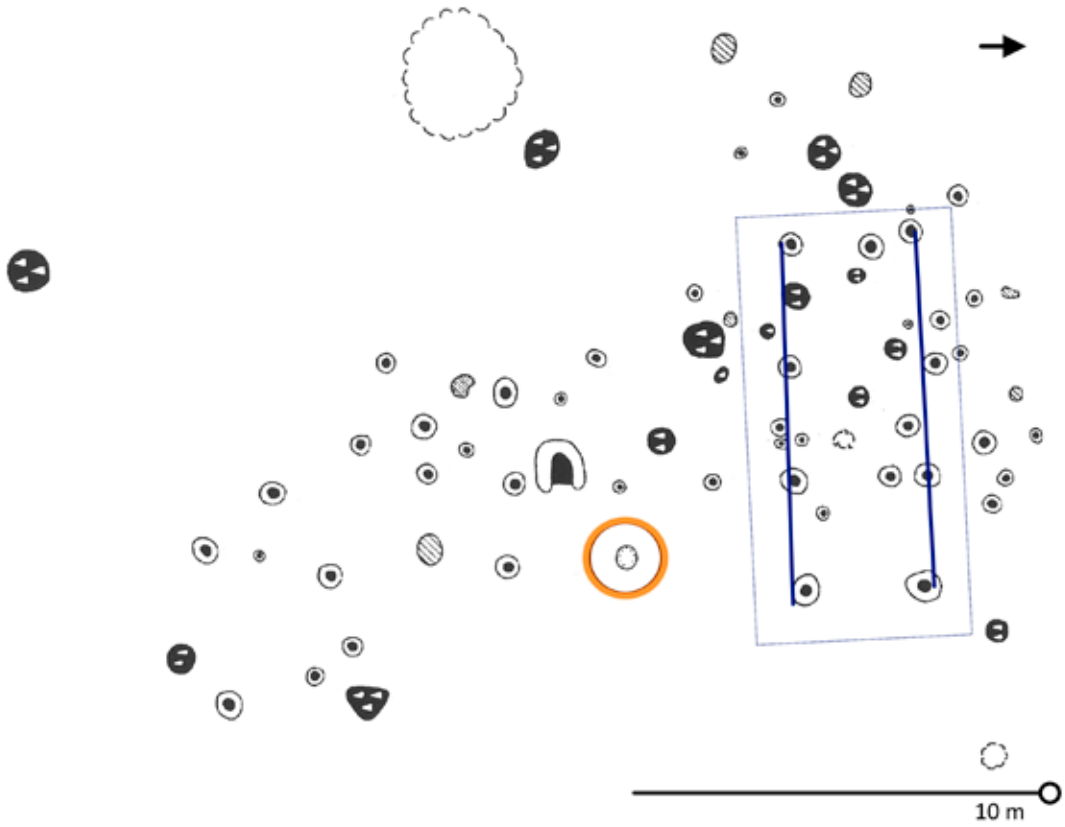


Fig. 13 – Plan of a longhouse (House 1) at one of the settlement areas (RAÄ 16) within the grave and settlement complex at Tallboda in Östergötland, eastern Sweden. Casting debris, in the form of mould fragments for a spectacle fibula (here: fig. 20) and an almost intact crucible, was recovered from a sooty pit in front of the entrance to the house.The pit where the casting debris was found is marked with an orange circle (reworked after K. Äijä, H. Lindborg and M. Schönbeck, 1996, fig. 7).

tration of bowls and fine tableware ceramics, interpreted as signs of feasting (Eriksson, 2008; Brorsson and Eriksson, 2011; Sörman, 2018, p. 136–138).

Topographically, cult-houses and burial sites tend to be located to slightly higher terrain, often on moraine or rocky hills in Sweden and Norway (Hjärthner-Holdar et al., eds., 2008; Sörman, 2018). Based on their location and find-material, these contexts often seem to have hosted various types of ritual activities, special ceremonies or feasts and funerary rites (Victor, 2002 and 2006; Kaul, 2006; Mattes, 2008). As testified by numerous such contexts with casting debris, production of bronze objects was also among the activities sometimes carried out in such arenas.

In **Ryssgärdet**, eastern Sweden, the dwelling area was less well-preserved; instead, ritual milieus with cult-houses situated at the topographically higher areas of the complex (which had not been ploughed, in contrast to the lower-laying settlement) were more well-preserved (Hjärthner-Holdar et al., eds., 2008). Most metalworking debris was found by the grave and cult-house contexts, located at two rocky hilltops in the northern area of the settlement (fig. 14). Bronze casting had been carried out in and/or in front of two small, robust post-built cult-houses. Casting debris was found both on the terrace/platform in front of one of the cult-houses, and on the slopes, where waste from the activities by the cult-houses had been dumped (Hjärthner-Holdar et al., eds., 2008). The cult-house areas had probably been used for feasting, ritual drinking, mortuary rituals and ceremonial gatherings (Eriksson, 2008; Hjärthner-Holdar et al., eds., 2008; Sörman, 2018, p. 80–91). In addition, a possible link to warfare and hunting wild game is suggested (Sörman, 2018, p. 89). The Ryssgärdet settlement spanned from the Late Neolithic through the Bronze Age. The cult-houses were difficult to date, but appear to have been most intensely used during period III–V (Karlenby, 2008b, p. 91ff). The types of bronzes produced at Ryssgärdet cannot be reconstructed based on the casting moulds, but the chemical composition of the melts and artefacts point to local casting of at least tweezers and awls (Eriksson and Grandin, 2008, p. 358). A possible connection between cult-houses and production of tools for razor kits is suggested. Ryssgärdet was probably among the largest grave and settlement complexes in its region. It might occasionally have functioned as an arena for gatherings, cult and feasts for a wider community, and parts of the bronze-working likely related to such occasions.

Similar cases of small cult-houses on high terrain in connection to settlements have been found at **Åbrunna** (Strucke and Holback, 2006) and **Nibble** (Artursson et al., eds., 2011), both in eastern Sweden. These sites also featured small post-built buildings or huts on higher ground, with traces of casting at these high-laying areas.

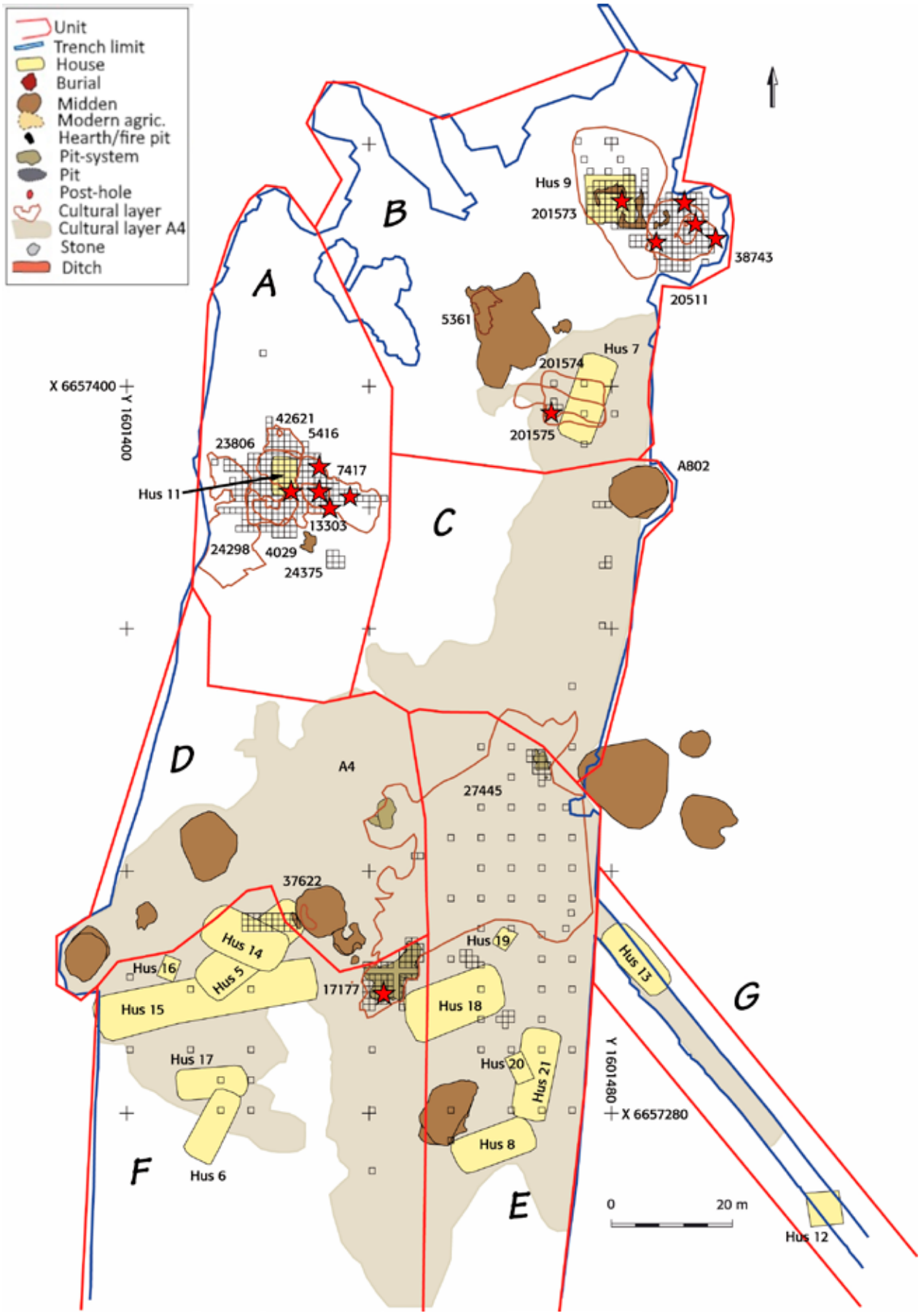


Fig. 14 – Plan of the settlement at Ryssgärdet, Uppland, eastern Sweden. Finds of crucible and mould fragments marked with red stars (reworked after T. Eriksson and A. Östling, 2005, fig. 5).

In Åbrunna, a crucible was found in a hearth at a platform in front of a small cult-house, exposing towards the settlement below (Sörman, 2018, p. 108–110; see here infra fig. 18). The same spatial set-up can be observed at **Hallunda**, the famous 'workshop' site at a high-laying burial ground within what was probably a larger grave and settlement complex (Jaanusson and Vahlne, 1975; Goldhahn, 2007; Sörman, 2018, p. 118–127). Like Joakim Goldhahn (2007, p. 293-306), I also regard this site as a cult-house milieu, however, I argue that the construction has more similarities with the post-built structures at Ryssgärdet and Åbrunna, and have proposed an alternative interpretation of this house where some of the most robust stone-lined 'furnaces' are instead suggested to be large post-holes to a quadratic building (Sörman, 2018, p. 124–126; here: fig. 15). Some of the well-preserved mould fragments found at this part of the site, show that swords, spearheads, neck-rings and socketed axes, were produced in this cult-house milieu (Vahlne, 1974; Sörman, 2018, p. 125).

Excavated sites with large burial sites and cult-house milieus, such as Hallunda, in eastern Sweden (Jaanusson and Vahlne, 1975) and **Hunn** in southern Norway, could perhaps be seen as larger grave and settlement complexes with seasonal function as assembly sites (see Melheim et al., 2016). Bronze casting could then sometimes have been performed in relation to these ceremonial meetings, which would explain its exposed location, its contexts in waste of ceremonial drinking etc, and the production of items with strong political connotations, such as swords and spearheads (Vahlne, 1974; Melheim, 2012, p. 191f; Melheim et al. 2016, p. 52).

Although the cult-house phenomenon appears to be slightly different in Denmark, we still see examples such as **Sandagergård** (see above) on Zealand, and **Brobakken** (Mikkelsen, 2015; here: fig. 16) on Jutland,

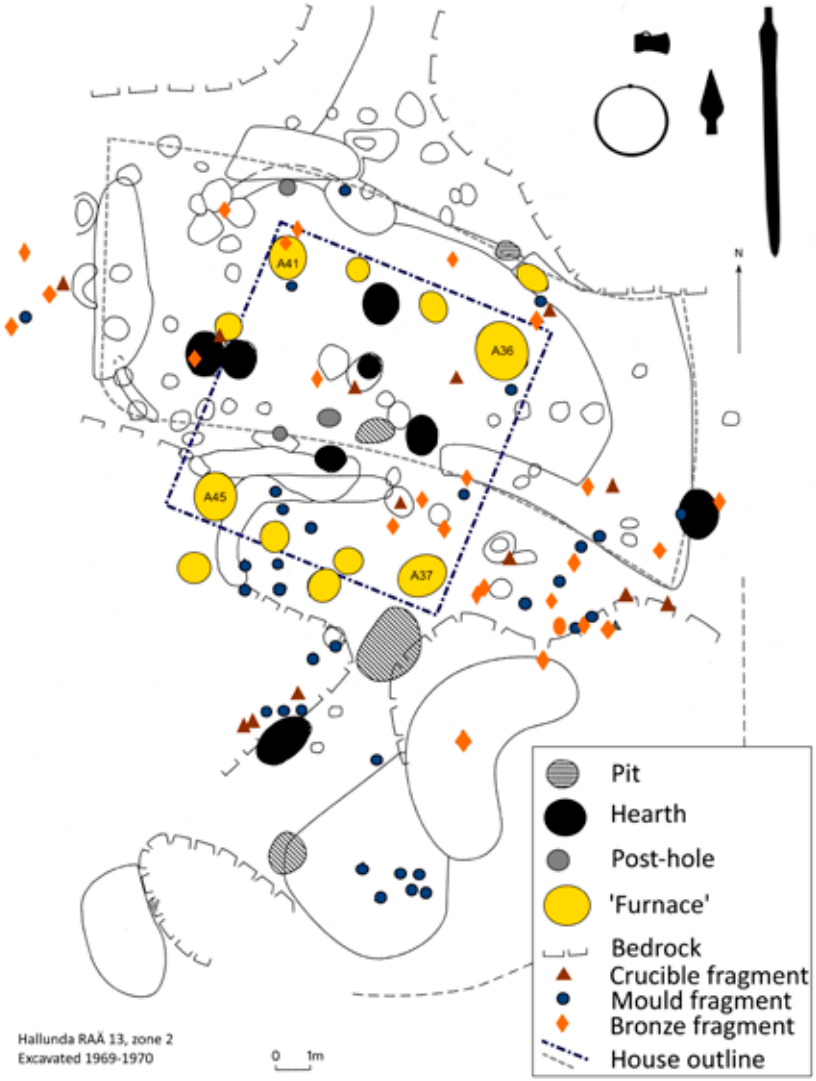


Fig. 15 – Plan of the 'workshop' or cult-house at the burial ground (RAÄ 13) at Hallunda, Södermanland in eastern Sweden. Two house interpretations are shown on this plan: grey dotted line corresponds to the original interpretation of this structure as a workshop/stone-foundation type cult-house, while the blue dotted line (forming a square shape) corresponds my proposed re-interpretation of some of the 'stone-lined furnaces' as corner post-holes in a four-post house. On the top left silhouettes of the objects cast (reworked after G. Vahlne, 1974, p. 16; 1989, p. 109, and D. Jantzen 2008, plate 95).

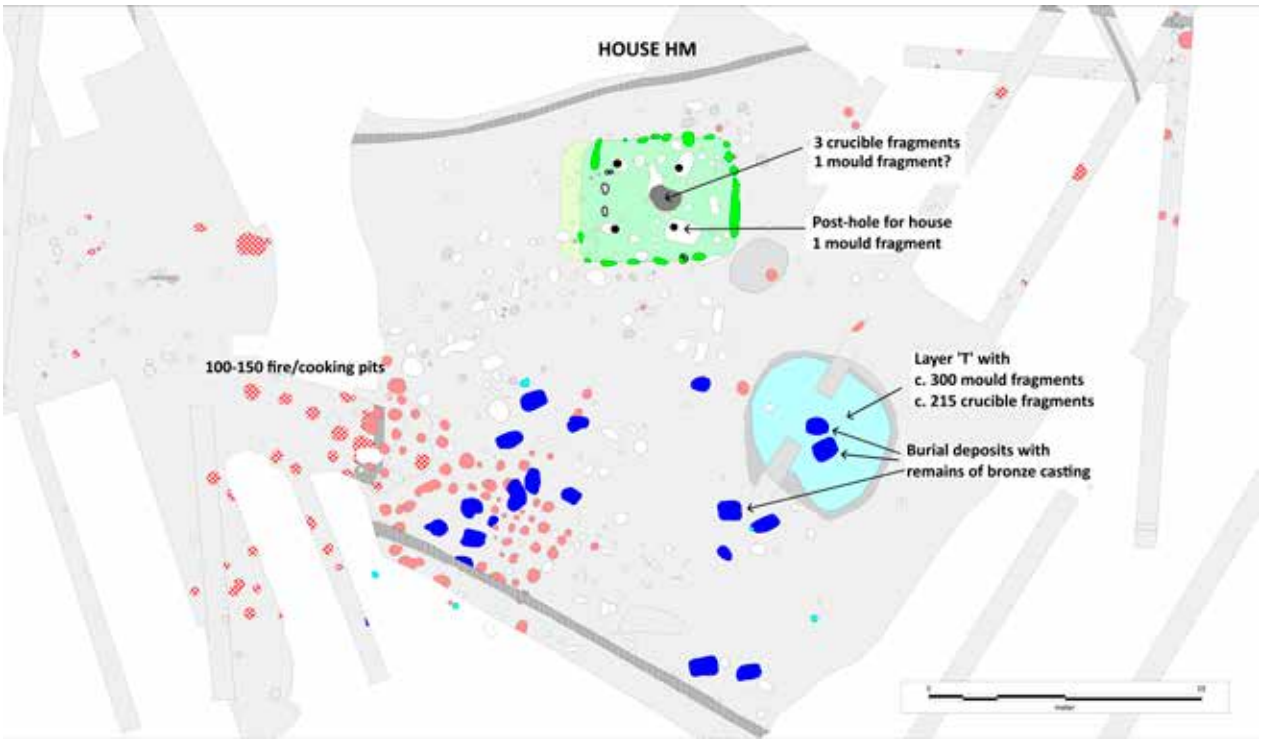


Fig. 16 – Parts of the excavated area at Brobakken, on Danish Jutland. The remains of a small house with traces of bronze casting were found next to a waste midden which included finds of casting debris and funerary depositions with human bones, dating to the Late Bronze Age. This context has here been interpreted as bronze casting in a grave and cult-house milieu, within a larger settlement complex (illustration from M. Mikkelsen, 2015, fig. 4).

where the association between burials, bronze casting and cult-house milieus is also evident. In Brobakken, casting debris, including casting moulds for swords, spearheads, a wide arm-ring and possibly spectacle fibulas, were found by a small, quadratic post-built house in connection to a waste midden which included casting debris and burial depositions, and a high degree of fine tableware ceramics (Mikkelsen, 2015). This find-pattern fits well with the ceremonial feasting and funerary ritual proposed for similar cult-house milieus in other parts of the Nordic area (Sörman, 2018, p. 170–173). These appear to be assembly sites at larger settlements, and important arenas for producing bronze objects in the Late Bronze Age.

Single farms

Finally, data from Sweden also testify of bronze casting in longhouse milieus at small, single farms. This interpretation is suggested for the Late Bronze Age settlements at Rambodal, Östergötland (Nyberg and Nilsson, 2012; Nilsson and Sörman, 2015), and Degeberga in Scania (Björk and Wickberg, 2011). Both sites, in use from Period IV to VI, were spatially limited to a few thousand square meters, and lacked obvious connections to contemporary ritual areas/burial grounds. In Degeberga, a mould for a Period IV-chisel had been deposited in a post-hole of a longhouse. In Rambodal a fragment of a broken soap stone mould for a socketed axe-head from Period V/VI was recovered from a cultural layer beside a longhouse (fig. 17). They seem to indicate a small-scale production of tools relating to smaller settlements, and thus confirm that metalworking was carried out at various levels of the settlement hierarchy, at households of different social standing. The implications of this will be further discussed in section 5.

Results: where was casting carried out in relation to the settled landscape?

As we have seen through the sites presented above, bronze casting debris is found in the settled landscape in the Bronze Age—dwellings, ritual sites and burial grounds at the core of the populated areas. There are no casting debris from free-laying sites at wider distance from the settlements, such as remote sites for temporary activities, shepards' stations or mineral extraction sites (Sörman, 2018, p. 59–64, appendix 1). Rather than hidden away, casting was carried out midst of the main arenas for Bronze Age life.

Summary and interpretation of findings

The contextual analysis of casting debris (Sörman, 2018), briefly synthesised and exemplified above, demonstrates several new insights about the casting debris, the production of bronze objects and its organisation in social space. These can be summarised as follows:

– It is often possible to reconstruct the approximate area/areas of production within excavated sites, despite the absence of specifically identified melting hearths. Discarded casting moulds and crucible fragments are largely present as secondary depositions in cultural layers, floor

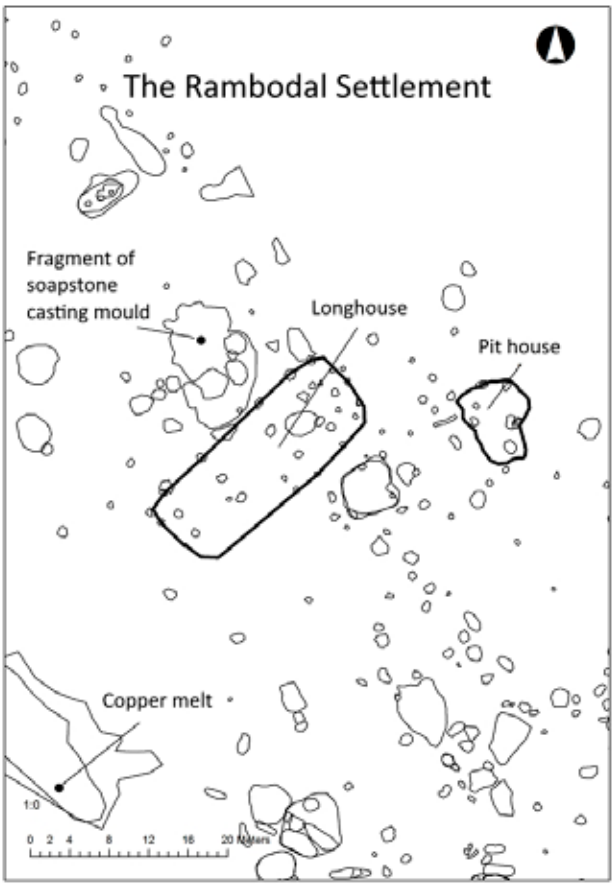


Fig. 17 – The small Late Bronze Age settlement at Rambodal, Östergötland, eastern Sweden, probably representing metalworking carried out at the lower level of the settlement hierarchy. Here, the making of a socketed axe head is indicated by the discarded fragment of a soapstone mould, recovered from a cultural layer just north of the house (reworked after P. Nilsson and A. Sörman, 2015, fig. 2).

layers and pits. The degree of preservation and level of excavation of cultural layers is decisive for the identification and recovery of bronze casting remains. Apart from a few cases of intact casting moulds placed as foundation offerings in Late Bronze Age longhouses, there are no other evidence suggesting intentional depositions of casting debris (in for example burials or cult-houses).

– Bronze casting sites from the Early Bronze Age, particularly Period I-II, are less well-known, and evidence has so far primarily turned up in Denmark, where casting debris sometimes feature at settlements with exceptionally long longhouses. Summing up, both the restricted presence of casting debris, and the strong representation of settlements with larger longhouses suggest that metalworking was more strictly centralised to certain farms and families in the Early Bronze Age (see Earle, 1997; Kristiansen, 1998; Vandkilde, 2017, p. 157). The data so far indicate that the Danish area, and the rich Jutland peninsula in western Scandinavia had a more developed presence of local casting in this period, and that metalworking was established later in for example eastern Sweden (Karlenby, 2008a, p. 64). As the number of excavated Early Bronze Age settlements are still low, notably in Sweden and Norway, this picture could change.

– In the Late Bronze Age, bronze casting remains turn up in two different social arenas. On the one hand in domestic areas within settlements, here called longhouse milieus. And on the other hand, in ritual areas with burials and/or cult-houses or other non-domestic structures, here called cult-house milieus. Thanks to the basic characteristics in topographic location, finds and feature types, these contexts can also be suggested for older excavations of sites where the methodology, lack of identified buildings etc., make them difficult to interpret, but where their similarities to data from modern excavations now allows for a better understanding (table 1). In this context, it can be mentioned that the famous Swedish 'workshop' at **Hallunda** has here been re-interpreted as a cult-house milieu with production amidst funerary monuments and a post-built cult-house (Sörman, 2018, p. 118–127; see also Goldhahn, 2007, p. 293–306 and 2013, p. 258–259), and that the famous **Skälby** site with two middens of fire-cracked stones with rich remains of casting—one of the first excavated 'workshop sites' in Sweden in the 1930s (Oldeberg, 1960)—is suggested to have been located midst of a low-laying longhouse milieu in a larger settlement (Sörman, 2018, p. 104–106).

– In longhouse milieus bronze casting was carried out indoors and outdoors, and has often left traces at several loci within larger excavated settlements. Indoors, there are traces in longhouses, such as at Apalle and Skuttunge kyrka, but also in other types of buildings, like the round building at Apalle settlement phase 3. There is also casting in open places in front of longhouses, such as for example at Tallboda and Fragtrup, or at yards in the middle of the settlement cluster, like at Apalle or Skuttunge kyrka. Object types produced are varied, but we can note the lack of clearly identified full-length swords, and the presence of moulds for belt ornaments and neck rings.

– In cult-house milieus and on burial grounds, the casting of bronze objects was also varied. The context of debris indicate production at activity areas outdoors, such as the platform in Åbrunna, and indoors in cult-house structures such as the cult-house in Sandagergård. There is often a relation between cult-houses and human bones and with burials. There is also a relation between such cult and grave areas and contemporary settlement sites —forming large complexes, clearly exemplified by sites such as Åbrunna, Nibble and Ryssgärdet. However, as the full extent of such sites is almost never determined it remains difficult to assess the relative stature and size of the various settlements with casting.

– Bronze casting was present at both larger and smaller settlements. The small ones, so far rarely subjected to excavation, perhaps for source critical reasons, have been identified in at least two cases, both from Sweden.

– Prestigious objects, such as weapons and large ornaments, were produced both in dwellings and at cult-houses. This demonstrates that advanced production of prestige goods was not organised in specialized, spatially secluded or centralized workshops. Instead, valuable bronzes came about in several different arenas and under various circumstances.

#	Site	Country	Type of remains	Type of artefacts cast (imprints in moulds)	Casting context	Dating	Reference	Comment
Mälar valley area (case study region)								
1	Alsta	Sweden	Ceramic mould fragments		Long-house milieu?	LBA?	Oldeberg 1960:45f	
2	Apalle	Sweden	Ceramic mould fragments, crucible fragments	Neck rings, socketed axeheads, tutuli, belt ornament, dress pin?, spectacle fibula?, hanging vessel?, sword/dagger?	Longhouse milieu	EBA-LBA	Ullén ed. 2003	
3	Bredåker	Sweden	Ceramic mould fragments, crucible fragments, bronze melts	Neck rings, dress pins with disc-shaped head, socketed axehead?	Longhouse milieu	LBA	Göthberg & Schutz eds 2006; Frölund & Schutz eds 2007	
4	Broby	Sweden	Ceramic mould fragments, crucible fragments	Neck rings	Cult-house milieu	LBA?	Schönbäck 1952; 1959; Ojala 2026: app.1	
5	Darsgärde	Sweden	Ceramic mould fragments	Neck ring	Cult-house milieu?	LBA?	Ambrosiani 1958; 1959	Possible/ uncertain
6	Fansta	Sweden	Ceramic mould fragments		Longhouse milieu?	LBA?	Åberg 2013	Possible/ uncertain
7	Fullerö	Sweden	Crucible fragment		Cult-house milieu?	LBA	Björck & Appelgren 2006	
8	Håga by	Sweden	Ceramic mould fragments, crucible fragments		Cult-house milieu	LBA	Forsberg & Hjärthner-Holdar 1985; Victor 2007: chapter 7	
9	Hällby	Sweden	Crucible fragments		?	LBA?	Hjärthner-Holdar 1993:80	
10	Kalvshälla	Sweden	Ceramic mould fragments		Cult-house milieu?	LBA	Andersson et al. 2009	
11	Kyrsta	Sweden	Ceramic mould fragments/crucible fragments?		Longhouse milieu	LBA?	Onsten-Molander & Wikborg 2006	Possible/ uncertain
12	Kälvesta	Sweden	Ceramic mould fragments, crucible fragments, 1 intact crucible	Neck ring	Cult-house milieu?		Johansson et al. 2011	Possible/ uncertain
13	Lilla Härnevi	Sweden	Ceramic mould fragments	Neck ring/hanging vessel?	Longhouse milieu	LBA	Karlenby 1998	
14	Lunda, Lovö	Sweden	Crucible fragments		Cult-house milieu?	LBA?	Petré 1982; 1984b	
15	Molnby	Sweden	Ceramic mould fragments, crucible fragments	Neck ring, spectacle fibula	Cult-house milieu and Longhouse milieu	LBA?	Hed Jakobsson et al. 2021	
16	Nibble	Sweden	Ceramic mould fragments, crucible fragments	Neck ring	Cult-house milieu	LBA	Artusson et al. 2011	
17	Nyvla	Sweden	Crucible fragment?		Cult-house milieu?	LBA	Fagerlund 2012	Possible/ uncertain
18	Plaisieren/Vinsta	Sweden	Crucible fragments		Cult-house milieu?	LBA?	Laurén 1969	
19	Ryssgärdet	Sweden	Ceramic mould fragments, crucible fragments, bronze melts		Cult-house milieu and Longhouse milieu	MBA-LBA?	Eriksson & Östling 2005; Hjärtner-Holdar et al. eds 2008	
20	Skeke	Sweden	Ceramic mould fragments, crucible fragments	Neck rings, dress pin?	Cult-house milieu	LBA	Larsson ed. 2014	
21	Skuttunge kyrka	Sweden	Ceramic mould fragments	Spectacle fibula?	Longhouse milieu	LBA	Seiler & Östling 2008	
22	Skälby	Sweden	Ceramic mould fragments, crucible fragments	Neck rings, dress pins with disc-shaped heads, belt ornaments, hanging vessels, spectacle fibulas, dagger, sword/dagger?, spearhead?, socketed	Longhouse milieu?	LBA	Oldeberg 1960	

Table 1 – Excavated sites in southern Scandinavia included in this study (see also figure 6. The sites feature clear or possible remains of bronze casting from the Bronze Age. The table summarizes their character, general dating, and object types cast according to mould imprints. For complete references, detailed information about each site and the casting remains recovered, see Sörman, 2018 (appendix 2).

23	Skämsta	Sweden	Crucible fragments		Longhouse milieu?	LBA	Frölund & Larsson 2002	Possible/ uncertain
24	Skölsta	Sweden	Crucible fragments		Longhouse milieu?	LBA?	Lucas & Lucas 2020	Possible/ uncertain
25	Sommaränge skog	Sweden	Crucible fragment		Cult-house milieu	EBA-LBA?	Forsman & Victor 2007	Possible/ uncertain
26	Stenvreten	Sweden	Crucible fragments		?	LBA?	Fagerlund 1994; Fagerlund & Hamilton 1995	Possible/ uncertain
27	Trekanten	Sweden	Ceramic mould fragments		Longhouse milieu	LBA?	Onsten-Molander & Wikborg 2006	Possible/ uncertain
28	Trollbo	Sweden	Ceramic mould fragments		Longhouse milieu	LBA	Åstrand 1998	
29	Vrå	Sweden	Ceramic mould fragments, crucible fragment?	Neck ring/dress pin	Longhouse milieu	LBA	Karlenby ed. 1997; Göthberg et al. eds. 2002	
30	Årby	Sweden	Ceramic mould fragment?		?	LBA?	Göthberg 1998	Possible/ uncertain
31	Erikslund	Sweden	Crucible fragment		?	LBA?	Hjärthner-Holdar 1993:77	
32	Vallby/ Trumslagarbacken	Sweden	Crucible, ceramic mould fragments	EBA tutulus?	Cult-house milieu?	EBA-LBA?	Simonsson 1959; 1966; Oldeberg 1974:241	
33	Bornsjön	Sweden	Ceramic mould fragments and one core	Neck ring? Socketed object	Longhouse milieu?	LBA?	Elfstrand 1981; Eklöf 1999	
34	Galtbacken	Sweden	Crucible fragments, ceramic mould fragments?		Cult-house milieu	LBA?	Dunér & Evanni 2003	
35	Hallunda	Sweden	Ceramic mould fragments, core fragments, crucible fragments	Neck rings, socketed axeheads, spearheads, swords, sword/dagger, razor/sickle, double-button	Cult-house milieu	LBA	Vahlne 1974; Jaanusson & Vahlne 1975; Bennett 1975; Jaanusson et al. 1978; Jaanusson 1981; Riksantikvarieämbetet 1998	
36	Hästhagen/Igelsta	Sweden	Crucible fragment, bronze melt		Cult-house milieu?	LBA?	Elfstrand 1986	
37	Karleby/Gärtuna	Sweden	Crucible fragments, ceramic mould fragments, core fragment		Cult-house milieu?	LBA?	Bennett 1985	
38	Vårberg	Sweden	Crucible		Cult-house milieu?	LBA?	Ferenius et al. 2011	Possible/ uncertain
39	Åbrunna	Sweden	Crucible fragment, crucible, tuyère?		Cult-house milieu	LBA	Strucke & Holback 2006	
40	Åkra Grindstugan	Sweden	Ceramic mould fragment		Cult-house milieu?	LBA?	Tesch 1975	
Eastern Sweden (except the Mälar valley area)								
41	Västra Bökestad	Sweden	Crucible, ceramic mould	Neck rings. Gold (residue in cricuble).	Cult-house milieu	LBA	Helander & Zetterlund 1997	
42	Tallboda	Sweden	Crucible, ceramic mould	Spectacle fibula	Longhouse milieu (but also on adjacent burial ground/cult-house milieu)	LBA (period V)	Äijä, Lindborg & Schönbäck 1996	
43	Pryssgården	Sweden	Ceramic mould, tuyère (see Thrane 2006)		Longhouse milieu	LBA	Borna-Ahlkvist, Lindgren-Hertz & Stålbom 1998	
44	Rambodal	Sweden	Soapstone mould fragment, copper melt	Socketed axehead	Longhouse milieu	LBA (period V-VI)	Nyberg & Nilsson 2012	

Table 1 (cntinued)

45	Bruatorp	Sweden	Bronze melt		Longhouse milieu	EBA (period II-III)	Dutra Leivas 2001	Possible/ uncertain
46	Kölbygärde	Sweden	Crucible fragments		Cult-house milieu	LBA	Ring et al. 2001	
Western Sweden and Norway								
47	Forsandmoen	Norway	Ceramic mould fragments, crucible fragments, soapstone mould	Socketed axehead	Longhouse milieu	LBA	Løken 1986; 1987; 1998; Weiler 1994:120	
48	Gunnarstorp	Norway	Ceramic mould fragments, crucible fragments		Cult-house milieu	BA	Wangen 2009	
49	Hunn	Norway	Ceramic mould fragments, crucible fragments, tuyère fragments	Neck rings, spearheads, sword, sword/dagger, belt ornament?, hanging vessel?	Cult-house milieu	BA	Resi 1986; Skre 1998; Melheim 2012:189; chapter 4.1.3.; Melheim et al. 2016	
50	Humlekärr/Lyse	Sweden	Ceramic mould fragments, crucible fragments, intact crucible	Neck ring/dress pin	Cult-house milieu	BA	Särlvik et al. 1977	
51	Bokenäs gamla kyrka	Sweden	Crucible fragments, 2 intact crucibles	Large object	Cult-house milieu?	BA	Niklasson 1948	
52	Hjälm	Sweden	Ceramic mould fragments, crucible fragments	Double button, dress pin with disc-shaped head	Cult-house milieu	LBA	Jonsäter 1979	
53	Jörlanda	Sweden	Crucible fragments		Longhouse milieu?	BA	Johansson 1995	
54	Tången	Sweden	Crucible fragment		Longhouse milieu?	BA	Knutsson 1978; Andersson 2005:124	
55	Kärra	Sweden	Crucible fragments		?	BA	Andersson 2005:124; Ragnesten 2001	
56	Hjälpesten/Kville	Sweden	Crucible fragments		?	BA	Toreld 2018	
57	Röra/Önnered	Sweden	Crucible fragments		?	BA	Andersson 1970; Andersson 2005:118ff	
58	Bratthammar	Sweden	Crucible fragments		Cult-house milieu?	BA	Andersson 1975; Andersson 2005:123	
59	Tanumshede	Sweden	Crucible fragments		Cult-house milieu	LBA	Öbrink 2015:90, 180	
60	Linnomstien	Norway	Crucible fragments		Cult-house milieu?	BA	Engebretsen 2009; Melheim 2012:225ff	
Southern Sweden and Denmark								
61	Store Tyrrestrup	Denmark	Ceramic mould fragments		Longhouse milieu	EBA	Nilsson 1996, 1997; Jensen 2002:115	
62	Skydstrup	Denmark	Crucible fragments		Longhouse milieu	EBA	Ethelberg 1995, 2000; Jensen 2002:117	
63	Lundbro II	Denmark	Crucible fragments	Sword/dagger	Longhouse milieu	EBA	Kristensen 2015	
64	Virksund	Denmark	Crucible fragments		Longhouse milieu	EBA	Kristensen 2015	
65	Rosgårde	Denmark	Ceramic mould fragments	Sickle	Longhouse milieu	EBA	Kristensen 2015	
66	Kluborg	Denmark	Crucible fragments		Longhouse milieu	EBA	Kristensen 2015	
67	Elinelund	Sweden	Crucible fragment		Longhouse milieu	EBA	Sarnäs & Nord Paulsson 2001	

Table 1 (cntinued)

68	Broåsen/Grimeton	Sweden	Ceramic mould fragments, crucible fragments	Neck ring, neck ring/arm ring, spearhead, sword, sword/dagger, tutulus?	Cult-house milieu?	EBA-LBA	Sarauw & Alin 1923; Svensson 1940	
69	Fosie IV	Sweden	Ceramic mould fragments, crucible fragments, tuyère fragments		Longhouse milieu	LBA	Björhem & Säfvestad 1993	
70	Brogård	Sweden	Ceramic mould fragments, crucible fragments		Longhouse milieu	BA	Carlie 1992	
71	Årup	Sweden	Crucible fragments		Longhouse milieu	LBA	Hanlon 2003	
72	Yngsjö	Sweden	Crucible fragments, ceramic mould fragments, soapstone mould fragments, bronze melts	Socketed axeheads, dress pin?	Longhouse milieu	LBA	Linderoth 2014	
73	Vä	Sweden	Crucible fragments, ceramic mould fragments, bronze melts	Sword/dagger	Longhouse milieu	EBA-LBA	Helgesson 2012	
74	Degeberga	Sweden	Intact ceramic mould	Socketed chisel	Longhouse milieu	LBA	Björk & Wickberg 2012	
75	Vrangelsro	Sweden	Ceramic mould fragments, crucible fragments		Cult-house milieu	EBA-LBA	Ängeby & Lindman 2017	
76	Södra Kristineberg	Sweden	Ceramic mould fragments, crucible fragments	Sword, sword/dagger/spearhead, arm ring/neck ring. Gold (remains in crucible).	?	BA	Högberg ed. 2011	
77	Vindblæs	Denmark	Ceramic mould fragments, crucible fragments	Spearheads			Vestergaard Nielsen 1956	
78	Mølgård, Håg	Denmark	Ceramic mould fragments, crucible fragments	Sword, sword/dagger, spearhead, double-button			Neergaard 1908	
79	Jyderup skov	Denmark	Ceramic mould fragments, crucible fragments				Thrane 1971	
80	Kirkebjerget, Voldtofte	Denmark	Ceramic mould fragments, core fragments, crucible fragments	Bronze lure, sword, spearheads, arm ring, hanging vessel, belt ornament?	?		Jensen 1967; Berglund 1982; Thrane 1975; 1993; Jantzen 2008:391-392	
81	Fragtrup	Denmark	Ceramic mould fragments, crucible fragments, bronze melts	Armring	Longhouse milieu	LBA	Draiby 1985	
82	Brobakken	Denmark	Ceramic mould fragments, crucible fragments, bronze melts	Spearheads, swords, swords/daggers, arm ring, spectacle fibula?	Cult-house milieu	LBA	Mikkelsen 2015	
83	Løgstrup SØ	Denmark	Ceramic mould fragments, crucible fragments		Cult-house milieu	LBA	Larsen et al. 2015	
84	Sandagergård	Denmark	Ceramic mould fragments, crucible fragments		Cult-house milieu	LBA	Kaul 1987	

Table 1 (end)

THE ROLE OF BRONZE CASTING IN LATE BRONZE AGE SOCIETY

The casting at settlements versus cultic sites does not correspond to a functional division between production of domestic objects versus prestige/ritual objects, which has sometimes been proposed (see Levy, 1991; Kristensen, 2015). The picture that emerges is that of a spatial organisation which falls outside of the traditional models, such as centralised workshops versus domestic production in the households. Metalworking in Late Bronze Age southern Scandinavia was practised in two main arenas—longhouse contexts and cult-house contexts respectively. The production in these arenas included a variety of objects, where casting of prestigious items is for example evident from both contexts. In the following discussion, I suggest that this production was structured in relation to the clients (i.e. the future owners of the produced objects), and that bronze casting was used as an important strategy in reinforcing the social structure.

The main argument developed throughout this discussion is threefold: 1) in the Late Bronze Age, casting developed into an elaborate, display-like practice, often performed as public rituals; 2) castings were staged and organised differently depending on the meaning and intended user of the manufactured object; 3) many bronzes were attributes of special social identities—primarily within the elite collective. Consequently, the casting of a new object was often motivated by, and linked to, initiations of persons into new roles. Hence, the act of casting not only materialized the physical object, but also shaped the identities, power relations and values which it embodied, and this manufacturing was adapted to various clients rather than redistributed from a centralised workshop. I therefore argue that we need to look beyond hierarchy and also consider heterarchy in craft production.

The arenas of bronze casting and the production as public ritual

Bronze casting was set up in a variety of indoor and outdoor settings; between graves, by cult-houses, in longhouses, at farmyards, or in other communal areas. The archaeological material from southern Scandinavia reveals no efforts to seclude, enclose or physically distance the areas where bronzes were cast, as has sometimes been suggested either for practical reasons of fire-hazard (e.g. Thrane, 2015, p. 124) or due to social and ritual taboos (Goldhahn, 2007). Instead, metalworking often appears in arenas which were visibly accessible, centrally located, or even spectacular. Bronze casting at larger grave- and settlement complexes often appears in central and conspicuous settings, suggesting that production was integrated and visible in the settled arena. We have seen the casting at yards, in houses and at open places in longhouse milieus, in particular from the well-preserved stratigraphy of Apalle. We have seen the plateaus and terraces in front of cult-houses, such as Hallunda, Åbrunna (fig. 18), Hunn and Ryssgärdet, where casting would have been exposed to the dwelling below. I therefore suggest that casting – the most dramatic event in the bronze-crafting sequence – could be performed as public or semi-public rituals.

Public rituals, performances, spectacles or ceremonies refer to memorable, manifest and strongly formalised rituals which to some extents are performed in front of an audience (DeMarrais, 2014, p. 157, 161). Such events are often important tools in the maintenance and negotiation of social order, by displaying, commenting, exaggerating and objectifying it (DeMarrais, 2014, p. 156; see also Geertz, 1980, p. 104). I suggest that Bronze Age bronze casting correspond to several of the traits that characterise public rituals (La Fontaine, 1986, p. 181–183; Bell 2009 [1997], p. 159–161; Inomata and Corben, 2006; DeMarrais, 2014, p. 161), such as: 1) performed in contexts which permitted, and even guided an audience; 2) evoked powerful sensual experiences that contrasted with everyday life—like the rhythmic sound of bellows, the intense heat and light and the perception of liquid metal; 3) demonstrated impressive and exclusive skills and techniques, which were difficult to reproduce without guided and repeated practice. Bronze Age casting technique thus has properties which readily lend themselves to dramatic displays (see also Molloy and Mödlinger, 2020, p. 207). It was thus particularly appropriate for spectacular rites of passage. Anne Maria Dobres has demonstrated that technological gestures are often witnessed by others, and thereby exploited to express of manipulate identities and interests (Dobres, 2000). This seems to have been the case with bronze casting, at least during the Late Bronze Age.

This interpretation calls for an update to the archaeological view on Bronze Age bronze crafting—both regarding visual representations and terminology. More open concepts, such as casting places or casting loci, are better suited to the embedded craft organisation which can be observed through the evidence. In contrast to traditional concepts of (male) specialists working at designated craft areas or workshops, often located in the edge of settlements, I suggest we should envision carefully staged events in settlements and ritual places. These probably featured audiences and onlookers taking part in the event from various distances (fig. 19).

Social projects and the motifs behind various casting events

The highly visible and varied organisation seen in the making of bronze objects can be explained by the social projects and motifs behind different castings. We might begin to observe where production of different bronzes was located and staged, based on identified object types in the recovered moulds (table 1; fig. 20). It should be emphasised that this builds on a very slim material, as only a minority of the casting moulds used in Bronze Age metalwork have survived to our days, and the proportion of those which has readable imprints/negatives are

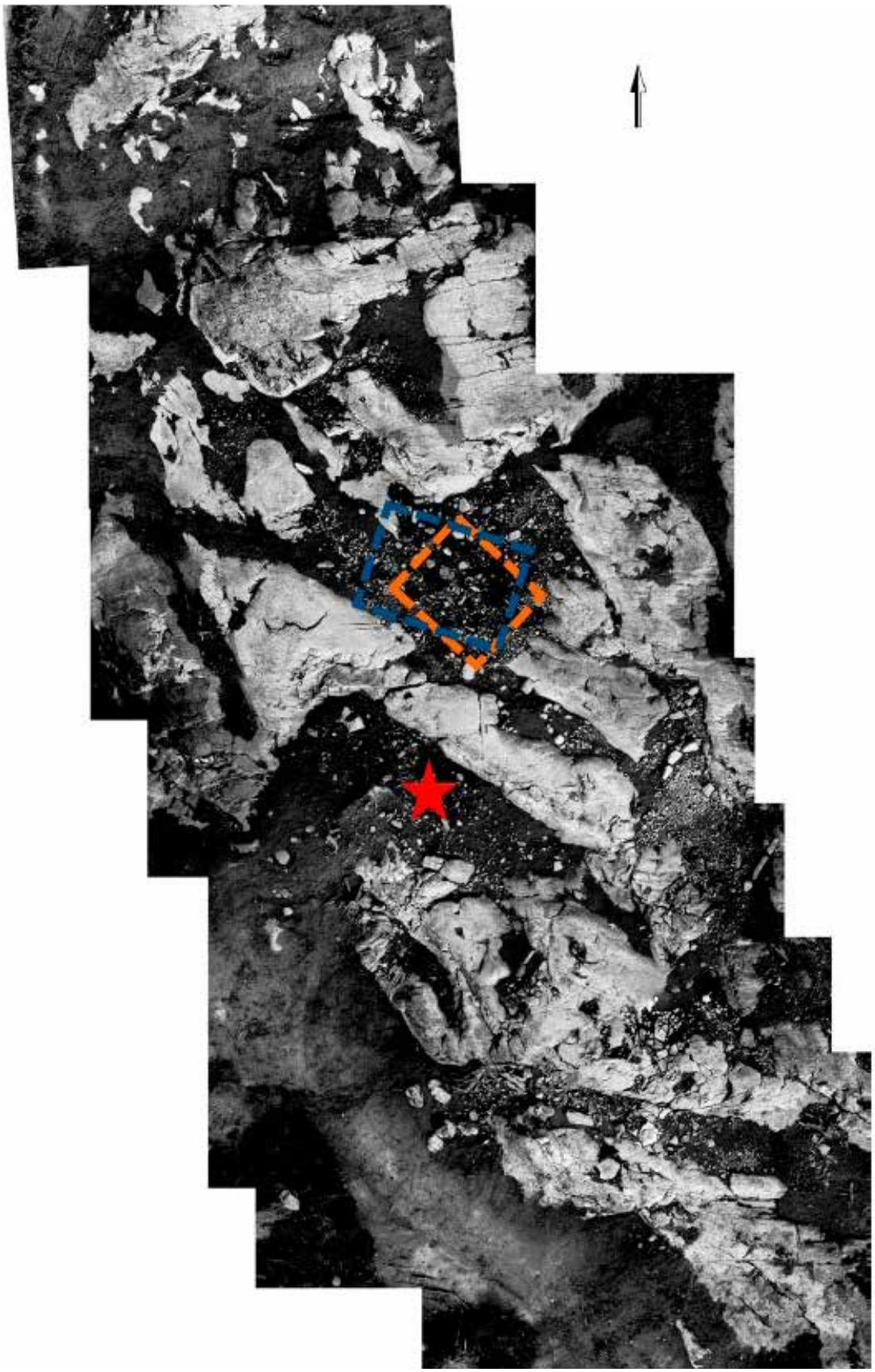


Fig. 18 – Overview of parts of the Åbrunna settlement in Södermanland, eastern Sweden. At this part of the settlement complex the remains of a succession of two small cult-houses (orange and blue rectangles on the photo) were found at the summit of a low rocky moraine hill. The red star marks the finds of casting debris and a possible melting hearth, at a terrace like platform just in front of the house, exposing towards the settlement below (photo: Kjell Olausson. Montage: Ulf Strucke; reworked after U. Strucke and T. Holback, 2006, fig. 28).



Fig. 19 – Interpretative drawing of a bronze casting event at the Late Bronze Age settlement at Pryssgården, Östergötland in eastern Sweden. Interpretation presented by Katarina Botwid, 2017 (drawing: Henning Cedmar-Brandstedt).

even fewer. Nevertheless, they can provide glimpses of object types cast in specific sites (but inversely, absence can never be used as negative evidence). Even though the material is meagre, these finds allow for the formulation of a tentative hypothesis which can be tested against future finds. The available evidence does not cover all known object types; the discussion therefore focuses on socketed tools and personal prestige objects.

The first category—socketed tools—were evidently produced at a wide range of sites and social contexts. The varied production contexts for axes and chisels fit well with the idea that these types of objects were involved in a wide range of social projects, and used by persons of varying social status in the community (Larsson, 1986). Axe production was sometimes staged at the longhouse —perhaps as an important event linked to the establishment of a new household (see Apalle; Ullén ed. 2003, and Yngsjö; Linderoth, 2014). Sometimes axes were produced at cult-houses in the same arenas where the production of weapons has also been testified (see Hallunda; Vahlne, 1974 and Brobakken; Mikkelsen, 2015). These axes were perhaps intended as combined tools-weapons to be carried as an individual possession by warriors or other persons, as known from rock art and other finds. Finally, socketed axes and chisels were sometimes produced at single farms, as demonstrated by finds at Degeberga and Rambodal (Björk and Wickberg, 2011; Nyberg and Nilsson, 2012). I suggest that these castings were performed by specialist crafters from larger settlements, who came to satellite farms to provide a new tool for these farms. This was most likely an important event for the household. Such a production event probably—like the axe itself—also manifested the household's kinship identity, power relations and political dependency.

The production of prestige goods was also staged in several arenas (table 1). The prestige objects will here be divided into two loosely separated groups: prestige objects as personal attributes (the more common: dress pins, neck- and arm-rings, knives, razors or 'razor sets') and prestige objects as symbols of power (the more exclusive: spectacle-shaped fibulas, large belt elements for female ceremonial costume, large weapons). The evidence suggests that large belt elements and possibly dress pins were primarily manufactured within the longhouse arena (table 1). Well-identified moulds for spectacle fibulas are known from both longhouse and cult-house milieus, as shown by examples such as Tallboda; Äijä, et al. 1996, and Brobakken; Mikkelsen, 2015 (fig. 20; table 1). Weapons and possibly tools for 'razor kits', however, were more commonly (but not exclusively) cast in cult-house contexts (see e.g. Ryssgärdet; Hjärthner-Holdar et al. eds, 2008, Hallunda; Vahlne, 1974 and Brobakken; Mikkelsen, 2015). Neck-rings and socketed axes were cast in both arenas (table 1). Considering the roles of these objects in male and female elite costumes and equipment, as demonstrated through the Early Bronze Age burial record where notably full-length swords and large belt ornaments are mutually exclusive (e.g. Bergerbrant, 2007, p. 8), this suggests a gender-based division for parts of the production. This tendency concerns the most prestigious objects—those acting as symbols of power, and having strong continuity in form and function throughout the Early to the Late Bronze Age. Following the argument about the public display-like character of the casting events presented above, I suggest that this pattern could mirror a practice whereby leaders and specialists within varoius elite domains/social institutions, sometimes also linked to female and male roles, received their insignia under different circumstances.

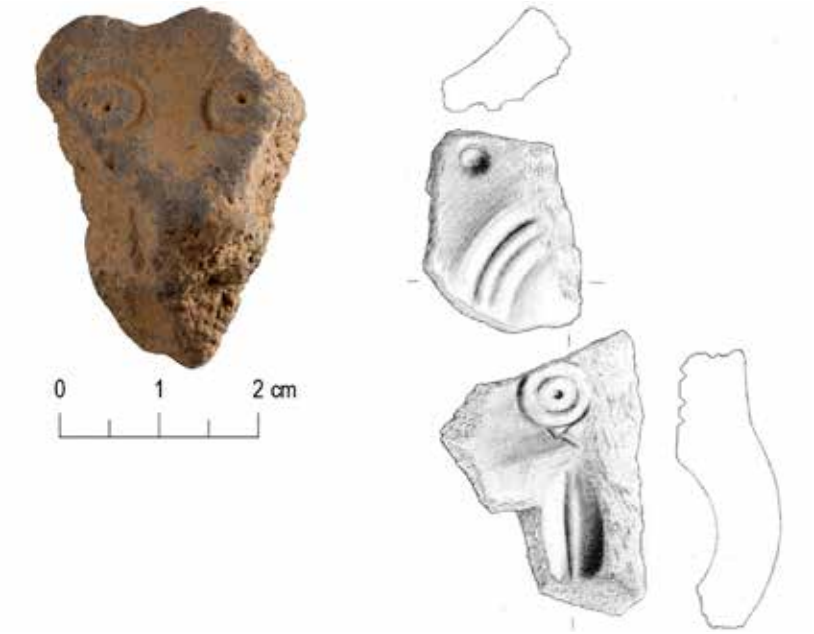


Fig. 20 – Mould fragments with identifiable imprints for spectacle fibulas. To the left: a fragment found in the vicinity of a stone-foundation type cult-house at the grave and settlement complex at Molnby, Uppland, Sweden (Hed Jakobsson et al., 2021; photo: Stefan Gustafsson, Arkeologikonsult AB); to the right: fragments found in a pit at the yard of a longhouse in grave and settlement complex at Tallboda, Östergötland, Sweden (Äijä, et al. 1996, here: fig. 13; drawing: Anders Eide).

The use of bronzes in costumes, and as symbolic personal attributes, implies that they had an important role in constructing various gendered power identities. The grand size and spectacular design of these attributes also indicate that such identities were often communicative and public in nature (Sørensen, 1997). This role as public markers of status and gender thus also seems to have structured their production. Castings of such objects were probably performed at a public scale, as indicated by the location of casting debris in these large settlement contexts. As suggested by Anne Lene Melheim and colleagues (2016), large cultic sites and associated settlements were probably used for assemblies for funerary ceremonies, but also trade and crafting. I suggest that some of these crafting events formed part of passage rituals where individuals within the elite collective entered into new roles, in ceremonies witnessed by the community. Examples of crafting taking place as part of communal ceremonies of this type are known from ethnographic literature, for example in the historical chiefdoms of BoCongo, where the chiefly insignia, in the form of highly symbolic iron bracelets, were produced as part of the inauguration rituals (e.g. Herbert, 1984, chapter 10 and 1993, p. 132; Blakely, 2006, p. 163, 166–167). From a contemporary Western horizon, it could be compared to a situation where wedding rings were to be cast during marriage ceremonies.

Hierarchy and heterarchy in the organisation of metalworking

The interpretation presented here implies that castings should probably be understood as an effective form of political ritual, wherein power relations and claims were manifested and physically transformed. Gatherings, feasts and political rituals that surrounded such passage rites seem to have taken place at the larger grave and settlement complexes of local leading households—in the cult and funerary arenas or longhouse milieus. Thus, no production was carried out in spheres outside of the households, at special assembly sites or regional centres such as hill-forts or in centralised workshops (see also Levy, 1991). These results are in line with recent interpretations of metalworking in Late Bronze Age northern Europe as 'embedded in the life of regular settlements' (Molloy and Mödlinger, 2020, p. 221–222). However, the Scandinavian data also underlines the variation in how craft was staged within settlements, illustrated for example by the fact that Nordic Late Bronze Age settlements may also include important ritual arenas. Taken together, this craft production has greater similarities with the ceremonial production in communal rituals of small-scale societies (e.g. Spielmann, 1998 and 2002; Carter, 2007; Nikolaidou, 2007), than with centralized workshop production in chiefdoms, palace economies or early states.

Inspiration for this diversified craft production in Nordic Bronze Age households can be drawn from the concept of heterarchical societal structure, signifying a society characterised by several, parallel arenas for exerting power and multiple sources for social prestige (Crumley, 1979; Levy, 1995). Specialised craft in heterarchical societies is, as pointed out by Elizabeth DeMarrais, generally organised on a household basis, and tied to several different clients rather than centralised production for a united elite (DeMarrais, 2013). The variation in the craft organisation

in Late Bronze Age southern Scandinavia and its adaptation to future owners of the produced objects has here been interpreted as a production oriented towards the clients. Rather than special workshop areas organised around the metalworker, the metalworkers seem to have arranged their craft around their clients—clients did not seek out the workshop of the smith; the smith came to them. The heterarchical structure would fit well with such a model.

How did this heterarchical production for a varied group of social elites relate to the small-scale production of tools at smaller, single-farms? In what sense was production also politically hierarchical in the Late Bronze Age? I agree with the position that small-scale production at smaller farms was probably dependent on skilled craftworkers from the larger settlements (e.g. Björhem and Magnusson Staaf, 2006, p. 166), rather than independently carried out by 'amateur' casters (e.g. Nilsson, 2011; Earle et al., 2022). There are three important arguments that support this view. Firstly, regardless of how 'simple' objects were to be cast, investment in specialised equipment such as moulds, crucibles, bellows and tools would still be needed. Even in cases where the axe was cast in a 'ready-made' stone mould, like the small farm in Rambodal, this would require a ceramic core with casting channels, which is technically challenging. Secondly, casting is dependent on experience and practical skill, which seems difficult to sustain based on such a small-scale and irregular production of tools for household needs. Thirdly, the ritualised forms of casting prestige objects speak against a parallel amateur production: if bronze casting was exploited as an important public ritual for manifesting the positions of important social institutions, it is difficult to envision this being compatible with bronze casting carried out anywhere by anyone. If these castings, as I argue, were made by specialist crafters who came to smaller satellite farms to provide a new tool, this was probably an important occasion where the production event probably—like the axe itself—manifested the household's kinship identity, power relations and political dependency.

The picture that emerges is that of a craft organised for and by the users, either by metalworkers visiting their households, or by setting up production in the grave and settlement complexes where they lived. Another indication that speaks for a joint craft collective, rather than several different levels of smiths, is the homogenous quality and similar methods in casting technology and technical ceramics over the Nordic Bronze Age area (Jantzen, 2008; Melheim, 2012; see also Sahlén, 2011). We can thereby talk of a hierarchical organisation, which to some degree confirms previous models of a more widespread production of tools in smaller households. At the same time, the material from these Scandinavian sites have also opened new windows into this production, suggesting a heterarchical organisation for important social institutions in society. The proposed organisation is visualised below in a diagram (fig. 21). This model can hopefully provide a useful hypothesis against which new casting sites can be tested in future excavations and research work.

CONCLUSIONS AND FINAL REFLECTIONS

The bronze crafting tradition in southern Scandinavia began as advanced but small-scale production in the Early Bronze Age. Known evidence from period I–II is so far limited to Denmark and southern Sweden. In this early phase, casting was performed in longhouses in settlements. Casting often appears in exceptionally large longhouses. Whether the connection to certain houses reflects monopolization by elite households, or crafting in shared, public buildings, is not yet clear, but a high degree of elite control seems plausible. Since casting was performed indoors it probably involved a rather limited number of people, such as an extended family or selected inhabitants and guests, rather than large audiences. This production thus seems to have been an affair concerning the household and its allies. The data from the earlier periods are less well-known, and this picture might change in the future.

From period III onwards and during the Late Bronze Age, bronze-working became more widespread and covered a much wider range of object types. Weapons, ritual paraphernalia, personal ornaments and dress attributes were now produced at grave and settlement complexes within all regions of southern Scandinavia. However, there are no signs of specialized production centres or centralised workshops. Rather than spatial and political monopolization by a centralized elite group, all production can, I argue, be considered household production. In larger households it was practised in two main arenas – longhouse contexts and cult-house contexts respectively. In the Late Bronze Age, the manufacturing of bronze objects occurred in households at various levels (hierarchy) and in various spheres within these households (heterarchy). This range seems to cover production in households with ritual or clan leaders, production in competing or collaborating households with various roles in the elite, and small-scale production in single households dependent on expert crafters from kin or allies.

The results of this study clarify the position of metalworking in physical and social space, which was previously hypothesized from finished objects and (neo-evolutionist) anthropological notions of specialized crafting in chiefdoms. The study demonstrates that bronze casting played an active and communicative role in social reproduction during the Late Bronze Age. This elaborate, socially meaningful and ritualised organisation of crafting contrasts with the specialised craft production in the form of workshops or attached specialists traditionally emphasized in Bronze Age research. The inconspicuous traces from the casting provide windows onto a different way of making and perceiving objects in small-scale communities.

Finally, some points of wider interest for craft studies can perhaps also be drawn from the Scandinavian data. The first point concerns approaching sites with metalworking, where there has been a tendency to categorise sites as 'production units' with either high or low status/

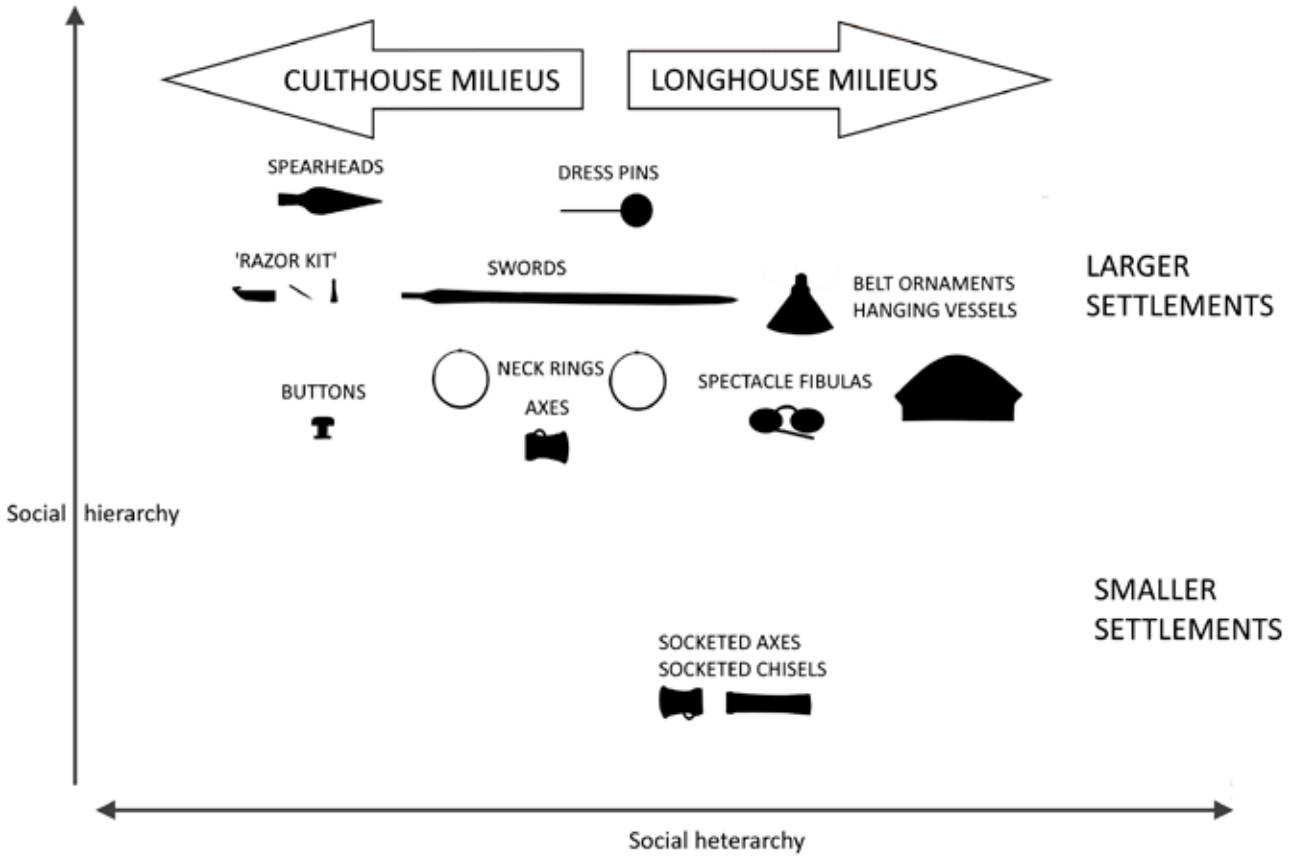


Fig. 21 – Model for the spatial and social organisation of casting bronze objects in the Late Bronze Age of southern Scandinavia. The tendencies of spatial and social differentiation (heterarchy) is shown on the X axis. The tendencies of differentiation in power is shown on the Y axis (hierarchy). The illustrated object types hint at a production where important items were produced in different places and under different circumstances, but it should be emphasised that it builds on very few surviving imprints of cast objects in mould fragments from excavated sites, and presents a more speculative aspect of this model – to be tested and adjusted as new finds emerge in the future (illustration by the author).

capacity, while the inner dynamic at these sites may remain obscure. The Scandinavian examples underline that spatial arrangements within sites holds great potential to inform about the social position of the craft. As Barry Molloy and Marianne Mödlinger recently stated: "Find contexts are a good indicator of the degree to which metalworking was integral to, and, we may argue, visible within societies" (Molloy and Mödlinger, 2020, p. 193). The second point concerns terminology, notably the notion of workshops when examining the organisation of specialised craft. This is a figure of thought that tend to bring about certain expectations (permanency, seclusion, one place hosting the full *chaîne opératoire*), that might hinder the observation of other forms of organising craft production in small-scale societies (Sörman, 2017; Costin, 2020). The specialised craft, even in chiefdoms, might not look as we have expected, and the terminology we employ should be open enough to allow for the data to surprise us.

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Session 3

The production process, from metal to finished objects

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Fine metal work from the Early Bronze Age Maikop kurgan, Kuban region, northern Caucasus (Russia)

Barbara Armbruster

Abstract: This paper deals with fine metal work from the primary burial of the large Early Bronze Age Maikop (Oshad) kurgan, northern Caucasus (Russia), discovered at the end of the 19th century. More precisely, it focuses on the technological aspects of the unique precious metal assemblage from Maikop, dated to the second half of the 4th millennium BC. The grave goods include thousands of gold and silver items, representing various functional categories, specific shapes and decorations. These artefacts comprise prestigious table ware and drinking tubes, as well as personal ornaments, among them series of appliqués to be sewn onto garments and a remarkable variety and quantity of beads, likely arranged in strings and worn as necklaces. The elaborate fine metalwork will be approached by tool mark analyses, form and function, and analogies to draw a picture of the know-how of Early Bronze Age goldsmiths in the Caucasus.

Keywords: Caucasus, Early Bronze Age, gold and silver working, Maikop culture, ornaments, Russia, vessels.

Résumé : Cet article traite des objets en métaux précieux provenant de la tombe primaire du grand kourgane de Maikop (Oshad) dans le nord du Caucase (Russie), datant de l'âge du Bronze ancien, découverte à la fin du XIXe siècle. Plus précisément, il se concentre sur les aspects technologiques de l'ensemble de Maikop, daté de la seconde moitié du IVe millénaire avant J.-C. Les biens funéraires consistent en des milliers d'objets en or et en argent, représentant diverses catégories fonctionnelles, des formes spécifiques et des décorations. Ces objets comprennent de la vaisselle de prestige et des tubes à boire, ainsi que des parures, notamment des séries d'appliques à coudre sur les vêtements et de nombreuses perles de formes variées, très probablement disposées en chaînes et portées en collier. L'orfèvrerie sera abordée par l'analyse des traces d'outils, de la morphologie et de la fonction, et par des analogies afin de dresser un tableau du savoir-faire des orfèvres de l'âge du Bronze ancien dans le Caucase.

Mots clés : Caucase, âge du Bronze ancien, orfèvrerie, culture de Maikop, parure, Russie, vaisselle.

The Early Bronze Age Maikop barrow, located in the Kuban region, northern Caucasus (now part of the Republic of Adygea, Russia), is considered as one of the most outstanding archaeological discoveries in Eurasia and beyond. Revealed at the end of the 19th century, the Oshad kurgan is a large burial mound of more than 11 m in height and about 200 m in diameter. It was excavated by Nikolai Ivanovich Veselovskij (Veselovskij, 1897 [1997]); Piotrovskij, 1998 and 2020). The Maikop complex is today dated to the second half of the 4th millennium BC, and is eponymous with the Early Bronze Age Maikop Culture (Ivanova, 2007; Piotrovskij, 2020). The northern Caucasian Maikop Culture coexists with the Early Bronze Age Kura-Araxes Culture in the southern Caucasus and with the Mesopotamian Uruk period (Hansen, 2014). The material culture excavated in the Maikop kurgan is particularly rich and is regarded as a unique cultural feature, unmatched in the Early Bronze Age in terms of artistic and symbolic characteristics, quantity and quality.

Thanks to the kind invitation by Jurij Ju. Piotrovskij, the author had the opportunity to examine a significant proportion of the precious metal objects from the Maikop kurgan in the Hermitage collections (Saint Petersburg, Russia), with a particular focus on the manufacturing details and comparisons. Surprisingly, the craftsmanship, techniques and manufacture of the gold and silver artefacts from this northern Caucasus area have, unlike those from other regions, received little scholarly attention.

Recent research, including a reappraisal of old archival data, has provided new insights. In particular, Veselovskij's original excavation reports, which feature early

sketches of the kurgan and a model of the detailed construction plan of the main tripartite funeral complex comprising three burial chambers (fig. 1), have been reviewed (Piotrovskij, 2020, p. 123, fig. 5, p. 126, fig. 8 and p. 133, fig. 10-11; Piotrovskij, 2021, p. 162, fig. 3, p. 166, fig. 6). These studies have also reviewed the chronology of the Maikop kurgan based on ^{14}C dating, examined its contextual setting and burial rituals, and updated the bibliographical outline (Piotrovskij, 2020 and 2021). The material culture is related to contemporaneous archaeological assemblages (Hansen, 2009, p. 31–33; and 2014; Ivanova, 2012; Piotrovskij, 2021). The precious metal objects, which are the main concern of this paper, are re-examined within their archaeological context and compared with similar finds, in particular in Eastern Europe and the Near East (Piotrovskij 1998, 2003, 2020 and 2021).

The main burial includes three individuals placed in separate but adjacent chambers: the primary male (skeleton 1) in the large chamber, and two companions, presumably a man and a woman (skeletons 2 and 3) in two smaller compartments. The kurgan contained a significant quantity of metal finds, including about 3 kg of gold and 5 kg of silver, with items such as sheet vessels, personal ornaments comprising strings of innumerable beads and arrangements of figured gold appliqués, as well as solid cast figurines with related tubular sticks. Moreover, weapons, tools, vessels and cauldrons made of arsenical copper, stone and pottery vessels, as well as a large number of carnelian and turquoise beads, were part of the Maikop grave goods. Notably, remnants of red pigment were found covering the interior of the grave, including

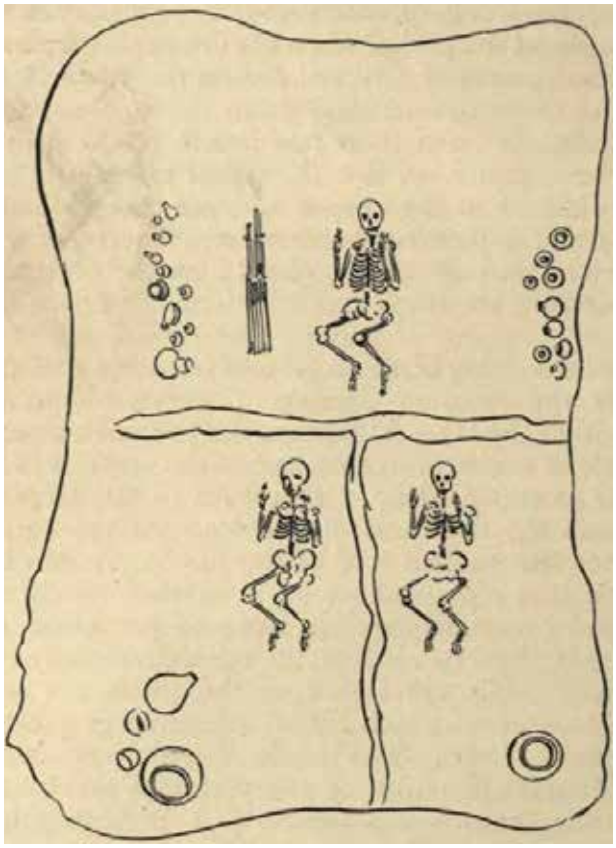


Fig. 1 – Plan of the Maikop burial (Rostovtzeff, 1922, fig. 1, via archive.org).



Fig 2 – a-d Massive silver and gold bull figurines originally fixed on hollow silver and gold rods, height c. 80 mm (© B. Armbruster)

the skeletons. Often interpreted as red ochre or cinnabar, it was shown quite early on that this substance is an inorganic compound known as red lead, a lead oxide with the formula Pb_3O_4 (Ivanova, 2012, p. 4–5).

In Chalcolithic and Bronze Age cultures gold and silver objects were symbols of holiness, belief and, by extension, power and prestige (Benzel, 2016). The sun- and moon-like colours, the pure and shiny qualities, and the unique material properties of silver and gold imbued these rare precious metals with sacred characteristics linked to eternity, ritual and the divine.

ANIMAL STYLE IN GOLD AND SILVER ARTEFACTS

The outstanding characteristic of the Maikop gold and silver assemblage is the local figurative animal style, which appears in various forms, both conceptually and through the choice of manufacturing techniques. On the one hand, it is embodied in individual animal representations, such as the three-dimensional bull figurines made of solid gold and silver (fig. 2a-b). These figures show highly naturalistic depictions, even in detailed anatomical features, such as the separation line on the hooves of cloven-hoofed animals (fig. 2c-d). On the other hand, zoomorphic representations are personified in hollow gold sheet appliqués featuring lions and bulls in complete lateral view, created in low-relief plastic work (fig. 3). Finally, two silver vessels bear traced depictions of animal friezes (figs. 5a and 6-8). In this case, linear images conceived as drawings in a two-dimensional format are realised on the convex surface of three-dimensional sheet metal bodies (fig. 4a).

The zoomorphic pictures mirror part of the local fauna at the time (Uerpmann and Uerpmann, 2010). Accordingly, the array of depiction panels encompasses various animal species (figs. 2-3 and 5a-7): predatory cats, including lions and cheetahs, bulls, wild goats, boars, horses, water birds and birds of prey (fig. 6-8). In addition, a bear standing on its hind legs is displayed with a tree resembling a palm and a landscape sketch featuring mountain ridges (fig. 8b-e). Maikop tableware, including these two decorated silver vessels with animal processions, was introduced early on, providing the first detailed graphic representation of the illustrative friezes (figs. 5a, 6 and 8) (Smirnov, 1909, pl. 2).

Recently, the significance of lion depictions in Maikop and beyond has been analysed for its symbolic meaning and set into its socio-historical context, related, amongst other things, to feline representations in Near Eastern art (Hansen, 2020a, p. 280–283 and 2020b). Emblematically, the lion, as a predator, represents strength, aristocratic status and power. It is particularly emphasised in Maikop through the multiplicity of 70 lion appliqués (fig. 3) associated with the richly equipped individual (skeleton 1).

Furthermore, the solid bull figurines and the numerous bull-shaped sheet appliqués from Maikop evoke the worship of the bull in Eurasia. The bull cult can be traced back to previous traditions, from Paleolithic to Neolithic depictions (Calegari, 1988; Francfort, 2021). Despite the large chronological gap, the Early Bronze Age Maikop animal style might have been a prototype for much later Iron Age zoomorphic images in Scythian, Samaritan or Celtic arts.



Fig. 3 – Lion shaped appliqués worked using dies with perforations for sewing onto garments. Remains of red lead oxide covering the skeleton (© B. Armbruster)

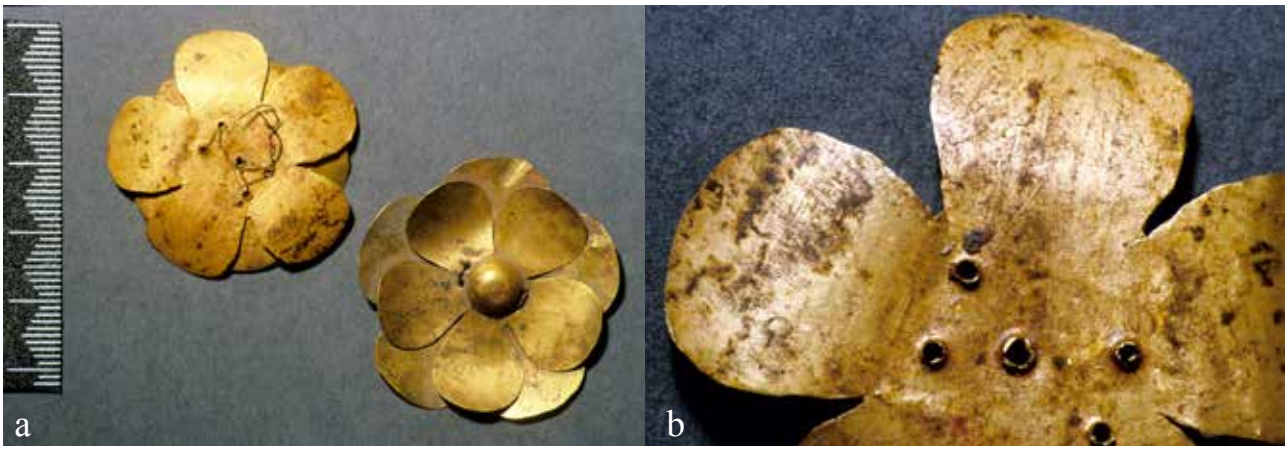


Fig. 4 – Doubled sheet rosettes, sheet work, cut contours, relief, perforations pushed through with a conical point (© B. Armbruster).

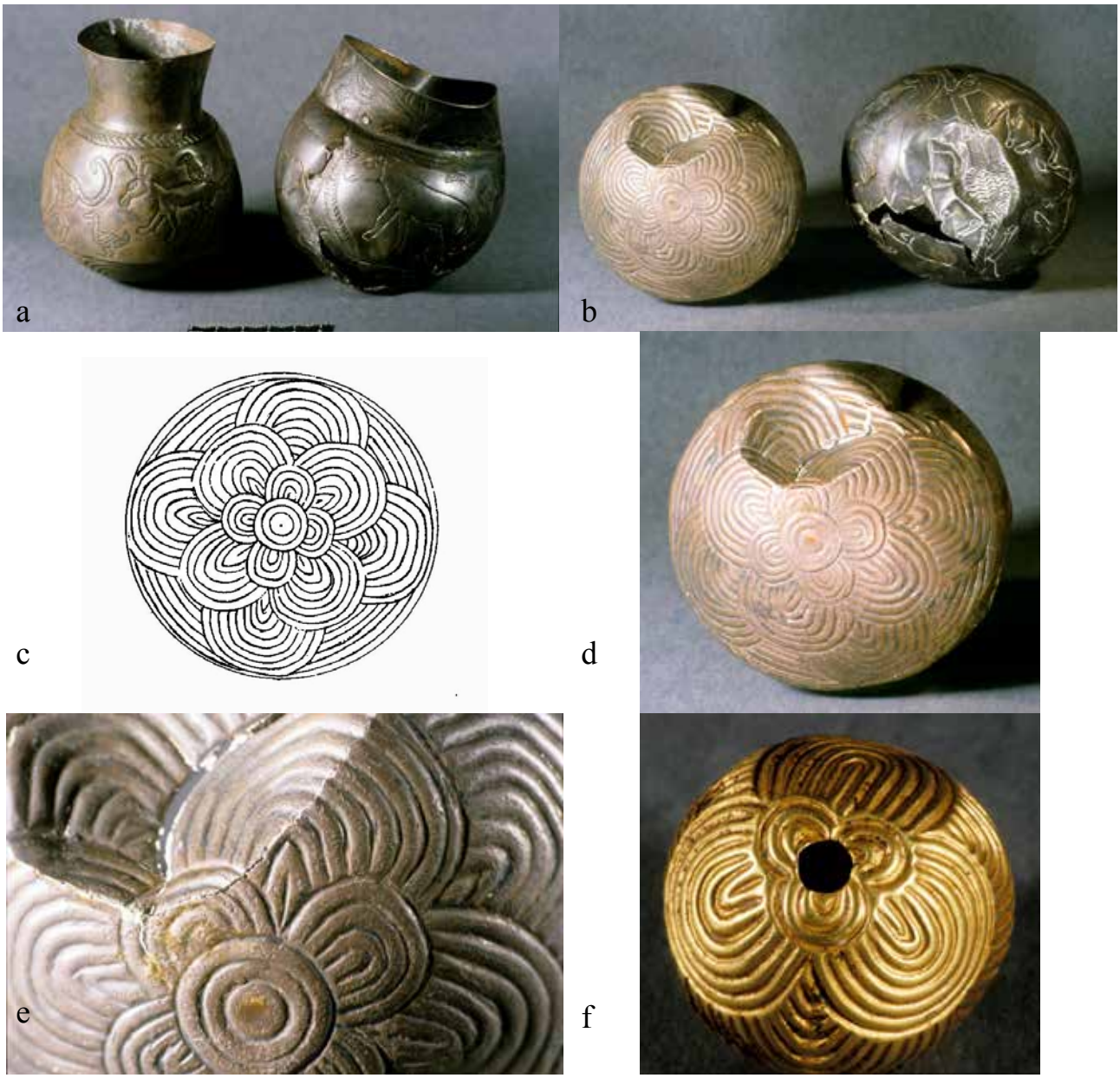


Fig. 5 – Silver sheet vessels with chased animal processions, one with landscape on the base, the other with rosette comparable with the much smaller rosette from a sheet bead (a-b, d-f: © B. Armbruster; c: drawing Smirnov, 1909, pl. 2, 10).

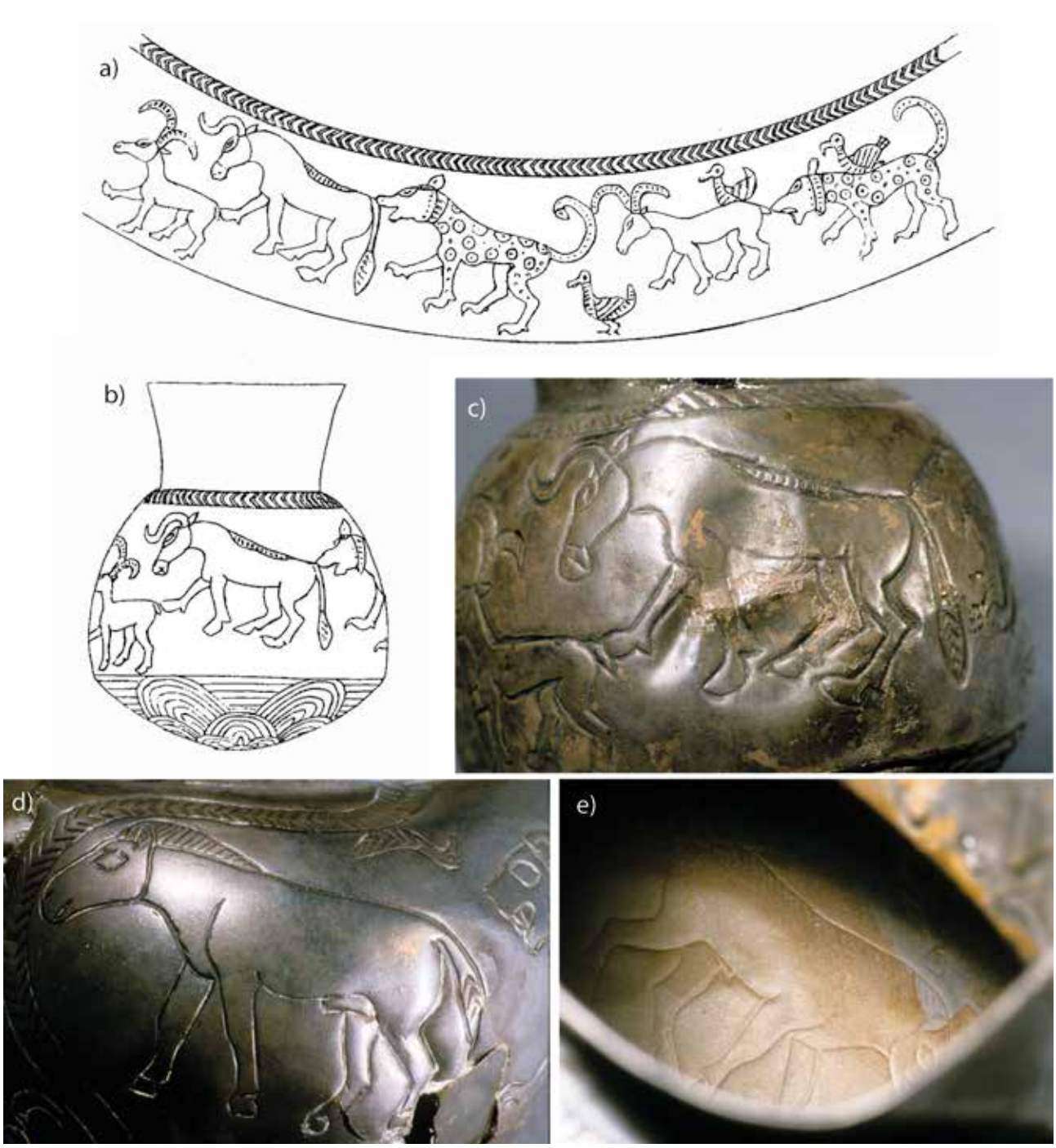
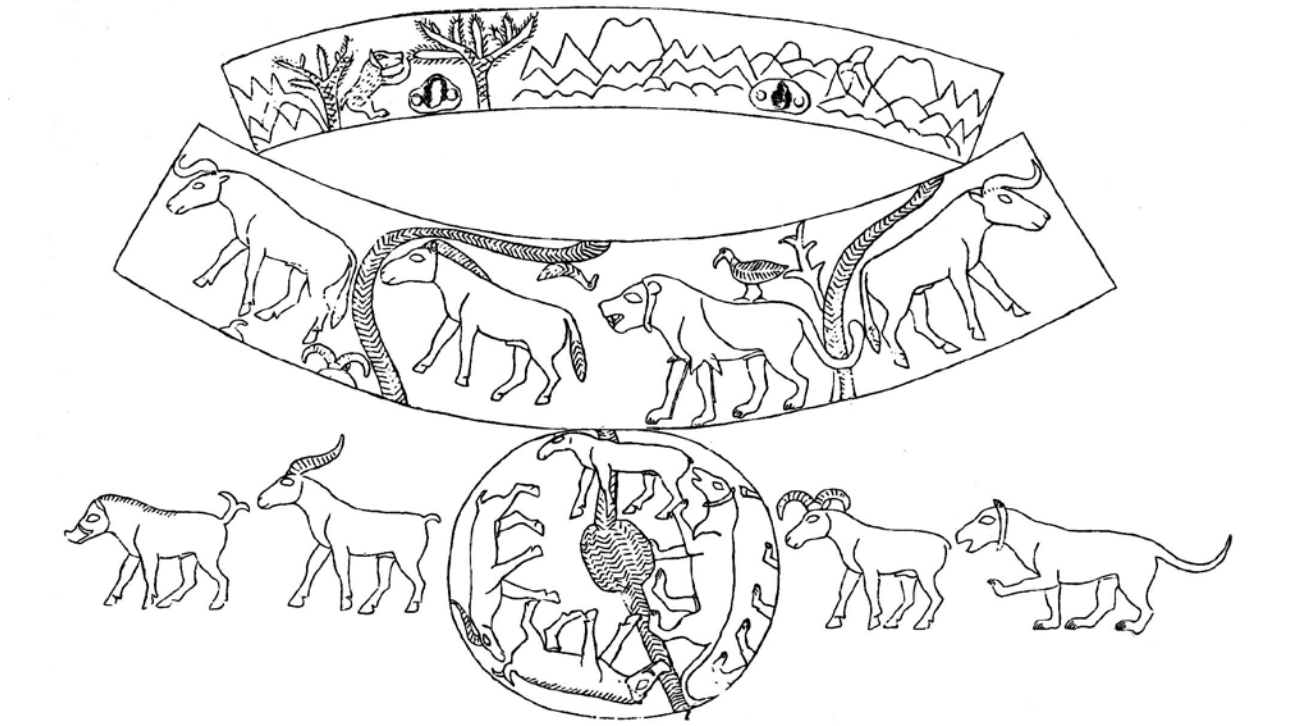


Fig. 6 – a: Animal procession's graphic unwinding and b: drawing of rosette vessel, detail of linear chasing; c: bull; d: horse, incised lines outside (landscape vessel); e: tool marks inside (a-b: drawings Smirnov, 1909, ll. 2, 10; c-e © B. Armbruster).



Fig. 7 – Predatory cats, water birds and birds of prey (© B. Armbruster).



a



b c



d e

Fig. 8 – a: Unwinding landscape vessel; b-c: Zickzack – chased and traced depiction of three mountain ridges outside and inside; d-e: "bear with palm tree", outside and inside (a: drawings Smirnov, 1909, pl. 2, 11; b-d: © B. Armbruster).

COMPARATIVE TECHNICAL CHARACTERISTICS AT THE INCEPTION OF GOLD METALLURGY

The Maikop precious metal collection has occasionally been mentioned in connection with other early fine metal arts and crafts, notably the earlier so-called "first gold of Mankind" from the Chalcolithic Varna necropolis (Bulgaria, mid-5th millennium BC; Ivanov, 1988), and the later Mesopotamian gold and silver work from the royal necropolis of Ur (Iraq, mid-3rd millennium BC; Zettler and Horne, 1998). However, while there are some similarities, the Maikop assemblage stands apart due to its own specific and unparalleled local metal production.

Technically, the Varna gold is largely based on casting, particularly lost-wax casting (for beads, thin two-dimensional plates and hollow three-dimensional objects such as arm rings), and on hammered rods for penannular or cylindrical beads (Leusch et al., 2015, p. 356–358). To a lesser extent, it includes thin sheet work manufactured by plastic shaping (e.g. appliqués and sheet fittings for bows or sceptres; Leusch et al., 2015, figs. 8 and 14). In comparison, hammered, die-shaped and chased sheet work predominates in the Maikop fine metalwork.

The serial production of beads and appliqués is a notable common feature in early fine metalworking. The beginning of serial fine metal production dates back to the Chalcolithic Varna necropolis, where large quantities of beads in various shapes and minor series of appliqués appear in rich grave assemblages (Leusch et al., 2014, fig. 7; Leusch, 2019, p. 62–71). Bead series also occur in other Chalcolithic sites, such as Durankulac, Bulgaria (Avramova, 2002, diagram 24, p. 202; Leusch, 2019, p. 63–65). Chalcolithic and Early Bronze Age gold and silver bead necklaces share the serial manufacturing concept with contemporary and earlier strings made of organic materials such as shell and bone, or inorganic stones, which predate the rise of metallurgy (Bonsall et al., 2017; Baysal, 2019).

Regarding serial production, the three mentioned archaeological sites of Varna, Maikop and Ur share the creation of metal beads, occasionally combined with coloured stone beads. The open ring-shaped beads from Varna have been compared to similar beads from the Maikop kurgan. Another common feature is the depiction of bulls and lions, though in Ur these appear as figurines. The Mesopotamian zoomorphic repertoire is extended by ram statues. However, the ring-shaped beads are in fact penannular, thus open ring beads made from hammered gold rods with rectangular cross section. These rods were wound around a cylindrical core to create a cylindrical spiral, which each ring was then individually cut off (Echt et al., 1991, p. 650–651; Leusch et al., 2014, fig. 9). This technique differs from the Maikop annular ring beads, which are closed disc rings (fig. 9a and c). Piotrovskij mentions comparable closed-ring beads from various other find spots (Piotrovskij, 2020, p. 137). In addition, Maikop offers series of appliqués, as personal ornaments sewn onto garments, which are similar to those found in the Varna grave goods, though their production is less significant.

In contrast, both Maikop and Ur have a common ground in the production of sheet vessels in gold and silver. For other associated functional categories of gold and silver artefacts, however, Varna, Maikop and Ur differ significantly in terms of morphology and fine metalworking practices (Leusch et al., 2014; Leusch et al., 2015; Armbruster, 2016; Alarcon et al., 2018).

TECHNOLOGICAL ASPECTS OF MAIKOP FINE METAL WORKING

The object groups from Maikop show basic fine metal manufacturing techniques well known from early gold metallurgy. However, considering the chronological context, they are applied in a sophisticated way. Tool mark analyses and surface topography of the objects enable a technical interpretation of their manufacture, use, and damage or recycling, along with deductions about the technical skills, tools and materials required for their creation. The technical repertoire of the Maikop material covers heat-involving processes such as melting, alloying, ingot casting, lost-wax casting and annealing. Cold-working techniques primarily involve plastic shaping methods such as hammering sheet products, vessel sinking, die forming, doming, and chasing to shape and decorate beads, appliqués, and vessels. Piercing with a conical point and cutting edges from sheet metal using a chisel are also part of plastic shaping. In these processes, the mechanical stress applied with the point or chisel exceeds the elasticity breaking point of the sheet metal, resulting in holes or severed edges. Joining techniques observed include riveting sheet metal (vessels; fig. 13d; 14b-c), plugging hollow figurines onto cylindrical rods, stitching elements together (rosettes; fig. 4) or onto a garment (appliqués; fig. 3), and finally stringing bead necklaces (fig. 9-11).

How can we imagine the fine metalworking craft, workshop equipment and organisation in the 4th millennium BC? Regrettably, Early Bronze Age goldsmiths' workshop structures are absent in the archaeological record and fine metalworking tools are seldom found. Therefore, the means of gold and silver production are poorly studied for the region. However, a glimpse into the toolset of Bronze Age fine metalworkers in Western Europe, where a large range of instruments have been preserved, offers useful parallels (Armbruster, 2021, 32-71; Armbruster, 2023; Boutoille and Peake, 2023).

Moreover, ancient iconographic sources from Egyptian tombs, dating to the 3rd and 2nd millennium BC, provide interesting analogies that offer an in-depth insight into the Bronze Age metallurgist's studios, materials, equipment, tool handling and workshop organisation. Fine metal workshops, with craftsmen at work, are depicted in low-relief carvings or coloured wall paintings (Scheel, 1989; Garenne-Marot, 1985; Sales, 2016). In the tomb of

Rekhmire (near Thebes, Egypt, about 1500 BC), fine metalworkers are shown weighing materials with scales and weights, working with variously shaped lithic hammers, adjusted in each case to a specific purpose, and using large passive stone anvils for sheet production. Furthermore, stakes presumably in bronze are used for vessel shaping. The artisans are using furnaces with bellows or blow pipes, forceps, tongs or stones to hold workpieces, as well as punches and a stone hammer for chasing. Besides, ethnoarchaeological reasoning and experimental archaeology provide technical analogies to enhance our understanding of ancient fine metalworking (Armbruster, 2014).

Generally, several tools were essential for Early Bronze Age fine metalworking, including its pyrotechnical processes and cold plastic shaping. Before transforming raw precious metals into objects, measuring tools were required. Balance scales and weights were needed for weighing, and touchstones to assay the quality of gold alloys through a colorimetric test. In addition, metalwork was often prepared and checked through the use of tracers, such as a compass, and a preliminary sketch.

The toolset of Early Bronze Age goldsmiths consisted of various materials, including inorganic stone, copper alloys or technical ceramics, as well as organic materials like antler, bone and hard wood. Utensils made of refractory and tempered clay, such as blow pipes (bellows), furnace linings, crucibles and casting moulds, were crucial for heat-intensive activities like alloying, melting, casting and annealing (Martinón-Torres and Rehren, 2014). Stone was a suitable material for casting moulds and percussion tools (hammer and anvil; Ambruster, 2010; Boutoille, 2019), while copper alloys may have been used for tools such as chisels and punches, as well as hammers (Armbruster, 2023). Hard organic materials were likely used for holding the workpiece with tongs, pliers or tweezers. They may also have been employed likewise for dies and punches or other percussion tools (hammer and anvil) for softer plastic shaping.

Decorated silver or gold sheet products with chased motifs were ornamented after forming. This is the case for the decorated beads, appliqués and vessels found at Maikop. During chasing these hollow sheet items were filled with a chaser's pitch, a mixture of brick dust, pitch, resin or wax, which could be easily liquefied by heat and hardened as it cooled (Corvin 2009).

Sheet work

Gold and silver sheet work is the most significant technical group in the Maikop collection, including smaller items such as beads, appliqués and elements presumably belonging to a diadem. Moreover, a remarkable set



Fig. 9 – Large variety of gold and silver beads – disc-shaped, hollow hemispheric, cylindrical, olive-shaped, spherical with or without chased motifs (© B. Armbruster)

of precious tableware is a part of the sheet assemblage, consisting of larger objects. Ancient sheet production was performed by manual beating, in order to transform an ingot into a thin sheet, and then eventually by hammering to form the object. For this purpose, both active and passive percussion tools made from materials such as stone, copper alloy or organic materials like antler, horn, bone or wood might have been used. Extensive transformation by plastic shaping induces brittleness and hardening in the metal. Therefore, annealing while forming gold or silver was repeatedly required to prevent cracking. Gold annealing, conducted around 700 degrees Celsius, resets the hardened microstructure and restores elasticity, which allows further deformation. Once the sheet metal was prepared, the workpieces' outlines had to be cut out with chisels on a solid surface, or the sheet could be directly hammered into shape, for instance a disc form.

The manufacturing processes of hollow sheet products were three-fold in Maikop. Smaller items, such as the series of hollow appliqués with relief, were made from a single sheet using a negative female die (matrix) and an appropriate male stamp (patrix) or punch, corresponding to the desired shapes of ring, bull or lion (fig. 3). On the other hand, individual chasing was also applied to create relief or linear tracing. For this step, punches, chisels and a type of a chaser's pitch were required (Corvin 2009). In the case of Maikop, individually formed objects, the surface finish of serially shaped sheet reliefs, or the reworking of cast surfaces were carried out by chasing.

Chasing, including repoussé, embossing and tracing, is a form of plastic shaping of thin metal sheet through the creation of relief (Brepohl, 1987, p. 165–168, fig. 59.1; Fröhlich and Fröhlich, 1974, p. 80; Corvin, 2009). In addition to vessel ornamentation, it was also used for the tiniest sheet beads with relief. Chasing requires simple tools, comprising a wide range of punches and chisels made of copper alloy, antler, bone or hardwood. These tools are driven and pushed using a percussive instrument, a hammer of stone, metal or organic materials. While the shaping instruments work on the surface from one side of the sheet, the other side must be rested on a soft support, such as chaser's pitch. In the case of vessel decoration, the container must be filled with chaser's pitch and chasing is executed from the outside. This way of chasing exclusively in repoussé from the front side is depicted in graphic representations of artisans in Egyptian wall paintings (fig. 12b). The same technique is described in detail in ancient literary sources (Brepohl, 1987, p. 166, fig. 58.1; Armbruster, 2024, fig. 6b). For annealing, the chaser's pitch must be removed by heating.

Beads

The most numerous objects are beads, which reflect ingenious creative effort and a significant serial production in Maikop (fig. 9-10). Some beads clearly bear wear marks. Piotrovskij described the bead morphology with 14 variants and reconstructed their spatial distribution in the grave (Piotrovskij, 2020, p. 134, fig. 12; p. 140, fig. 14–15; Piotrovskij, 2021, p. 162, fig. 3). A total of 5,671 gold beads (weighing 1,036 g), 961 silver beads (weighing more than 63 g), 58 turquoise beads and 1,266 carnelian beads were found in relation with the main burial, something without direct parallels found in the Near East (Piotrovskij, 1998, p. 84–90; Piotrovskij, 2021, p. 161). Piotrovskij emphasises the uniqueness of Maikop's diverse bead production. However, he mentions some comparisons for closed, disc-shaped ring beads (Piotrovskij, 2020, p. 136–137).

Beads in gold, silver, turquoise and carnelian were found in all three burials. Nevertheless, the spatial distribution shows a concentration around skeleton 1, in the largest of the three burial chambers (Piotrovskij, 2021, p. 162, fig. 3). Piotrovskij also mentions other parallels, such as the Russian find complex from Staromyshastovsky (Krasnodar region), where over 2,500 beads were found in a lidded silver vessel (Piotrovskij, 2021, p. 163; Korenevskiy, 2016, p. 202 fig. 1,7).

The morphological variety of gold beads is notable, including solid discoid flat beads, hollow discoid sheet beads, hollow hemispherical beads, hollow hemispherical beads mechanically closed with a disc, cylindrical sheet beads, cylindrical beads with enclosed sides, olive- or barrel-shaped beads with chased ornamentation, unornamented spherical beads in various sizes, and spherical beads with notched or chased motifs (figs. 10 and 11; Piotrovskij 1998, p. 85 and 89; Piotrovskij 2020, p. 134, 4–10; p. 140–141, fig. 14 and 15,4). Silver beads are mostly small perforated discs strung together. The numerous disc-shaped beads in gold or silver are actually closed discoid rings, most likely cut from sheets and perforated using a conical point or circular cutter (fig. 9a).

The manufacturing techniques for jointless hollow globular beads made from thin sheets have been investigated and convincingly demonstrated through experimental archaeology, conducted by V. A. Trifonov and N. I. Shishlina for beads from an Early Bronze Age site in the Maikop region (Trifonov and Shishlina, 2019). The authors were able to demonstrate conclusively a purely plastic shaping process from one single piece of gold sheet, starting from a perforated disc and using a doming block, ball punches of various sizes and a percussive instrument to shape a sphere (Trifonov and Shishlina, 2019, fig. 4). They emphasised the necessity of repeated annealing during the process to maintain the malleability of the material. Similar techniques of hammering and chasing are likely used for hollow olive- or barrel-shaped, or even cylindrical, beads with closed sides (fig. 10-11). Detailed X-ray and SEM imaging, as well as metal analysis, may provide further insights into the bead manufacturing process.

Hollow hemispherical beads were more simply made by doming small sheet discs, as evidenced by the folds on the edges of the deepened hemispheres (fig. 9b).

The five larger and individually manufactured beads were laid close to skeleton 1, near the chest or abdomen.



Fig. 10 – Examples from the large variety of gold beads with chased motifs (© B. Armbruster)

They include three beads with elongated fluting, one large spherical bead with a deeply chased rosette pattern, and one elongated bead with swollen decoration in the centre (fig. 5f; fig. 11a-e; Piotrovskij, 1998, p. 90; Piotrovskij, 2020, p. 134, nos. 1–3). Optical observation revealed that all these beads are jointless, presumably made from a single piece of sheet metal and bearing elaborated decoration, as described above.

The homogeneity of the bead series suggests that initial blanks of identical measurements were cut using the same tool or template. These preconditions made it possible to achieve such uniformity. The elegant appearance and sophisticated design are largely due to this successful homogenisation and standardisation.

Appliqués

The gold appliqués were found on the body of the main individual (skeleton 1), covering their attire. The inventory, morphology and spatial distribution of these ornamental trimmings in the burial have been recently documented (Piotrovskij, 2021, p. 161–162, fig. 3). The hollow appliqués consist of 33 large lions in lateral view stepping right, 37 smaller lions stepping left (fig. 3), 23 smaller











Fig. 11 – Beads worked individually from one single sheet by sinking and chased, b-c: details of the chased decoration (© B. Armbruster)

appliqués shaped like bulls in lateral view facing right, and 40 ring-shaped elements (Piotrovskij, 1998, p. 90).

These hollow sheet appliqués, all manufactured in series, were shaped in relief using negative dies or swage blocks and positive punches. These tools might have been created in hard organic materials. The appliqués were partially reworked by chasing relief details from the front side. The contours were then carefully cut with a chisel after die shaping, leaving sharp and/or rough edges.

It appears the appliqués were sewn onto garments, as they each bear between 3 and 7 small holes for attachment. The perforations were made by pushing a conical point through the sheet from the reverse, creating a small sharp ridge on the front. While the zoomorphic appliqués are quite naturalistic, 10 stylised rosettes feature more abstract floral designs (fig. 4a-b).

The floral-shaped appliqués are constructed from two superimposed sheets, each with five petals (fig. 4a). The petals were cut from a hammered sheet disc, while the

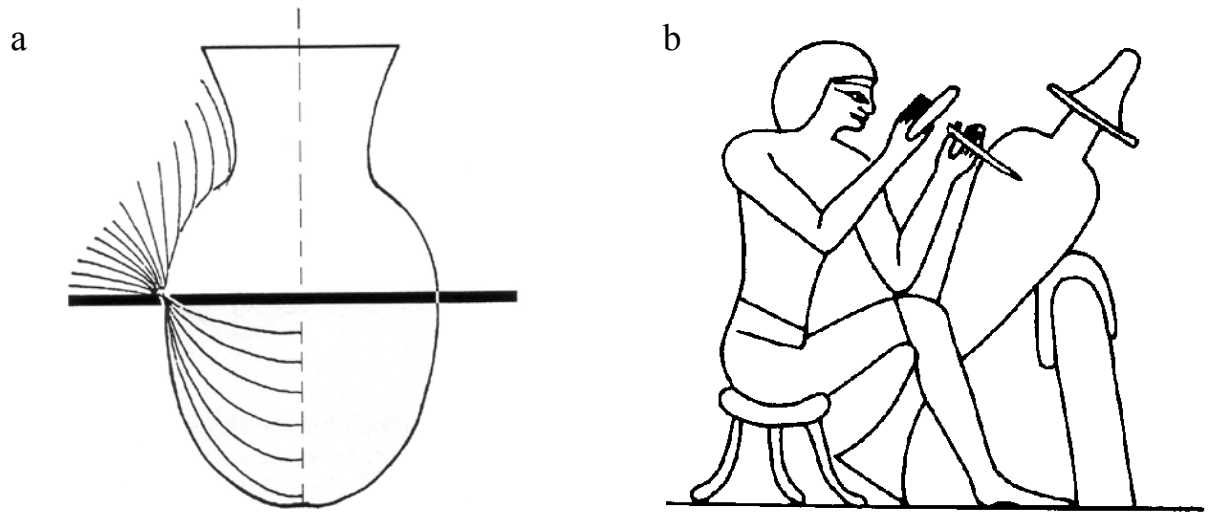


Fig. 12 – a: Complex operational chain of the plastic shaping process – from the cast plate to the hollow sheet body with narrow neck (Fröhlich and Fröhlich, 1974, p. 80); b: Egyptian goldsmith decorating a metal vessel with a metal punch and a stone hammer (Scheel, 1989).

central boss on the upper petal sheet was created with a ball punch. The upper and the lower sheets were pierced four and five times, respectively (fig. 4a-b).

Tableware

Description

The morphology of the precious metal vessels and their spatial distribution has been outlined by Piotrovskij (Piotrovskij, 2021, p. 166, fig. 6). The morphology of several silver and arsenical copper containers from the Maikop kurgan can be compared with ceramics found in the grave, suggesting local production of metal vessels (Piotrovskij, 2020, p. 164–165).

The Maikop assemblage includes two golden containers: a bottle-shaped specimen with an ovoid body, an elongated neck and an embossed rib at the base of the neck (fig. 13a and c); and a small slightly conical bowl (Piotrovskij, 1998, p. 90, nos. 283–284). Three silver vessels are decorated, of which two bear the already mentioned animal friezes. The plain undecorated silver vessels include: a small hemispherical cup, a shallow bowl, a slightly conical cup and several larger pitchers—or vase-shaped containers with globular bodies and narrow necks (Piotrovskij, 2020, p. 153–165; Piotrovskij, 2021, p. 166, fig. 6).

Of the 14 silver vessels, two are enhanced with gold sheet elements attached by riveting, creating a bicoloured effect. One of these is a bicoloured bottle-shaped vessel with an ovoid body, elongated neck and a small omphalos at the base, morphologically similar to the gold bottle. It differs in the collar decoration, featuring a gold sheet ribbon around the neck, situated at its transition to the body and fixed by three gold rivets (fig. 13b and d). The other bicoloured container is smaller, ovoid in shape and with two lateral golden grip plates with suspension system. The grip plates are chased, oval in shape, perforated with two lateral holes for rivets and a vertical one for suspending the hanging vessel (fig. 14a-b). One of the plain silver vessels, with a globular body and a high cylindrical neck, bears two quadrangular silver suspension grip plates, fixed laterally with four rivets each (fig. 14c and e). Both gold grip plates are chased in relief and perforated vertically once for the suspension and on both sides for attachment with four rivets.

Making and decorating Early Bronze Age precious sheet vessels

The gold and silver sheet vessels from Maikop were all realised by the plastic shaping process of sinking, which corresponds to the detailed descriptions of preindustrial vessel manufacturing by the German monk Theophilus, 12th century AD, and the Italian goldsmith Benvenuto, 16th century AD (Fröhlich and Fröhlich, 1974, p. 80; Brepohl, 1987, p. 165–168, fig. 59.1). The sinking process involves various steps of forming a cast disc-shaped plate using an active hammer and a passive anvil or stake (Armbruster, 2024, p. 22 fig. 7). Sinking differs significantly from modern vessels' manufacture by raising, which is based on shaping of a large and thin sheet of metal (Untracht, 1975, p. 247–252). As with the smaller hammered and chased objects, the successive plastic transformation of a cast disc-shaped blank into a hollow, three-dimensional sheet body, requires frequent annealing (fig. 12a).

The decoration techniques of the Maikop tableware include chasing, which creates a visual relief effect that plays with light and shadow, as well as the bicoloured application of riveted gold sheet elements on silver, creating a bichrome effect. Chasing has been applied in various ways to the precious metal vessels. On the one hand, a single relief rib has been created on the neck of the gold bottle (fig. 13c), while a more complex fluted relief ornament covers the entire body of a fragmented flask-shaped silver container (Piotrovskij, 2020, p. 158 fig. 29, 4). On the other hand, drawing-like incisions have cre-



Fig. 13 – Two bottle-shaped vessels with ovoid body, narrow cylindrical neck, decorative collar and small omphalos bottom, Left: height 136 mm, gold bottle with chased rib; right: height 199 mm, bicoloured silver bottle with gold ribbon collar applied by riveting (© B. Armbruster)

ated animal friezes and a landscape depiction on two silver vessels, one of which also features a rosette motif (fig. 5b right, 8a) while the other displays a landscape at the bottom (fig. 5a left, c-e).

Linear and relief chasing on both vessels and beads was executed using punches and tracers of various shapes, which were struck with a percussion tool such as a handheld cushion stone or a shafted hammer. The hollow space of a sheet container must be filled with chaser's pitch during the chasing process.

Bull figurines
Sceptres versus drinking tubes

Four solid bull figurines, two in gold and two in silver in fully plastic design, are provided with a large vertical perforation. This recess was intended for putting the animal on a tubular silver or gold rod (fig. 2; Aruz and Wallenfels 2003; Trifonov et al. 2022, fig. 2-6). Their height is about 80 mm. The small bulls display astonishing anatomical details including specific elaboration of the tail over the backbone and hair at the horns, with special attention to legs, ankles, feet and the characteristic claws of artiodactyls (fig. 2a-d).

The three-dimensional animal figures were cast in the round using the lost-wax technique over a cylindrical core whereby the large tubular perforation was left out during the casting process. The ornamentation was partially completed in the wax model and achieved by casting. However, after polishing the cast surface, parts of the decoration were realised by tracing lines using a tracer punch and a percussive instrument. The finely incised depictions of cattle hair and the separation lines on the bull's hooves are particularly remarkable (fig. 2c-d; Piotrovskij, 2013a, p. 313, fig. 20.15-20.26)

The reconstruction of the primary burial, based on excavation field sketches and an ancient photograph, reveals the position of eight silver tubes, approxi-



Fig. 14 – Ovoid and globular silver vessels, two with riveted gold or silver sheet attachments (© B. Armbruster)

mately one metre long, half of which have gold terminals (Veselovskij, 1897 [1997]; Piotrovskij, 2020, p. 133, fig. 10 and 11; p. 143, fig. 17; Trifonov et al., 2022, figs. 2–6). Previously interpreted as ceremonial sceptres, these tubes were provided with perforated silver tips (Piotrovskij, 2013a, p. 313, fig. 20.17). Four of them were also equipped with bull figurines attached at the top. Today, these objects have been reconsidered and are seen as precious metal drinking tubes. This allows for a comparison with the golden drinking straw and a silver drinking tube found in the royal cemetery of Ur, Mesopotamia, as well as with an illustration on a cylinder seal from Ur representing a drinking ritual with people sitting around a high vessel and drinking through straws (Trifonov et al., 2022, fig. 7, nos. 1–3).

DARK STONE IMPLEMENTS RELATED TO GOLD

Finally, two dark stone implements, both provided with gold fittings, should be mentioned (Piotrovskij, 2020, p. 149, fig. 22, 2; p. 151, fig. 24, 1; p. 158, fig. 29, 1). One of these, an elongated dark-green stone tool, is described



Fig. 15 – Black fine-grained stone vessel with gold sheet fitting and lid; two openings and three perforations around the rim, perfect round shape – use of rotary motion in stone vessel production? Diam. 53 mm (© B. Armbruster).

as a grinding stone with a gold-decorated base (Piotrovskij, 2020, p. 146). However, this narrow and oblong stone plate may actually be a touch stone, an assaying instrument used by goldsmiths (Moore and Oddy, 1985).

The other enigmatic object is a hollow sphere about 53 mm in diameter, made from fine-grained black stone. The hollow stone body is thin-walled and features two openings of different diameters along with three smaller perforations evenly spaced around the rim of the largest hole (fig. 15a). The flawless globular shape, both inside and out, suggests that rotary motion was employed for the creation of this hollow and thin-walled artefact. Its surface is polished to a satin finish, which is evenly executed across the entire piece.

The stone sphere is associated with two gold sheet fittings. One of these is shaped like a cylinder, worked in one piece with an adjacent curved disc that fits perfectly in curvature, with three corresponding perforations matching the upper part of the globular stone body and its opening (fig. 15b-c). The second fitting, a small cylindrical cup, fits snugly as a capsule-shaped seal to the previously described cylinder. Initially, these three pieces were interpreted as components of a lidded stone vessel, but later studies suggested they might form part of a sceptre, resembling battle maces crafted from less prestigious materials (Piotrovskij, 2013b, p. 311, fig. 20.7; Piotrovskij, 2020, p. 158 fig. 29, 1).

FINAL REMARKS

The significant gold and silver found as grave goods in the large Maikop kurgan offer insights into apparently highly developed local production know-how, a sophisticated art and craft tradition of the 4th millennium BC, in aesthetic, symbolic and technical terms. Moreover, the pieces testify to a high level of fine metalworking technology and expertise, with evidence of serial production in the Early Bronze Age Caucasus. The ancient goldsmiths were skilled in conceiving and manufacturing a large variety of sheet work, including beads, appliqués, drinking tubes and vessels, as well as solid cast figurines.

The unparalleled accumulation of wealth in the large Maikop kurgan is outstanding in its extent within early sedentary societies and suggests elaborate burial customs and rituals. Furthermore, it supports the existence of extensive economic and cultural exchanges, facilitating access to considerable quantities of precious materials, including gold, silver, arsenical copper, turquoise and carnelian.

Future detailed material analyses, including trace element and isotopic studies, could help characterise the specifics of these materials and explore their provenance. Archaeometric and comparative studies will further contribute to exploring the contact zones of the Maikop burial mound's occupants and their broader community.

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Crafting Innovation: The Emergence and Evolution of Tin Bronze Metallurgy on the Prehistoric Iranian Plateau

Omid Oudbashi

Abstract: The production of metal artefacts using tin bronze appeared on the Iranian Plateau in the 3rd millennium BCE (Early and Middle Bronze Age). This technique became common during the 2nd millennium BCE (Late Bronze Age to Iron Age I) and emerged as the primary copper-based metallurgical technology during the 1st millennium BCE (Iron Age II and III). According to existing research, the spread of tin bronze artefacts on the Iranian Plateau during the 3rd to 1st millennia BCE is known from only a limited number of archaeometallurgical studies. However, recent years have seen a growing number of archaeometallurgical and laboratory investigations aimed at understanding tin bronze production during the Bronze and Iron Ages (3rd to 1st millennia BCE). These studies have provided new insights into copper-based metallurgy of the period, revealing a shift from impure copper/arsenical copper to tin bronze in western and south-western Iran during the 3rd millennium BCE, the widespread use of tin bronze in western, northern, and central Iran during the 2nd millennium BCE, and, ultimately, the adoption of tin bronze as the predominant copper alloy across much of the Iranian Plateau during the 1st millennium BCE. Nonetheless, eastern Iran has yielded only a limited number of tin bronze artefacts from Iron Age II–III and the Achaemenid period.

Keywords: Iranian Plateau, Ancient Metallurgy, Bronze Age, Iron Age, Arsenical Copper, Tin Bronze, Alloying

Résumé : La production d'objets métalliques en bronze à l'étain est apparue sur le plateau iranien au III^{e} millénaire avant notre ère (âge du Bronze ancien et moyen). Cette technique s'est généralisée au cours du II^{e} millénaire avant notre ère (âge du Bronze final à l'âge du Fer I) et s'est imposée comme la principale méthode métallurgique à base de cuivre au cours du I^{er} millénaire avant notre ère (âge du Fer II et III). Selon les recherches existantes, la diffusion des objets en bronze à l'étain sur le plateau iranien au cours des II^{e} et I^{er} millénaires avant notre ère n'est connue que grâce à un nombre limité d'études archéométallurgiques. Cependant, ces dernières années ont vu se multiplier les recherches archéométallurgiques et les études en laboratoire visant à comprendre la production de bronze à l'étain pendant l'âge du Bronze et l'âge du Fer (III^{e} au I^{er} millénaire avant notre ère). Ces études ont apporté de nouvelles connaissances sur la métallurgie à base de cuivre de cette période, révélant un passage du cuivre impur/cuivre arsenié au bronze à l'étain dans l'ouest et le sud-ouest de l'Iran au cours du III^{e} millénaire avant notre ère, l'utilisation répandue du bronze à l'étain dans l'ouest, le nord et le centre de l'Iran au cours du II^{e} millénaire avant notre ère et, finalement, l'adoption du bronze à l'étain comme alliage de cuivre prédominant dans une grande partie du plateau iranien au cours du I^{er} millénaire avant notre ère. Néanmoins, l'est de l'Iran n'a livré qu'un nombre limité d'artefacts en bronze à l'étain datant de l'âge du Fer II-III et de la période achéménide.

Mots clés : plateau Iranien, ancienne métallurgie, âge, du Bronze, cuivre arsenié, bronze à l'étain, alliage.

For a long period, the Iranian Plateau has been considered one of the pioneering regions in the early development of metallurgy in the prehistoric world, alongside the Caucasus and Anatolia (Thornton, 2009a). This is due to over 10,000 years of evidence for copper-based metallurgy, including mining, smelting, and manufacturing. The process began in the Middle Neolithic period with the shaping of small native copper fragments. It progressed to the melting of native copper and the smelting of various copper ores during the Chalcolithic era. This led to the production of copper and arsenical copper, followed by the emergence and spread of tin bronze during the Bronze and Iron Ages, respectively (Pigott, 1999; 2004; Thornton, 2009a; Helwing, 2013). Furthermore, the Iranian Plateau is rich in metal resources and polymetallic ores, a factor that likely contributed to the early

appearance of diverse copper alloy technologies in antiquity (Thornton, 2009a; Weeks, 2013).

At the beginning of the 21st century, our knowledge of prehistoric copper-based metallurgy on the Iranian Plateau was limited to the findings of a few archaeological excavations and laboratory analyses conducted during the second half of the 20th century (Wertime, 1968, 1973; Moorey, 1969 and 1982; Vatandoost-Haghighi, 1977; Pigott et al., 1982; Fleming and Swann, 1993; Pigott, 1999). In recent years, however, archaeological excavations and scientific analyses have shed new light on early copper-based metallurgy on the Iranian Plateau, particularly concerning the emergence and spread of tin bronze metallurgy.

For several decades, the following questions were raised, yet clear answers remained elusive:

– When did tin bronze technology first emerge and develop on the Iranian Plateau?

– Which region(s) did tin bronze technology originate from, and how did it spread across the Iranian Plateau?

– Where were the ore sources located that supplied copper and tin for the production of tin bronze in prehistoric times?

– Where were the early tin bronze artefacts produced (i.e. workshops) on the Iranian Plateau?

Although these main questions, along with several others, have not yet been answered satisfactorily, and some remain entirely unresolved, recent archaeological and archaeometallurgical studies, particularly over the past two decades, have shed light on several key issues.

In recent years, a comprehensive effort has been made to understand the rise and development of tin bronze metallurgy in antiquity, particularly with a focus on the Near East and Western Asia. This has involved close attention to archaeological finds, analytical results, and geological information (Pigott, 2004, 2011 and 2021). One notable recent study was published by Cuénod et al. (2015), focusing on the available analytical data for more than 5,000 copper-based artefacts from Iran and neighbouring regions. Although this work represented a significant contribution to the field, it primarily involved the evaluation and assessment of analytical data from Iranian artefacts, many of which had both clear and uncertain provenance. In contrast, this chapter aims to provide a comprehensive overview of tin bronze metallurgy on the Iranian Plateau during the Bronze and Iron Ages, as well as the Achaemenid period (3rd to 1st millennium BCE; see table 1), based on the analysis of artefacts with well-documented provenance. It also places emphasis on more recently analysed artefacts, although the available analytical and archaeological data may still be insufficient to fully address some of the outstanding questions in this field.

EARLY COPPER METALLURGY: AN OVERVIEW OF PRE-BRONZE DEVELOPMENTS

The earliest evidence of copper metalworking on the Iranian Plateau (fig. 1) is a rolled bead made of native copper from the Neolithic site of Ali Kosh in western Iran, dated to the late 8th/early 7th millennium BCE (Smith, 1969). However, the widespread adoption of copper use occurred much later, in the early to mid-6th millennium BCE, when small native copper tools and ornaments became commonly used in late Neolithic villages across various parts of the Iranian Plateau (fig. 1), including Tappeh Yahya in southern Iran, Tappeh Sialk in central Iran, Tal-e Mushki in the Fars region, Tappeh Sang-e Chakhmaq in northeastern Iran, Chogha Sefid and Chogha Sabz in western Iran, Tappeh Zagheh in north-central Iran, and Hotu Cave in northern Iran (Thornton, 2009a; Helwing, 2013, p. 112). These findings indicate that native copper metallurgy was widespread during the late Neolithic period.

Regarding manufacturing technology, recent analyses of copper artefacts from late Neolithic and transitional Chalcolithic sites in the Fars region demonstrate that these artefacts were produced from native copper containing trace impurities, probably shaped through cold hammering and annealing (Weeks, 2008). Furthermore, geochemical analysis of Neolithic native copper artefacts from Fars suggests that copper sources in Talmesi, central Iran, may have supplied the raw materials (Begemann and Schmitt-Strecker, 2009).

Archaeometallurgical studies indicate intensive copper production in the central Iranian Plateau during the Chalcolithic period (c. 5500–3000 BCE), especially throughout the 4th millennium BCE, as evidenced at sites such as Tal-i Iblis, Tappeh Hissar, and Arisman (Pigott,

	Period	Sub-period	Date (BCE)
3rd millennium BCE	Bronze Age (BA)	Early Bronze Age (EBA)	c. 3000-2500
		Middle Bronze Age (MBA)	c. 2500-2000
2nd millennium BCE		Late Bronze Age (LBA)	c. 2000-1500
	Iron Age (IA)	Iron Age I (IA I)	c. 1500-1000
1st millennium BCE		Iron Age II (IA II)	c. 1000-800
		Iron Age III (IA III)	c. 800-600
	Achaemenid	-	c. 550-330

Table 1 – The prehistoric and historic periods of the Iranian Plateau from the 3rd to the 1st millennium BCE, including their sub-periods and corresponding dates.

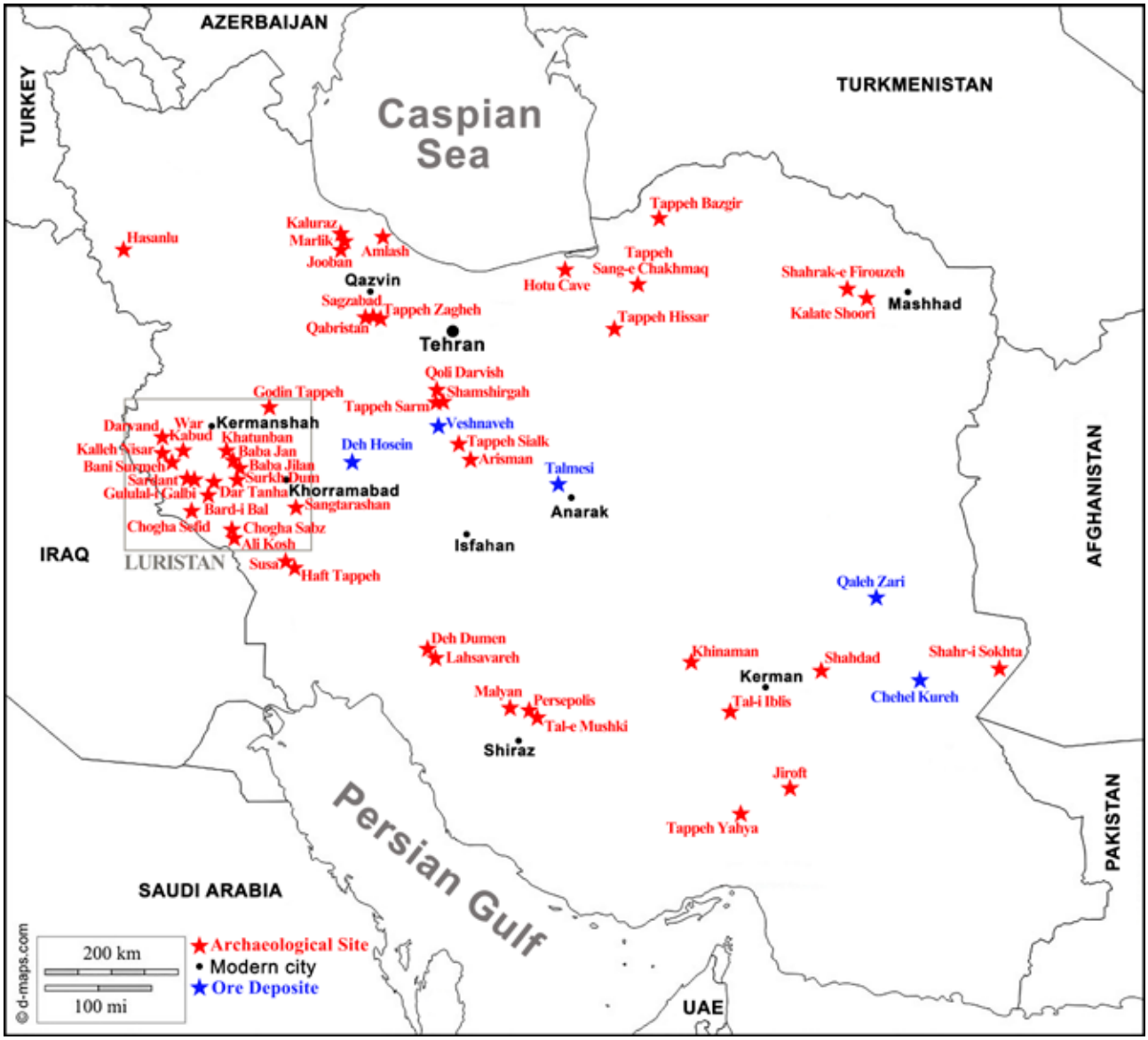


Fig. 1 – Map of modern Iran showing the locations of archaeological sites, modern cities and ore deposits mentioned in the text.

2004; Thornton, 2009a). Excavations at Chalcolithic settlements reveal the emergence and development of copper ore smelting. The earliest evidence of metal smelting on the Iranian Plateau is found at the Chalcolithic site of Tal-i Iblis in south-eastern Iran, located near the rich copper ore deposits of the Kerman region. This site contains a large-scale copper smelting area featuring numerous slagged crucibles, malachite (copper ore) fragments, and charcoal dated to various levels of the Chalcolithic period (Caldwell, 1968; Frame, 2004). Although some scholars have argued that this early copper-working site might reflect only the melting of native copper, the presence of materials related to copper ore smelting, along with precise dating of different occupation levels (Voigt and Dyson, 1992, p. 143–146), demonstrates early copper smelting activity comparable to that of Anatolia and Mesopotamia, dating to the late 6th and early 5th millennia BCE (Thornton, 2009a).

While early Chalcolithic copper smelting primarily produced impure copper, evidence for arsenical copper production also appears towards the end of the 5th millennium BCE (Thornton, 2009a and 2010). Early arsenical copper artefacts have been found in late 5th millennium BCE layers at sites such as Susa, Tappeh Yahya, and Tappeh Hissar (Benoit, 2004; Thornton, 2009b; 2010). However, the current data remain insufficient to fully understand the transition from shaping and melting native copper to smelting copper ores and producing arsenical copper (Thornton, 2009a). By the beginning of the 4th millennium BCE, copper-based metallurgy became clearer, with large-scale copper smelting and copper, possibly arsenical copper, production evidenced at early 4th millennium BCE levels at sites including Susa, Qabristan, Tappeh Hissar, Tappeh Yahya, and Tappeh Sialk (Majidzadeh, 1979 and 1989; Chegini et al., 2000; Benoit, 2004; Thornton, 2009b and 2010).

Moreover, late Chalcolithic copper metallurgy (4th millennium BCE) included the co-smelting of sulfidic copper ores and likely deliberate arsenical copper production, as observed at Tappeh Hissar, Tappeh Yahya, and Arisman (Thornton et al., 2002; Thornton, 2009b; Vatandoust et al., 2011). The presence of speiss slags dating from the late 4th to early 3rd millennium BCE further confirms intentional arsenical copper production in the late Chalcolithic to Early Bronze Age (EBA) of the Iranian Plateau (Thornton et al., 2009; Rehren et al., 2012).

TIN BRONZE, ARSENICAL COPPER, AND IMPURE COPPER: A SUMMARY

Before presenting the archaeological evidence for prehistoric tin bronze metallurgy in Iran, it is essential to clarify what is meant by 'tin bronze' and to distinguish it from other ancient copper-based materials such as impure copper and arsenical copper. These distinctions are crucial for assessing the technological choices made by ancient metalworkers and for understanding the broader context of alloying practices in early metallurgical traditions.

Tin bronze refers to an intentional alloy of copper with tin, typically containing > 1 wt% of tin, although some experts believe that the intentional alloy should contain > 2–3 wt% of tin (Pigott, 2004; Oudbashi et al., 2012). At these levels, tin significantly alters the mechanical and physical properties of copper, improving hardness, strength, and casting performance (Scott, 1991). It also affects the corrosion resistance property of copper, although it may not have been the case for prehistoric metalworkers (Scott, 2002). Although minor amounts of tin can occur naturally in some copper ores, these do not usually produce alloys with significantly enhanced material properties and are therefore generally considered unintentional or accidental. The presence of tin at trace levels can nevertheless be useful as a fingerprint for provenance studies (Pollard and Bray, 2014; Pernicka, 2014). By contrast, copper-based artefacts with consistent tin contents in the range of 1–15 wt% are widely interpreted as the result of deliberate alloying in the prehistoric context, indicating a high degree of metallurgical knowledge (Oudbashi et al., 2012).

From a modern metallurgical viewpoint, binary tin bronze alloys are classified as low-tin and high-tin according to their tin concentration, with low-tin bronzes containing c. < 15 wt% tin, while high-tin alloys contain tin between c. 15 and 35 wt% (Scott, 1991; Meeks, 1993; Ingo et al., 2002; Saraiva et al., 2022). This classification is based on the highest limit of tin solubility in copper under equilibrium conditions: 15.8 wt% (Saunders and Miodownik, 1994; Park et al., 2009). The difference between modern metallurgy and the prehistoric definition of tin bronze lies in archaeologists classifying tin bronzes with around 1–5 wt% tin as low-tin, artefacts with around 6–12 wt% tin as medium-tin bronze, and high-tin bronzes as those with higher tin content. This is a general definition and varies between cultures and regions. Accordingly, this chapter will adopt the classification more familiar to archaeologists, although modern metallurgical terms and definitions will sometimes be used when necessary.

The early tin bronze artefacts are made of alloys with tin content < 15 wt%, often exhibiting variable tin concentrations. This variability may result from the use of uncontrolled alloying methods. Various procedures for producing tin bronze alloys in ancient times have been proposed and discussed in the literature (Pigott, 2004; Rovira et al., 2009; Figueiredo et al., 2010; Murillo-Barroso et al., 2010; Valério et al., 2013; Erb-Satullo et al., 2015; Farci et al., 2017; Rademakers and Farci, 2018; Berger et al., 2019):

– Co-smelting of copper and tin ores: This method involves smelting copper and tin ores together in a single process, allowing tin to alloy with copper during the initial extraction from the ore.

– Cementation of metallic copper with cassiterite: In this process, metallic copper is heated in the presence of cassiterite (tin oxide), causing tin to diffuse into the copper and form a tin bronze alloy.

– Use of a complex Sn-bearing copper ore for smelting: Some copper ores naturally contain tin within their mineral composition; smelting such complex ores can produce tin bronze directly without adding separate tin sources.

– Metal recycling or re-melting of broken metallic pieces: This method involves melting down existing tin bronze artefacts or scrap metal, mixing them to produce new tin bronze items, which may result in variable tin concentrations.

– Melting of metallic copper and tin together in the crucible: This deliberate alloying technique entails combining pure metallic copper and metallic tin and melting them together to produce tin bronze with controlled tin content.

Apart from the final method, which may have allowed ancient metalworkers to control the Cu/Sn ratio precisely in the finished products, it was likely relatively difficult to regulate the tin content in the final metal (artefact or ingot). However, direct alloying of metallic copper and tin appears to have been unlikely in early tin bronzes, with these early examples produced using entirely uncontrolled methods.

To fully appreciate the significance of tin bronze, it is important to compare it with two other categories: impure copper and arsenical copper. Impure copper typically refers to copper containing a range of minor elements (< 1 wt%) such as iron, nickel, antimony, tin, lead, or arsenic, introduced unintentionally through the smelting of polymetallic ores. These trace elements may slightly influence the working properties of the metal (Junk, 2003; Atzeni; 2005), but were not deliberately added. As such, impure copper does not reflect conscious alloying choices and is generally regarded as a-product of early, less refined metallurgical processes.

Arsenical copper, by contrast, occupies an important place in early metallurgical traditions and is often viewed as a precursor to tin bronze (Coghlan, 1975; Lechtman

and Klein, 1999; Lechtman, 1996). It contains deliberately or semi-deliberately introduced arsenic, usually through the smelting of arsenic-rich copper ores or, in some cases, by adding specific arsenic-bearing minerals to the smelt (Lechtman and Klein, 1999). Arsenical copper improves upon the mechanical properties of pure copper, increasing hardness and reducing casting porosity (Junk, 2003). However, its production posed health risks due to the toxic fumes released during smelting and working (Martin, 2017; González-Fernández et al., 2018). Despite these challenges, arsenical copper was widespread in early metallurgy, including in Iran, and often coexisted with early tin bronze traditions (Thornton, 2009a).

According to the literature, an arsenic content of less than 2 wt% may indicate that it entered the composition as an impurity from As-bearing copper ores such as tennantite, $(Cu,Fe)_{12}As_4S_{13}$ (Grey Copper), and this can be considered an accidental alloy (Coghlan, 1975). At higher arsenic contents, Coghlan (1975) also suggested that intentional alloying may have occurred through three metallurgical procedures:

– Contemporaneous smelting of copper oxide ores with realgar (As_4S_4) or orpiment (As_2S_3).

– Use of ores with high arsenic content, such as arsenopyrite or tennantite, mixed with copper sulphides.

– Adding realgar or orpiment directly to the melt during smelting.

Furthermore, Boscher (2016) suggested and discussed the following methods for producing arsenical copper (or arsenical bronze), noting that true alloying in the modern sense occurs only in the last two processes:

– Reduction of copper arsenates.

– Co-smelting of copper oxides with copper sulfarsenides.

– Co-smelting of copper oxides with iron arsenides or sulfarsenides.

– Adding copper arsenides or arsenates to molten copper.

– Use of speiss (a metallurgical by-product rich in arsenic and other metals).

Thornton et al. (2009) and Rehren et al. (2012) also suggest that speiss (an iron-arsenide alloy) is a quasi-metallic material, usually formed as an accidental by-product of copper or lead smelting, as observed in analyses of materials from Arisman and Tappeh Hissar. They propose that speiss was deliberately produced to provide arsenic as an alloying component for arsenical copper.

Furthermore, a high content of lead could be another aspect of the composition of ancient copper-based alloys. Lead may have entered the composition accidentally, due to the presence of significant amounts of lead in the smelted ores, or intentionally, by adding lead to the melt or smelting lead-bearing copper ores (Scott, 1991; Valério et al., 2012). Due to the immiscibility of lead in copper, a mixture of copper with lead does not produce a true alloy; for this reason, copper alloys with high lead content are referred to as leaded copper, leaded tin bronze, etc. (Scott, 1991). Generally, prehistoric copper-based artefacts from Iran contain very low levels of lead, and lead played no specific role in the prehistoric copper metallurgy of the region (Oudbashi, 2019a; 2019b). However, leaded copper-based artefacts become significantly more common during the Persian (pre-Islamic historic) and Islamic periods, due to lead's beneficial effect on the fluidity of the melt for casting purposes (Oudbashi et al. 2023a; 2025).

The technological and logistical requirements for producing tin bronze were significantly more demanding than those for impure or arsenical copper. Unlike arsenic, which could be introduced through naturally occurring copper ores, tin typically had to be sourced separately, often from distant regions, and intentionally combined with copper. Notably, there is some evidence of ore sources bearing both copper and tin, such as the ancient mine of Deh Hosein in western Iran (Nazafati ,2006), which was used for early tin bronzes. However, tin bronze technology primarily relied on the use of separate copper and tin sources. This process required knowledge of tin minerals such as cassiterite, control over smelting and alloying techniques, and likely the existence of exchange networks or organised procurement strategies. In this sense, the consistent appearance of tin bronze artefacts in the archaeological record reflects not only an awareness of its material advantages but also deliberate technological planning.

The motivations for producing tin bronze in prehistoric Iran and elsewhere were likely diverse and multifaceted. From a functional perspective, tin bronze offered significantly superior hardness and workability compared to impure or arsenical copper (Coghlan , 1975; Scott, 1991). These enhanced mechanical properties made tin bronze an ideal material for manufacturing a wide range of tools, weapons, and utilitarian artefacts that required greater durability and efficiency. Additionally, tin bronze's improved casting properties allowed for more complex and refined shapes, which may have contributed to its widespread adoption. Beyond practical advantages, the production and possession of tin bronze artefacts may also have held social or symbolic significance, potentially reflecting status or specialised craft knowledge within prehistoric communities. Thus, the emergence of tin bronze technology was driven not only by technical improvements but also by broader cultural and economic factors that encouraged the deliberate and sustained use of this alloy.

THIRD MILLENNIUM BCE: EARLY TIN BRONZES

Western and South-western Iran

Thanks to excavations and archaeometallurgical studies, copper-based metallurgy in western and south-western Iran during the late 4th to 3rd millennium BCE is now relatively well understood, particularly owing to recent archaeometallurgical research.

One of the earliest archaeometallurgical studies in southwestern Iran was the analytical research conducted on artefacts excavated from Susa (Tallon, 1987). Susa is one of the few settlements to show a notable presence of tin bronze as early as the early 3rd millennium BCE. Although the number of tin bronze artefacts dating to the first quarter of the 3rd millennium BCE is very limited, their quantity increases significantly during the second quarter (Berthoud et al., 1982; Tallon, 1987). Thanks to the large-scale metal collections excavated from the Chalcolithic and Bronze Age (Proto-Elamite to Old Elamite) levels of Susa (Susa I to Susa V, mid-6th to early 2nd millennia BCE), chemical analyses of numerous artefacts have provided a partially clear picture of the emergence and development of copper-based metallurgy in the prehistoric Susiana Plain (Berthoud et al., 1982; Malfoy and Menu, 1987). The results indicate that intermediate arsenical copper (As < 5 wt%) was utilised throughout these periods. The transition from arsenic to tin as the principal alloying element (whether deliberate or accidental) coincides with the first appearance of true tin bronzes during the Susa IVa period, c. 2500 BCE. High-tin bronzes began to appear during the Susa V period, c. 2100–1900 BCE (Malfoy and Menu, 1987, also see De Ryck et al., 2003, p. 265, figs. 5 and 6). One challenge in analysing the Susa copper-based artefacts is that, although a considerable number of artefacts (479 in total) have been examined, the dating of this analysed collection requires careful revision (Tallon, 1987). Nevertheless, based on the available dating, it is clear that early tin bronzes appeared at the beginning of the Middle Bronze Age (MBA) or Old Elamite period in Susa (Malfoy and Menu, 1987).

Large-scale archaeological excavations in Luristan, western Iran, conducted by the Belgian Archaeological Mission in Iran (BAMI) during the 1960s and 1970s, led to the discovery of a significant collection of ritual bronze artefacts from Early to Middle Bronze Age graveyards, dated to the late 4th and 3rd millennia BCE. These artefacts include, for example, vessels, weapons, and ornaments, which were found in graves at several excavated sites in the Pusht-i Kuh region, including Kalleh Nisar, Bani Surmeh, Dar Tanha, Mehr War Kabud (War Kabud), Gululal-i Galbi, Sardant, and Darvand (Haerinck and Overlaet, 2006, 2008 and 2010). The chemical analysis of a series of these excavated artefacts revealed a highly significant aspect of copper-based metallurgy in western Iran: the early production of tin bronze. Analysis of a substantial number of copper-based artefacts from Early to Middle Bronze Age sites in the Pusht-i Kuh region showed that, among 58 artefacts dated to the 3rd millennium BCE, 19 were made of tin bronze, 30 were composed of arsenical copper, and 9 consisted of impure copper with tin and arsenic contents < 1 wt% (Begemann et al., 2008). In addition, a group of artefacts from various stratigraphic levels of Kalleh Nisar, specifically, Area A-I (c. 3200–2800/2700 BCE), Area A-II (c. 2150–2000 BCE), and Area C (c. 2950–2300 BCE), were analysed by Fleming et al. (2005). The results revealed that 24 out of 41 artefacts were made of tin bronze (> 1 wt% tin), although arsenic content was not reported, preventing identification of potential arsenical copper artefacts. Notably, all 5 artefacts analysed from Area A-I were made of tin bronze, while 15 out of 19 artefacts from Area C and 4 out of 17 from Area A-II were also made of tin bronze. These findings indicate that the earliest known use of tin bronze for artefact production in the region appears in the assemblage from Area A-I of the Kalleh Nisar Bronze Age cemetery in Luristan, dated to approximately 3200–2800/2700 BCE (Fleming et al., 2005; Begemann et al., 2008).

Another important archaeological site excavated in western Iran is Godin Tappeh, situated on the north-eastern fringes of ancient Luristan. The site was excavated between 1965 and 1973 by T. Cuyler Young Jr., under the auspices of the Royal Ontario Museum in Toronto (Young Jr., 1969; Youn Jr. and Levine, 1974), and its occupational sequence spans from the Neolithic to the Iron Age. A comprehensive archaeometallurgical study has been conducted on the copper-based artefacts recovered from Godin Tappeh, revealing the evolution and transformation of copper-based metallurgy across different levels and periods of the site (Frame, 2010). Chemical analyses of 35 copper-based artefacts dated to the late 4th to 3rd millennium BCE, from archaeological levels VI:1, IV, III, III:6, III:5, and III:4, indicate that only 7 of these artefacts were made of tin bronze. In contrast, 3 artefacts were composed of impure copper, and the majority, 25 artefacts, were manufactured from arsenical copper.

Recent excavations at the Bronze Age cemetery of Deh Dumen in south-western Iran have resulted in the discovery of numerous metal vessels and ritual artefacts within the end of the early to the middle Bronze Age graves, dated to the mid-3rd millennium BCE (Miszkiewicz et al., 2022). Chemical analysis of eight vessels revealed that tin bronze was the predominant alloy used in their production. However, arsenical copper was also identified, most notably in the large metal discs placed at the bases of two tin bronze vessels (Oudbashi et al., 2016; Oudbashi and Naseri, 2017).

Figure 2a presents a bivariate scatter plot of tin versus arsenic concentrations in 103 analysed artefacts from the Pusht-i Kuh region (including Bani Surmeh, Kalleh Nisar, Dar Tanha, Mehr War Kabud, Sardant, Gululal-i Galbi, and Darvand), as well as from Godin Tappeh and Deh Dumen. It is important to note that the analytical data from the artefacts of Susa were excluded from this plot due to concerns regarding the accuracy of their dating, although a similar plot for Susa was previously produced by De Ryck et al. (2003).

The scatter plot displays tin and arsenic contents ranging from approximately 0–10 wt% for tin and 0–4 wt% for arsenic. One notable exception is an artefact from Godin Tappeh, which exhibits an unusually high arsenic content exceeding 8 wt%. Based on their chemical composition, the artefacts can be categorised as follows: impure copper (n=10), arsenical copper (n = 60), tin bronze (n = 25), and tin bronze with arsenic > 1 wt% (n = 8). The artefacts from the Pusht-i Kuh sites have been dated to the Early and Middle Bronze Age. As mentioned above, several artefacts with high tin content originate from Kalleh

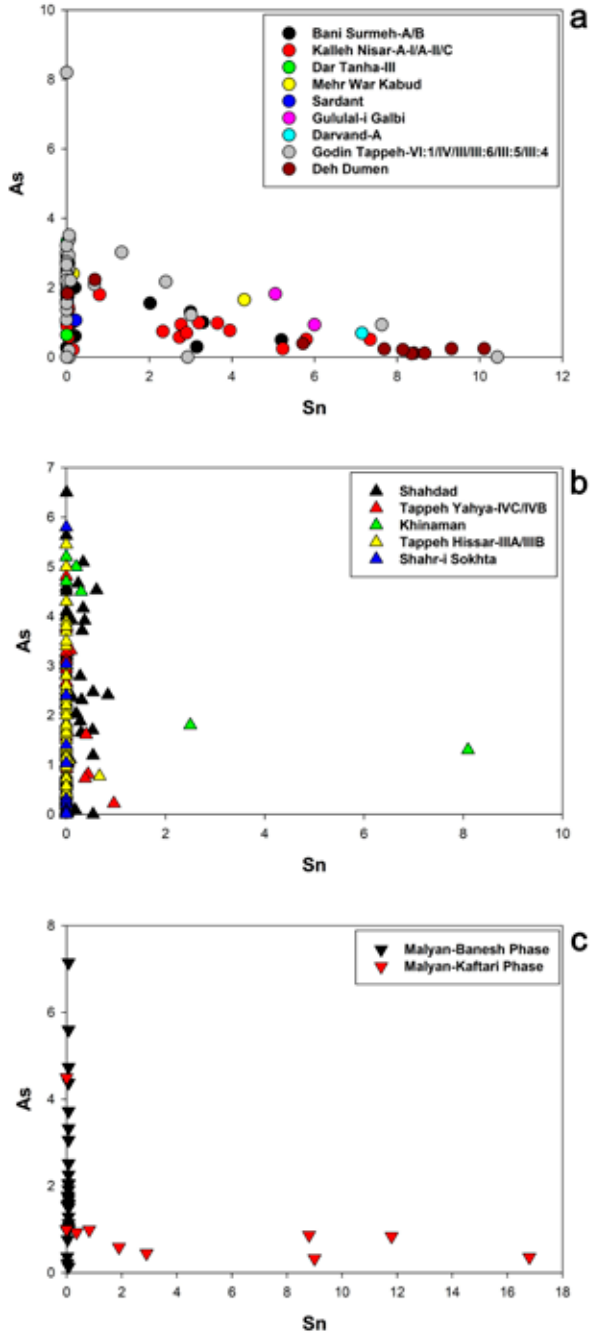


Fig. 2 – Three bivariate scatter plots of tin (Sn) versus arsenic (As) in the composition of analysed copper-based artefacts from the Iranian Plateau, dated to the Early and Middle Bronze Age: a) data from 103 artefacts from the Pusht-i Kuh region of Luristan, Godin Tappeh, and Deh Dumen in western and south-western Iran, 3rd millennium BCE; b) data from 216 artefacts from eastern Iran, 3rd millennium BCE; c) data from 40 artefacts from Malyan in south-central Iran, late 4th to 3rd/early 2nd millennium BCE.

Nisar Areas A-I and C, and are dated to the early 3rd millennium BCE. The Deh Dumen artefacts, dated to the mid-3rd millennium BCE, were predominantly made of tin bronze. These findings suggest that both tin bronze and arsenical copper were used concurrently in western and south-western Iran during the 3rd millennium BCE. However, tin bronze appears to have become more prevalent by the mid-3rd millennium BCE, corresponding to the onset of the Middle Bronze Age.

Eastern Iran

Excavations at various Early and Middle Bronze Age archaeological sites in eastern Iran have uncovered numerous copper-based artefacts, along with evidence of copper smelting technologies. The sites that have been analysed, Shahdad, Khinaman, Tappeh Yahya, Tappeh Hissar, and Shahr-i Sokhta, provide valuable insights into the development and characteristics of copper-based metallurgy in this region (Curtis, 1988; Thornton et al., 2002; Hauptmann et al., 2003; Thornton, 2009b; Meier, 2015).

The well-known Bronze Age site of Shahr-i Sokhta, located in Sistan and dating to the late 4th to 3rd millennia BCE, represents a large-scale prehistoric urban settlement in eastern Iran. Extensive excavations at the site have uncovered both copper smelting evidence and numerous copper-based artefacts. Analytical studies of ores, slags, and metal artefacts from the Early Bronze Age (c. 2700–2500 BCE) indicate that co-smelting of complex copper ores, both oxidic and sulphidic, within crucibles was the primary metallurgical process at that time. Two copper sources located to the west and north-west of the site, Qaleh Zari and Chehel Kureh, may have supplied the raw materials (Hauptmann et al., 2003). The analysis of 21 metal artefacts—including copper prills, lumps, ingots, and tools—revealed variable arsenic contents, reflecting the production of arsenical copper alongside impure copper. Notably, no tin was identified or measured in any of the samples (Helmig, 1986).

Similarly, the chemical analysis of numerous metal artefacts from Tappeh Yahya has provided a comprehensive picture of copper-based metallurgy in south-eastern Iran (Vatandoost-Haghighi, 1977; Thornton et al., 2002; Meier, 2011). These artefacts, dating to the late Chalcolithic and Bronze Age from levels IVC and IVB (3rd millennium BCE), showed no evidence of tin bronze. Instead, arsenic appears to have been the principal alloying element in most artefacts (Thornton et al., 2002; Meier, 2011).

In Shahdad, another significant Bronze Age site in eastern Iran, metallurgical workshops and copper-based artefacts further illuminate copper production during the 3rd millennium BCE. Although comprehensive analytical studies of the metallurgical materials from Shahdad remain limited, available data suggest that arsenical copper was the dominant alloying technology during this period (Vatandoost-Haghighi, 1977; Meier, 2015; 2011; Oudbashi et al., 2017). Altogether, these analytical studies consistently indicate that tin bronze metallurgy was not practiced during the Bronze Age in the eastern regions of Iran. Across the 3rd and 2nd millennia BCE, no clear evidence of tin bronze has been found in the eastern parts of the Lut Desert. In contrast, arsenical copper appears to have been the prevailing alloy in this region (Thornton et al., 2002; Hauptmann et al., 2003; Meier, 2011; 2015; 2019). Nevertheless, two copper artefacts containing tin

(2.5 and 8.1 wt% Sn) have been reported from Khinaman (also known as Khenaman), a Bronze Age cemetery in the Lut Desert associated with the Shahdad civilization (Curtis, 1988; Maxwell-Hyslop, 1988).

The lack of analytical data concerning copper-based metallurgy during the 3rd millennium BCE in north-eastern Iran has left this region largely unexplored in terms of understanding the potential emergence of tin bronze. However, recent limited analyses of copper-based artefacts from the early to middle Bronze Age site of Kalate Shoori, located near Neyshabur, have provided some insight. The results indicate that arsenical copper was the predominant material used in the production of copper-based artefacts at this site (Basafa et al., 2021).

Figure 2b presents a scatter plot of tin (Sn) versus arsenic (As) content in 216 analysed artefacts recovered from the sites of Shahdad, Khinaman, Tappeh Yahya, Shahr-i Sokhta, and Tappeh Hissar. It is noteworthy that artefacts from Shahdad, Tappeh Hissar, Shahr-i Sokhta, and Tappeh Yahya all display a wide range of arsenic concentrations, varying from up to 8 wt%, while their tin content remains below 1 wt%, detected only in trace amounts. The plot clearly illustrates that the vast majority of these artefacts were produced using either impure copper (Sn and As < 1 wt%) or arsenical copper (As > 1 wt%). Remarkably, only two artefacts from Khinaman, out of the 216 analysed, are identified as tin bronzes (Sn > 1 wt%).

Central and South-central Iran

This region, bounded by the southern edge of the Alborz Mountains to the north and the southern reaches of the Fars region to the south, encompasses a vast area with a rich copper-based metallurgical history predating the Bronze Age. Geographically, it roughly includes the central desert and the modern provinces of Fars, Isfahan, and Yazd. Numerous archaeometallurgical studies have revealed the existence of significant copper and arsenical copper production centres at sites such as Tappeh Sialk and Arisman (Ghirshman, 1938; Chegini et al., 2000; Nezafati and Pernicka, 2006; Nezafati et al., 2008; Nokandeh, 2010; Vatandoust et al., 2011; Rehren et al., 2012). While these investigations have uncovered various aspects of copper-based metallurgy in central and south-central Iran, they primarily focus on materials from the 5th to 4th millennia BCE, and only limited evidence points to the continuity of arsenical copper production into the early 3rd millennium BCE. One exceptional case is a tin bronze pin from Sialk III5 (mid-4th millennium BCE), reportedly made of tin bronze (Halm, 1939, p. 206–207). However, the analytical methodology and results are unclear, and the dating of this artefact is considered questionable and in need of reassessment (Helwing, 2021). Furthermore, the absence of Bronze Age levels (c. 2900–1500 BCE) in many key archaeological sites in central Iran, such as Tappeh Sialk and Arisman (Shaikh Baikloo Islam et al., 2016), has resulted in a significant gap in our understanding of copper-based metallurgical practices in the region during this period.

The only analysed site in south-central Iran is Malyan. Excavations at Malyan, a significant archaeological site located in the Kur River Basin of central Fars and identified as ancient Anshan, the highland capital of Elam (Sumner, 2003), have revealed evidence of metallurgical activities dating back to the Banesh phase (c. 3400–2800 BCE) and the Kaftari phase (c. 2200–1600 BCE). Evidence for copper smelting derives from Operation Banesh-TUV, Levels 2–3, where slag, metal fragments, and furnace remains were found in domestic contexts. Additionally, some buildings excavated in Operation Banesh-ABC also yielded indications of copper smelting (Pigott et al., 2003a). Chemical analyses of 30 artefacts showed that the copper contained arsenic, lead, and, in one instance, antimony (Pigott et al., 2003a). Furthermore, ten artefacts dated to the Kaftari phase underwent chemical compositional analysis (Pigott et al., 2003b). PIXE analysis revealed that six of these artefacts are made of tin bronze, with tin detected in varying amounts; two artefacts are composed of arsenical copper, and the remainder are impure copper. The tin bronze artefacts from the Kaftari phase constitute the earliest evidence of bronze metallurgy in south-central Iran (see fig. 2c).

2ND MILLENNIUM BCE: DEVELOPMENT OF TIN BRONZE METALLURGY

Western and South-western Iran

In contrast to the more extensively studied copper-based metallurgy of the 3rd millennium BCE, investigations into metallurgical practices during the 2nd millennium BCE in western Iran and Luristan remain comparatively limited. Nevertheless, the majority of copper-based artefacts analysed from Godin Tappeh are dated to the 3rd millennium BCE. More specifically, analysis of 18 copper-based artefacts from the 2nd millennium BCE levels at Godin Tappeh (Periods III:2 and Post III:2) revealed that 13 of these artefacts are composed of tin bronze, while the remaining five consist of arsenical and impure copper (Frame, 2010). Notably, tin bronze artefacts are far more prevalent in Period III:2 (1900–1600 BCE), with 12 out of 14 analysed pieces made from this alloy, compared to only one out of four in the subsequent Post III:2 period (1600–1400 BCE). This pattern suggests a greater reliance on tin bronze during the earlier part of the 2nd millennium BCE at Godin Tappeh, with a possible decline in its use during the later centuries of this era.

Analytical studies of artefacts from Susa are largely confined to the end of the 3rd millennium BCE, with only a limited number of items from the Susa V phase (late 3rd to early 2nd millennium BCE) having been analysed and interpreted (De Ryck et al., 2003). These artefacts have been discussed previously in conjunction with the broader 3rd millennium BCE collection from the site.

Beyond Susa itself, metallurgical investigations at the Middle Elamite site of Haft Tappeh, located near Susa and dating to the 14th century BCE—a period slightly after the close of the Bronze Age in the Iranian Plateau—have provided further insights. Haft Tappeh, identified as the capital of the Elamite king Tepti Ahar, was extensively excavated, revealing substantial evidence of copper production and metallurgy within its industrial sector. This evidence includes a furnace, crucibles, ingots, slags, and various metal artefacts (Negahban, 1991). A comprehensive multi-analytical study of the metal artefacts, ingots/prills, and slags from Haft Tappeh indicated that metallurgical activities there were characterised by small-scale production of copper and tin bronze items. These were manufactured from sulphidic copper raw materials through a two-stage smelting process, including roasting of the ores to produce matte and smelting matte to produce metallic copper. The first stage yielded a copper matte, which was subsequently refined to produce copper ingots/prills with reduced impurity levels. The coexistence of tin bronze and impure copper artefacts suggests that copper was likely produced using this two-stage smelting technique, followed by an uncontrolled alloying method, probably cementation, to introduce tin (Vatandoost-Haghighi, 1977; Oudbashi et al., 2019; Oudbashi and Mishmastnehi, 2020).

Figure 3a presents a bivariate scatter plot of tin (Sn) versus arsenic (As) concentrations in the composition of analysed artefacts and ingots from the sites of Godin Tappeh and Haft Tappeh. Among the 33 artefacts analysed from Haft Tappeh, 12 were identified as tin bronze, exhibiting a variable range of tin content. However, only two of these artefacts contain arsenic levels exceeding 1 wt%, indicating that arsenic was not a predominant alloying component in the majority of the tin bronzes from this site. Additionally, analysis of the Haft Tappeh ingots revealed that four contain tin in significant quantities (> 1 wt%), further supporting the presence and utilisation of tin bronze at the site. As previously discussed, the artefacts from Godin Tappeh similarly demonstrate a predominance of tin bronze during the 2nd millennium BCE, with 13 out of 18 artefacts from this period composed of tin bronze. This collective data strongly suggests that tin bronze had become the primary copper-based alloy used in western and south-western Iran during the 2nd millennium BCE. Nonetheless, there is also evidence of continued, albeit less frequent, use of low-arsenical copper and arsenical tin bronze. In particular, several tin bronze artefacts from both sites, especially those from Godin Tappeh, display arsenic levels above 1 wt%, indicating either deliberate alloying with arsenic or the use of arsenic-rich copper sources. This combination of alloying practices reflects a period of technological transition and experimentation in regional metallurgical traditions.

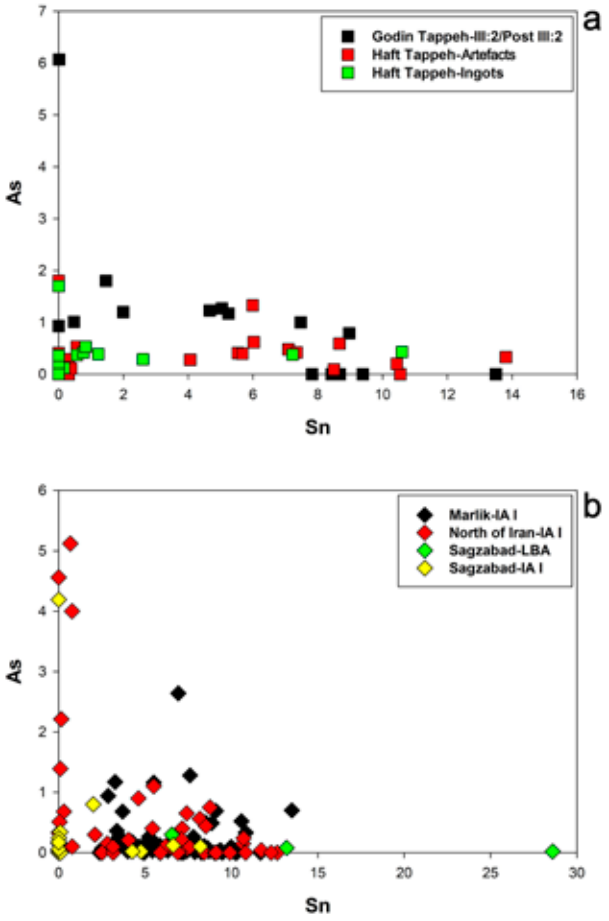


Fig. 3 – Two bivariate scatter plots of Sn versus As in the composition of copper-based artefacts from the Late Bronze Age and Iron Age I in the Iranian Plateau: a) data from 33 artefacts and 26 ingots/prills from Haft Tappeh, and 18 artefacts from Godin Tappeh in western and south-western Iran, 2nd millennium BCE; b) data from 128 copper-based artefacts from northern Iran, 2nd millennium BCE.

Northern Iran

Although northern Iran and the southern littoral of the Caspian Sea are rich in archaeological sites and cultural remains dating to the 2nd millennium BCE, the majority of excavated and documented settlements in the region pertain to the Iron Age I (IA I), approximately dated to 1400–1000 BCE. Notable among these are the excavations carried out by Iranian archaeologists at Marlik and Kaluraz (Hakemi, 1968; Negahban, 1996), as well as investigations conducted by Japanese missions in the Deylamān district and the Gorgan Plain (Sugimura 2008). Despite the archaeological richness of this area, archaeometallurgical research has been relatively limited, with analytical work primarily focused on artefacts from Marlik, c. 1400–1000 BCE, and a number of artefac recovered from other sites in northern Iran. These include Kaluraz, 1400–1000 BCE, Amlash, 1200–1000 BCE, Jooban (or Joobon), 1200–900 BCE, and a broader group of artefacts attributed generally to the southern Caspian region, 1200–1000 BCE (Vatandoost-Haghighi, 1977; Oudbashi and Hessari, 2017).

These findings indicate that tin bronze metallurgy was the dominant copper-based technological tradition in northern Iran during the latter half of the 2nd millen-

nium BCE. The use of arsenical copper appears to have been rare, although the occurrence of arsenic in some tin bronzes implies either intentional combination or the influence of arsenic-bearing copper ores. This technological preference aligns with broader metallurgical trends observed in western/south-western Iran during the same period.

Sagzabad represents another significant site in the study of copper-based metallurgy during the 2nd millennium BCE in northern Iran. Situated in the Qazvin Plain, the site encompasses occupational phases dating to the Late Bronze Age (LBA) and the Iron Age I (IA I), spanning the 2nd and 1st millennia BCE (Negahban, 1973 and 1977; Malek Shahmirzadi, 1977).

Figure 3b presents a scatter plot of tin (Sn) versus arsenic (As) content based on the compositional analysis of 128 copper-based artefacts from these northern Iranian sites, dated to the 2nd millennium BCE. The results show that tin bronze was the predominant alloy, with 81 artefacts identified as tin bronze (Sn > 1 wt%). In contrast, only 8 artefacts were classified as impure copper (Sn and As < 1 wt%), and 5 as arsenical copper (As > 1 wt% and Sn < 1 wt%). Additionally, 5 artefacts exhibit both elevated tin and arsenic contents, suggesting the use of arsenical tin bronze. Archaeometallurgical analysis of 19 copper-based artefacts recovered from the LBA and IA I levels of Sagzabad has contributed valuable information regarding the technological choices made by the inhabitants. Of the analysed artefacts, 10 were identified as being composed of impure copper: Sn and As < 1 wt%; while 8 were made of tin bronze: Sn > 1 wt%. Additionally, one artefact from the IA I context was found to be composed of arsenical copper: As > 1 wt% (Mortazavi et al., 2011; Oudbashi et al., 2021a; see here fig. 3b).

Eastern Iran

Many of the 3rd millennium BCE settlements in eastern Iran were abandoned in the 2nd millennium BCE, as is observable at Shahdad and Shahr-i Sokhta, or continued only for a short time at the beginning of the 2nd millennium BCE, such as at Tappeh Hissar (Thornton, 2009b). Nevertheless, archaeological evidence reveals copper-based metalworking in both north-eastern and south-eastern Iran during the Late Bronze Age. The large number of copper-based artefacts discovered at Tappeh Bazgir, including more than 700 items of varying dimensions and forms, constitutes one of the most important metallurgical assemblages in north-eastern Iran, dating to the Late Bronze Age, 1800–1700 BCE (Nokandeh et al., 2006). The metal artefacts from this site have previously been analysed, although detailed chemical data have yet to be published. Nevertheless, chemical analysis of 171 copper-based artefacts revealed that, apart from two tin bronze buttons, all of the analysed items were likely made of arsenical copper alloy (Lorenz, 2008). Additionally, a published report on a few artefacts from Tappeh Bazgir confirmed the use of arsenical copper in their production (Moslehi et al., 2014). The discovery of a large-scale hoard of copper-based artefacts at Tappeh Bazgir, situated on the western borders of Khorasan, highlights the significance of the region—and of north-eastern Iran more broadly—in copper metallurgy during the Late Bronze Age.

Another recently excavated Late Bronze Age site in north-eastern Iran is Shahrak-e Firouzeh, located near Neyshabur. This site represents a Late Bronze Age settlement in Khorasan and demonstrates connections with the prominent cultures of the 2nd millennium BCE in Greater Khorasan and Central Asia, including the Bactria-Margiana Archaeological Complex/Greater Khorasan Civilisation (BMAC/GKC), dated to c. 2100–1700 BCE (Basafa, 2016; 2022). Analysis of a group of copper-based artefacts from the site revealed that 8 out of 23 artefacts were made of low-arsenical copper, while only 2 were identified as low-tin bronze (Oudbashi et al., 2020). The remaining artefacts were composed of impure copper. Furthermore, copper-based artefacts from Level IIIC of Tappeh Hissar (c. 2100–1700 BCE) exhibited a similar alloy composition pattern, with impure copper and arsenical copper being the predominant materials, and only one artefact identified as tin bronze (Thornton, 2009b; see here fig. 4a).

Tappeh Yahya is the only archaeological site in south-eastern Iran that remained occupied during the 2nd and even into the 1st millennium BCE. Excavation of Level IVA (c. 1800–1400 BCE) revealed a substantial collection of metal artefacts, of which 33 have been analysed (Thornton et al., 2002). The chemical data confirmed that impure copper and arsenical copper were the predominant materials, while seven tin bronze artefacts (with > 1 t% tin) were identified among the 33 analysed items (fig. 4b).

Central Iran

This region is confined to the central desert and its surrounding areas, and, as mentioned previously, reveals rich archaeological discoveries from the 5th to 3rd millennium BCE. However, the absence of Bronze Age (c. 2900–1500 BCE) levels in many well-known archaeological sites in north-central and central Iran has resulted in a gap in our knowledge of copper-based metallurgy in this region. Nevertheless, a recent archaeometallurgical study at Qoli Darvish, near Qom, has revealed some interesting aspects of copper-based metallurgy in central Iran during the 2nd millennium BCE (Nezafati and Stöllner, 2017). Four metal artefacts dating to the beginning of the 2nd millennium BCE (Late Bronze Age) were analysed, and the results showed a variety of compositions: one impure copper, two arsenical copper, and one tin bronze artefact. This suggests the parallel use of arsenical copper and tin bronze at the site, although the small number of analysed artefacts does not provide a comprehensive view of copper-based metallurgy in the central Iranian Plateau during the 2nd millennium BCE (fig. 4c). These artefacts, along with those from the Tappeh Sarm Iron Age site (discussed later), show some correlation with the Veshnaveh copper

source, located to the south of these sites (Nezafati and Stöllner, 2017).

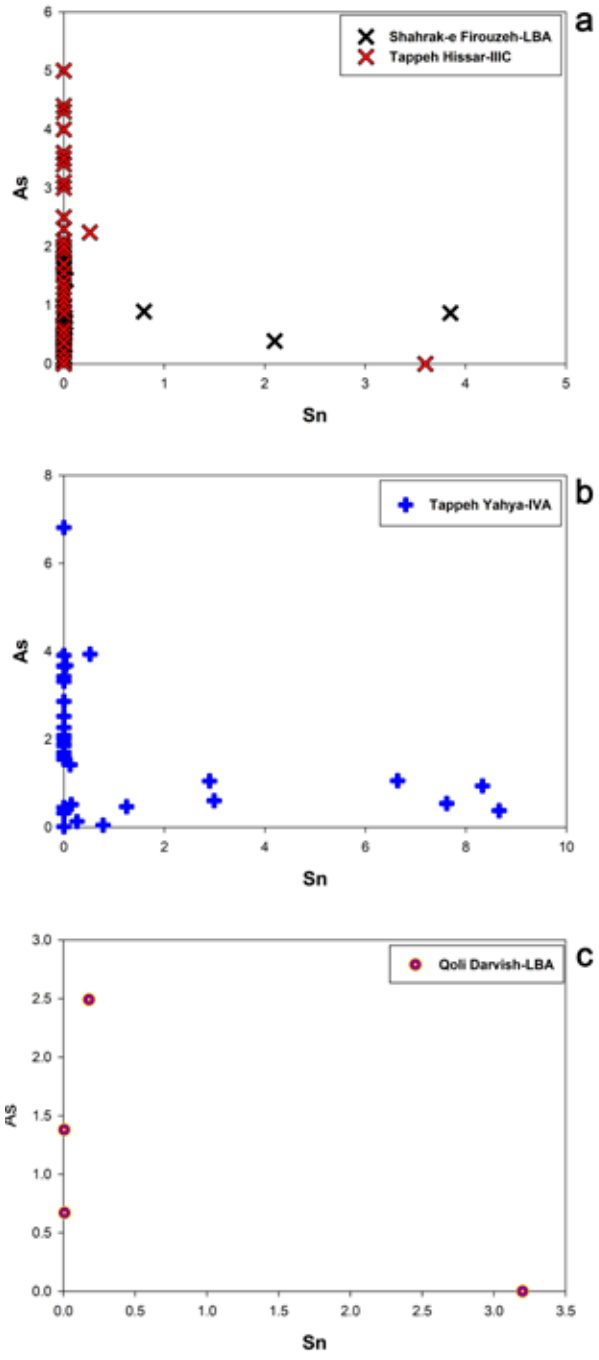


Fig. 4 – Three bivariate scatter plots of Sn versus As in the composition of copper-based artefacts from the Late Bronze Age and Iron Age I in the Iranian Plateau: a) data from 23 artefacts from Shahrak-e Firouzeh and 54 from Level IIIC at Tappeh Hissar in north-eastern Iran, 2nd millennium BCE; b) data from 33 artefacts from Level IVA at Tappeh Yahya in eastern Iran, 2nd millennium BCE; c) data from 4 artefacts from Qoli Darvish in central Iran, 2nd millennium BCE.

1ST MILLENNIUM BCE: TIN BRONZE AS THE PREDOMINANT ALLOY

Western Iran

One of the most striking phenomena in the Iron Age of western Iran is the unusually large quantity of bronzes produced in the Luristan region, including artefacts deposited especially in cemeteries and graves (Moorey, 1982; Overlaet, 2005; Pigott, 2009). These are among the best-known categories of archaeological finds in Near Eastern art and archaeology (Muscarella, 1988; Moorey, 1982 and 1969). They include a series of decorative and ritual bronze artefacts of a specific local style, dating from Iron Age II (IA II) and Iron Age III (IA III) c. 1000–600 BCE, of the Iranian Plateau (Overlaet, 2004 and 2005). Indeed, very few bronzes come from controlled excavations in the Luristan region, and most were collected through large-scale illegal excavations carried out by local people from the late 1920s onwards. Only a few excavations in Luristan yielded examples of these bronzes before the 2000s: the most significant were Erich F. Schmidt's single campaign at the sanctuary site of Surkh Dum in Pish-i Kuh in 1938 (Schmidt et al., 1989) and Louis Vanden Berghe's fifteen campaigns, all at cemetery sites in Pusht-i Kuh, between 1965 and 1979 (Haerinck and Overlaet, 2004). Additionally, Iranian archaeologists have excavated about half a dozen more bronzes from the cemetery site of Khatunban in Pish-i Kuh (Haerinck et al., 2004). The only other settlement site excavated in Luristan, Baba Jan in Pish-i Kuh, about 60 km north of Surkh Dum, yielded a Janus-headed tube and perhaps a zoomorphic pin (Muscarella, 1988).

Interestingly, recent archaeological excavations in Pish-i Kuh of Luristan have led to the discovery of an Iron Age II–III sanctuary and a significant number of Luristan Bronzes at Sangtarashan, near Khorramabad (Oudbashi et al., 2013; Malekzadeh et al., 2017). Furthermore, the excavation of Baba Jilan uncovered an Iron Age II–III cemetery in the north of Pish-i Kuh with some examples of Luristan bronzes as well as other bronze artefacts (Hasanpur et al., 2015).

Both the Sangtarashan and Baba Jilan collections were subjected to archaeometallurgical studies to understand the chemical composition, provenance, and manufacturing techniques used to produce the Luristan Bronzes (Oudbashi and Davami, 2014; Oudbashi and Hasanpour, 2018; Oudbashi et al., 2021b and 2021c). Furthermore, a group of artefacts from earlier excavations in Luristan have also been analysed, for example, artefacts from the two Iron Age graveyards of War Kabud and Bard-i Bal (Pish-i Kuh), and Godin Tappeh (Fleming et al., 2005 and 2006; Frame, 2010). Figure 5a shows a bivariate scatter plot of Sn versus As in the composition of 131 analysed artefacts from western Iran (Luristan). Almost all artefacts are made of tin bronze with variable tin content, while six artefacts from Godin Tappeh show arsenical copper and impure copper.

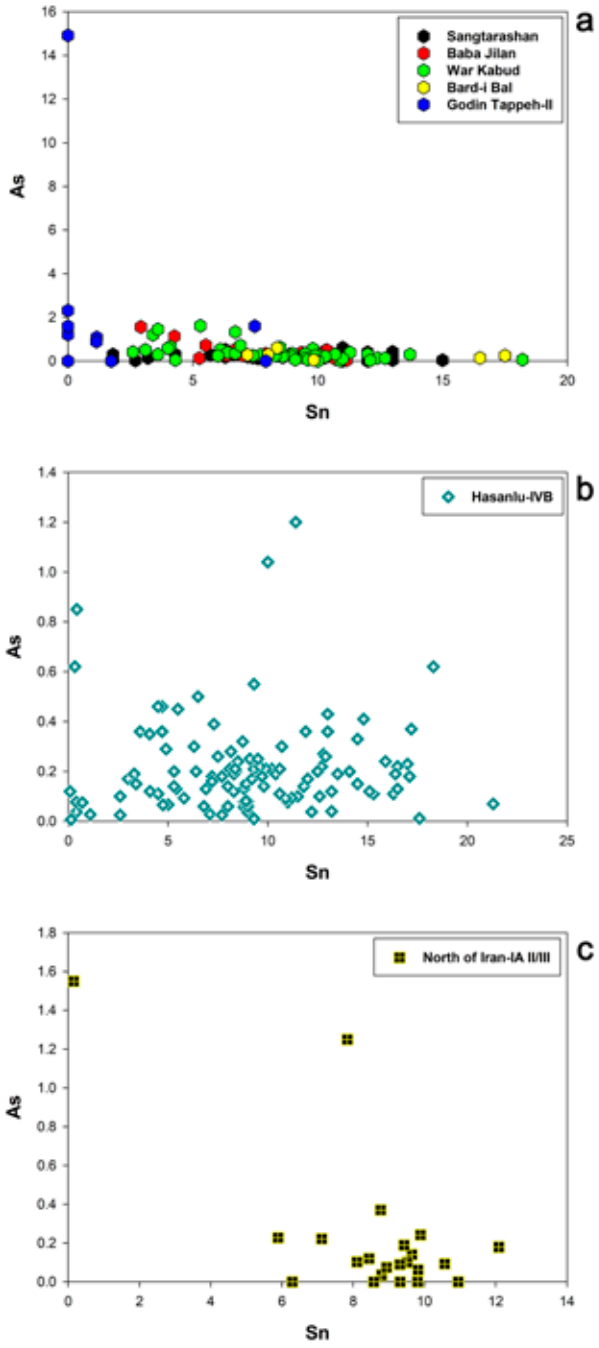


Fig. 5 – Three bivariate scatter plots of Sn versus As in the composition of copper-based artefacts from the Iron Age II–III in the Iranian Plateau: a) data from 131 artefacts from western Iran, 1st millennium BCE; b) data from 112 artefacts from Hasanlu in north-western Iran, 1st millennium BCE; c) data from 22 artefacts from northern Iran, 1st millennium BCE.

North-western Iran

Although many copper-based artefacts were discovered from the Iron Age II and III sites of north-western Iran (Muscarella, 1988), only artefacts from Hasanlu have been subjected to a comprehensive archaeometallurgical study (Fleming et al., 2011). In total, 112 artefacts from the Hasanlu IVB level were analysed, and the results showed that tin bronze was the predominant alloy with variable tin content (1.1–21.3 wt%), while only seven artefacts were made of impure copper. No arsenical copper was detected among the analysed artefacts, but two tin bronzes showed a comparatively higher concentration of arsenic (1.04 and 1.2 wt%; fig. 5b).

Northern Iran

Northern Iran, including the southern littoral of the Caspian Sea (especially modern Gilan), was settled in Iron Age II–III, and many Iron Age cemeteries and sites have been discovered through archaeological excavations (Haerinck, 1988; Khalatbari, 2004a, 2004b and 2004c). Unfortunately, most of the metal finds have not been subjected to archaeometallurgical studies. Analytical work on artefacts excavated from Iron Age II–III sites in northern Iran has been limited to early chemical analyses published by Vatandoost-Haghighi (1977) and Vatandoust (1999). According to analytical data, 20 of 22 analysed artefacts from northern Iran were made of tin bronze, with just one artefact made of arsenical copper, and another made of tin bronze with As > 1 wt% (fig. 5c).

Central Iran

Archaeological excavations related to the 1st millennium BCE in central Iran remain limited, and consequently, the number of analysed copper-based artefacts from this period is also quite small. However, recent excavations at Tappeh Sarm, near Qom, have revealed an Iron Age III cemetery situated near the site of Shamshirgah (Nezafati and Stöllner, 2017). Among the 13 analysed artefacts from this site, 10 were identified as tin bronzes, containing approximately 2 to 12 wt% tin, while the remaining three were made of impure copper. The metallurgical analysis of the Tappeh Sarm artefacts thus confirms the use of tin bronze during Iron Age III in central Iran (fig. 6a).

Eastern and South-central Iran

The only archaeological site in eastern Iran with levels attributed to the 1st millennium BCE is Tappeh Yahya, as Period III dates to the 8th–6th centuries BCE (IA III) and Period II to the Achaemenid period (c. 550–330 BCE) (Thornton et al., 2002). Analysis of three artefacts from Period III showed impure copper and low-arsenical copper, while 13 artefacts from Period II showed the continuity of arsenical copper usage and three examples of tin bronze (fig. 6b). A recent archaeometallurgical study of finds from the Iron Age II/III cemetery of Lahsavareh in south-western/south-central Iran, south-west of the Bronze Age site of Deh Dumen, also revealed the use of tin bronze with variable tin content (1.6–12.1 wt% tin) for producing different types of ritual artefacts (Habibzadeh et al., 2025). Furthermore, a recent study of 14 artefacts discovered at Persepolis (Achaemenid empire) demonstrated tin bronze and leaded tin bronze as the predominant alloys for producing weapons and tools (Oudbashi et al., 2023a).

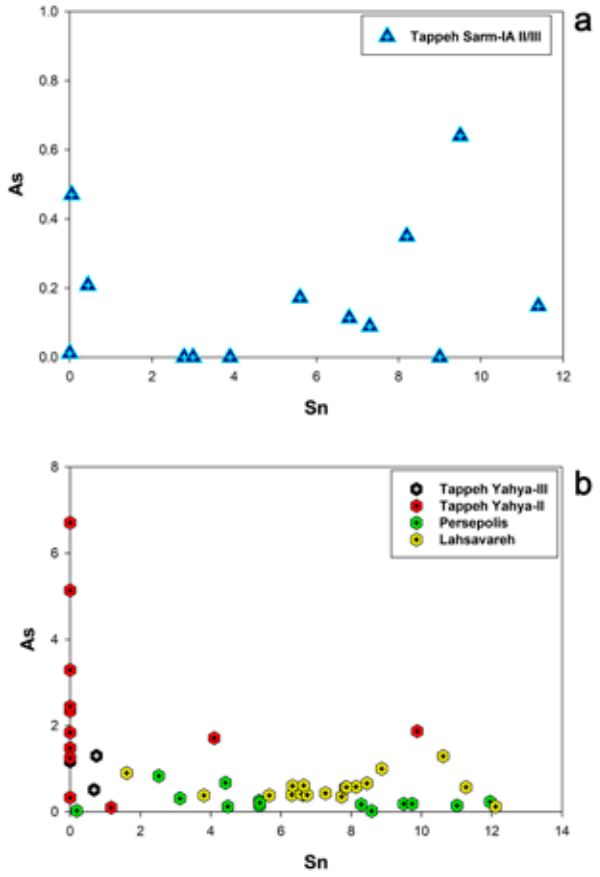


Fig. 6 – Two bivariate scatter plots of Sn versus As in the composition of copper-based artefacts from the Iron Age II–III and the Achaemenid period in the Iranian Plateau: a) data from 13 artefacts from Tappeh Sarm in central Iran, 1st millennium BCE; b) data from 49 artefacts from Levels II and III at Tappeh Yahya, Persepolis, and Lahsavareh in eastern and south-central Iran, 1st millennium BCE.

TIN BRONZE PRODUCTION: A PREHISTORIC EVOLUTION

From Arsenical Copper to Tin Bronze

Figure 7 presents two columnar diagrams illustrating the distribution of tin and arsenic content in the analysed artefacts from the 3rd, 2nd, and 1st millennia BCE. The tin percentage diagram (fig. 7a) and the arsenic percentage diagram (fig. 7b) are based on the results of analyses of 1005 copper-based artefacts (table 2). According to the diagram in figure 7a, it is evident that early tin bronzes from the 3rd millennium BCE contained a lower percentage of tin compared to artefacts from the 2nd and 1st millennia BCE, generally with a tin content between 1 and 11 percent. Most of the artefacts exhibit tin contents ranging from 1–3 and 7–9 wt%. Additionally, the majority of analysed artefacts from the 3rd millennium BCE are made from copper alloys containing less than 1 wt% tin (impure copper and arsenical copper). Furthermore, tin content increases later in the Late Bronze Age and Iron Age I (2nd millennium BCE), with half of the analysed artefacts composed of tin bronze. The distribution of tin content in this period is broader, ranging from 1 to 19 percent. This pattern continues in the Iron Age II and III as well as the Achaemenid period (1st millennium BCE), in which tin bronze artefacts predominate with a higher tin content. In contrast, arsenic content follows a different trend: artefacts with high arsenic content are predominant in the 3rd millennium BCE, with a subsequent decline in later millennia. The highest arsenic content observed across all periods is between 1–3 wt%, and the number of arsenical copper artefacts with elevated arsenic levels diminishes over the three millennia.

The tin content in artefacts dating back to the Bronze and Iron Ages of Iran shows a wide range of compositions, particularly in the later periods. Although some experts suggest a relationship between tin content and artefact function or typology (Moorey, 1994; El Morr and Pernot, 2011), this pattern has not been observed in prehistoric Iranian bronzes. As mentioned earlier, this may be due to the use of uncontrolled alloying methods in early tin bronze production. Various types of artefacts were produced with differing amounts of tin, indicating no clear relationship between alloy composition and typology. This has been particularly evident in Iron Age tin bronze artefacts from western Iran (Oudbashi, 2019a and 2019b; Oudbashi et al., 2021b).

Development of Tin Bronze on the Iranian Plateau

According to the available analytical data, tin bronze technology emerged in western and south-western Iran by at least the middle of the 3rd millennium BCE. Evidence of tin bronze artefacts has been identified in materials excavated from Early to Middle Bronze Age cemeteries in these regions, such as Deh Dumen and Kalleh Nisar. Additionally, tin bronze was also found in artefacts from Susa and Godin Tappeh from the same period. Interestingly, arsenical copper, unalloyed copper, and tin bronze were used concurrently in the region, reflecting a transitional phase from arsenical copper and copper metallurgy to the adoption of tin bronze as a new alloying tradition (fig. 8).

The only studied case of copper-based metallurgy in central Iran is Malyan. Artefacts from the Banesh phase (3400–2800 BCE) are made of impure copper and arsenical copper, while those from the Kaftari phase (2200–1600 BCE) demonstrate a variety of compositions, including tin bronze, arsenical copper, and impure copper. This represents a clear example of the transition from arsenical copper to tin bronze production during the 3rd millennium BCE (Pigott et al., 2003a and 2003b). Artefacts produced at the end of the 4th and beginning of the 3rd millennia BCE show no evidence of tin bronze, whereas those from the end of the 3rd and beginning of the 2nd millennia BCE are increasingly composed of tin bronze alloys with varying tin content (fig. 8).

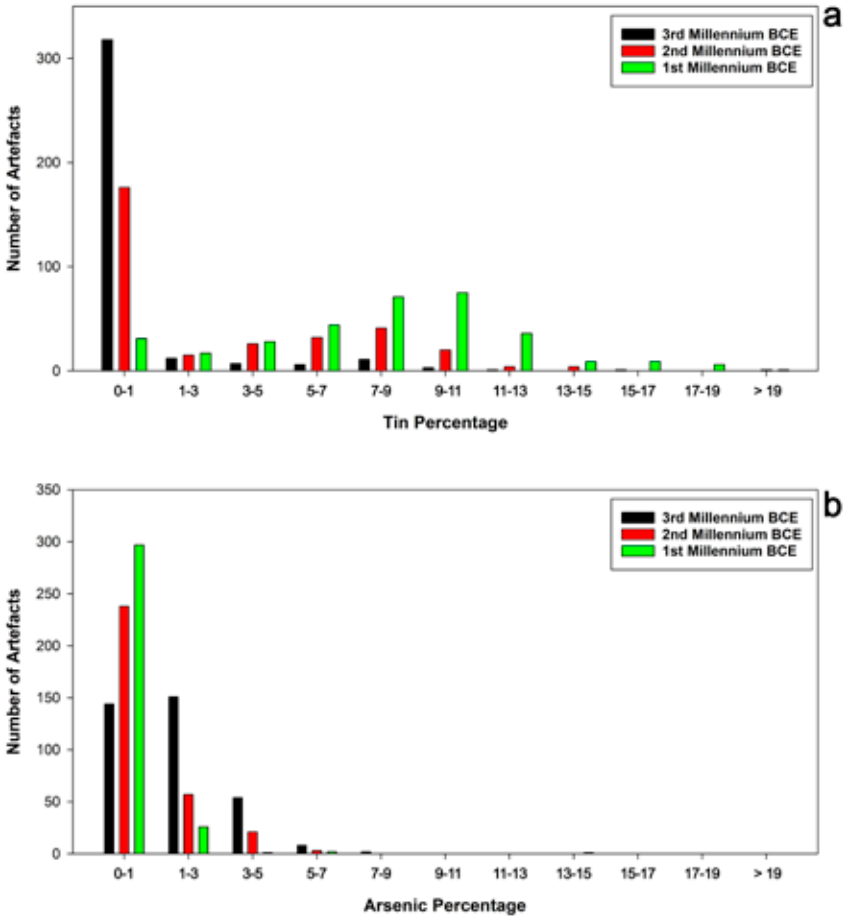


Fig. 7 – Two columnar diagrams showing the distribution of alloying elements in the analysed copper-based artefacts from the prehistoric Iranian Plateau: a) tin content distribution based on the analysis of 1005 artefacts; b) arsenic content distribution based on the analysis of 1005 artefacts.

	Region	Site	Date	Level/ Phase/Area	Analysis Method	No. of Analysed Artefacts	Reference
3rd Millennium BCE	Western and South-western	Kalleh Nisar	3200–2000 BCE	A-I/A-II/C	OES, NAA, PIXE	22	Fleming et al,, 2005; Begemann et al,, 2008
		Bani Surmeh	3rd millennium BCE	A/B	OES, NAA	19	Begemann et al,, 2008
		Dar Tanha	3rd millennium BCE	III	OES, NAA	6	Begemann et al,, 2008
		Mehr War Kabud	3rd millennium BCE	EBA/MBA	OES, NAA	3	Begemann et al,, 2008
		Gululal-i Galbi	3rd millennium BCE	EBA/MBA	OES, NAA	3	Begemann et al,, 2008
		Sardant	3rd millennium BCE	EBA/MBA	OES, NAA	4	Begemann et al,, 2008
		Darvand	3rd millennium BCE	A	OES, NAA	1	Begemann et al,, 2008
		Godin Tappeh	2950–1900 BCE	IV/III/III:6/ III:5/III:4	EPMA	35	Frame, 2010
		Deh Dumen	c. 2500 BCE	EBA/MBA	OES, EDS	10	Oudbashi et al,, 2016; Oudbashi and Naseri, 2017

Table 2 – Details of the archaeological sites and analysed copper-based artefacts from various regions of the Iranian Plateau, dated to the 3rd to 1st millennia BCE. This information is discussed in the manuscript and has also been used to generate graphs and plots.

3rd Millennium BCE	Eastern	Shahdad	2800–2400 BCE	EBA/MBA	AAS, XRF	42	Meier, 2011; Vatandoost-Haghighi, 1977; Oudbashi et al,, 2017
		Khinaman	c. 2200–2000 BCE	MBA	XRF	12	Curtis, 1988
		Tappeh Yahya	3100–2900/2400–2000 BCE	IVC/IVB	ICP-MS	37	Thornton et al., 2002; Meier, 2011
		Tappeh Hissar	2800–2000 BCE	IIIA/IIIB	PIXE	104	Thronton, 2009b
		Shahr-i Sokhta	2700–2500 BCE	EBA/MBA	-	21	Helmig, 1986
	Central and south-centrall	Malyan	3400–2800/2200–1600 BCE	Banesh/ Kaftari	PIXE	40	Pigott et al,, 2003a and 2003b
2nd Millennium BCE	Western and South-western	Haft Tappeh	1400 BCE	Middle Elamite	PIXE, AAS	59	Oudbashi et al., 2019; Vatandoost-Haghighi, 1977
		Godin Tappeh	1900–1400 BCE	III:2/Post III:2	EPMA	18	Frame, 2010
	Northern	Marlik	1400–1000 BCE	IA I	ICP-MS, AAS	65	Oudbashi and Hessari, 2017, Vatandoost-Haghighi, 1977
		North of Iran-Kaluraz	1400–1000 BCE	IA I	AAS	3	Vatandoost-Haghighi, 1977
		North of Iran-Amlash	1200–1000 BCE	IA I	AAS	3	Vatandoost-Haghighi, 1977
		North of Iran-Gilan	1200–900 BCE	IA I	AAS	2	Vatandoost-Haghighi, 1977
		North of Iran-Jooban	1200–900 BCE	IA I	AAS	1	Vatandoost-Haghighi, 1977
		North of Iran-South of the Caspian Sea	1400–900 BCE	IA I	AAS	35	Vatandoost-Haghighi, 1977
		Sagzabad	1800–1000 BCE	LBA/IA I	ICP-OES	19	Oudbashi et al., 2021a; Mortazavi et al., 2011
	Eastern	Shahrak-e Firouzeh	2100–1700 BCE	LBA	ICP-OES	23	Oudbashi et al., 2020
		Tappeh Hissar	2100–1700 BCE	IIIC	PIXE	54	Thornton, 2009b
		Tappeh Yahya	1800–1400 BCE	IVA	ICP-MS	33	Thronton et al,, 2002
	Central	Qoli Darvish	2000–1500 BCE	LBA	XRF	4	Nezafati and Stöllner,, 2017
1st millennium BCE	Western	Sangtarashan	800–600 BCE	IA III	ICP-OES	46	Oudbashi et al., 2021b
		Baba Jilan	800–600 BCE	IA III	ICP-OES	21	Oudbashi and Hasanpour, 2018
		War Kabud	800–600 BCE	IA III	PIXE	47	Fleming et al,, 2006
		Bard-i Bal	800–600 BCE	IA III	PIXE	6	Fleming et al,, 2005
		Godin Tappeh	800–600 BCE	II	EPMA	11	Frame, 2010
	North-western	Hasanlu	1050–800 BCE	IVB	PIXE	112	Fleming et al., 2011,; Vatandoost-Haghighi, 1977
	Northern	North of Iran	1000–700 BCE	IA II/III	AAS, EDS, ICP	22	Vatandoost-Haghighi ,1977; Vatandoust, 1999
	Central	Tappeh Sarm	1000–600 BCE	IA II/III	XRF	13	Nezafati and Stöllner, 2017
	Eastern and south-central	Tappeh Yahya	800–330 BCE	III/II	ICP-MS	16	Thronton et al,, 2002
		Lahsavareh	1100–600 BCE	IA II/III	XRF	19	Habibzadeh et al., 2025
		Persepolis	550–330 BCE	Achaemenid	ICP-OES	14	Oudbashi et al., 2023a
	Total					**1005**	

Table 2 (continued) – Details of the archaeological sites and analysed copper-based artefacts from various regions of the Iranian Plateau, dated to the 3rd to 1st millennia BCE. This information is discussed in the manuscript and has also been used to generate graphs and plots.

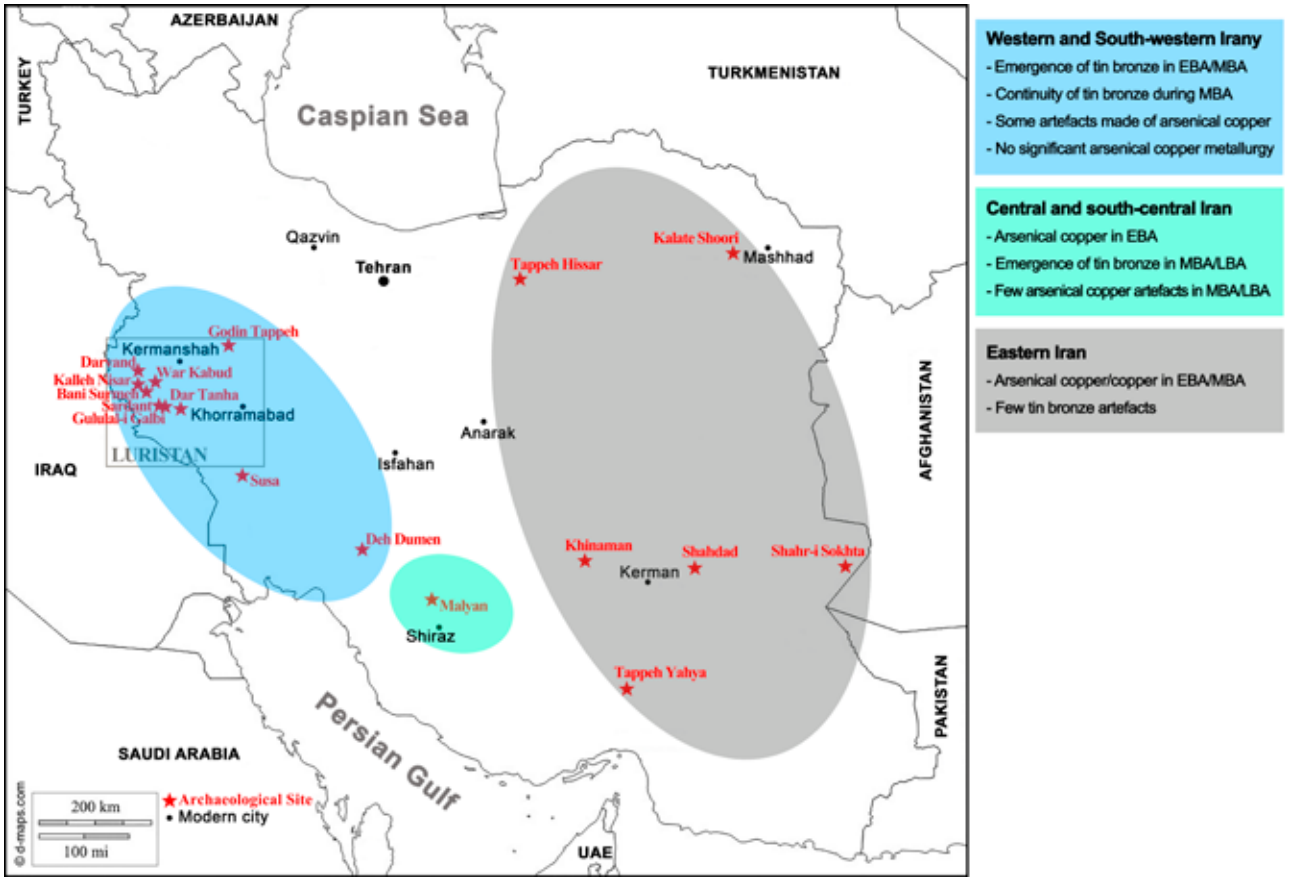


Fig. 8 – Map of modern Iran showing the locations of 3rd-millennium BCE archaeological sites from which copper-based artefacts were analysed, along with information on regional copper-based metallurgy.

Eastern Iran (from north to south) presents a markedly different pattern of copper-based metallurgy in the 3rd millennium BCE. Numerous analysed artefacts and metallurgical materials from well-known archaeological sites—such as Shahdad, Shahr-i Sokhta, Tappeh Yahya, Kalate Shoori, and Tappeh Hissar—show no evidence of tin bronze metallurgy. The only indication of tin bronze comes from two artefacts excavated from the Khinaman cemetery. Notably, Khinaman is a Middle Bronze Age cemetery located on the western fringe of eastern Iran, very close to Malyan and Deh Dumen. The typology of various artefacts from Deh Dumen reveals close connections with both western and eastern sites (Oudbashi et al., 2023b). In particular, similarities between certain metal artefacts from Deh Dumen and those found in Shahdad, Jiroft, or Tappeh Hissar suggest that there were interactions between south-western Iran and the prominent Bronze Age cultures of the eastern Iranian Plateau (Oudbashi et al., 2016 and 2023b). Therefore, while trade in metals between these regions during the 3rd millennium BCE is possible, the lack of tin bronze among the analysed artefacts from Tappeh Hissar and Shahdad highlights the need for further archaeometallurgical studies to better understand the potential connections between western and eastern Iran during this period.

The 2nd millennium BCE also displays a partially similar pattern of copper-based metallurgy to that of the 3rd millennium BCE (fig. 9). The western and south-western archaeological sites show evidence of tin bronze metallurgy, with some examples of impure copper and arsenical copper. However, the proportion of tin bronze compared with arsenical copper increased during the 2nd millennium BCE, and arsenical copper became rare, as seen at Haft Tappeh and Godin Tappeh. Tin content varies in the composition of the analysed artefacts, likely due to the use of uncontrolled alloying processes. These include either the cementation of metallic copper with tin ores or the direct smelting of copper–tin complex ores, as has been observed at Haft Tappeh (Oudbashi and Mishmastnehi, 2020).

Northern Iran also shows tin bronze as the predominant alloy used during the 2nd millennium BCE, although some arsenical copper and impure copper artefacts have also been identified. Tin content varies among the tin bronze artefacts from the region, suggesting that uncontrolled alloying methods were probably applied. The only example of copper-based artefact analysis in central Iran for this period comes from a few artefacts from Qoli Darvish, comprising one tin bronze, one copper, and two arsenical copper artefacts.

Eastern Iran in the 2nd millennium BCE displays a similar pattern to that of the 3rd millennium BCE, with

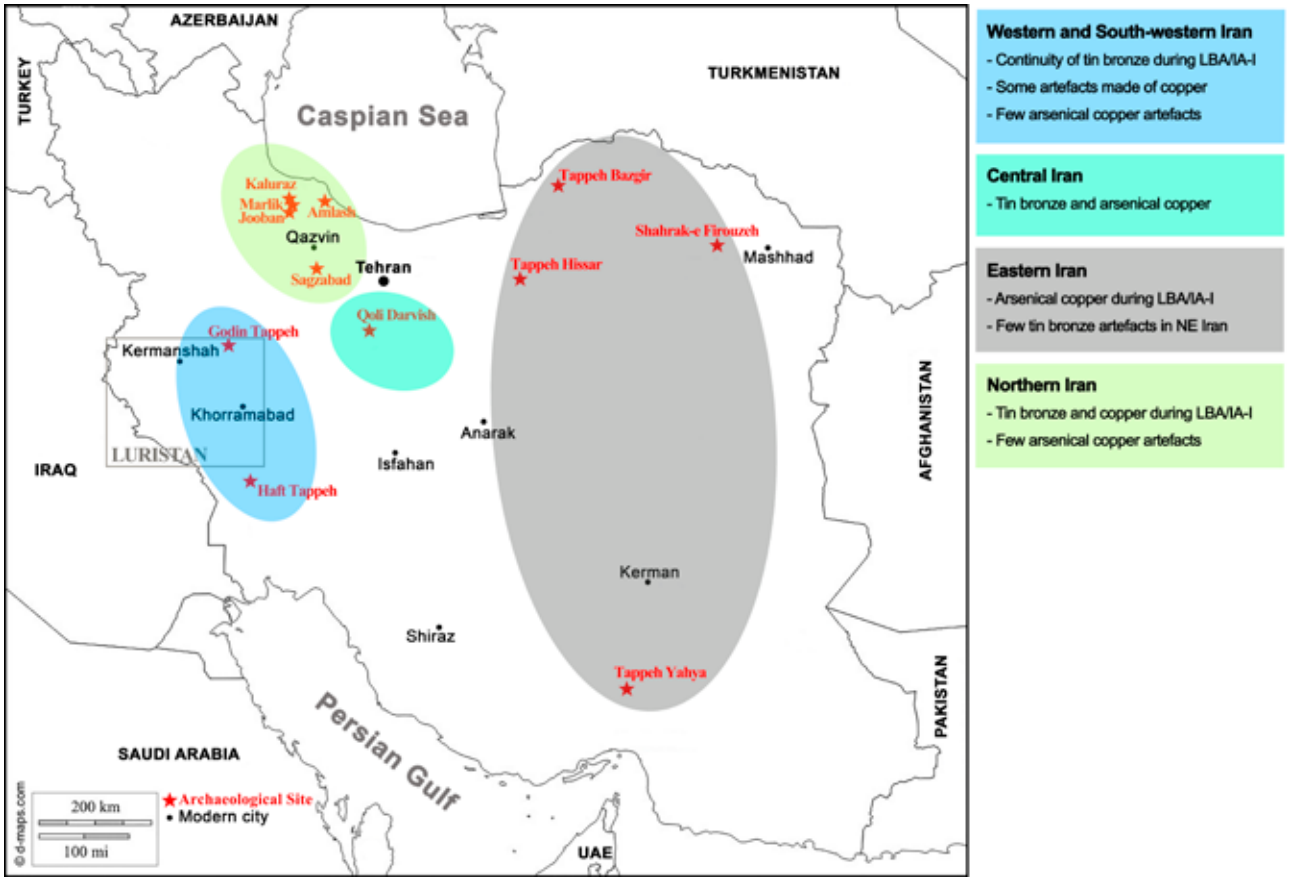


Fig. 9 – Map of modern Iran showing the locations of 2nd millennium BCE archaeological sites from which copper-based artefacts were analysed, along with information on regional copper-based metallurgy.

copper and arsenical copper remaining the predominant metals. However, a few more examples of tin bronze have been identified at Shahrak-e Firouzeh (north-eastern Iran) and Tappeh Yahya (south-eastern Iran). The tin content in these tin bronze artefacts is relatively low (< 10 wt%), similar to that observed in artefacts from western/southwestern Iran in the 3rd millennium BCE, and lower than that in artefacts from later periods, such as the Late Bronze Age and Iron Age. This may be due to the use of direct smelting of tin-bearing copper ores, as has also been observed at the Deh Hosein mine (Nezafati, 2006).

The Iron Age II and III can be considered the era of tin bronze metallurgy on the Iranian Plateau, as tin bronze was the predominant metal used for producing various decorative, ritual, and daily-use artefacts (fig. 10). Iron also emerged during this period, as seen at Hasanlu and in Luristan (Moorey, 1982; Muscarella, 1988; Pigott, 1989). Nevertheless, numerous metal artefacts from Iron Age II–III sites across western, north-western, northern, and central Iran were made of tin bronze. Arsenical copper and impure copper are rare, with only a few examples identified among the analysed artefacts. The only site in south-eastern Iran with Iron Age and Achaemenid levels is Tappeh Yahya. Analysis of artefacts from this site revealed a pattern consistent with that of the 3rd and 2nd millennia BCE in eastern/south-eastern Iran, arsenical copper predominates, with only three tin bronze artefacts identified in the Achaemenid level. This aligns with the earlier copper-based metallurgy of the Bronze Age and Iron Age I at Tappeh Yahya, where copper and arsenical copper were the main alloys. Artefacts from Persepolis were also made of tin bronze, but the available data from the Achaemenid period remain insufficient to form a comprehensive picture of copper-based technology in c. 550–330 BCE on the Iranian Plateau. As Cuénod et al. (2015, p. 44) stated:

> " In western Iran, aside from very early uses in Luristan, the idea of using tin-bronze may have come from the Mesopotamian neighbours, but while more and more objects were made of tin-bronze throughout the third and second millennia BC, it seems possible that the metal kept a valuable status well into the Iron Age: it is indeed only by the late second millennium that almost all copper alloy work is bronze."

The findings of the current study align with their conclusions, although they provide a broader picture of the rise and development of tin bronze metallurgy over three millennia, particularly due to more detailed information from different regions of the Near East, Mesopotamia and the Iranian Plateau. Nevertheless, the origin of tin, as well as the processes and methods of alloying copper with tin, remain unclear. Recent work by Nima Nezafati (2006)

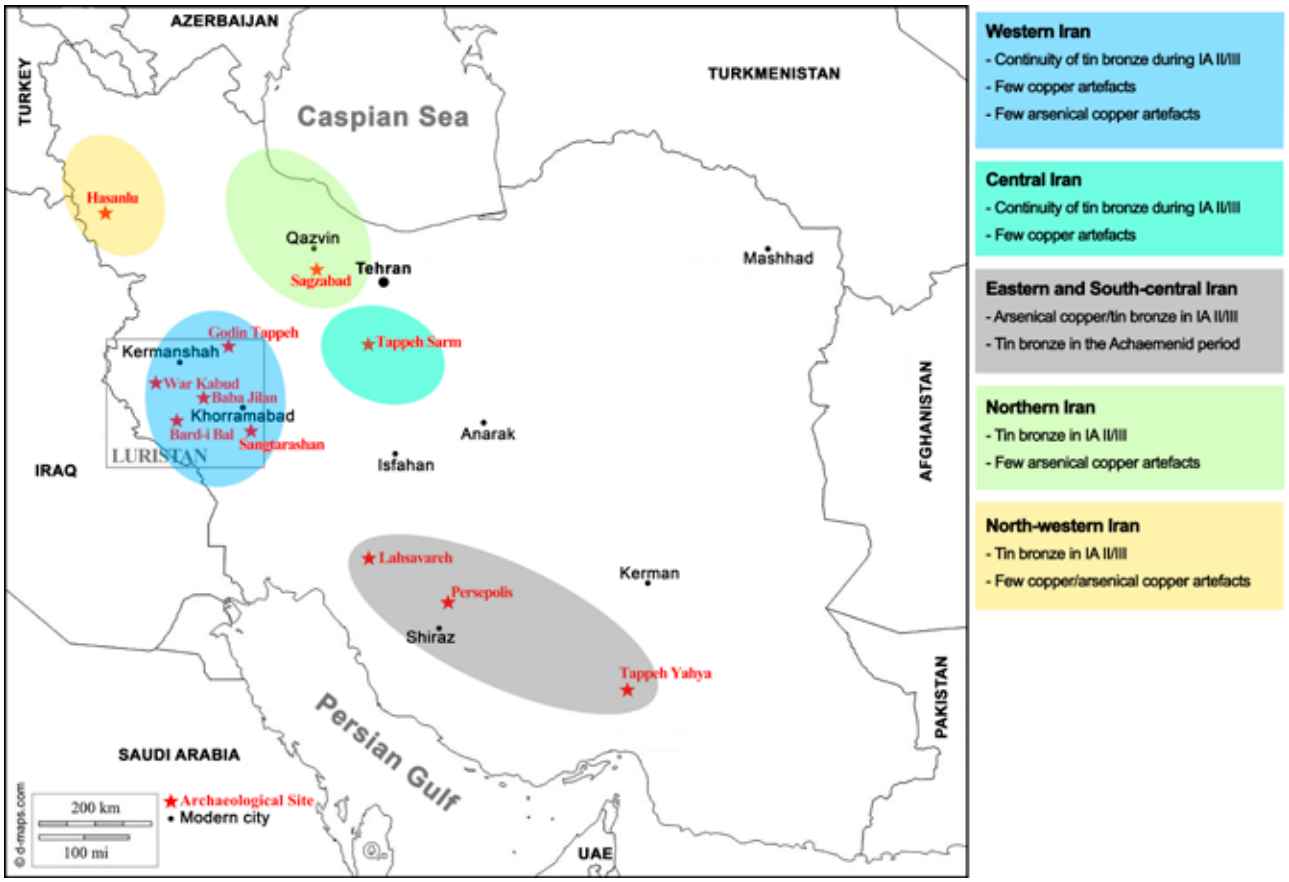


Fig. 10 – Map of modern Iran showing the locations of 1st millennium BCE archaeological sites from which copper-based artefacts were analysed, along with information on regional copper-based metallurgy.

offers some insights into tin supply and tin bronze production on the Iranian Plateau.

CONCLUSIONS

Although the Iranian Plateau is known as one of the pioneering regions in the emergence of early metallurgy in the ancient world, numerous questions about the beginning and development of copper-based metallurgy on the Plateau have not been fully answered. One of the main questions concerns the rise of tin bronze metallurgy in the 3rd millennium BCE and its development in subsequent millennia. Many archaeological excavations on the Iranian Plateau have led to the discovery of numerous copper-based artefacts as well as metallurgical materials, but only a few findings have been studied from an archaeometallurgical viewpoint. Nevertheless, the limited available data can help us shape a general view of the rise and development of tin bronze metallurgy during the Bronze and Iron Ages on the Plateau (3rd–1st millennium BCE). By describing and comparing the data, it has been shown that tin bronze emerged in western and south-western Iran in the middle of the 3rd millennium BCE and that this technology developed and continued in the region. Early examples of tin bronze artefacts were observed alongside arsenical copper and copper artefacts at EBA and MBA archaeological sites in the Zagros Mountains and Khuzestan Plain, while no evidence of tin bronze was found in eastern and central Iran at the same time. By the end of the 3rd millennium BCE, tin bronze had appeared in central Iran. The 2nd millennium BCE (LBA and IA-1) marked the development of tin bronze metallurgy in central and northern Iran, although tin bronze remained a rare material in the eastern half of the Plateau. Finally, tin bronze was the predominant alloy in most regions of the Iranian Plateau during the 1st millennium BCE, including western, north-western, northern, and central Iran, although available data from eastern Iran is insufficient for firm conclusions. Nevertheless, a few artefacts dated to the Achaemenian period are made of tin bronze. Consequently, the transmission from copper/arsenical copper to tin bronze as a new and likely more suitable alloy, with no toxicity and better mechanical properties, on the Iranian Plateau was very slow and took around 2,000 years to become widespread throughout the Plateau, although the western part can be considered the centre of tin bronze technology in prehistoric times.

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Bronze weapons as funerary furniture in tombs of the Talysh area (Azerbaijan and Iran)

and the contribution of their archaeometallurgical analyses

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Abstract: This paper is based on research carried out over five years (2012-2016) under the joint Franco-Azerbaijani archaeological Mission of the Lenkoran River valley, in the Lenkoran basin and along the river's tributaries in the province of Lerik, which dealt with the question of the transition between Bronze and Iron Ages in southern Azerbaijan (and was co-directed by M. Casanova† and A. Alekperov†). It will address the main features of the composition and the distribution of metal artefacts within the burials, with comparisons in the wider context of Talysh (Iran and Azerbaijan) as well as neighbouring regions of the Caucasus. The contribution of technological studies applied to archaeological metallic material (copper alloys) will be discussed based on the results of recent X-radiography and PIXE analyses conducted by the French laboratory C2RMF, on a set of objects, partly previously discovered by J. de Morgan (1889-1901) and partly found during the recent fieldwork.

Keywords: Talish, Azerbaijan, Iran, South Caucasus, Late Bronze Age, Early Iron Age, Copper alloy, Weaponry, Dagger, Archaeometallurgy..

Résumé : Cet article repose sur des recherches menées durant cinq ans (2012-2016) dans le cadre de la Mission archéologique franco-azerbaïdjanaise de la vallée du Lenkoran, dans le bassin du fleuve Lenkoran et le long de ses affluents, dans la province de Lerik. Ces travaux, codirigés par M. Casanova† et A. Alekperov†, portaient sur la question de la transition entre l'âge du Bronze et l'âge du Fer dans le sud de l'Azerbaïdjan. L'étude présentera les principales caractéristiques de la composition et de la répartition des artefacts métalliques découverts en contextes funéraires, avec des comparaisons situées dans le cadre plus large du Talysh (Iran et Azerbaïdjan) ainsi que dans les régions voisines du Caucase. La contribution des études technologiques appliquées au matériel archéologique métallique (alliages cuivreux) sera également examinée, sur la base des résultats récents de radiographie X et d'analyses PIXE réalisées par le laboratoire français du C2RMF sur un ensemble d'objets provenant du Talysh, en partie découverts par J. de Morgan entre 1889 et 1901, et en partie issus des travaux de terrain récents.Mots-clés : Talysh, Azerbaïdjan, Iran, Caucase méridional, âge du Bronze récent, âge du Fer ancien, alliage cuivreux, armement, dague, archéométallurgie.

Mots clés : Talish, Azerbaidjan, Iran, Sud Caucase, Bronze récent, Premier âge du Fer, alliage cuivreux, armes, poignard, archéométallurgie.

Between 1889 and 1891, Jacques de Morgan conducted explorations across the Caucasus, Iran, and Anatolia as part of his scientific mission in Persia. Thus, in 1890, he explored the former Russian Talysh—now the Lenkoran and Lerik districts of the Republic of Azerbaijan—and in 1901 the Persian Talysh—now the Ardabil and Gilan Provinces of Iran. Thirteen sites located in Azerbaijan were explored—Hovil, Amarat, Conu, Tülü Aspa-Hiz, Veri, Razgov, Mistan, Hiveri, Çayrud, Kraveladi, Cucu Tuk, Monidigah, and Mistaïl—as well as ten sites in Iran—Qal'a, Khodja Daoud Köpru, Namin, Tchila-Khane, Lor-Daghi, Chagoula-Derre, Vajalik, Tach-Koprü, Hasan Zamini, and Shir Shir (fig. 1). The sites of Dokalian and Agha Evlar, also explored in 1901 in Iran, are located outside the Talysh region, on the other side of the great Ardabil plain. For this study, the current toponymy of the sites was chosen, as presented in the excavation reports of the Lenkoran Mission, rather than the names used at the time of Morgan's exploration (table 1).

As a result of its extensive excavations, several thousand artefacts were uncovered. Upon his return to France, Morgan donated this remarkable collection to the Musée

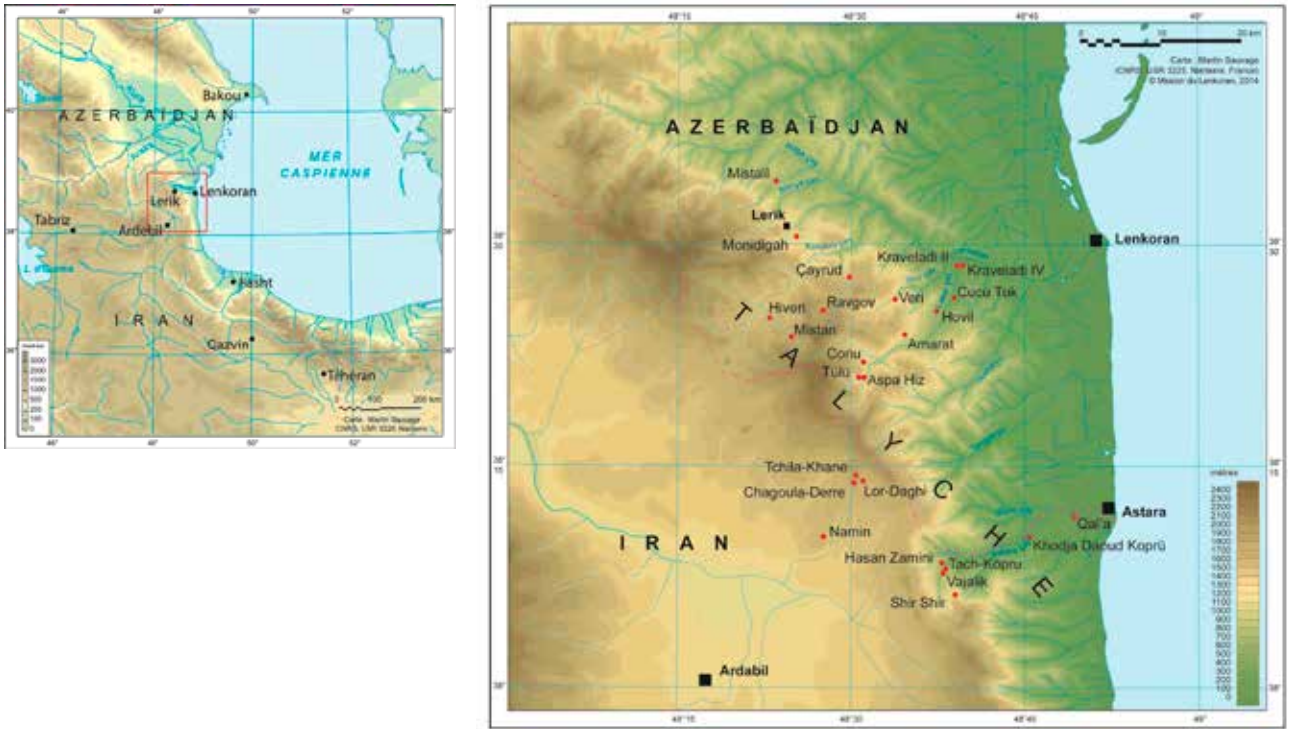


Fig. 1 – Sites from the Late Bronze Age and Early Iron Age in the Talysh area (maps: M. Sauvage/Archaeological Mission in Lenkoran).

After Morgan 1896 and 1905	Current toponymy	International Phonetic Alphabet
Kravéladi	Kraveladi	kʁaveladi
Hôvil	Hovil	ovil
Djüodjikash	Cucu Tuk	dʒu dʒu tuk
Véri	Veri	veʁi
Razgoour	Razgov	ʁazgɔv
Amarat	Amarat	amaʁat
Mistan	Mistan	mistan
Tülü Aspa-Hiz	Tülü Aspa-Hiz	tyly aspa-iz
Djönü	Conu	dʒɔnu
Hivéri	Hiveri	ivɛʁi
Mistaïl	Mistaïl	mistail
Monidighia	Monidigah	monidiga
Tchïrou	Çayrud	tʃajʁud
Qal'a	Qal'a	kala
Khodja Daoud keuprü	Khodja Daoud Köprü	kodʒa daud kopʁy
Nâmin	Namin	namin
Tchila-Khané	Tchila-Khane	tʃila kane
Lor-Daghi	Lor-Daghi	lɔʁ dagi
Chagoula-Dérré	Chagoula-Derre	ʃagula deʁe
Vadjalik	Vajalik	vadʒalik
Tach-koprü	Tach-köprü	taʃ kopʁy
Hassan-Zamini	Hasan Zamini	asan zamini
Chir-Chir	Shir Shir	ʃiʁ ʃiʁ

Table 1 – Comparison between the site names given by Jacques de Morgan and their current toponymy and current pronunciation.

des Antiquités Nationales (MAN) in Saint-Germain-en-Laye. The assemblage includes pottery, ornaments, weapons, and tools, spanning a wide chronological range from the second millennium to the early first millennium BCE (table 2).

The NABIALLA Project, a French-Azerbaijani archaeological collaboration, addresses two complementary research objectives. First, the Morgan Project aims

Chronological framework of the Talysh	
Middle Bonze Age	2100-1600 BCE
Early Bronze Age	1600-1300 BCE
Iron Age I	1300-1100 BCE
Iron Age II	1000-800 BCE
Iron Age III	800-600 BCE

Table 2 – Chronology from the Middle Bronze Age to Iron Age III for the Talysh region.

to re-examine artefacts previously excavated and preserved in public collections, both within Azerbaijan and abroad—particularly those housed at the MAN—in light of recent archaeological findings. Second, the Lenkoran Project involves systematic fieldwork focused on Bronze and Iron Age necropolises in the Lenkoran and Lerik districts of Azerbaijan. Together, these initiatives seek to enhance our understanding of regional funerary practices during these periods.

As part of the Morgan Project, a selection of bronze weaponry was subjected to archaeometallurgical analysis, including PIXE (Particle-Induced X-ray Emission) and X-radiography, in order to better characterize the composition of the metal objects and to determine the manufacturing techniques used in the production of the daggers. This article presents the results of these analyses.

THE SCIENTIFIC BACKGROUND

For the last 20 years, new methods in archaeology have been developed in Azerbaijan and many new discoveries have been made by chance or through the opportunity afforded by archaeological surveys prompted by huge public projects and the Tbilisi-Baku-Ceyhan pipelines constructed through Azerbaijan, Georgia and Turkey during the period 2003-2005 (Schachner, 2002; Sagona, 2004; Smith, 2005; Shanshishvili and Narimanishvili, 2012).

Within this framework, the NABIALLA Project (Necropolises in Azerbaijan during the Bronze and Iron Ages in the Lerik and Lenkoran Areas) was set up within a scientific cooperation agreement signed in 2011 which involved the CNRS (UMR 7041 ArScAn, Nanterre), the Archaeological and Ethnographical Institute of the Azerbaijani Academy of Sciences, the University of Lyon 2, the French Ministry of Culture with its General Directorate for Heritage and the French Museums Service, and the National Museum of Archaeology (MAN, Saint-Germain-en-Laye).

Running for five years (2012–2016) under the supervision of Michèle Casanova, the late Professor of Near Eastern Archaeology (Lyon 2 University) and Abuzar Alakbarov, late researcher at the National Institute for Archaeology and Ethnography of Azerbaijan, the new French-Azerbaijani archaeological joint project dealt with two specific topics. On the one hand (the Lenkoran Axis), it aimed to study the necropolises of the Lenkoran and Lerik areas (Republic of Azerbaijan) during the Bronze and Iron Ages (including fieldwork) and, on the other hand (the Morgan Axis, under the supervision of C. Lorre: Lorre, 1997 and 2008 ; Lorre et al., dir., 2009), it included the new study and re-examination of archaeological material formerly discovered at the end of the 19th century by the archaeologist Jacques de Morgan when he explored the Talysh area (Morgan 1896; 1905). All this archaeological material previously discovered and stored in public collections, either in Azerbaijan or abroad (especially in France), was to be studied in comparison with archaeological remains found more recently (Lorre, 2012; Casanova et al., 2016).

Indeed, the MAN keeps in its Collection for Comparative Archaeology a wide range of Caucasian archaeological artefacts (stone implements, ceramics and metallic weapons, ornaments and figurines) partly originating from the excavations conducted on either side of the Russian-Persian border by the two Morgan brothers, at the end of the 19th century. This collection has been partially published and several past studies go back to a time when current techniques of observation and analysis were not yet in use. Before the NABIALLA Project started and throughout its course, the MAN's collection was checked, sorted and restored. An online photographic catalogue, still partial, exists on the French national database Joconde. Several academic works (from the École du Louvre and University of Paris 1– Panthéon-Sorbonne) have re-examined parts of this material, in particular that from the Lenkoran necropolises of Conu and Aspa Hiz (Haze, 2010; Manceau, 2010), while two PhD theses have also been defended on the technical working issues and prehistoric uses of carnelian in the area concerned (Debrabant, 2016) and on funerary practices and material culture in the Talysh at the end of the Bronze Age and beginning of the Iron Age (Haze, 2018). In the meantime, further research has led to a better understanding of Morgan's personality and his scientific activities (a special exhibition about Morgan took place in 2007–2008 and a special conference in 2008, thanks to cooperation with the University Paris 1 – Panthéon-Sorbonne and the High School for Mining Engineers of Mines-ParisTech).

The Franco-Azerbaijani archaeological Mission of the Lenkoran River valley directed by Michèle Casanova and Abuzar Alakbarov, in the Lenkoran basin and along the river's tributaries in the province of Lerik in southern Azerbaijan (2012–2016) resumed fieldwork with a first attempt at a chronological point of view. The new archaeological discoveries and studies confirm the extensive chronological scope of the Talysh area's occupancy from the Middle Bronze Age to the Iron Age, with rich and valuable funerary material which may express a flourishing and even powerful state of civilisation. 14C dating was carried out on tomb 1144 from the Monidigah site in Lenkoran. It provided chronological ranges for three people buried in the tomb: between 1055 and 899 BC; between 978 and 827 BC; and between 1209 and 1016 BC. Although the ranges are fairly wide, these results indicate that these people were buried in the Early Iron Age, between EIA I and EIA II (Haze, 2018, p. 161).

The first stages of the NABIALLA Project have led us in particular to update the state of knowledge concerning funeral practices of the Bronze/Iron transition in this region. Prospecting for sites such as Mistail, Conu, Amarat and particularly excavating sites such as Kraveladi, Cucu Tuk and Monidigah allowed us to complete observations made by Morgan in his time and brought back original elements on burial practices in this area, in comparison with more recent works on the neighbouring Iranian territory (Begemann et al., 2008; Oudbashi et al., 2012; Piller, 2013).

TYPES AND CONTEXTS OF WEAPONS

Weapons were found in large quantities in the graves of the Talysh. Among the 1,666 objects from the Talysh tombs—combining those held in the collections of the MAN and those unearthed during excavations by the Franco-Azerbaijani Archaeological Mission in Lenkoran—341 are weapons. These include bladed weapons, projectile weapons, polearms, and close-combat weapons (fig. 2). These include draft weapons, throwing weapons, pole weapons or fist weapons. The amount of the different categories of armament reflects well the discoveries described by Jacques de Morgan in his publications. Spearheads and arrowheads are much more numerous. They are followed by the daggers, which include particular pieces with molded handle allowing many chronological comparisons. Knives, swords and axes occur in small quantities, and pikes and armour plates are almost absent.

The catalogue of forms is wide enough for each category of weapons. Materials are also quite heterogeneous. Copper alloys are the most widely used for making weapons, accounting for almost three quarters of the corpus. Iron is used too, mainly for spearheads, and there are also weapons made of stone and some bimetallic ones, copper alloy and iron. The materials used for the weapons' manufacture also provide good chronological indications. Nevertheless, it is necessary to be cautious as copper alloy weapons were still manufactured during the Iron Age. It is therefore normal to find a large majority of copper alloy artefacts. Among these artefacts, certain types of weapons were most commonly uncovered in Talysh tombs:

– *Arrowheads:* 106 arrowheads were discovered in Talysh, with a wide variety of shapes and materials. Almost all the arrowheads are made of copper alloy, but a small number from the Conu settlement are made of stone and obsidian. From a typological point of view, they are composed of two parts, a tang or socket and an ogival, triangular or biconvex point, simple or with barbs. The origin of obsidian arrowheads can be traced back to Armenia, where this type, which represents a masterpiece of obsidian cutting, is characteristic of the Karmir-Berd culture (third and last phase of the Middle Bronze Age in Armenia: 27th–16th centuries BC; Santrot, dir., 1996, p. 60). A batch of this type of arrowhead was also found in a tomb in the Horom necropolis in the Shirak region of Armenia. They are of a later date and this tomb dates their use to the Early Iron Age: 12th–9th centuries BC (Fichet de Clairfontaine, dir., 2007, p. 166–168).

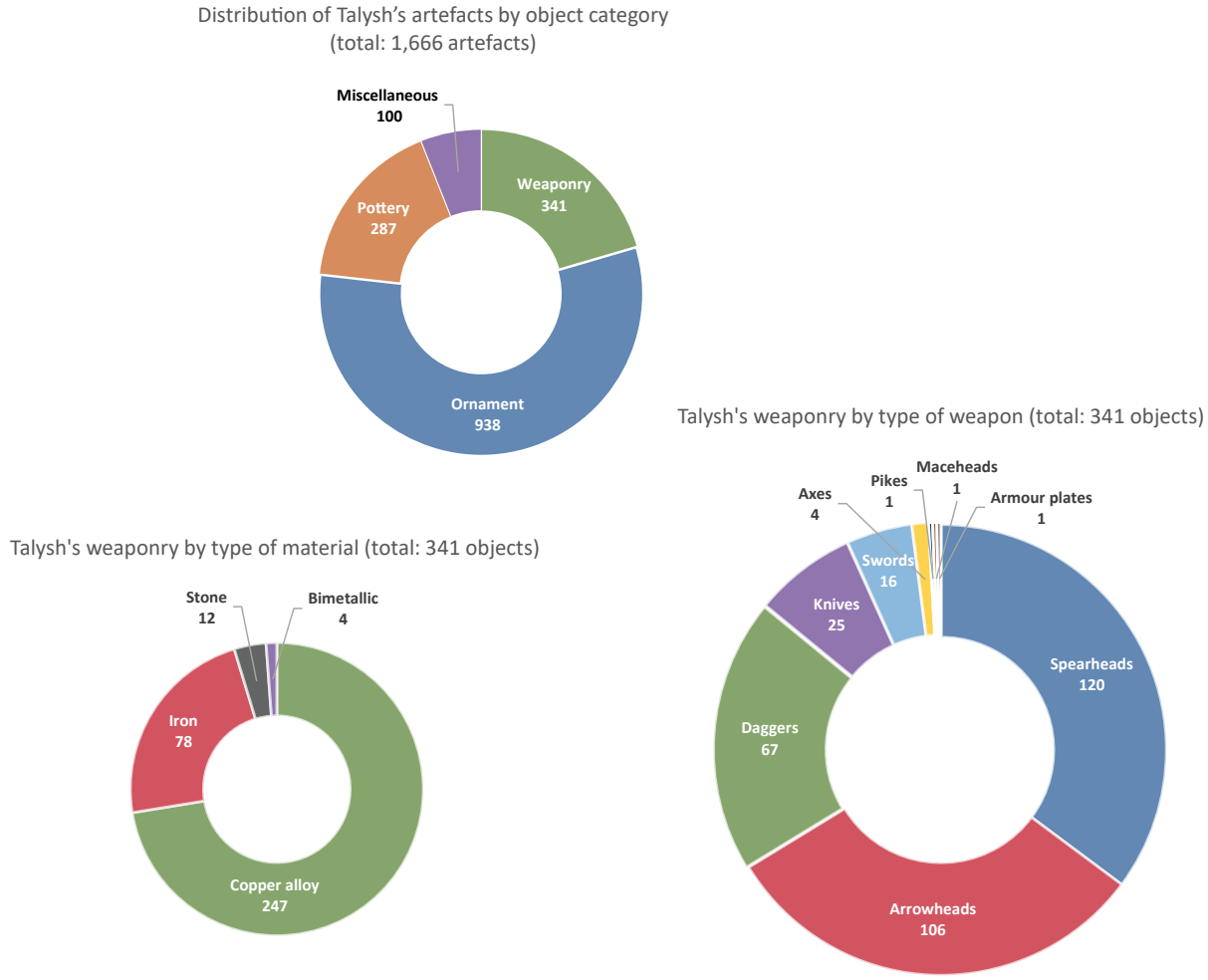


Fig. 2 – Distribution of artefacts discovered in the Talysh graves (1,666 objects, including 341 weapons).

– *Spearheads:* 116 are in MAN's collections and four were discovered during recent excavations in Lenkoran. The corpus of spears is fairly homogeneous, with very little variability in shape. Almost all the pieces are fitted with a socket: 115 specimens have been discovered in the Talysh graves and show little variability in size or blade shape. There is great parity in materials, with 58 spearheads made of iron and 62 of copper alloy. The most common form, with a biconvex blade (fig. 3, 4-6), is widespread in the Caucasus, where it is characteristic of the Early Iron Age from the 12th to the 9th century BC (Fichet de Clairfontaine, 2007, p. 171). Iron spearheads first appeared in Transcaucasia at the end of the second millennium BC. Examples, dated to Period II of the Final Bronze Age in Transcaucasia (12th–9th centuries BC) are known from Armenia, Georgia and Azerbaijan, from where they spread to northern and north-western Iran around the Caspian Sea and to the Koban Culture in the Caucasus (Curtis and Kruszynski, 2002, p. 65).

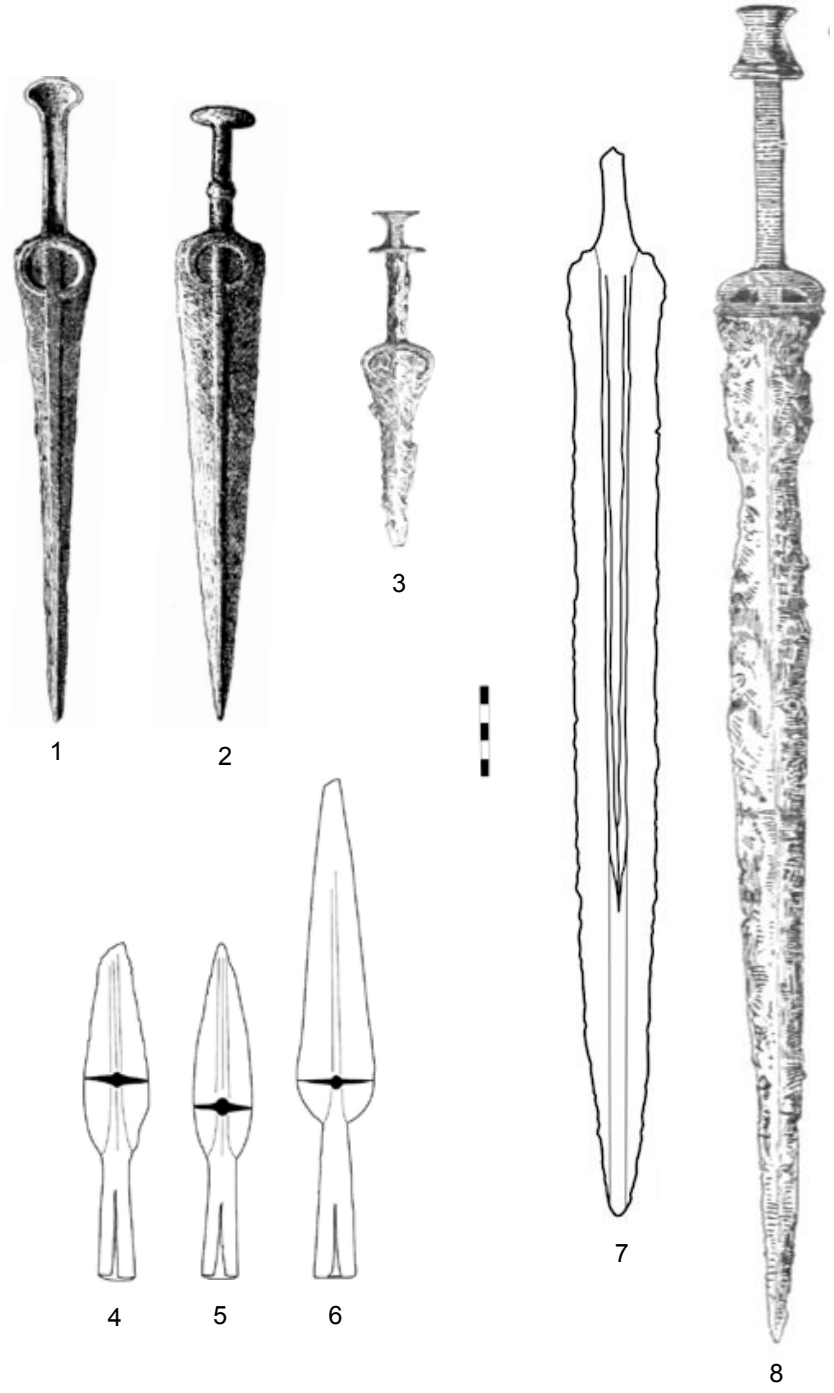


Fig. 3 – Weaponry discovered in the Talysh. 1-2: copper alloy dagger, Veri. 3: iron and copper alloy dagger, Chagoula-Derre. 4-6: iron spear head, Conu. 7: copper alloy sword, Conu. 8: iron and copper alloy sword, Chagoula-Derre. (1-2 and 8: after Morgan, 1896; 3: after Morgan, 1905; 4-7: after Haze, 2018).

– *Knives:* This category of material is defined by single-edged weapons, which must therefore be distinguished from double-edged weapons such as daggers or swords. There are only a few examples of such weapons in the Talysh graves, all varying in size and shape. Sixteen are made of iron and nine of copper alloy. Knives are very rare in funerary contexts, certainly because their status was not that of a weapon. Most of these objects were definitely everyday tools, and very few were actually used as weapons. Their rarity and poor state of preservation make them difficult to date typochronologically.

– *Daggers:* Daggers are by far the most common bladed weapon found in Talysh graves. There is little variability in the shape of the two-edged blades, which are mostly triangular, ogival or biconcave. Talysh daggers differ mainly in the way they are fitted, usually with a simple tang to which is attached a handle, probably most commonly made of wood, which has now disappeared. The other hafting technique, which is very common in this region, involves daggers with a metal handle cast and welded to the blade, or daggers cast in a single piece, handle and blade, in a mould. The corpus of Talysh daggers involved in our study includes 59 artefacts, the vast majority of which are made of copper alloy: 55 daggers in copper alloy, one in iron and three bimetallic, combining copper alloy and iron. Daggers with a tang were very common throughout the Near and Middle East from the third millennium BC. Triangular blades were particularly common in Transcaucasia during the Early Bronze Age (Gernez, 2007, p. 449). Regarding moulded-handled daggers, various works have already established typologies of daggers from north-west Iran, including some examples of the Talysh. I. N. Medvedskaya bases his typology on the shapes of the handles and classifies the Talysh daggers in the South Caspian context (Medvedskaya, 1982, fig. 9), while much more recently, B. Rafiei Alavi has proposed a typology of daggers based on the crescent-shaped guards very common innorth-western Iran and in Talysh (Rafiei Alavi, 2014). These daggers feature a wide variety of handle shapes. Thus, daggers with a non-functional crescent guard are the most represented in Talish (fig. 3, 1–3). These daggers show an evolution of the models with a functional crescent guard that appeared in Iran in the Late Bronze Age between 1600 and 1300 BC (Rafiei Alavi, 2014, fig. 3). Talysh models developed with the Iron Age, which saw their number increase considerably. Numerous examples can be found in north-western Iran at Marlik, Khurvin and as far as the Oman peninsula (Rafiei Alavi, 2014, fig. 9 and 10). All these daggers date back to the Early Iron Age, between 1300 and 1000 BC. Iron and bimetallic daggers appeared with the Iron Age II in Iran around 1000-800 BC (fig. 3, 3). Daggers with a non-functional crescent hilt were still in use, but in decreasing number. A new type of weapon appeared, on which the crescent-shaped guard became functional again (Rafiei Alavi, 2014, p. 14). These types of daggers are the most recent to have been discovered in Talysh tombs.

– *Swords:* Talysh swords are all made of copper alloy and all have the same type of fittings: a tang with or without a rivet. With no very specific morphological features, these swords are difficult to date precisely. A type of rapier that is elongated, fairly thin and has a very pronounced midrib is characteristic of Transcaucasia, where it developed during the Middle Bronze Age and up until the beginning of the Late Bronze Age (Abramishvili, 2001).

A bimetallic sword, unique in the Talysh corpus, was discovered at the Chagoula-Derre site and is the only one with a moulded handle. It consists of a large iron blade and a functional crescent-shaped copper alloy guard (fig. 3, 8). This sword is very similar to the bimetallic daggers described above and dates from the Iron Age II, between 1000 and 800 BC (Haze, 2018, p. 209).

THE ARCHAEOMETALLURGICAL STUDY: THE CASE OF DAGGERS

The archaeometallurgical study had two purposes. On the one hand, it was to determine precisely the elemental composition of the copper alloys used to cast the different types of objects. For that purpose, PIXE analyses were conducted on metal objects with the AGLAE Particle Accelerator (Accélérateur Grand Louvre d'Analyses Elémentaires). On the other hand, it was to better identify the hafting techniques. For that purpose, the C2RMF used X-radiography on 13 daggers, resulting in the establishment of a new typology of these daggers, based on this particular feature. This study would allow us to create a reference framework that could be further expanded in the future through similar analyses.

Experimental methods

Samples were analysed by PIXE, which is at present the most adequate method to conduct this study (fig. 4). The heritage value of the objects selected meant that the least invasive and destructive method possible had to be used. So the analysis had to be done directly on the surface (corrosion layers were carefully removed from a 1 mm diameter zone, prior to the analysis). The element list needs to be as large as possible, with for each element a low limit of detection (from 10 to 100 ppm). The PIXE technique using the AGLAE facility perfectly met our needs: it combines a good accuracy and an excellent sensitivity, thanks to the very low background of the spectra and the use of an energy selective Cobalt filter. The external micro-beam allowed us to focus the analysis only on the small zone of interest (50 micrometres diameter), thus avoiding most of the contamination problems due to corrosion.

Moreover, a series of X-rays have therefore been taken from the front, side and three-quarter views and allowed us to determine the different types of handling technique (fig. 4).

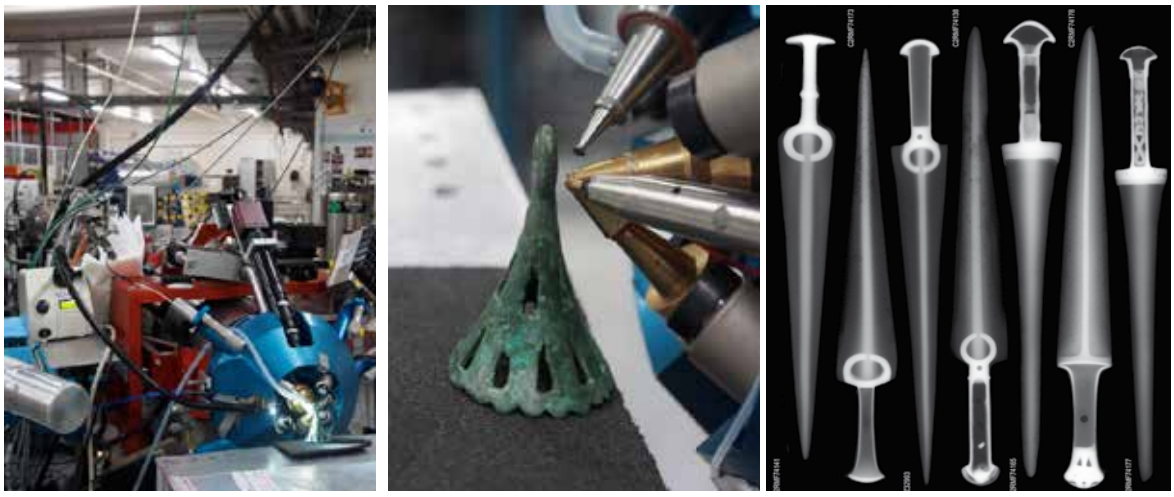


Fig. 4 – The various methods used during this study. PIXE analyses AGLAE and X-radiography.

The corpus

Analyses were conducted on 58 metal objects including 43 weapons (table 3). These objects come from sites in southern Azerbaijan (Mistan, Aspa Hiz, Amarat, Veri, Hovil, Cucu Tuk and Conu) and North-Western part of Iran (Agha Evlar, Tchila Khané, Chagoula Derré, Chir Chir and Khodja Daoud Köprü). These different sites are only known for their necropolises dating back to the Late Bronze Age and Early Iron Age, around 1600 and 1000 BC, that is to say a relatively long-time span. Among these artefacts we find ornaments such as bracelets, pendants, zoomorphic figurines, beads, pins or belt plaques, and weaponry such as spearheads, daggers and swords only discovered in funerary contexts.

Results

Alloy compositions

On the first graph (fig. 5), the artefacts are categorised here by type of ornament or weapon: bracelet, figurines, spearheads or daggers, each represented by a different symbol. On the abscissa is indicated the tin content in each object, and on the ordinate, the lead content. Thus, we can distinguish three categories of alloy:

– Low-tin bronze: with a tin content between 0 and 6 %.

– Bronze: with a tin content between 6 and 12 %.

– High-tin bronze: with a tin content exceeding 12 %.

Tin contents are extremely variable. For example, two spearheads are made of unalloyed copper, whereas others are made of bronze, in which the tin content ranges from 1 to 19 %

We see as well that most artefacts are made of unleaded bronze (Cu-Sn, with less than 2 % lead). Finally, the results also show that there is no simple correlation between the alloy composition and the type of artefact.

The second graph (fig. 6) is similar to the previous one, but at this point, the objects are being studied according to their place of discovery. And it is possible to note that there is no simple correlation between the alloy composition and the place of discovery.

Impurities pattern

This new figure (fig. 7) shows the level of impurities present in the 58 objects. Copper, lead, tin, antimony and arsenic, contents which are present in larger quantities for some artefacts, do not appear here. Each bar corresponds to one artefact and presents the cumulative content of different impurities. We see that the trace elements are also very heterogeneous, suggesting diverse metal provenance. For example, the spearhead numbered C2RMF74160 on the graph (MAN : 33760.03), has a high level of iron, whereas the other spearhead, numbered C2RMF74159 on the graph (MAN : 33742.02), while very similar in shape and alloy, exhibits a totally different impurities pattern.

Outline of the metal composition

To sum up concerning the metal composition of the artefacts from the Southern Caucasian collections of the MAN, we first may recall that we identified a large discrepancy both for the alloy composition and for the associated impurities pattern (fig. 8).

The whiskers plots here presented help us to give a better definition of the metal composition. The central square dot plots the median value for each chemical element, whereas the two whiskers define the interquartile range: half of the artefacts fit into this range. Small circles and stars represent the outliers.

The most common alloy composition consists therefore in a bronze containing virtually no lead, the tin content varying from 5 to 12 %, whatever the artefact type or place of discovery. At this stage, no attempt will be made to discuss the metal provenance, given how diverse the impurities patterns we recorded were. To be noticed

Site	N° MAN	Type	N° EROS base
Mistan (Az)	33998	Dagger	C2RMF74137
Aspa Hiz (Az)	33958	Dagger	C2RMF74138
Amarat (Az)	34003.01	Spearhead	C2RMF74139
	34003.02	Spearhead	C2RMF74140
Veri (Az)	33543/A	Dagger	FZ32993
	33543/I	Dagger	C2RMF74141
	33543/F	Dagger	C2RMF74142
	33539	Dagger	FZ33022
	33540.01	Dagger	FZ33023
	33540.02	Dagger	FZ33024
	33541	Dagger	FZ33025
	33554	Knife	C2RMF74143
	33537.04	Sword	FZ33040
Hovil (Az)	33983/A	Dagger	FZ33033
	33983.02	Sword	FZ33034
Conu (Az)	33856.02	Armour plate	C2RMF74147
	33865	Dagger	C2RMF74158
	33867	Sword	FZ33032
	33866	Dagger	FZ33031
	33742.02	Spearhead	C2RMF74159
	33760.03	Spearhead	C2RMF74160
	33742.03	Spearhead	C2RMF74161
	33742.01	Spearhead	C2RMF74162
	33743.02	Spearhead	C2RMF74163
	33868	Spearhead	C2RMF74164
Djuodji Kach (Az)	34028	Sword	FZ33036
Agha Evlar (Ir)	57938	Dagger	C2RMF74165
	57937	Dagger	C2RMF74166
	57940	Sword	C2RMF74167
	57942	Spearhead	C2RMF74168
Tchila-Khane (Ir)	57736	Dagger	C2RMF74171
	57740	Dagger	C2RMF74172
	57738	Dagger	C2RMF74173
	57734	Dagger	C2RMF74174
	57732	Dagger	C2RMF74175
	57727	Dagger	C2RMF74176
Chagoula-Derre (Ir)	57840	Dagger	C2RMF74177
	57841	Dagger	C2RMF74178
Shir Shir (Ir)	57857	Dagger	C2RMF74179
	57849	Dagger	C2RMF74180
	57856	Dagger	C2RMF74181
	57851	Dagger	C2RMF74182
Khodja Daoud Köprü (Ir)	57701	Sword	FZ33035

Table 3 – List of analysed weapons.

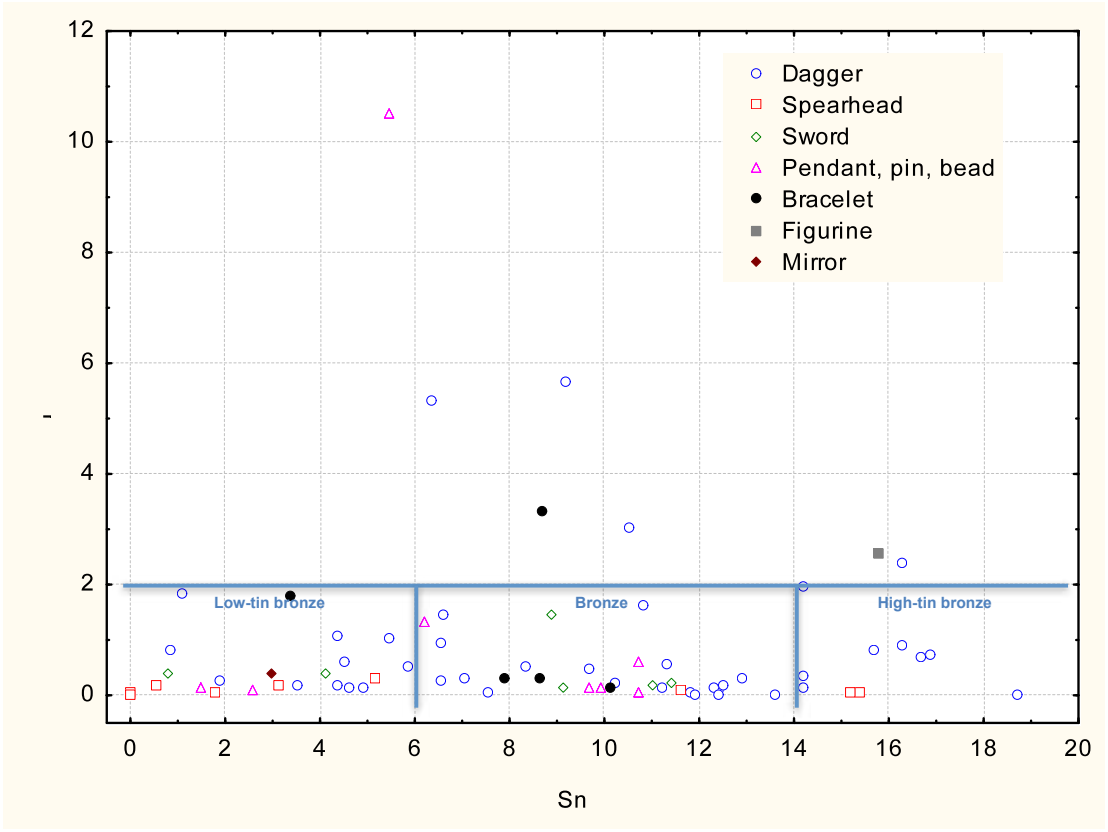


Fig. 5 – Alloy composition in relation to artefact types.

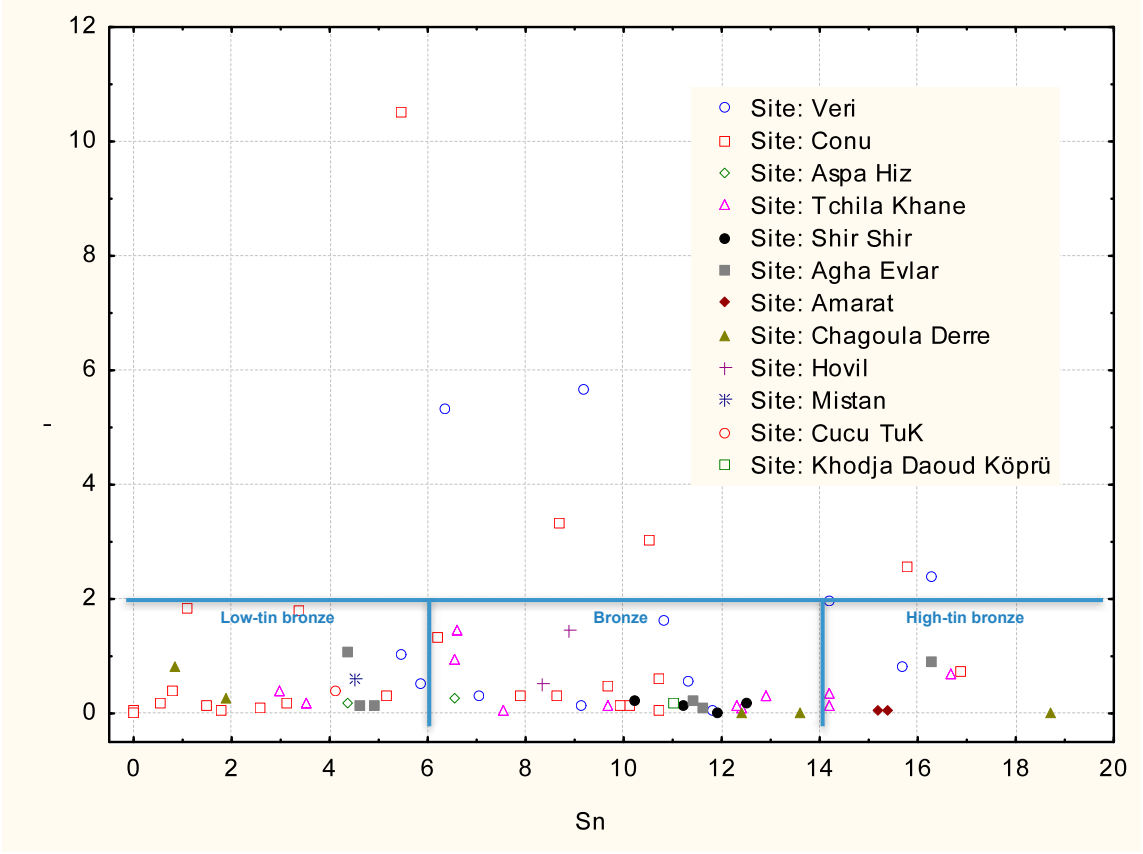


Fig. 6 – Alloy composition in relation to place of discovery.

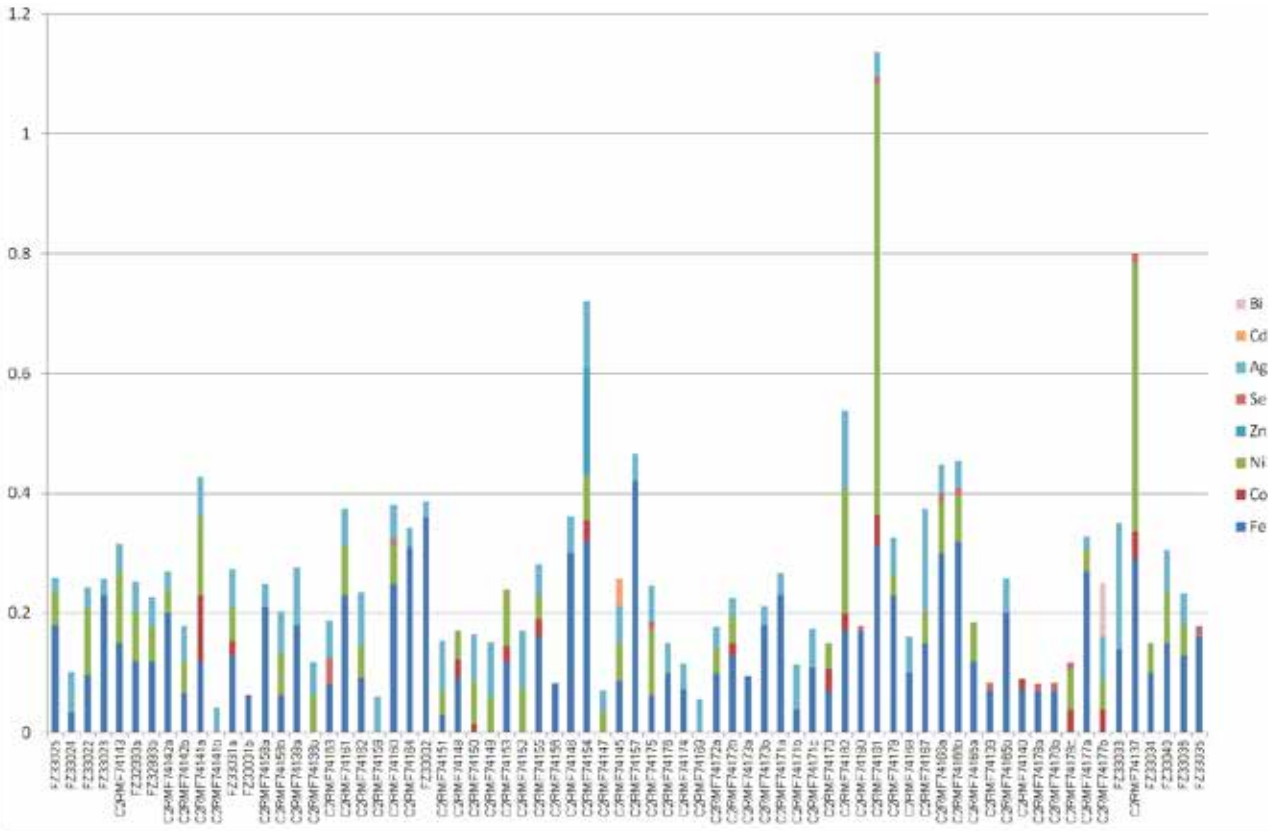


Fig. 7 – Trace elements in alloy compositions of every artefact (ornaments or weapons).

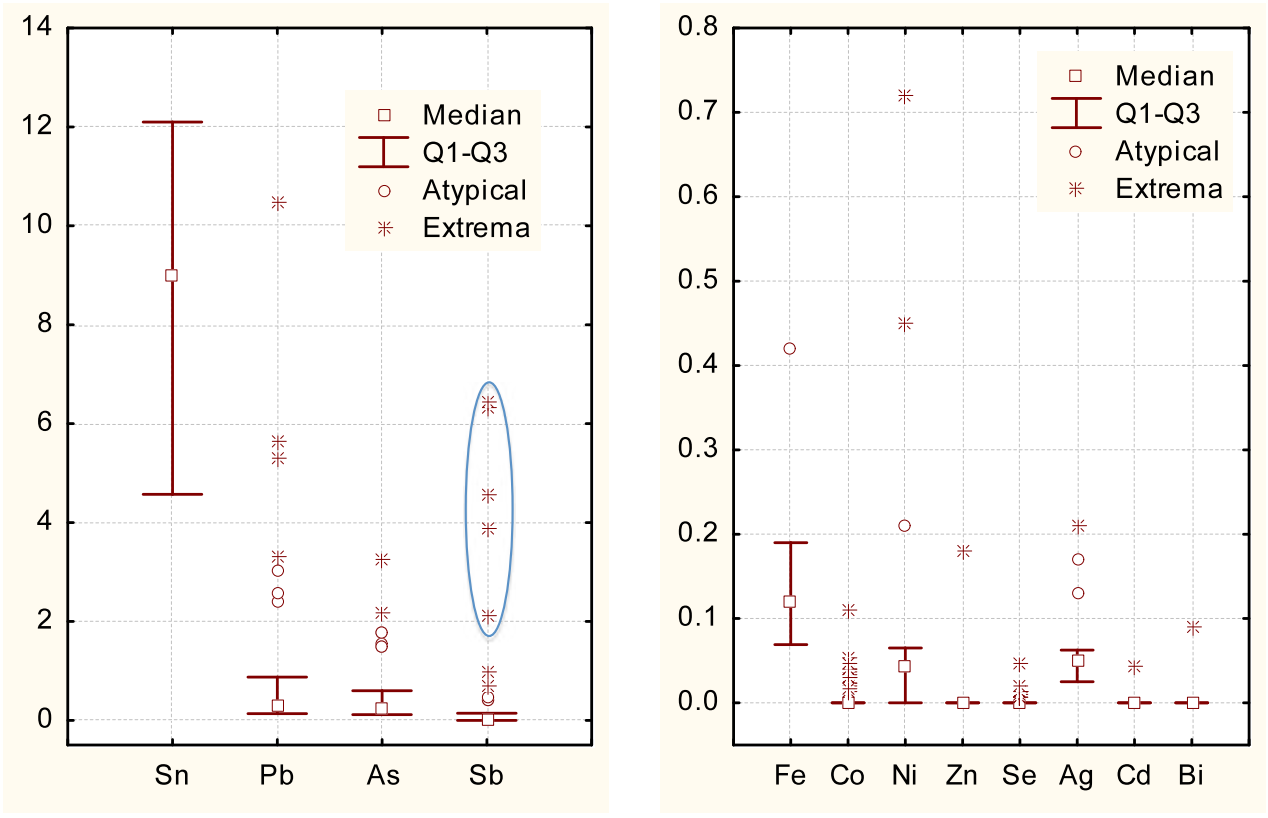


Fig. 8 – Southern Caucasian collections from the MAN: outline of the metal composition.

is the fact that some very high levels of antimony were detected: five artefacts contained more than 2% of antimony (up to 6%!). Since four of them are related to dagger handles, we will come back later to this point: we first need to give more details of the manufacturing technique used to cast the different daggers.

A focus on the daggers: alloy composition

Out of the 27 tested daggers, 13 daggers were tested by PIXE in two or three different locations, both on the blade and the hafting, in order to check the homogeneity of the metal composition, since it already appeared, as we have just seen, that they were cast in several pieces.

As a result (fig. 9), firstly there are the tin and lead contents and associated impurities, where high levels of antimony are particularly obvious for four handles. It is very apparent here that the alloy composition of the blades clearly differs from the handles:

– most of the blades are related to the Caucasian canonical bronze definition given, that is to say a bronze containing 5 to 12 % tin;

– extreme values of the alloy composition systematically refer to the handles (low-tin, high-tin, high-antimony).

A question then arises: did metallurgists want to achieve a metal polychrome effect, a yellow blade opposed to a red handle (with low-tin) or to a white handle (with high-tin, or with high-antimony)?

The contribution of the X-ray analysis

The X-radiography of the 13 daggers led us to establish a new typology of the daggers, based on the hafting techniques. We not only took X-rays from the front, but also from the side and from a three-quarter profile. This allowed us to determine four different types of hafting techniques (fig. 10).

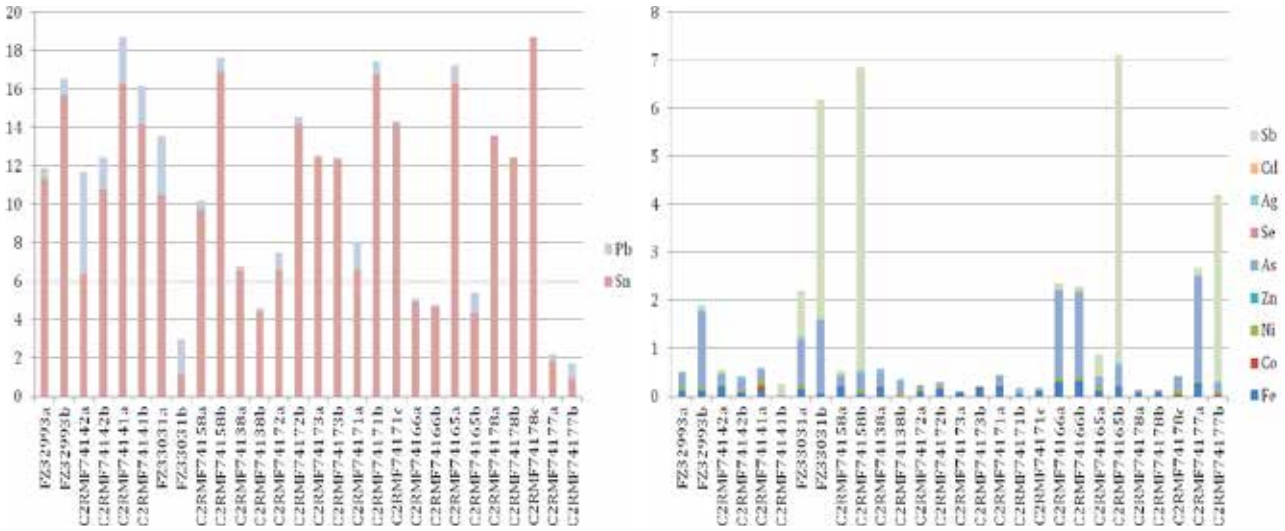


Fig. 9 – Several analyses have been conducted on each dagger (a, b, c) to compare the alloy compositions of the various parts (blade, handle, guard, pommel). Comparison of tin and lead levels (left) and level of impurities (right).

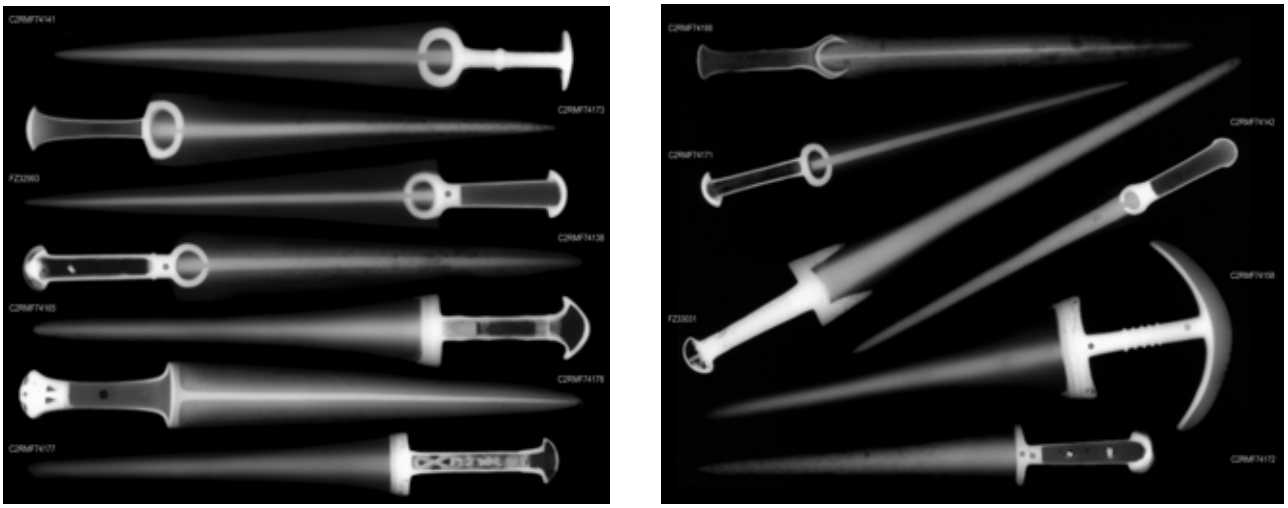


Fig. 10 – X-ray radiograph from the front side.



Fig. 11 – General view, radiograph and detail of type 1 dagger (Agha Evlar : 57937).

Type 1 (fig. 11): The dagger was cast in one piece, in a unique primary casting. We cannot see in fact any evidence of joining on the radiography, and the alloy composition is exactly the same at both locations tested. Only one dagger belongs to this category (Agha Evlar : 57937).

Type 2 (fig. 12): The dagger was cast in one piece except the pommel. During a primary casting, the blade, the guard and the grip were cast together, as one unique piece. Then during a secondary casting, the pommel was directly cast on the grip, using a lost-wax cast technique. On the radiograph we can see evidence of joining between the pommel and the grip but none between the guard and the blade. Only one dagger belongs to this category as well (Chagoula Derre : 57841).

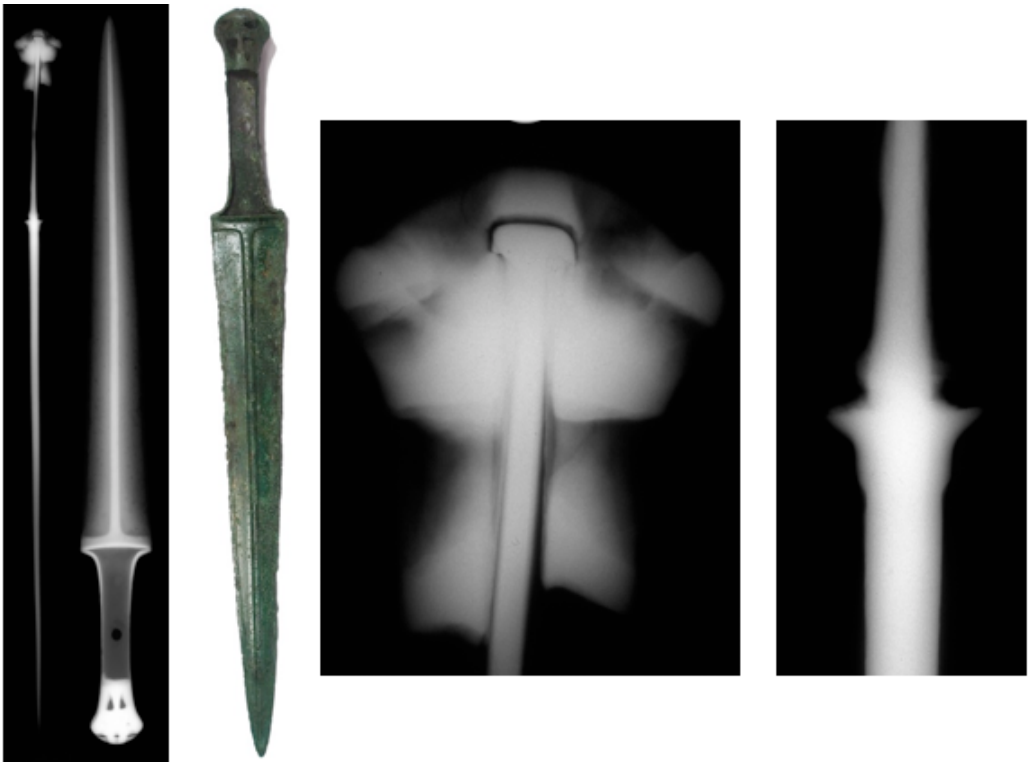


Fig. 12 – General view, radiograph and details of type 2 dagger (Chagoula Derre: 57841).

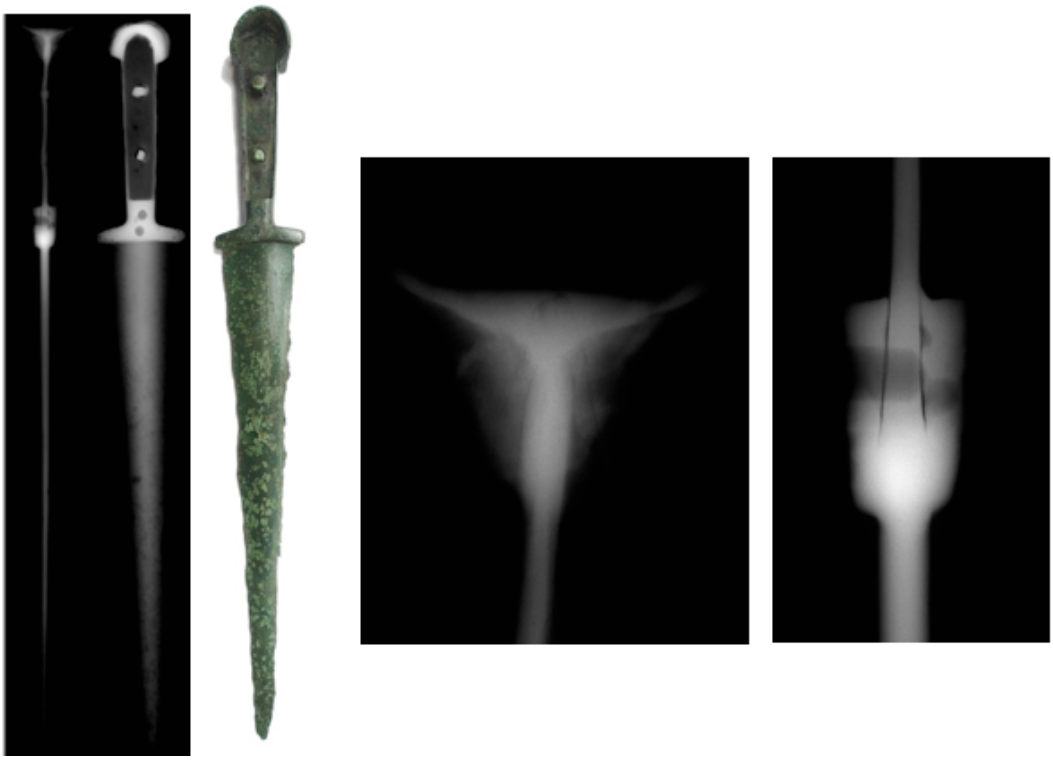


Fig. 13 – General view, radiograph and details of a type 3 dagger (Tchila Khane: 57740).

Type 3 (fig. 13): The dagger was cast in one piece except the guard and the pommel. During a primary casting, the blade and the grip were cast together. Then during a secondary casting, the guard and the pommel were separately cast on the grip, using a lost-wax cast technique. We can clearly see on the radiograph evidence of a join between the pommel and the grip and another between the guard and the blade. Five daggers belong to this category (Veri : 33543.A, 33543.F ; Tchila Khane : 57736, 57738, 57740).

Type 4 (fig. 14): The blade was shaped with a tang and obtained from a primary casting. The handle –that is

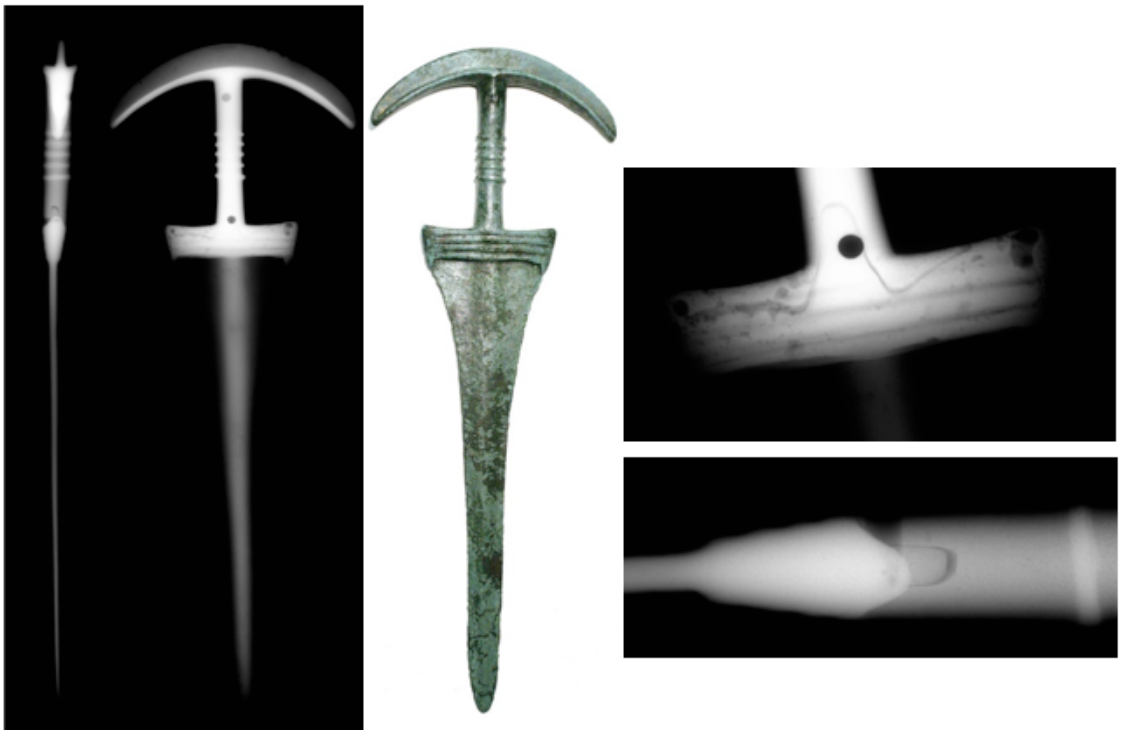


Fig. 14 – General view, radiograph and details of a type 4 dagger (Conu: 33865).

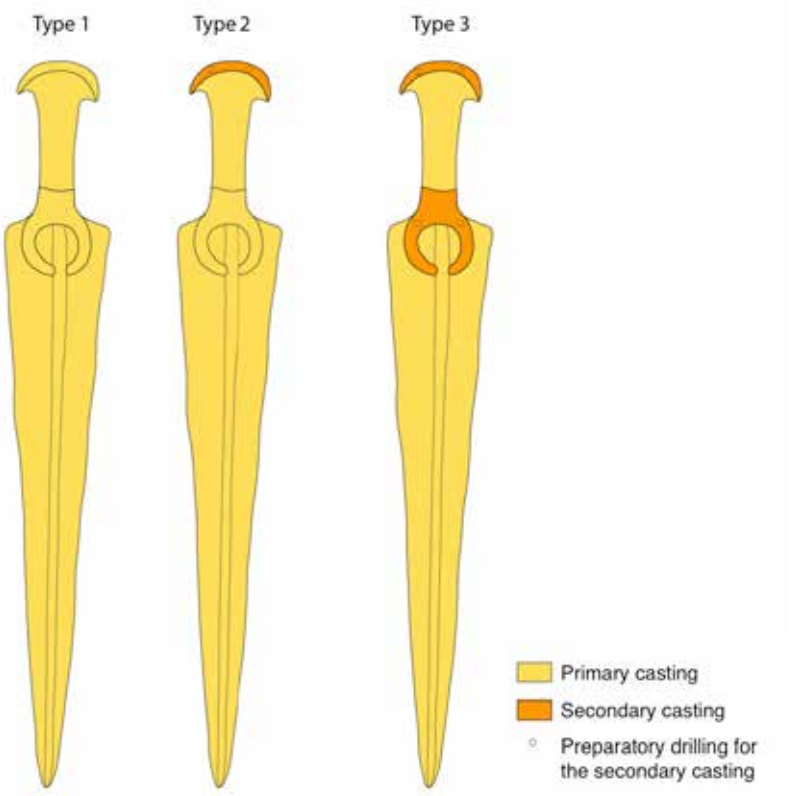


Fig. 15 – Primary casting and secondary casting for types 1, 2 and 3.

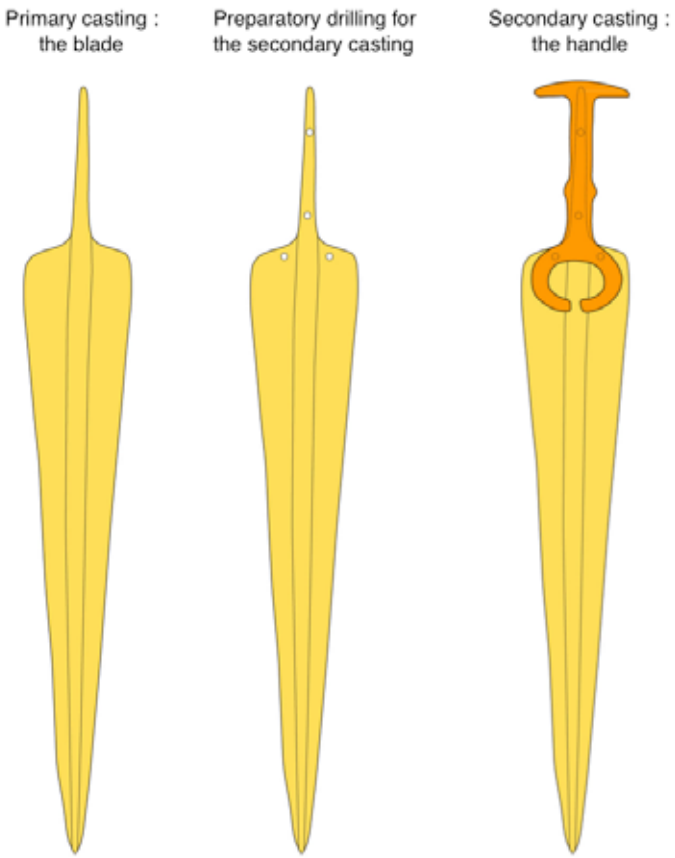


Fig. 16 – Primary casting and secondary casting for type 4.

to say a unique piece encompassing the guard, the grip and the pommel – was cast on the tang during a secondary casting. On the radiograph we can see here the tang inside the handle. This is the most common type, with 20 daggers of which only 6 still possess their grip (Conu : 33865, 33866 ; Veri : 33543.I ; Aspa Hiz : 33958 ; Agha Evlar : 57938 ; Chagoula Derre : 57840).

Various phases of manufacturing: patterns of primary and secondary casting

For types 2 and 3, preparatory drilling can be made on the guard and the pommel to prepare the secondary casting (fig. 15). This ensures that the secondary casting is held to the primary casting by mechanical means. In this way, assembly is inevitably successful, even if welding of the secondary casting to the primary casting is not achieved. For the assembly of the knob, when the preparatory drilling does not seem to be present on the radiograph, it seems obvious from observation that the knob is moulded during the primary casting to a very specific shape that can allow mechanical assembly during the secondary casting.

For type 4, the blade is cast with its fitting tang during a primary casting, then preparatory drilling is carried out on the tang and/or on the base of the blade (a part which is then covered by the guard) to ensure the fixing of the secondary casting on the primary casting (fig. 16).

CONCLUSION

These analyses by PIXE have allowed us to determine that there was a wide variety of alloy compositions, both in proportions of lead and tin and in the level of impurities. This great diversity unfortunately does not allow us to discuss the source of the metal. Nevertheless, it appears that the most common alloy composition consists of a bronze almost not containing lead and with a tin content varying from 5 to 12%, this regardless of the type of object or the place of discovery. This study has provided data that we can compare with the studies already carried out or bring in as a first reference to the geographical area of the Talysh Mountains.

Radiography carried out on the daggers also allowed us to identify four types of fitting characterised by the identification of primary and secondary casting during the manufacturing process. These X-rays, combined with PIXE analysis, which detected high levels of antimony in four handles, show a tendency among metallurgists to use two distinct alloys for making the same dagger, perhaps in order to obtain a metal polychrome effect.

In recent years, these types of archaeometallurgical studies have been developed in Iran and in the Caucasus. Studies have been conducted, for example in Iran, in the Luristan area, to determine the origin of the ores thanks to the chemical composition of artefacts (Begemann et al., 2008), or in the Caucasus in order to determine the origin of bronze and iron metallurgies.

There are similarities with some studies conducted in Iran, where, in Haft Tappeh, for the Middle Elamite Period (1500-1100 BCE), the variety of copper alloy composition shows that the metalworking may not have followed a specific process and that an uncontrolled smelting and alloying procedure has been applied. But we must also remember that the ore sources of Elamite metallurgy have not been identified yet (Oudbashi et al., 2012, p. 167). Moreover, in Sangtarashan Iron Age site, the analysis performed on 10 broken vessels shows that the variability of the tin content cannot be considered as an alloying pattern based on tin (Oudbashi et al., 2012, p. 167).

In the Caucasus, this kind of study, although still rare, has been multiplied in the last couple of years. So, studies have been carried out in Georgia to determine the emergence of iron metallurgy (Erb-Satullo et al., 2014) and in Azerbaijan to understand the origins of metallurgy from the end of the Neolithic period (Courcier et al., 2016). But these pieces of research are based on the study of metallurgical production areas. Here is the limit of our corpus which is only composed of objects coming from a funerary context. It will be necessary in the future to find out settlements and craft production areas in a region where only the necropolises have been documented.

Awaiting such discoveries, it appeared to us interesting to keep on studying bronze objects from a well identified and undisturbed burial context. In this regard, the metallic objects discovered in the graves excavated on the site of Monidigah in 2016 by the French-Azerbaijani archaeological Mission of the Lenkoran Valley, always within the NABIALLA program, were the subject of similar analyses. So, 20 copper alloy objects, ornaments and weapons coming from two clearly identified graves, were analysed by the same PIXE method. Although it has not yet been possible to exploit the results of these analyses, this new data, extending the sample in terms of the typology of objects and the variety of provenances, would make it possible to obtain more statistically significant results and would help to considerably improve the referential for the South Caucasus area.

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Making Bronze Age Solid-Hilted Swords: From *Chaînes Opératoires* to Craftspeople

Léonard Dumont

Abstract: Investigating the organisation of production of Bronze Age metalworkers is challenging because of the lack of direct archaeological traces related to bronze production. Workshops are scarcely excavated and are mostly known indirectly through waste pits containing leftovers from the production such as moulds fragments. Studying the context of production must therefore rely on indirect evidence coming from the artefacts themselves. One type of object can indeed be produced using different techniques. These technological choices are not only influenced by crafter's creativity: they also depend on socio-cultural factors. This makes possible the identification of production groups through common technological choices made at different steps of the chaîne opératoire, i.e. groups of metalworkers sharing common techniques and know-how. A recent PhD thesis by the author provides an overview of the production techniques of Bronze Age solid-hilted swords in Europe (Dumont, 2022). This paper aims at summarising the main results of this study. Using X-ray imaging techniques, such as radiography and CT-scan, as well as data from published studies, technological data of 634 swords in Europe out of 2,588 currently listed was collected. A technological classification framework was created to identify different chaînes opératoires. Using this new tool, it is possible to study of the evolution of the organisation of production of these swords throughout Bronze Age Europe. Three main phases are identified. The experimentation phase (1800–1450 BC) is characterised by several small-scale production units and a low technological standardisation. The monopoly phase (1450–900 BC) shows a stronger technological and stylistic standardisation. Swords may have been produced to order by few and centralised production units. Finally, the disruption phase (900–800 BC) sees the development of many different chaînes opératoires at the same time as a typological diversification. This matches a nuclearization of the production units linked to the emergence of new groups of users.

Keywords: Bronze Age, metallurgy, material culture, weaponry, *chaîne opératoire*, techno-typology

Résumé : L'étude de l'organisation de la production métallique de l'âge du Bronze est particulièrement complexe en raison de la rareté des traces archéologiques directement liées à cette activité. Les vestiges liés aux ateliers sont en effet extrêmement ténus et ceux-ci sont généralement connus de manière indirecte, grâce aux déchets (fragments de moules, restes métalliques etc.) provenant de fosses situées à proximité. À cela s'ajoute la rareté des moules en contexte funéraire, qui ne permet pas d'identifier les sépultures d'artisans métallurgistes. Ces artisans et leur organisation restent ainsi largement méconnus. Afin de pallier ce manque de données, l'étude indirecte des métallurgistes à travers les objets qu'ils ont produits est une solution. La production d'un même type d'objet peut en effet être réalisée de différentes manières, avec des choix différents pouvant être opérés à chaque étape de la chaîne opératoire. Ces choix reflètent la manière de faire de l'artisan, qui dépend de sa créativité personnelle, des caractéristiques de l'objet à produire, mais aussi du contexte socio-culturel dans lequel il évolue, avec par exemple l'influence de son apprentissage et des contacts avec d'autres artisans : c'est l'habitus. L'influence de facteurs socio-culturels sur les choix techniques faits par les artisans métallurgistes rend possible l'identification de groupes de production, c'est-à-dire de groupes de producteurs partageant les mêmes techniques et savoir-faire, grâce à l'identification de choix communs aux mêmes étapes de la chaîne opératoire. Sans présager des liens ou de la structure de ces groupes, ces choix communs suggèrent que ces artisans partagent un même habitus et peuvent donc évoluer dans des contextes culturels proches. L'étude des techniques de production à partir des produits finis peut donc apporter de précieux éléments afin de restituer l'organisation socio-économique de la production métallique protohistorique. Un récent travail de thèse par l'auteur propose une synthèse sur les techniques de production des épées à poignée métallique de l'âge du Bronze en Europe, qui permet de renouveler nos connaissances sur les artisans à l'origine de ces armes (Dumont, 2022). Cette contribution vise à rendre compte des principaux résultats de ce travail doctoral. L'étude des techniques de production des épées à poignée métallique de l'âge du Bronze ne peut se faire par le seul examen de surface. Les artisans se sont en effet efforcés d'effacer la majeure partie des stigmates issus du processus de fabrication. Des méthodes non invasives d'imagerie par rayons X ont donc été employées. En compilant les études déjà publiées employant ces méthodes et en réalisant

des examens inédits sur des armes provenant de France, de Belgique et des Pays-Bas, quelque 634 épées ont livré des données technologiques sur les 2 588 recensées en Europe. Ces données ont été employées pour l'élaboration d'une techno-typologie, c'est-à-dire d'une classification fondée uniquement sur des caractéristiques technologiques. Dix types techniques ont ainsi été identifiés. L'objectif était d'identifier les principales chaînes opératoires employées à l'échelle de l'Europe, durant toute la période. Ce nouvel outil offre un baromètre permettant d'évaluer la variabilité des techniques de production dans le temps et dans l'espace.
Trois phases sont ainsi identifiées dans la production des épées à poignée métallique de l'âge du Bronze. La première phase est celle d'expérimentation. Il s'agit de la période durant laquelle les épées à poignée métallique apparaissent et commencent à gagner l'ensemble de l'Europe, entre le Bz A2 et le Bz B (1800-1450 av. J.-C.). Bien que les données technologiques manquent pour pouvoir correctement évaluer la diversité des chaînes opératoires à cette période, il semble exister une importante diversité, tant technique que stylistique. Cette hétérogénéité traduit vraisemblablement l'existence de multiples petites unités de production, fabriquant des épées à petite échelle, peut-être sur commande.
La deuxième phase, dite de monopole, s'étend du Bz C au Ha B1 (1450-900 av. J.-C.). Elle se différencie de la phase précédente par le développement d'une nouvelle chaîne opératoire, appelée « principe de l'épée à fusée octogonale » (Achtkantschwert-Prinzip), qui s'impose en Europe centrale. Durant plus de cinq siècles, la quasi-totalité des épées à poignée métallique découvertes entre la zone nord-alpine et le bassin des Carpates sont produites de la même manière. Cette technique concerne exclusivement les épées de la tradition nord-alpine, formées des épées à fusée octogonale (Bz C), du type Riegsee (Bz D), à fusée à trois bourrelets (Ha A) et enfin à pommeau en coupelle (Ha B1). Malgré les évolutions stylistiques au cours du temps, la forme générale de la poignée change peu, tout comme son importante ornementation qui reste cohérente. En dépit de cette apparente standardisation, toutes sont des pièces uniques, individualisées par leur ornementation. Cette homogénéité technologique traduit une centralisation de la production au sein d'un même groupe de production. L'individualisation des productions pourrait correspondre à un système de fabrication à la demande et sur mesure. Finalement l'existence de copies montre que ces épées n'étaient pas accessibles à tous. Il pourrait ainsi s'agir d'un système de production contrôlée par un groupe social.
Finalement, la situation change abruptement durant le Ha B2/3 (900-800 av. J.-C.) : il s'agit de la phase de rupture. Si le principe de l'épée à fusée octogonale ne disparaît pas, il semble devenir marginal avec le développement de multiples nouvelles chaînes opératoires qui coexistent. Ces bouleversements technologiques s'accompagnent d'une diversification typologique ainsi que de changements dans la répartition des épées à poignée métallique. Il semble ainsi émerger de nouveaux groupes de production, peut-être en lien avec de nouveaux utilisateurs, dans ce qui semble être un contexte d'ouverture de la production et de l'utilisation de ces épées.

Mots-clés : âge du Bronze, métallurgie, culture matérielle, armement chaîne opératoire, techno-typologie.

Studying Bronze Age metalworkers and their organisation is a challenging task. Archaeological traces left by craftspeople producing bronze artefacts are indeed very scarce. First, very few metallurgy-related tools have been found in funerary contexts during the Bronze Age at a European scale (Nessel, 2013; 2019; Jockenhövel, 2018). Even when such tools were discovered in graves, the interpretation of the context regarding the activity of the deceased is extremely difficult (Molloy and Mödlinger, 2020, p. 173–176). Tools can also exceptionally come from so-called 'tool hoards' interpreted as the toolkits of a metalworker or a workshop, like the hoards from Génelard, France (Thevenot, 1998) and Murnau, Germany (Nessel, 2023). Yet, like graves, the interpretation of tool hoards is difficult. Indeed, these assemblages could be the result of a selection made within one or several workshops across a short or long period of time. They may therefore not be good representations of metalworker's organisation and know-how. Metalworkers are therefore almost completely anonymous for this period.

Furthermore, direct archaeological evidence of metallurgical activities is also rare (Molloy and Mödlinger, 2020, p. 183–184). Very few metallurgical workshops were excavated and well documented. The recently excavated workshops discovered in Montélimar (France) shows how tenuous the archaeological traces of this type of activity can be. The workshop was only detected thanks to the good preservation of Bronze Age ground layers and through the distribution of bronze artefacts production wastes (Cousseran-Néré et al., 2023; see also Mélin and Néré in this volume). If the ground layers were not preserved, there would have been almost nothing left for archaeologists to identify a workshop in this location. Remains and waste of metallurgical activities indicating the existence of workshops are usually discovered not in the workshop itself but in neighbouring waste pits. This way, many production sites have been identified in the British Islands (Adams et al., 2020) as well as in Scandinavia (Jantzen, 2008) thanks to the large number of clay moulds fragments (e.g. Mörtz, 2019). Depending on the good preservation of the metallurgical wastes, these sites can provide an overview of the different objects that were produced as well as a good documentation of the *chaîne opératoire*. This is for example the case with the fragments of moulds linked to a Late Bronze Age workshop in Aubervilliers (France), where pins and sword chapes were produced using clay moulds (Mélin et al. 2020; Mélin and Nerré, this volume). Archaeological traces of Bronze Age metallurgy therefore essentially consist in secondary contexts, whereas the actual workshops, i.e. the space where metalworkers were producing bronze artefacts, is usually missing. Addressing issues regarding the socio-economic organisation of production (seasonality, mobility, scale, level of specialisation etc.) is therefore complicated if not impossible.

Considering the lack of direct archaeological evidence left by Bronze Age metalworkers, studying them indirectly through the artefacts they manufactured can provide valuable inputs regarding the context of the production and its organisation. The manufacture of bronze

artefacts can indeed involve many different techniques at each step of the *chaîne opératoire*. An important technological variability is often observed, sometimes within one type of object and within one region or period (e.g. Schwenzer, 2004; Kienlin, 2008; Nordez, 2019). This variability is related to technological choices made by metalworkers. This way of making bronze objects vary according to the metalworkers' *habitus*. This means that technological choices are not only a matter of personal choices but are also determined by the societies and the communities crafters belong to (Mauss, 1936; Nørgaard, 2018, p. 255–265). It means that technological choices are not only made based on the characteristics of the manufactured artefacts but are also influenced by socio-cultural factors (Latour, 1992; Lemonnier, 1993). This variability can therefore be used to identify different production groups, i.e. "a number of producers sharing a technology […] without suggesting their relative independence from one another or implying the size or structure of the work group" (Costin, 1991, p. 33).

The identification of production groups is an essential step to investigate the organisation of production of Bronze Age metalwork. By comparing types defined using stylistic features and different *chaînes opératoires* matching different production group, it would be possible to develop a better understanding of the relations between production groups and communities using bronze artefacts. For example, identifying different *chaînes opératoires* within a single type of artefact would show that different production groups and probably different workshops were involved in the production of objects sharing similar stylistic features. Similarly, different types of objects produced with the same technological choices would indicate that production groups were able to adapt their production to match different styles and possibly different groups of users. Combining stylistic and technological investigation would therefore result in a better understanding of the organisation of production, also providing useful models to understand the relations between metalworkers and users, which is essential to study the modes of diffusion of bronze artefacts.

If the stylistic evolution of Bronze Age metalwork has been studied extensively since the end of the 19th century, large-scale and in-depth technological studies beyond a few artefacts remain relatively scarce (Schwenzer, 2004; Kienlin, 2008; Mödlinger, 2011; Lagarde-Cardona 2012; Bunnefeld, 2016; Nørgaard, 2018; Nordez, 2019; Adams et al., 2020; Iaia and Dolfini, 2021). A recent PhD dissertation provides new insights into the production of Bronze Age solid-hilted swords using X-ray imaging techniques (Dumont, 2022). This new study gives an overview of the evolution of production groups manufacturing solid-hilted swords throughout Bronze Age at a European scale. After presenting the state of the art on Bronze Age solid-hilted swords, the methods used to investigate production techniques and the *chaînes opératoires*, this article will introduce the main results of the dissertation regarding the organisation of production.

STATE OF THE ART

Typochronology

Bronze Age solid-hilted swords have been extensively studied since the end of the 19th century. Because of their overall good state of preservation, the diverse shapes and ornaments as well as their unequivocal identification, they have been valued by private collectors and early museums, and therefore by scholars interested in archaeology (Dumont, 2022, p. 27–30). Research on Bronze Age swords took a turn at the beginning of the 20th century, when archaeologists, especially in Germany, started systematic typological studies (e.g. Naue, 1903). This typological approach was dominant for most of the 20th century, with a strong focus on stylistic features. Ernst Sprockhoff was among the firsts to also develop a geographic approach. By producing lists and distribution maps for every type he identified, he tried to understand the connections between different regions during the Bronze Age at a European scale (Sprockhoff, 1931; 1934). To that end, he tried to identify the geographic origin of a type (*Heimat*, Sprockhoff, 1930, p. VIII) by making a relation between the geographic concentrations observed on distribution maps and the supposed production centres.

Sprockhoff's approach combining a typological classification based on stylistic features and distribution maps to identify the regions where workshops were located has been extensively used in archaeological literature until now. It is mainly based on two assumptions that are usually not explicitly mentioned. Sprockhoff's first assumption correlates spatial concentrations of artefacts of one type and the regions where it was produced. This is a misinterpretation of distribution maps, which only show where artefacts were abandoned and found. Distribution patterns are indeed influenced by the state of research in different areas, the preservation of the artefacts that can vary according to the environment, and the selection operated by Bronze Age populations in the artefacts placed in different contexts (Stjernquist, 1967; 1970; 1985). Even if the areas where artefacts were used could be determined from distribution map, there is still an important gap to identify production centres. In the Bronze Age, production and consumption areas are indeed not necessarily the same, as suggested by the discovery of moulds sometimes far from the concentrations of objects they were used to produce (e.g. Gambari et al., 2007; Nordez, 2019, p. 59; Lachenal, 2022).

The second assumption is that the productions of different workshops can be identified using the morphological and decorative variability of the objects. It assumes that metalworkers are in total control of the aspect of the artefacts they produce. For Bronze Age Europe, our knowledge of the organisation of production doesn't allow for a precise identification of the participants in the decision process leading to the adoption of certain shapes and ornaments. Craftspeople could be the only

ones deciding but the end users could also be involved, for example with 'attached specialists' producing upon command and sponsored by an elite controlling a part or the whole production (Costin, 1991, p. 11–13).

Although the relevance of this approach for identifying production centres has been criticised (Eggers, 1951, p. 23–27; Torbrügge, 1965, p. 75–79, 91; Neipert, 2006, p. 24–27), it remained widely used after the second World War. This methodology has usually been used implicitly, as the connection between typology, distribution patterns and production centres was probably considered trivial (Holste, 1953; Cowen, 1955; Müller-Karpe, 1961). H. Ottenjann is one of few explicitly stating that variations in decorations and distribution maps could be used to locate production areas (*Werkstattkreise*; Ottenjann, 1969). The exact same model has remained widely used in most publications, for example in the framework of the *Prähistorische Bronzefunde* series and beyond (e.g. Schauer, 1971, p. 181; Kemenczei, 1991, p. 36; Harding, 1995, p. 67; Quillfeldt, 1995, p. 197; Stockhammer, 2004, p. 100; Wüstemann, 2004, p. 78, etc.).

Although there is an abundant literature on Bronze Age solid-hilted swords, there is a striking lack of reflection about the significance of typological classifications regarding the organisation of production and the diffusion of artefacts. For these matters, studying production techniques seem to have more potential. There is indeed no doubt the production of swords was made by specialists, meaning technological choices are made by craftspeople alone, whereas this is not certain when it comes to stylistic features (see above).

Production techniques

Yet, production techniques have received far less attention than shapes and ornaments used to build typological classifications. The first technological investigations were performed in Germany at the end of the 1950s and during the 1960s with the development of X-ray radiography in archaeology (e.g. Drescher, 1958; Driehaus, 1959; 1961; Hundt, 1962; 1965). Most studies concern one or a few objects. Publications are therefore mostly descriptive, illustrating the potential of this new method. H. J. Hundt (1965) is the only one who tried to summarise the results of the X-ray examinations performed at the Römisch-Germanisches Zentralmuseum (Mainz, Germany). He identified different technological traditions in the production of Bronze Age solid-hilted swords and was one of the first to create a techno-chronology to summarise the evolution of techniques for a type of bronze object.

However, this trend to investigate production techniques using X-rays did not last very long. After the 1960s, D. Ankner is one of the only one publishing results of X-ray investigations on Bronze Age swords in line with H. J. Hundt (Ankner, 1977). This method was also not used much outside Germany. J.-P. Mohen installed a radiography device at the Musée des Antiquités Nationales, which was occasionally used to investigate bronze artefacts (Mohen, 1970; 1971; 1973). This was also the case in Switzerland where V. Rychner also investigated some artefacts, including a few Bronze Age swords (Rychner, 1977; 1987). Despite the potential offered by this new technique for investigating production techniques, it was never deployed at a large scale and remained only used for a few case studies. The trend initiated in Germany rapidly declined as other methods, especially elemental and isotopic analyses, grown in popularity from the 1980s onwards.

Since the early 2000s, we observe a renewed interest for imaging technique for investigating production techniques, especially for complex artefacts such as solid-hilted daggers (Schwenzer, 2004) and swords (Bunnefeld and Schwenzer, 2011; Mödlinger, 2011; Bunnefeld, 2016). This is correlated with the development of new techniques such as computed tomography (CT-scan), which enables the 3D reconstruction of the object's structure using X-rays. This is a powerful tool for investigating the *chaînes opératoires* of complex artefacts formed of several elements fixed together using different techniques, like swords (Mödlinger, 2008; Dumont et al., 2020; 2021). These new studies provide information on the manufacture of swords in northern (Bunnefeld, 2016) and central Europe (Mödlinger, 2011). The goal of my dissertation was to investigate western European swords in order to fill this gap in the history of research and then propose an overview of the production techniques and their variations in time and space at a European scale (Dumont, 2022).

METHODS

Surface observations

The technological investigation starts with the observation of the objects' surfaces. On some artefacts, traces of the production process can indeed remain visible. This is for example the case of the Late Bronze Age antenna swords from the Vénat (France) hoard (fig. 1), one of the biggest Bronze Age hoard discovered in France (Coffyn et al., 1981). The hilt of this sword shows important porosity with many blow holes visible on the surface, resulting from gas trapped in the bronze during the casting. There are also several breaches in the bronze structure showing it was not cast in one piece but rather in at least four steps, each casting being made on the top of the previous one. This technique is known as over casting or secondary casting. The surface of the pommel also carries information regarding the casting technique. The rim around the holes close to one of the antennae as well as the transition between the two castings of the pommel suggest they were made using lost-wax casting.

However, the sword from Vénat is an exception. The important porosity indicates the sword may be a miscast, selected to be abandoned in the hoard rather than to be melted down, although the cutting edges seem to have

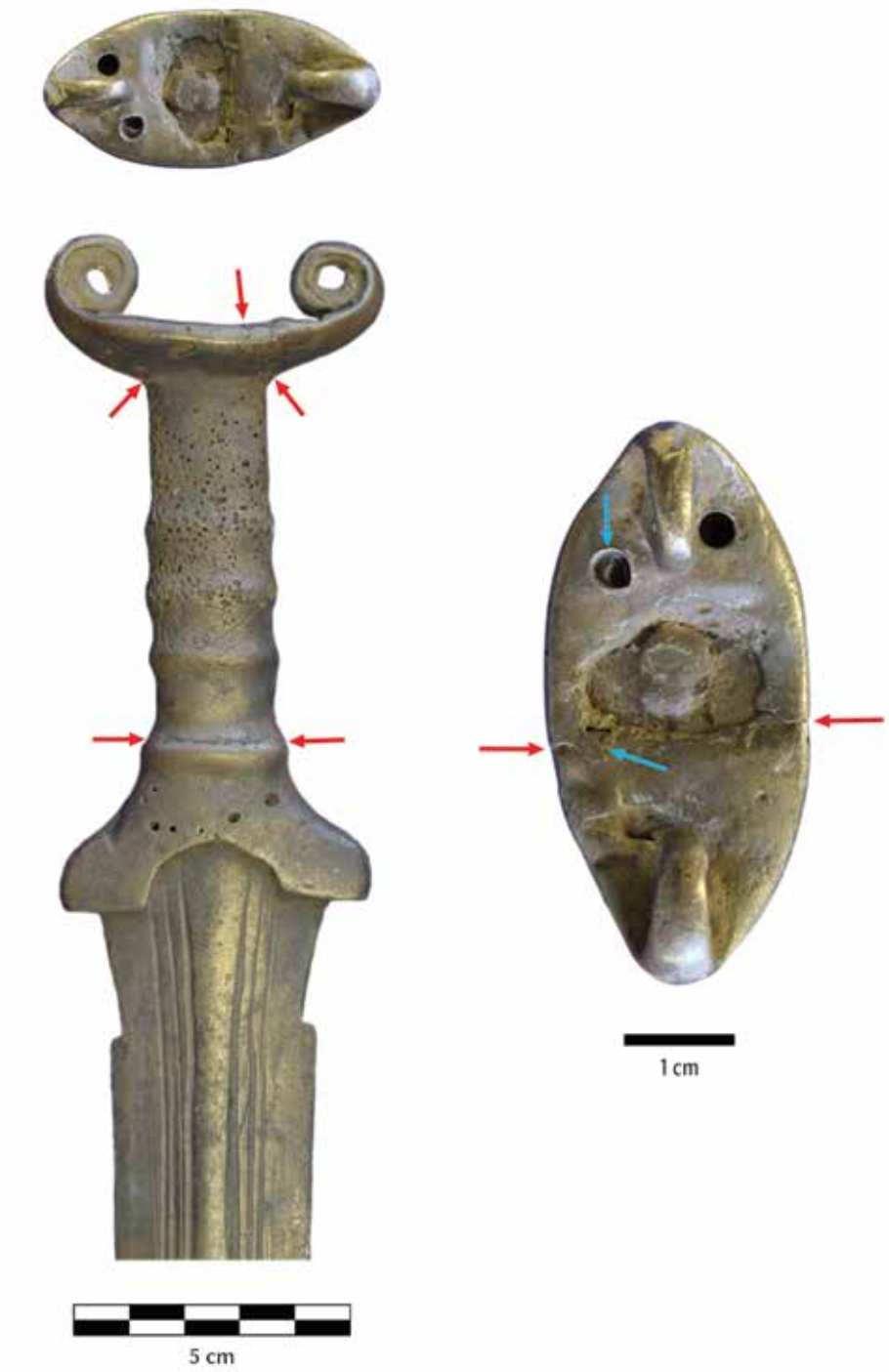


Fig. 1 – Hilt of the antennae sword from Vénat (Saint-Yrieix-sur-Charente, France). Red arrows indicate breaks in the hilt resulting from multiple castings. Blue arrows points at the traces of wax working on the pommel. © L. Dumont..

been sharpened. Although casting mistakes are precious for understanding casting techniques, they are scarcely discovered. Most Bronze Age solid-hilted swords were carefully crafted and finished, erasing most of the traces from the production process. There are therefore less traces visible compared to other types of bronze objects with a rougher finish, such as axe heads (Kuijpers, 2017). The ornamentation patterns can also be used to investigate production techniques (e.g. Berger, 2012; Nørgaard, 2018), but most swords found in Western Europe are undecorated.

We must therefore find other ways to reconstruct the *chaînes opératoires* and identify different technological choices revealing the different production groups behind the manufacture of Bronze Age solid-hilted swords. Invasive methods, such as metallographic analyses giving information on post-casting treatments (e.g. Kienlin, 2008; Kuijpers, 2017), or elemental as well as isotopic analyses (e.g. Mödlinger, 2011; Ling et al., 2019;

Mödlinger et al., 2021), were ruled out considering the difficulty to sample such precious artefacts. We rather chose to focus on non-invasive X-ray imaging techniques to investigate the casting and fixation techniques used to manufacture solid-hilted swords.

Radiography

Radiography is based on the ability of X-rays to pass through the matter. X-rays are light, it is therefore possible to use them to produce images, either with an analog film or a detector producing a digital image. As X-rays are attenuated according to the materials they go through and their thickness, the exposition of the film or detector varies. It produces a grayscale image with variations in the grey intensity reflecting the structure of the investigated artefacts. As it is widely used in different context (medicine, industry, heritage etc.), it is the most accessible technique to investigate production techniques in a non-invasive way. It is indeed relatively cheap, and it is easy to find a laboratory to perform this type of analysis, whether it is specialised in heritage applications or not.

Despite the advantages and potential of this method for reconstructing the *chaînes opératoires* of Bronze Age metalwork, it also has limits, especially in the case of very complex artefacts formed of several elements fixed using different techniques. As the images produced using X-rays are in two dimensions, several overlapping elements can produce images that are very complicated to interpret. This is the case of the Late Bronze Age Auvernier sword from L'Épineuse (Vénarey-lès-Laumes, France). The X-ray (fig. 2) of the lower part of the hilt is easy to interpret: we clearly see the outline of the tang, the part of the blade the hilt is fixed on, and the hilt completely includes it without any room between both parts. The outline of the tang remains visible, and many pores are located at the interface, meaning that the hilt was produced by secondary casting directly on the top of the tang. The upper part of the hilt is more complex, making the interpretation more complicated. There seems to be a shallow part in the central part of the hilt with two rivets, the depression being covered by a thin sheet of bronze. Although nothing is visible on the surface, there are breaks in the metal visible on the X-ray suggesting the upper part of the hilt involved multiple castings. First, the upper part of the grip was cast over the lower part. It is hollow in its centre and a trapezoidal bronze piece seems to be inserted in it. The lower part of the pommel was then cast over the grip. The upper part of the pommel was probably cast separately and fixed on the top of an organic piece that is no longer preserved. The fixation seems to be made with two short bronze rods on each side of the pommel. An explanatory drawing regarding the interpretation of the X-ray is provided on fig. 2. This interpretation remains hypothetic as the 2D image resulting

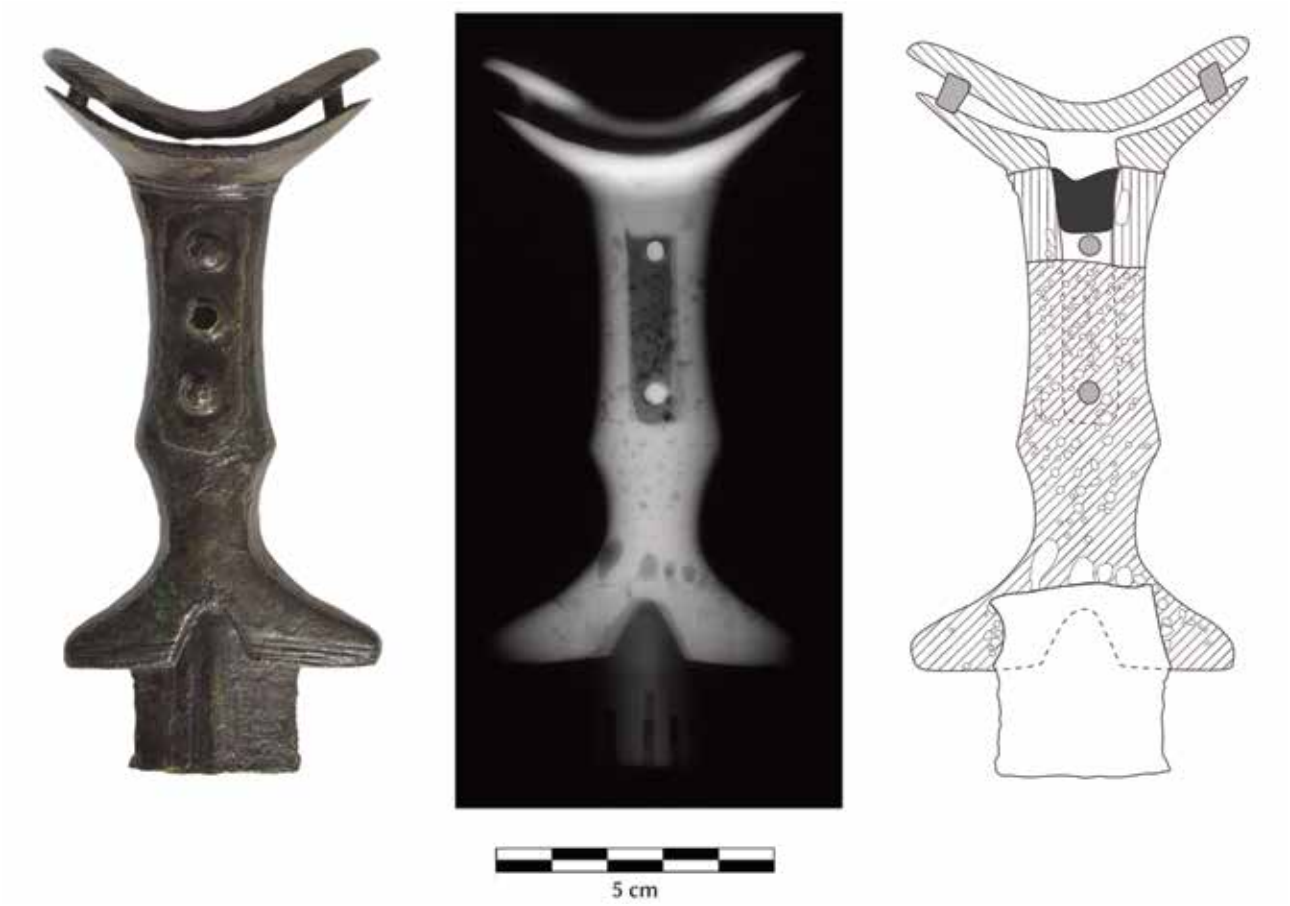


Fig. 2 – X-ray of the L'Épineuse sword's hilt (Vénarey-lès-Laumes, France). © E. Lambert, L. Dumont.

from the radiography doesn't allow for a clear understanding of the upper structure of the hilt.

CT-scan

CT-scan is an X-ray-based imaging technique relying on digital radiography to produce a 3D reconstruction of the investigated samples, including their inner structure. It consists in performing multiple X-rays of the same object, which is each time slightly rotated. By collecting multiple projections of one artefact under different angles, it is possible to reconstruct cross-sections. By stacking them up, the volume and structure can be digitally reconstructed in a totally non-invasive way. For investigating solid-hilted swords production techniques, we used high-resolution computed tomography (µCT) of the hilt area, mostly at Ghent University Centre for X-ray Tomography (UGCT). µCTs were performed using the HECTOR (High Energy CT Optimised for Research) setup (Masschaele et al., 2013). It is equipped with a X-ray WorX XWT 240-SE microfocus source which was operated at 220 kV and 60 W. A 1 mm copper filter was placed on the X-rays source to minimize beam hardening artefacts. 1,401 or 1,501 projections were acquired with a 1s acquisition time on a Varex XRD 4343 flat panel detector with a 2,880 × 2,880 pixel matrix or on a PerkinElmer 1620 CN3 CS flat panel detector with a 2,024 × 2,024 pixel matrix, enabling a reconstruction with an average voxel size of 80 µm.
CT-scan allows for a non-invasive technological investigation by revealing the hilt structure in two and three dimensions. It provides information regarding the casting of this part, its quality and the fixation technique(s) used to fix the hilt to the blade. One of the swords found in the Rhône river in Grigny (Rhône, France) shows the potential of this technique (fig. 3). The 2D cross-sections show the hilt was cast over the tang, whose outline remains visible. It also shows hollow parts on the central part of the grip and within the pommel that were not visible from the outside, probably filled by corrosion products. It shows this hilt was originally made by a combination of bronze and organic materials inlayed in the grip and the pommel. They are not preserved anymore but CT-scan clearly shows the difference between uncorroded bronze and corrosion products, revealing the structure of the hilt invisible from the surface. CT-scan can also be used to visualize hidden surface, like the surface of the tang



Fig. 3 – Photo and CT-scan of the hilt of a sword from Grigny (France). © I. Josipovic, L. Dumont.

located under the hilt, which can carry production traces or even counting marks left by the metalworker (Dumont et al., 2021).

CHAÎNES OPÉRATOIRES

Techno-typology

Using the different methods presented above allows for the identification of different *chaînes opératoires* corresponding to different technological choices made in the manufacture of Bronze Age solid-hilted swords. To that end, a techno-typological framework was created (fig. 4) based on 634 swords investigated using X-ray imaging techniques, out of 2588 listed in Europe (Dumont, 2024). This classification framework consists in three main types of swords, according to the type of hilts they are equipped with: full (EPP), hollow (EPC) or with a flanged tang framed with bronze pieces (ELCM). There are also semi-metallic hilts whose structure is made partly of bronze and partly of organic materials (type EPSM) which will not be discussed in this article as they are scarce and mostly limited to northern Europe.

Methods used for investigating production techniques do not allow for the identification of many different *chaînes opératoires* for full hilts (EPP). They are simply divided in two types: the ones cast in one piece with the blade (EPP1) and the ones produced by secondary casting over the tang (EPP2). X-ray based imaging technique enable the identification of a stronger technological diversity for hollow-hilted swords (EPC). Two features are used to identify technological types. The first is the shape of the hollow part of the hilt, which depends on the core it was cast on (see below). This core can replicate the shape of the hilt (EPC1) or the shape of the tang of the blade it is associated to (EPC2) or be independent (EPC3). The second feature is the shape of the tang, which influences the way the hilt is fixed to the blade. The tang can be short (inserted only inside the guard), bipartite (inserted inside the guard and the grip) or rod-like (narrow tang going all the way through the hilt from the guard until the pommel). This classification therefore takes into account the design of the hilt, how it is cast and how it is fixed to the blade. As only 5 swords belong to the ELCM type, characterized by a flanged tang framed with bronze pieces (Dumont, 2024), no further divisions were made.

Of course, other features may have been included in this classification frameworks. Some of them were deliberately excluded, such as the number of rivets, which can vary during the life of the object, for example if it had to be repaired. The goal of the techno-typology is also to identify the main *chaînes opératoires* and technological variations at a European scale, and not to provide a systematic and comprehensive description of all techniques. Only features that could be well observed and understood using X-ray imaging techniques were therefore included.

Although we cannot provide here an in-depth description of every single technological type identified, we will describe below the main ones encountered in Europe and their principal features.

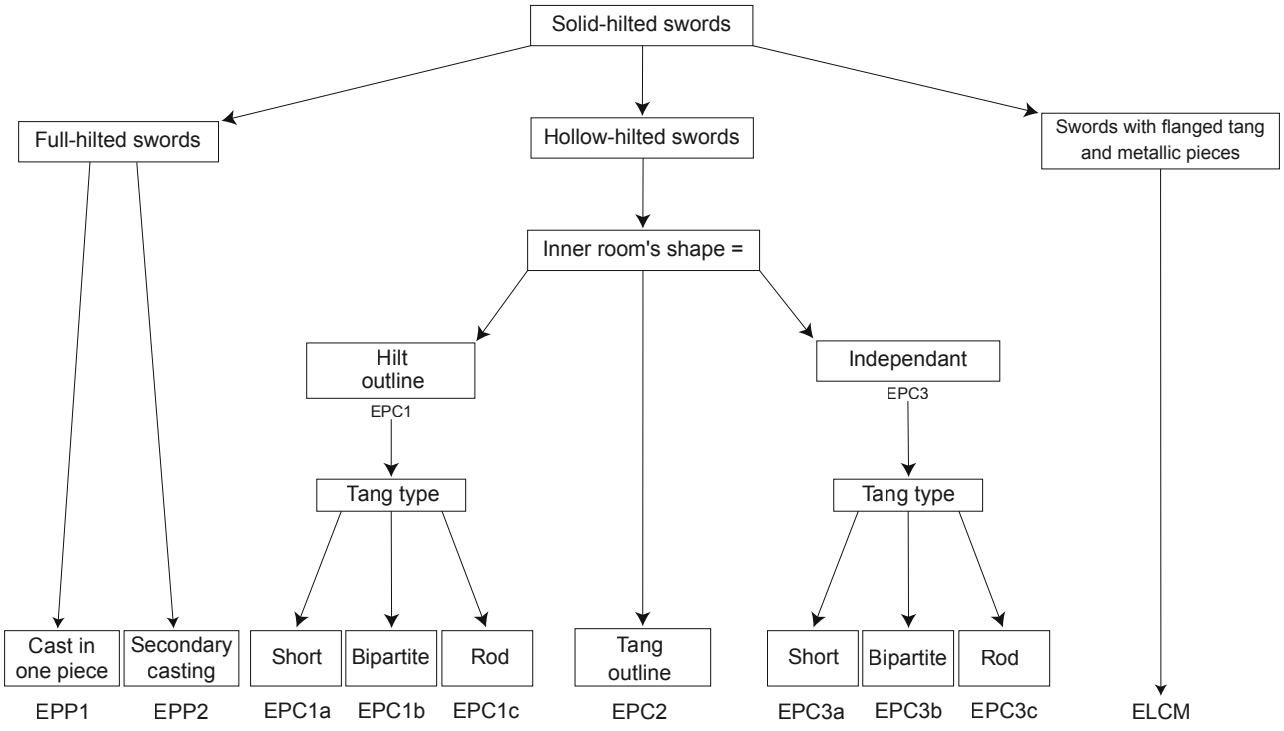


Fig. 4 – Technological classification framework of Bronze Age solid-hilted swords (Dumont, 2022).

Full hilt

Unlike hollow-hilted swords whose blade is inserted within the hilt by an opening at the base of the guard, swords equipped with a full bronze hilt are characterised by the absence of room within the hilt. These totally solid hilts can be achieved twofold: by casting the hilt and blade together as a single piece (type EPP1), or by casting the hilt directly over the tang of the blade (type EPP2). The first option is very uncommon among European Bronze Age solid-hilted swords. Only 6 swords produced this way are currently identified in Europe using X-ray imaging techniques. Most of them belong to the Prejmer type. These swords are known to be imitations of three-ribbed and cup-shaped pommel swords during Ha A and Ha B1 (ca. 1200–950 BC) and they are mostly found in eastern central Europe (Vachta, 2008; Novotná, 2014, p. 74).

Most full hilts are produced by secondary casting, meaning by casting the hilt directly over the top of the blade. This technique is easily identified as the outline of the tang over which the hilt is cast remains visible (figs. 2 and 3, see also infra fig. 6, EPP2). The temperature of the bronze as well as its quick cooldown after the casting does not allow for a weld between both parts. The fixation is therefore done by mechanical contact between the hilt and the tang. In some cases, notches or holes in the tang enable a strong fixation as the metal flows withing these parts, preventing any separation. In other cases, such features are not detected. Using a blade equipped with a short and narrow tang, this may lead to a weaker fixation. Porosity located at the interface between the hilt and the tang is also typical of this technique. When casting the hilt over the blade, the melted bronze gets in contact with the tang, producing a faster cooldown and solidification. Gas produced during the operation can then stay trapped within the metal. Secondary casting can be made using different types of mould. Permanent moulds, for example in stone or in bronze, can be used, but they require a perfect fit with the top of the blade. Lost-wax casting was probably widely used because of its versatility, as the wax model can be adapted to any kind of tang. However, X-ray imaging techniques do not enable the identification of the precise casting technique. All swords with a secondary cast hilt are therefore included in type EPP2, although they may correspond to slightly different *chaînes opératoires*.

Hollow hilt

Swords equipped with a hollow hilt show a greater technological variability than the ones with full hilts as imaging techniques allow for a better characterisation of their production techniques. The choice was made to classify them according to two features: the shape of their hollow part, which depends on the way they were cast, and the shape of the tang they are fixed on, which influences the fixation techniques.

The production of hollow hilts is made with mould including a core. When bronze is poured inside the mould, it is filling the space between the core and the outer part(s). After the casting, the core is removed, leaving a hollow room inside the hilt. This type of casting over a core can be done using the lost-wax technique (fig. 5). It is also possible to use a mould made of stone or bronze, like the one from Erlingshofen (Germany, Bavaria). This reusable bronze mould is made of two parts each one with half the hilt imprint. When joined together, the shape of the hilt is complete and a bronze core is inserted between both parts (Overbeck, 2018, p. 81–82).

The shape of the core used during the casting and therefore the shape of the hollow part of the hilt is an important feature, as variations can be connected to different casting techniques and can have an effect on the way the hilt is fixed to the blade. If the shape of the core reproduces the outline of the hilt (type EPC1), it is usually wider in central part of the grip or in the pommel than at its base (fig. 6, EPC1a, EPC1c). This means the core cannot be removed and reused after the casting, unlike the Erlingshofen mould. A single use core, typically made of clay and destroyed after the casting, must therefore be used. On the contrary, when the core shape does not match the outline of the hilt nor the shape of the tang (type EPC3), it can simply be conical (fig. 6, EPC3b) and

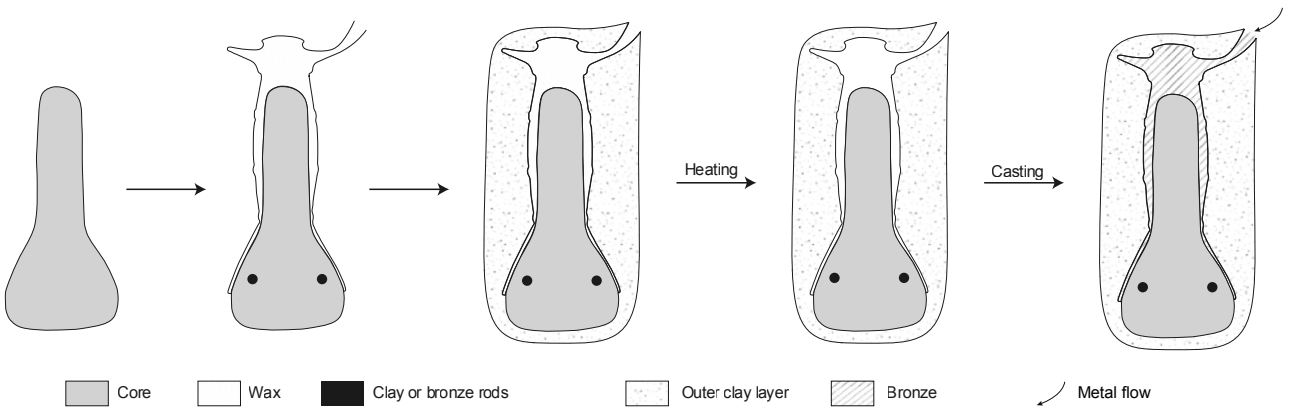


Fig. 5 – Main steps of the production of a hollow hilt by lost-wax casting. © L. Dumont.

reused for multiple castings. Finally, the hollow part of the hilt can also exceptionally match the shape of the tang (fig. 6, EPC2). In that case (type EPC2), the hilt needs to match one specific blade, whereas types EPC1 and EPC2 are more versatile as they can match different types of blades.

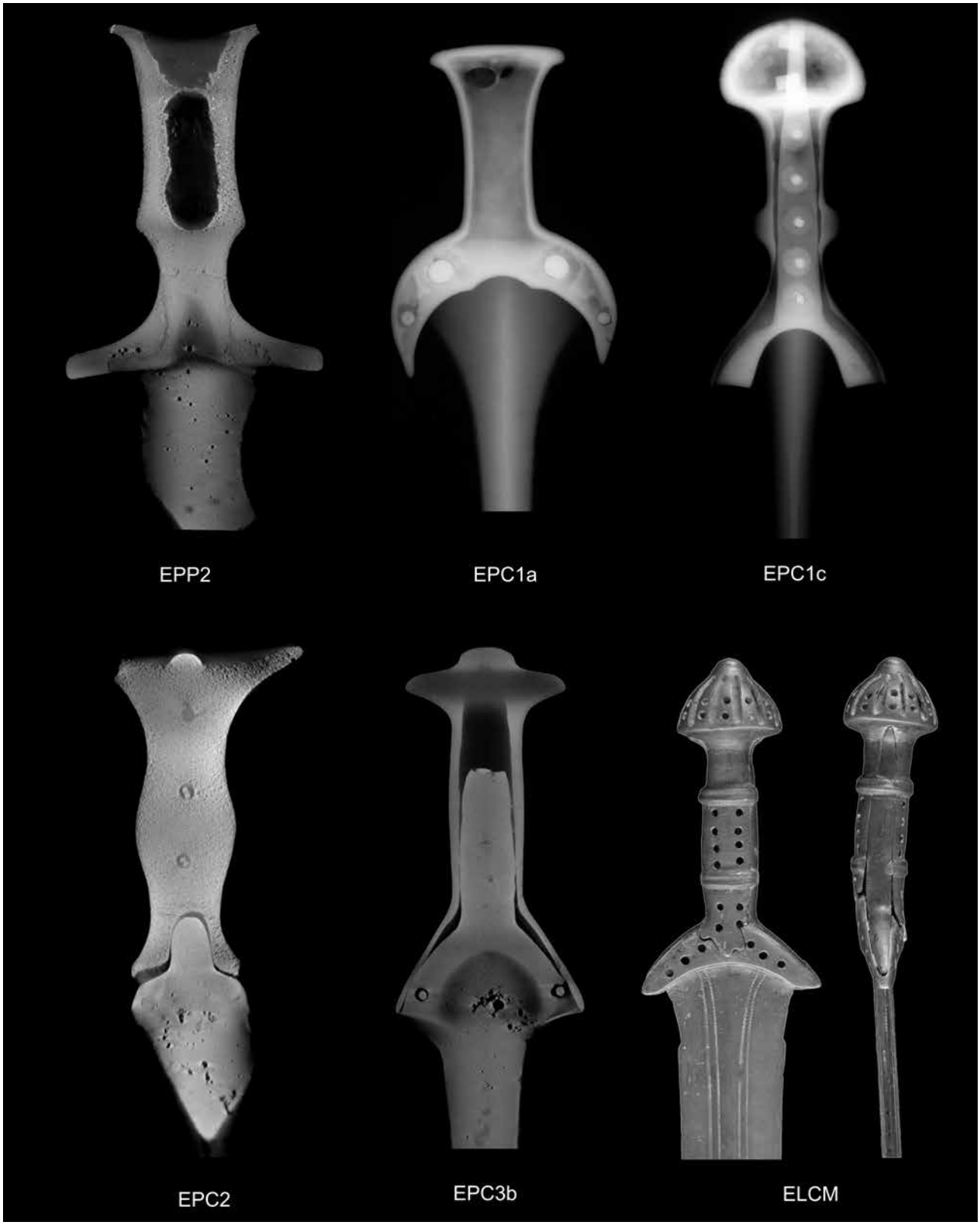


Fig. 6 – Overview of the main technological types of Bronze Age solid-hilted swords. EPP2. Grigny (France), © I. Josipovic, L. Dumont. EPC1a. Mont-Saint-Aignan (France), © La Fabrique de Patrimoine en Normandie. EPC1c. Between Tournus and Farges (France), © E. Lambert. EPC2. Saint-Romain-en-Gal (France), © I. Josipovic, L. Dumont. EPC3b. Champagneux (France), © I. Josipovic, L. Dumont. ELCM. Montbellet (France), © L. Dumont.

For types EPC1 and EPC3, variations are identified based on the type of tang they are fixed on. Tangs can be either short, bipartite or rod-like. Short tangs are inserted only up to the guard of the hilt. This type of tang associated to a hollow hilt only allows for a fixation using rivets (fig. 6, EPC1a). Longer tangs inserted within the guard and the grip (bipartite) or all the way up until the pommel (rod-like) enable more complex techniques used for a stronger fixation. Rivets alone can still be used, but some swords are also equipped with a hilt fixed with no rivets, only by locking both elements together. The tang is in that case forced inside the hilt and the fixation is made by mechanical contact between the tang and the inner walls of the hilt. This contact can be made within the grip for bipartite tangs or within the pommel for rod-like tangs. Finally, these techniques can be combined. Some swords are made with a hilt first locked with the tang and then reinforced with rivets (fig. 6, EPC1c, EPC3b).

Flanged hilt and bronze pieces

The last type identified in the techno-typology includes a small group of swords (5 so far) characterized by a flanged hilt framed with bronze pieces (fig. 6, ELCM). This type of hilt is not designed as the hollow hilts. Instead of having a flat tang inserted inside the hilt by a slit at the base of the guard, they have flanged tangs with a hilt composed of one or several elements riveted on each side, with the sides of the tang remaining visible. This type of tang is mostly found in swords that used to be equipped with an organic hilt. This similarity suggests these swords are made with a blade initially designed for an organic hilt, and that a customized bronze hilt was made to replace it.

Although the 5 swords belonging to type ELCM are not found in the same regions, they share similar stylistic features, especially very typical perforations of the hilt that are not known among other types of solid-hilted swords. However, they are not all produced the same way. Most are made with a single bronze piece with a central slit in which the tang fits and is fixed with rivets. The sword from Montbellet (France, Saône-et-Loire) is designed differently: the hilt is composed of two pieces locked on the tang, requiring no rivets. Considering the differences in the distribution of these swords, their morphology and the techniques, they probably do not come from the same workshop. As they are all using a blade designed for an organic hilt, the similar decoration using perforations could be an imitation of ornaments commonly found in hilts made of wood or other organic materials.

Organic and bronze hilt

There are also a few swords whose hilt is composed both of bronze and organic elements. This category does not include swords with bronze hilt adorned with inlays of organic materials such as Auvernier and Tachlovice types swords. In this case, the organic elements are purely ornamental and do not play a functional role in the hilt structure. These swords, between solid-hilted and organic-hilted swords, are classified separately. The classification is simpler: four types are identified based on the way the bronze part of the hilt is fixed to the blade. It can be cast with the blade (type EPSM1), cast over it (type EPSM2), riveted (type EPSM3) or locked (type EPSM4).

ORGANISATION OF PRODUCTION

Experimentation phase

This technological classification of Bronze Age solid-hilted swords is a tool to evaluate the homogeneity or heterogeneity of the *chaînes opératoires* both in time and space. It provides a barometer to identify chronological and spatial variations in the organisation of production. Using this tool, three main phases are identified: the experimentation, 'monopoly' and disruption phases.

The experimentation phase matches the first development of solid-hilted swords in Bronze Age Europe starting at the 18th century BC (Schulz, 2004-2005). It is characterized by a technological and stylistic diversity and well-identified types, each of them comprising few swords. In eastern and northern Europe, most swords fit in the Hajdúsámson-Apa and Au-Valsømagle types (Bunnefeld, 2016, p. 19–20), which include several variants. In central Europe and especially in the northern Alpine region, the Spatzenhausen type appears during Bz B (Holste, 1953, p. 13–15). In western Europe, most solid-hilted swords belong to types Tréboul-Saint-Brandan and Le Cheylounet-Jugnes (Daugas and Vuaillat, 2009; Dumont 2022, p. 159–167).

Only the production techniques of the Le Cheylounet-Jugnes swords were properly investigated (Daugas and Vuaillat, 2009). They are all made in the same way and all belong to type EPC3a, with a hollow hilt fixed to a short-tanged blade using rivets. Apart from these swords, the available technological data regarding these early solid-hilted swords is very limited due to the lack of technological investigation using X-ray imaging techniques (fig. 7).

Yet, available images for these swords suggest different *chaînes opératoires* were used, hence a low technological standardisation. Spatzenhausen swords are commonly made with an opened pommel in its centre, matching the presence of an inner canal between the hilt's inner room and its surface (Hundt, 1965, p. 43), which could match a stand for keeping the core in place within the mould and removed after the casting (Schwenzer 2004, p. 147; Mödlinger, 2011, p. 32). Finally, although technological data lacks about Hajdúsámson-Apa swords, the existence of hilts fully made of bronze as well as composite ones with gold or organic pieces (Meller, 2010) gives an insight into their diversity.

This typological and technological diversity matches the existence of multiple production groups. Consider-

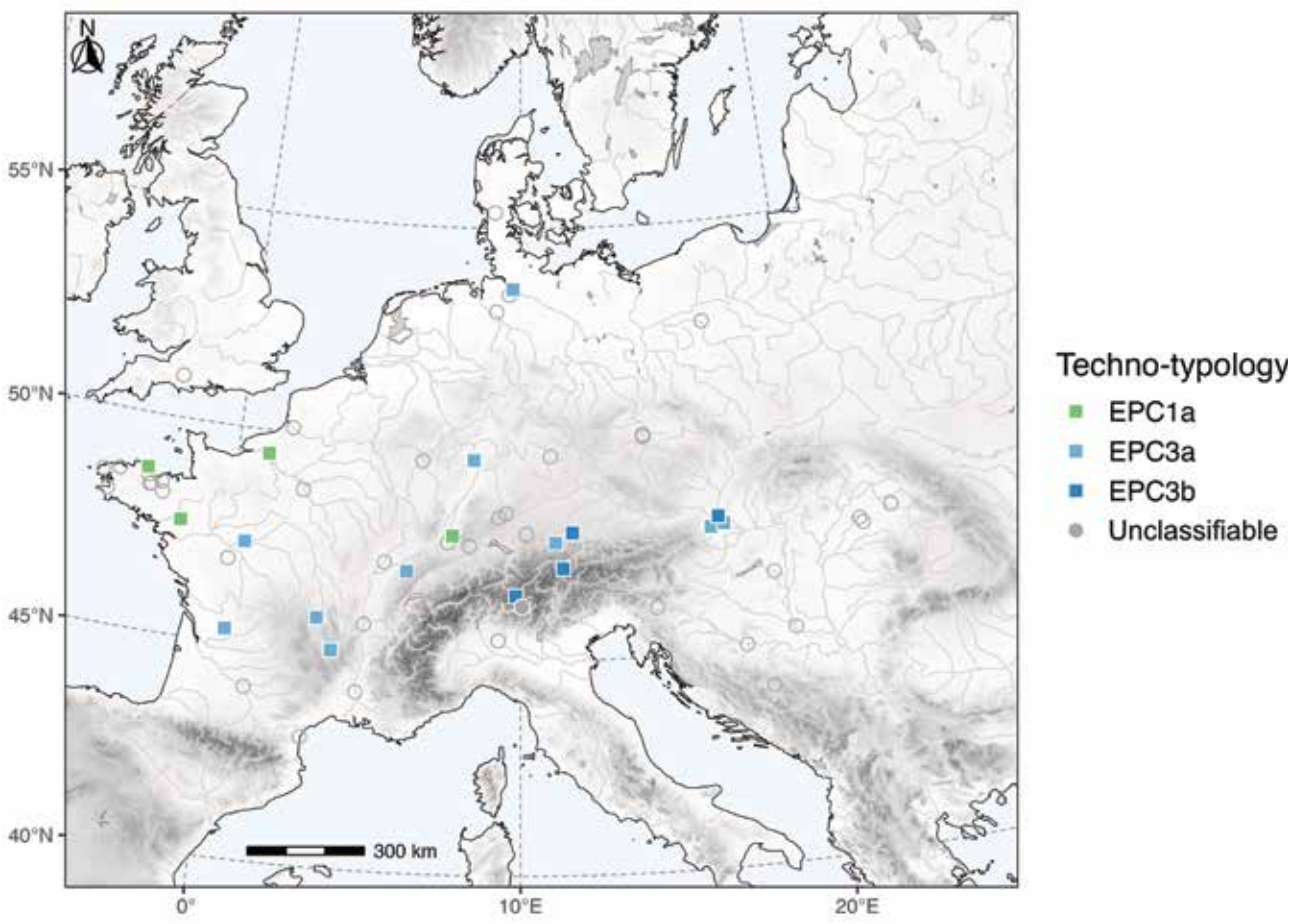


Fig. 7 – Distribution of solid-hilted swords during the experimentation phase (Bz A2-B, ca. 1800-1450 BC) according to their technological type (see fig. 4). Swords that were not X-rayed are indicated by a black circle. Data: Dumont, 2024.

ing the few swords discovered (about 10 for each type, see Dumont, 2024), this probably corresponds to a small-scaled and versatile production units sporadically making swords among other types of objects. Although data is lacking to quantify it, the apparent technological diversity within Hajdúsámson-Apa and Au-Valsømagle swords (Bunnefeld, 2016, p. 45–48, p. 58–60) and the existence of peculiar techniques involving different materials (Meller, 2010) suggest different small and versatile production groups were involved in the production of swords, sometimes experimenting with techniques that were not subsequently used. In the absence of direct archaeological traces, workshops cannot be located. We must note that this technological creativity during the early stages of solid-hilted swords development is not associated to a low quality or sloppy production. On the contrary, investigated swords from the Le Cheylounet-Jugnes and Hajdúsámson-Apa types (Daugas and Vuaillat, 2009; Meller, 2010; Bunnefeld, 2016) show a very good casting quality with a low porosity and a good-quality fixation with up to 6 rivets. Craftspeople were therefore very careful in their work and a form of attached production with crafters producing swords in small quantities and made to order for sponsors of the craftspeople.

’Monopoly’ phase

The situation changes abruptly in the middle of the 15th century BC (Bz C) with the introduction of a new type of sword in central Europe: the octagonal-hilted swords (*Achtkantschwerter*). Octagonal-hilted swords are named after the typical octagonal cross-section of their hilt (Quillfeldt, 1995, p. 45–93). Although the shape of the hilt and its ornamentation takes root in earlier types, such as swords of type Spatzenhausen (Hundt, 1962), they introduce a new technique to fix the hilt to the blade. The tang becomes longer compared to swords from Bz A and B: it is bipartite and reach the centre of the grip. Thanks to this shape, the fixation no longer only relies on rivets. The tang is first locked within the hollow hilt. It is forced inside it by making contact with the inner walls. Once both parts locked, the fixation is strengthened with two rivets on each side of the guard (fig. 6, EPC3b). This technique enables a strong fixation without multiplying the rivets. Using multiple rivets can indeed be challenging. The rivet holes need to be carefully positioned in the moulds, or they have to be drilled and perfectly aligned on the hilt and on the tang. The difficulty of the task increases with the number of rivets. This technique is known as the octagonal-hilted sword principle

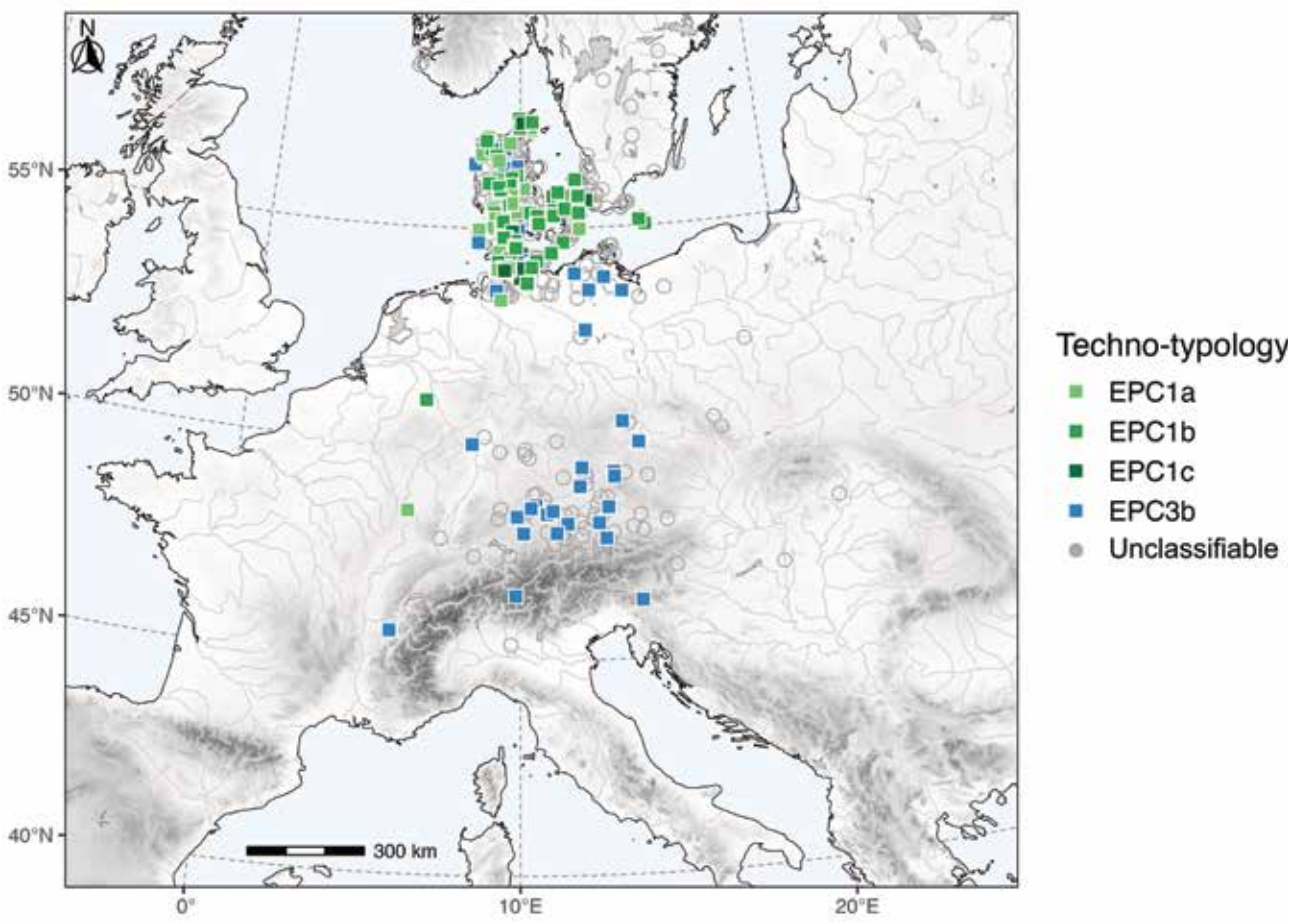


Fig. 8 – Distribution of Bz C (ca. 1450-1300 BC) and Period II (ca. 1500-1330 BC) solid-hilted swords ("monopoly phase") according to their technological type (see fig. 4). Swords that were not X-rayed are indicated by a black circle. Data: Dumont, 2024.

(*Achtkantschwert-Prinzip*, Hundt, 1965, p. 54). This new *chaîne opératoire* matches technological type EPC3b.

The development of the *Achtkantschwert-Prinzip* during Bz C marks the start of a new technological tradition, first in the north-alpine region and then in Central Europe. Most solid-hilted swords found in the north-alpine region and in the Carpathian Basin from Bronze C to Ha B1 (ca. 1450-900 BC) are produced in the same way (Dumont, 2022, 2024). Octagonal-hilted swords are found both in the North-Alpine region and in southern Scandinavia (fig. 8) Despite slight stylistic variations, all X-rayed Riegsee type swords (Bz D), three-ribbed swords (*Dreiwultschwerter*, Ha A) and swords with a cup-shaped pommel (*Schalenknaufschwerter*, Ha B1) belong to type EPC3b and were produced according to the *Achtkantschwert-Prinzip* (fig. 9). The technological standardisation is only valid for central Europe. In northern Europe, typical nordic swords are made with a bronze hilt with different shapes and ornaments as well as with different *chaînes opératoires*, including hollow-hilts cast over a core reproducing the hilt outline (types EPC1a-c, Bunnefeld, 2016; see here figs. 8-9). This *chaîne opératoire* combining a hollow hilt and a bipartite tang fixed by locking both parts and adding two rivets seems to have been considered as the most efficient or suitable for the production of swords. This strong technological consistency suggests a centralised production within a few workshops, probably operating in the same region. Over such a long period, a production scattered across many production units would have more chances to result in a diversification of the *chaînes opératoires*. In the total absence of moulds for casting this type of hilts, the production centre(s) cannot be located. It remains unclear whether blades were manufactured alongside hilts or if they were produced in different workshops. Although X-ray imaging techniques provide a good way of documenting the casting of the hilt and its fixation to the blade, it gives less information regarding the production of the latter.

Swords produced according the *Achtkantschwert-Prinzip* also forms a homogenous stylistic group. Although we observe slight variations in the shape and ornamentation of the hilt and the blade, the tang keeps the same shape, the outline of the hilt does not change much and the graphic ornamentation composed of thin engraved patterns covering the hilt surface remains consistent between Bz C and Ha B1. Except for octagonal-hilted swords, found both in the north-alpine region and in southern Scandinavia (Bunnefeld, 2014), swords of the North-Alpine tradition also share similar distribution patterns. They are usually found between the Rhine

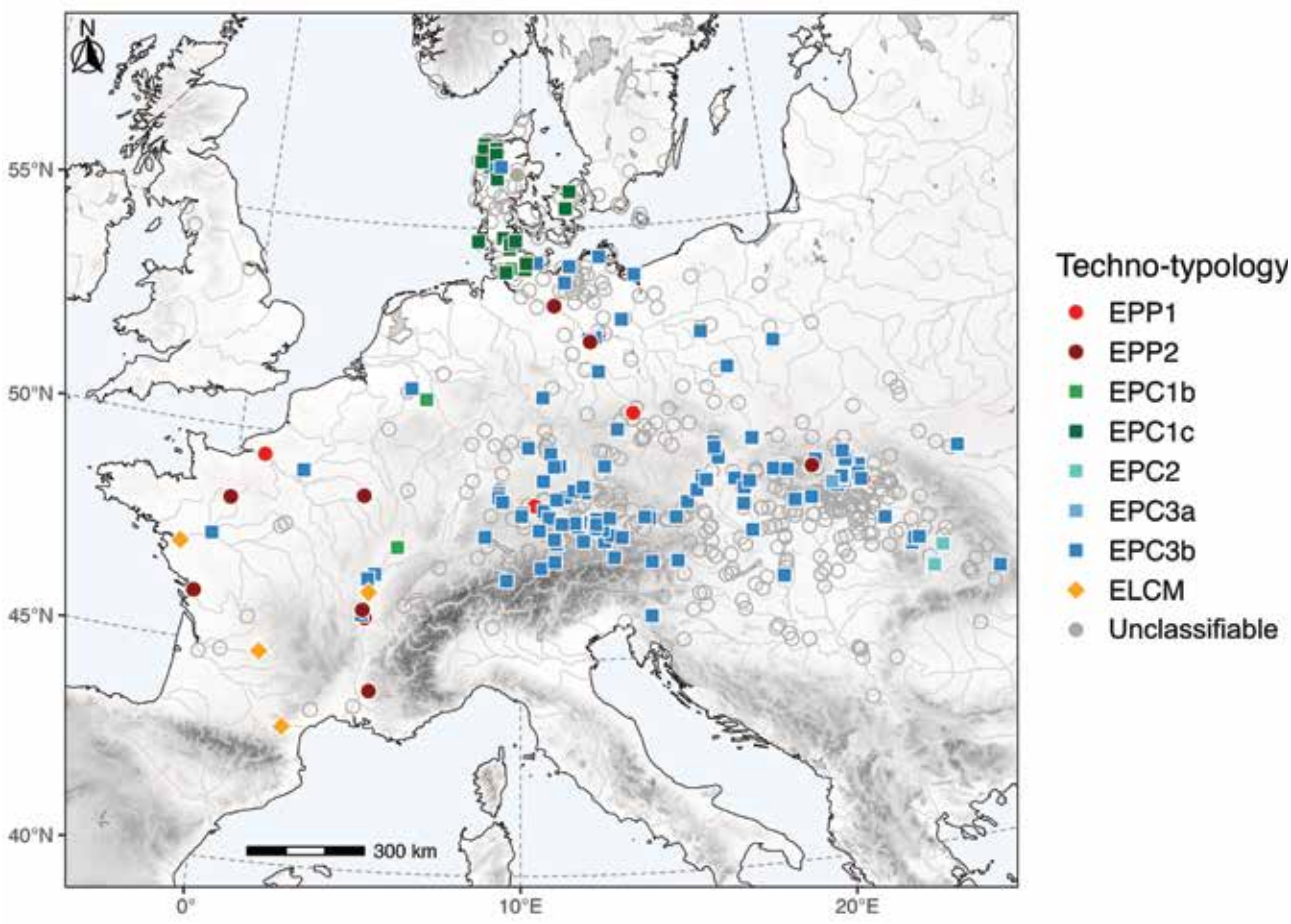


Fig. 9 – Distribution of Bz D to Ha B1 (ca. 1300-950 BC) solid-hilted swords ("monopoly phase") according to their technological type (see fig. 4). Swords that were not X-rayed are indicated by a black circle. Data: Dumont, 2024.

valley and the Carpathian Basin, alongside a west-east axis (fig. 9). This indicates a continuity in the consumption habits of the users of these swords, which do not seem to vary much regarding the continuity both in the style and deposition practices (Dumont, 2022, plates 111, 116, 125, 131).

Swords of the north-alpine tradition are manufactured following the same *chaîne opératoire* and share some stylistic features. Within one type, they can look a lot like each other. Yet, they are all unique. The individualisation is made through the ornamentation of the hilt, which makes each sword unique. They are therefore not mass produced. This unicity is probably achieved using lost-wax casting, which allows the production of relatively standardised wax models that can be individually decorated. This production could involve attached specialists manufacturing swords to order for their sponsors, who may have been involved in the choice of the ornamentation of the hilt. This could explain the technological homogeneity of octagonal-hilted swords found both in the north-alpine region and in southern Scandinavia (they all come from the same workshops) combined to the diversity of their ornamentation (sponsors in both regions do not share the same taste). In that scenario, the access to this kind of artefacts would be restricted to a category of the population, hence the existence of imitations, like the swords of type Prejmer (Vachta, 2008; Novotná, 2014, p. 74).

Disruption phase

The organisation of production changes abruptly at the end of the Bronze Age, during Ha B2/3 (ca 9th c. BC). This last period is characterised by a typological and technological diversification. Unlike the monopoly phase during which solid-hilted swords mostly belonged to a single type (e.g. swords with a cup-shaped pommel during Ha B1), several types co-existed during Ha B2/3. Most swords then belonged to types Mörigen, Auvernier, Tachlovice and to several types of antennae swords (Dumont, 2022, p. 248–304). Despite this apparent diversity, swords are more standardised. Whereas earlier solid-hilted swords were individualised through the ornamentation of the hilt, Ha B2/3 swords types are more homogenous as the graphic decoration is less important and the development of reusable moulds made of stone or bronze enabled serial production (Dumont, 2021).

This phase also saw the outbreak of multiple technological traditions and *chaînes opératoires* existing together in Europe (fig. 10), contrasting with the homogeneity and technological standardisation observed ear-

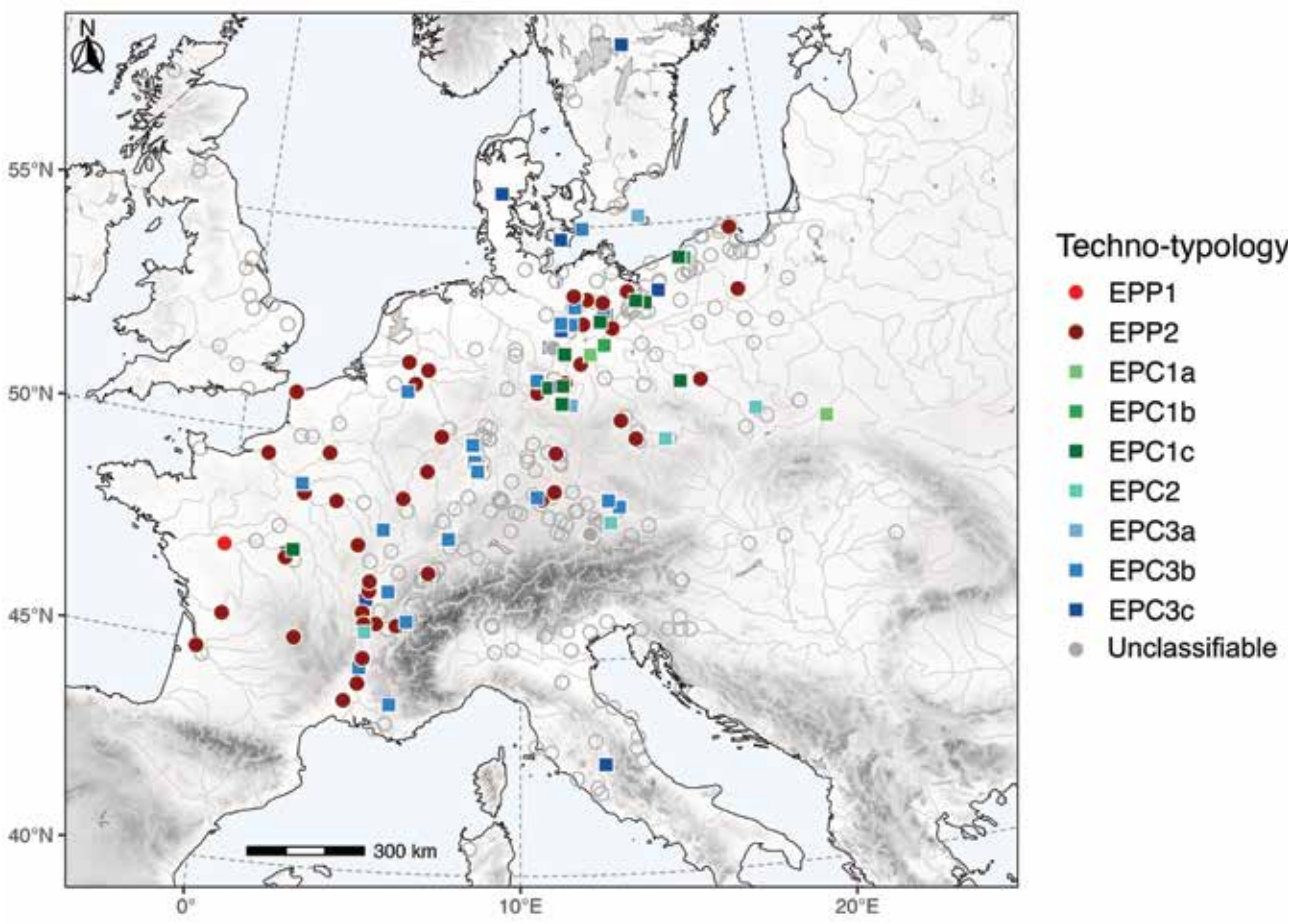


Fig. 9 – Distribution of Bz D to Ha B1 (ca. 1300-950 BC) solid-hilted swords ("monopoly phase") according to their technological type (see fig. 4). Swords that were not X-rayed are indicated by a black circle. Data: Dumont, 2024.

lier. The *Achtkantschwert-Prinzip* still exists: this *chaîne opératoire* is still used to make antennae swords of type Tarquinia, mostly found in the Italic Peninsula and around the Alps (Dumont, 2022, p. 296–301; Dumont, 2024). In parallel, less specialised, and more versatile techniques are used, especially the secondary casting (type EPP2). This technique is particularly used to produce swords found alongside the Saône and Rhône valleys, as well as in the southern Baltic region. Unlike the north-alpine tradition, characterized by a very specialised set of techniques only used in the framework of solid-hilted production, the important use of secondary casting cannot be interpreted as the result of a centralised production. This is indeed a widespread technique across Bronze Age Europe, used to produce artefacts, such as pins, but also to repair broken or flawed objects (Drescher, 1958). Instead, the development of this technique alongside several other *chaînes opératoires* can be linked to a nuclearization of the production centres. Swords are now produced is many smaller workshops by less specialised and more versatile craftspersons. The coexistence of different technological traditions in several regions, especially south of the Baltic Sea where there are also swords of types EPC1a-c sometimes made without rivets (Bugaj, 2005), shows that swords found in the same region were produced by different production groups.

The stylistic and technological homogeneity characterizing the monopoly phase disappeared at the very end of the Bronze Age. The monopoly phase showed a strong stylistic and technological homogeneity, with a stylistic tradition matching a *chaîne opératoire*. During the 9th century BC, this is no longer the case. We do not observe any correlation between production techniques and types of swords. For example, there are swords of the Mörigen type with a solid hilt produced by secondary casting (type EPP2) as well as with hollow hilts belonging to types EPC1b, EPC1c, EPC2, EPC3a, EPC3b and EPC3C (Dumont, 2022, pl. 142; 2024). During the disruption phase, the manufacture of solid-hilted swords does not seem to be restricted to a single production group. It rather seems to have opened up to many production units that includes craftspeople with different *habitus* and possibly for different socio-cultural backgrounds.

The typological diversification observed during Ha B2/3 as well as the evolution of the distribution pattern of solid-hilted swords, which are not found anymore in the Carpathian Basin but rather between the Saône-Rhône axis and the southern Baltic region (fig. 10), also indicates possible changes in the users. Could these variations be correlated with the development of new groups of sword bearers, different from the groups of the monopoly phase. The organisation of production is therefore different. The

existence of reusable moulds made of bronze (Erlingshofen, Germany: Overbeck, 2018, p. 81–82) or stone (Lac du Bourget, France: Kerouanton, 2023, p. 164) shows that these swords may have been serially produced, possibly in relation with an unregulated production which is no longer limited to a limited group of users sponsoring the crafters.

CONCLUSION

The investigation of production techniques and the development of a technological classification framework have proved to be effective tools to fill the gap created by the lack of direct archaeological traces connected to metalworking activities. They offer a new barometer to explore the variations in the organisation of production of solid-hilted swords throughout Bronze Age Europe.

The manufacture of the earliest solid-hilted swords during Bz A2 and Bz B is not well documented as few of these swords have been X-rayed. Available data suggests an important technological diversity with the use of peculiar techniques that are not used any further in later periods. Together with the typological diversity and the small number of swords known in Europe, this seems to be an experimental phase. Several versatile production units were probably involved in their manufacture. Although the scale of the production cannot be determined precisely, the few swords found for that phase indicate they may have been prestige artefacts carefully crafted and dedicated to a very small portion of the population.

Changes occurred in the middle of the 15th century BC (Bz C) with the outbreak of octagonal-hilted swords. They were manufactured in a new way with a hollow hilt fixed to the blade by locking the tang inside the hilt and adding two rivets on the guard. As virtually all solid-hilted swords found between the Rhine valley and the Carpathian Basin until the 10th century BC (Ha B1) are manufactured in the exact same way, this phase corresponds to the centralisation of the production within a single production group. Considering the high degree of technological standardisation, they were probably made by a few highly-specialised craftspersons. These swords were also all unique and may have been made to order. They were probably not widely available and their access was probably restricted to a part of the population. This socio-cultural group may have sponsored the crafters involved in the manufacture of these swords, making it a form of attached production.

Things changed in a radical way at the very end of the Bronze Age during Ha B2/3 (ca 9th century BC) with the outbreak of multiple technological traditions and the use of less-specialised techniques such as over-casting, as well as reusable moulds enabling serial production. At that time, the production of solid-hilted swords probably opened up to a wider range of craftspeople, in line with an increase in demand. This nuclearization of the production centres at the end of the Bronze Age matched changes in the morphology, decoration and distribution of these swords. This period is thus characterised by important changes in the organisation of production, consumption and diffusion of solid-hilted swords, probably corresponding to the emergence of new groups of users and producers.

The underlying reasons of the major changes observed in the production and consumption of solid-hilted swords at the very end of the Bronze Age are not well understood. This would require more technological data to get a better understanding of the geographic variations in production techniques, especially in the north-alpine region and in the Italic peninsula, where few swords were investigated using X-ray imaging techniques. This would also require a wider study including other types of metalwork to determine the scale and extent of the changes observed through solid-hilted swords.

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Session 4

Exchanges and uses of metal:
from archaeological contexts to the laboratory

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An Overview on Metal Artefact Deposits in Southwest Asia during the Iron Age

Zahra Hashemi

Abstract: This paper addresses the concept of 'metal artefact deposits' in societies of southwest Asia during the Iron Age (end of the 2nd to the beginning of the 1st millennium BCE). The act of deposition in its various forms has a long history through time and space. Archaeology attests that for thousands of years, man, in different societies, has intentionally deposited objects in specific places, temporarily or permanently, for various reasons. Dedication in temples or tombs, hiding valuable objects as treasure and storing working or personal materials are among different intentions which are hidden behind the act of deposition. These reasons are not easy to ascertain at the time of discovery. The content, the environment of the deposit and the act of deposition are among the decisive characteristics which can inform us about the reason for the action.
Through a typological approach based on different physical characteristics, this study tries to classify different types of deposits and identify different intentions which could lie behind the act of deposition. Thus, the diversity of deposits will be evaluated according to different regions of southwest Asia during the Iron Age.

Keywords: Archaeology, Votive deposit, Hoard, Favissa, Construction deposit, Treasure, Craft hoard, Economic hoard, Metal

Résumé : Cet article aborde le concept de « dépôts d'artefacts métalliques » dans les sociétés de l'Asie du Sud-Ouest à l'âge du Fer (fin du IIe-début du Ier millénaire avant notre ère). L'acte de dépôt, sous ses différentes formes, a une longue histoire à travers le temps et l'espace. L'archéologie atteste que, depuis des milliers d'années, l'Homme, dans différentes sociétés, a intentionnellement déposé des objets dans des lieux spécifiques, de manière temporaire ou permanente, pour diverses raisons. La dédicace dans les temples ou les tombes, la dissimulation d'objets de valeur en tant que trésor et le stockage de matériel de travail ou de matériel personnel sont parmi les intentions qui se cachent derrière l'acte de dépôt. Ces raisons ne sont pas faciles à déterminer au moment de la découverte. Le contenu, l'environnement du dépôt et la manière dont on le réalise sont parmi les caractéristiques décisives qui peuvent nous informer sur la raison de l'action.
À travers une présentation typologique basée sur différentes caractéristiques physiques, cette étude tente de classer différents types de dépôts et d'identifier différentes intentions qui pourraient présider à l'acte de dépôt. Ainsi, la diversité des dépôts sera évaluée en fonction des différentes régions de l'Asie du Sud-Ouest pendant l'âge du Fer.

Mots clés: archéologie, dépôt votif, *favissa*, dépôt de construction, trésor, dépôts d'artisan, dépôt économique, métal

The word 'deposit', borrowed from the classical Latin 'depositum', comes from the verb 'to deposit' which means to put, to place. The dictionary describes it in an anthropic sense, as "to put something to someone's care" or "to put something in a safe place" (Rey and Morvan, 2005, p. 2280–2281). Based on this definition, we define 'deposit' as one or more artefacts selected and deposited, for some reason, deliberately in a specifically chosen place in a specific manner, temporarily or permanently. It refers primarily to an act of deposition, which must be intentional, and acknowledged. It therefore involves the choice of objects, the environment of deposition and how the objects are placed.

In European archaeology generally the word 'hoard' is used for these deposits. In this study we intentionally avoid using this word, because its definition in the dictionary is always followed by the notion of 'hiding' and 'keeping in secret'.[1] As it's not possible to match these

1. Oxford dictionary: "A collection of money, food, valuable objects, etc., especially one that somebody keeps in a secret place so that other people will not find or steal it" (https://www.oxfordlearnersdictionaries.com/definition/english/hoard_1). Britannica :"A large amount of something valuable that is kept hidden" (https://www.britannica.com/dictionary/hoard).

notions with some cases in ritual spaces, we prefer to use the word 'deposits' as a more neutral and inclusive term.

Since the end of the 19th century, different researchers have tried to find motivations behinds acts of artefact deposition and this subject remains in active discussion. Dedication in ritual places, hiding the valuable artefacts and storing bullion or working materials are among different intentions which can exist behind the act of deposition.

A large range of material, such as clay, bone, ivory and stone can be found in artefact deposits. The material of concern to us here is limited to metal, in all its forms from raw material to final product.

Numerous metal artefact deposits in European Bronze Age cultures have been investigated. David Coombs and Richard Bradley were pioneer researchers on this topic (Coombs, 1975; Bradley, 1985). Recent work by Sylvie Boulud-Gazo, Muriel Mélin and Marilou Nordez also outlines an interesting scheme of different typologies of metal artefact deposits in the northwestern Atlantic region (Boloud-Gazo et al., 2017). Concerning southwest Asia, Richard Ellis and Judith Bjorkman provided a broad overview of the widespread phenomenon of 'foundation deposits' (Ellis, 1968; Bjorkman, 1994). However, metal artefacts didn't form the principal material of these deposits. Occasional discoveries in the large region of southwest Asia gave rise to several articles containing case studies (see below, deposits in different regions). In 1988, Graham Philip dedicated a more general study to metallic deposits of the Bronze Age in the Levant (Philip, 1988). More recently, in the 21st century, researchers such as Miriam S. Belmuth, Tzilla Eshel, and Elon D. Heymans have focused their work on a special type of metal artefact deposit known as 'hacksilber' (silver fragments), widespread mainly in the Levant (Belmuth, 2001; Eshel et al., 2018; 2023; Heymans, 2021). Our knowledge thus suffers from the lack of a general study covering the whole region of southwest Asia, to give an overview considering different types of and motivations for metal artefact deposits. To give a significant geographical comparative study, in this work, our focus will be on the Iron Age period and our analyses will be through space within this chronological framework. For a future study, it would be particularly interesting to undertake a diachronic study covering the entirety of the Metal Ages. This would let us analyze the evolution of these practices through time. This paper also seizes the opportunity to set up a typology for metal artefact deposits within this geographic and chronological framework, introducing the main elements to consider.

It's important to point out that funerary artefacts, which can be gifts or the deceased's personal effects, are in some ways a type of deposit. However, as a large domain, that deserves to be discussed in a separate paper. It is not our purpose here.

CHARACTERISTICS OF ARTEFACTS DEPOSITS

Several characteristics should be considered in the classification of artefact deposits (fig. 1): the contents, the environment and the modality of the act of deposition.

1. *The content of deposits* can include artefacts in different materials (here metal), state (final product, semi-product, raw material, broken or fragment of artefact) and category (weapon, vessel, jewellery, tools, etc.). These contents can be homogeneous and be made up of the identical material, state, category or type of artefacts; or they can be heterogeneous, made up of a variety of different materials, states, categories and types of artefacts.

2. *The environment* that receives the deposit can be natural and not associated with any anthropic construction – for example, a hole or cave (or more commonly a river in European archaeological contexts) – or it can be associated with an anthropic place constructed by humans such as a building. The physical characteristics of these environments, such as dry land and water bodies, should be considered in analyzing accessibility and the possibility of recovering the deposit. The archaeological interpretations of function of the place that receives the deposit can also associate it with various ritual, palatial, domestic, economic, artisanal or administrative spheres.

3. *The act of deposition* can be realized during different moments of life of the place which receives the deposition, in different locations and in a variety of forms and gestures: in a jar, wrapped in a textile, put on the floor, put on an altar or in a niche, buried beneath the floor, put at the foundation level or in the masonry of walls during construction/restoration, put in the building during the occupation, or put in the backfill or throughout the building at the end of its occupation. Identification of the gesture of deposition could also provide precious information. For example, deposits could be hidden without any signalization or conversely be marked by something. Such spatial markers indicate that deposits were not intended to be hidden and that the location could be identified. This information is crucial to identify the function of deposits. Along with the gesture of deposition, the internal organization of the deposit is also meaningful. A deposit can be realized in one step (uni-phase) or realized in successive different steps (multi-phase). The reopening of the deposit can be for repairing, removing or adding artefacts.

These informational elements, although crucial, are unfortunately not easy to recognize in old excavations. The particular intention of mentioning these characteristics here is to provide clues to be observed during future excavations. In cases where they are recognizable, they can help us to understand the motivation behind the act of deposition and allow us to propose functions and utilities of deposits.

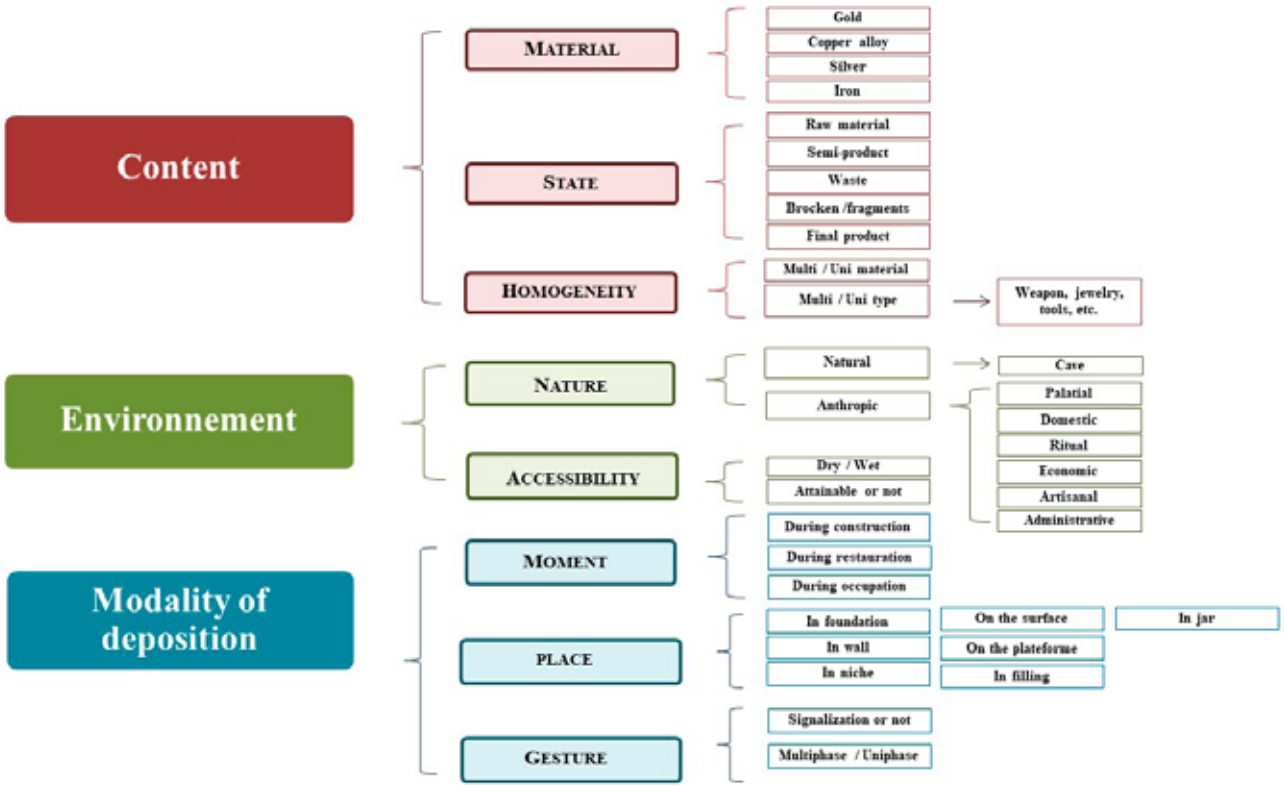


Fig. 1 – Different characteristics of metal artefact deposits.

FUNCTIONS OF ARTEFACTS DEPOSITS

Different intentions may lie behind an act of deposition (fig. 2):
1. *Dedication* (to a specific living or dead person, deity, supernatural power, building or place) for protection and commemoration or against malediction
2. *Storage*
3. *Concealment*

Dedication relates to the category of votive deposits. Storage and concealment, on the other hand, relate to the category of hoards. Votive deposits are generally permanent deposits, which means that they are not intended to change function even if they can change place. It doesn't mean that they have never been reused. A votive deposit, once deposited, can be reopened, used for a ceremony and deposited again. It can be repaired, and artefacts can be added or removed for different occasions. In some situations, such as natural and military disasters, votive deposits can even be exceptionally used by the same community or by enemies for other purposes. Hoards, on the other hand, are temporary deposits. They are intended to be recovered. However, for some of them, this didn't happen, and that is how they came to us.

With this array of characteristics and intentions, votive deposits and hoards can be classified into different sub-categories according to their environment, the modality of the act of their deposition and, in some cases, their contents.

Votive Deposits

Votive deposits can be classified to four subcategories:
1. *Offering*
2 Favissa
3.*Construction deposit*
4. *Closure deposit*

Offering

This refers to artefacts dedicated to a ritual place (natural or anthropic) during its use. Offerings are generally exposed, for example on a platform, in a niche, on an altar, on the floor, etc. The powers and specialities of each deity or place generally influence the types of objects dedicated. They cover a huge variety of materials and categories.

Favissa

This refers to a particular category of votive deposit dedicated to a ritual place. Contrary to offerings, which are generally exposed, favissae are not exposed. They are generally part of (for example, an excess of) temple offerings buried or stored in adjoining chambers, inside or near a ritual place. The word favissa has a Latin origin used in the Roman world. The earliest definition of the term appears in the first century BCE work of Roman author Terentius Varro, who refers to votive objects in temples which are in excess of temple offerings (Varro,

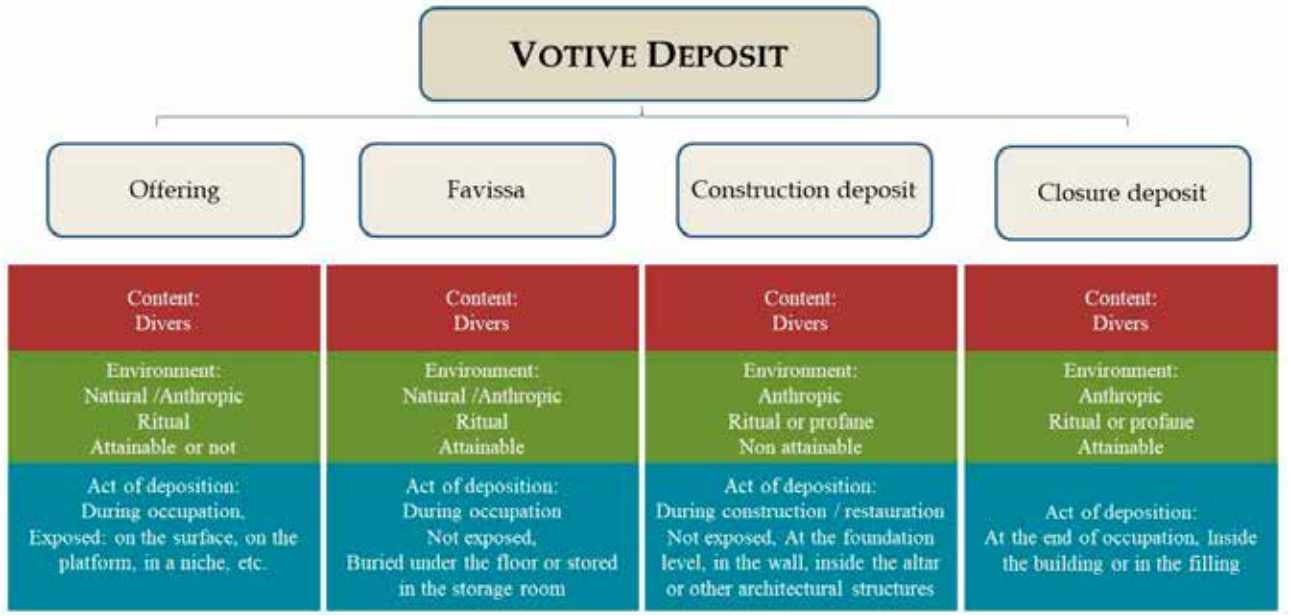


Fig. 2 – Different characteristics of votive deposits.

On the Latin Language, Vol. II: Books 8-10; Gellius, Aulus, The Attic Nights, II.10). Greco-Roman dictionaries define it as follows: "votive pits or ex-votos that were grouped together to make room in the sanctuary" (Thuillier et al., 2002, p. 98). Later archaeologists used this term outside the Greco-Roman world for the Eastern and Egyptian world. Jean Claude Margueron used it for some Bronze Age deposits in Mari, in Syria (Margueron, 2004, p. 563).

Construction deposit

This refers to artefacts deposited in the architectural elements of a building such as in the foundations or in the masonry of walls or altars, during the construction or restoration of a building. Although the act is ritual, the building is not necessarily a temple; it can be linked to a royal, administrative or domestic context. Construction deposits are not visible and are generally sealed when the building or structure is in use. They can have a role of sanctification, or protection of the building (symbolically guaranteeing its stability), or commemoration of an event. Generally, the expression 'foundation deposit' is used for this type of deposit even when it has not been found in the foundations. In this paper, the term 'construction deposit' is preferred because of its broader signification. What differentiates the favissa from construction deposits is that a favissa has a mandatory relation to the ritual sphere and its deposition takes place during the use of the building.

Closure deposit

This refers to artefacts placed at the end of a building's occupation to mark a dedication or commemoration of a historical event. A closure deposit is not necessarily linked to a ritual place. It can also be deposited in a profane building. Identification of closure deposits is very difficult. Artefacts found in the fill of a building can be intentionally deposited or be there accidentally, found in the soil that was used to fill the place.

Hoards

Hoards can be classified in three different sub-categories (fig. 3):

1. *Treasure*
2. *Craft hoard*
3. *Economic hoard*

Treasure

This refers to a category of non-exposed deposits stored or hidden in a profane building or natural milieu. Treasure includes valuable objects belonging to private, royal or administrative institutions. It's very difficult to differentiate treasure from offerings in a natural milieu. For example, artefacts deposited in the cavities of a cave can belong to both categories. In some cases, environmental characteristics can help. For example, a non-recoverable environment such as the bottom of a river or other wet milieu makes a votive context more conceivable than a hoard, which is perceived to be recoverable.

Craft hoard

This refers to a deposit including a mix of items related to metalworking activity such as tools, ingots, fragments, and broken artefacts, stored for re-melting or repairing. They are generally associated with profane contexts including domestic and artisanal contexts.

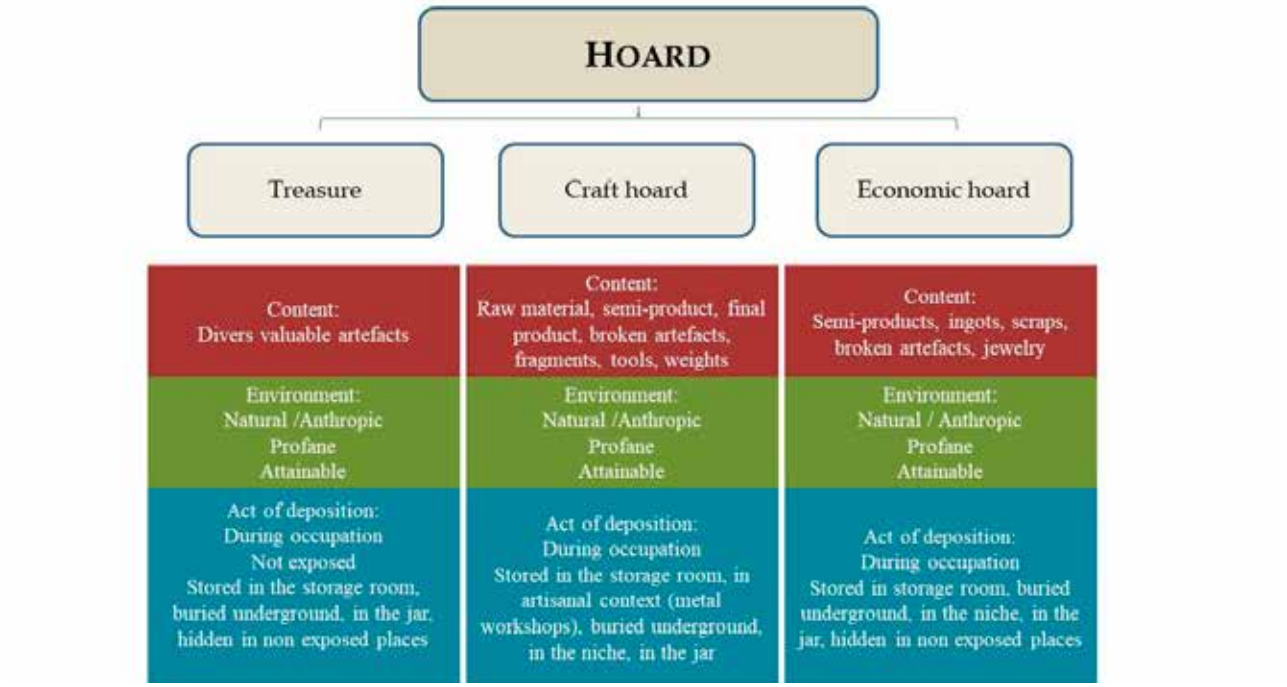


Fig. 3 – Different characteristics of hoards.

Economic hoards

This refers to deposits including fragments, broken artefacts and scraps hidden or stored somewhere intended to be used as currency, bullion and exchange. Economic hoards are thus generally in invisible positions buried underground, or put in non-exposed places.

Of course, differentiation between craft hoard and economic hoard is not always easy. Fragments, broken artefacts, scraps and weights can belong to both categories. There are some other elements of archaeological information, such as context and environment, which may help to differentiate them.

To these categories, it is possible to add others. Here, only the more common deposits in southwestern Asia are mentioned. The determination of the intentions behind the act of deposition remains delicate and the hypotheses formulated here are not absolute. In addition, these typo-functional classifications are not a starting point for analyses. They should, rather, grow out from the overall set of data as an end-result or interpretation, if at all.

METAL ARTEFACT DEPOSITS IN SOUTHWEST ASIA

Before the Iron Age

Archaeology attests that the history of metal artefact deposition in southwest Asia, in its various forms, goes back to at least the 4th millennium BCE (Moorey, 1982, p. 21). Votive deposits dedicated to deities (offerings, favissae) and the accumulation of valuable artefacts by elites (treasures) were two principal practices of deposition during these early periods. Regarding the accumulation of artefacts by elites, Arslan Tepe in Anatolia provides evidence of a group of copper-alloy artefacts, mostly weapons, found tied together and deposited near the wall of a prominent elite residence (Di Nocera, 2010, p. 257). One of the most impressive and ancient examples of metal artefact deposition in a natural environment is found in the Levant, in the Nahal Mishmar cave. Dated to the mid-4th millennium BCE, the cave contained more than four hundred elaborately crafted and sophisticated copper-alloy artefacts, representing a wide range of categories, placed within its natural cavities (Moorey, 1988, p. 171, 182). This significant deposit could either have been dedicated to the natural environment, and thus be interpreted as a votive deposit (offering or favissa), or it may have been intentionally hidden there, and thus be interpreted as a hoard (treasure)

During the Bronze Age (3rd-2nd millennia BCE), advancements in ore extraction methods led to a significant increase in metal production. Consequently, the deposition of metal artefacts gained importance throughout western Asia. However, ore deposits were not evenly distributed across regions, and thus, practices related to metal deposition varied from one area to another. In Mesopotamia, although metal artefacts were included in many deposits, those composed exclusively or predominantly of metal items are relatively rare. During the 2nd millennium BCE, the Levant became one of the key regions where metal artefact deposits became frequent and are attested through sites such as Nahariyeh, Ugarit, and Byblos (Dothan, 1956, p. 19–20; Philip, 1988; Al-Maqdissi, 2008). Among these, Byblos stands out as a remarkable example, where large numbers of metal objects—includ-

ing vessels, figurines, pins, jewellery, and a significant number of weapons—were buried in pits or jars, either near or within the masonry of various temples and sanctuaries. These deposits were mostly interpreted as favissae (Dunand, 1939; 1954; Benoit, 2003, p. 305–307).

Among the important practices of metal artefact deposition during the Bronze Age, one can particularly highlight the placement of metallic pegs and tablets at the foundation level of both sacred and profane (public and royal) buildings. Notable examples include the copper pegs from the Inanna temple in Nippur (Muscarella, 1988, p. 303–305), the copper pegs from the Ningirsu temple in Lagash (Ellis, 1968, p. 51), and bronze inscribed plates, pegs, and other objects found in square cavities at the corners of temples in Mari (Parrot, 1940, p. 5–6). Metallic pegs and tablets illustrate the diversity of artefacts included in such deposits. In some instances, even small metal fragments were placed at the foundation level of buildings, suggesting that the intrinsic value of the metal was also a factor in the practice (Ellis, 1968, p. 132). This custom was part of a broader tradition observed across Mesopotamia and neighbouring regions. It is also referenced in textual sources and is generally referred to by scholars as a 'foundation deposit'. This ritual involved placing votive or commemorative objects within the foundations, walls, or other architectural elements during construction. In our categorization, such practices can be classified as construction deposits.

Jar deposits are another important practice of metal artefact deposition during the Bronze Age in western Asia. These deposits generally include complete objects or a mix of complete and fragmented objects (scrap) as well as tools and weights, placed inside ceramic jars and buried beneath buildings. They represent common materials in circulation. These jar deposits could represent either objects collected by craftsmen for re-melting or similar, thus being associated with a craft hoard, or bullion for exchange, associated with an economic hoard.[(2)] The financial character of metal in exchange networks is attested in textual resources from the middle of the 3rd millennium BCE (Powell, 1978; Peyronel, 2010). Even though copper and gold are present in these economic deposits, silver seems to gain progressively in particular importance as a means of exchange and transaction from the Bronze to the Iron Age (Eshel et al., 2023).

During the Iron Age

After this brief overview of Chalcolithic and Bronze Age deposits, we now turn our focus to the Iron Age, covering the period from approximately the 13th century BCE to the end of the 7th century BCE (fig. 4).

The Caucasus and Anatolia (table 1)

Around the middle of the 2nd millennium BCE, a rupture in cultural traditions occurred in the Caucasus. This period is marked by a significant increase in the production of metal objects, both in their sophistication and in their volume of production (Chernykh, 1992, p. 275–295). Metal artefact deposits (mostly copper alloy) gained increasing importance in ritual contexts. Nazerlabi (Davitashvili et al., 2021) and Shilda (Maisuradze and Inanishvili, 2006) are examples of sanctuaries in Georgia, in the Caucasus, characterized by circular stone structures dated to the 13th–8th centuries BCE. Thousands of metal artefacts—spanning categories such as weapons and ornaments—were buried in various pits, in some cases inside jars. Their placement in pits beneath the floor suggests post-construction deposition. For this reason, they are best interpreted as favissae associated with the sanctuaries, rather than construction deposits. Bronze ingots and half-finished items are abundant among these deposits, suggesting that metalworkers may have been involved in the ritual practices. Another hypothesis—more delicate to pursue—is that these practices involved the hiding or stockpiling of metal in ritual spaces.

A large number of metal artefact deposits in the Caucasus are associated with the Colchis culture, which spanned from around 1600 to 700 BCE in western Georgia (Apakidze, 2000, p. 185; Apakidze, 2009, p. 12; Lordkipanidze, 1991, p. 95–109). These deposits, which often contain ingots and unfinished items, are referred to in Georgian and Russian literature as the 'Colchis hoards.' They are generally interpreted as 'founders' or merchants' deposits', intended for later use and having an economic function (Kuftin, 1949, p. 222; Kuftin, 1950, p. 162). As such, they can be categorized as economic or craft hoards.

At the beginning of the 1st millennium BCE, the Urartian kingdom (9th–7th centuries BCE) emerged in eastern Anatolia, the Caucasus, and northwestern Iran. One of the key activities in Urartian temples was the offering of metal artefacts—especially weapons—to the god Haldi. Ayanis (Çilingiroğlu and Salvini, 2001) and Toprakkale (Barnett, 1950) are two notable examples of Urartian temples rich in metal offerings. At Ayanis, hundreds of bronze weapons—such as shields, spears, helmets, and quivers—some inscribed with royal names, were found on a platform (altar) within the temple. Others were attached to the walls using hobnails. According to Altan Çilingiroğlu, offerings in Urartian sanctuaries, after being displayed for a period, were eventually stored in a special room within the temple, possibly due to an excess of offerings (Çilingiroğlu, 2012, p. 175). Thus, items deposited on platforms or fixed to walls can be considered as offerings, while those stored in dedicated rooms are more accurately interpreted as favissae.

The practice of hanging metal artefacts on the walls of Urartian temples is also depicted in the Assyrian reliefs of the Musasir temple at Khorsabad (Botta and Flandin, 1849, pl. 141; Merhav, 1991, fig. 4a). Both Urartian and Assyrian textual sources mention the metal richness of Urartian temples. Of particular note is the Kelishin stele, which records a pilgrimage to Musasir temple by the Urartian kings Ispuini and Menua. The stele describes their offerings to the god Haldi, including many metal

2. Arnaud et al., 1979; Huot and Naccaro, 2019.



Fig. 4 – Map of Western Asia showing the location of sites with metal artefact deposits mentioned in this paper (©Z. Hashemi).

weapons, standards, and vessels (Merhav, 1991, p. 10). Later, in 714 BCE, Sargon II of Assyria attacked Musasir. The Assyrian annals detail the looted treasures of the Musasir temple, including bronze and silver vessels and bronze statues (Merhav, 1991, p. 12).

Urartian fortresses also contained storage rooms linked to the royal sphere, where metal objects—ranging from finished products to semi-product and ingots of various forms—were stored. Other storage rooms contained primarily luxury or inscribed items, such as bronze bowls at Teishebaini (Piotrovsky, 1970, p. 153) or bronze plaques at Giyimli (Taşyürek, 1977). These can be considered as royal treasuries or hoards.

In sum, Urartian metal artefact deposits include royal treasuries as well as ritual offerings and favissae within temples. A further hypothesis is that some stored artefacts may have been intended for the use of royal or temple staff in their daily functions.

Mesopotamia (table 2)

During the first few centuries of the 1st millennium BCE, Mesopotamia was largely under the rule of the Assyrian Empire, a powerful political entity that maintained rivalries with Urartu to the north, Babylonia to the south, Elam to the southeast, and the Zagros mountain dwellers to the east. The Mesopotamian Plain itself is a region poor in metallic resources. However, archaeology, iconography, and epigraphy all attest to the abundance of metal in Assyria. This metal arrived through war spoils, tribute, taxation, and official gifts. The southwest palace of Sennacherib in Nineveh illustrates the acquisition of metal booty from a Chaldaean settlement (Reade, 1983, fig. 61). Since metal is recyclable, Assyrian artists and metalworkers could apply their stylistic traditions during the re-melting and re-production of imported artefacts. Such artefacts were stored in various royal storage facilities. The fort of Shalmaneser at Nimrud presents a remarkable example of Assyrian royal treasures in storage rooms (Mallowan, 1966). A particularly striking discovery was a huge assemblage of bi-pyramidal iron ingots—amounting to 160 tons—found in Sargon's palace at Khorsabad (Place, 1867, pl. 71; Oates and Oates, 2001, p. 249). This deposit was likely made up partly of spoils and iron tributes collected from Anatolia. It is also worth noting that storage rooms containing only weapons deposits are generally interpreted as arsenals (Mallowan, 1966, p. 376).

Site	Region	Content			Environement		Modality of action		Type of deposit
		Material	Categories	State	Nature	Context	Moment	Gesture	
Nazalebi	Caucasus	Copper alloy	Weapons, Ornament	Final and semi-final products	Anthropic	Circular sanctuary	During occupation	In a pit beneath the floor	Favissa
Nazalebi	Caucasus	Mostly Copper alloy, but also other materials such as stone beads	Weapons, Jewellery, Tools	Final and semi-final products	Anthropic	Circular sanctuary	During occupation	Inside jar, beneath the floor	Favissa
Shilda	Caucasus	Copper alloy	Weapons, Ornaments	Final and semi-final products	Anthropic	Circular sanctuary	During occupation	Inside jar, beneath the floor	Favissa
Shilda	Caucasus	Copper alloy	Weapons, Ornaments	Final and semi-final products	Anthropic	Circular sanctuary	During occupation	Inside jar, beneath the floor	Favissa
Shilda	Caucasus	Copper alloy	Weapons, Ornaments	Final and semi-final products	Anthropic	Circular sanctuary	During occupation	Inside jar, beneath the floor	Favissa
Shilda	Caucasus	Copper alloy, stone	Ornaments, Figurines	Final and semi-final products	Anthropic	Circular sanctuary	During occupation	Inside jar, beneath the floor	Favissa
Shilda	Caucasus	Copper alloy	Weapons,Ornaments, Figurines	Final and semi-final products, Mold	Anthropic	Circular sanctuary	Not clear	At the foundation level	Favissa
Ayanis	Caucasus	Copper alloy	Weapons	Final products	Anthropic	Temple	During occupation	Put on a plateforme / fixed on the wall	Temple Offering
Ayanis	Caucasus	Copper alloy	Weapons	Final products	Anthropic	Temple	During occupation	stored in storage room	Favissa
Toprakkale	Caucasus	Copper alloy		Final products	Anthropic	Temple	During occupation	Put on a plateforme / fixed on the wall	Temple Offering
Teishebaini (Karmir Blour)	Caucasus	Copper alloy	Differents categories	Final and semi-final products	Anthropic	Fortress	During occupation	Stored in storage room	Treasure
Giyimli	Anatolia	Copper alloy	Metal sheets, Ornament, Horse equipments	Final products	Anthropic	Fortress	Unclear	stored in storage room	Treasure?

Table 1 – Iron Age deposits from Caucasus and Anatolia.

Site	Region	Content			Environement		Modality of action		Type of deposit
		Material	Categories	State	Nature	Context	Moment	Gesture	
Nimrud	Mesopotamia	Copper alloy	Lion weights	Final products	Anthropic	Palatial	During construction	Beneath the gate of the North-West Palace throne room	Construction deposit
Nimrud	Mesopotamia	Differents materials	Different categories	Final products	Anthropic	Palatial	During occupation	In the storage room of shalmanasar fort	Treasure
Khorsabad	Mesopotamia	Iron	Bipyramidal ingots	Semi-products (Ingot)	Anthropic	Palatial	During occupation	In the storage room of sargon palace	Treasure
Assur	Mesopotamia	Differents metals	Beads+ fragments	Raw materials, fragments, broken artefacts	Anthropic	Palatial	During construction	At foundation level of each corner of Ziggurant of Assur	Construction deposit
Assur	Mesopotamia	Gold + Silver	Fragments	Fragments	Anthropic	Palatial	During construction	At foundation level of Nabu temple	Construction deposit
Nippur	Mesopotamia	Silver	Chunks of silver, beads	Fragments, final products	Anthropic	Domestic	During occupation	In a ceramic vessel	Treasure/economic hoard

Tables 2 – Iron Age deposits from Mésopotamia

Site	Region	Content			Environement		Modality of action		Type of deposit
		Material	Categories	State	Nature	Context	Moment	Gesture	
Susa	Susiana Plain	Gold + Silver + Copper alloy + Stone	Figurines, Ornaments, Tools	Final products	Anthropic	Temple	During occupation	Buried underground near the Insusinak temple	Favissa
Susa	Susiana Plain	Gold+ Silver + copper alloy, Ivory, Terracotta	Ornements, scrap of gold and silver, Figurines, tools, weapons, Cylinder seals	Final product, fragments	Anthropic	Temple	During occupation	Buried underground near the Insusinak temple	Favissa
Susa	Susiana Plain	Copper alloy	Modele of a ritual scene	Final products	Anthropic	Unclear	During construction	Put in the wall of a building	Construction deposit
Tchoga Zanbil	Susiana Plain	Differents metals	Weapons, Tools, Vessels, Figurines	Final products	Anthropic	Temple	During construction	Put in a pit under the floor of the ante-cella of Kiririsha East temple,	Construction deposit

Tables 3 – Iron Age deposits from the Susiana plain.

While much of the metal in Assyrian culture belonged to royal treasuries, another significant tradition finds its origins in the Bronze Age: construction deposits. These consist of artefacts placed at the foundation levels of buildings—both sacred and profane—as ritual acts of protection or commemoration. Assyrian kings were particularly devoted to this practice. Although stone tablets, clay cylinders, and prisms—inscribed with royal proclamations (Lackenbacher, 1990)—are the most prominent forms of construction deposits, other materials such as metal tablets, figurines, beads made of semi-precious stones, seals, and shells are also attested in various contexts and mentioned in texts. In one of the inscriptions from Khorsabad, Sargon II declares that he buried gold, silver, copper, and precious stones at the foundation level of a structure, probably a city gate. Similar declarations are found from Esarhaddon, Sennacherib, and Nebuchadnezzar II (Ellis, 1968, p. 135). Regarding metal specifically, numerous small objects—such as beads, fragments of iron and lead, and inscribed disks of gold and silver—were buried at each corner of the ziggurat at Assur (Ellis, 1968, p. 132–133). Likewise, in the Nabu Temple, over a kilogram of gold and silver fragments was found at the foundation level (Ellis, 1968, p. 137). The northwest Palace at Nimrud also contained bronze zoomorphic weights buried beneath its gate floor (Layard, 1853, p. 601-602; Oates and Oates, 2001, p. 247). Metal tablets, in particular, were a recurring type of deposit from the time of Shalmaneser I (13th century BCE) onward (Ellis, 1968, p. 174). However, this practice fell out of favour by the end of the Assyrian period. Neo-Babylonian rulers did not adopt it, though it was briefly revived during the Achaemenid period (Schmidt, 1953, p. 1, 70, 79, figs. 29, 42A-B, 43)—which lies beyond the chronological scope of this study.

It is also important to note that foundation deposits were not confined to royal or divine architecture; they could also be extended into the domestic sphere and be buried beneath the floors of private buildings (Wiggermann, 1992, Text I, lines 152, 155). As Bachhuber (2018, p. 276) observes: "…metal objects could become tokens of hidden power or objects that had been transformed into actions through communion with the cosmological realm."

Susiana plain (table 3)

The Susiana Plain, situated between the Mesopotamian Plain and the Iranian Plateau, maintained mutual contacts with both regions. In terms of artefact deposition, it followed the Mesopotamian tradition: the practice of placing construction deposits at the foundation level of buildings, which began in the Bronze Age and continued into the Iron Age. Tchoga Zanbil and Susa are two major Elamite sites on the Susiana Plain, where metal vessels, jewellery, figurines, weapons, and ingots have been discovered—either deposited on the surface, beneath floors, or embedded within the masonry of temples and sanctuaries (Ghirshman, 1968, p. 22, plates XVIII–XXI; p. 24, figs. 7–8; Ghirshman, 1966, p. 100–101, plates LIV, LV, XCII, XCIII).[3] These deposits, depending on their location and manner of deposition, can be categorized as offerings (when placed visibly in ritual contexts), favissae (when buried in pits beneath the floors of sanctuaries), or construction deposits (when placed at the foundation level or embedded within building walls). A remarkable example of a construction deposit is the bronze model of King Shilhak-Inshushinak, which represents a ritual scene and dates to the 12th century BCE. It was embedded in a block of plaster within a wall of a building in Susa (Jéquier et al., 1905, fig. 5).[4]

Iranian Plateau (table 4)

On the Iranian Plateau, despite its importance as a metal-supplying region, the situation is quite different from that in neighbouring areas. Even though ritual sites have been identified from as early as the 7th millennium BCE (Schmidt, 1937, p. 177; Negahban, 1979; Majidzadeh, 2001, p. 143; Sarlak, 2011, p. 394), all forms of temple offerings remain rare throughout the entire Metal Ages. What appears to be a more common ritual practice in this region is the custom of in-filling buildings at the end of their occupation. The Jiran Temple at Tepe Ozbaki, dating to the 5th millennium BCE (Majidzadeh, 2010, p. 112), as well as Iron Age sites such as Zar Bolagh (Malekzadeh et al., 2014, p. 174), Qoli Darvish (Sarlak, 2011, p. 392), and Tepe Ozbaki (Majidzadeh, 2001, p. 8–10)[5] are all examples of in-filled buildings that demonstrate the long-standing history of this practice on the Iranian Plateau. In some cases—such as at Qoli Darvish—artefacts including ceramic vessels and bronze bars have been found within the in-filling layers (Sarlak, 2011, p. 393). However, it remains unclear whether these objects were intentionally deposited or ended up there accidentally. If intentional, they can be interpreted as closure deposits. The custom of in-filling ritual buildings is also observed in regions neighbouring the Iranian Plateau. For example, Nush-i Jan in the central Zagros region (Stronach and Roaf, 2007, p. 91) and Tepe Bazgir in the Gorgan Plain (Moslehi et al., 2014, p. 112) both show evidence of this practice. Tepe Bazgir is a particularly noteworthy case: around 700 copper-alloy vessels, weapons, and tools—dated to the 2nd millennium BCE—were found piled in a large pit (approximately 4 × 3 × 1.5 meters) dug beneath a filled building. These artefacts may have been deposited either at the end of the building's occupation (closure deposits) or during its use (as favissae or a treasure). However, due to the limited extent of archaeological investigation at the site, the exact motivation behind the deposition cannot be definitively determined.

The Chaleh Ghar Cave, located between Qom and Kashan, represents an exceptional and significant case on the Iranian Plateau, where a metal supply site is directly associated with ritual practice. Chaleh Ghar lies in close proximity to the Veshnaveh copper mine and is itself a

3. https://collections.louvre.fr/ark:/53355/cl010180456

4. http://www.louvre.fr/oeuvre-notices/sit-shamshi.

5. http://www.iranicaonline.org/articles/palace-architecture

prehistoric mining site. Approximately one thousand artefacts—comprising various materials and categories such as jewellery, beads, rings, earrings, and coins—were deposited in a wet area within cavities of the copper mine. Some artefacts appear to have been thrown into the cave from the outside. This act is interpreted as a form of votive deposition (Bagherpour-Kashani and Stöllner, 2011; Overlaet, 2011). Copper ore extraction at Veshnaveh dates back to the 3rd millennium BCE. However, 14C dating places the votive deposits at Chaleh Ghar between the 8th century BCE and the 8th century AD. Chronological patterns indicate that in the earlier phases, only ceramic objects were typically deposited. It was not until the Sasanian period that beads, jewellery—especially distinctive finger rings—and votive plates began to appear. Thus, for the purposes of this study, which focuses on the Iron Age, it appears that metal did not play a significant ritual role during that period at this site. It is mentioned here to highlight the association between a copper mine and ritual deposition

Zagros Mountains (table 5)

The Zagros region is located in a strategic place between the Iranian Plateau (rich in metallic resources) and the Mesopotamian Plain (an important consumer region). The communication routes connecting these two regions pass through the heart of the Zagros. Due to the abundance of natural resources, the Zagros was of significant economic and political interest. While cultural influences from neighbouring regions are evident, a distinct culture—shaped by the environment and lifestyle—appears to have developed in this area. One of the most famous expressions of this culture is a series of remarkable metal artefacts known as the Luristan Bronzes. Although many of these artefacts have been discovered in funerary contexts, sanctuaries were also favoured locations for their deposition. Surkh Dum-i Lori and Sangtarashan are two of the most significant sanctuaries in Luristan that contained these elaborate metal artefacts in votive deposits. At Surkh Dum-i Lori (Schmidt et al., 1989), nearly two thousand artefacts, predominantly ornaments and particularly pins, were discovered within the masonry of the walls and beneath the floors of a rectangular structure interpreted as a sanctuary. These findings are considered as construction deposits and are dated to the 9th–8th centuries BCE, though some artefacts may be from earlier periods.

Sangtarashan (Hashemi et al., 2023) is another Iron Age sanctuary located in the central Zagros, where approximately one hundred metal artefacts (mostly bronze, some iron), grouped in packages of 2 to 30 items, were placed beneath the floor of a circular building. These packages were deposited at various depths within an elongated pit. The two dominant categories of artefacts were vessels and weapons. The deposition likely occurred over an extended period, at varying intervals, involving multiple packages. Of the sixteen packages discovered, two were not found in the pit or beneath the floor but rather on the surface, with collapsed stones from the northern wall covering them. This suggests these packages were initially exposed and only later buried, possibly as favissae. This two-step offering practice shows similarities to Urartian traditions. On the other hand, the circular stone architecture, the pit-burial of artefact packages, artefact typologies, and chronological elements display strong parallels with Caucasian sanctuaries such as Shilda and Nazarlabi in Georgia. In a later phase at Sangtarashan, rectangular structures were constructed over the earlier circular building. More than one thousand artefacts—made from a wider variety of materials (bronze, iron, semi-precious stones, stone, terracotta, etc.) and representing diverse categories (weapons, vessels, jewellery, figurines, standards, tools, etc.)—were scattered throughout the site and embedded in wall masonry. These may have been deposited during construction or restoration (construction deposits) or thrown into the building at its abandonment (closure deposits). The damaged state of the architecture prevents more precise interpretations.

Further north in the Zagros, depositional practices align more closely with Urartian and Assyrian traditions. The Hasanlu IVB destruction level (ca. 9th century BCE) is a striking example: storage rooms and treasuries in temples and elite buildings contained assemblages of diverse materials and artefact categories, including many bronze and iron weapons and ornaments, some wrapped in textile bundles (Dyson, 1989, p. 120–126).

Further south, in the territory of the Elamite kingdom, the Kalmakareh Cave appears to have served as a repository for precious metal artefacts belonging to local elites or royalty. Numerous silver and gold artefacts—including vessels, masks, and ornaments, now scattered across various museums—are attributed to this cave. Unfortunately, they were recovered exclusively through illegal looting. However, testimonies from looters and workers, along with limited archaeological evidence, suggest that artefacts were placed in the natural cavities of the cave.[6] Some artefacts bear royal inscriptions, allowing them to be dated to the 7th–6th centuries BCE. They may have been dedicated directly to the cave as offerings or may have originally belonged to a primary sanctuary (favissa) or royal treasury, later transferred to the cave for reasons now unknown.

Across western Asia, caves appear to have been long-standing sacred spaces for the deposition of metal artefacts throughout history.

Arabian Peninsula (table 6)

According to both textual sources and archaeological evidence, the Arabian Peninsula was one of the principal source regions for raw materials during the Bronze and Iron Ages. Magan, identified as present-day Oman, is recognized as a major copper source (Cohen, 1975; Weeks, 2016; Giardino, 2019), while Dilmun, identified as present-day Bahrain, functioned as an important commer-

6. https://chaharrah.tv/events/kalmakare/

Site	Region	Content			Environement		Modality of action		Type of deposit
		Material	Categories	State	Nature	Context	Moment	Gesture	
Chaleh Ghar	Iranian Plateau	Metals, stones, potteries	Potteries, Ornements	Final products	Natural (Cave/mine)	Mine	During occupation	Put in a wet area inside a mine. Artefacts were also thrown inside from outside	Offering
Tepe Bazgir	Gorgan plain	Copper alloy	Vessels, Weapons, Tools	Final products	Anthropic	Unclear	Unclear	Put in a pit under the floor of a building. The building was filled up at the end of its occupation	Favissa/Treasure

Tables 4 – Iron Age deposits from the Iranian Plateau

Site	Region	Content			Environement		Modality of action		Type of deposit
		Material	Categories	State	Nature	Context	Moment	Gesture	
Nush-I Jan	Zagros	Silver	Scrap, Ornements	Final product, semi-final, fragments	Anthropic	Fortress / Temple	During occupation	Put in a jar and buried under the floor a fort, near a temple	Economic hoard
Sangtarashan	Zagros	Copper alloy, Iron stone, terracotta	Weapons, Ornaments, Vessels, Figurines, Tools	Final products	Anthropic	Sanctuary	Not clear (during construction or at the end of the occupation)	Put in the walls and/or thrown inside the building at the end of the occupation	Construction deposit / Closure deposit
Sangtarashan	Zagros	Copper alloy, Iron	Weapons, Vessels	Final products	Anthropic	Sanctuary	During occupation	Buried in a pit, beneath the floor	Favissa
Sangtarashan	Zagros	Copper alloy, Iron	Weapons, Vessels	Final products	Anthropic	Sanctuary	During occupation	Put on the floor	Offering
Surkh Dum-I Lori	Zagros	Metal	Variety of categories	Final products	Anthropic	Sanctuary	During construction/restoration	Put in the walls and also buried beneath the floors	Construction deposit
Hasanlu	Zagros	Different materials	Variety of categories	Final products	Anthropic	Temple	During occupation	Un clear (maybe put on the floor)	Offering?
Hasanlu	Zagros	Different materials	Variety of categories	Final products	Anthropic	Prominant building	During occupation	Unclear (fallen from second floor at the moment of destruction?)	Treasure?
Kalmakareh	Zagros	Silver + Gold	Vessels, Figurines, Masks, Ornaments	Final products	Natural	Unclear		Put in the natural cavities of the cave	Favissa? Treasure? Offering?

Tables 5 – Iron Age deposits from the Zagros.

cial hub for metal exchange (Pettinato, 1983, p. 77–78; Weeks, 2016). Thus, it is not surprising to find significant metal artefact deposits in various contexts, particularly those associated with metal production. Saruq al-Hadid (Weeks et al., 2017) in Abu Dhabi and As-Safah / Uqdat al-Bakrah (Genchi et al., 2007) in Oman are two remarkable early Iron Age examples. In both sites, numerous metal artefacts—including high-quality finished objects, semi-finished products, and production waste (slags)—were deposited on the desert surface, with little accompanying architectural evidence.

At Saruq al-Hadid, the finds include gold, copper alloy, and iron artefacts, along with slags, furnaces, and technical ceramics (see Franke et al. in this publication). In contrast, at As-Safah, the artefacts are primarily copper alloy, with few slags and limited technical ceramics. These sites are interpreted as ritual centres connected to metalworking activities, likely involving the participation of metalworkers themselves (Lehner et al., 2023). Deposits can thus be considered as offerings or favissae. The site of Mudhmar, also in Oman, provides another example, where metal artefact deposits—comprising only finished objects such as quivers, arrowheads, bimetallic daggers, snake-shaped figurines, and miniature weapons were placed, on the floor of a prominent building, possibly offering a ritual context (Gernez and Giraud, 2019; Jean et al., 2021)

The presence of raw materials and production waste in votive deposits in the Arabian Peninsula is also evidenced by jar deposits. At Masafi 1 (in the United Arab Emirates), more than one hundred metal masses—including complete and fragmented ingots, irregularly shaped metal fragments, and furnace debris—were placed in jars, sealed with plugs of raw earth, and buried in pits beneath the floors of communal buildings (Benoist et al., 2023). Similarly, at Bithnah (UAE), copper prills—likely recovered directly from the furnace—were deposited in a snake-decorated jar. This jar was accompanied by a small pile of slag placed in front of the snake's head, and everything was buried together beneath the floor of a building (Benoist, 2007, p. 38).

Levant (table 7)

In the Levant, jar deposits are among the most characteristic forms of artefact deposition during the Iron Age. These deposits generally consist of small, complete or fragmented artefacts placed inside ceramic vessels and buried beneath the floors of buildings. The tradition of ceramic jar deposits dates back to at least the 3rd millennium BCE and is attested throughout the western Asian region (Matthews, 1994; Moorey, 1994, p. 238; Peyronel, 2010). However, this practice became increasingly common and widespread during the Iron Age. Tel Dan provides an example of an Iron Age jar deposit containing bronze weapons, figurines, and jewellery (Ilan, 1992), which may be interpreted as a hidden treasure. While bronze and gold items are occasionally found in jars, silver appear to dominate in the Iron Age jar deposits. These deposits, composed exclusively of small silver items, are referred to as 'cut silver' or 'hacksilber' and typically include damaged or fragmented jewellery, ingots, and shapeless silver pieces—such as hacked sheets, tokens, wires, rods, coils, and bars. These items were commonly wrapped in textiles and buried beneath the floors of various buildings.

Silver jar deposits first appeared in the 3rd millennium BCE, but became increasingly common during the 2nd millennium BCE (Eshel et al., 2023), and particularly in the 1st millennium BCE. Several dozen examples have been identified in the Levant (Kletter, 2013). One example from Tel Dor (Stern, 2001) features silver pieces divided into several bundles, wrapped in textiles, with some bundles sealed with clay bullae. The jar was covered with a bowl before being buried under the building. At Ein Hofez (Alexandre, 2013), jars containing silver fragments were found leaning against the internal walls of a house, positioned between two floor levels. At Tel Keisan (Nodet, 1980, p. 325), a jar containing silver bundles wrapped in textiles was discovered in the courtyard of a domestic complex. In some cases—such as Tel Miqne-Ekron (Golani and Sass, 1998) and Beth Shean (Thompson, 2009)—assemblages of hacksilber were found beneath building floors without any ceramic jar containers.

Several scholars have investigated the function of hacksilber (Belmuth, 2001; Thompson, 2003; Kletter, 2013; Eshel et al., 2018; Heymans, 2021; Eshel et al., 2023). Some interpret these deposits as craft hoards, representing the metalworkers' stock for recycling. However, the dominant hypothesis views them as a form of currency, bullion, or transactional material, thus classifying them as economic hoards. The exclusive use of silver in these deposits is significant. There are no comparable hoards in gold or copper.

While the Levant remains one of the most important regions for hacksilber deposits, similar finds have been identified in other areas, including the Arabian Peninsula (Krauss et al., 1983) and the Zagros. For instance, at Nush-i Jan in the central Zagros (Bivar, 1971; Curtis, 1984), a ceramic jar containing silver scraps, ingots, and jewellery was found buried beneath the floor of an Iron Age fortress.

Levantine caves were also favoured places for concealing valuable objects. In Wadi el-Makkuk, gold, bronze, and silver jewellery and scraps were found buried just below the surface of a cave (Sass, 2002).

DISCUSSION

Metal artefact deposits played an important role during the Metal Ages of southwest Asia. Metal weapons as offerings and treasure are among the most representative deposits during the Chalcolithic period. In the Bronze Age, we see a diversification in the forms and contents of metal artefact deposition. Favissae, jar deposits, con-

Site	Region	Content			Environement		Modality of action		Type of deposit
		Material	Categories	State	Nature	Context	Moment	Gesture	
Saruq Al-Hadid	Arabian Peninsula	Copper alloy + Iron + Gold + silver+ Lead+ Stone + semi precious stone	Figurines, Weapons, vessels, Ingots, Ornaments, Tools	Final and semi-final products, Waste and tools of production	Unclear	Ritual/industrial place	Not clear	Speared on the surface of the desert over an area of 1km or buried within or beneath dunes up to 6m deep	Votive depposit?
As-Safah (Uqdat al-Bakrah)	Arabian Peninsula	Differents metals	Differents categories	Final and semi-final products, Waste and tools of production	Unclear	Unclear	Unclear	Speared on the surface of the desert with few architectural elements	?
Mudhmar 1	Arabian Peninsula	Copper alloy	Weapons, Figurines	Final products and unfinished artefacts	Natural	Unclear	Unclear	Put into karstic cavities along the slope. As water flowed down from the karstic system and cavities, the hidden deposits were transported along with colluvial sediments	?
Mudhmar 2	Arabian Peninsula	Copper alloy	Weapons	Final products	Anthropic	Unclear	During occupation	Put on the floor	Offering
Masafi 1	Arabian Peninsula	Copper alloy, Terracotta	Scrap, tools	Ingot (semi-final product), Tools of production, Fragments,	Anthropic	Collective building	During occupation	Put in a jar and buried in a pit under the floor of a collective building	Votive depposit?
Bithnah	Arabian Peninsula	Copper	Prils	Raw materials, Wastes of production	Anthropic	Unclear	During occupation	Put in a jar and buried in a pit under the floor of a building	Votive depposit?

Table 6 – Iron Age deposits from the Arabian Peninsula.

Site	Region	Content			Environement		Modality of action		Type of deposit
		Material	Categories	State	Nature	Context	Moment	Gesture	
Tel Akko	Levant	Silver	Scrap	Fragments, semi-products	Anthropic	Domestic / artisanal	During occupation	Put in a jar and buried in a pit under the floor of a building	Economic hoard
Ein Hofez	Levant	Silver	Scrap	Fragments, semi-products	Anthropic	Domestic	During occupation	Putt in jars. Jars were leaning against internal wall of a house, between two floors	Economic hoard
Tel Dor	Levant	Silver	Scrap	Fragments, semi-products	Anthropic	Unclear	During occupation	Contents was divided into several bundles, wrapped in textiles, put in a jar. Jar was covered by a bowl and buried under the floor of a building	Economic hoard
Tel Keisan	Levant	Silver	Scrap	Fragments, semi-products	Anthropic	Domestic	During occupation	Content, in four bundles, wrapped in textiles, was put in a jar. Jar was put in the courtyard of a domestic complex	Economic hoard
Wadi el-Makkuk	Levant	Silver, Copper, Gold, Stone	Scrap, ingots, Jewelry	Fragments, semi-products, final products	Natural	Unclear	Unclear	Buried beneath the surface of a cave	Economic hoard
Beth Shean	Levant	Silver + Gold	ingots and jewelry	Fragments, semi-products, final products	Anthropic	Temple	Unclear	Buried at the foundation level of a building	Economic hoard
Tel Miqne-Ekron	Levant	Silver	Brocken and damaged jewelry, scrap	Fragments, final products	Anthropic	Unclear	During occupation	Put in a jar and buried under the floor of a building	Economic hoard
Tel Miqne-Ekron	Levant	Silver	Brocken and damaged jewelry, scrap	Fragments, final products	Anthropic	Unclear	During occupation	On the floor of a building	?

Table 7 – Iron Age deposits from the Levant.

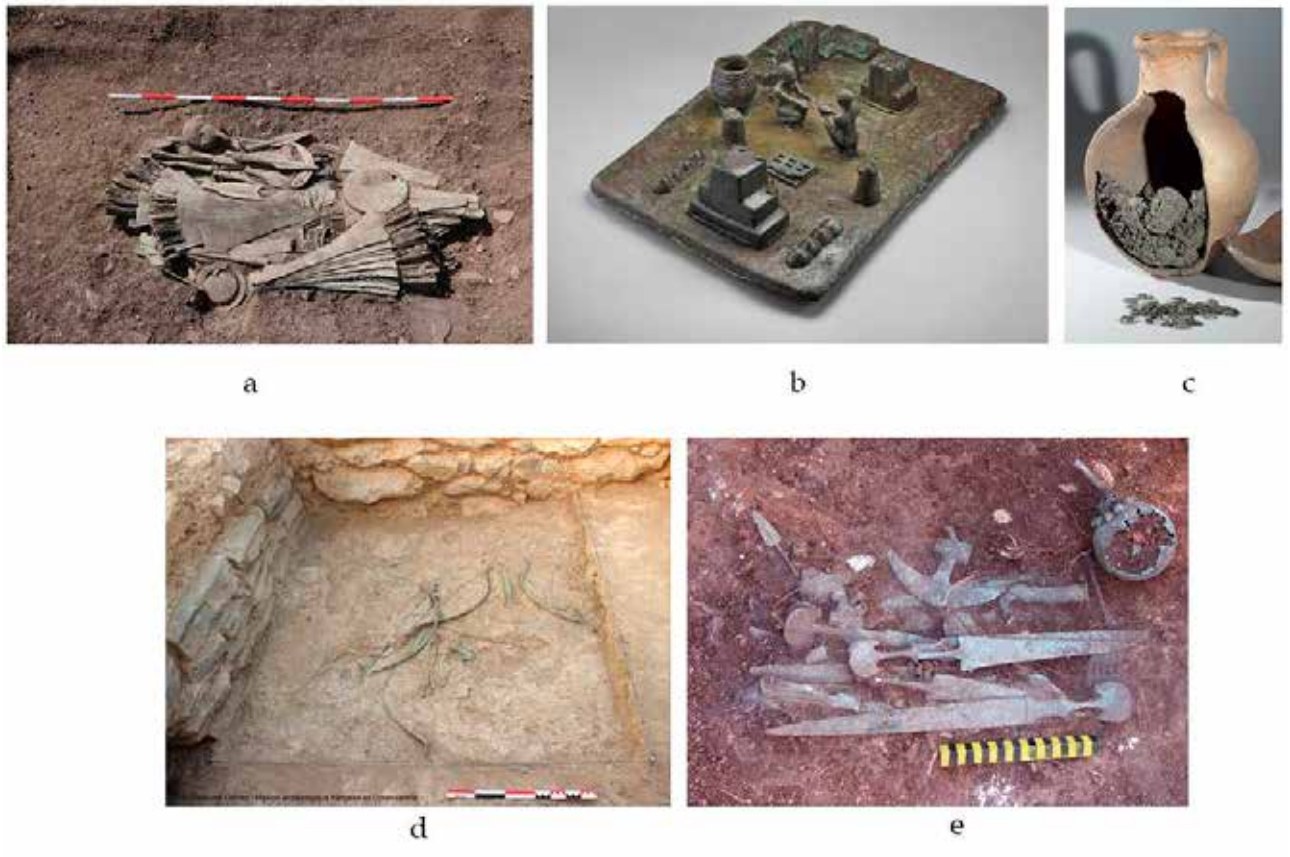


Fig. 5 – Examples of different deposits: a. Nazarlabi, Votive deposit (photo: Archive Prof. Dr. Felix Blocher); b. Susa, Construction deposit, Louvre Museum, SB 2743 (photo : Louvre site des collections) ; c. Tel Dor, Economic hoard , The Israel Museum (photo: Eshel et al., 2018, fig. 5a); d. Mudhmar East, Votive deposit (photo: Genez, Giraud, 2017, Fig. 7.9. Guillaume Gernez); e. Sangtarashan, Votive deposit (Photo: Archive of Sangtarashan's archaeological mission).

struction deposits, offerings, economic hoards, and craft hoards containing various categories of artefacts are all attested during this period.

However, during the Iron Age, there appears to be a significant increase in the density of metal artefacts across various contexts. Religion, economy, and craftsmanship were three major domains associated with the practice of metal deposition. Construction deposits, favissae, royal and elite treasures stored in storage rooms, and economic hoards in the form of hacksilber are among the most characteristic types of deposits of this era.

Generally, no consistent association can be found between the type of artefacts and the type of deposit. Final artefacts in circulation, such as weapons, jewellery, and vessels, make up the content of the deposits. However, in certain regions—such as Susiana and the Zagros—an association between vessels and weapons can be observed in votive deposits. Regarding the homogeneity of deposits, both multi-type and uni-type assemblages are attested. In some regions, the presence of semi-final products and production waste in votive deposits is noteworthy. Copper alloy is the most common material in votive deposits and craft hoards. Silver, mostly in the form of small fragments, is dominant in economic hoards. However, regional variations must be considered for a more nuanced understanding.

From a broader perspective, the end of the 2nd and the beginning of the 1st millennium BCE in western Asia coincided with the rise of powerful political entities, such as Assyria, Urartu, and Elam. Intense interactions—including peaceful trade, rivalries, and military confrontations—took place among these powers. Metal was not only a luxury material in both divine and royal contexts but also a fundamental resource for weapons, tools, and economic exchange. However, the uneven distribution of metal ores meant unequal access between different societies—and even within a society. Thus, trade and imperial expansion, through spoil, tributes, and taxation, greatly contributed to the movement of metal artefacts from source regions to consumer regions.

On the Mesopotamian Plain, during the Iron Age, Assyria, as a dominant political power, imported metal through tribute, tax, and war booty. In Assyria, royal and administrative treasures and arsenals formed the majority of metal deposits. While metal was not the principal material in votive deposits, it was nevertheless included—especially in construction deposits, a long-standing Mesopotamian tradition. The presence of metal fragments in these contexts underlines the intrinsic value of metal in a land where its natural occurrence was absent.

In the Caucasus, Anatolia, the Zagros, and the Arabian Peninsula, the ritual and votive nature of metal deposits

is especially pronounced. Deposits as offerings, favissae, and construction-related deposits are numerous. Except in the Zagros, where the picture is still unclear, other regions are clearly identified as important metal supply zones. There are striking similarities in architecture, artefact typologies, and deposition practices between the Caucasus and the Zagros. In both regions, ritual spaces with stone structures contain votive metal deposits buried beneath the floors of sanctuaries, functioning either as favissae or construction-related offerings. A further parallel lies in the multi-phase (two-step) ritual process: first, offerings are made visible on platforms or open surfaces, then they are hidden—either buried or stored.

In the Zagros, votive deposits typically consist of final artefacts—mostly weapons, vessels, and jewellery. These multi-type assemblages vary from sanctuary to sanctuary. In contrast, Caucasian sites also include ingots and semi-finished products, indicating a link between ritual and metalworking activity. A similar pattern is evident in the Arabian Peninsula, where industrial, administrative, and ritual practices often co-occur, making it difficult to clearly distinguish between their functions. It is plausible that in these metal-rich areas, metalworking and metalworkers held significant social status and were closely involved in religious activities.

The prevalence of votive deposits is not uniform across all supply regions. The Iranian Plateau, despite being a major copper-producing region, follows a different trajectory. Very little evidence exists for either votive deposits or hoards, and the reasons remain unclear. It appears that the practice of metal deposition was not a common ritual tradition in this area.

Susiana and the Zagros played an intermediary role between Mesopotamia and the Iranian Plateau. Some practices in these regions, such as favissae and construction deposits, resemble Mesopotamian rituals, while other practices—like the temple fillings at Nush-i Jan—follow traditions closer to those of the Iranian Plateau. However, the typology of deposit contents reveals a character specific to the Zagros. In the northern Zagros, near the Assyrian frontier, local elites seem to have adopted Assyrian royal traditions, with storage rooms housing treasures that include many metal weapons and ornaments influenced by Assyrian and Urartian styles.

In the Levant, metal votive deposits—once common in the 2nd millennium BCE—lost importance during the Iron Age. Instead, economic hoards, particularly hacksilber in domestic contexts, became more prevalent. The collapse of Bronze Age trade networks likely played a role. The absence of centralized political power in the Levant—unlike in Mesopotamia and Anatolia—may have led to a more localized and fragmented metal economy, where individual communities managed their own acquisition, storage, and recycling. Similar phenomena, albeit on a smaller scale, can be observed in peripheral regions such as the Zagros and the Arabian Peninsula, where jar deposits buried beneath building floors have been discovered. Although some of these jars contain bronze and gold, silver appears to dominate. This suggests that silver was the preferred metal for trade, with fragmented pieces functioning as pre-monetary exchange units.

To conclude, two main factors seem to have shaped the distribution and modality of Iron Age metal artefact deposits in different regions of southwest Asia: political authority and environmental conditions. In supply regions, metal and metalworking had a central role in religious contexts. In consumer regions governed by powerful states, the palatial and administrative sphere was dominant. While local traditions are more apparent in ritual deposits, the influence of empires is more visible in secular hoards and treasuries.

In terms of natural environment, unlike Europe, where metal deposits in wetlands and rivers are common, such practices have not been investigated in southwest Asia. Thus, the role of water-related deposition remains unresolved. However, it is certain that caves have been privileged natural settings for metal artefact deposition in the region—from the Chalcolithic period through the Iron Age.

Finally, this paper should not be seen as a conclusive study, but rather as an overview of the current state of research on metal artefact deposits in Iron Age southwest Asia. Interpretations are inevitably shaped by research focus and the quantity and quality of archaeological investigations across regions. Consequently, the typology of and motivations behind metal deposits are likely to evolve as new discoveries are made.

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Life and Death of Middle Bronze Age axes. The case of the Medocan hoards

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Abstract: The successive discoveries of two Middle Bronze Age flanged axe-heads hoards on the shores of Lake Léon (Landes, France) provided an opportunity to reassess the question of standardisation and homogeneity among so-called Médoc-type axes, characteristic of southwestern France between the 16th and 14th centuries BCE. This era is marked by a high density of metal hoards outside any known domestic or funerary context, especially large trapezoidal axe-heads averaging 740 g in weight and 20 cm in length. Between the rescue excavation of the first hoard in 2017 (30 axe-heads) and the excavation of the second in 2024 (10 axe-heads), an analytical protocol was developed to characterise the production and deposition of these artefacts. Based on an extended corpus of more than 300 Médoc-type axe-heads, the study examined morphology, mass, alloy composition, metal provenance, and traces of use and discard. Even if the whole protocol could not be applied on all the objects, the results are already significant.
3D morphometric analyses reveal the existence of replicas cast from shared moulds: within the Léon hoard, only eight axe-heads are unique, while the others fall into distinct groups of duplicates. Certain similarities between Médoc and Landes assemblages suggest regional technical networks. However, statistical analysis of weights and volumes shows no metrological regularity, ruling out any hypothesis of weight-based standardisation or monetary use. The relative homogeneity observed may instead reflect technical constraints or workshop-specific manufacturing habits.
Macroscopic observations confirm actual use and partial resharpening of cutting edges, implying the deposition of still-functional tools. Elemental and isotopic analyses indicate a homogeneous bronze derived from a single metal source and the axe-heads were probably cast from a single batch. Considering an extended corpus, the deposition practices (axe-heads set vertically with edges facing upward, often in wetland contexts) suggest a repeated, possibly ritualised behaviour at a regional scale within the atlantic area. Overall, the results point to coordinated production and deposition within a shared technical and symbolic tradition, locally differentiated through subtle variations. This protocol aims to be applied to other hoards to refine the conclusions.

Keywords: Aquitaine (France), Médoc (France), Middle Bronze Age, Atlantic Bronze Age, flanged axe-heads, hoard, standardisation, 3D morphometry, archaeometallurgy, lead isotope analysis.

Résumé : Les découvertes successives de deux dépôts de haches à rebords de type médocain de l'âge du Bronze moyen, sur les berges du lac de Léon (Landes), ont offert l'occasion de réactualiser les hypothèses relatives à la standardisation et à l'homogénéité de cette typologie de lames, caractéristique du Sud-Ouest de la France. Le phénomène médocain du Bronze moyen (XVIe-XIVe siècle av. J.-C.) se caractérise par une forte densité de dépôts métalliques, sans qu'aucun lien n'ait pu être établi avec des structures domestiques ou funéraires. Ces dépôts sont essentiellement composés de lames de hache trapézoïdales massives, pesant en moyenne 740 g pour une vingtaine de centimètres de longueur. Ces objets se concentrent principalement en Aquitaine et sur ses marges.
Entre le sauvetage du premier dépôt de Léon en 2017 (trente haches) et la fouille en caisson du second en 2024 (dix haches), un protocole d'analyse a été élaboré afin de caractériser la production et les conditions de dépôt de ces objets. Ce protocole, appliqué d'abord au cas de Léon, puis étendu au corpus des lames de haches médocaines conservées au Musée d'Aquitaine et aux mesures de plus de trois cents exemplaires étudiés antérieurement, vise à déterminer le degré d'homogénéité du corpus à travers plusieurs critères : morphologie, masse, composition métallique, provenance de la matière première, traces d'usage et modalités d'abandon. Tous les volets n'ont pu être appliqués à l'ensemble du corpus, mais les résultats obtenus sur des échantillons représentatifs permettent déjà d'en évaluer la pertinence.
L'étude morphométrique, fondée sur la photogrammétrie et le scanner 3D, met en évidence une variété de formes limitée et l'existence de répliques issues de mêmes moules. La comparaison des modèles virtuels révèle des défauts de coulée similaires, confirmant la production sérielle à partir de moules communs, notamment au sein des dépôts. Dans le dépôt 1 de Léon, seules huit lames de hache sur trente sont uniques, les autres se répartissant en huit groupes correspondant à des moules ayant servi plusieurs fois. Certaines similarités interrégionales (entre objets landais et médocains, de part et d'autre de l'estuaire de la Gironde) suggèrent des traditions techniques

partagées, sans toutefois permettre d'affirmer l'usage de moules identiques.
L'analyse statistique des masses et volumes ne met en évidence aucune construction métrologique stable : aucune standardisation n'apparaît à l'échelle du corpus, écartant ainsi l'hypothèse d'un rôle monétaire de ces lames de hache par un critère pondéral. La relative homogénéité massique observée pourrait découler de contraintes techniques ou d'habitudes de fabrication propres à certains ateliers. Les variations de masse et de volume entre dépôts témoignent d'une production diversifiée, sans contrôle normatif strict.
Lorsque l'état de conservation le permet, l'examen macroscopique des tranchants montre des traces d'utilisation et d'affûtage fréquentes, notamment dans les dépôts monofonctionnels composés uniquement de lames de hache. Pour Léon, près de la moitié des exemplaires présentent un tranchant « asymétrique », indiquant un affûtage encore possible du côté opposé au tranchant émoussé. Ces observations suggèrent que les lames de hache ont eu un cycle de vie court, depuis leur fabrication jusqu'à leur dépôt pouvant sembler prématuré du point de vue fonctionnel, et peut-être dévolues à un usage très spécifique. L'analyse élémentaire des alliages révèle une composition homogène : le bronze ne comporte pas d'adjonction significative de plomb et présente un ratio cuivre/étain stable autour de 6:1, en accord avec la tendance régionale du corpus médocain. Les analyses isotopiques du plomb indiquent une origine commune du métal employé, suggérant l'usage d'un lot unique de matière première (probablement d'environ 20 kg), suffisant pour produire les trente lames de hache du premier dépôt de Léon. Ces données témoignent d'un approvisionnement structuré, peut-être fondé sur des échanges réguliers entre la côte orientale du golfe de Gascogne et une source métallifère spécifique.
L'étude des rares dépôts en place révèle enfin des similitudes notables dans les pratiques de dépôt. À Léon comme à Saint-Germain-d'Esteuil, les lames de hache sont déposées verticalement, tranchant vers le haut, parfois surmontées d'un ou plusieurs exemplaires disposés horizontalement. Des dispositions comparables sont observées pour les dépôts de Soulac-sur-Mer à l'extrême nord du Médoc, ainsi qu'ailleurs le long de l'Atlantique. Cette récurrence des gestes de dépôt, associée à la localisation fréquente des dépôts à l'interface entre milieux humides et secs, suggère une pratique ritualisée, inscrite dans des traditions régionales cohérentes dans le domaine atlantique, bien que présentant des variantes locales (présence de contenants, nombre et types d'objets).
En croisant l'ensemble des résultats (morphologiques, métallurgiques et contextuels) il apparaît que les lames de hache de Léon ont été fondues à partir d'un même lot de métal et déposées dans un intervalle de temps restreint. Plusieurs exemplaires ont été conçus pour un usage très spécifique, au vu de leur dépôt alors même que l'outil est encore utilisable : la finalité de ces objets était ainsi probablement anticipée dès leur fabrication. En observant un corpus plus large, l'homogénéité des formes, des compositions et des modes de dépôt traduit ainsi l'existence d'une tradition technique et symbolique commune à l'échelle régionale, tout en conservant des particularismes propres à certains groupes ou ateliers.
Ce protocole fondé sur la confrontation de données morphométriques, analytiques et contextuelles, constitue une base de travail innovante pour l'étude des dépôts du Bronze moyen dans le Sud-Ouest de la France. Son application à d'autres ensembles permettra d'affiner la compréhension des dynamiques de production, d'échange et de dépôt, et d'approfondir la question du rôle social et symbolique de ces objets dans les sociétés du Bronze moyen aquitain.

Mots clés : Aquitaine (France), Médoc (France), âge du Bronze moyen, Bronze atlantique, hache à rebords, dépôt, standardisation, morphométrie 3D, archéométallurgie, analyses isotopiques.

One of the most spectacular manifestations of the complex relationship between economy, technology and the symbolic sphere during the Middle Bronze Age (MBA) in south-western France (16th-14th centuries BCE), mainly in the most recent phases of this period (15th-14th centuries BCE), is the hoarding of large quantities of metal objects, mainly axe-heads, in a context where settlement and funerary patterns remain otherwise almost unknown. This regional phenomenon, well known in many other parts of Europe, has received attention in recent times. Céline Lagarde-Cardona has provided, in the framework of a larger synthesis about MBA metallurgy, a comprehensive approach of the hoards, of their composition, and the metallurgical techniques implemented in the making of the objects (Lagarde-Cardona, 2012). Some years later, Florian Couderc offered a synthesis focusing on the spatial distribution of these hoards in the specific area of the Medoc, west of the mouth of the Garonne River (Couderc, 2017). Both works offered a synthesis about the dynamics of the investigation from the late 19th century to the beginnings of the 21st. We will therefore limit ourselves, in this introduction, to summarize the main aspects of this process.

In the south-western Atlantic region, from the Charente River almost to the Pyrenees in the south, during the Middle Bronze Age, hoarding became quite a common practice while it was not frequent in the Early Bronze Age (fig. 1). 98 hoards have been found, among which 57 were located in the Medoc, the area where this process is the densest. Most of the hoards included exclusively axes-heads: in the Medoc, it was the case of 43 out of 57 of them. The most frequent type of axe-head (618 out of 822 in Aquitaine, 330 out of 403 in the sole Medoc: Couderc, 2017, p. 543) corresponds to a flanged axe having the general shape of a trapeze, weighing generally between 400 and 800 g, considered local and therefore named 'medocan axe' (*hache médocaine*). In most cases, the exact context of the discovery is unknown, but F. Couderc (2017, p. 544–554) demonstrated that in the Medoc most of the hoards were located at the interface between wet- and drylands. These axe-heads are sometimes associated with others from other origins (Central and northern Atlantic France, continental, mediterranean: Couderc, 2017, p. 543) but they can also provide the totality of the hoard, especially in the southern areas. It is for instance the case for two hoards studied for the first time in this paper, found at the southern edge of the lake of Léon (Landes).

There were few proposals of interpretations to explain this phenomenon in its regional context, beside the initial proposal of possible hiding places (Couderc, 2017, p. 531). Couderc emphasized the fact that the core region

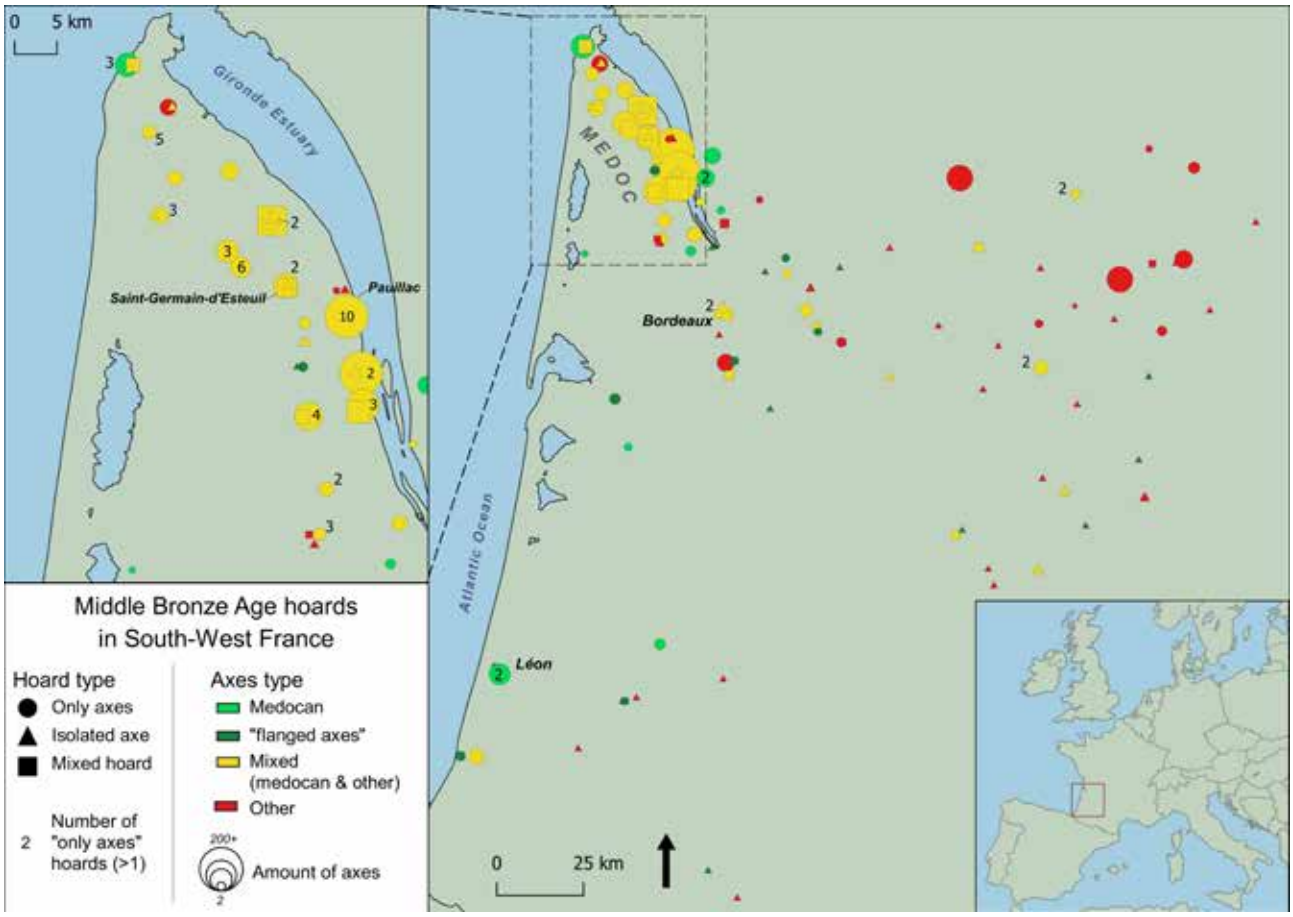


Fig. 1 – Map with location of the area of study. Left: the Medoc area.

where these hoards are observed is well connected to MBA long-distance trade networks, while it is deprived of the minerals allowing for copper-alloy metallurgy. In his opinion, the intensity of the hoarding practices would reflect the intensity of trade, and the location of most of the Medoc hoards near wetlands would be linked to the importance of sea- and river borne trade. Moreover, this phenomenon would have to be understood in a ritual framework (Couderc, 2017, p. 545–550).

In 2017, the recovery *in situ* of a MBA axe-heads hoard in Léon (Landes) gave the opportunity to extensively study the hoard itself and all the objects that were deposited in it (Gestreau, 2018). Later on, the mass removal of a second hoard, distant *c.* 30 m from the first one (Ihuel et al., 2021), and its subsequent excavation in laboratory offered a similar possibility. These discoveries have led to the elaboration of a study protocol allowing for a biographical study of the axe-heads, from their making to their burying. It involves analytical methods, 3D imagery, mathematic and statistical analyses, and very classical macroscopic observations. It was later extended to a larger corpus, with important context-dependant variants from one case to another. The results of this study are presented here.

Through the implementation of this protocol, we would like to address the specific question of the heterogeneity vs. the homogeneity of the hoarded axe-heads. This concerns chiefly their shape, volume and mass, all topics often linked with the issue of standardization. Standardization is itself linked with the idea that these hoards could have been a reserve of value and that the axe-heads could have been actually some form of currency. Even if the hypothesis has been rarely formulated concerning Medocan flanged axe-heads hoards, it appears frequently for explaining similar processes in different regions, especially since the 1980s and the researches of Jacques Briard on Armorican socketed axes (Briard, 1987a; 1987b; 2001; Briard and Rivallain, 1987).

We aim here at assessing if Medocan axe-heads were or were not standardized. Homogeneity and heterogeneity can also characterize the metal itself, its origins and the making of the alloy. Recent progress into research have shown that scales of integration regarding Bronze Age metal trade were underestimated (Ling et al., 2013; 2014; Melheim et al., 2018), while the intensity of recycling can in contrast have been overestimated. A long-distance, dense and permanent flow of metal seems to have characterized most of the Middle and Late Bronze Age, rather than scarcity and local recycling. In such cases, the relation between the metal supply chain, the making of the object, its use and hoarding must be reconsidered, as well as the temporality of this chain of events. The use(s) of each one of the axes could also be similar or on the contrary dissimilar, with an underlying question: did

all the axe-heads deposited in the same hoard have had a similar use, or on the contrary were they similar objects having been used for different purposes? Last, but not least, the motives for their final burying may be quite the same from hoard to hoard, but may on the contrary vary, and depend on the history of each object or of the assemblage to which they belong. In other words, we intend to consider the biography of the hoarded Medocan axes, from their birth to their burying.

DATASET CONSTITUTION

Our dataset gathers 370 axe-heads, directly examined by us or known through the bibliography, belonging to 21 hoards. This material may have been recovered during archaeological excavations of some hoards but, more often (in the many cases of old discoveries) the recovery occurred without real archaeological supervision. Among this dataset, 117 axe-heads were recorded in 3D using photogrammetry and/or 3D scanning (see *infra*). Two hoards found on the shores of the Lake of Léon (Landes, France), gathering in total 40 axe-heads, have been directly observed by members of the team at each step of their recovery and study.

The hoards from Léon

In 2015, two hoards were identified by metal detectorist Marc Houzé at the southern edge of the Lake of Léon (Landes, France). Both were recovered by archaeologists of the French Ministry of Culture, the first one (hoard 1) in 2017, the second one (hoard 2) in 2021 (Gestreau, 2017; Ihuel et al., 2022). One axe-head belonging to hoard 2 was retrieved at the moment of its discovery in 2015. Distant of about 30 m, both were exclusively constituted of flanged bronze axes of the Medocan type (fig. 2). Both were underwater, but very close to the surface, at the time of their recovery (fig. 3). The area where they were found had been removed in the recent past (the 1960's), when the shores of the lake were landscaped (fig. 4); a survey was made, but did not allow for the discovery of any other archaeological feature than the pits where the objects were placed. The first hoard (Léon, hoard 1) was excavated on the spot, by scuba diver Grégory Bonnin, in 2017. Observations were complicated: as a result of the shallow depth of the hoard, a lot of suspended particles obscured the water. The hoard was constituted of 30 bronze axe-heads. 28 among these 30 axes were found in primary position, inside a 30 cm diameter pit, while 2 others were found lying at the bottom of the lake previously to the excavation (fig. 5). It is very possible that they were indeed in horizontal position on top of the hoard, as in Le Chalet hoard 2 (Saint-Germain-d'Esteuil, Gironde: Roussot-Laroque, 1999). The pit was 50 cm deep, and the axe-heads were laid standing on 3 levels, with the blade oriented upward or downward, sometimes alternatively. The top level gathered 7 axe-heads found in primary position. The medium level gathered 8 axe-heads,

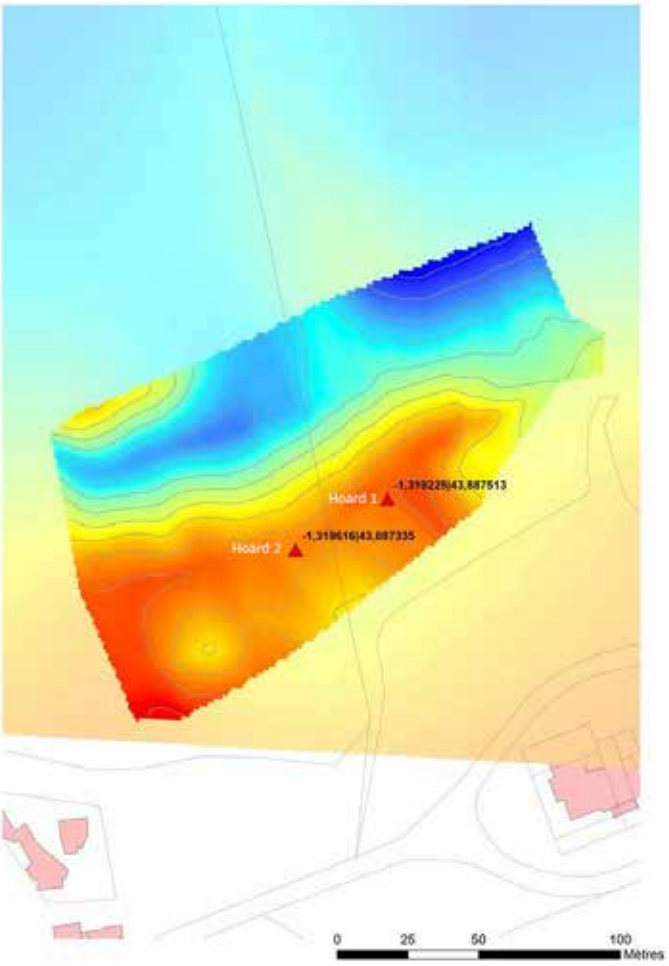


Fig. 2 – Location of the two hoards from Léon Lake (Landes, France). From Gestreau, 2018, fig. 7, p. 6.



Fig. 3 – Léon Lake, southern shore, where the hoards were found. From Gestreau, 2018, fig. 2, p. 4.

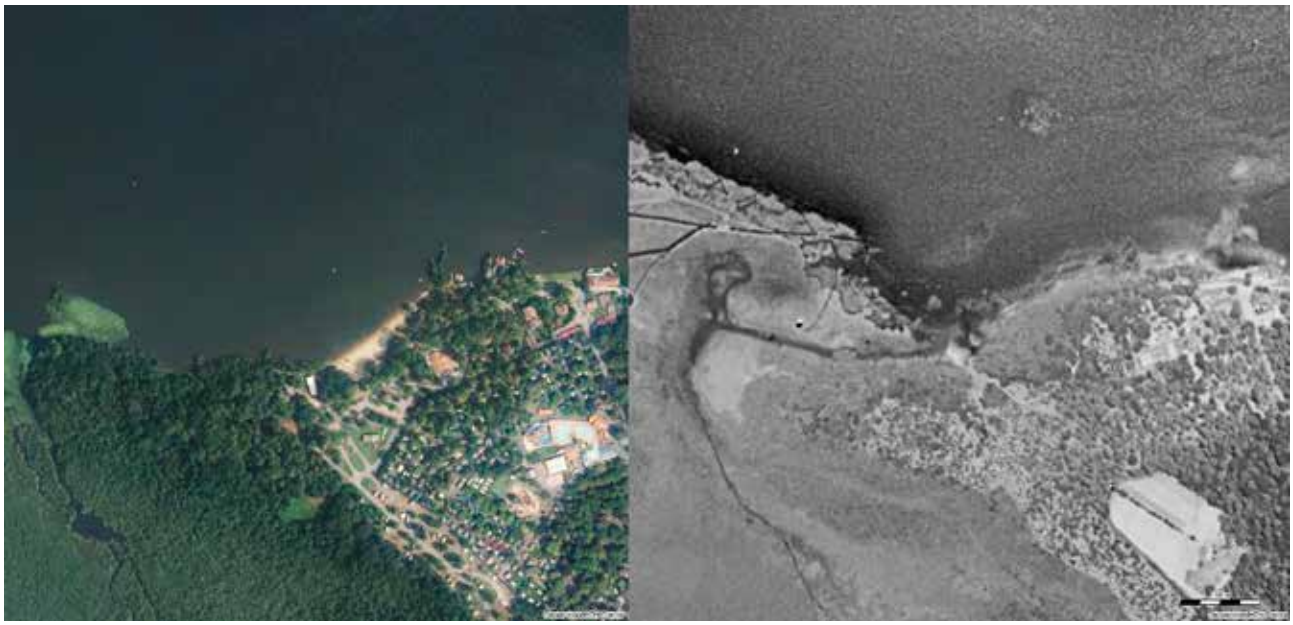


Fig. 4 – Léon Lake, southern shore, nowadays compared with 1964. From Gestreau, 2018, fig. 3, p. 4.

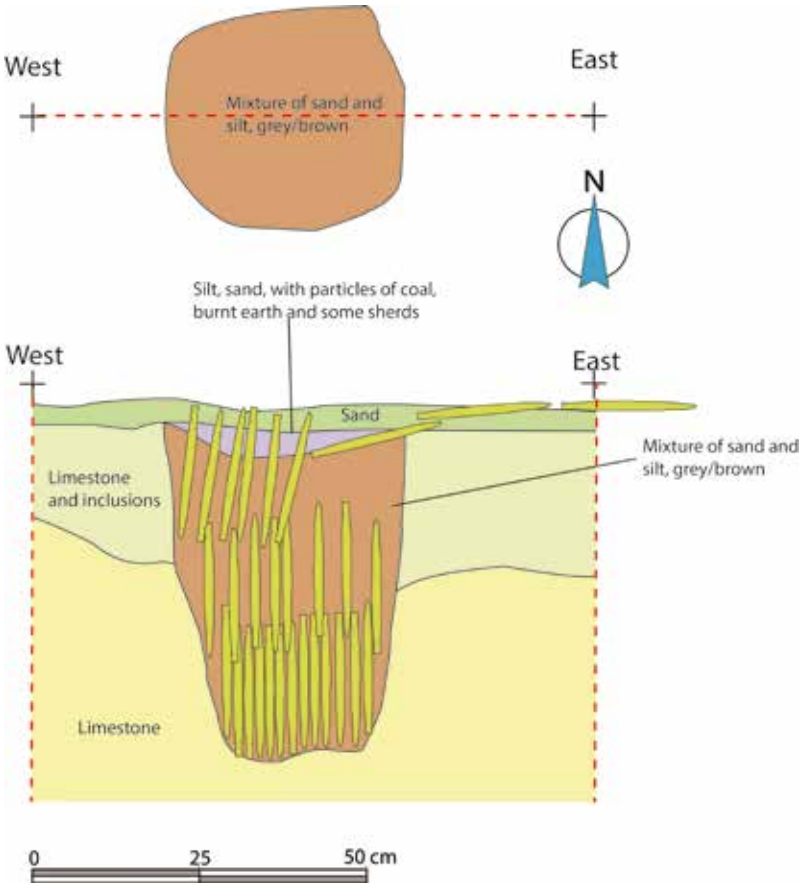


Fig. 5 – Schematic plan (up) and section (down) of Léon hoard 1, after Gestreau, 2018, fig. 8 p. 7, redrawn.

while the bottom one was made of 13 axe-heads. They were not systematically adjoined, which probably means that the pit was filled with earth (a greyish mixture of sand and silt) while the axe-heads were buried, or that they were maintained by some perishable material later substituted by colluvium (Gestreau, 2018).

The second hoard (Léon, hoard 2) was also detected in 2015, some 30 m east from hoard 1 (fig. 6). One axe-head, also lying on the bottom of the lake, was retrieved at the time of its discovery (fig. 7, no. 1). In order to optimize the

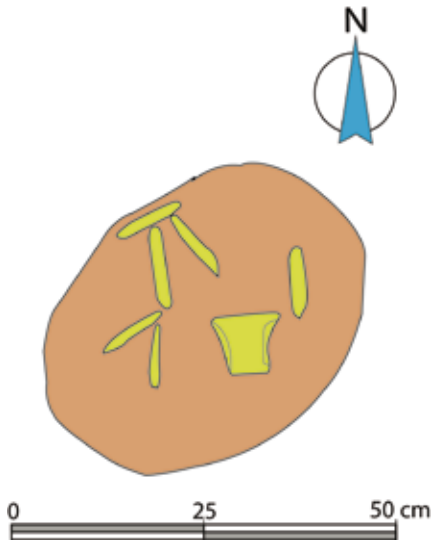


Fig. 6 – Schematic plan of Léon hoard 2, before its retrieval. From Gestreau, 2018, fig. 10, p. 9.

possibilities for direct observation, and given the absence of surrounding archaeological context, the hoard was extracted as a single mass in September 2022 for allowing an excavation in a laboratory. A barrel was driven into the ground around the hoard and extracted with an excavator. However, the bottom piece that was supposed to close the lower

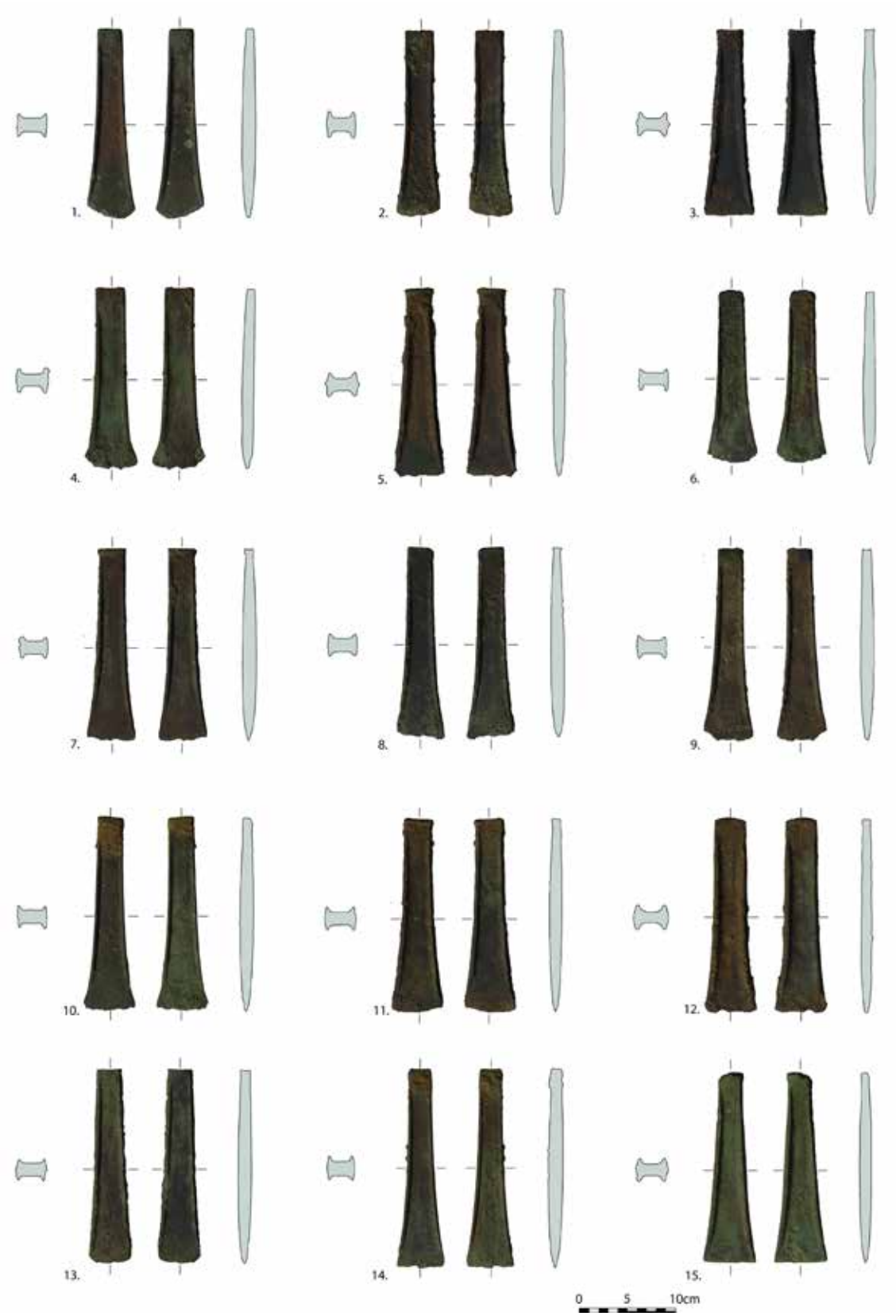


Fig. 7 – Axe-heads from the hoards of Léon 2 (no. 1) and Léon 1 (nos. 2-15). The numbers are those of the inventory given during their recovery (nos. 1-3) or during the 2017 excavation.

part of the barrel was bent in the process, and therefore was not hermetic any more: part of the sediment was washed down through the opening at the time of the removal of the sample (Ihuel et al., 2022).

The excavation in laboratory took place in March 2024, and revealed that the hoard included ten axe-heads: the one discovered at the bottom of the lake in 2015, and the nine others recuperated during the excavation process. None of them was found in primary position: they were literally sucked down when a depression of 40 × 15 cm was created by the washing of the sediment through the bottom of the barrel (fig. 8 and 9). Nonetheless, the excavation could establish that the axe-heads were originally deposited in an ovoid pit roughly oriented north/south, long c. 40 cm, wide c.18 cm, and deep 10 cm (fig. 10). At the centre of the pit, a small depression 20 cm long, 10 cm



Fig. 8 – Axe-heads from Léon hoard 2, seen from the "north". They were sucked into a depression due to the washing of the sediment through an opening on the bottom of the container.

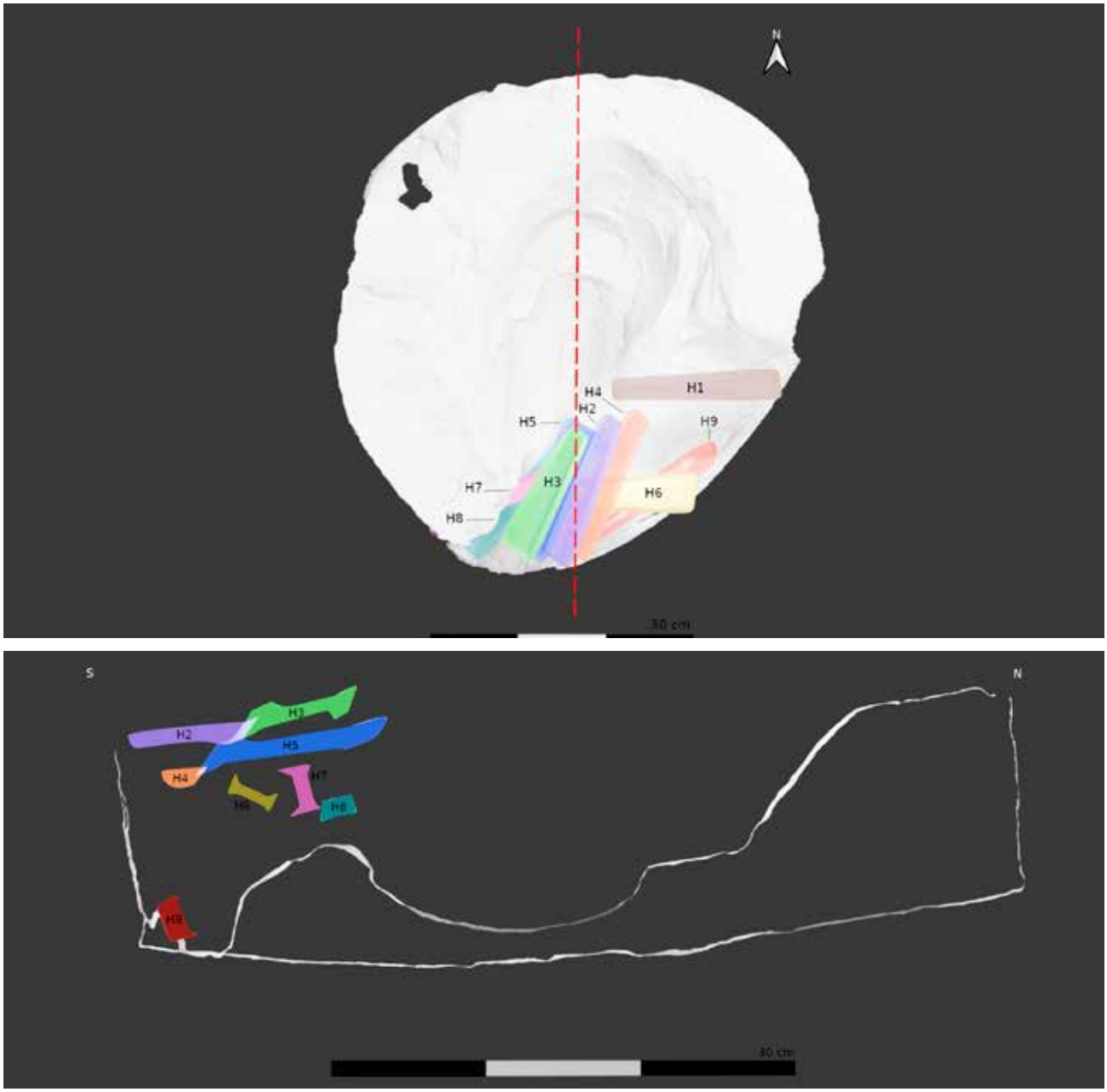


Fig. 9 – Plan and cross-section from Léon hoard 2, after the 3D reconstruction.



Fig. 10 – The pit of Léon hoard 2 where the axe-heads were deposited, probably vertically, seen from the "south".



Fig. 11 – Adjoining axe-heads from Léon hoard 2, seen from the "west".

large and 5 cm deep was observed. Most of the axe-heads were found with a slight tilt toward the opening in the bottom of the barrel. Their orientation was dissimilar: six of them had the edge of the blade downward, another upward. Two others were found in horizontal position. Five axe-heads were adjoining (fig. 11). It is too early yet to conclude with certainty, but it seems possible to infer that the axe-heads were deposited adjoining, mostly oriented in the same way and standing blade upward, as in the hoard 1.

These two hoards provide us with two set of axe-heads deposited simultaneously and distant a few meters away the one from the other (table 1). Even if the complete analytic protocol could only be applied to the 30 axe-heads of hoard 1 (fig.12-13) and one axe-head of hoard 2 (the one retrieved in 2015), the comparison between both allows for some comparison that enlighten the processes at stake during hoarding.

Other hoards

Our study also takes into account the axe-heads from four different hoards (table 2; all are on deposit at the Musée d'Aquitaine, Bordeaux): Le Chalet hoard 1 and Le Chalet hoard 2 (Saint-Germain-d'Esteuil), Le Pouyalet hoard 2 (Pauillac) and Minjacq (Martillac; this hoard contains axe-heads of *Martillac* type, which would pre-exist the Medoc axes). All these hoards except le Chalet 1 only contained axe-heads (they belong to Lagarde-Cardona's type A: Lagarde-Cardona, 2012, p. 198): 25 in Le Chalet 2, 16 in Le Pouyalet 2, at least 24 in Minjacq. Le Chalet 1 contained 33 axe-heads and 17 other objects (Lagarde-Cardona, 2012, p. 149–156). For different reasons, we could not study all of these axe-heads: 15 have been taken into account for le Chalet 1, 24 for le Chalet 2, 10 for Pouyalet 2, 14 for Minjacq.

Two of these hoards have been recovered in an archaeological context: Le Chalet 1 and 2. Both hoards were deposited into vases. In le Chalet 2, the axe-heads were disposed concentrically, their blade up, with one lying flat on top (Roussot-Laroque, 1999).

These hoards provide therefore 63 axes in total. Others objects, found isolated or from smaller hoards, will be referred to in other parts of this paper for addressing some specific topics.

ANALYTIC PROTOCOL

The protocol we introduce here was elaborated for studying the hoards from Léon, and aims at assessing the homogeneity or on the contrary the heterogeneity of the origins of the alloyed metals, the shape of the objects, their mass and volume, their use and their forms of discard/abandonment/deposition. This protocol remains in part theoretical because it has not been yet integrally implemented for the study of one specific hoard (even it is almost the case for Léon hoard 1). It should, though, be the case for Léon hoard 2. Yet, all of the steps of this protocol have been tested on a significant part of our dataset, and all have demonstrated their relevance and the accuracy of the data they returned. We present therefore this protocol in a methodological perspective, even if the results obtained during the elaboration of its different steps have – we believe- an undeniable interest.

As we will show, this protocol is particularly relevant for an application to case studies, as it focuses on

Inventory number	Length (cm)	Width, base of the blade (cm)	Width, heel (cm)	Edge of the blade	Weight (g)	Sample ID	Mould (certain)	Figure
1.2	19.2	4.6	3	curved, asymmetric	658.7	BDX25092		7.2
1.3	19.3	5.3	2.9	straight	634	BDX25093		7.3
1.4	18.8	5.6	3.2	curved, symmetric	679.3	BDX25094		7.4
1.5	19.6	5.2	3	straight	648.2	BDX25095		7.5
1.6	18.1	5.3	2.7	curved, symmetric	525.3	BDX25096		7.6
1.7	20.1	5	3	straight	666.9	BDX25097		7.7
1.8	19.7	5.1	2.7	curved, asymmetric	618.6	BDX25098	A-Le1	7.8
1.9	19.9	5.2	2.7	curved, asymmetric	612	BDX25099		7.9
1.10	20	5.3	2.7	straight	602.1	BDX25100		7.10
1.11	20.1	5.3	3	curved, asymmetric	642.8	BDX25101		7.11
1.12	20.2	5.4	3.2	straight	765.7	BDX25102		7.12
1.13	20.1	4.5	2.6	curved, symmetric	595.3	BDX25103		7.13
1.14	20.8	4.8	2.5	straight	668.2	BDX25104	C-Le1	7.14
1.15	19.8	5.4	2.5	straight	625.5	BDX25105		7.15
1.16	20	5.2	2.9	straight	647.7	BDX25106	A-Le1	8.16
1.17	20.2	4.4	2.5	curved, symmetric	719.3	BDX25107		8.17
1.18	20.1	4.9	2.5	straight	630.9	BDX25108		8.18
1.19	18.8	5.3	3.1	curved, symmetric	741.6	BDX25109		8.19
1.20	19.9	4.8	2.8	curved, asymmetric	661.6	BDX25110		8.20
1.21	19.1	4.8	2.9	curved, asymmetric	627.5	BDX25111		8.21
1.22	19.5	5.3	2.7	straight	626.2	BDX25112		8.22
1.23	18.9	5.2	2.9	curved, symmetric	619.1	BDX25113	B-Le1	8.23
1.24	20	5	2.8	curved, asymmetric	660.6	BDX25114	A-Le1	8.24
1.25	20.1	5	3	curved, asymmetric	661.8	BDX25115	A-Le1	9.25
1.26	19.3	5.2	3.1	curved, symmetric	683.7	BDX25116		9.26
1.27	20	4.9	2.8	curved, asymmetric	643.5	BDX25117		9.27
1.28	19.3	5.2	2.9	curved, asymmetric	662.7	BDX25118	B-Le1	9.28
1.29	20.1	5.4	2.8	curved, asymmetric	663.5	BDX25119		9.29
1.30	20.5	4.6	2.6	curved, asymmetric	660	BDX25120	C-Le1	9.30
1.31	20.1	5	2.7	curved, asymmetric	643.2	BDX25121		9.31
Total weight hoard 1					**1906**			
2.0 (axe no. 1, 2015)	19.8	4.9	2.6	curved, asymmetric	616.6	BDX25091		7.1
2.1	20	4.7	2.5	straight	592.2			
2.2	19.7	4.7	2.7	straight	592.7			
2.3	19.9	4.4	2.7	curved, asymmetric	603.4			
2.4	19.3	4.8	3	curved, asymmetric	565.5			
2.5	19.3	4.7	2.7	curved, symmetric	601			
2.6	19.2	4.7	2.6	straight	566.1			
2.7	19.7	4.8	3	straight	618.1			
2.8	19.2	5.1	2.8	straight	590			
2.9	19.9	4.8	2.8	straight	567.4			
Total weight hoard 2					**1191**			
Total weight hoards 1 and 2					**3097**			

Table 1– Axe-heads from Léon Hoards 1 and 2.

the axe-heads as individual objects and on specific hoards as groups of objects. Other approaches have dealt with variation among Middle Bronze Age metallic production, from the making of the alloy (recipe) to the morphometry of the objects (Forel et al., 2009; Wilczek et al. 2015; Gabillot et al. 2017a and b). These works privileged a 2D approach of axe-heads measurements and a thorough statistical analysis allowing for reassessing typological assignations and technical connectivity between different regions of Western Europe. We believe that our approaches are complementary, as they apply to different scales of analysis.

Step 1. Excavation and recovery of the axes; recording of field data

This part of the protocol could only be implemented for the hoard 2 from Léon, as it was the only unexcavated context we had the opportunity to study. As we said, the hoard was retrieved in one block, conditioned into a barrel. The axe-heads were still embedded in the sediment taken from the site. The hope was that the axe-heads would have stayed into their primary positions, which was not the case (fig. 14). Hoard 2 from Léon was excavated in laboratory, but we believe the methods we introduce here can also be implemented in the field, especially because most of them are not original and belong to the usual toolbox of field archaeology.

The aim is to obtain a comprehensive 3D recording of the stratigraphy and of all the taphonomic observations made during the excavation. For this, the first condition is, of course, to perform a stratigraphic excavation and to record all relevant observation. In order to obtain the 3D model of the stratigraphy, 3D recording has to be performed at each interface between stratigraphic units. Coded markers will allow for the alinement of the models of the successive interfaces, therefore allowing for a computerized volumetric reconstruction of the stratigra-

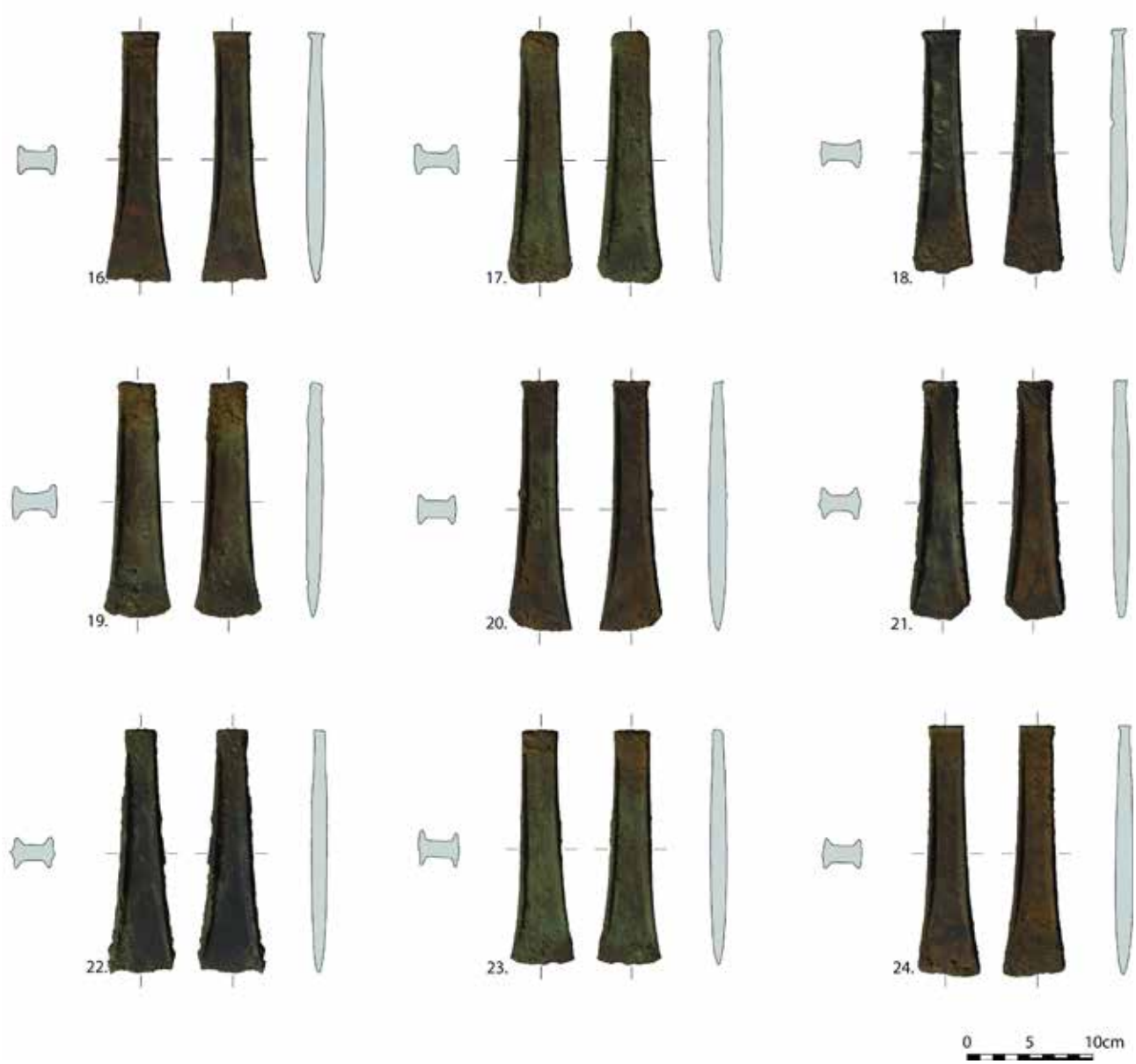


Fig. 12 – Axe-heads from the hoard of Léon 1. The numbers are those of the inventory given during the 2017 excavation.

phy of the hoard. If possible, these markers should be placed outside and around the excavation area in order to avoid obscuring part of the hoard and its stratigraphy. Given the importance of the position of each axe-head for determining depositional (i.e. gestures) and post-depositional processes (i.e. taphonomy), each phase of the excavation of the hoard itself was recorded: the upper part of each axe-head appears in the 3D model. This method allows for recording with maximal accuracy the location of each artefact. Once these artefacts are stabilised, they can be individually digitalized and virtually relocated to their original location. This last step could not be implemented in the framework of this study for lack of time, however.

In the specific case of Léon hoard 2, a photogrammetry of the entire stratigraphy was carried out and allows to situate each axe-head in its specific layer. As the hoard was contained in a metal drum, the photogrammetry was carried out using a ring flash to cancel out the problematic lighting conditions, and coded markers were positioned on the drum itself and around it, so that each photogrammetry could be referenced without obscuring part of the sediment.

Step 2: general study of the objects

All the objects we studied belong to the same type of axe-heads, the Medocan one: there was no need therefore for a typological study *stricto sensu*. Macroscopic analysis was aimed at studying use wear, observing stigmata related to technical processes performed during the making sequence (polishing, finishing of the axe-head, hammering of its bottom, initial sharpening of the blade when possible) or afterwards during maintenance/repair sequences (re-sharpening of the blade is the most obvious). All these observations contribute to the assessment

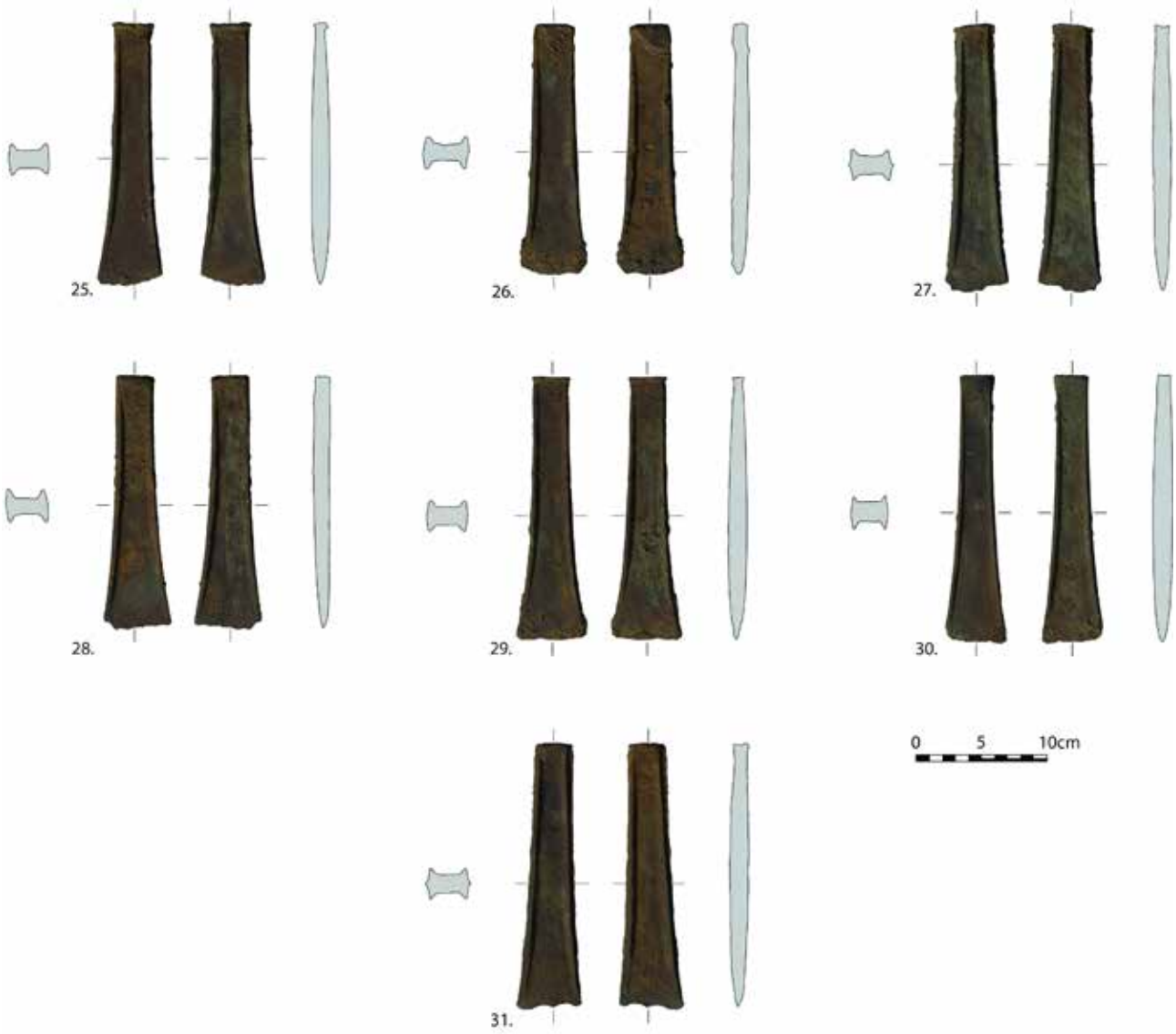


Fig. 13 – Axe-heads from the hoard of Léon 1. The numbers are those of the inventory given during their recovery (1-3) or during the 2017 excavation.

of homogeneity vs. heterogeneity into production processes, maintenance practices and uses.

Step 3. Assessing variability in shape, mass, and volume

The assessment of morphometric variability plays a central role in our project. Homogeneity in shape and mass may reflect homogeneity in use of the object: an identical tool for performing the same technical gesture. Homogeneity in volumetric morphology may reflect homogeneity in production. Medocan axe-heads were moulded in a two-parts mould. Evaluating their dimorphism allows for estimating which axe-heads could have been melted in the same moulds, as these would share most of their proportions. Homogeneity in mass, volume or included in some dimensions can be related to standardization, i.e. producing the objects according to notional norms originating from outside the technical sphere *stricto sensu*. For instance, if axe-heads were used as ingots for trade or even as currencies (as it is frequently admitted, see Introduction), their masses may be expected to have tended towards a certain homogeneity as the institutions of trade would represent an incentive towards standardization.

For addressing these questions, we developed a method involving different methods from manual measurement to 3D modelling of the objects, computerized processing of the 3D models, mathematics and statistical tests.

3D digitalisation of the axe-heads

In the framework of this research, 3D digitalization of the axe-heads has been performed through two different methods: scanning by Structured Light Scanner (SLS) and photogrammetry. The pros and cons of both methods

Hoard	Inventory number	Length (cm)	Width, base of the blade (cm)	Edge of the blade (cm)	Weight (g)	Mould (certain)
Le Chalet, hoard 1	D2009.I.10	19.6	5.5	curved, symetric	757.3	
	D2009.I.11	19	5.7	curved, symmetric	677.2	
	D2009.I.12	19	5.4	curved, asymmetric	692.9	C-Cha
	D2009.I.14	19.4	5.3	straight	720	
	D2009.I.15	19.5	5	straight	747.8	
	D2009.I.16	19.5	5.5	curved, asymmetric	663.4	C-Cha
	D2009.I.17	18.9	5.2	curved, asymmetric	703.8	
	D2009.I.18	15.7	4.9	curved, asymmetric	570	
	D2009.I.19	16.1	5	straight	408.1	
	D2009.I.20	16	5	curved, asymmetric	378.7	
	D2009.I.5	19.2	5.5	straight	715.3	
	D2009.I.6	19.5	5.2	curved, asymmetric	768.4	
	D2009.I.7	19.4	5.6	curved, asymmetric	737.4	
	D2009.I.8	20.2	5.7	curved, asymmetric	766.2	
	D2009.I.4	20	5.5	straight	767.7	
Le Chalet, hoard 2	D2009.I.2	20.3	5	*oxidized (straight ?)*	765.6	B-Cha
	D2009.I.50	20.7	5.3	*oxidized (straight ?)*	771.8	B-Cha
	D2009.I.51	20.5	5.2	straight	747	
	D2009.I.52	20.5	5.3	*oxidized (straight ?)*	749.3	
	D2009.I.53	20.9	5.7	straight	741.5	
	D2009.I.54	20	5.5	curved, asymmetric	721.7	
	D2009.I.55	20	5.6	curved, asymmetric	768.2	
	D2009.I.57	20.5	5.3	straight	766.7	
	D2009.I.58	16	4.7	curved, asymmetric	403.5	
	D2009.I.59	20.3	5.2	straight	754.4	D-Cha
	D2009.I.60	20.4	5.5	*damaged*	741.1	
	D2009.I.61	16.9	5	*oxidized (straight ?)*	414.6	A-Cha
	D2009.I.63	19.9	5.1	straight	759.8	B-Cha
	D2009.I.64	20.3	5.3	straight	758.6	
	D2009.I.65	18	5.3	curved, symmetric	650.5	
	D2009.I.66	15.6	4.7	curved, symmetric	389.9	
	D2009.I.67	15.2	4.9	curved, symmetric	409.4	
	D2009.I.68	16.7	5	straight	422	A-Cha
	D2009.I.69	19.8	5.1	straight	742.5	D-Cha
	D2009.I.70	15.8	4.5	curved, asymmetric	378.8	
	D2009.I.71	16.3	4.6	curved, asymmetric	432.8	
	D2009.I.72	16.7	5	straight	420.5	A-Cha
	D2009.I.73	15.7	4.4	straight	395	
	D2009.I.75	20.5	5	straight	779.4	
Le Pouyalet hoard 2	60.77.2	20.1	5.5	curved, symmetric	759.5	
	60.77.1	19.3	5.7	curved, asymmetric	784.1	
	60.74.3	21	5.6	straight	811.9	A-Pou2
	60.74.2	20.7	5.7	straight inclined	797.1	A-Pou2
	60.74.1	20.4	5.6	straight inclined	794.2	A-Pou2
	60.77.7	19.5	5.6	straight	771.1	C-Pou2
	60.77.5	19.7	5.5	straight	768.8	C-Pou2
	60.77.3	19.9	5.7	curved, symmetric	745.6	B-Pou2
	60.77.6	19.9	5.1	straight	769.4	B-Pou2
	60.77.4	19.7	5	curved, asymmetric	760.9	B-Pou2
Minjacq	2000.11.4	18.9	6.5	curved, symmetric	690.8	
	2000.11.3	14.7	6	straight	367.2	
	2000.11.7	17.7	6.6	curved, symmetric	638.3	
	2000.11.8	19.8	6.7	curved, symmetric	676.8	
	2000.11.6	18	6.8	curved, symmetric	658.9	
	2000.11.11	18	6.5	curved, asymmetric	633.7	
	2000.11.14	17	6.1	curved, symmetric	680.4	
	2000.11.2	13.8	3.7	curved, symmetric	262.5	
	2000.11.5	14.7	7.1	curved, symmetric	581.2	
	2000.11.13	15	6.5	curved, symmetric	539.6	
	2000.11.12	15	6	curved, asymmetric	504.1	
	2000.11.1	11.3	3.8	curved, symmetric	180.4	
	2000.11.9	11.6	7.5	curved, symmetric	372.4	
	2000.11.10	12.9	6.4	curved	335.2	

Table 2 (left page) – Axe-heads from the hoards taken into account in this study.



Fig. 14 – The indoor excavation of the hoard 2 from Léon. Phases of excavation (2) were preceded and followed by photogrammetric recording (1 and 3). Note the coded markers on the inside and outside wall of the container and on its support.

are well known: SLS is a high-cost method, but acquisition time is reduced and it provides almost directly a digital twin of the artefact at a 1:1 scale. Photogrammetry, on the other hand, is a low-cost method, but it is also much less time-effective than SLS, and the digital model has as a second step, to be scaled, a possible source for error. All the 30 axe-heads from Léon hoard 1 were modelled through both methods, as one from Léon hoard 2, while all the others axe-heads of the corpus were recorded by photogrammetry.

The SLS used was an Artec Space Spider 2, with a certified minimum resolution of 0. mm. We were able to process the entire corpus in a single day. As the purpose of this SLS is the recording of small artefacts, it allowed for an optimal result (i.e. recording useful details, but not too precise, at the risk of generating heavier models for minimal useful gain). Like all SLSs, Artec Space Spider 2 is used for standardization, metrology and comparison of virtual models, but not for other purposes (in this respect, the production of textures is not up to the standard of current 3D visualization). The digitalisation by photogrammetry was implemented on the same objects, not only to compare to the SLS data, but also to fill the texture gap, and finally for experimental and teaching purposes.

The experiment showed differences in the volume calculated between the SLS-based models and the photogrammetry-based ones, but very slight (less than plus or minus 1 %). These differences may be due to inaccuracies in the photogrammetric digitalization (in the homothety of the model, for example, or in the uniformity/size of the meshes), but it may also be due to the calculation of the volume itself (which may be slightly distorted by the calculation itself, particularly in the case of aberrant faces on meshes topology).

The photogrammetry software used was Agisoft Metashape. Although the use of this solution does not meet the FAIR principles, Metashape is nevertheless the preferred solution in Humanities because it enables data to be processed from A to Z, while taking advantage of full integration of the hardware resources available (RAM, GPU, processor), unlike the alternative open source softwares, in particular Meshroom and Micmac.

This 3D recording allows for producing a high-quality graphic documentation. 3D models can be represented according to orthographic projections, and cross-sections can be inferred from the model. We obtain through this process a very accurate representation of the object, allowing moreover for comparison with objects drawn in 2D. But as we will see, the use of 3D recording has many more implications.

Assessing regularity in weight and standardization

In order to discuss the hypothesis according which Bronze Age axe-heads production would follow a notional metrology, data are analysed using two main methods: a Frequency Distribution Analysis (FDA) and a Cosine Quantogram Analysis (CQA).

The FDA aims at observing the distribution of the data, while taking into account the possible imprecision of weighing/measuring practices in ancient times (Poigt, 2022, p. 84–86). For this reason, the distribution curves

are given with a margin of error of 5 %. In other words, a value of 100 g will return all the sample data with a mass between 95 g and 105 g - i.e. between 100 g − 5 % and + 5 %.

CQA is a non-inductive mathematical-statistical method developed specifically to identify a *quantum* in a given sample, in other words a unit structuring that sample. It is essentially based on the identification of a smallest common integer divisor for the most represented values in the sample. This method was developed by David Kendall (1974), based in particular on the work of Thom (1955) and Broadbent (1955; 1956). Since the late 1990s, it has become the preferred method of investigation in archaeological metrology research (Pare, 1999; Pakkanen, 2011; Ialongo and Rahmstorf, 2018; 2019; Rahmstorf, 2019).

These two analyses are carried out using version 3.2 of the MetroTB tool (Poigt, 2022b). The combination of these two methods makes it possible to determine inductively and non-inductively whether the samples analysed are likely to be defined according to metrological modalities, and to characterise these distributions. Metrological distribution is expected to correspond to a series of clusters of values corresponding to at least one unit, its multiples and divisors. A similar metrological distribution between different datasets (different hoards, for instance) would imply that different geographical areas would share the same metrology.

On the other hand, a unimodal and symmetrical distribution would suggest technical habitus, Yet, a normal distribution around same value peaks in different geographical area would imply similarities in techniques going beyond a shared typology: common *habitus* suggesting complex relationship of knowledge transfer through apprenticeship beyond a local scale.

Assessing regularity in morphology

This part of the protocol had the double objective to identify similarity or on the contrary dimorphism between the different axe-heads. It also aims at detecting replication of blades, thus suggesting the use of a unique mould. There is a long tradition of research on this topic, based on the detection of common defects appearing in different axe-heads (see for instance Roussot, 1973, p. 131; and Lagarde-Cardona, 2012, p. 124, 243). We propose to go beyond this macroscopic observation and make an optimal use of the 3D models that allow for infinite manipulation of the axe-heads' digital twins. Firstly, the existence of the 3D model allows for a computerized, high-precision calculation of the volume of the object and therefore of its density, precious data for metrological and technical analyses. Secondly, the use of virtual models allows for experiences impossible in the real world, as for example the superposition of two objects, or better said of the point clouds obtained through their 3D digitalization. This task has been carried out using the software CloudCompare, a tool developed for electrical engineering which is used to compare 3D objects and identify differences between them, through the computation of the distances between the virtual models.

CloudCompare only allows for a comparison by pairs. The first step is to superimpose very accurately two different 3D models, using reference points (the ends of the flanges for example: fig. 15). One model is converted to a cloud of points, while the other (that will be used as reference), appears as an object with multiple faces (meshed model). The software computes the distances between the points of the cloud of and the closest face of the meshed model. If the distance between the points and the surface is close to 0, the objects are very similar or identical. A colour range graphically expresses the series of distances computed by the algorithm on the meshed object. A graph compiles the distances and gives a mean and a standard-deviation (fig. 16). A few initial tests aimed first at comparing the reference axe-head to itself (to determine the significance of the human-induced error, unavoidable in this process) and second very different axe-heads with each other. On this basis, we determined that a distance greater than 1 mm between two closest points is discriminant: in this case, the two axes compared are not considered as "identical". On the contrary, a field of values close to zero means identical axes.

The correct reading of the mean and the standard deviation is a key to understand the results. The mean of the series of distances between two axes is generally close to 0, as we compared similar axe-heads. If the standard deviation is high, it means that the values are too spread around the mean. It is in fact hiding "extreme" values that offset each other, and then the axes-heads are not so identical despite the 0-mean value. On the other hand, a mean and a standard-deviation close to 0 ±1 mm give good hints to consider two axe-heads as identical, maybe proceeding from the same mould.

From these CloudCompare comparisons, we sort the results according to three degrees of confidence. The fact that two axe-heads proceed from the same mould is considered 'unlikely' if the distances between the two models calculated are too great (fig. 17a). A common mould is considered 'probable' if the distances calculated show that two axe-heads were identical, in the absence of any other diagnostic element (like common casting defects or specific feature: fig. 17b). Finally, several axe-heads showing valid distances between their superimposed models and replicated casting defects lead to the conclusion of a 'certain' common mould (fig. 17c). Such approach allows for optimizing the use of information: casting defects are for instance very likely to be erased during the finishing of the axe-head by hammering, polishing, etc.

The sample analysed through this process gathers in total 119 axe-heads: over this total, some axe-heads that are too different need direct comparison. A preliminary sorting was made by comparing roughly their profiles. An orthophotograph of each axe-head has been extracted from their 3D model, from which it is easy to trace the

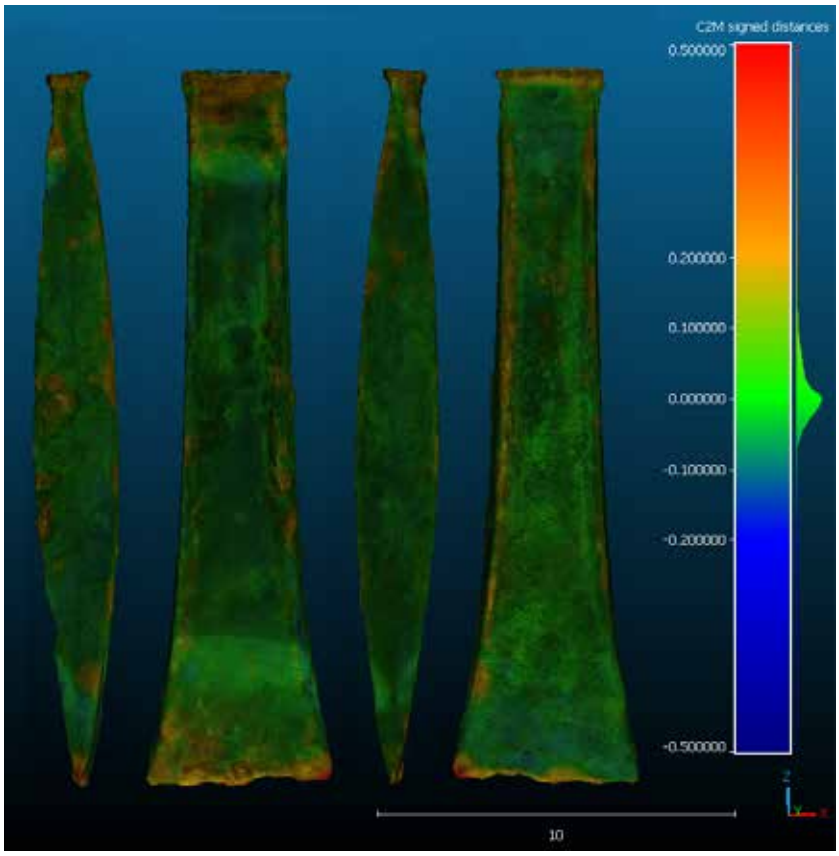


Fig. 15 – Compilation of the distances between the axes no. 8 and no. 16 from Léon, hoard 1, and visualisation on the model of the common (green) and different parts (blue/red).

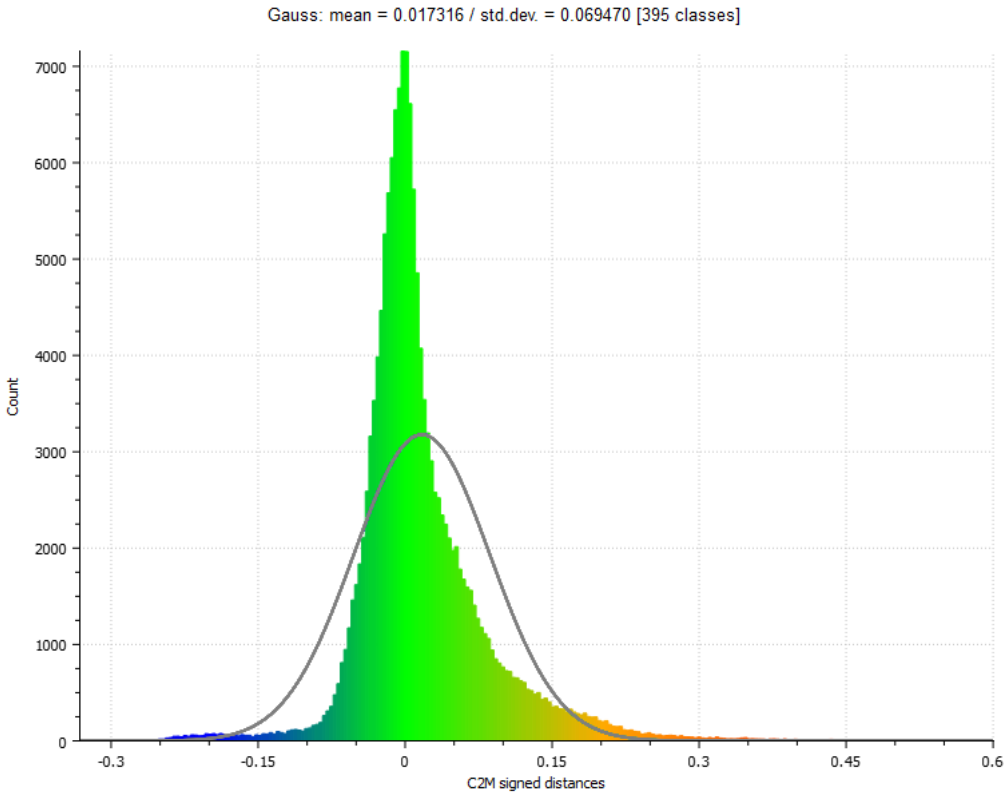


Fig. 16 – Graph compiling the distances and showing mean and standard-deviation between axe-head n°8 and n°16 from Léon. The mean and the standard-deviation are expressed in centimetres.

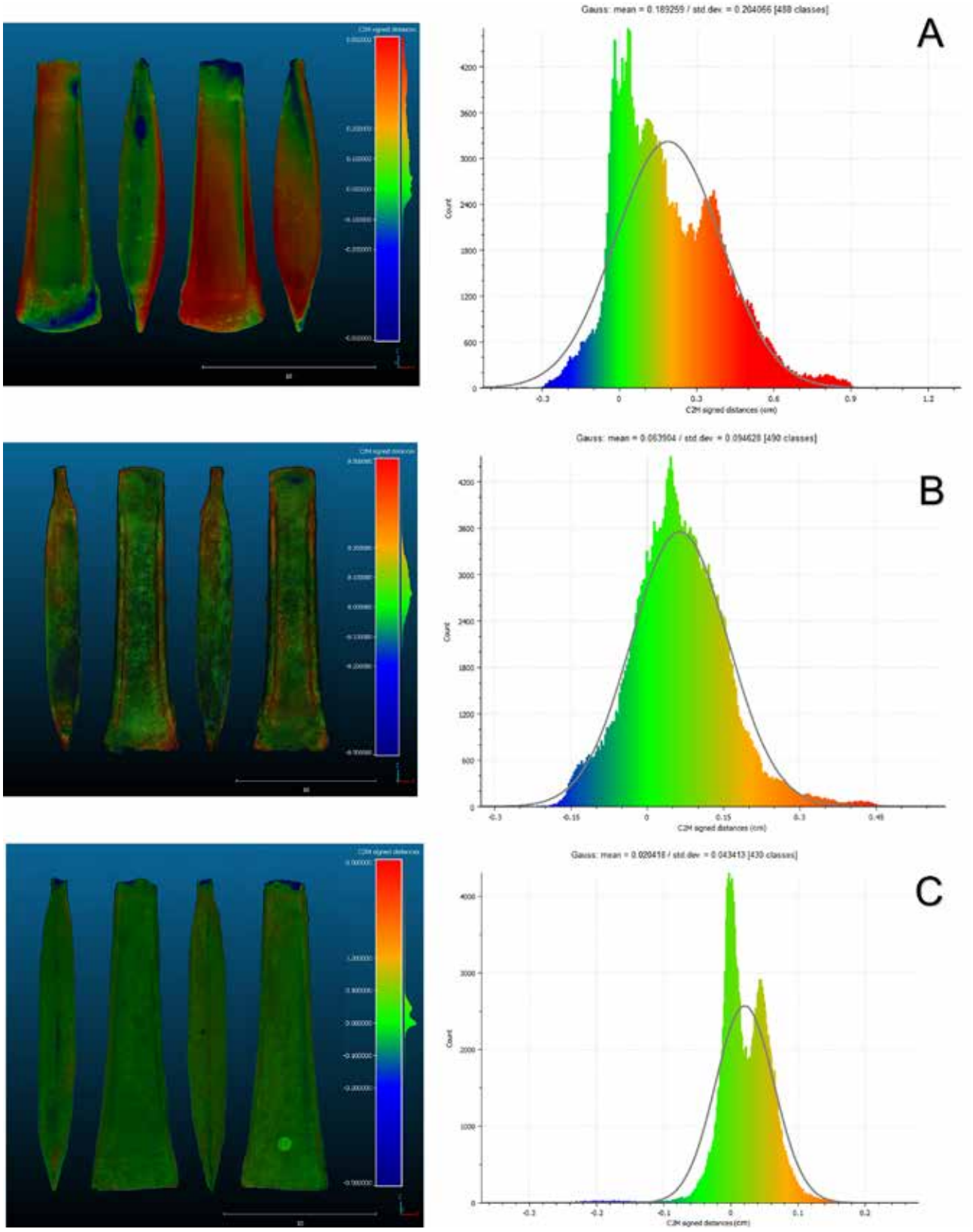


Fig. 17 – Outputs of CloudCompare comparison, showing the compilation of distances for axes that are too different to be considered similar (a&b) and axes that show distances acceptable to conceive a common mould or a replica (c).

profile of the object, and then compare which axe-heads share the same profile (fig. 18). Comparison is made step by step, increasing the window from the very local (within a specific hoard) to the regional. While performing this comparison, we deliberately ignored the cutting edge and the heel because the proportion of these parts depends on post-melting phases (finishing, maintenance and sharpening, etc.).

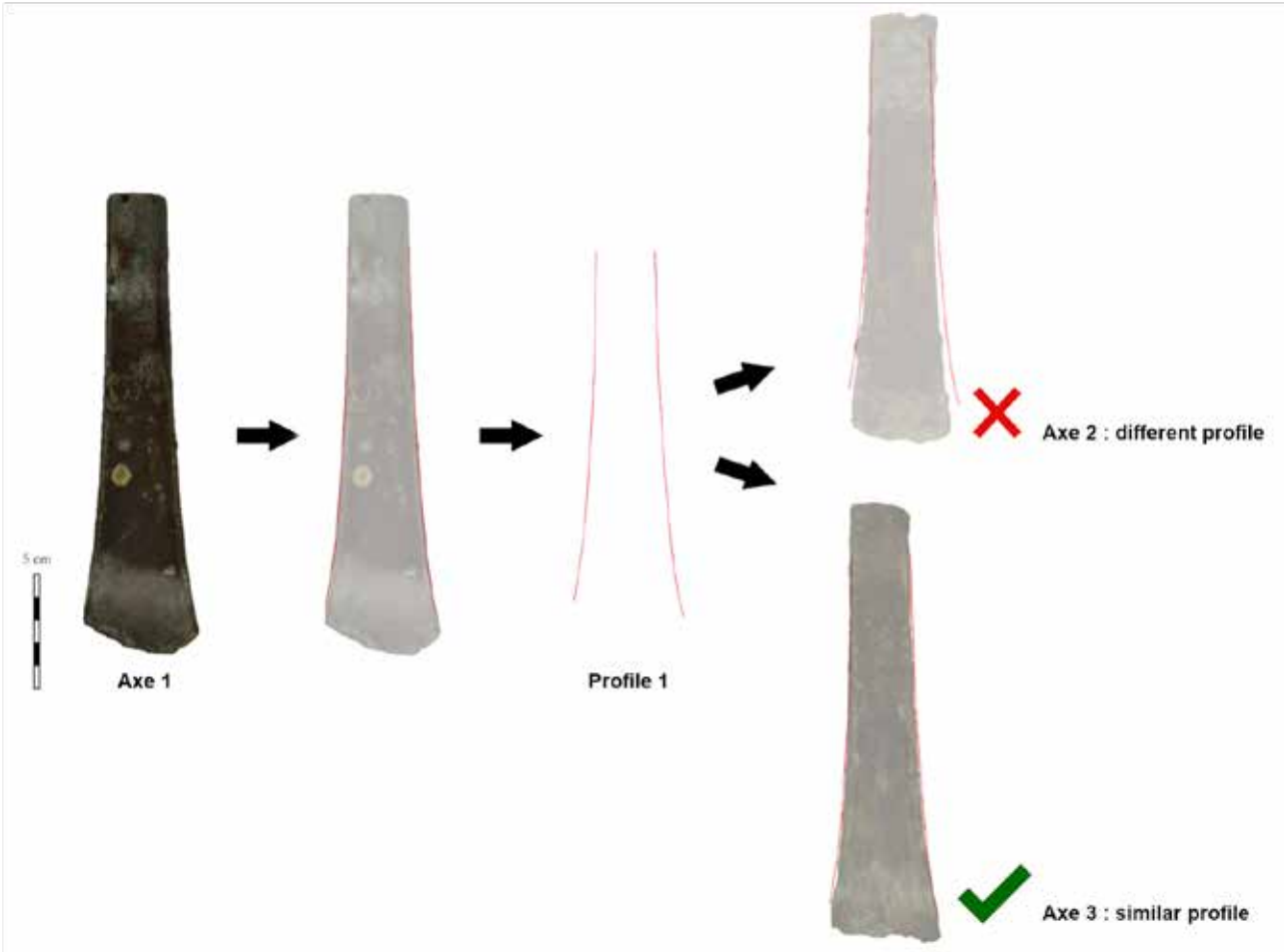


Fig. 18 – Methodology to gather profiles within hoards.

Assessing diversity in the origin of metal and in the making of alloys.

One of the main questions regarding the biography of our axes is obviously the nature of the metal used in their making. Firstly, there is the question of the origin of this metal: given that the south Atlantic Coast of France is devoid of sources of copper or tin ores, these metals must have come from other regions. Secondly, the alloying practices could have been more or less homogeneous. As for the origins of metals, only the copper sources can be assessed through the analysis of lead isotope ratios. Elemental compositions were also measured to determine the nature of the alloys.

The use of lead isotope ratios to study the provenance of metal artefacts has been a relatively common practice in archaeology since the early work of Brill and Wampler (1967; see Killik et al., 2020; Artioli et al., 2020 for a review). These ratios are specific to the geological context and are characteristic of the age of ore formation (Allègre, 2005). The lead isotopic signal, however, lies on a mixing line between the value of the copper source and that of the alloying elements. For bronze (Cu-Sn alloy), it is highly likely that two types of ore (containing copper and tin respectively) were used, but it is assumed that the lead comes mainly from copper ore (which is predominant by mass).

Isotopes 206, 207 and 208 are the products of the radioactive decay of uranium 238, uranium 235 and thorium 232, respectively. Isotope 204 is the only one that is not radiogenic. This aspect also presents a limiting factor: only geological formations of sufficiently different ages can be discriminated. This poses challenges for the Mediterranean area. There, ore deposits were formed during two geological episodes relatively close in time: the Variscan/Hercynian (Paleozoic) and Alpine (Mesozoic-Cenozoic) orogenies (Killick et al., 2020).

In addition to the use of isotope ratios, Albarède et al. (2012) have proposed the use of three independent geological parameters (T, μ, κ):

– T is an approximation of the geological age of the region from which the ores come (model age).

– μ corresponds to the $^{238}U/^{204}Pb$ ratio of the Earth's crust;

– κ corresponds to the ratio $^{232}Th/^{238}U$ and reflects the geological history of the continental province from which the ores originate.

These parameters reflect the geological history of the ore deposits. The objective here is not to attribute a precise source (this will be the subject of a later study), but to discuss the possible common origin of the metal ores.

Once again, our aim is to assess homogeneity vs diversity at all scales, i.e. from the very local (e.g. a specific hoard) to the regional (between different hoards

found in different areas). However, in this study, only the 30 axe-heads of Léon hoard 1 and one proceeding from Léon hoard 2 have been fully analysed (i.e. lead isotope ratios and elemental composition). In a nearby future, all the axe-heads from Léon hoard 2 should also be analysed.

Each artefact was sampled twice using a single-use saw blade. The first sample was taken from the heel of the axe-heads, after which the surface was mechanically cleaned to remove surface corrosion. These samples were used to measure lead isotope ratios. The second sample, a few cubic millimetres in size, was taken from the edge of the blades. These micro-samples were mounted, then ground and polished to a 0.25 mm diamond finish to create a surface suitable for SEM-EDS analyses.

The elemental composition of the samples was obtained by energy-dispersive X-ray fluorescence spectrometry using two Oxford Ultim Max 100 spectrometers, coupled with scanning electron microscopy imaging (JEOL JSM IT500HR variable-pressure microscope). Measurements were carried out under a partial vacuum (20 Pa) with an acceleration voltage of 20 kV to avoid charging phenomena. The acquisition time was 60 seconds per spectrum over the 0–20 keV energy range. For all EDS spectra, the dead time during acquisition was around 30 %, with an average number of counts per spectrum greater than 10^6.

Due to the presence of arsenic (As) and lead (Pb) in the same samples, the As L ray series and the Pb M ray series were used for EDS analyses to avoid line overlap with the As K ray series and Pb L ray series. Six measurements were carried out on each sample, with the area analysed in each measurement being approximately 5.10^{-2} mm^2. For each sample, the compositional mean (Aitchison, 1986) of the six measurements was used. Results are expressed as mass percentages, normalized to 100 %. Values below 0.5 % should be interpreted with caution, but they are retained in the general composition as they provide qualitative information.

Lead isotope ratios were measured by multi-collection inductively coupled plasma mass spectrometry (MC-ICP-MS) at the Service d'analyse des roches et minéraux (SARM) of the Centre de recherches pétrographiques et géochimiques (UMR 7358 CRPG, Vandoeuvre-lès-Nancy).

Samples were weighed into 15 mL Savillex vial, and HNO_3 was added. The solution was heated at 115°C for at least 72 hours, evaporated, then mixed with HCl and heated again for 24 hours or until the sample was completely dissolved. After evaporation, 1 mL of 0.8 M HBr was added to place the sample in the same medium as that used in the ion exchange column.

Each sample was loaded onto approximately 50 microliters of AG1X8 resin in micro-columns (see Manhes et al., 1980), then 2 mL of 0.8 M HBr were used for elution. Lead was collected in 2 mL of 6M HCl (4 × 0.5 mL), dried, and redissolved in 1 mL of 0.5 M HNO_3.

Pb analyses were performed on an MC-ICP-MS (Neptune Plus, Thermo Electron) using Tl (NIST 997) as an external standard for mass bias (White et al., 2000). The Tl and Pb values used for NIST 981 are those of Thirlwall (2002).

T, μ, and κ were calculated from the $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios according to Albarède and Juteau (1984) and Albarède et al. (2012; the parameters used for the calculation are those of these authors).

Data analysis was carried out using R version 4.4.0 (2024-04-24) (R Core Team, 2024) and the nexus 0.3.0 package (Frerebeau & Philippe, 2024).

RESULTS

The different steps of the protocol have been presented in their order of succession in the analytical process. However, our analytical *chaîne opératoire* does not parallel the ancient one. For instance, as the sampling needed for lead isotope and elemental composition analysis are destructive, they were performed last. For presenting the results, we will follow the 'biographical' order, from the making of the axes to their burying. We will consider them as individuals (the axe-heads) and as constituent of different groups, considered at different scales (hoard, grouping of hoards, technical group of the Medocan axe-heads).

Metal sources and alloys making.

The alloys used to make the 31 axe-heads from the Léon hoards we could analyse are binary copper-tin alloys (bronze). Arsenic (As), iron (Fe), sulphur (S), nickel (Ni), and zinc (Zn) are present as trace elements. Lead (Pb) content is generally a few tenths of a percent, always below 0.5 % (table 3; Frerebeau, 2024). It is therefore reasonable to assume that no lead was intentionally added to the alloys. With the exception of one individual sample with a higher Cu/Sn ratio (BDX25105), all the axes show similar, slightly scattered Cu and Sn contents, with an average Cu/Sn ratio of 6:1 (table 3; fig. 19).

Similarly, the lead isotope ratios show little dispersion (all ratios have coefficients of variation less than or equal to 0.2 %; table 4; Frerebeau, 2024). Only two samples show ratios that deviate noticeably from the rest of the values: BDX25110 and BDX25116 (fig. 20).

Lead model ages range from 344 to 503 Ma (table 5; fig. 21). The origin of the ores is therefore to be sought in formations of Paleozoic age. Interestingly, the distribution of model ages is quite old (mean age of 451 ± 27 Ma)

	Cu	Sn	As	Pb	Fe	S	Ni	Zn
mean	84.78	13.82	0.24	0.24	0.07	0.32	0.4	0.13
min.	82.72	7.84	0.12	0.17	0.05	0.2	0.19	0.12
Q25	83.81	13.32	0.22	0.2	0.06	0.27	0.37	0.13
Q50	84.4	14.16	0.24	0.24	0.07	0.3	0.41	0.13
Q75	85.19	14.83	0.27	0.28	0.07	0.38	0.45	0.14
max.	90.71	15.73	0.35	0.37	0.16	0.54	0.58	0.17

Table 3 – Summary statistics of elemental compositions (Q25, Q50, Q75: first, second and third quartile).

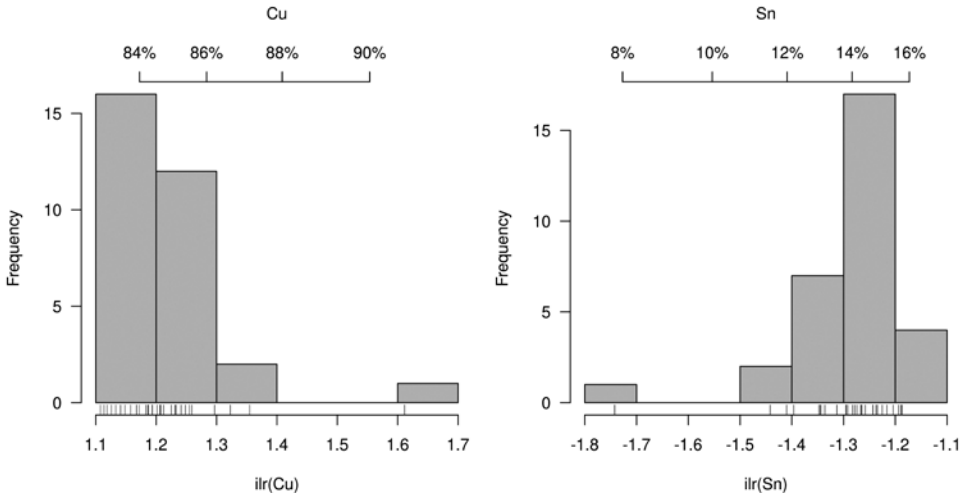


Fig. 19 – Histograms of copper (Cu) and tin (Sn) contents. See Filzmoser et al., 2009 for methodology.

	206Pb/204Pb	207Pb/204Pb	208Pb/204Pb	207Pb/206Pb	206Pb/207Pb	208Pb/206Pb
min.	18.078	15.654	38.296	0.855	1.155	2.102
Q25	18.136	15.657	38.358	0.861	1.158	2.112
Q50	18.155	15.658	38.378	0.863	1.159	2.114
Q75	18.178	15.659	38.391	0.863	1.161	2.115
max.	18.319	15.664	38.506	0.866	1.17	2.118
mean	18.16	15.658	38.378	0.862	1.16	2.113
sd	0.041	0.002	0.033	0.002	0.003	0.003
CV (%)	0.224	0.014	0.085	0.218	0.219	0.143

Table 4 – Summary statistics of lead isotope ratios (Q25, Q50, Q75: first, second and third quartile; sd: standard deviation; CV: coefficient of variation).

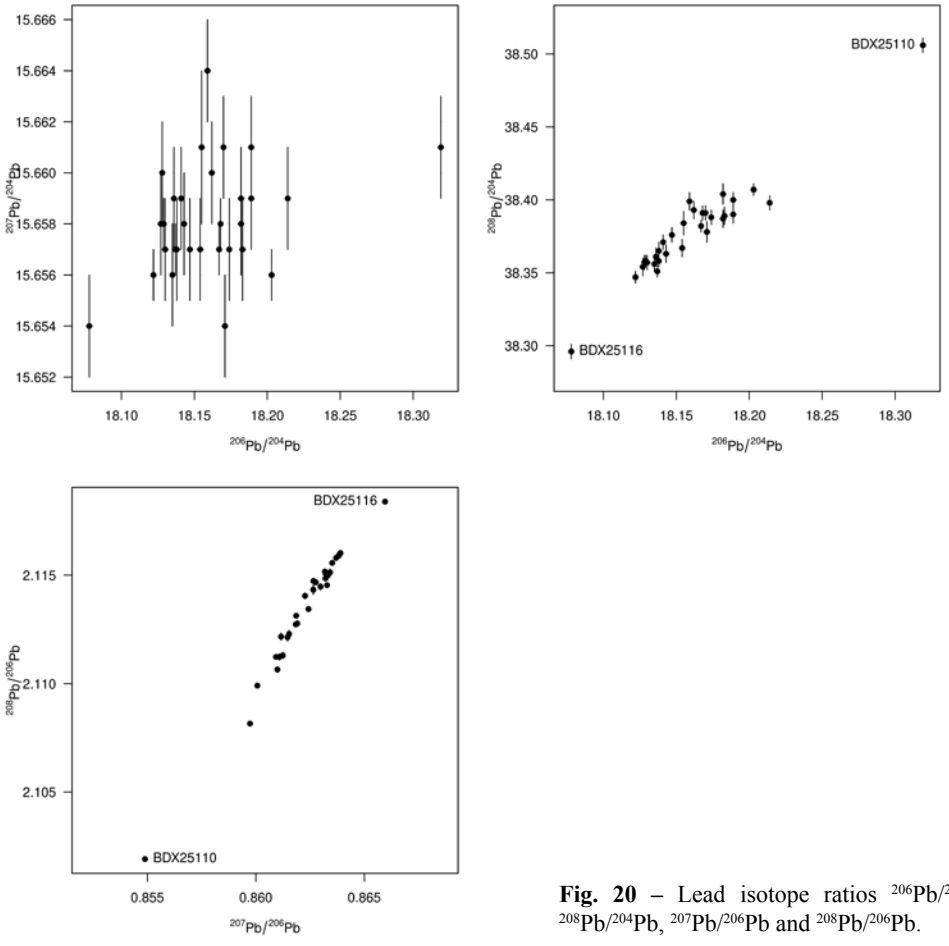


Fig. 20 – Lead isotope ratios $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$, $^{207}Pb/^{206}Pb$ and $^{208}Pb/^{206}Pb$.

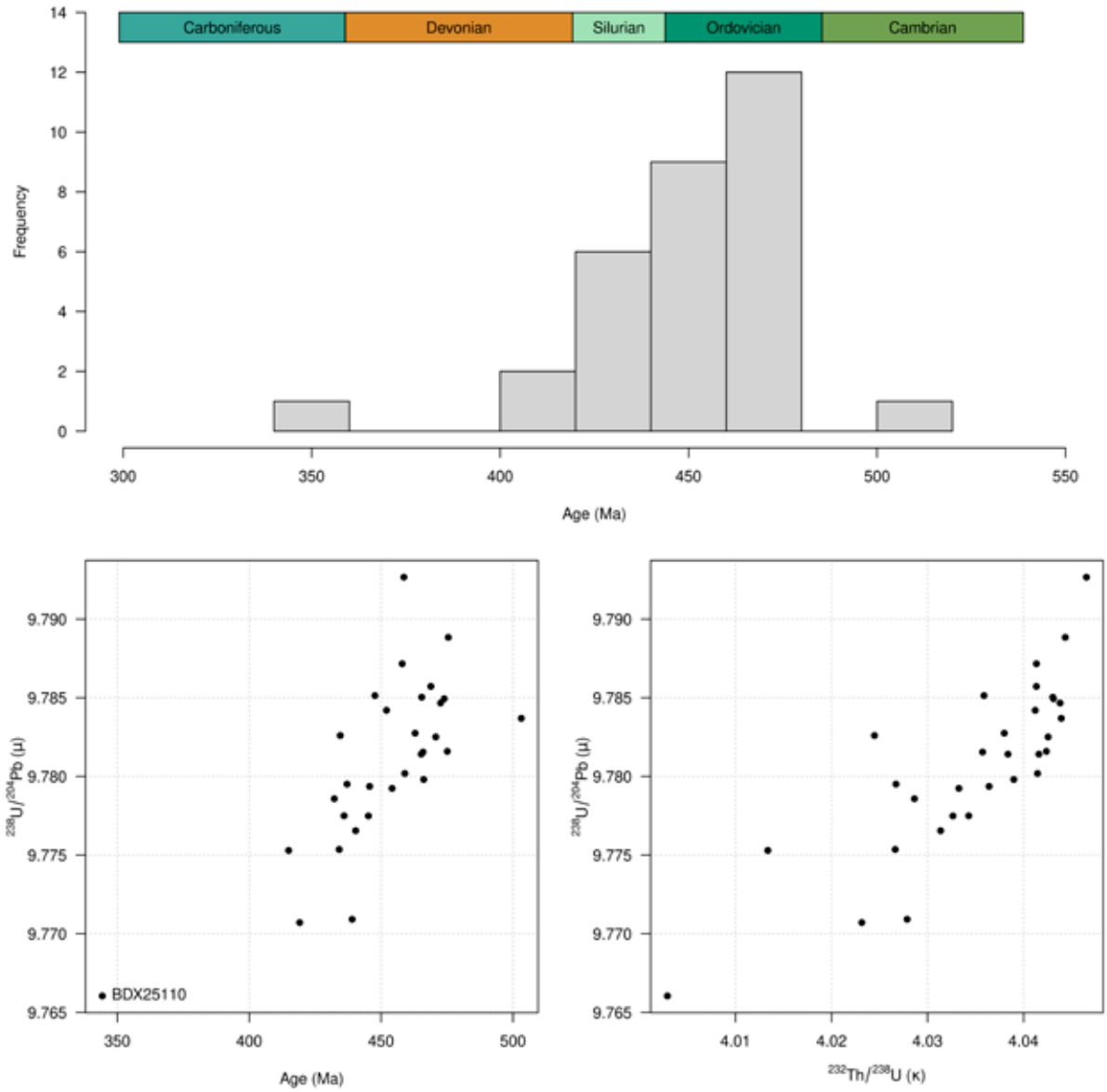
	age	mu	kappa
BDX25091	471	9.783	4.043
BDX25092	435	9.783	4.024
BDX25093	440	9.777	4.031
BDX25094	439	9.771	4.028
BDX25095	436	9.777	4.034
BDX25096	452	9.784	4.041
BDX25097	459	9.793	4.047
BDX25098	458	9.787	4.041
BDX25099	419	9.771	4.023
BDX25100	475	9.789	4.044
BDX25101	474	9.785	4.043
BDX25102	463	9.783	4.038
BDX25103	437	9.78	4.027
BDX25104	434	9.775	4.027
BDX25105	465	9.781	4.042
BDX25106	445	9.777	4.033
BDX25107	466	9.780	4.039
BDX25108	466	9.782	4.036
BDX25109	475	9.782	4.042
BDX25110	344	9.766	4.003
BDX25111	448	9.785	4.036
BDX25112	473	9.785	4.044
BDX25113	446	9.779	4.036
BDX25114	469	9.786	4.041
BDX25115	465	9.781	4.038
BDX25116	503	9.784	4.044
BDX25117	459	9.780	4.041
BDX25118	454	9.779	4.033
BDX25119	432	9.779	4.029
BDX25120	465	9.785	4.043
BDX25121	415	9.775	4.013

Table 5 – Geological parameters calculated from lead isotope ratios (ages in Ma).

and extends from the Lower Ordovician to the Upper Devonian, i.e., before the Variscan/Hercynian orogeny that began in the Devonian (c. 420 Ma) and corresponds to the formation of the majority of European and Mediterranean ore deposits (Killick et al., 2020). These ages allow for the exclusion of sources corresponding to very ancient formations (Scandinavian Shield and Pan-African orogeny), as well as the most recent formations (Alpine orogeny). In fact, the calculated ages correspond to the Caledonian orogeny (c. 530–400 Ma).

These results tend to suggest a common geological origin of the copper ores for all the 31 axe-heads, with the exception of BDX25110, which has a younger model age (Carboniferous). However, BDX25110 has a similar elemental composition to the rest of the axe-heads, despite a potentially different geological origin.

Fig. 21 – Geological model ages and $^{238}U/^{204}Pb$ (μ) and $^{232}Th/^{238}U$ (κ) ratios.



Inside one specific hoard, Léon hoard 1, metal origin seems therefore quite homogeneous. More surprisingly, the only axe-head from Léon hoard 2 that was analysed (BDX 25091) has an identical lead isotope ratio. Such result can be interpreted in two different ways. A first explanation would be that the French south-western coast had privileged relation with one specific ore-mining area. The second explanation would be that a copper load of at least 20 kg (the approximate weight of metal in the Léon 1 hoard) arrived in the region and the all the metal needed to cast 29 out of the 30 axe-heads of Léon 1 hoard (and at least one of Léon hoard 2) was taken out of this load. Both explanations do not contradict each other, but as we will see, the second one seems at this point more likely than the first. The alloying recipes seem consistent, and denotes a technical homogeneity that seems to expand beyond the Léon micro-region (Lagarde-Cardona, 2012, p. 190 has similar results). Processes that could induce significant variability, as the accumulation of axes over a long period, the intervention of many different makers, diversity in the geographical origin of the axes collected into the hoard, important recycling of metal, seem absent.

Making the axe-heads: moulding and finishing

Moulding

Moulding was always made in a 2-parts mould, probably made out of stone or clay (Lagarde-Cardona, 2012, p. 107). In Léon hoard 1, 8 distinct profiles could be identified; 13 different profiles for the two hoards of Saint-Germain-d'Esteuil, and 3 others for Pouyalet 2 (Pauillac). The Martillac hoard contains axe-heads that are too different from one another or too fragmentary. 8 profiles present in different hoards were identified, although with less certainty.

3D comparison (using CloudCompare, see before) returns the following results:

– *Léon hoard 1*: one mould (mould A-Le1) has been used for the casting of 4 axe-heads (nos. 8, 16, 24 and 25), as well as the only one analysed coming from Léon hoard 2. Two other moulds (B-Le1 and C-Le1) have been used for casting each at least two of the axe-heads (nos. 23 & 28: mould B; nos. 14 & 30: mould C). Five other probable moulds (D-Le1, E-Le1, F-Le1, G-Le1 and H-Le1) seem to have been used for the making of fourteen other axe-heads, but there are no casting defects to confirm this. Eight axe-heads are unique. The results for Léon 1 are illustrated in figure 22.

– *Chalet hoards 1 and 2*: four distinct moulds were identified with good probability, in spite of the significant corrosion gangues that could complicate the comparison of the digital 3D models. The first (A-Cha) has been used for casting 3 axe-heads (D2009.I68, D2009.I61, D2009.I72; the second one (B-Cha) formed the series D2209.I50, D2009.I02 and D2009.I63. The third one (C-Cha) has been used for axe-heads D2009.I12 and D2009.I16, and the fourth one (D-Cha) for axe-heads D2009.I59 and D2009.I69. Two very similar axe-heads with no common flaws suggest that they were probably cast in the same mould, without other evidence than the millimetric morphological resemblance (D2009.I17 and D2009.I7).

– *Pouyalet 2 hoard* revealed three different groups of profiles. One series of three axe-heads had already been identified as proceeding from the same mould in a previous study (Lagarde-Cardona, 2012, p. 124): it has also been detected with our protocol (mould A-Pou2: 60.74.1, 60.74.2, 60.74.3). Moreover, one other series of three axe-heads (60.77.03, 60.77.04, 60.77.06)

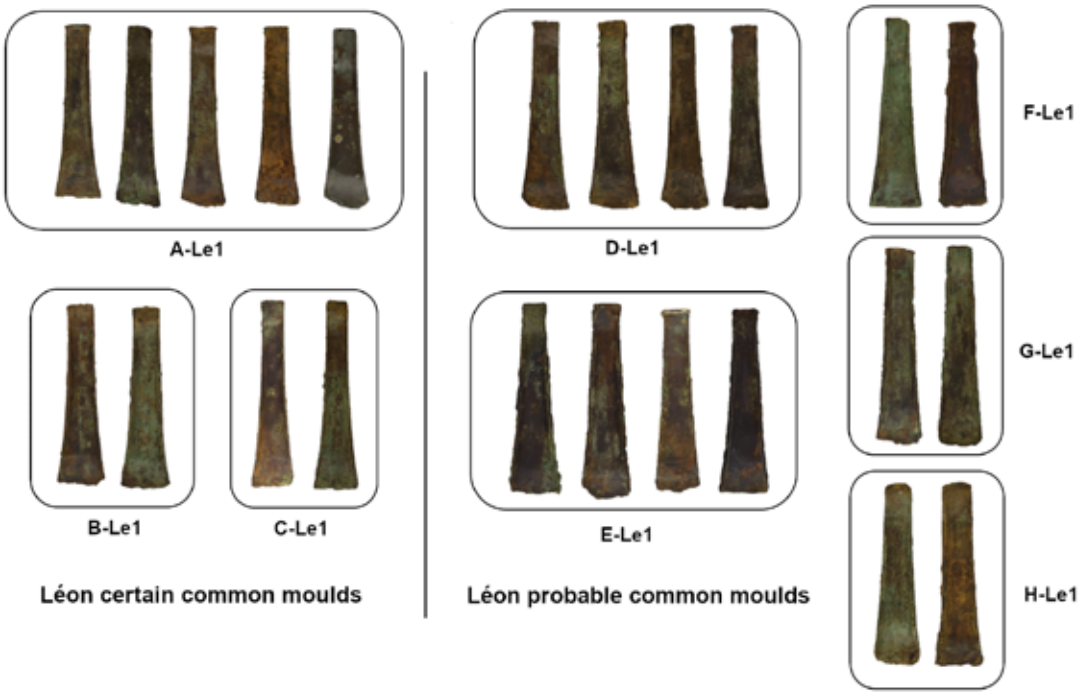


Fig. 22 – Results of common moulds analysis performed on Léon 1 hoard.

seem to have been cast in the same mould (B-Pou2), while another was used for making a pair of axe-heads (60.77.05, 60.77.07: C-Pou2). They show the best results of this study, despite the lack of casting defects (probably erased during the polishing) that could have brought an additional confirmation.

Axe-heads from Léon hoard 1 and Chalet hoard 1 and 2 seem to share similarities (the fact that they are the three largest hoards in the study undoubtedly biases this result). In Médoc, the axe-head 60.77.2 from Pouyalet 2 and the axe-head D2009.I6 from Le Chalet appear similar in terms of the distances calculated between their two 3D models. Outside the hoards that constitute the bulk of our sample, an axe-head from Ygos-Saint-Saturnin (60.99.1) show compatibilities with the axe-head no. 6 of Léon hoard 1, distant of about 50 km. Remarkably, axe-head no.6 is also the lighter of the hoard, even if it is not an outlier in any other aspect). Near the Gironde estuary, axe 60.47.1 from Cubnezais and the axe-head D91.16.1 from Lesparre-Médoc, seem to match together while the two sites are distant of more than 50 km, on different sides of the river.

Once again, there are no casting defects to fully validate these hypotheses and only the distances computing allows perceiving such comparisons.

Finishing of the axes

After the casting, the axe-heads could receive a series of modification: hammering of the heel to erase the traces of the pouring cup and to ease the fitting of the handle, polishing of the surface (including the erasure of the casting seam) and sharpening of the edge are the most obvious. Lagarde-Cardona (2012, p. 201–202) noticed that axes-heads, when they were the only type of artefacts in a specific hoard were well finished, meaning that no objects were deposited right after their casting. The observations made for the Léon hoards confirm this idea. In Léon hoard 1, most of the casting seams were erased, except for 7 axe-heads (nos. 3, 5, 13, 21, 22, 27, 31; fig. 6.3, 6.5, 6.13; 7.21, 7.22; 8.27, 8.31), a feature sometimes related with an imperfect fitting of the two halves of the mould. In Léon hoard 2, all of the casting seams were erased by polishing. Remarkably, in hoard 1, the axe-heads poorly polished do not belong to any of the three main groups (A-Le1, B-Le1, C-Le1). Axe-heads nos. 3, 21 and 22 belong to a same hypothetical group (together with no. 18) attributed to mould E-Le1, object no. 5 to possible mould F-Le1 (together with axe-head no. 15), and nos.13 and 27 to possible mould G-Le1. This feature seems linked with technical habits, and is not related systematically to an absence of use of the object: 4 of these 7 axe-heads were clearly worn out.

Using the axes

The use of the axes can be approached from two different perspectives. The first one is related to their morphology and their mass: besides determining its inertia and therefore its potential as a cutting tool, they can also relate to forms of abstract value depending on the weight and quality of the metal used. The other possible approach focuses on the use wear of the objects.

Volumes, masses and (possible) use

In the framework of this study, we could obtain directly (through direct measuring) or indirectly (thanks to previous studies) the weight of 370 axe-heads. Considered globally, they spread from c. 350 g to c. 850 g (fig. 23). The values are gathered mostly around 410 g, 657 g and 763 g. Nevertheless, these values present no arithmetical relationships that can suggest metrological features. Yet, the geographical and chronological extent can somehow blur the picture.

Reducing the spectrum to more cohesive samples may allow for figuring more local or short-lived standardization patterns. The two hoards from Léon provide a good case-study for very local and short-term behaviours, as they are distant only some 30 meters, and at least one mould is common to axe-heads belonging to both of them. As a reminder, hoard 1 contained thirty axe-heads, hoard 2 ten axe-heads.

The histogram of the masses of the two hoards shows that they follow a symmetrical, unimodal distribution (fig. 24). The masses of hoard 1 show a greater dispersion (with the presence of extreme values) and the interquartile ranges of the two repositories do not overlap, but this may be attributable to the small sample size of hoard 2.

The FDA highlights the general symmetrical distribution within the two hoards, taken separately or together, even if the masses of the axe-heads from hoard 2 are clearly lighter than within hoard 1. No multiple clusters of values – indicative of metrological distributions – can be distinguished and the difference between the two hoards cannot be understood as the subproduct of a metrological intention. The CQA show sinusoidal curves that are expected when dealing with samples normally distributed and they do not indicate construction around a metrological unit. The same applies if we consider globally the masses of the 370 Medocan axe-heads, allowing once more for discarding the idea of standardisation or metrology of the product, at least according to their mass.

Yet, what is obvious is that each hoard contains axe-heads of similar weight, while the difference of the mean mass of the axe-heads belonging to two different hoards could be significant even at a very short distance in space and time. Weights of Léon hoard 1 axe-heads spread from c. 525 g to c. 765 g, with a peak of values around c. 640 g and a mean of 649 g. In hoard 2 (contemporary to hoard 1 and distant 30 m), they spread from c. 566 g to c. 634 g, with a peak of values around c. 590 g, and a mean of 591,2 g (fig. 25). Axe-heads from hoard 2 are therefore significantly lighter than those from hoard 1, in spite of their proximity in time and space).

These observations demonstrates that the mass or the volume (forcefully related) were not linked with a metrology, not even at the scale of a very small territory, and

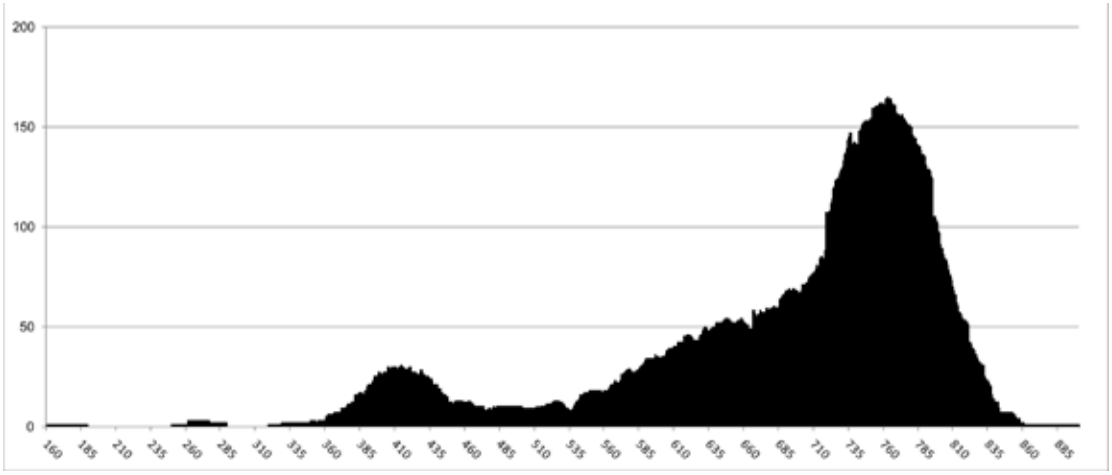


Fig. 23 – Frequency Distribution Analysis (FDA, with 5% tolerance) chart of the 370 axes masses measured in the framework of this study.

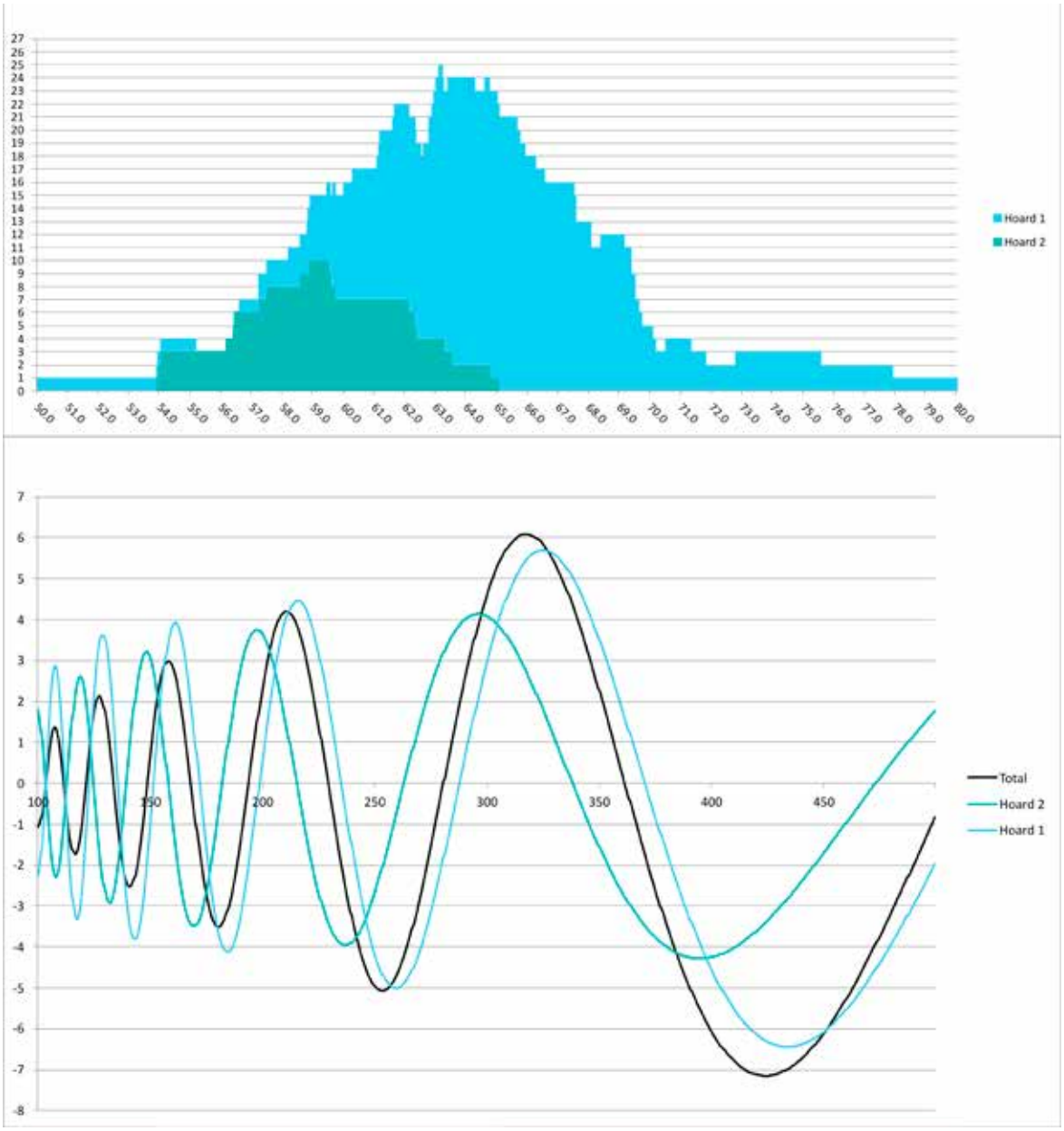


Fig. 24 – Stacked chart of the Frequency Distribution Analysis (FDA, with 5% tolerance) and Cosine Quantogram Analysis (CQA) curves of the axe masses from hoards 1 and 2 found at Léon.

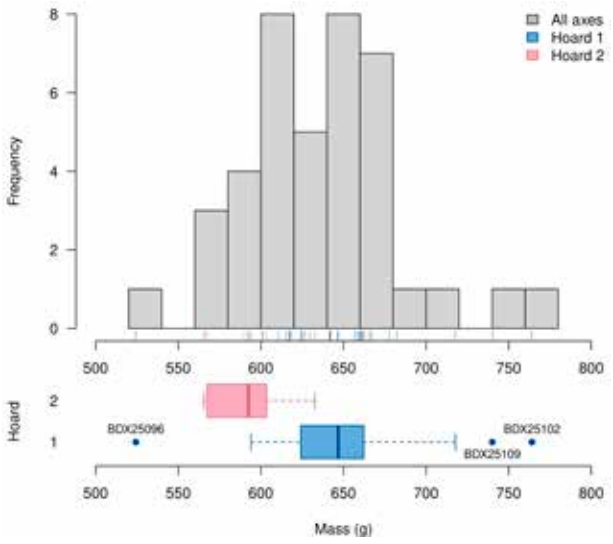


Fig. 25 – Distribution of the axe-heads from Léon hoards according to their mass.

we can therefore discard the hypothesis of their use as a currency based on a standard mass of metal. The relationship between the objects, their volume and mass must probably be understood as the result of a technical routine, the repetition of similar technical gestures aimed at the realisation of objects of similar shape and properties. Yet, these routines seem to vary from one productive context to another: in spite of being similar in shape, the axe-heads seem to be different in masses and volumes from one hoard to another, a situation clearly demonstrated by the Léon example.

The masses of the Medocan axe-heads spread over a range of c.450 g (fig. 23). If their general shape remains the same, the inertia of the objects must have significantly varied, as well as the strength needed for manipulating them repeatedly. This can suggest that the mass/volume of the objects were linked with their anticipated use, and that, therefore, axes were produced at least initially for a specific task.

Wear and use

Lagarde-Cardona (2012) already noticed that the axe-heads deposited into 'axes-only' hoards were often worn by use. The observations made on the Léon hoards confirm this fact. Wear is not easy to detect, as a short use can result in superficial wear whereas a good resharpening of the blade may erase traces. Moreover, post-depositional processes may have altered the edge. It seemed therefore wise to limit ourselves to general observations, allowing for a first characterization of the density/diversity of technical use(s) of the axes.

Three wear patterns have been discerned, taking into account the possible chipping of the edge as a consequence of post-depositional processes: one resulting in a straight edge of the blade, the other in an asymmetrical curve, the last in a symmetrical curve. The first one is characterized by a straight edge and symmetrical angles between the edge and the sides of the blade. It can result from a limited use (or from no use at all) after the sharpening of the blade consecutive to the casting, or from a drastic resharpening of the edge. In that configuration, the more the axe is used, the nearer the edge of the blade is from the wings of the axe-head (e.g.: Léon hoard 1, axes nos. 15 and 17). The second one is a symmetric wear, resulting in a curved edge and obtuse angles between the blade and the sides of the axes. The third one is an asymmetric wear, resulting in a sharp angle on one extremity of the edge and an obtuse one on the other side, and an asymmetrically curved edge. In Léon hoard 1, 9 blades had a straight edge, 14 an asymmetric one, 7 a symmetrically curved one. In Léon hoard 2, 6 had a straight edge, 3 an asymmetric one, 1 a symmetrically curved one. There is no obvious relationship between the use wear and any other characteristic of the axes. Most of the axe-heads produced into mould A-Le1 have an asymmetrical use wear, but one has a straight edge (no. 16). Only in two cases (nos. 5 and 22) a straight edge seems to be related with clear casting seams, even if both axe-heads seem to have been used.

The prevalence of asymmetric wear (17 out of 40 axes) is probably indicative of the fact that the axes had a short life-cycle. Discarding axe-heads that present such a wear seems premature in relation to their potential, as it would be sufficient to reverse the orientation of the blade in relation to the handle for exploiting the other side of the edge.

Discarding the axes: the constitution of the hoards

When a hoard is exclusively made of Medocan axe-heads, the objects are complete: fragmented axe-heads can only be found into mixed hoards. Only a few of these hoards have been excavated according to archaeological methodologies, but the observations made allow for making the hypothesis of possible patterns. In Léon, the hoards were deposited into pits with a circular opening, while in Le Chalet, a jar was used as container. In Le Chalet 2, the axe-heads were disposed concentrically, while in Léon 1, they seem to have been laid in several levels of lined-up objects. In Léon 2, the shape of the pit suggests a similar pattern, probably limited to one level only. But beyond these differences, patterns can be detected regarding the deposition processes. All axe-heads were deposited without their handle, and the geometry of the hoards shows that all objects were deposited simultaneously. At Léon 1 and Le Chalet 2, the axe-heads were disposed vertically, with the blade up. At Le Chalet 2, an axe-head was laid horizontally on top of the others. It is probable that the horizontal position of the two top axe-heads of Léon 1 corresponds to a same pattern. Even if in the Léon 2 hoard axe-heads were found in secondary position, it seems likely that the hoard had originally a similar morphology, with most of the axe-heads laid vertically while one or two others were laid horizontally on the top. These similarities between

Léon and Le Chalet are significant, as these hoards are respectively at the southern and the northern boundaries of the Medocan axes hoards area of distribution. These similarities suggest that gestures related with the constitution of an axe-heads hoard were repetitive, if not ritualized, at a regional scale. These observations converge with Couderc's (2017) conclusions, who emphasized the fact that these ritualized hoards took place at the interface between wetlands and drylands (a situation also observed at Léon).

Individual trajectories of different axes: the case of the outliers

Some of the objects are outliers in some aspects (mass, composition, origin of the metal). The observations made for Léon hoard 1, encompassing all steps from the making to the hoarding, allow for assessing the significance of these outliers and determine if these objects had a different trajectory before their simultaneous deposition with others or not.

Outliers: the metal properties

In Léon hoard 1, two axe-heads only (out of 30: nos. 20 and 26) are made with a metal which isotopic values differ significantly from the others. Yet, these axes do not differ in any other point of view from the others. Axe no. 20 belongs to the hypothetical 'mould D-Le1' group, together with 3 other axe-heads (nos. 7, 9, 11), none of them presenting any specificity differencing them from the other objects of the hoard.

One object differs from a compositional point of view (axe no. 15), but not from any other aspect. It belongs to the hypothetic 'mould F-Le1' group together with axe 5, which is not an outlier.

Outliers: the masses

One axe-head (no. 6) has a mass significantly inferior from the mean of the hoard, but it is its only specificity. Masses of axes nos. 12 and 19 are significantly higher than the mean. Axe-head no. 12 may have been cast in the same mould than axe-head no. 17 (not an outlier from any point of view), while axe-heads nos. 6 and 19 are isolated.

No object cumulates significant differences (i.e. a different metal *and* a different mass or shape) that would suggest that its trajectory differed significantly from the others. The specificities of these objects can therefore be interpreted as the discrete results of the very reduced diversity in technical practices and in uses. Axe-head no. 6 lighter weight (as well as its shorter dimensions) is probably the result of the use of a mould slightly smaller than the others, while nos. 19, 12 and probably 17 (very worn by use) were cast into one somehow bigger. The compositional differences observed for axe-head no. 15 can be related with contextual reasons (possibly a lack of tin at the moment of the making), as well as the different isotopic characteristics of axe-heads nos. 20 and 26 (a lack of new copper freshly arrived?).

DISCUSSION

Homogeneity vs diversity: a general assessment

Homogeneity and diversity regarding the constitution of axe-heads hoards can be assessed at two different scales: regional and local.

At a regional scale, from the northern part of the Gironde to the south of the Landes, deposition patterns seem relatively regular, at least as far as hoards containing exclusively axe-heads are concerned, even if too few of these hoards were excavated according to archaeological techniques. The axe-heads hoards are by far the most frequent kind of hoards in the Medoc and western Landes area, a first, obvious observation which characterizes regularity into hoarding practices. Medocan axe type dominates and is often exclusive (it is the case in Léon and Le Chalet 2), therefore showing that this specific hoarding practice corresponds to a technological horizon: this relationship between technique and hoarding practices is important, as will be emphasized later on.

Some regularity at a regional scale can also be inferred from the arrangement of the hoards: in both Léon hoards and in Le Chalet 2, most of the axe-heads were laid out vertically, blade up, while one or two of them were laid horizontally on top. In every hoard, wear seem highly variable from one axe-head to another: the constitution of the assemblages seems therefore to respond to the same dynamics, bringing together objects differently worn out.

However, beyond these common points, differences also appear: in our study area, the otherwise common practice of deposition in jars seems characteristic from the Medoc area (at least 6 cases), while the few southern hoards seem to be deposited into bare pits. Beyond that, as we will emphasize later on, the different hoards are characterized by interrelated specificities: the mean mass and therefore volume of the axe-heads is different form one hoard to another, even at a very local scale as demonstrated by the Léon example. Léon hoards 1 and 2 are distant only some 30m. They were probably deposited over a short period of time (we have no mean to determine which one is the oldest, at this point): one axe-head from Léon hoard 2 was made using the same metal and was cast into a mould also used for casting 4 of the axe-heads from hoard 1. Yet, the mean mass of the axe-heads from hoard 2 is significantly lower than the hoard 1 one. The axe-heads from hoard 2 were significantly lighter (around 50 g lighter) than those from hoard 1. The axe-heads from both hoards are themselves quite light in comparison with others. This difference in mean mass and volume is correlated with the fact that the moulds used in the making of the axe-heads of one specific hoard are normally not used elsewhere.

At a local scale, on the other hand, homogeneity appears first through the technical characteristics of the axes. Results from Léon 1 hoard suggest that the metal used for making almost all the axe-heads of the hoard could proceed from the same stock or at least from metal from a same origin. There is no local ore deposit in the Atlantic coast of southern France, so metal was forcefully imported. We do not have, for now, much information about the temporality of trade, i.e. the frequency with which metal arrived in a determined area. Indirect information suggests that the volumes traded in one specific expedition could not be very important (Gorgues and Milcent, 2018). The procurement of important volumes of metal would therefore have necessitated dense connections with metal-producing regions, whether through overland or maritime ways. At this point, it seems sensible to hypothesize that, on the long-term, metals from very diverse origin were used in any European Bronze Age region (Ling et al., 2013; 2014; Melheim et al., 2018). The homogeneity of the metal used in Léon 1 suggests that the time span between the procurement of the metal mass and the making of the object was short, therefore minimizing the probabilities for the mixture of coppers from different origins, or even the simultaneous deposition of axe-heads made from metal of different origins. This, in turn, suggests a rather streamlined process from the metal procurement to the making of the axes and their final burying.

Homogeneity also appears at a local scale through the metrics of the axe-heads and their mass: as seen before, the masses of the axe-heads of one specific hoard is normally distributed around a mean value. We interpret this fact as the result of a social/technical choice, a deliberate will of producing axe-heads having roughly the same mass and/or volume, made at a local scale. It cannot be the result of the homogeneity of the moulds used, as we have seen that different moulds were used for casting the axe-heads of a same hoard: this choice intervened before the making of the moulds, and the inner volume of the moulds has to be understood as a consequence of this choice. This fact appears more significant even if we consider that, in spite of the recurrence of axe-heads of a same type, the hoards seem to have a strong individuality from one main point of view: the mean mass/volume of the objects each of them contain, as already emphasized. The different hoards seem to have had a discrete, yet undisputable individuality from the point of view of the volume of metal used for making the axe-heads and the masses of the objects.

At this same local scale, the factors of heterogeneity are firstly the differences among the moulds used. Some were used for casting up to 5 axe-heads, while others only for one. This difference may be due to a certain extent to the difference of material used, stone for the moulds having been used for making several axe-heads, clay or even sand for the others. Yet, this difference into casting contrasts with the homogeneity of the metal source and alloying differences have also been observed in wear, probably reflecting specificity in the intensity of use rather than in its nature.

Agents in time: the dynamics of the constitution of a hoard

As we have seen, there is a commonality of technical practices, in the making of the axes but also probably in their use. Hoarding patterns, in turn, are similar, and this similarity alone allows for interpreting the constitution of a hoard as the consequence of a ritual (Couderc, 2017). This means that the persons involved into the making of the hoards shared a common technical and symbolic background. On the other hand, the strong individuality of the different hoards studied suggests that the action itself was the result of a cohesive small group, probably a local community as the main factor for differentiation seems to be linked with space.

Different actors can be identified within the group. First, the homogeneity observed into the making of bronze, from the origin of copper sources (at least) to the copper/tin proportions, suggests that a fairly reduced group of persons – perhaps one person only- was involved into this process. In contrast, the technical diversity observed in the making of the axe-heads (differences in the shape of the moulds and the material used for making them, in the finishing/polishing of the axe-heads) probably betrays the fact that, beside the alloying of the metals and its casting, all other steps were implemented by a diversity of actors (the making of the moulds and the finishing of the axe-heads, first of all). This diversity probably reflects the number of persons or corporate groups involved into this collective process. For Léon hoard 1, for instance, we can hypothesize that a maximum of 14 agents/corporate groups (corresponding to the maximum number of moulds we could identify) would have been involved into the sequence of actions that resulted into the making of the hoard.

All these agents cooperated over actions that seem to extend only over a short period of time: the homogeneity of the metal source (at least in Léon hoard 1) as well as the technical specificities individualizing each hoard probably show a streamlined, short-duration process from the making of the axes to their burying, as emphasized before. We propose here that the hoard was actually the conclusion of a coherent, planned process that begun with the procurement of the metal and continued with the making of the axes and their use, before their final, ritual, discarding. In other word, the procurement of the metal would have aimed at the making of a specific set of tools (hence their compositional homogeneity), made for a specific action performed by a limited group (hence their morphological homogeneity) and buried at the closure of the action (hence the different levels of wear). This proposition, at this point, must be understood as a hypothesis. Our results are still partial and do not allow for determining the degree of generalization of the patterns we observed. Yet, the Léon case study clearly points towards this direction, and no observation made in other parts of the area of distribution of the Medocan axe-heads seems to contradict our hypothesis.

The purpose of this chain of actions can be discussed: it began with a technical action, involved different actors at a community level, and was concluded by a ritual. It can therefore be interpreted as the result of a planned collective endeavour. The differences observed in the mass of the axe-heads could suggest that this endeavour varied in nature through places or time: the inertia of the axes would not be the same and would not allow for a totally similar technical action. Yet, recent works have demonstrated that the main factor conditioning the efficiency of an axe resides in its haft and in the haft/head assembly, no in its head alone (Dolfini et al., 2023), which means that differences in masses could be levelled by hafting techniques. This idea allows for hypothesizing that the hoarding ritual is the conclusion of a normalized chain of actions (maybe itself a ritual) identical in nature in all places where hoards exclusively composed of Medocan axe-heads were observed. In other words, the collective endeavour we identify had a normalized/ritualized dimension not only in the hoarding practices but over the whole sequence of actions, beginning with the making of the metal: axes were made for a specific purpose that supposed their ritualized burying once the process was complete. The different makers may also have been the users. Differences in wear and finishing/polishing may betray differences into proactiveness of the agents (some were more involved than the others in the collective effort) or into the technical skills or perfectionism of each one of them (some would accept axe-heads less polished or less regular in shapes than others).

This reconstruction provides a framework explaining the differences of mean masses observed from one hoard to another. Two variables can suffer micro-variations: the exact volume/mass of metal obtained through trade and the exact number of persons involved in the process. This makes the ratio of metal available per person variable to some extent that was probably very difficult to anticipate in the Bronze Age technical conditions: we propose that the variations of the mean mass of the axe-heads from one hoard to another result from this uncertainty. The very punctual recourse to other different metal sources (2 cases out of 30 in Léon hoard 1) can result from a punctual adaptation process to an unanticipated situation. This interpretation also supposes that all actors of the process was entitled to a roughly similar mass of metal, therefore suggesting redistribution processes among peers, probably outside of market processes.

It is difficult to determine what was *the exact* action that was performed through this complex chain of events, beside the fact that it was linked with woodworking and had a collaborative dimension at a local scale. Yet, the fact that they were not reused – even when they were almost new – nor recycled suggest that their use made them unfit for any other further purpose. The most straightforward explanation is that these objects, through their use, were loaded with *mana*, this supernatural energy studied by Marcel Mauss (1902-1903, p. 108–122) and which he defines as "what makes the value of things and people, religious value, magical value and even social value". This value may have become incommensurable in the profane word, for good or for bad, and the objects had to be ritually discarded from it. The use of the axes for clearance of symbolically significant wooden areas, procurement of timber and/or carpentry work for the making of specific building or boats are possible explanations, all compatible with the wetlands/drylands interface location of the hoards emphasized by Florian Couderc (2017), but other probably exist.

CONCLUSION

The protocol we introduced could not be systematically applied to all our dataset, but allows for connecting the results acquired in different case studies The systematic analysis of the isotope signature of all the axe-heads from Léon Hoard 1 allows for demonstrating, for the first time, the homogeneity of the metal stock used for making almost of all the objects of one specific hoard. Statistic approaches demonstrates that the mass or volume of the axe-heads was not standardized, not even at a very local scale, and on the contrary responded to micro-local social and technical choices linked, among other factors, to metal availability. Morphometric approaches based on 3D recording of the axes allowed for assessing the number of moulds used to produce the axes of one specific hoard. In the fast-moving fields of isotope studies and/or 3D approaches (see Théo Enudde's work in this volume), the possibility we had to put together such high-resolution data remains infrequent, even exceptional.

By connecting the data acquired during this investigation, we could hypothesize that all of the axe-heads of one Medocan hoard were cast from one specific lot of bronze probably prepared by a reduced number of specialists (maybe one), from a homogeneous metal stock. They were cast in a very short span of time, possibly by the different persons or corporate groups that would use them. They were used for a specific, probably common and unique, purpose. And finally, they were buried together. These axes, as their makers and users, had their individuality but belonged to a local group, itself part of a bigger regional entity. They were made for a specific task, so specific that they would have to be discarded once their purpose fulfilled. In other words, their end was anticipated at the very beginning of their existence.

This is a hypothetical scenario. We know it is valid at least at a local scale (it applies to Leon hoard 1), and we believe it applies to other Medocan hoards (the scope of our study) and beyond: further research, applied to other sets of closely-related hoards (from a geographical standpoint) could allow for verifying its relevance.[1]

1. Data availability statement: Elemental compositions and lead isotope ratios are available in https://doi.org/10.5281/zenodo.14036191.

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Gold from the desert: Exploring the possibility of precious metal artefact production at Iron Age Saruq al-Hadid (Dubai, UAE)

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Abstract: Saruq al-Hadid (Dubai, UAE) is one of the most significant but enigmatic archaeological sites in southeastern Arabia and is characterised by a great quantity and diversity of deposited artefacts. Particularly noteworthy are copper-base, iron, and precious metal objects, often found alongside related production debris. The site was occupied from at least the 3rd millennium BCE through to the Iron Age, with periodic reuse in the late pre-Islamic and early Islamic periods. However, most artefacts can be attributed to the Iron Age, reflecting the site's significance and integration within extensive economic and cultural networks at that time. These materials are buried within sand dunes up to 6 m deep and spread across an area of about 1 km^2. This makes it challenging, from an archaeological perspective, to establish direct associations between finished artefacts and production debris. Consequently, analytical studies were employed to explore the potential existence of on-site workshops, and the relation between finished and semi-finished artefacts and working debris, in addition to studies on composition and working techniques and the provenance of raw materials. This paper focuses on precious metal artefacts – made of gold, silver and electrum – and the potential existence of on-site workshops for their production. We discuss a variety of production techniques and possible cultural preferences regarding style and colour. The range of artefacts raises the question of Saruq al-Hadid's role and importance within local and long-distance networks of cultural contact and exchange in the Iron Age.

Keywords: exchange networks, gold, granulation, Iron Age, precious metal production, southeastern Arabia, working techniques.

Résumé : Saruq al-Hadid (Dubaï, Émirats arabes unis) est l'un des sites archéologiques les plus importants, mais aussi les plus énigmatiques du sud-est de la péninsule Arabique. Il se distingue notamment par la grande quantité et la diversité des artefacts qui y ont été découverts. Parmi ceux-ci, les objets en cuivre, en fer et en métaux précieux sont particulièrement remarquables, souvent retrouvés avec des résidus liés à leur production.
Le site fut occupé dès le III^e millénaire avant notre ère et jusqu'à l'âge du Fer, avec des réoccupations périodiques à la fin de la période préislamique et au début de la période islamique. Toutefois, la majorité des artefacts datent de l'âge du Fer, témoignant de l'importance du site et de son intégration dans de vastes réseaux économiques et culturels à cette époque.
Ces matériaux sont enfouis sous des dunes de sable pouvant atteindre six mètres de profondeur et répartis sur une superficie d'environ un kilomètre carré. Cela complique, d'un point de vue archéologique, l'établissement de liens directs entre les objets finis et les déchets de production. Ainsi, des études analytiques ont été menées afin d'examiner la possible existence d'ateliers sur le site, ainsi que les relations entre artefacts finis, semi-finis et déchets de travail. Ces recherches portent également sur la composition, les techniques de fabrication et la provenance des matières premières.
Cet article se concentre sur les artefacts en métaux précieux – or, argent et électrum – et sur la possible existence d'ateliers locaux dédiés à leur production. Il aborde différentes techniques de fabrication et les préférences culturelles potentielles en matière de style et de couleur. La diversité des artefacts soulève enfin la question du rôle et de l'importance de Saruq al-Hadid dans les réseaux de contact et d'échanges culturels, tant locaux que longue distance, à l'âge du Fer..

Mots clés : âge du Fer, granulation, métallurgie, orfèvrerie, techniques, péninsule Arabique, réseaux d'échanges.

The fascination with precious metal artefacts and the skilled techniques associated with their production has a long tradition, as attested by the interest of ancient historians, such as Herodotus, Pliny the Elder, Gregorius Agricola or Vanoccio Biringuccio, in collecting and reporting on production techniques and recipes (e.g. Carroll, 1974 or Moorey, 1994). This fascination continues today, with an expanding corpus of research on ancient

gold enhancing our understanding of the subject. The archaeological exploration of ancient production processes and associated precious metal workshops, however, remains incomplete and ongoing, in part because precious metal artefacts are more often restricted for analysis than other archaeological materials.

In this context, the large corpus of precious metals from Saruq al-Hadid (Dubai, UAE) is an important source of information, offering the potential to expand our knowledge of ancient precious metal production and use. Saruq al-Hadid is well known for its rich and varied material assemblage, comprising, for example, copper-base and ferrous artefacts, copper-base production debris, pottery often decorated with snake imagery, decorative shells, soft stone vessels, semi-precious stones in the form of beads or seals, and wooden artefacts (Karacic et al., 2017; Weeks et al., 2017; Boraik Radwan, 2018; Roberts et al., 2019; Stepanov et al., 2019; Weeks, 2023).

A distinct characteristic of the site is its location within the northern extension of the Rub' al-Khali desert, in a still active dune field (figs. 1 and 2). The site was



Fig. 1 – Location of the sites discussed in this article (©David-Cuny).

intermittently occupied from the Neolithic period, with more persistent if seasonal occupation from the Bronze Age, but its largest corpus of finds belongs to the early Iron Age (Iron II period) deposits dating to c. 1000-800 BCE (fig. 3). Subsequent phases of occupation can be identified from the late pre-Islamic period into the early Islamic period in the 11th century AD (Weeks et al., 2019a; Weeks et al., 2023; Franke, in press). Within the ongoing discussion of the nature of human occupation of the site, Weeks et al. (2018) proposed a temporary (likely seasonal) but persistent use of the location. This comprises in particular the stratigraphic units of Horizon II dating to the Iron II period, from which also the majority of precious metal finds derive (table 1).

At this time, socio-economic and ritual aspects shaped the site's material culture; persistent temporary (seasonal) gatherings of groups that can be documented at Saruq al-Hadid represent an important mobile aspect of the Iron Age settlement landscape in southeastern Arabia, otherwise known largely from sedentary sites.

At Saruq al-Hadid, gold and silver-base finished artefacts are present in various shapes and kinds ranging from jewellery to decorative and ritualised artefacts. Most precious metal finds are varieties of beads or small ringlets in addition to plaques and singularities, such as finger rings or miniature artefacts (Boraik Radwan, 2018, GR 5547; Valente et al., 2020, fig. 13). The contemporary appearance of working remnants—in the form of foils, sheets, ribbons and wires, as well as semi-finished or broken precious items—indicates the possibility of gold and silver working at the site. Moreover, the presence of both finished and semi-finished precious metal artefacts raises the question of whether, and to what extent, these material groups might reflect a *chaîne opératoire* for the production of precious metal artefacts on site during the early Iron Age. This question arises as there is little to no direct evidence, in the form of pyrotechnological installations or tools, for spatially delimited precious metal working areas at Saruq al-Hadid.

Furthermore, particular types of gold beads seem to dominate the archaeological record and raise questions regarding the possibility that Saruq al-Hadid may have been not only a production centre connected to the wider region but also a centre that influenced stylistic norms of gold jewellery production and use during the Iron Age. The production of artefacts in other materials is attested at Saruq al-Hadid. For example, production and use of stone tools is evident for the Early and Middle Bronze Ages (Moore et al., 2022; Al-Kassem et al., 2024), while copper smelting and working residues are a significant part of the Iron Age material record of the site (Weeks et al., 2023). Later occupation layers from the pre-Islamic and early Islamic eras exhibit events of scavenging and the recycling of not only copper but also iron (Franke, 2017a; Stepanov et al., 2019; Valente et al., 2020; Franke, in press). Residues from the carving of shell and animal bone are also known from prehistoric contexts at the site, and woodworking might also have been undertaken there (Weeks et al., 2017, fig. 7, 10; Weeks et al., 2019b). The combined evidence indicates an environment that—despite its location in the desert fringes—was an important place not only for communal gathering but also for craft activities.

Such remains, furthermore, highlight the importance of Saruq al-Hadid within Iron Age exchange networks in southeast Arabia and beyond. The precious metal artefacts from Saruq al-Hadid are not singular to the site, and parallels are known from the wider Near East. It is, however, striking that no other sites in southeastern Arabia exhibit comparable amounts of finished precious metal artefacts or working residues. This raises the possibility that Saruq al-Hadid may have functioned as a (or even *the*) primary location for the production and distribution of such artefacts.

Previous research has shown that Saruq al-Hadid is part not only of regional exchange networks but also of long-distance exchange systems. Wood specimens from the site, for example, have been identified as potential imports from the Levant or Iran (Newton, 2016), while iron sword fragments and bi-metallic daggers connect the site by their style, type and geochemical composition to northern Iran (Stepanov et al., 2019; Weeks and Petrie, in press). Copper-base braziers display imagery that is unprecedented in the region and links the site to northern Mesopotamia (Potts, 2009), while depictions carved on marine shells resemble Assyrian iconography (Weeks et al., 2019b) and (imitations of) scarabs connect the site, possibly indirectly, to Egypt and the Levant (Boraik Radwan, 2018, p. 148–149). This evidence clearly shows that Saruq al-Hadid was deeply enmeshed in expansive Iron Age trade networks that facilitated the exchange of materials, technology, imagery and ideas. In this paper, we explore whether Saruq al-Hadid was a production centre for precious metal artefacts during the early Iron Age. We focus on three major questions:

1) Can waste and production materials from the site be linked with finished artefacts found there?

2) To what extent can we establish a *chaîne opératoire* for the production of gold and silver-base artefacts on site? And, if production is indicated;

3) Were gold and silver-base artefacts produced exclusively for the site itself, or were those products part of the wider exchange system of Iron Age southeastern Arabia?

These questions are explored through macroscopic and microscopic observations as well as geochemical analysis of artefacts and production residues, alongside consideration of their archaeological contexts and dating. We focus primarily on finds excavated during three field seasons of the Saruq al-Hadid Archaeological Research Project (SHARP) at the site from 2014 to 2017 (Weeks et al., 2017; Weeks et al., 2018). In addition, we incorporate finds excavated by the Polish Mission (Wygnańska et al., 2022) and already published data in particular from the Sanisera Archaeology Institute team (Soriano et al., 2018), alongside finds from excavations by the Dubai Municipality and other teams published in the Saruq al-Hadid Archaeological Museum catalogue (Boraik Radwan, 2018).



Fig. 2 – Different kinds of beads found in their original arrangement in the central sector at Saruq al-Hadid (©Dubai Culture & Arts Authority).

ON STRATIGRAPHY

The stratigraphic relationships of precious metal artefacts from Saruq al-Hadid are difficult to understand due to the site's complex taphonomy (fig. 3). The majority of gold-base artefacts (n = 65) derive from relatively secure Iron II period contexts within Horizon II and a significant but lower number (n = 43) were excavated within mixed early Iron Age contexts of Horizons I-II (table 1). This describes an intermediate phase between the upper strongly mixed layers in Horizon I (spanning the early Iron Age to the early Islamic period) and the Iron II period deposits of Horizon II.[1] A small number of gold-base artefacts (n = 10) came from Iron I layers within 'concentrated activity areas' of Horizon III (c. 1300-1000 BCE). A single silver-base artefact was recovered from the Wadi Suq to Late Bronze Age layers of Horizon IV (c. 1750-1300 BCE), and no gold-base artefacts were excavated within the earliest layer, Horizon V, dating to the early Wadi Suq period (c. 2000-1750 BCE).[2] The precious metal finds from Horizons IV and III are typologically similar to artefacts from the later Iron Age Horizons, and may be intrusive within these early strata, reflecting the taphonomy of the site and the effect of moving sand dunes. A further five gold-base artefacts were found within the surface layers of Horizon I; and 19 artefacts were not assigned to contexts. The concentration of precious metal finds within Horizon II suggests most silver and gold-base artefacts from Saruq al-Hadid were deposited during the Iron II period, specifically from c. 1000-800 BCE based on a substantial series of radiocarbon determinations (Weeks et al., 2019a; Alkhalid et al., 2024; here: table 1).

1. For a detailed discussion of the stratigraphy at Saruq al-Hadid see Weeks et al., 2019a and, more recently, Alkhalid et al., 2024.
2. In total, three silver-base beads were registered during SHARP excavations, one of which derived from the intermediate phase Horizons I-II, a second one was found within deposits of Horizon IV and a third artefact was unstratified.

ON THE KINDS OF ARTEFACTS

The assemblage of precious metal artefacts from Saruq al-Hadid comprises a large variety of kinds, styles and types of artefacts, and represents one of the largest corpora of precious metals in ancient Arabia. During three SHARP excavation seasons alone, 143 items (table 1) came to light, of which 62 are finished artefacts and 81 are different kinds of working remnants and misfit. The Sanisera Archaeology Institute Mission excavated more than 448 individual items during four long seasons (Soriano et al., 2018, p. 1) and the excavations of the Polish Centre of Mediterranean Archaeology (2017–2018) and Polish Archaeoconsultant company (2019–2020) excavated 59 precious metal artefacts (table 1). These numbers might easily be doubled, as they do not include multiple gold finds from earlier excavations by the Jordanian Mission and Dubai Municipality (Al-Khraysheh and An-Nashef, 2007, p. 81–89; Nashef, 2010; Herrmann et al., 2012, fig. 6c-e) and unpublished artefacts excavated by further teams from, for example, Germany (Dr. Thomas Urban and Partner, Brandenburg; Tübingen University) and Spain (Seville University).

The majority of finished artefacts can be categorised as jewellery and within this category, beads are the most common artefact type. Rings (open and closed) are much less frequent. They may have been finger, toe, ear or nose rings but may also have been used in the decoration of hair or fabrics. Bracelets, on the other hand - which are common among copper-base artefacts at Saruq al-Hadid —are not known among the precious metal finds from the site.

Many beads comprise a combination of individual spheres that are shaped into small ringlets with an average size of about 4–10 mm in diameter; individual granules are on average about 0.8 mm in diameter with few smaller and larger exceptions (Weeks et al., 2017, fig. 22; Al-Khraysheh and An-Nashef, 2007, p. 86–88; here: fig. 4, nos. 11–16). Very rare exceptions are ringlets with only five to six spheres, but which are about 3 to 10 mm in diameter. These beads can be elaborated by the addition of extra rows of spheres, either horizontally or vertically. Beads that are built from horizontally-added rows consist of two rows only (fig. 4, nos. 11 and 14), whereas beads built from vertically-added (stacked) spheres are typically arranged into tubular compositions that are two to 12 rows or more long (fig. 4, nos. 12, 15 and 19). A small number of artefacts combine spheres with sheet metal or filigree to create complex compositions. Prominent examples are beads

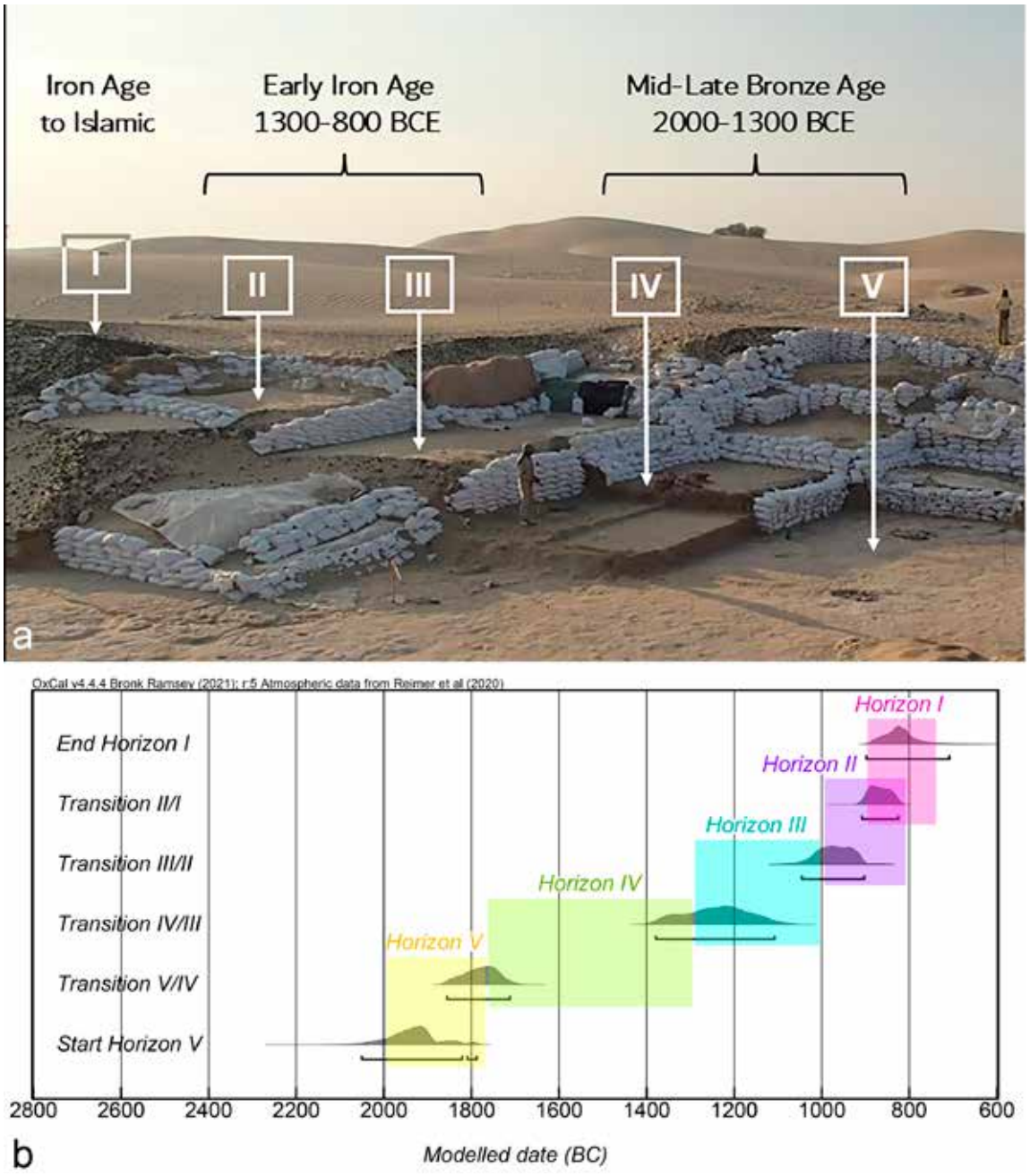


Fig. 3 – Chronological boundaries of the archaeological horizons at Saruq al-Hadid, based on modelled radiocarbon determinations and typological analyses of ceramics (Weeks et al., 2019a).

Horizon	Period	Description	No. gold and silver-base finds	
			SHARP	Polish Mission
I		Surface	5	0
Between [I-II]	EIA+	[slump]	43	8
II	Early Iron Age	Dispersed varied activities	65	51
III	IA I	Concentrated activities	10	0
IV	Wadi Suq - LBA	Midden deposit	1 (Ag)	0
V	Wadi Suq	Diffuse midden, structures	0	0
Other	[unassigned]		19 (2 × Ag)	0
Total			**143**	**59**

Table 1 – Number of gold and silver-base artifacts in the respective horizons excavated at Saruq al-Hadid. Note that the majority of finds derived from IA II contexts.



Fig. 4 – The assemblage of precious-metal artefacts from Saruq al-Hadid comprises a great variety of finished artefacts, as well as working remnants and misfits (©SHARP/David-Cuny).

with a conical sheet metal body that was capped with one to three rows of spheres at their lower and upper ends (fig. 4, no. 18). In addition to beads, finger rings and pendant-like artefacts were also produced in intricate arrangements combining sheet metal, spheres and filigree (Boraik Radwan, 2018, p. 107, 116–117).

The second most common group of beads on the site includes a wide range of spherical, cylindrical or barrel shaped beads (fig. 4, nos. 1-6). While the latter comprise the largest group within sheet-beads, a typological differentiation between various kinds of spherical sheet-beads is not always decisive (Weeks et al., 2017, fig. 22; Al-Khraysheh and An-Nashef, 2007, p. 84); variations may have been common and 'perfection' not a necessity. Barrel beads are in most cases between 2 and 5 mm in length, with an average diameter of c. 3-5 mm but can be exceptionally larger or smaller; decorations, such as indents, are rare (here: fig. 4, no.3; Boraik Radwan, 2018, GR1868, bottom left).

A rather extraordinary type is described by the term 'horn-shaped artefact', several design variations of which are found at the site (fig. 4, no. 23 and fig. 5). Typically, these are bi-metallic, comparatively dense and massive items, consisting of a (potentially cast) silver core covered with a gold-base foil (Al-Khraysheh and An-Nashef, 2007, p. 85; Boraik Radwan, 2018, p. 108). Variations are commonly seen in their horn-like extensions, which can either be straight, or bent inwards or outwards, and also within their broadly cylindrical cores that are worked into different shapes and sizes. A shallow depression can frequently be found in the top of the core element between the horn-shaped appendages and opposite a central seam-like extension (variant 1); but the exact extension and shape of these details vary among individual artefacts. Only a few examples do not exhibit a seam-like extension (variant 2). On average, these items are about 15–30 mm wide and about 20–30 mm long, and weigh about 30 to 40 g, placing them among the heaviest precious metal artefacts from the site.

The function of the horn-shaped artefacts is still uncertain, but they are often described as hair accessories, or nose or earrings (compare, e.g. Boraik Radwan, 2018, fig. 23 and Soriano et al., 2018, p. 3), although no functional details conclusively indicate how these artefacts may have been worn. However, it is possible that they had a purely symbolic function and were experienced in this form as finished and complete. Rare jewellery items are so-called cage-beads (fig. 4, no. 20), a term that describes an intricate filigree arrangement of (nearly) completely fused but originally twisted wires that either leave an open space in their centre—which is why they are associated with cages—or spiral around a core (Weeks et al., 2017, fig. 22, SF29674; Boraik Radwan, 2018, p. 109). Several artefacts display filigree work or show designs with spheres that appear to have been prepared for mounting semi-precious stones. These include (finger) ring fragments worked in filigree, a carnelian pendant mounted on a metal sheet and adorned with spheres, and tassel-shaped objects crafted from twisted strips (or wires), topped with spheres and two wire-like extensions (Soriano et al., 2018, fig. 10; Boraik Radwan, 2018, p. 107 and 116–117). Twisted strips are also used in the production of elongated 'tubular' beads that are capped with spheres at their top and bottom (Boraik Radwan, 2018, p. 110). None of the latter items were discovered in SHARP excavations, but they are known from other areas of the site.



Fig. 5 – Horn-shaped artefact SF25873. Note the plate-like area in the centre of the artefact (©SHARP/David-Cuny).

Decorative and non-jewellery items include plaques, which comprise a minority of precious metal items on the site. Some of these metal sheets are blank, but the majority are decorated with depictions of geometrical patterns or zoomorphic figures commonly worked in *repoussé* (fig. 4, nos. 24 and 25). In most cases the plaques show piercings at their edges, indicating that they may originally have been intended to be attached to garments or wooden items (fig. 4, nos. 10, 24, 25). A particularly well-crafted example depicts a hare (fig. 4, no. 24). Noteworthy are the edges of the sheet metal that are so tightly cut off at the section displaying the hare's ear, an imperfection that contrasts with the otherwise delicate depiction of the animal. Here, the cut is—in contrast to all other three corners —rounded, and it is possible that it stems from a secondary treatment related to the reuse or recycling of the sheet.

A small minority of gold-base items can be related to the group of symbolic, ceremonial or potentially ritual (miniature) artefacts. Despite their absence within SHARP excavations, they are an important group of gold-base artefacts that are strongly interwoven with the symbolic and ritual nature of the site (Weeks et al., 2023). Their presence in areas other than the SHARP excavations may be an indication of their spatial importance within the site as a whole. Among those are a miniature bow with a quiver (Valente et al., 2020, fig. 13), and miniature snake 'figurines' or figurative animal depictions (Boraik Radwan, 2018, p. 113 and 115). All of these items have copper-base counterparts, and their rare occurrence in precious metals highlights the wider significance of these symbols for the site and its participating communities.

Only a few artefacts are best described as misfits, failures or unfinished artefacts. Evident examples are a bead worked from gold-base sheet metal and a gold-base wire-shaped ringlet with a ribbon fused onto it. The latter artefact seems to be a misfit during working and may have been kept as spare material (fig. 4, no. 21). The sheet bead shows its originally inward-folded (upper and lower) edges bent upwards and seems to have been—possibly intentionally—unfolded (fig. 6). This effect classifies the bead as a working remnant rather than damaged during burial conditions or failure. A particularly important example is a small ring-shaped item with indents on its outer surface (fig. 7, no. 1). It is a perfect facsimile of two finished artefacts from the site that show granulated spheres that were brazed into such indents within a ring-base (fig. 7, no. 2).

A particular group among the working remnants are partly fused, cut, split, twisted or knotted wires, strips and ribbons that reflect working techniques evidenced in finished artefacts from the site (fig. 8). These kinds of



Fig. 6 – The upper and lower rims of sheet bead SF26345 seem to have been intentionally unfolded possibly to reuse the material. Note the original edges that were roughly cut (©SHARP/David-Cuny).



Fig. 7 – SF33355 (1) is a perfect facsimile of finished artefacts from the site; the indents were possibly intended to be filled with granules, as seen in the finished specimen SF21804 (2) (©SHARP/David-Cuny).

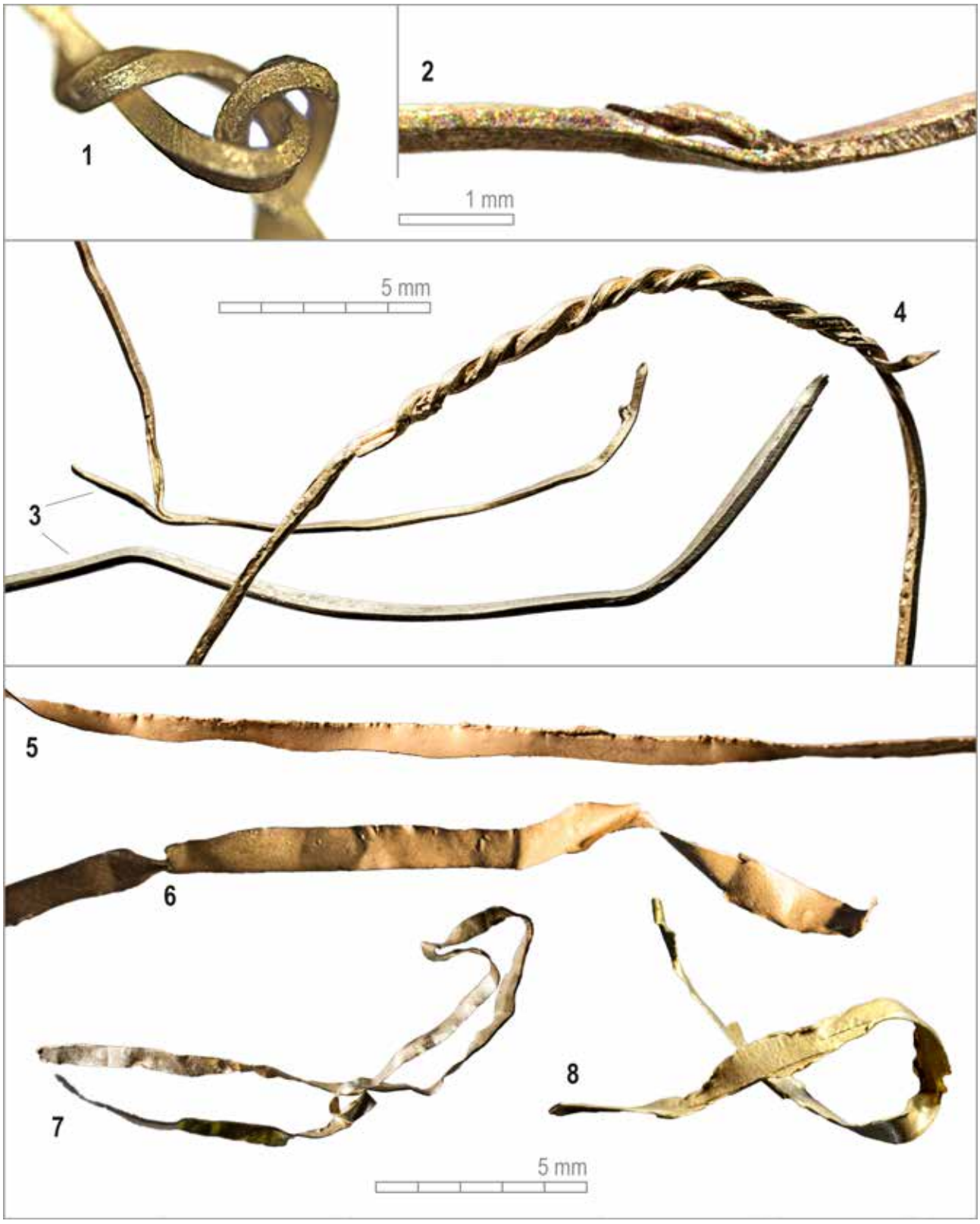


Fig. 8 – Golden wires and ribbons from Saruq al-Hadid often show signs of processing such as twisting, splitting, cutting or knotting. Note the incised marks along the cutting edges of nos. 5 and 8 (©SHARP/David-Cuny).

pre-worked items are often found in bundles that mark them as potential spare working material (fig. 4, nos. 7 and 8). Only a few of them were discovered, but they are part of a larger corpus of bundled or unbundled semi-finished strips, ribbons, wires or sheet fragments (see also Al-Khraysheh and An-Nashef, 2007, p. 83). Ribbons often display indented linear marks along their cut edges (fig. 8, nos. 5 and 8), indicating that they were cut from larger sheet metal units for further processing. More importantly, these marks show that ribbons were not ran-



Fig. 9 – Half of an ingot (SF25478) from Saruq al-Hadid (©SHARP/David-Cuny).

domly cut off but that their final width was intentionally planned and, therefore, marked before cutting.

Only three semi-finished artefacts in the form of unworked raw material are known from the site. These comprise one potential (half) ingot fragment (SF25478) in the form of a small disk (Franke, 2017a, p. 617-618; here: fig. 9); one amorphous piece of (casting) debris; and one similarly irregularly shaped piece that is described as ingot fragment (Soriano et al., 2018, fig. 11). Despite the significant typological variability within the precious metal assemblage from Saruq al-Hadid, recurring styles and techniques raise the possibility of specific local trends in gold-base jewellery design at the site. In particular, beads built from (rows of) spheres are very prominent in the corpus, and working remnants and misfits indicate their likely production on site.

ON PRODUCTION TECHNIQUES

There is little to no primary evidence that supports the identification of working areas for the production of precious metal artefacts at Saruq al-Hadid. This is not necessarily surprising, as ancient gold working is typically not associated with large pyrotechnological installations or workshops, nor with specific sets of tools that are diagnostic of this craft. For example, ethnographical research has shown that the sophisticated and specialised gold workers of the Asante people (Ghana) employed an anvil, bellows made of goat skin, some hammers, a pair of pliers and two to three files, in addition to a brass blowpipe and an olive oil lamp for soldering (Wilson, 2002, p. 16). Based on the lack of direct evidence from Saruq al-Hadid in the form of pyrometallurgical installations (e.g. furnaces, forges), associated residues (e.g. crucibles), or tools, we need to identify secondary markers to verify or reject the hypothesis that precious metals were worked at the site, while recognising the difficulties created by the site's complex taphonomy.

To our knowledge, Saruq al-Hadid is the only late prehistoric site on the Arabian Peninsula that evidences the co-occurrence of substantial numbers of finished and semi-finished precious metal artefacts. This co-occurrence strongly suggests a direct link between these two artefact classes, supporting the contention that the working of precious metals was a component of the activities at Saruq al-Hadid. In this section we will explore different steps in precious metal artefact production and discuss to what degree these activities could have been undertaken at the site.

To identify whether working remnants were the basis of precious metal artefacts from Saruq al-Hadid, ten 'finished' and 22 'semi-finished' artefacts were selected for geochemical and microscopic analysis. In addition, micro-photography on site by one of the authors (HD-C) supported many fundamental observations and conclusions. Due to a particular interest in the identification of working techniques for beads composed of individual spheres, sheet beads were not a focus for analysis; an exception here is SF26831, which was worked from a metal sheet at its centre and capped by three rows of spheres on each end (fig. 4, no. 18). The selected semi-finished artefacts were fragments of wires, sheets and ribbons. Complete artefacts were only available for non-invasive and semi-quantitative (SEM-EDS) analysis; working remnants were quantitatively analysed with LA-ICP-MS.[3] Thus, the analytical nature of the data sets differs significantly (quantitative versus qualitative) and their comparison can be challenging. Nevertheless, in this study these analyses allowed the reliable detection and differentiation of major compositional trends.

Precious metal working processes are associated with some specific tools, including pliers, files or hammers as mentioned above (also Moorey, 1994, p. 226). Such tools are present among the wide range of copper-base finds from Saruq al-Hadid but could also have been produced from a variety of (in)organic materials, including wood, bone, or stone. Their presence on site, however, does not necessarily directly relate them to the activities of metal craftspeople. We have to consider that ancient craftspeople—as today—highly valued their tools and discarded them probably only when broken beyond repair. Last but not least, most production processes included the

3. Elemental LA-ICP-MS in combination with XRF analysis for major elements were performed at the Goethe University Frankfurt a.M., Germany under the supervision of Sabine Klein. Semi-quantitative analysis was performed with a JEOL-6010 Scanning Electron Microscope at the University of New England, Australia by Kristina A Franke.

influence of heat (e.g. for annealing), and excavations at Saruq al-Hadid have produced many hearths, of varying dimensions, with associated charcoal remains, but none of them could be directly linked to the working with precious metals..

Beating

The production process of gold-base sheets and foils is known as beating, whereby a thin ingot is flattened into sheet metal (Maryon, 1949, p. 103; Darque-Ceretti and Aucouturier, 2013, p. 648–649). Evelyn Darque-Ceretti and Marc Aucouturier (2013, p. 654) mention the use of ingots with a thickness of about 5 mm in this process. Two such potential ingot fragments are known from Saruq al-Hadid. One is the semi-circular gold-base artefact SF25478, c. 7 mm wide and c. 2 mm thick (fig. 9). Soriano et al. (2018, p. 7) report a similar fragment, of more irregular shape, that also seems to have been cut (into half) and which is c. 10 mm wide and 4 mm thick. The beating process is already attested from the 3rd millennium BCE in ancient southwest Asia but is rather complex and requires technological know-how (Moorey, 1994, p. 226; Darque-Ceretti and Aucouturier, 2013, p. 653–654).

The tools required for this process, however, are simple and only an anvil and a (roundish) stone/pebble are needed. To produce thinner foils and leaves, the material can be beaten between thin organic materials—e.g. animal intestines (Giumlia-Mair, 2020, p. 5). While many different kinds of cobbles or pounding stones were excavated within the Iron Age layers at Saruq al-Hadid, a clearly identifiable anvil stone has not yet come to light. The evident halving of the ingots may be related to the ritualisation of production processes and is also observed with other kinds of finds at the site, although this requires further exploration. It is noteworthy that the beating process is facilitated by the purity of the material, but near-pure gold is hardly evident at Saruq al-Hadid (see below section On Taste and Particular Choices) even though refining of gold has been known since the 2nd millennium BCE (Asderaki and Rehren, 2008, p. 511).

Cutting

Once the gold-base sheet metal had been beaten into shape, the material could be cut into, for example, ribbons for further processing. Sheet and foil fragments are relatively rare on site and most preserved examples are relatively small, not exceeding 10 mm^2. Therefore, the best evidence for the process of cutting derives from microscopy and micro-photography of ribbons and plaques. These studies show that most edges are irregular, i.e. zig-zagging, indicating the use of sharp or pointed tools, such as awls, knives or chisels (fig. 8, nos. 5–8). Noteworthy are additional incised lines that are preserved along some of these cutting edges that indicate that cuts were not random; rather, sections of sheet metal were divided and marked before the final cutting itself (fig. 8, nos. 5 and 8).

Wire production

Prehistoric wires were regularly produced by either hammering metal into shape, creating a square cross-section (fig. 8, nos. 1–4), or by strip or block twisting, creating a circular cross-section (Carroll, 1972; Oddy, 1977; Northover, 1995; Armbruster, 2000, p. 102, 105–107; here: fig. 4, nos. 20 and 21).[4] Strip-twisting can either be applied by rolling a thin, narrow metal sheet between two hard surfaces or by drawing the material through a hole in a so-called drawplate or drawing-die (Caroll, 1972; Oddy, 1977, p. 84–85); twisting a square wire is called block-twisting and can also be produced by twisting square rods with the help of a pair of pliers at each end (Oddy, 1977, p. 83). All techniques leave different kinds of working traces behind, such as indents and impressions through hammering, larger grooves on rolled strip- or block-twisted wires, and narrow, elongated grooves when the material is drawn strip-twisted (Williams, 1924, pl. XIX and XX; Carroll, 1972, fig. 8 and 10; Oddy, 1977, fig. 6). With the latter technique, horizontal lines are often visible along the produced wire, caused by the material being repeatedly drawn through a hole in the drawplate (Carroll, 1972, p. 322).[5]

All of these processes were applied under the influence of heat, causing a partial fusion of the grooves and making the detection of the working technique more difficult. Hammering and strip-twisting are both evident at Saruq al-Hadid. Simple ring-shaped items, including the previously mentioned incised core of a semi-finished bead (fig. 4, no. 22 and fig. 7, no. 1; for working fragments see also fig. 8, nos. 1–4), are examples of wires with square cross-section, while wires used in cage beads are round in cross-section and show elongated, narrow grooves, and were probably drawn strip-twisted (fig. 4, no. 20 and 21). Rolled strip-twisted wires were applied in the decoration of the tassel-shaped gold-base artefact (Boraik Radwan, 2018, p. 107) but may have also been applied with the decoration of the rim of a small copper bowl (Boraik Radwan, 2018, p. 77). Two prepared wire fragments were excavated in the Polish sector, one of which was produced by strip twisting and shows large, loose grooves that give the impression that the fragment could have been twisted further. The second fragment shows thin elongated and narrow grooves that may stem from draw strip-twisting and resemble the wires used in cage beads. Clear evidence of the production of a wire by twisting two individual strips

4. Wires with a round cross-section can also be produced by smoothing off the edges of wires with square cross-sections but only with loss of material (Armbruster, 2000, p. 104).

5. The date of the invention of the technique for producing wires by drawing a solid rod is still under debate, but recent findings suggest that this may have already taken place in Europe during the Bronze Age. Evidence for this is provided by a single potential drawing plate found at Isleham in Great Britain. However, Northover (1995) suggested that this technique was short-lived and had fallen into oblivion. Compare for a controversial discussion, for example, Northover, 1995; Armbruster, 2000, p. 107; and Özşen, 2019.

can be seen in a small section of a wire with a rectangular cross-section from the SHARP excavations (fig. 8, no. 4).

Deformation

Deformation techniques applied at Saruq al-Hadid are diverse and range from 'simple' hammering into shape to intricate filigree work. Plaques from Saruq al-Hadid also show the application of incised patterns and *repoussé* that may have been embossed or punched. The singularity of the motifs found at Saruq al-Hadid may imply the individual crafting without embossing but rather with punching, although their total number is too low to be conclusive. A simple form of *repoussé* was also applied on sheet beads in the shape of, for example, a dotted pattern, but only few examples exist (fig. 4, no. 3). Plaques have also been perforated—probably with awls—from outside-in as well as from inside-out to provide for their attachment to a second material (fig. 4, compare nos. 24 and 25). Deformation also includes the production of spherical, cylindrical or barrel-shaped beads from sheets or ribbons (fig. 4, nos. 1 and 3). Here, we often find that the upper and lower edges of the beads are roughly cut and folded inwards (compare fig. 6). In some cases, folding had not been applied, but it remains uncertain whether those artefacts were finished or intended for further processing. Some sheet beads show such intricate shapes that additional shaping tools (i.e. stems) may have been used in their production. Also, it is feasible that ribbons were coiled in preparation for cutting individual beads. Here, a ribbon (or wire) is wound around a cylindrical core to create a spiral from which individual loop sections can then be cut; the latter can be further developed into beads (e.g. Leusch et al., 2014, p. 173–174). This technique is suggested to be used for mass production and potential candidates are small cylindrical beads from Saruq al-Hadid, but the evidence from the site is not explicit and a large number of sheet beads are barrel shaped or spherical (compare fig. 4, nos. 1–3).

Deliberate deformation is also applied on granulated spheres from Saruq al-Hadid, a technique that seems contradictory at first, since one of the major advantages of granulation is to produce perfectly round spheres without additional tools (e.g. moulds). However, the deformation of the originally round spheres is one of the strongest characteristic features of granulated beads at the site (fig. 4, nos. 11 and 14; fig. 7). While flat surfaces on the upper, lower or outer sides may also be caused during production or use, diagonally shaped inner edges or diamond-shaped granules are indeed deliberate designs, a conclusion that is supported by the frequent appearance of this type among gold-base beads from Saruq al-Hadid. However, spheres with flattened top and bottom surfaces may also have been deliberately shaped to facilitate the stacking of several ringlets into multi-row compositions.

Gilding

In order to produce larger golden artefacts with a limited amount of gold, gilding techniques were developed from the 3rd millennium BCE onwards, but their identification and differentiation is not always possible without invasive analysis (Oddy, 1981). During foil or leaf gilding, a gold-base foil (or leaf)[6] is mechanically applied to a second material, followed by repeatedly pressing and burnishing (Oddy, 1981, p. 74–77; Darque-Ceretti and Aucouturier, 2013, p. 649; Giumlia-Mair, 2020, p. 5); the mechanical application of foils (instead of leaves) onto a second material is also called plating. When metal is plated or mechanically gilded, adhesion is low and can more easily cause corrosion of the subjacent material (Hauptmann, 2020, p. 330). Egyptian sources report on the use of organic adhesives to improve the technique's quality (Oddy, 1981, p. 76; Giumlia-Mair, 2020, p. 3–5). In contrast, diffusion gilding causes the fusion of two materials, whereby a leaf (or foil) is directly fused with a metal core under the influence of moderate heat and repetitive pressing and punching (Schlosser et al., 2012; Hauptmann, 2020, p. 330–331). Depletion gilding is evident from, for example, Ur in 3rd millennium BCE Mesopotamia and exploits the higher affinity of copper for oxidation compared to gold and silver (La Niece, 1995; Hauptmann and Klein, 2016, p. 87–88). Under the influence of heat and oxygen, the copper content is oxidised and, consequently, the amount of gold (and silver) on the surface of the artefact enriches; the oxidised copper on the artefact's surface has to be removed mechanically (Hauptmann and Klein, 2016, p. 87; Hauptmann, 2020, p. 331–332). Depletion gilding requires higher quantities of copper in the gold, which are not evident at Saruq al-Hadid.

At Saruq al-Hadid, foil gilding was applied in the production of horn-shaped artefacts, but due to the lack of invasive analysis it is difficult to clearly distinguish the exact technique that was used (fig. 5). However, microscopic analysis showed folds within the gold layers of some of these artefacts that suggest foil gilding rather than fusion gilding. These folds occur alongside burnishing lines that are very fine, regular and parallel (which distinguishes them from use ware) and that indicate further flattening of the applied gold layer. Some artefacts also show partially detached foil as result of the corrosion process of their silver-base cores. The use of foil gilding at Saruq al-Hadid is further supported by the discovery of two gold-base sheets in the shape of horn-shaped artefacts but without a silver-base core (Boraik Radwan, 2018, p. 108). Both finds still bear impressions and creases that imply their previous application on a solid core of unknown material; in addition, one find exhibits the (insufficiently burnished?) overlapping ends of the gold-base foil at its bottom. It is therefore possible that the original core was removed—maybe as part of recycling activities at a later stage at Saruq al-Hadid (on recycling see: Franke, 2017a; Stepanov et al., 2019; Valente et al., 2020; Weeks et al., 2023; Franke, in press.; for the artefact see: Boraik Radwan, 2018, fig. 23). It is noteworthy that both empty gold-

6. The difference between foil and leaf gold-base metals lays in their thickness (Giumlia-Mair, 2020, p. 2); foil can support its own weight (thickness > 10 µm), while leaf cannot support its own weight (thickness < 2-10 µm).

base foil artefacts do not show any traces of the central seam-like extension that is characteristic of variant 1. Also, horn-shaped artefacts from Saruq al-Hadid often show corroded silver on their surfaces, which supports the evidence of plating rather than diffusion gilding (Al-Khraysheh and An-Nashef, 2007, fig. 12; here: fig. 5).

The use of materials other than silver, such as organic substances or pastes, as core material for this type of artefact is not known from Saruq al-Hadid, whereas there is ample evidence of well-preserved wooden and bone artefacts, and also vitreous paste beads from the site (Franke, 2017b; Weeks et al., 2017, p. 39–42).

It is still possible that both gilding techniques were applied on site. The major advantage of diffusion gilding - in contrast to foil or leaf gilding - is that it enables post-gilding deformation. This could explain variations in shape, in particular of the horn-shaped extensions, observed within the Saruq al-Hadid corpus. Soriano et al. (2018, p. 7 and fig. 9), for example, discovered traces on artefacts from Saruq al-Hadid indicating hammering that may derive from punching during diffusion gilding or from post-gilding deformation. However, different shapes could also have been obtained by using differently cast cores (see below). It is possible that both kinds of technologies were applied in the production of horn-shaped artefacts but at different times, which we cannot distinguish stratigraphically.

Granulation

Granulation is primarily applied to gold-base metals but occasionally also used with silver-base material at Saruq al-Hadid (fig. 10). This technique is a relatively 'simple' process, in which small pieces of metal are dropped into a hot source— either ash or liquids, such as water or oil—to form metal droplets (Carroll, 1974). These

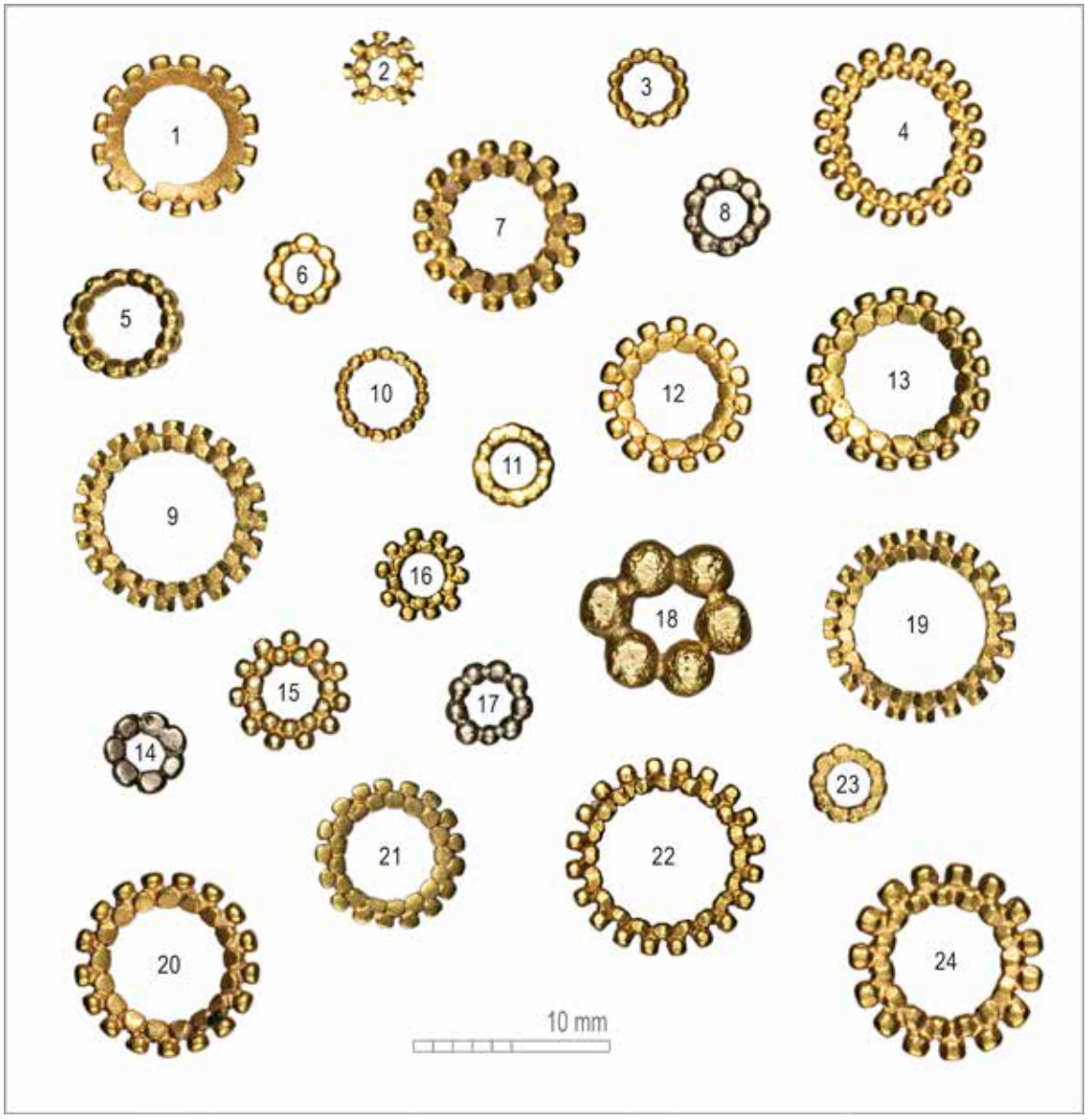


Fig. 10 – Different types of beads made from multiple spheres. Note the intentional deformation of the spheres observed in most of these beads at Saruq al-Hadid and the wide range of represented colours (©SHARP/David-Cuny).

droplets may be of different sizes and are, in most cases, hand sorted after production to facilitate the use of either similarly-sized granules or a deliberate combination of differently-sized granules (e.g. Loepp and Maass, 2017). Although Saruq al-Hadid has produced many hearths and ash-pits that could theoretically have been used to produce granules in ash, no individual gold or silver-base granules have been found associated with such installations. Thus, assumptions about the application of ash for granule production remain hypothetical; the use of liquids for granulation would also have been possible at the site.

The fusion of individual spheres into an artefact, or onto a second material, may employ different techniques: i) soldering (or brazing); ii) flux fusion (also called copper compound); and iii) direct fusion (or sintering or fritting). Of these techniques, only direct fusion has not been identified in relation to the fusion of granulated beads from Saruq al-Hadid. Soldering is based on differences in melting points arising from the proportions of silver and/or copper within the metal; a solder with a lower melting point than the primary metal enables fusion without remelting (and consequently reshaping) individual granules during the process.

At Saruq al-Hadid, analysed solders most often showed increased silver rather than increased copper levels in bonding areas between individual granules. Such joints are relatively wide and unique in their microstructure and are recognised by an amorphous and grainy texture that is accompanied by a seam-like structure (fig. 11b-d). The detection of a single spot of a different composition and surface texture on the surface of a sphere in bead SF25386 indicates the use of a solder with increased silver contents (fig. 12b); the c. 13 wt% Ag measured on the spilled solder strongly contrasts with the c. 2 wt% Ag measured on the top of the granule itself. Additionally, optical microscopy and micro-photography confirmed lighter or more reddish colourations in fusion gaps than in granules, indicating the addition of silver or copper to the metal that caused this change in colour (fig. 11b). Flux fusion, where a copper powder is used for soldering, was much less commonly applied at Saruq al-Hadid. Indicators comprise strongly increased copper contents and a dendritic structure in bonding areas (Born et al., 2009, p. 26); and out of nine analysed beads within the SHARP study, only one evidenced this technique (fig. 13).

Granulation is one of the most frequently applied working techniques at Saruq al-Hadid and is nearly exclusively found in bead (ringlet) production. Exceptions are the singular tassel-shaped artefact, a ring bezel with a semi-precious stone inlay and a braided ring, all of which are dec-



Fig. 11 – Bead SF289789 (a) was produced using a solder with increased silver content. Note the characteristic microstructure in the bonding area (b–d) (a ©SHARP/David-Cuny, b-c: optical microscopy ©SHARP/Franke; d: BSE image ©SHARP/Franke).

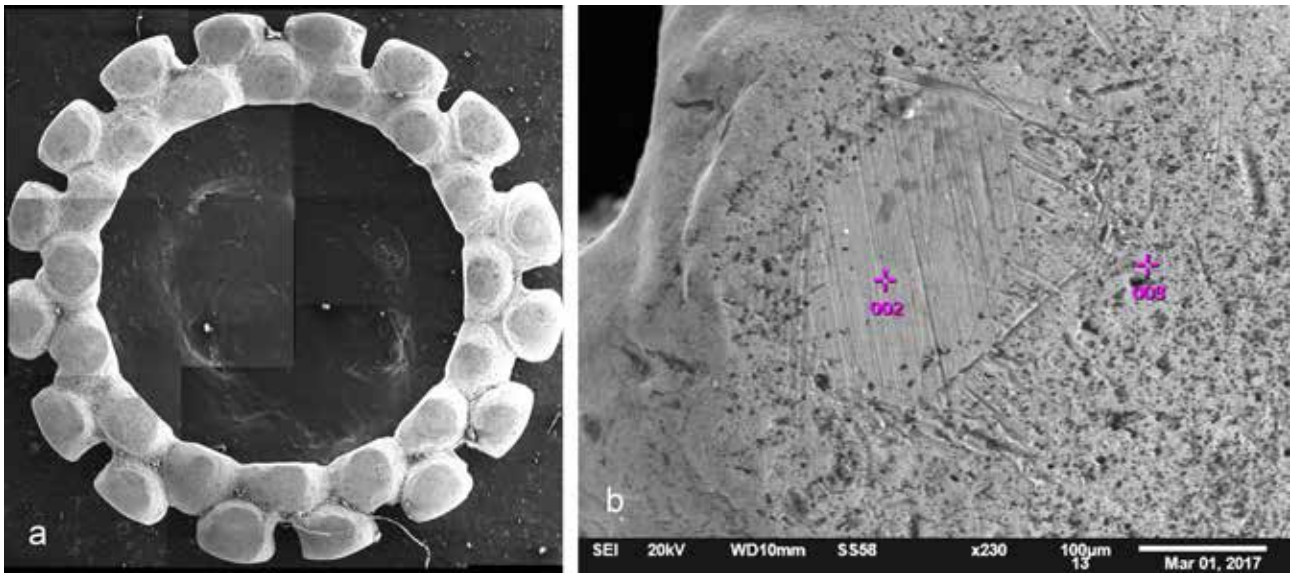


Fig. 12 – On the surface of one granule in bead SF25386 (a), a splatter of solder with elevated silver levels was detected (b) (BSE images ©SHARP/Franke). Note the indents between the individual spheres visible on the left side of the bead (a).

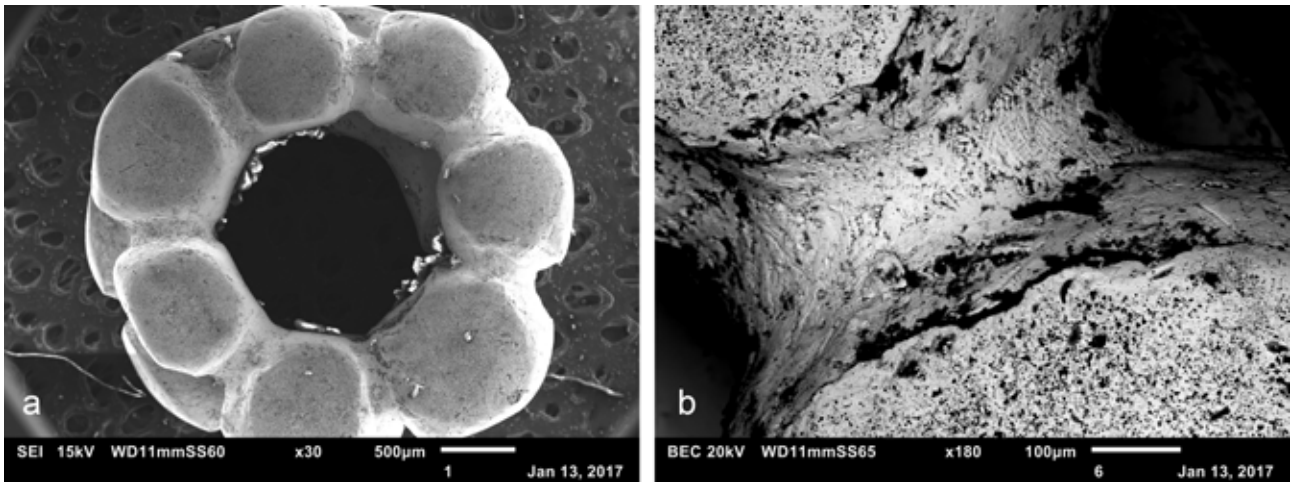


Fig. 13 – Bead SF25385 (a) was produced using a copper powder. Note the characteristic microstructure in the bonding area (b) (BSE images ©SHARP/ Franke).

orated with spheres that imply granulation by the shape of their bonding areas and their style of application (Boraik Radwan, 2018, p. 107 and 116–117). Granulated beads range from simple circular arrangements of individual spheres to multi-row beads, with vertically and horizontally joined granules. While additional horizontal spheres are joined individually into the gaps between the spheres of the inner ringlet, vertically combined examples most often consist of individual granulated ringlets that are joined to create tubular beads with two to ten rows or more.

Casting and 'fake granulation'

The casting of artefacts is well evidenced for copper-base items at Saruq al-Hadid, and some of the precious metals were also identified as casts. A small number of spherical beads show distinguishing features that identify them as casts: i) The metal is significantly thicker than that used in sheet beads; ii) their inner surfaces show a rough and irregular texture; and iii) a single example shows an overhanging rim with a rough texture (fig. 14, nos. 1 and 2). All these features indicate that these beads were produced via lost-wax casting. This technique is known in many variations and a full discussion of its complexity exceeds the scope of this paper (e.g. Hunt, 1980 or Davey, 2009). However, lost-wax casting generally uses the effect of a shapable and meltable material (such as wax) that is encased in a second material (e.g. clay, sand), and that is melted and replaced by hot metal that is poured into the resulting cavity. Lost-wax casting has the particular advantage of producing round shapes and intricate designs that cannot easily be achieved with bivalve mould casting (Davey, 2009). Some of these beads also show complex shapes that are more easily achieved with casting than by shaping from sheet metal (Leuch et al., 2014, p. 175; here: fig. 14, no. 2). It has been suggested that very small



Fig. 14 – Some beads at Saruq al-Hadid were also cast. Note the rough inner surfaces of beads SF34250 (1) and SF20035 (2), the texture of the outer rim in bead SF20035 (2t) and the rounded but irregular edges of the individual spheres in bead SF28245 in addition to casting cavities (3) (©SHARP/David-Cuny).

lost wax castings were manufactured with the help of a so-called casting tree, on which several items could be cast at once (Armbruster and Meyer, 2024, p. 21–22). This process is further simplified when using a mould to produce wax moulding blanks. Some beads from Saruq al-Hadid appear to be identical and may have been produced in such a process (fig. 10, nos. 9 and 19).

In addition, a bead composed of individual spheres appeared to be cast rather than granulated (fig. 14, no. 3). This kind of bead comprises a particular type that was labelled by Soriano et al. (2018, fig. 1) as 'flower-shaped bead'. They are either designed from a single row (fig. 14, no. 3) or double vertical rows and consist of up to seven individual spheres. Indicative markers for lost-wax casting can be found, for example, in the round upper edges, areas showing casting porosity and the rather porous surface texture. In addition, Soriano et al. (2018, p. 5–6) identified several other beads as cast artefacts that also resemble markers of granulation.

Although not of precious metal, further examples of the use of the casting technique include nine lead beads and one metallic antimony bead found at Saruq al-Hadid (fig. 15). These beads were designed to look as though they were created by fusing individual spheres, but clear casting seams on their outer edges show that they were cast in a bivalve mould. Moreover, the number of top spheres differs from the number of bottom spheres in individual artefacts, indicating the use of top and bottom mould pairs with different numbers of depressions (fig. 15, nos. 2–5). In their uncorroded metallic state these beads would have been silver in colour, and they may have been intended as potential 'replacements' for granulated precious metal beads.

Overall, the techniques applied to the working of precious metals at Saruq al-Hadid are manifold. They range from beating, to the production of semi-finished working materials, to the shaping of a variety of different kinds of artefact classes and types. The contemporary evidence of ingot fragments, working remnants and finished artefacts, however, supports the existence on site of a *chaîne opératoire* including the above-described working techniques. Whether individual workshops were responsible for individual steps or whether one (or several) worshop(s) supported the entire working chain is uncertain at this stage.

ON TASTE AND PARTICULAR CHOICES

In the analysis of gold-base artefacts, silver and copper contents are significant markers in the identification not only of particular working properties (e.g. melting point, hardness) but also of particular colours and, to a lesser degree, in the distinction between natural compositions and deliberate alloys.

In the previous section, we explored the working of precious metals at Saruq al-Hadid, and that finished artefacts and working remnants likely belong to a set of artefacts that reflect workshop activities at the site. Elemental analyses allow us to discuss aspects of the working of precious metals and, more importantly, possible cultural preferences in metal colours in general and in relation to particular artefact groups that may have guided technological practices.

The geochemical compositions of 44 artefacts from Saruq al-Hadid—including working remnants (sheets, ribbons and wires) and finished artefacts (beads composed from or with the addition of spheres), together with the bonding areas between individual spheres—are plotted on the ternary Au-Ag-Cu diagram (fig. 16). Here, it is possible to assess the extent to which they exhibit different colours and to explore the nature of compositional clusters for categories of precious metal artefacts from Saruq al-Hadid.

Finished artefacts (beads) only display two compositional ranges: i) those with high gold levels (HGL) of c. 80–98 wt% Au (n = 6); and ii) those with low gold levels (LGL) of c. 23 and c. 34 wt% Au (n = 2). Within

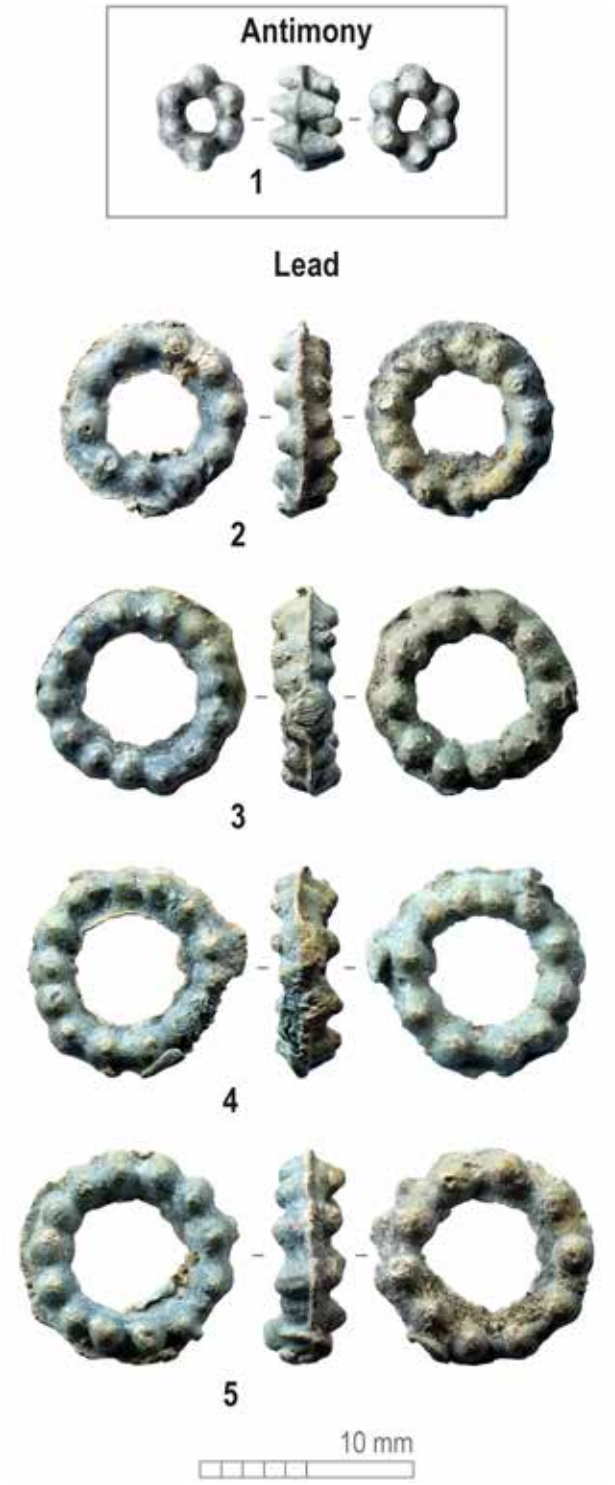


Fig. 15 – Selection of cast beads. The slightly larger pieces were made of lead (2-5), while a single smaller artefact was made of antimony (1). Note the difference in the number of ‚spheres' between top and bottom sides of beads 2-5 (©SHARP/David-Cuny).

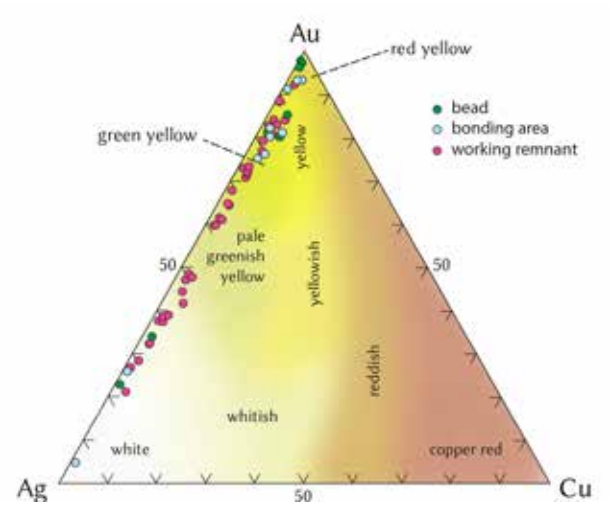


Fig. 16 – Ternary diagram with gold (Au), silver (Ag) and copper (Cu) showing the different geochemical compositions and colours of the analysed beads, as well as the bonding areas between individual spheres (qualitative; SEM-EDS) and working remnants (quantitative; LA-ICP-MS). Note the analytical gap between 50 and 60 wt% Au. While working remnants are distributed across almost the entire compositional range of gold-silver alloys, the analysed finished artefacts plot only within certain compositions (©SHARP/Franke).

the HGL group we can further distinguish between those artefacts produced of nearly pure gold (96-98 wt% Au; HGL1; n = 3) and those with lower gold levels of c. 80-85 wt% Au (HGL2; n = 3).

The colour of beads with HGL1 values is broadly yellow, with a reddish touch, while those within group HGL2 display a slight shift from yellow towards greenish yellow (fig. 16). Beads with LGL are within the range of whitish gold and appear silver in colour, based on their high silver content (compare also fig. 10). Copper levels are on average low (Cu ≤ 5 wt%) and do not significantly alter the artefacts' colour towards red. However, two artefacts with HGL2 levels exhibit relatively high amounts of copper of c. 4 and 5 wt% Cu, which shifts their colour back from greenish yellow to rather yellow (fig. 16). Nearly all beads fall into the same compositional range within which working remnants (i.e. ribbons and wires) plot. However, no working remnants plot together with nearly pure gold artefacts (HGL1). Bonding areas analysed between individual spheres, of which most have been identified as solders, similarly plot within the range of working remnants but—reflecting their nature as solders and in comparison, to gold-base artefacts—have higher silver and, in exceptional cases, also higher copper levels.

Working remnants display nearly the entire range of gold levels within the diagram and their colour also significantly shifts from yellow towards green-yellow in contrast to the analysed artefacts described above. Here, we have to add the group of medium gold levels (MGL) that splits into MGL1 with c. 60-70 wt% Au and MGL2 with c. 40-50 wt% Au. No samples fall into the range of 50-60 wt% Au and the diagram shows a significant gap between two major groups with either gold levels ≥ 60 wt% Au or ≤ 50 wt% Au (fig. 16). The same is true for gold levels above 92 wt% Au and below 20 wt% Au; no working remnants and only one solder of nearly pure silver lies within the latter range.

Working remnants show a wide variety in gold levels, but they also seem to cluster at particular levels more than at others (fig. 16). The wide range of compositions

within this artefact group could hint towards either the use of different precious metal sources with varying silver and gold contents, or the mixing of gold-base and silver-base metals to (roughly) achieve certain colours. The small clusters (as well as the larger two gaps) within this wide range, on the other hand, indicate the production of particular compositions or recipes and may hint towards individual batches that may have derived from the same workshops. Furthermore, we would like to argue that the sample set of 37 specimens (out of a total of 83 excavated working remnants) is representative and that the identified compositional clusters—defined as much by gaps as by compositional similarity—represent true groups.

The study by Soriano et al. (2018) supports this result, although it is important to note that their study is based on different kinds of finished artefacts including only one wire-like fragment—in contrast to the present study that focuses on beads composed of spheres in combination with wire, ribbon and sheet fragments. However, the differences in the kinds of artefacts analysed by each study are complementary. The results from Soriano et al. (2018) show two major similar clusters within the range of HGL samples, while the groups MGL and LGL are represented by only two artefacts, respectively. Six out of 14 analysed artefacts fall into the range of HGL; four consisting of nearly pure gold (HGL1) and two plotting within or close to the HGL2 group. Here, we would need to extend our HGL2 group to about 71–87 wt% Au, which represents finished artefacts with two different colours of yellow and green yellow (fig. 16). The same is true for artefacts produced from nearly pure gold and the range of HGL1 samples must be increased by 2 wt% to about 94–98 wt% Au. This result is significant and indicates that those artefacts were not primarily produced in yellow or white gold but also in a visibly greener and redder yellow gold. It is noteworthy that each of these groups includes two artefacts worked from gold-base sheet metal (i.e. barrel bead and an embossed sheet) respectively, which describe an artefact group that was not geochemically analysed within the SHARP analytical programme. All further artefacts are beads that consist of spheres; these are all primarily described as produced by lost-wax casting (Soriano et al., 2018, p. 5).

Furthermore, the study by Soriano et al. (2018) also exhibits a gap between c. 50-60 wt% Au and no artefacts produced from nearly pure silver. No results are evident for the MGL1 range—with a pale greenish colour—where only working remnants plot within the SHARP study. Importantly, this range describes the hardest gold-silver alloy, and the ideal combination for increased hardness lies at about 65 wt% Au and 35 wt% Ag, with a 1:1 atomic ratio of both metals. In addition, this kind of material offers ideal properties as a solder, featuring a substantial decrease in melting point compared to (nearly) pure gold. This, combined with a relatively broad melting range between solid and liquid, allows for precise control during soldering, where the goal is to induce a surface texture change without completely dissolving the material.

Since no analysed solders were detected at this compositional range, it is reasonable to assume that this kind of composition (in wires or ribbons) was not used in this state but was mixed with another composition to be used for soldering. Here, it seems feasible that this composition was mixed with the metal that was originally used to produce the individual granules that were to be soldered into ringlets. One reason may have been to equal out the apparently strong colour differences. Its colour, however, made it well distinguishable from precious metals used in the production of (granulated) beads, which supports this hypothesis. Noteworthy are also two artefacts with about 50 wt% Au (MGL2; Soriano et al., 2018, table 2 and fig. 5); they are both wire-like artefacts, but neither (granulated) beads nor sheet beads are present in this group. Their colour ranges at a level where pale green-yellow shifts towards whitish and only working remnants represent this group in the SHARP study (fig. 16). These artefacts are also harder than nearly pure silver or silver coloured LGL artefacts but of a similar silvery colour. Moreover, this alloy also offers a second advantage: while (nearly) pure silver is strongly affected by corrosion and patination, silver with higher gold content is more resistant to both surface discolouration and corrosion. The result that nearly all artefacts within MGL are represented by wire-like finds supports the idea that these different MGL compositions were primarily produced to make artefacts that required a particular strength (e.g. simple rings) but in two different colours of pale green-yellow and white—gold and silver—and with the advantage of being less affected by corrosion or discolouration. The lack of artefacts within group MGL1, however, may be due to the low frequency of these kinds of artefacts in the combined studies.

Significantly, we can note that silver-coloured artefacts held considerable value at Saruq al-Hadid. This is evidenced by the working remnants of group MGL2 but also by working remnants and two finished silver-base artefacts in group LGL. These findings underscore the appreciation for this kind of silvery colour, that is indistinguishable to the naked eye from nearly pure silver despite its compositional difference.

In addition, the original colour of nine cast lead beads and the single cast antimony bead, that all resemble granulation in their style, was certainly whitish silvery (fig. 15). These finds further highlight the significance of this colour group and raise the question of favourable cultural attitudes to such ‘pale’ metal. Silver granulation is far more complex and also far less common than gold granulation. Bead SF30731 may serve as a prime example of potential pitfalls encountered in silver granulation, especially when employing increased silver contents in soldering, a technique frequently applied at the site (fig. 17). A single example reported by Soriano et al. (2018, sample 1405_54) may have been produced from a silver-base material but may have been soldered with a copper powder. While its overall shape is well preserved, its joints (and one individual sphere) were highly affected by corrosion. A third silver-base artefact, SF28245, appears to be cast and resembles a shape that is also known from gold-base artefacts from the site (fig. 14, no. 3). These examples may indicate that smiths at Saruq al-Hadid were not as well trained in silver granulation as



Fig. 17 – Bead SF30731 was produced from nearly pure silver and soldered with a high-silver agent. In contrast to gold-base granulated beads, the individual spheres deformed during soldering (©SHARP/David-Cuny).

in gold granulation but still aimed to fulfil the demand for artefacts of this colour.

The addition of gold to silver, however, is deliberate and was most likely undertaken to protect the metal from corrosion. All analysed artefacts from Saruq al-Hadid (besides the above-mentioned bead 1405_54, Soriano et al., 2018) are well preserved. This was not the case with the silver-base cores of the horn-shaped artefacts, which regularly show corrosion where the gilding failed to protect the metal (fig. 5). This indicates that the cores of these artefacts were made of purer silver. This may also highlight the precious character of gold. No amount of this material seems to have been wasted when not necessary for visual or technological reasons. Limited access to silver—and for the smiths limited exposure to the materiality of silver—may well have influenced the limited number of silver-base artefacts on the site, while at the same time increasing the interest in this particular colour. The evidence of the metallic lead and antimony beads further supports the idea that a certain level of demand for this colour existed at Saruq al-Hadid during the early Iron Age. In particular, lead (and maybe also antimony) may have been more easily accessible and thus somewhat cheaper alternatives to silver at particular times.

Moreover, a chronological factor for the preference for particular colours or styles during the early Iron Age cannot be ruled out at this stage. It is possible that particular colour choices, such as silver, were only temporary trends across the several centuries of Iron Age activities at the site.

In regard to copper contents in gold-base artefacts from Saruq al-Hadid, it is noteworthy that natural amounts of copper in gold are normally low and typically do not exceed 1–2 wt% Cu (Hauptmann, 2020, p. 320). This fits with the copper levels found in finished artefacts as well as those of many analysed working remnants (fig. 16). However, higher copper levels (but still hardly exceeding 5 wt% Cu) are also present, primarily being detected in working remnants and less frequently in bonding areas between granules in finished beads. It is noteworthy that the three artefacts of nearly pure gold, which do not plot with any working remnants, show the lowest copper levels within our study (fig. 16). The same is true for nearly pure gold artefacts studied by Soriano et al. (2018); almost all exhibit copper levels are below 1 wt%. Hence, the addition of copper to gold-base metal seems to fulfil primarily technological needs to support soldering. Higher copper contents that shift the colour from yellow to red are not evident at Saruq al-Hadid, and this metal appears to have played no major role in precious metal production at the site despite (or maybe even because of) its abundance of copper artefacts. The gap between the two major colour clusters of variations in yellow (60–98 wt% Au) and white (20–40 wt% Au) may reflect the use of different base materials for these alloys. However, none of the silver-base cores of the horn-shaped artefacts was available for analysis, so we cannot compare this composition to our silver-base LGL and MGL2 samples.

This discussion is further complicated by the wide range of gold-silver alloys within natural deposits (e.g. Rehren et al., 1996; Hauptmann, 2020). The present study, however, shows that analysed gold-base artefacts in the form of working remnants are present within the entire range of potential compositions of gold and silver but also cluster at certain levels. The combined evidence of these two observations supports the idea that the composition of the majority of gold-base artefacts results from deliberate alloying. Also, certain compositions represent both, particular colours and technological advantages. Hence, the deliberate mixing of gold and silver-base metals seems probable even if different kinds of natural alloys may have been the base for these artefacts. Adding gold

to silver-base alloy protects and hardens the metal, while adding silver to a gold-base alloy improves the metal's hardness and lowers the melting point for brazing. The alloy that is represented by the compositional gap between 50–60 wt% Au, on the other hand, does not present any discernible advantages in comparison to either lower or higher gold levels: it neither provides a new colour (since it is pale greenish-yellow) nor does it offer better working conditions within the already employed colour range of pale and greenish-yellow. In other words, this compositional range may simply have not offered any advantages that would have promoted its deliberate production.

ON DELIBERATE CHOICES IN STYLE

The distinctive collection of precious metal artefacts from Saruq al-Hadid shows some diversity, not only in the kinds of artefacts produced but more importantly also in their techniques of production. A notable characteristic of the corpus is the high proportion of jewellery and in particular beads, in contrast to, e.g. (finger) rings or pendants that are unique finds. Most common are 'simple' beads worked from sheet metal (or cast, in exceptional cases) and beads that are composed of multiple spheres. Non-invasive analyses indicate that most of the latter were produced by different kinds of granulation processes. In contrast to Soriano et al. (2018), our study shows that cast artefacts are the exception.

In fact, despite arguing that most of the analysed beads in their study are produced by lost-wax casting, Soriano et al. (2018) stated that the interpretation of some specimens remains uncertain. Indeed, some of the published examples show the distinct features of soldering seams and amorphous texture, and significant compositional differences between individual spheres and bonding areas that may indicate granulation rather than casting (Soriano et al., 2018, fig. 4 and 6b, table 3). Here, the cast examples worked from lead and antimony that resemble granulation are again important and emphasise the interest in this particular style independent from the applied working technique (fig. 15).

The combined number of analysed finished beads is admittedly limited compared to the large quantity of this kind of artefact found at Saruq al-Hadid, and both studies demonstrate that a distinction between granulation and (lost-wax) casting remains challenging despite considerable effort. This is even more difficult with on-site methods, such as field microscopy and micro-photography. While both studies clearly show that casting was part of the production process of beads that include multiple spheres, we would argue that granulation rather than casting was the dominant working technique at Saruq al-Hadid. However, it is striking that particular artefact types were produced using granulation as well as by casting.

The different working techniques encountered for similar designs at Saruq al-Hadid may represent finer chronological units than we can currently present for the early Iron Age beads and their appearance over more than 300 years. Consequently, a chronological component and a shift towards one or the other working technique cannot be ruled out within the rather large time span of their appearance. This may certainly also apply to the different results on gold artefacts from Saruq al-Hadid. Our present understanding of site stratigraphy and taphonomy precludes the development of a more refined chronology for the precious metal artefacts form the early Iron Age; moreover, the lack of discrete working areas at Saruq al-Hadid further limits the potential to explore spatio-temporal differences in technological choices. The existence of the same type of beads but produced with different methods highlights that style overruled production technique (whether contemporary or within a chronological shift). Small bead ringlets designed from individual spheres were clearly favoured at the site regardless of the manufacturing method used to produce them, a fact that is further emphasised by the cast lead and antimony ringlets.

Here, a third characteristic within the corpus of precious metals is noteworthy: many beads show intentional deformation (fig. 10). Although granulation offers the advantage of creating near-perfect globular spheres, this effect was seldom used at Saruq al-Hadid. Most beads designed from spheres exhibit flat edges on their inner and outer but also on their top and bottom sides. Importantly, flat edges are not limited to cast beads—which would be far less astonishing, but they are also evident with granulated beads.

In some cases, flattening seems to have been part of the production process and does not necessarily solely indicate a design preference. This may be particularly true for beads with flattened inner surfaces, and it is possible that such beads were worked around (e.g. wooden) cylinders or cones to facilitate the brazing process. However, since it is also possible to preserve a perfectly spherical appearance without any such appliances, the deformation must have been part of the final desired design, whether it was due to working techniques or to later shaping. A similar idea may apply to spheres that are flattened on their top and bottom surfaces, as seen in most ringlets. We have already discussed that tubular beads with multiple vertical rows are produced from stacked individual ringlets and the flattening of these surfaces certainly facilitated this kind of production. In some cases, flat outer surfaces may also be caused by use or depositional damage but, again, the flattening most often appears regular and exact, suggesting intention rather than randomness. The most obvious deliberate manipulation is represented by diagonal and diamond-shaped patterns with spheres (fig. 10, e.g. nos. 7, 9, 19, 24). This very particular design seems to be commonly applied on beads from Saruq al-Hadid and is regularly found with granulated (fig. 12a) but also with cast ringlets (Soriano et al., 2018, fig. 2). The co-occurrence of this design on granulated and cast beads further emphasises that working techniques were subordinated to design preferences.

The granulation technique was apparently not chosen to attain a perfect spherical design. Also, a diamond-shaped effect would potentially have been more

easily achieved via casting. Hence, the application of the granulation technique for this design may have been based on a 'custom' (shaped by culture, geography, and time) associated with the site rather than with specific technological considerations. As stated earlier, granulation does not require a complex set of tools and preparation. More importantly, no final adjustments, such as filing off potential casting rims, is necessary, offering the benefit of less loss of precious metal during processing. In this, lost-wax casting is certainly also more efficient than mould casting but still less efficient than granulation (compare fig. 15). Consequently, it may have been more useful to produce 5 mm beads by granulation and then deform these accordingly under the influence of heat than cast such items which needed final adjustments. Hence, the deformation of granulated spheres may be an advantageous technique reflecting 'cultural customs' that integrated practicality.

DISCUSSION AND CONCLUSIONS

In the previous sections we discussed the corpus of finished and semi-finished precious metal artefacts from Saruq al-Hadid. The diversity and volume of this assemblage are unparalleled within late prehistoric Arabia. When considering the ultimate purpose of the deposited precious metal artefacts, the materials more strongly correlate with work sequences of craftsmen than with consumption patterns of non-specialists. This is particularly evident when comparing the Saruq al-Hadid assemblage to finds from the wider region. Here, an (unprovenanced) collection from Yemen is particularly important. In 1973, Geoffrey Turner published a small part of the Muncherjee Collection, held in the Aden Museum, which included a wide variety of gold-base jewellery (Turner, 1973, p. 172). He suggested a Qatabanian (southern Yemen) origin and dated the artefacts from the 8th/7th to the 6th/5th centuries BCE (fig. 1). These dates are somewhat later than the finds from Saruq al-Hadid but are based on "..no stratigraphic dating evidence and very little comparative material ..." (Turner, 1973, p. 127).

In this collection, we find some of the unique singularities evident at Saruq al-Hadid, such as the bezel of a ring mounted with a semi-precious stone that is designed with granulation on its fitting (Turner, 1973, pl. L, no. 6; Boraik Radwan, 2018, p. 117) but also the wide range of ringlets and beads designed from individual spheres that are evident at Saruq al-Hadid (figs. 4 and 10). More importantly, these ringlets and beads are in many cases part of more complex designs (i.e. earrings, pendants) and are decorative key elements (Turner, 1973, pl. XLIX, H, J, K; pl. L, nos. 4, 5; pl. LI, nos. 12, 13, 15). Here we find single row ringlets worked around a ring-shaped inner wire (Turner, 1973, pl. XLIX, J, right, bottom), beads built from two vertically aligned ringlets (Turner, 1973, pl. XLIX, K, right, bottom), as well as tubular beads composed of a central sheet metal and capped with a single row or two rows of ringlets (Turner, 1973, pl. LI, nos. 12, 13 and 15). The publication also shows the same kind of ringlets and beads listed above as singular items (Turner, 1973, pl. LII, nos. 22 and 23; pl. LIII, nos. 34, 35, 37, 38; pl. LIV, no. 42) in addition to tubes built up from wires and capped by spheres (Turner, 1973, pl. LII, no. 24). Noteworthy are two beads composed of only five and six but very globular spheres that find their comparison in several gold and silver-base finds from Saruq al-Hadid (Turner, 1973, pl. LIII, nos. 34–35; here fig. 4, no. 13; fig. 10, no. 18). Some items are similar in style and arrangement but show significant variations in comparison to the finds from Saruq al-Hadid. Among them are tubular beads composed of stacked ringlets (Al-Khraysheh and An-Nashef, 2007, fig. 15; Boraik Radwan, 2018, p. 110; here: fig. 4, no. 19) but that never exceed 10 rows within the collection from Yemen (Turner, 1973, pl. LIII, no. 36), or spheres arranged around an inner ring-shaped wire but with two horizontally aligned rows (Turner, 1973, pl. LIV, no. 40), which are only evident with a single row at Saruq al-Hadid (fig. 7, no. 2). Tubular sheet beads are similarly capped with a single row of spheres/ringlets (Turner, 1973, pl. LIV, nos. 42 and 43) but are shorter than at Saruq al-Hadid (Boraik Radwan, 2018, p. 110). Earrings with "two adjacent conical bell-shaped beads" (Turner, 1973, p. 130 and pl. XLIX, G) are comparable in their general arrangement to the tassel-shaped items from Saruq al-Hadid but are missing the wire-like ('horn-shaped') extensions (Boraik Radwan, 2018, p. 107). While the artefacts from Yemen have a clearly defined function as components of earrings, the finds from Saruq al-Hadid show no functional attribute.

Also, several types commonly attested at Saruq al-Hadid are not evident within the collection from Yemen, such as the very characteristic cage beads or horn-shaped artefacts (Al-Khraysheh and An-Nashef, 2007, fig. 12; Boraik Radwan, 2018, p. 108 and GR 1868, bottom left; Soriano et al., 2018, fig. 2, bottom centre; here fig. 4. nos. 20 and 23). Also, the (cast) so-called flower-shaped bead (Soriano et al., 2018, fig. 1, middle row left, centre; here fig. 14, no. 3) is not represented in Turner's collection. Similarly, no spherical sheet (or cast) beads are present despite a single example of a spherical bead composed of two half elements (Turner, 1973, pl. LII, no. 18) that does not find any comparisons within the Saruq al-Hadid assemblage. Since Turner (1973) only published drawings but no photos, it is difficult to estimate the extent to which flattened granule surfaces are not depicted or were not evident.

In some cases, flat surfaces seem to have been illustrated, but the drawings are often inconsistent in their side and front views and no distinct conclusions can be drawn from them. In this, it remains uncertain whether the precious metal finds from Yemen were potentially produced within Saruq al-Hadid workshops and the differences highlighted between the two collections suggest otherwise. However, the spectrum presented by Turner (1973) clearly shows the widespread connectivity of a particular style in gold-artefact production. More importantly, it

supports the hypothesis that gold (and silver-base) beads and ringlets were not merely produced at Saruq al-Hadid, but possibly traded as single items, with the intention to be integrated into more complex and intricate jewellery artefacts at their destination.

Another important collection of comparable gold-base jewellery derives from the southern Levant, with well exemplified finds from Tell Tawilan and Tell Fara/Beth Pelet (fig. 1). At Tell Tawilan, a gold hoard was excavated during the 1980s that comprised gold-base jewellery, in particular earrings (Ogden, 1995).

Ogden (1995, p. 75) dated the hoard to the 10th/9th century BCE in comparison to finds from Tell Fara/Beth Pelet. Several artefacts are described as tassel earrings of different styles and with varying details. Noteworthy are some similar attributes in comparison to the finds from Saruq al-Hadid. The upper bell-shaped part is in some cases similarly composed of block-twisted wires with the functional wire extensions attached. The lower part that displays the 'tassels' is in most cases composed differently. However, one specimen exhibits the larger globules that cap each individual 'tassel' and that are characteristic for the Saruq al-Hadid artefacts. Two of these items also show a granulated decoration that bonds the upper (bell-shaped) part with the (functional) wire extension on their tops. The hoard also included an earring with three attached granulated beads that are composed of three vertically stacked rows of granules (Ogden, 1995, fig. 8.18 and 8.19; Verduci, 2014, fig. 4:2). The beads from Tell Tawilan are possibly slightly larger in diameter (c. 7 mm in comparison to Saruq al-Hadid c. 4–6 mm) than the beads composed of a single and two rows from Saruq al-Hadid. Ogden (1995, p. 72) proposed that these granulated ringlets were added later—perhaps for safekeeping during deposition—and were originally not intended as part of the design. In contrast to the finds from Yemen, this seems plausible and the attached ringlets fit less clearly into the overall composition; a matching second earring did not show such ringlets (Ogden, 1995, fig. 8.17 and 8.18). The best match with Saruq al-Hadid's gold-base jewellery, however, is a singular granulated bead that is composed of two horizontally aligned rows (Ogden, 1995, fig. 8.33). The important detail lies in the diamond-shaped spheres and the overall composition, which strongly resemble finds from Saruq al-Hadid. The bead from Tawilan is, with a diameter of c. 15 mm, slightly larger than average granulated beads from both sites but matches the rare, larger ringlets of this particular type with a diameter of about 10 mm at Saruq al-Hadid (Ogden, 1995, p. 74; here: fig. 4, no. 11, fig. 8a, and fig. 10, no. 24). Geochemical analysis (Ogden, 1995, table 8.2.) indicated (in particular with loop earrings) some higher copper levels than seen in the gold and silver-base finds from Saruq al-Hadid. Two analyses of the above-described granulated bead, however, gave about 3 wt% Cu, well within the range of copper levels seen at Saruq al-Hadid.

The tassel earrings from Tell Fara/Beth Pelet derive from IA II burials and are similar in their general appearance but seem to have been worked differently than the finds from Saruq al-Hadid (compare Petrie, 1930, p. 11, pl. XXXIII, nos. 381 and 384, and pl. XXXVII, bottom right with Boraik Radwan, 2018, p. 107). However, several tubular beads—also found in IA II burials and in an arrangement with carnelian beads—are built from four and five vertically added rows of spheres and closely resemble a shorter version of the tubular beads from Saruq al-Hadid (Petrie, 1930, p. 11 and pl. XXXVII, bottom right; compare here: fig. 2 and fig. 4, no. 19). In addition, several silver-base ringlets composed of small and also larger spheres are comparable to the beads from Saruq al-Hadid and are displayed as spacer beads (Petrie, 1930, p. 11 and pl. XXXVII, bottom right; here fig. 10, nos. 10 and 18).

The small number of plaques left behind from Saruq al-Hadid may similarly support the result that precious metal artefacts at Saruq al-Hadid were intended to be part of more complex items and were not necessarily worked to their final form at the site. A common characteristic of these sheet metals is their roughly cut edges. These contrast with their piercings, which were probably intended for the subsequent application of the plaques. Their semi-finished character may support the idea that these sheets were intended to be traded as they were meant to be fixed to a second material (e.g. wood, bone, fabric) at their destination only.

Two comparable Levantine finds derive from more recent works in Jerusalem/Israel and were found as part of the Temple Mount Project (TMP) in 2020[7] and the Pilgrimage Road Project (PRP) in 2024 (fig. 1).[8] The bead from the PRP consists of two rows, each with 7 spheres with flattened surfaces and is a very good match to beads from Saruq al-Hadid (FN no. 9). However, it was discovered in the debris of a Roman structure and is thus considerably younger.[9] The bead from the TMP dates to the IA II and consists of four vertical and two horizontal rows which have not been found as such at Saruq al-Hadid, but which are comparable to single ringlets with two horizontal rows of eight spheres each from the site (fig. 10, nos. 2, 15 and 16). The flat surfaces and indents visible between individual spheres of the TMP bead, however, are two important details that are shared with the single ringlet beads from Saruq al-Hadid (for indents see fig. 12a).

Short tubular beads composed of four rows and of eight rows but capped with larger spheres at both ends are also known from the queens' tombs at Nimrud (Hussein,

7. *Temple Mount Project: Salvaging Heritage from Archaeological Crime Debris*. https://www.jpost.com/israel-news/sifting-the-past-605135; accessed 10/2025; *Find and Finder of the Month: A Rare Gold Bead from the First Temple Period found by Binyamin Milt*. https://tmsifting.org/en/2020/11/26/find-and-finder-of-the-month-a-rare-gold-bead-from-the-first-temple-period/ accessed 10/2025.
8. *The Pilgrimage Road*. https://cityofdavid.org.il/en/the-pilgrimage-road/; accessed 10/2025.
9. *Rare Gold Bead from the City of David more than 1,600 Years Old Discovered in Jerusalem*. https://cityofdavid.org.il/en/rare-gold-bead-from-the-city-of-david-more-than-1600-years-old-discovered-in-jerusalem-eng/; accessed 10/2025.

2016, pl. 53a). These can be compared to the larger examples from Saruq al-Hadid (Boraik Radwan, 2018, p. 110; here fig. 4, no. 19).

There is also a strong degree of similarity between artefacts from Saruq al-Hadid and an unprovenanced collection of gold beads from Iran, and dated to about 1000 BCE (fig. 1). The Iranian collection includes granulated tubular beads but—more importantly—a flower-shaped bead and a double ringlet, both with deformed granules that are regularly detected with beads from Saruq al-Hadid (Dubin 2009, p. 52, fig. 40). Unlike the beads from Saruq al-Hadid, however, the spheres here are arranged around a disc-like centre. This detail is uncommon with Saruq al-Hadid beads, which exhibit only small flattened inner circles (fig. 10, no. 1). A cage bead from Marlik—but of a rather different arrangement than evident at Saruq al-Hadid (Negahban, 1996, pl. 56)—and a horn-shaped (hollow?) gold-base foil artefact from Lorestan (Louvre Collections, AO 14012)[10], which is comparable to variant 2 at Saruq al-Hadid, add to the range of comparable artefacts from Iran (fig. 1).

Finally, cage beads found in Georgia that are on display in the Georgian National Museum, Tbilisi, are a relatively close match in their overall composition to finds from Saruq al-Hadid (compare also Dibba below; here: fig. 1 and fig. 4, no. 20). A tubular bead composed of five (stacked) vertical rows from Armenia may be a further link to the Caucasus when comparing the individual rows of this bead to single ringlets or double row beads with flattened surfaces on their top and bottom from Saruq al-Hadid (Jakubiak et al., 2017, fig. 9; here: fig. 4, nos. 12 and 13 and fig. 13a).

There are also local comparanda to the Saruq al-Hadid assemblage within southeastern Arabia, including some of the bead types less commonly encountered in the wider region. From Daba al-Bayah (Oman), for example, derives a broadly similar cage bead (Frenez et al., 2020, fig. 9b); and at Bat (Oman) a spherical sheet bead was excavated (Weisgerber, 2007, p. 9 bottom figure; here: fig. 1). At Bat, granulated beads were also discovered. One of these consists of differently sized spheres, a composition that is not evident at Saruq al-Hadid (Loepp and Maass, 2017, fig. 1). A second artefact comprises a single ringlet with two horizontal rows possibly made of copper and is in its material comparable to a single find from Saruq al-Hadid. A third bead from Bat consists of several vertical rows that are flattened on the inside, a detail that compares to multi-row beads from Saruq al-Hadid (Weisgerber, 2007, p. 9 bottom figure; compare here: fig. 4, no. 19). The latter two beads are not published as individual finds and it is difficult to discern the precise details of their shape from the published report and images (Weisgerber, 2007).

Comparable beads composed of spheres were also recovered from Rumeilah in Al Ain (UAE), of which one shows deformed surfaces (Boucharlat and Lombard, 1985, pl. 73, no. 10; here: fig. 1). The publication does not list any information on the bead's size, but the find may rather compare to the rare but evident beads with larger spheres of more than 3 mm in diameter. In addition, several comparable copper-base artefacts (e.g. arrowheads, a dagger and bracelets) demonstrate that the site is broadly contemporary with Saruq al-Hadid (Boucharlat and Lombard, 1985, pl. 62 and 63). Horn-shaped artefacts have been excavated in early Iron Age burials at Jebel al-Buhais in Sharjah (UAE; here: fig. 1), but they do not show a seam-like extension in the core's centre and, therefore, rather resemble the less common variant 2 from Saruq al-Hadid (Jasim, 2023, fig. 351).

Additionally, the Jebel al-Buhais Iron Age burials exhibit further important parallels, with many containing copper-base artefacts such as arrowheads and daggers that resemble the copper-base inventory from Saruq al-Hadid. Gold-base jewellery is, on the other hand, rare at Jebel al-Buhais (Jasim, 2023).

The same is possibly true for the horn-shaped artefacts from Bida Bint Saud in Abu Dhabi (UAE) that are on display in the Al Ain Museum (UAE) and they are comparable to the horn-shaped variant 2 from Saruq al-Hadid.

The copper industry at Saruq al-Hadid seems to have been deeply interwoven with the local economy, as seen at contemporary sites such as Bithnah, Masafi or Adam in burials and ritualised contexts (Benoist et al., 2015; Gernez and Jean, 2021; Jean et al., 2021; here: fig. 1). This similarly applies to the production and deposition of precious metals in Saruq al-Hadid but with many fewer comparable finds. Beyond that, there appears to be a strong connection to long-distance trade, reflected in very similar ideas about precious jewellery and its styles, even more so than in copper-base and ferrous artefacts from Saruq al-Hadid, which also display strong connections to wider West Asian styles. There are more examples and comparable finds that indicate the role of Saruq al-Hadid as a trading hub and highlight its connections to the nearby and the wider regions. These require a detailed discussion that extends beyond the remit of this paper and will be presented in a future publication. The discussion above, however, demonstrates the importance of Saruq al-Hadid and its gold (and silver-base) jewellery production for the early Iron Age exchange systems. Despite the lack of actual workshops, the material left behind displays the entire *chaîne opératoire* from beating ingots into sheet metal to cutting strips, to hammering and twisting wires in shape, and producing gold and silver-base artefacts. The lack of workshops and tools is not very surprising, and fits well with the currently understood pattern of persistent but temporary/seasonal use of the site, where craftspeople would arrive and leave with their tool sets. Ethnographical examples support the reconstructed temporary and transient character of craft activities at Saruq al-Hadid; precious metal smiths in particular are known to have operated without fixed workshops and, even if sedentary, to produce a very limited repertoire of tools and equipment (e.g. Armbruster, 1995, p. 130; Wilson, 2002).

The number of precious metal finds deposited at Saruq al-Hadid is exceptional and presently without comparison in ancient Arabia. It is not only the sheer number of arte-

10. Louvre collections. https://collections.louvre.fr/en/ark:/53355/cl010130418; accessed 10/225.

facts, reaching into the thousands but also the ratio in which the two categories of finished and semi-finished precious metal finds appear at the site. The quantity of semi-finished artefacts from excavations by SHARP and the Polish Mission is at least equal to and potentially 1.3 times greater than the quantity of excavated finished artefacts, depending on the classification of semi-finished and misfits pieces. This ratio highlights the significance of working remnants at Saruq al-Hadid. Working remnants were not randomly left behind; rather, they demonstrate that precious metals were an important component of cultural practices at the site and contributed to its significance within early Iron Age exchange networks. Individual finds demonstrate a direct connection between the two artefact groups of finished and semi-finished items. The most significant examples include pre-shaped and prepared strips, ribbons, and wires that have already been cut, twisted, fused, or split.

An additional single but significant example is the ring-shaped item with indents on its outer surface (fig. 7a). This find seems to be a semi-product for a ringlet with granules attached to its indentations (fig. 7b). Only a few complete artefacts are known from the site, but they directly relate working remnants with finished artefacts supporting the production of precious metal artefacts on site. The presence of such a quantity of valuable finished and semi-finished materials left behind at Saruq al-Hadid poses a puzzle. The question of whether it was removed from circulation solely or partly for ritual reasons remains unresolved; it certainly must have held significant economic value not only for the site but for wider regional exchange systems.

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Producing, Using and Hoarding Metal Objects in Late Bronze Age 3: Multi-Element Metal Analysis, 3D Morphometry and Techno-Functional Study of the Axe Blades from Bourbonnais (France)

Théo Enudde, Pierre-Yves Milcent and Benoît Mille

Abstract: The metal economy at the end of the Bronze Age in Western Europe remains poorly understood, partly due to the lack of identifiable bronze workshops in the archaeological record. This article explores this issue through the study of 46 winged axe blades from Late Bronze Age 3 (950–800 BCE), mainly from recent excavations at the Jenzat hillfort in Bourbonnais (Allier département, France). The aim is to identify technical traditions, to assess standardization using techno-functional analysis and 3D morphometry, and to investigate metal sourcing through multi-element analysis.
Techno-functional analysis revealed that the blades were functional tools before their disassembly and hoarding, with wear traces confirming their use. The chaîne opératoire study showed careful finishing, indicating technical investment up to the finishing steps. Wear levels varied considerably, and hammering techniques on blade tops challenged traditional typologies.
Morphometric analysis showed high standardization, particularly in outline blade dimensions. 3D modelling identified new typological criteria, suggesting revisions to classifications. Identification of blades cast from the same mould or at least moulds using the same model and displaying the same degree of wear allowed proposal of a synchronicity between the various hoards from Jenzat hillfort and a neighbouring hoard from Charroux.
Multi-element ICP-MS-MS analysis, conducted at the C2RMF laboratory, identified three distinct alloy types, possibly influenced by supply constraints. Lead content variability raises questions about strict alloy composition control, especially for the blades coming from the same mould: it suggests that control of the metal supply was managed by the consumers or an intermediary rather than by the bronze metallurgists. The absence of real bronze workshops in the Late Bronze Age is also an indication that would support the control of the metal supply by individuals other than the bronze artisans.
Trace elements indicate a remarkably homogenous pattern of copper impurities, typical of the fahlore type, similar to contemporary objects from western continental domain regions.
These findings challenge the traditional divide between Atlantic and continental cultural spheres, suggesting a technical and economic gradient, at least in some regions. This study also highlights the importance of an integrative approach to better understand protohistoric metallurgy's socio-economic mechanisms

Keywords: Late Bronze Age, Bronze Economy, Hoard, Axe Blade, Winged Axe, Socketed Axe, Multi-Element Analysis, 3D Morphometrics, Bourbonnais.

Résumé : L'économie du métal à la fin de l'âge du Bronze en Europe occidentale reste encore mal comprise, notamment en raison de l'indigence des vestiges clairement identifiables d'ateliers de bronziers. La plupart du temps en effet, les indices de production ne sont pas associés à un espace avec des aménagements spécifiques, ce qui interroge même sur la notion d'atelier en tant que lieu de production spécialement dédié à la fabrication d'objets métalliques. C'est pourquoi l'étude des objets finis retrouvés en contexte de dépôts constitue une approche essentielle pour appréhender les modalités de production, de circulation et d'utilisation du métal. Cet article propose d'examiner cette question à travers l'étude d'un corpus de 47 lames de hache à ailerons du Bronze final 3 (950-800 av. J.-C.), majoritairement issues des fouilles récentes menées sur l'habitat fortifié de Jenzat (Allier, France) par Pierre-Yves Milcent dans le cadre du PCR « Le Pays de Gannat de la Protohistoire à l'Antiquité » dans la région du Bourbonnais. L'objectif est d'évaluer le degré de standardisation de ces objets, d'identifier d'éventuelles traditions techniques et d'aborder la question de la gestion de l'approvisionnement en métal ainsi que l'usage fonctionnel de ces lames, en mobilisant une méthodologie combinant approche techno-fonctionnelle, morphométrie 3D et analyse multi-élémentaire du métal. Le choix d'aborder ces questionnements au prisme des lames de hache est motivé par la part prépondérante qu'occupent ces objets au sein de la masse de métal enfouie dans les dépôts de cette époque.
L'approche techno-fonctionnelle a permis de documenter l'ensemble des traces liées à la fabrication, à l'usage et à l'entretien des objets. Les résultats montrent que toutes les lames ont été préparées pour être pleinement fonctionnelles et que la majorité d'entre elles portent des traces d'utilisation, confirmant ainsi leur fonction d'outils avant qu'elles ne soient désolidarisées de leur emmanchement

puis mises en dépôt. Par ailleurs, l'étude de la chaîne opératoire révèle un soin particulier apporté à la finition, dénotant un investissement technique porté à l'apparence des objets. L'analyse de l'usure a également permis de mettre en évidence une forte variabilité dans les degrés d'usage des lames avant leur démontage et leur enfouissement. Enfin, la mise en évidence de multiples modes de finition du sommet par martelage a permis d'invalider l'utilisation de la morphologie de cette partie des objets comme critère typologique.
L'étude morphométrique a permis de quantifier le degré d'usure des lames grâce à un Indice Morphométrique d'Usure (IMU) et d'examiner leur standardisation indépendamment des modifications induites par l'usage. L'analyse des coefficients de variation des dimensions dont la valeur est pertinente (essentiellement la partie médiane de la lame et ses contours externes) révèle un haut degré de standardisation, ce qui pourrait plaider en faveur d'un approvisionnement à partir de lieux de production proches et peu nombreux. L'acquisition de modèles 3D a également permis de proposer plusieurs critères typologiques nouveaux, indépendants des opérations de finition et de l'usure, qui ouvrent la voie à une révision des typologies existantes. En outre, l'analyse comparée par morphométrie 3D a rendu possible l'identification de 6 groupes de « lames jumelles », c'est-à-dire d'objets produits à partir d'un même moule ou *a minima* d'un même modèle. Le croisement de ces nouvelles données avec les degrés d'usure estimés des objets a en outre mis en évidence la synchronicité d'une grande partie des dépôts du site de Jenzat, ainsi que d'un dépôt localisé sur la commune voisine de Charroux.
Enfin, les analyses multi-élémentaires des compositions chimiques des objets par ICP-MS-MS conduites au C2RMF ont permis de caractériser les alliages utilisés et d'identifier des tendances spécifiques en matière d'approvisionnement en métal. Alors même que les lames ont des formes très standardisées et homogènes, les teneurs en étain et en plomb sont variables, avec trois types de bronzes au plomb. En particulier, les teneurs en plomb montrent une variabilité notable, remettant en question l'hypothèse d'un contrôle strict et purement technique sur les compositions des alliages. Faut-il en déduire que le contrôle sur la matière première métallique en amont de la fabrication était assuré non pas par le métallurgiste, mais par un intermédiaire ou bien, plus simplement, par le commanditaire ? Il semble en tout cas que les contraintes d'approvisionnement en métal l'emportaient sur les choix techniques.
L'analyse des éléments traces indique en revanche une remarquable homogénéité dans les sources de cuivre exploitées, ce dernier étant probablement issu de minerais sulfurés de type fahlerz à l'instar des objets contemporains issus de l'ouest du domaine culturel continental. En comparaison des bronzes atlantiques et continentaux, les caractéristiques hybrides observées dans le métal utilisé pour la fabrication des lames de hache du Bourbonnais apportent aussi un nouvel éclairage sur les dynamiques de production et de circulation des métaux à la fin de l'âge du Bronze en Europe occidentale. Ces résultats remettent en question la vision traditionnelle distinguant de façon trop stricte les sphères culturelles atlantique et continentale en suggérant plutôt l'existence d'un gradient technique et économique est-ouest. Cette observation valable pour le Bourbonnais invite à reconsidérer ce qui a parfois été proposé pour d'autres régions, ce qui souligne la complexité des réalités culturelles à l'extrême fin de l'âge du Bronze. Cette étude souligne enfin l'importance d'une approche intégrative pour mieux appréhender les mécanismes socio-économiques de la métallurgie protohistorique.

Mots clés : âge du Bronze Final, économie du Bronze, dépôt métallique, lame de hache, hache à ailerons, hache à douille, analyses multi-élémentaires, morphométrie 3D, Bourbonnais.

INTRODUCTION

The workshop issue

Bronze and its economy are central topics of interest for archaeologists studying the Bronze Age in Western Europe.(1) However, this economy remains difficult to grasp, even in the latest phase of the period, when production had diversified and objects were hoarded in larger quantities. Despite widespread assumptions and recent excavation work during the last decade, the comprehension of bronze-smithing or goldsmithing workshops remains rather lacunary and unsatisfactory. In nearly all archaeological sites where clues indicating bronze object manufacturing have been found, these remains are either displaced or poorly characterized. They are often discovered discarded in pits, in secondary positions, which provide little information regarding their original layout and organization. Whenever they do appear to be in situ, they are rather sparse and seemingly integrated within the domestic spaces. As such, the lack of data would make the use of the term 'workshop' improper (that is, where it signifies a permanent and specialized place distinct from the domestic sphere and characterized by specific installations); the notions of 'workspace' and 'place of production' appear more neutral and suitable. Workshop conditions, however, are exceptionally met on sites like Fort Harrouard at Sorel-Moussel, Eure-et-Loir (Mohen and Bailloud, 1987; Mohen and Walter, 1998), but the excavations there were conducted fifty years ago and did not follow modern methodologies. Under these circumstances, the use of the term workshop, defined as a specialized space dedicated to metal production, is problematic when not properly substantiated. It misleadingly suggests that archaeologists can readily identify and understand these workshops, which is rarely the case; it would be more appropriate to refer to production sites. Since the places where finished objects were manufactured remain poorly understood, studying and comprehending the mechanisms of metal production and use is particularly challenging. A different viable approach is to investigate them indirectly, primarily through the study of finished products.

What models exist for the economy of bronze object production in protohistoric societies?

Few concrete models have been proposed to explain the economy of metal object production in protohistoric societies (Needham, 1998; Molloy and Mödlinger, 2020), and none have been definitively validated to date. This

1. This paper mainly consists of a master's thesis conducted at the Université de Toulouse Jean-Jaurès (Enudde, 2023)

is why it is important to formalize more systematically the various theoretical models that could be used to account for the possible economic patterns of the Bronze Age (fig. 1). Should we consider the existence of independent bronze craftsmen—artisans who controlled their own metal supply, determined their workplaces, and set the terms of exchange? Or should we instead assume that producers were not full-time specialists but rather craftsmen dependent on commissioners who provided the metal, requiring them to travel frequently to carry out their work? An intermediate scenario is also conceivable: producers operating under the control of an elite that monopolized the metal supply and the trade in finished products. Or perhaps a combination of all these models within a highly diverse economic system?

Axe blades as proxies: representativeness and functions

In the absence of remains that can be identified as manufacturing workshops, addressing these questions necessarily involves studying the finished objects found in the context of hoards. For the Late Bronze Age 3 (LBA 3, 950–800 BCE), one of the most frequently discovered object categories is the axe blade (Briard and Verron, 1976; Kibbert, 1984; Bordas, 2023). These blades often represent the predominant functional category for the mass of metal buried in a hoard. Beyond their archaeological ubiquity, these objects may have been involved in multiple spheres of activity within protohistoric societies. Woodworking, warfare, butchery (either strictly for food or for sacrificial purposes), and even exchange as currency objects are all potential functions that make axe blades a relevant proxy for studying the bronze economy. Surprisingly, there has been little recent research in this direction for winged axe blades from the LBA. Approaching the bronze economy through the lens of axe blades requires addressing several objectives. In the absence of true workshops and given the extensive recycling of metal, how can we characterize metal stock and supply? How can we determine production methods and organization? Can we identify technical traditions and groups of objects produced by the same artisan or workshop? Finally, how can we characterize the use of axe blades from their new condition to their hoarded state?

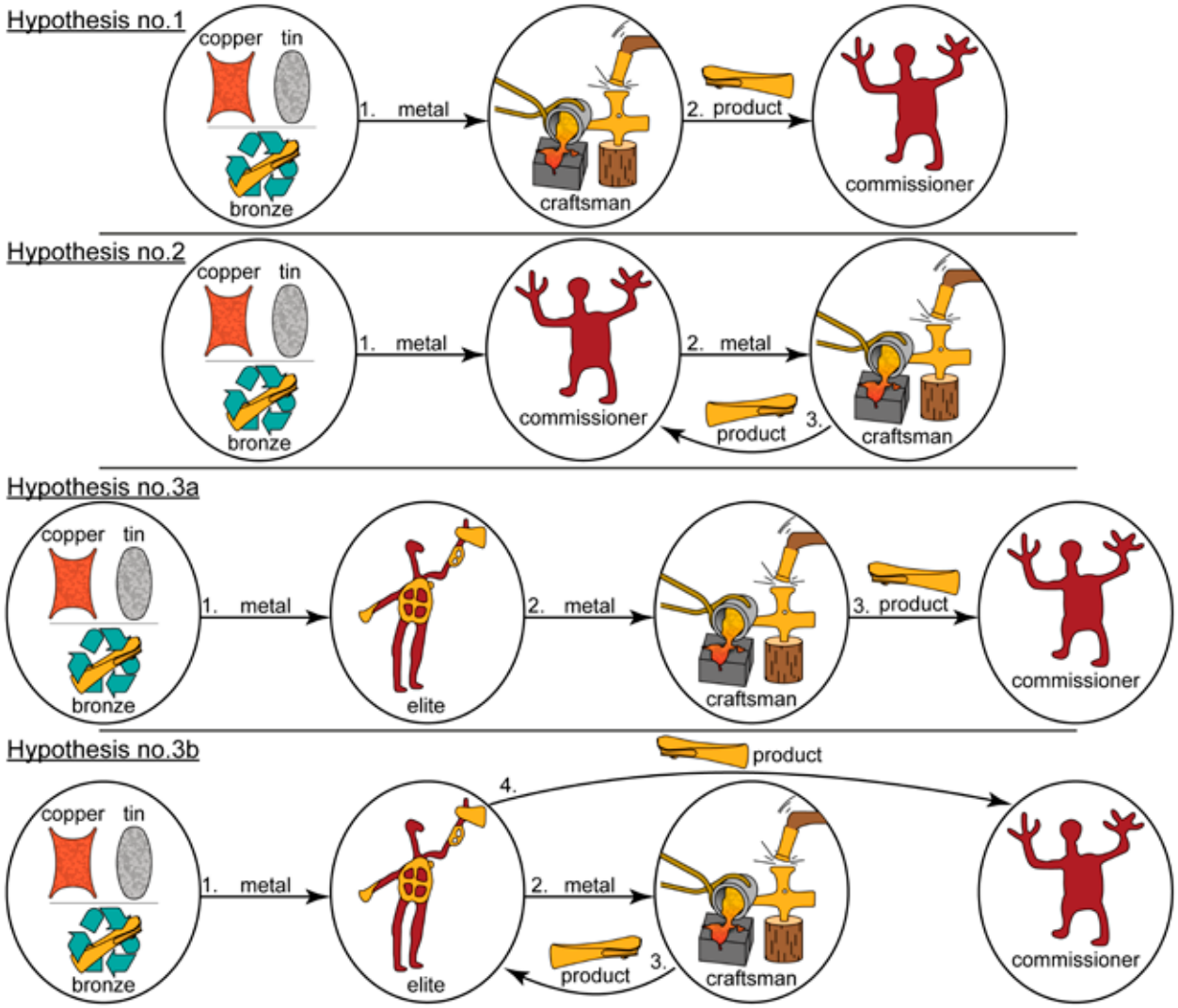


Fig. 1 – Proposed theoretical models of the economy of metal object production during the LBA (CAD T. Enudde)

THE STATE OF RESEARCH: BETWEEN BLIND SPOTS AND INSIGHTS

To conduct this study on the metal economy, we have selected a corpus limited to a specific period (LBA 3), a particular context (bronze hoards), and a micro-region (northern Auvergne, called Bourbonnais, which is today's 'département de l'Allier', in central France). After reviewing how this type of artifact has been approached so far, we will present the corpus.

In France

During LBA 3, winged axe blades were very common and proportionally outnumbered socketed axe blades in continental cultures. In Atlantic cultures, their distribution is more complex: they are rare north of the Loire bend but appear more frequently in the Armorican Massif, sometimes in numbers equal to those of socketed blades (Bordas, 2023, vol. 2, map 77). In his study area (France and neighbouring regions), F. Bordas records 1,068 winged blades from approximately 360 LBA 3 hoards, including recent discoveries. These blades account for nearly 400 kg of immobilized metal, considering an estimated average weight of around 350 g per object. Overall, winged axe blades from LBA 3 in France have been distinctively identified as one of the most important and widespread diagnostic artefacts for the period (Coffyn et al., 1981). Paradoxically however, they have not been the subject of any specific study to date. This is perhaps because their specificity as artefacts has made them unsuitable for common typological classification methods (Briard and Verron, 1976). This leaves a blatant blind spot in the research that the present paper aims to contribute to reducing.

A tradition of research focused primarily on palstaves and flanged axe blades from the Middle Bronze Age

Fortunately, in France, the past twenty years have been fruitful in terms of advances in research on axe blades, and copper-based alloy artefacts in general. In addition to the significant documentation gathered by the authors mentioned earlier, the work of C. Véber (2009) on the technological and multi-element analytical aspects of LBA 3 winged axe blade production should be mentioned. Although these artefacts represent only one of many categories studied in her PhD thesis on the hoards from Sarre-Lorraine, the main technological characteristics of winged axe blades are outlined. This remains by far the most thorough study for LBA 3 winged axe blades to date and provides ample analytical data. A second important area of research should be mentioned: although it focuses on Middle Bronze Age palstaves and flanged axe blades, it nevertheless forms the methodological basis for the present study. Antoine Verney initiated the first research aimed at identifying palstaves made from the same moulds in Normandy; he was inspired in particular by the way numismatists identified series of coins made from the same dies (Verney and Verron, 1996). More recently, the work of B. Forel et al. (2009) highlighted the great potential of morphometric analysis applied to palstave axe blades. The use of Discrete Cosine Transform (DCT) for analysis of the axe outlines, and its application to a corpus of almost 400 axe blades, allowed the traditional typology to be challenged by morphometry-based classification. This methodological advance was exploited in the following decade, in work still primarily focused on MBA axe blades. A major development was the combination of morphometry with a techno-functional approach, relying mostly on metallography, and multi-element composition analysis using Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES). This methodological framework was developed in order to use axe blades from the MBA as an indicator for studying the bronze economy. In particular, F. Monna et al (2013) highlighted the relevance of techno-functional aspects in combination with the morphometric analysis: only the portion of the outline of the axe blade that is directly representative of the mould is conserved in order to ensure the relevance of the results. This quantified and objective approach allows for a better understanding of the production, circulation and use of axe blades during the MBA and of the differences in production control modalities between neighbouring regions. But it should be noted that the aforementioned studies used 2D based morphometric data derived from drawings. This limitation was outlined in J. Wilczek et al. (2015), which this time used a new Elliptic Fourier Analysis, and which advocated for the use of 3D acquisition techniques to further enhance objectivity and repeatability. Notably, a key conclusion of this study resides in the importance of integrating more parameters of shape variation than only the outline of the side-view of the object. Further statistical development for processing the morphometric data, as well as their combination with a techno-functional approach and ICP-AES analysis, allowed for a new understanding of the standardization of artefacts and the bronze economy during the second half of the MBA (Gabillot et al., 2016; Mordant and Wirth, 2017). This method was also applied to a mixed corpus of palstave axe blades and axe-ingots (Gabillot, 2021). Here, the acquisition of 3D models was obtained by photogrammetry and their comparison by a Principal Component Analysis of the mean distance between each model, but without truly excluding from the comparative analysis the parts modified by the use of the objects. It was completed by an ICP-AES analysis and a technological study. This methodological and conceptual approach provides a basis that can be applied and perfected for the study of LBA axe blades, although the use of photogrammetry can be questioned as it is very time consuming (in comparison with 3D scanning) and the software used (Agisoft Photoscan) allows for only a limited degree of monitoring and control over the error margins of the models, especially since these may vary depending on the camera used and the users themselves.

Typologies to reconsider

The winged axe blades with subterminal wings attributed to the LBA 3 in Western Europe have been the subject of only a single in-depth study, conducted in the late 1970s by K. Kibbert (1984), who established the conventional typology. This classification has never been revised and remains in use today (Joachim and Weber, 2006). French scholars, for their part, have long refrained from proposing subdivisions within this category (Briard and Verron, 1976), although some have attempted to refine Kibbert's typology by adding a few local variants (Chardenoux and Courtois, 1979). Kibbert's classification distinguishes two types: a minority type, referred to as Geseke-Biblis, and a majority type, known as Homburg. The distinction between these two categories is based on a 'constriction' (*Einziehung*; Kibbert, 1984: 159), meaning a narrowing of the blade's outline between the broader proximal end of the wings and the narrower distal end. Kibbert set the threshold at 5 mm: if the narrowing is equal to or greater than this value, the blade is classified as Homburg type; otherwise, it belongs to the Geseke-Biblis type. Kibbert notes that the Homburg type appears to be more common in continental contexts, whereas the Geseke-Biblis type is more prevalent in Atlantic regions. Recent research by F. Bordas (2023) tends to confirm this observation. However, it is worth noting that the 5 mm threshold proposed by Kibbert is entirely arbitrary and would require validation through statistical analysis. Kibbert also proposed subdividing the Homburg type into several typo-chronological variants based on the morphology of the top of the blades. He interpreted this as evidence of a technological evolution in mould design over time. Based on these same observations, he suggested that the Atlantic blades of the Geseke-Biblis type were more 'archaic' than the continental blades of the Homburg type. However, the absence of a techno-functional study that considers alterations induced by manufacturing processes and wear makes these observations somewhat questionable.

THE CORPUS IN CONTEXT: THE AXE BLADES FROM THE BOURBONNAIS

The majority of the known axe blades from LBA 3 in the Bourbonnais consist of recent discoveries, the older findings (mostly in the 19th century) accounting for relatively few: 27 axe blades out of a total of 85 (fig. 2). It should be noted that this is an estimation based on

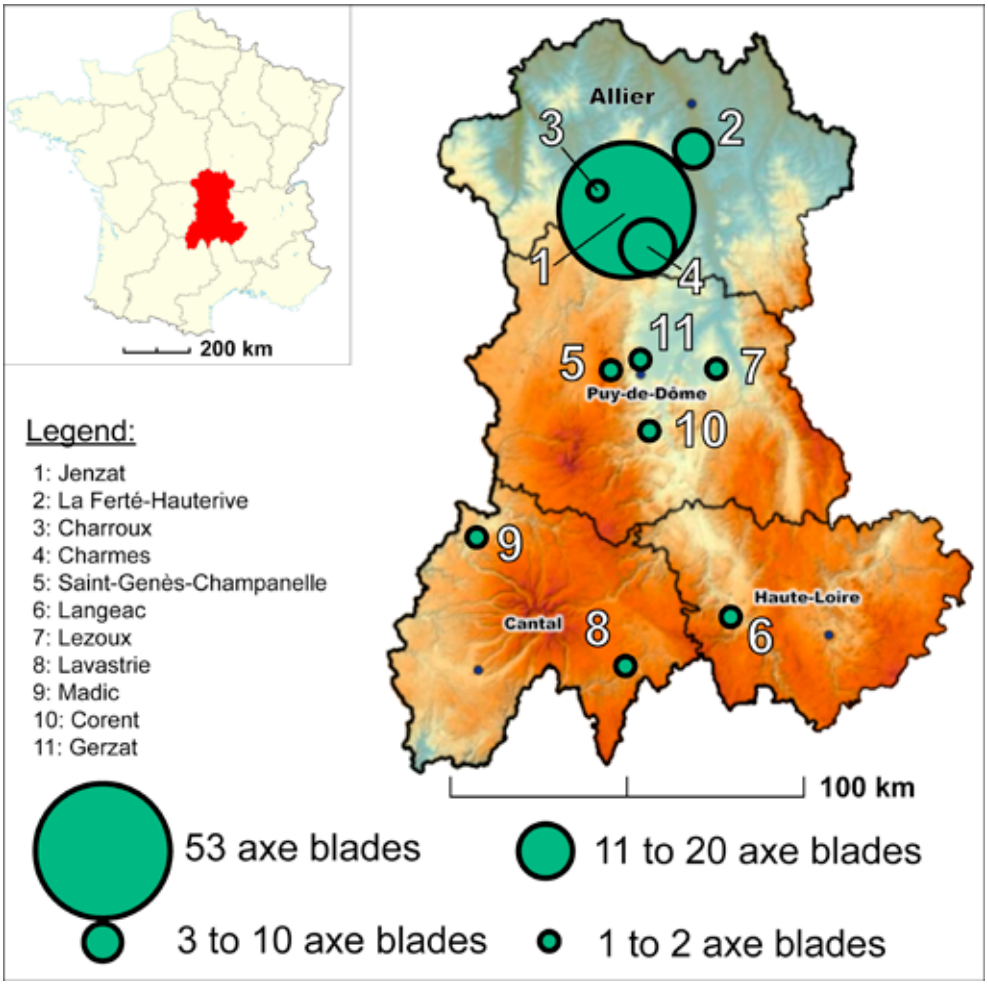


Fig. 2 – Distribution map of LBA 3 axe blades in Auvergne (T. Enudde).

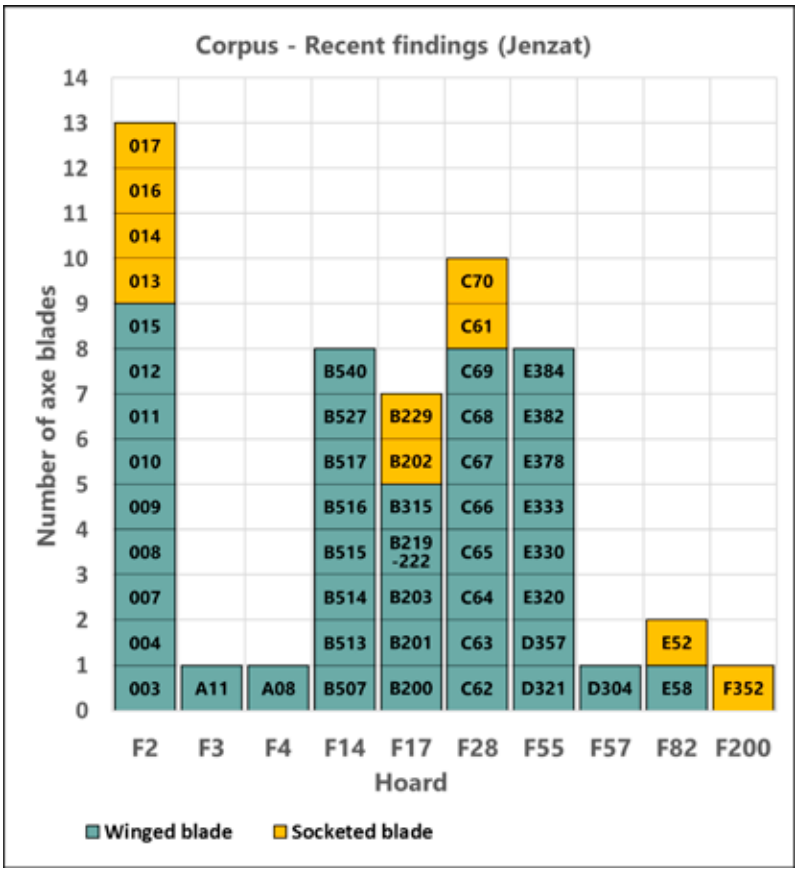


Fig. 3 – Winged and socketed axe blades from recent discoveries in the corpus (T. Enudde).

the data available in the literature, as the exact number remains a little hazy (Tudot, 1861; De Mortillet, 1894; Abauzit, 1962a, 1962b; Millotte, 1963a, 1963b; Chardenoux and Courtois, 1979).

The corpus for this study consists of 47 axe blades (46 winged, one socketed) from LBA 3 that were discovered in the southern Bourbonnais and still well preserved. Of these, 43 come from recent excavations led by Pierre-Yves Milcent at the fortified hillfort settlement of Jenzat as part of the project "Le Pays de Gannat, de la Protohistoire à l'Antiquité" (Milcent and Lallemand, 2023; Milcent, 2025). These were recovered from 9 of the 18 hoards uncovered since 2017. The remaining 4 blades originate from 19th-century hoard discoveries in Jenzat (1 blade), Charroux (1 blade; 2.8 km from Jenzat in a straight line but on the opposite bank of the Sioule river), and La Ferté-Hauterive (2 blades; 30 km north-northeast of Jenzat). They are preserved at the Anne de Beaujeu Museum in Moulins (fig. 3 and 4). Overall, these blades are in excellent condition, with patinas preserving numerous manufacturing and usage traces. This state of preservation results mainly from the fact that most Jenzat blades were excavated in situ by archaeologists, avoiding damage from looting by unlawful detectorists or inappropriate 'restoration' practices. Additionally, their localization in a forested area likely protected them from modern agricultural chemical intrusion.

These winged blades constitute the majority of known LBA 3 axe blades in the study area: 46 out of a total of 62.

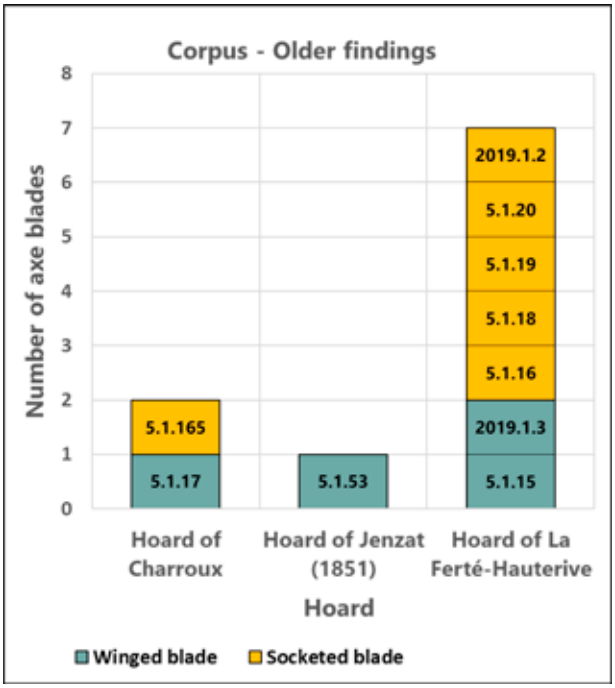


Fig. 4 – Axe blades from hoards discovered in earlier periods (T. Enudde).

The remaining socketed blades, while part of the hoarded assemblage, are not considered here as their morphological specificity would require a distinct study. However, a polygonal socketed blade of the Meldreth type (Blade C70 from Jenzat Hoard F28), a model typically associated with southern Britain (Briard and Verron, 1976; Chardenoux and Courtois, 1979; Schmidt and Burgess, 1981), was still included in the study in consideration of its uniqueness and 'exoticism'. Moreover, a bronze mould valve used to manufacture similar Meldreth type blades (Object 41 from Jenzat Hoard F2) was discovered by an unlawful detectorist in 2017—this object in particular is extremely rare, both in absolute terms and even more in this region; this further motivates the inclusion of the socketed blade C70 in this study. It should be noted that one winged blade in the corpus (009 from Jenzat Hoard F2) notably bears a St. Andrew's cross mark on the right lateral groove, approximately at the level of the ring (fig. 5). Although already known in the literature, the function of this distinctive mark remains unquestioned, though it is unlikely to be decorative as it was concealed when the object was hafted. Research work about this feature has so far been inconclusive, and the present paper does not aim at tackling it. However, this peculiar characteristic deserves mention as it is the only form of 'ornamentation' (in the loosest sense of the term) borne by winged axe blades. Could it be a workshop mark? The question remains open. This feature is known on only six objects from central France: two marked blades from the Graçay hoard, Cher (Cordier, 2009; 2202 and 5), one from near Vendôme, Loir-et-Cher (Cordier, 2009; 3046), one from Tonnerre, Yonne (Guillaumet et al., 1981), and two mould valves from the Saint-Martin-Le-Beau hoard, Indre-et-Loire (Cordier, 2009; 2831). This suggests a regional characteristic associated with the middle Loire basin. The presence of such a marked blade in the Lower Auvergne raises questions about object circulation, as well as the movement of moulds, models, and possibly artisans themselves.

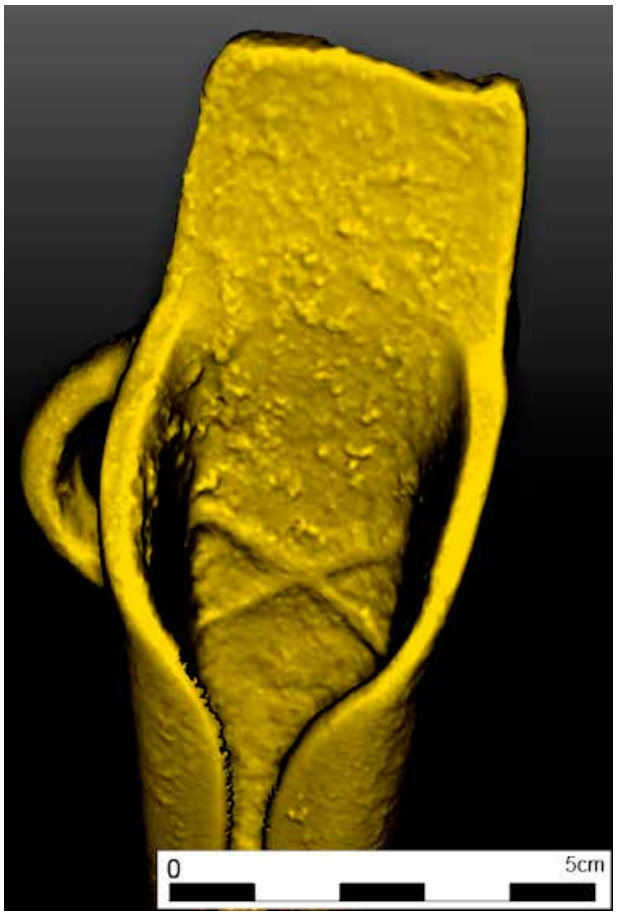


Fig. 5 – Highlighting the St. Andrew's cross symbol on blade 009 from Jenzat Hoard F2 (T. Enudde).

An exceptional context: the Jenzat hillfort site

Most of the axe blades in the corpus come from a single site: the fortified hillfort of Jenzat. This site, located on the northern slopes of the Massif Central, sits atop a rocky plateau rising 160 metres above the right bank of the Sioule River, a tributary of the Allier River (fig. 6). It is dated to the end of the LBA 3 (9th century BCE) based on metal artefacts, ceramics, and a radiocarbon date. A rampart, reinforced by a ditch, cuts across the plateau, enclosing an area of approximately 35 ha. This surface area is significantly larger than the norm for hillforts of this period in France, which cover around 4 ha on average (Milcent and Couderc, 2021). A rock fold running parallel to the rampart appears to play a role in the organization of the internal space. Various parts of the site have yielded artefacts and domestic features characteristic of a permanent habitat. However, what makes the site truly exceptional is the series of metal hoards it contains: in addition to several poorly documented hoards discovered in the 18th and 19th centuries, recent excavations have uncovered 11 intact hoards as well as the remains of 7 looted ones. Of the 18 metal hoards identified at the Jenzat site, 9 contained between 1 and 13 axe blades, usually along with many other types of generally intact artefacts: these are mostly wagon and horse harness, weapons (swords, spears), adornment (torcs, bracelets, pendants, beads…), vessels, various tools (mostly sickles and knives, along with tools related to woodwork), and ingots. When their original positioning could be observed, the axe blades generally appeared intact and clustered in the upper part of the hoard. However, one winged axe blade had been broken in two: blade B219-222 from Jenzat hoard F17. Additionally, within this same hoard, another blade, B315, was represented only by its distal half. Although these objects account for only 52 pieces (including 42 winged axe blades) out of the 1,265 metal remains collected at the site since 2017—just 4% in terms of artefact count—their combined mass represents nearly 50% of the total weight of metal recovered: 20.4 kg out of 40.9 kg. The significant predominance of axe blades in terms of hoarded metal mass at Jenzat underscores their relevance as a key proxy for studying bronze production.

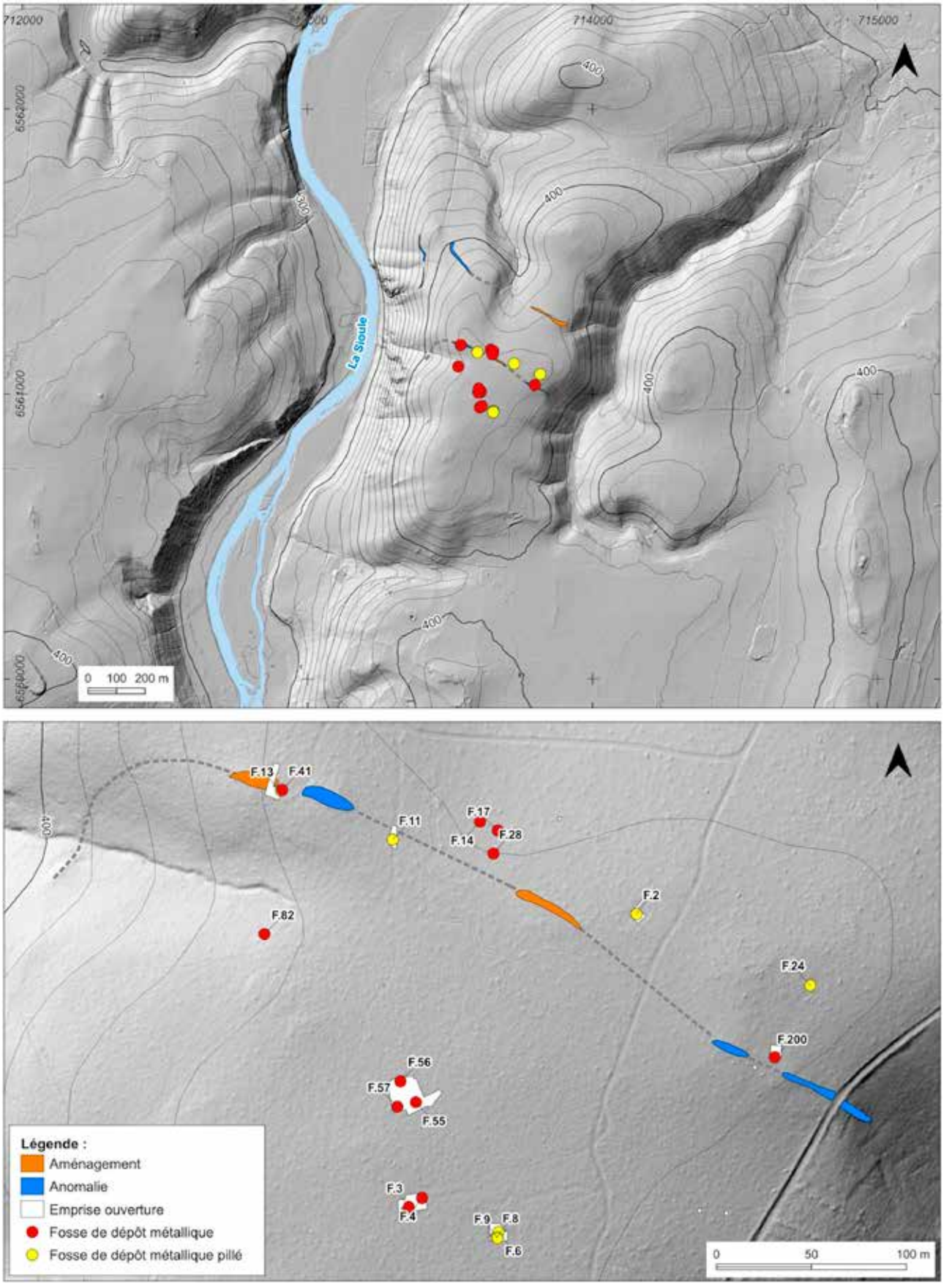


Fig. 6 – Plan of the Jenzat site, 2024 field campaign (Milcent and Lallemand, forthcoming, CAD F. Müller).

METHODOLOGY: CROSS-DISCIPLINARY APPROACHES

To better understand the metal economy through the study of winged axe blades from the Bourbonnais, a specific methodology has been developed, combining for the first time three complementary approaches: multi-element ICP-MS-MS analyses, a morphometric study including 3D analysis, and a techno-functional and traceological approach.

Multi-element compositional analyses

The compositional analyses using ICP-MS-MS (Inductively Coupled Plasma – Tandem Mass Spectrometry) were conducted at the C2RMF laboratory under the supervision of Benoît Mille. These analyses had two main objectives. On the one hand, measuring the concentrations of major elements (copper—Cu, tin—Sn, and lead—Pb) allows for the identification of alloy types used and provides insight into the technical tradition of the producers. On the other hand, measuring the concentrations of trace elements documents the impurities introduced by the alloying elements (these impurities originate primarily from the copper). This provides information on the types of mineralization exploited and refines the chemical signature of a given copper stock. This, in turn, may help address questions related to recycling and the circulation of raw materials (which will be further explored in the future through lead isotope analyses). Of the 67 elements quantified, we have focused here on those most relevant for potential bibliographic comparisons (Rychner and Kläntschi, 1995; Bourgarit and Mille, 2014; Pernicka, 2014), while the complete dataset will be considered in a subsequent study. The focus elements are: sulphur (S), iron (Fe), cobalt (Co), nickel (Ni), zinc (Zn), arsenic (As), silver (Ag), antimony (Sb), and bismuth (Bi). To ensure comparability of copper impurity levels between objects, each variable has been standardized: it is calculated by subtracting the mean and then dividing the difference by the standard deviation. As the study is still ongoing, only part of the corpus has been analysed: 40 axe blades out of 47. The following blades could not be included at this stage: E320, E330, E333, E378, E382, E384 (all from Jenzat Hoard F55) and E58 from Jenzat Hoard F82.

Morphometry and the contribution of 3D analysis

The Morphometric Wear Index (MWI)

The morphometric study aims to assess both the degree of wear and the potential standardization of winged axe blade production. Estimating the degree of wear is particularly useful for discussing and objectifying typological classification criteria. This is achieved through the calculation of a Morphometric Wear Index (MWI). Derived from industrial practices, this method consists of calculating a ratio between two dimensions of the object—one constant and the other variable—to estimate how much the object has shortened through use and resharpening (Izamshah et al., 2017). The selected variable is the length of the blade (the active part of the object). The constant is the ratio between the total length of the object (excluding the top, as it depends on the variable post-casting regularization process) and the remaining blade length (fig. 7). This choice is based on the assumption that the ratio between the total length of a "new" blade and the wings remains fixed. While this is an approximation, it does not hinder the study as long as the examined objects are morphometrically homogeneous—which is the case for the selected corpus.

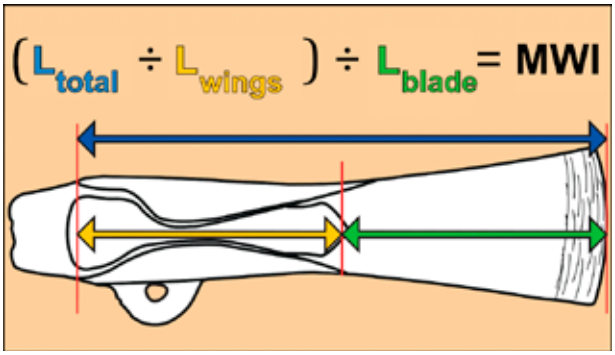


Fig. 7 – Calculation of the Morphometric Wear Index (T. Enudde).

Morphometric standardization

The degree of standardization within the series is estimated by observing the Coefficients of Variation (CV) for each measured dimension (fig. 8). This coefficient is calculated as the ratio of the standard deviation to the mean, multiplied by 100, and is expressed as a percentage (Chenorkian, 1996). A low CV corresponds to a high degree of standardization, and vice versa. A CV of 5 % or less indicates very high standardization, suggesting that a standardized pattern was likely used to ensure consistent reproducibility. The 0 %–5 % range accounts for the margin of human error in repeating a standardized task (Birch & Martinón-Torres, 2019). The range between 5 % and 58% corresponds to variable degrees of standardization, while a CV above 58 % signals a lack of standardization (Eerkens & Bettinger, 2001).

A new approach to axe blade analysis: 3D morphometry

An innovative 3D morphometric analysis method has also been developed. It aims to identify groups of objects originating from the same mould or following the same model, thereby tracing the production of a single craftsman or a group of craftsmen. The method designed for this study is based on comparing objects as point clouds, retaining only the parts that remain unaltered after casting. This

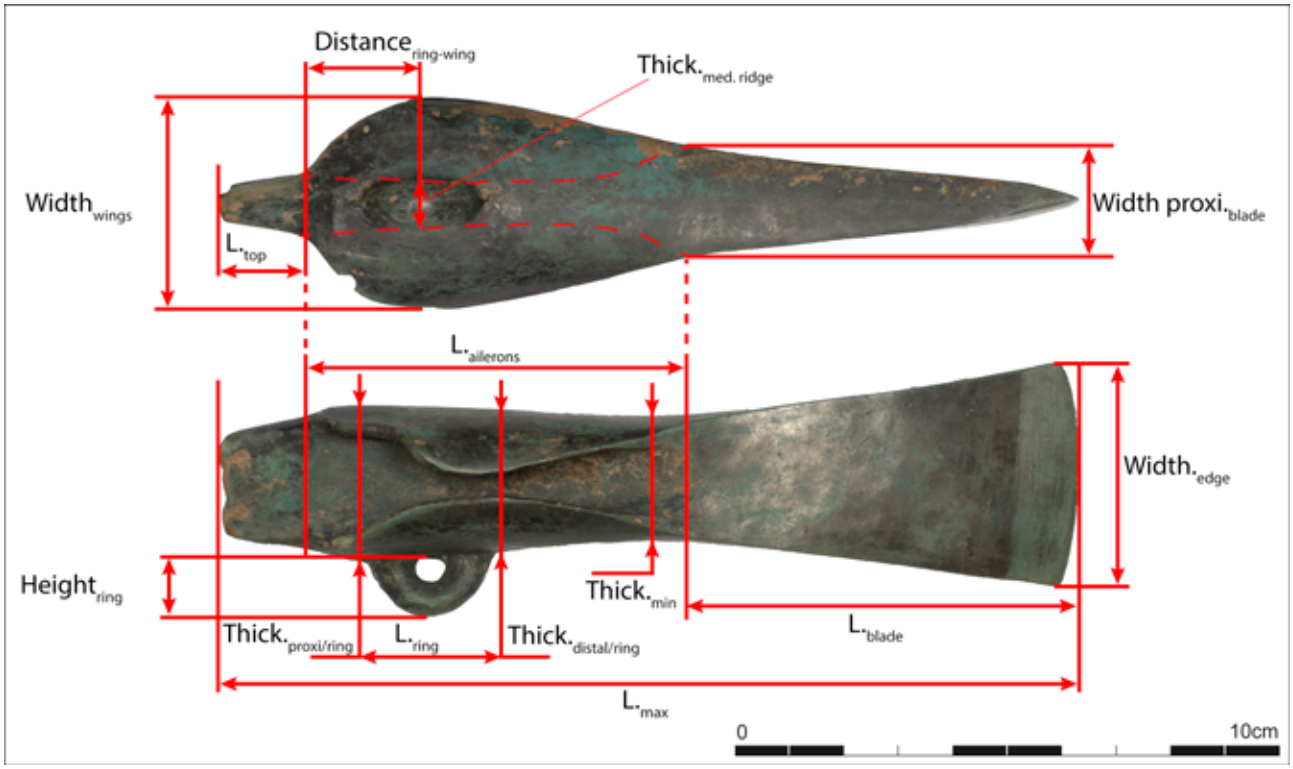


Fig. 8 – Morphometric criteria for measuring coefficients of variation (T. Enudde).

means excluding modifications resulting from post-casting processes (removal of casting sprues), hafting (bending of the wings), and wear. The selected areas for comparison include the central portion of the medial ridge, the ring, and the proximal part of the blade (fig. 9). Morphological data acquisition was conducted using structured light scanning with an Artec Spider handheld scanner. This technique allows for high-resolution 3D model acquisition, with an error margin of 100 µm horizontally and 50 µm vertically. Considering both technological and taphonomic biases, the threshold below which two models are considered indistinguishable is set at 360 µm (0.36 mm). In such cases, the objects are classified as 'twin blades', meaning they were cast from the same mould or from moulds derived from the same model. The 3D models are compared through a nearest-neighbour mean-distance analysis applied to the generated point clouds. These results are then compiled into a matrix and subjected to hierarchical clustering analysis (HCA) based on a Pearson correlation similarity index. A 95% similarity threshold (Chenorkian, 1996; Sabilla et al., 2019), combined with an average distance between 3D models below 360 µm, is used to identify twin blades. Both criteria must be met for objects to be classified as such. The validity and relevance of this method depend on an initial filtering process that eliminates all 3D model features potentially altered after casting. This requires a preliminary techno-functional analysis of each object before applying the morphometric comparison.

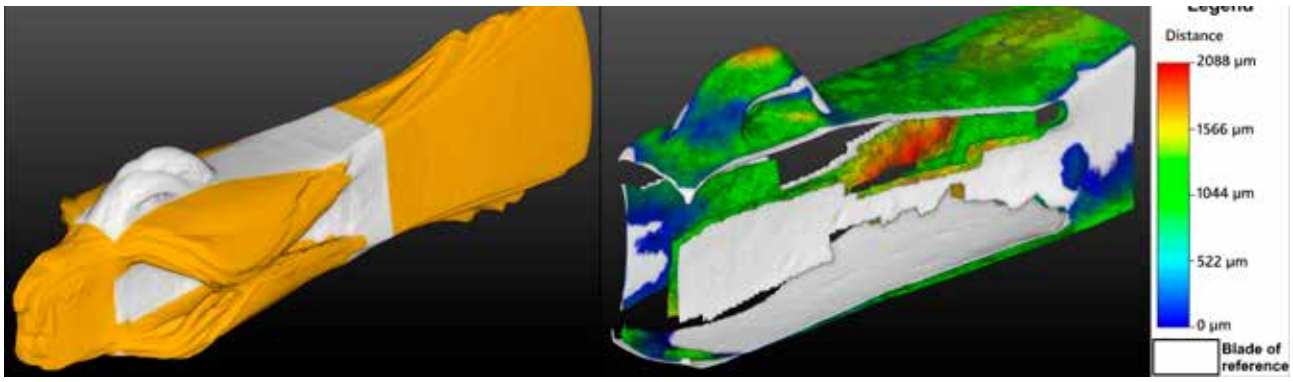


Fig. 9 – Model aggregating different blade shapes, with selected areas for morphometric comparison highlighted in white. Right: Comparison between blades C64 and C67 from Jenat Hoard F28. The generated scalar field highlights zones of maximum variation between the compared blade and the reference blade, in white (T. Enudde).

The techno-functional analysis

The techno-functional approach aims to characterize and interpret traces related to the manufacturing, maintenance, use, circulation, and hoarding of axe blades. In addition to being a necessary prerequisite for the 3D morphometric study, it addresses questions regarding the technical traditions of artisans as well as the biography of objects. For the sake of clarity, each plane and morphological element of the axe blades has been designated using standardized terminology (fig. 10). The studied objects were cleaned following a protocol that, while adhering to the principles of conservation-restoration for archaeological metal artefacts, is based on the methods outlined by C. Gutiérrez and I. Martin to allow for traceological observations (2015). Data were collected with the naked eye as well as using a Zeiss stereomicroscope with zoom and an automated stage (Axiozoom V16 model, with a maximum magnification of × 250), which enabled more precise documentation of features initially identified with the naked eye. This equipment also allows for measurements at a very small scale (µm). In the absence of a dedicated experimental reference framework, we relied on existing studies (Ottaway and Kienlin, 1998; Roberts and Ottaway, 2003; Véber, 2009; Mélin, 2012; Dolfini and Crellin, 2016, Dolfini et al., 2023).

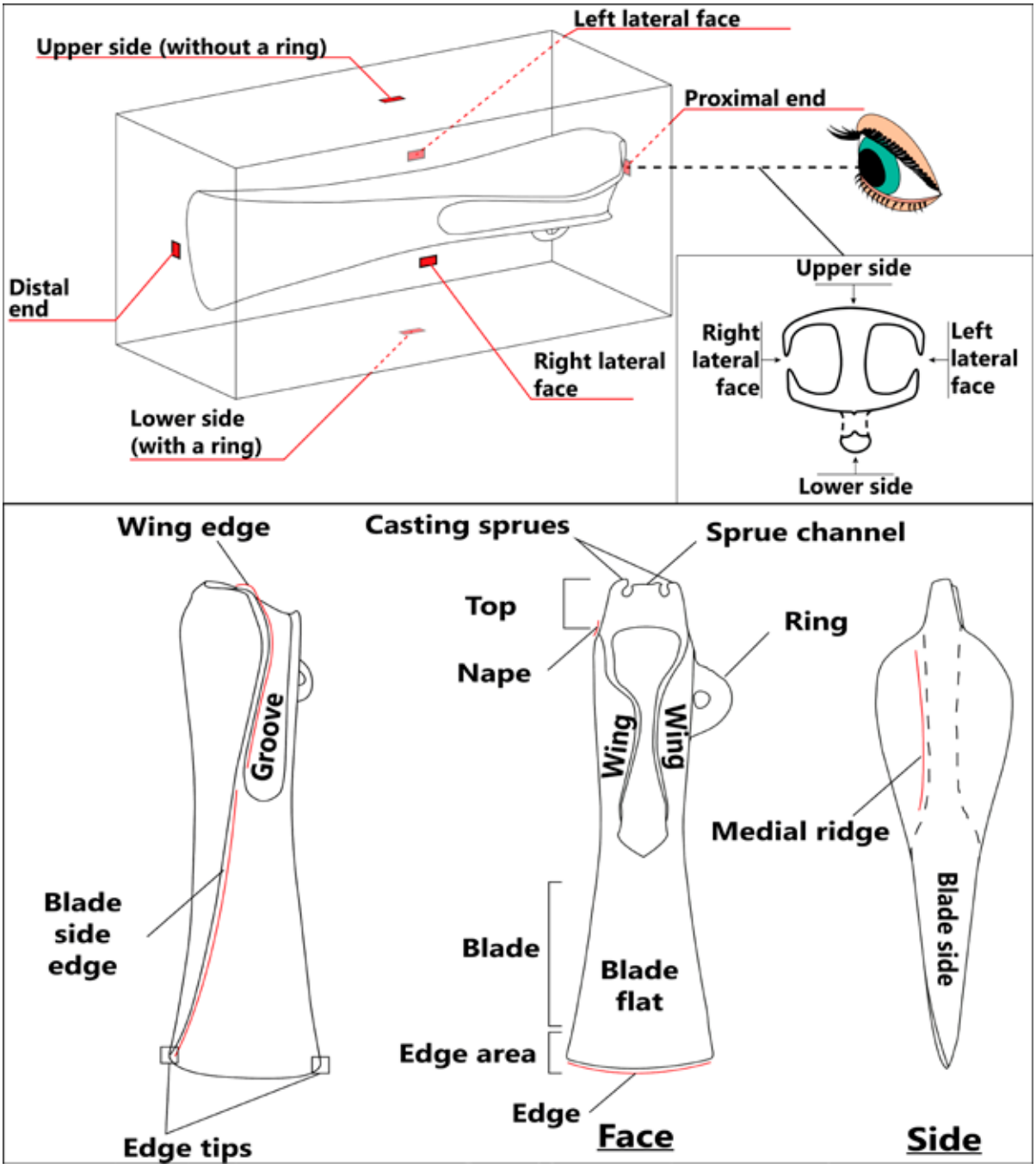


Fig. 10 – Standardized terminology for describing winged axe blades (T. Enudde).

RESULTS

A tentative techno-functional approach for LBA 3 winged axe blades

The different traces referenced are presented in the theoretical order of their appearance throughout the object's lifecycle. However, this 'chronology' is not rigid, and some features remain poorly understood.

The production phase

Features considered to belong to the production phase are those related to the mould in which the object was cast, as well as the casting process itself. This stage of the operational sequence can be documented by observing rare evidence that was not erased by finishing operations, such as casting defects (fig. 11).

The post-casting shaping phase

The shaping phase corresponds to the steps in the operational sequence aimed at modifying the raw cast form. At the end of this stage, the object has its final shape. The observed actions include:

– removal of the casting cone and hammering down of the casting sprues;

– breakage of the blade's top;

– flattening of the mould seam line;

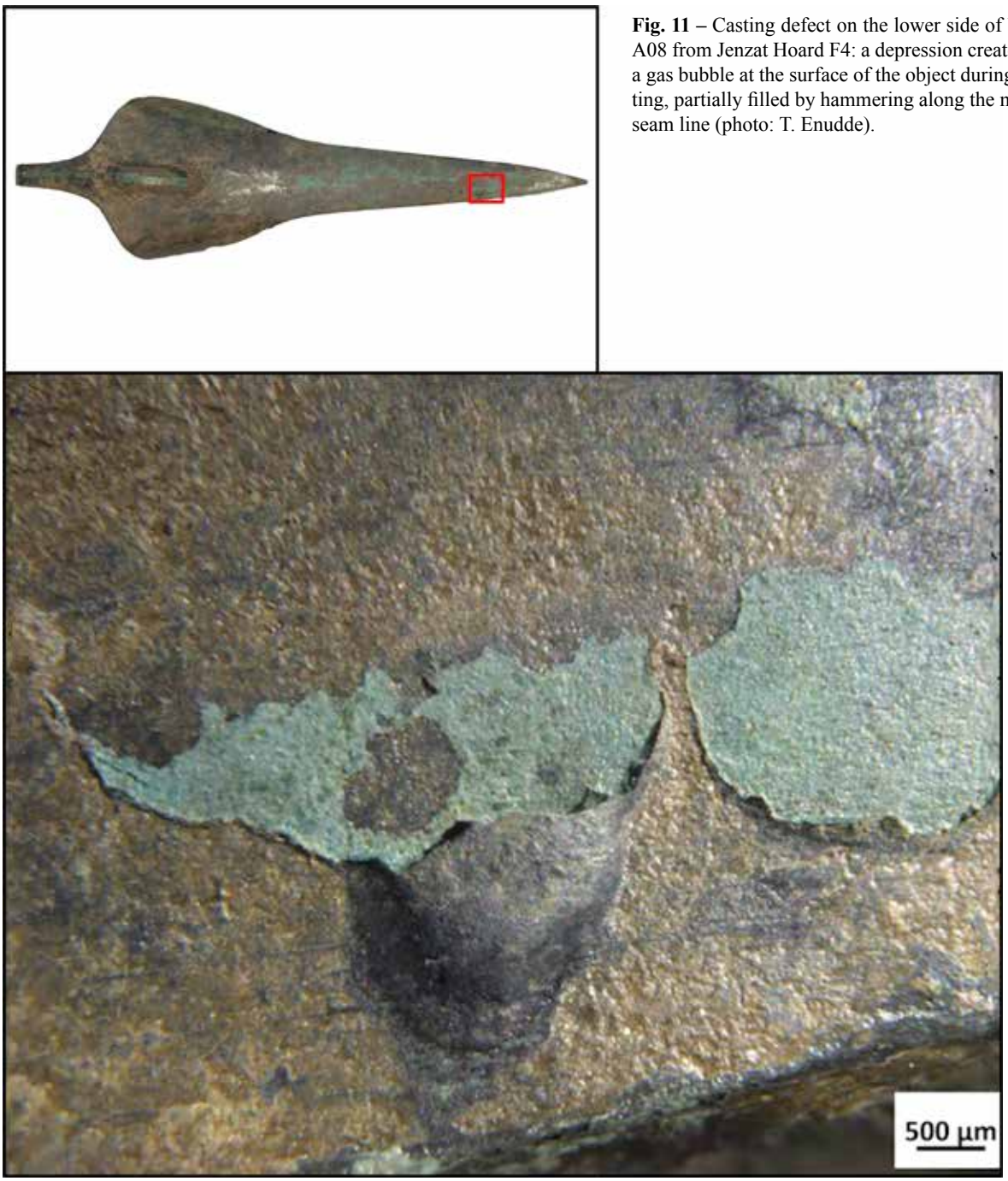


Fig. 11 – Casting defect on the lower side of blade A08 from Jenzat Hoard F4: a depression created by a gas bubble at the surface of the object during casting, partially filled by hammering along the mould seam line (photo: T. Enudde).

– incomplete flashing removal;
– hammering traces.

The comprehensive descriptions and illustrations for these traces can be found in Annex 4.

The finishing and hafting phase

The finishing phase is the stage in the *chaîne opératoire* where the blade undergoes the final modifications that make it a functional tool in its definitive form. This mainly involves surface polishing (visible on the surface texture), bending of the wings onto the handle, and sharpening of the cutting edge. Sharpening traces, in particular, appear as a band of 10 to 25 mm from the cutting edge, where numerous parallel striations mark the surface (fig. 12). In the literature, this observation is interpreted as traces of sharpening by abrasion (Ottaway and Kienlin, 1998; Véber, 2009; Mélin, 2012). Breakage or cracking of the wings may happen during the hafting or re-hafting process (fig. 13).

The 'life' of the object after its manufacture: use, wear, and maintenance

As functional objects, axe blades undergo a series of events during their use that can alter their morphology. These include repeated hammering and resharpening, damages incurred during use, and possible handle

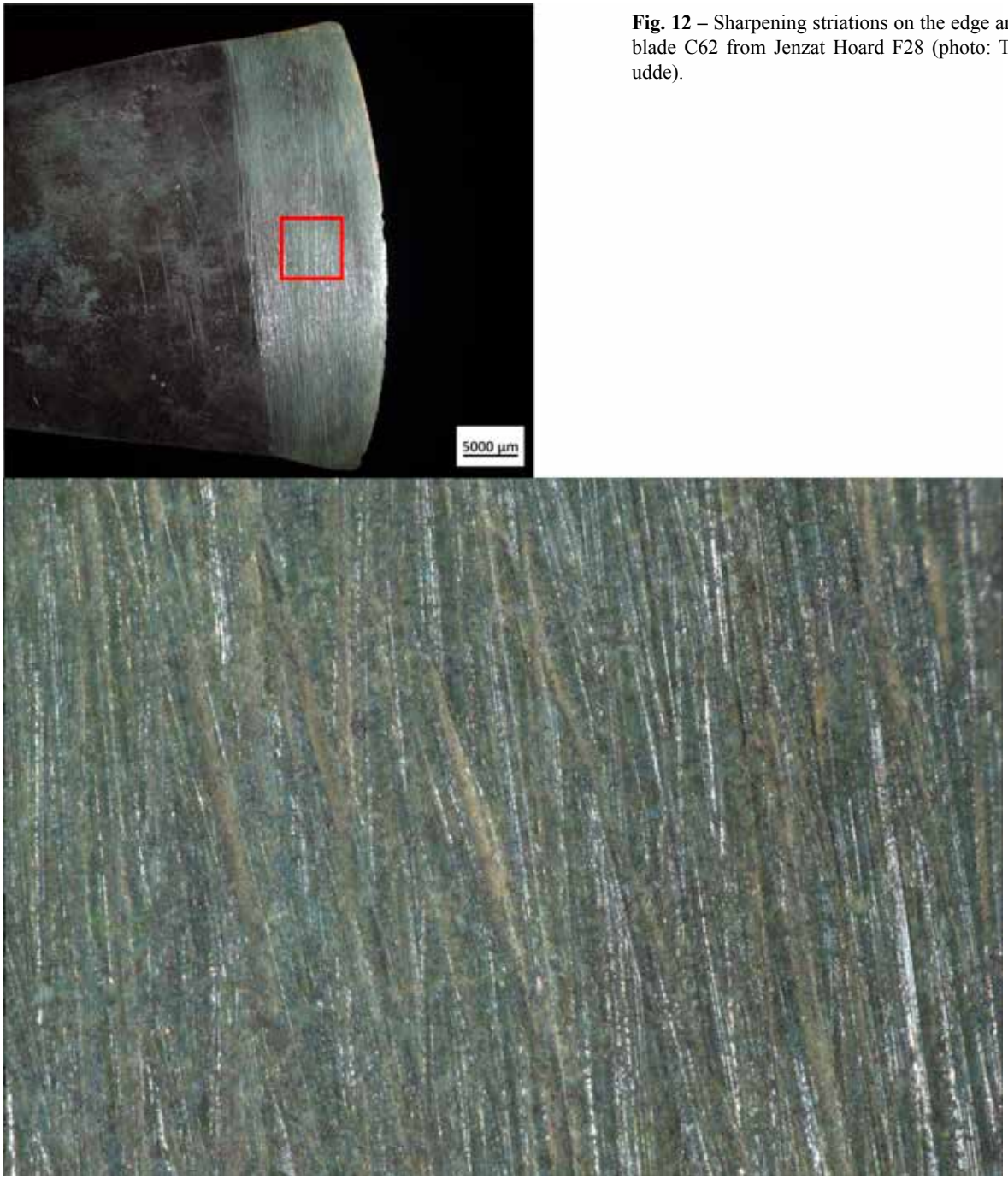


Fig. 12 – Sharpening striations on the edge area of blade C62 from Jenzat Hoard F28 (photo: T. Enudde).

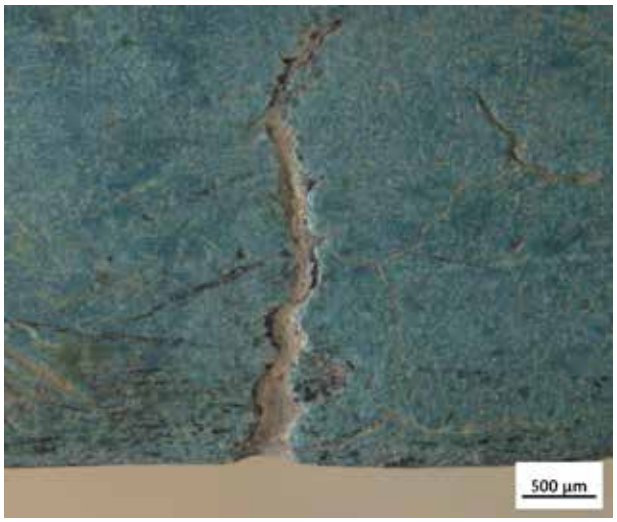


Fig. 13 – Microfracture possibly resulting from bending and hafting on the upper right wing of blade B200 from Jenzat Hoard F17 (photo: T. Enudde).

replacements. These elements can be documented by observing the following traces (the more numerous or pronounced they are, the higher the degree of use). A first group of traces concerns the deformation of the distal part of the blade, directly resulting from maintenance operations (hammering, sharpening, and handle replacement):

– radius of the arc formed by the cutting edge;
– blade flaring;
– asymmetry of the cutting edge;
– pinching ridges;
– asymmetry of the blade profile;
– faring of the wings.

A second group of indicators consists of traces resulting from damage sustained by the object during use:

– blade denting;
– broken ring;
– completely broken wing;
– chipping/denting of the cutting edge;
– notching of the wing edge.

The comprehensive descriptions and illustrations for these traces can be found in Annex 5.

Contributions of the techno-functional approach: a distinct operational sequence and obsolete morphotypological classifications

A clear majority of the blades show traces of use (table 1). Proper identification of these marks is essential in order to distinguish them from traces resulting from the manufacturing process. The techno-functional and use-wear analysis reveals that all 47 axe blades (the winged axe blades as well as the socketed axe blade of the Meldreth type), were objects prepared for functional use. None of them are casting failures or unfinished products. With the exception of blades B315 and B219-222 from Jenzat hoard F17, none of the blades in the corpus have been intentionally broken—that is, deliberately rendered unusable (Knight, 2017). But all these blades had been removed from their hafts before being hoarded, so that they were no longer functional as axes. Traces related to the manufacturing process demonstrate a high level of craftsmanship and care in the production of the axe blades. The rarity and small size of casting defects further confirm this. Additionally, the mould seam line has been particularly meticulously erased across the entire series of axe blades. However, a distinction can be made between different areas of the blades: while the seam line is completely erased on the lower and upper sides of the objects, it remains slightly raised on the ring and proximal section. Notably, these are the areas concealed when the blade is hafted, suggesting that the primary goal of these operations was aesthetic in nature. Finally, casting sprues appear in a "flattened" state on approximately one-third of the blades, with their tops seemingly hammered down (fig. 14). This variation likely results from different hammering techniques used for finishing—either a simple folding down of the sprue stubs or a more thorough levelling to erase the relief. This observation invalidates typological classifications based on the shape of the blade's top, as it appears to depend primarily on finishing operations.

Morphometry and wear index

The techno-functional analysis has also documented sharpening and resharpening marks on the cutting edges. The quasi-stratigraphic observation of these marks (fig. 15) further confirms the recurrent nature of this operation, leading to a significant reduction in blade length over time. Based on these observations, the 45 selected winged blades (excluding blade B315 due to its fragmentary state) were classified according to their Morphometric Wear Index (MWI), from the lowest value (least worn) to the highest (most worn). The MWI ranges from 0.261 to 0.351, with a total spread of 0.090. This classification was then divided into four quartiles of equivalent sample size (table 2). Cross-referencing this distribution with the previously mentioned techno-functional criteria reveals a positive correlation between the level of wear and five qualitative wear-related features (fig. 16): pinching ridges, blade flare, the radius of the arc formed by the cutting edge, cutting edge asymmetry, and blade profile asymmetry. These morphological criteria should therefore be excluded from typological classifications, as they are directly linked to the objects' wear. The full dataset of the morphometric analysis can be found in Annex 1.

3D morphometry: a lead toward new classification criteria?

The acquisition of 3D models of the objects using structured light scanning has enabled cross-sectional observations that revealed morphological features in the 45 studied winged blades which had never been previously considered (fig. 17). The selected sections correspond to areas identified through techno-functional analysis as mostly unaffected by post-casting operations or object wear. These include:

No.	Notch on a wing	Casting defect	Mold line	Casting sprues	Hammering marks	Breakage of the top/socket	Breakage on a wing	Incomplete flashing removal on the ring	Sharpening marks	Edge asymmetry	Radius of the circular arc formed by the cutting edge	Pinch ridges	Asymmetry of the blade profile	Flaring of the blade	Broken ring	Flaring of the wings	Broken wing	Old breakage of the edge (small: <1 to	Old breakage of the edge (medium: >3 to 8 mm)	Old breakage of the edge (big: >8mm)	Use marks	Dent on a side edge of the blade
003	0	0	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	n/a	n/a	n/a	n/a	1
004	0	0	0	1	1	0	1	0	0	1	1	0	0	1	0	1	0	n/a	n/a	n/a	n/a	1
007	0	0	0	1	1	0	1	0	0	0	1	0	0	1	0	0	1	n/a	n/a	n/a	n/a	0
008	1	0	1	1	1	0	1	0	1	1	1	0	0	1	0	0	0	n/a	n/a	n/a	n/a	0
009	0	0	0	0	1	1	0	1	1	1	1	1	1	1	0	1	0	n/a	n/a	n/a	n/a	1
010	1	0	1	1	1	0	1	1	1	0	1	0	0	1	0	0	0	n/a	n/a	n/a	n/a	1
011	0	0	1	1	1	0	1	0	0	1	1	1	1	1	0	0	0	n/a	n/a	n/a	n/a	0
012	0	0	1	0	1	0	1	1	1	1	1	1	0	1	0	1	0	n/a	n/a	n/a	n/a	0
015	0	0	1	0	1	0	1	1	1	1	1	1	0	1	0	0	0	n/a	n/a	n/a	n/a	1
2019.1.3	1	1	1	1	1	0	1	0	0	1	1	1	1	1	0	0	0	1	0	0	n/a	1
5.1.15	0	1	1	1	1	1	1	1	0	1	1	1	1	1	0	0	0	0	1	0	n/a	0
5.1.17	n/c	0	1	0	1	1	0	0	0	1	1	1	0	1	0	1	0	n/a	n/a	n/a	n/a	n/a
5.1.53	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	n/a	0
A08	1	1	1	1	1	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	1
A11	0	0	1	0	1	0	1	1	1	1	1	1	1	1	0	0	1	1	0	0	1	1
B200	1	0	0	1	1	1	1	0	0	1	1	1	0	1	0	0	0	1	1	0	1	1
B201	1	0	1	1	1	0	1	0	1	1	1	1	0	1	0	1	0	1	0	0	1	0
B203	0	0	1	1	1	1	1	0	0	1	1	1	1	1	0	1	0	1	1	0	1	0
B219-B222	0	0	1	1	1	0	1	0	1	0	1	0	0	1	0	1	0	0	1	0	1	1
B315	n/a	0	0	n/a	1	n/a	n/a	n/c	1	0	1	1	0	1	0	n/a	n/a	0	0	1	1	0
B507	0	0	0	0	1	0	1	0	0	1	1	0	0	1	0	0	0	0	0	0	1	1
B513	0	0	1	0	1	0	1	0	0	1	1	1	1	1	0	0	0	1	0	0	1	0
B514	0	0	1	0	1	0	1	0	0	1	1	1	0	1	0	0	0	0	1	0	1	1
B515	0	0	1	1	1	0	1	0	1	1	1	1	0	1	0	1	0	0	0	0	1	0
B516	1	0	1	1	1	0	1	0	1	1	1	1	0	1	0	0	0	1	1	0	1	0
B517	1	0	0	1	1	0	1	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0
B527	1	0	0	1	1	0	1	0	1	1	1	1	0	1	0	1	0	1	1	1	1	0
B540	1	0	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
C62	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
C63	1	0	1	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
C64	1	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	1	0	1	1
C65	0	0	1	1	1	0	1	0	0	1	1	1	0	1	0	0	0	0	1	0	1	1
C66	0	0	1	1	1	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0
C67	1	1	1	0	1	0	1	0	1	0	1	1	0	1	0	1	0	1	1	1	1	0
C68	1	0	1	0	1	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0
C69	0	0	1	1	1	0	1	0	1	1	1	1	1	1	0	1	0	1	0	0	1	0
C70	n/c	0	1	n/c	1	1	n/c	0	1	0	1	0	0	1	0	n/c	n/c	0	0	0	0	0
D304	0	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	1	0	0	0	1	0
D321	0	0	1	1	1	1	0	1	1	0	0	1	1	1	0	0	0	0	0	0	1	1
D357	0	0	1	0	1	0	1	1	1	0	0	1	1	0	0	0	0	0	0	0	1	0
E320	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	0	0	1	0
E330	0	1	1	1	1	0	0	0	1	1	1	0	1	1	0	0	0	0	0	0	1	1
E333	0	1	1	0	1	0	1	1	0	1	0	0	1	1	0	0	0	0	0	0	1	1
E378	0	0	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	1	0	0	1	1
E382	1	1	1	1	1	0	0	0	1	0	1	1	1	1	0	0	0	0	0	0	1	1
E384	0	0	1	1	1	0	1	1	1	1	0	0	0	0	0	0	0	1	0	0	1	1
E58	0	1	1	1	1	0	1	1	1	1	1	1	0	1	0	0	0	1	0	0	1	0
Total (47)	**15**	**10**	**38**	**31**	**47**	**12**	**37**	**17**	**31**	**29**	**33**	**27**	**13**	**36**	**0**	**14**	**4**	**15**	**10**	**3**	**27**	**20**

Table 1 – Summary of all operational sequence and use-wear traces observed on the objects.

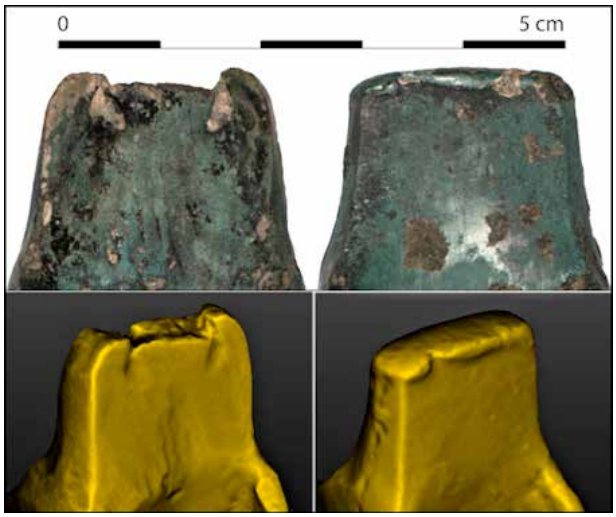


Fig. 14 – Comparison of the tops of winged blades C66 (left) and C67 (right), both from Jenzat Hoard F28 (photo: T. Enudde). The 3D model of C67 clearly shows the metal ridge resulting from hammering during finishing.

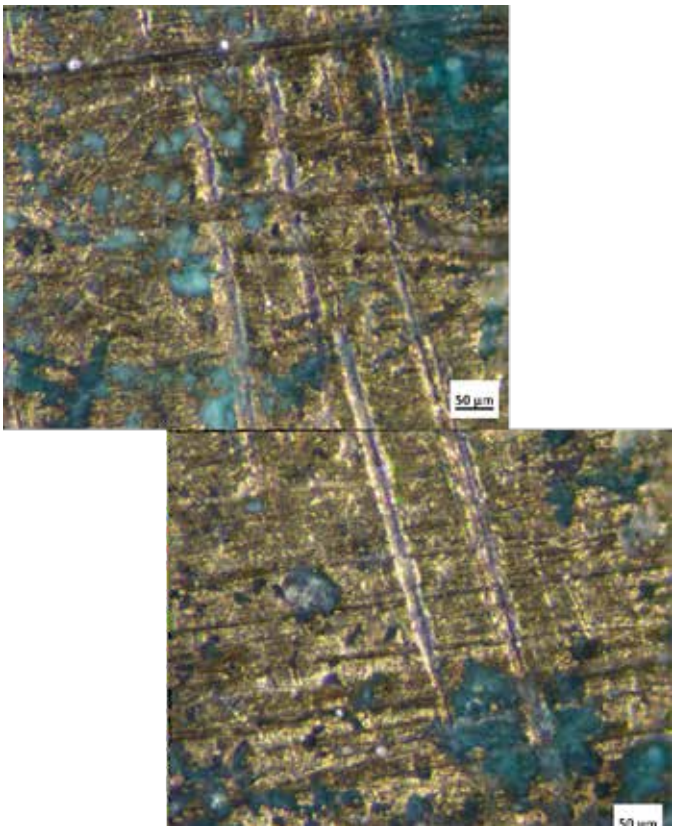


Fig. 15 – Sharpening striations on blade B219-222 from Jenzat Hoard F17, intersecting (bottom panel) and being intersected by (top panel) use-related scratches (photo: T. Enudde). This observation identifies at least three phases in the object's lifecycle: an initial sharpening, followed by use, and then a resharpening.

No.	Morphometric Wear Index	Quartile
D357	0.261	1st quartile
E320	0.279	
C64	0.286	
C63	0.287	
C68	0.287	
C62	0.289	
C66	0.289	
A08	0.290	
E333	0.293	
B219-222	0.293	
E330	0.295	
B540	0.295	2nd quartile
B517	0.296	
009	0.299	
B527	0.300	
5.1.53	0.300	
B515	0.301	
C69	0.302	
D321	0.304	
015	0.305	
007	0.307	
E382	0.307	
012	0.308	3rd quartile
004	0.308	
003	0.309	
C67	0.313	
010	0.315	
B514	0.315	
C65	0.316	
008	0.317	
D304	0.318	
011	0.318	
E384	0.319	
2019.1.3	0.320	4th quartile
B513	0.320	
B516	0.322	
B507	0.324	
B203	0.325	
B200	0.329	
5.1.17	0.334	
E58	0.336	
E378	0.337	
5.1.15	0.337	
A11	0.348	
B201	0.351	

Table 2 – Distribution of the 45 winged axe blades according to their Morphometric Wear Index (MWI).

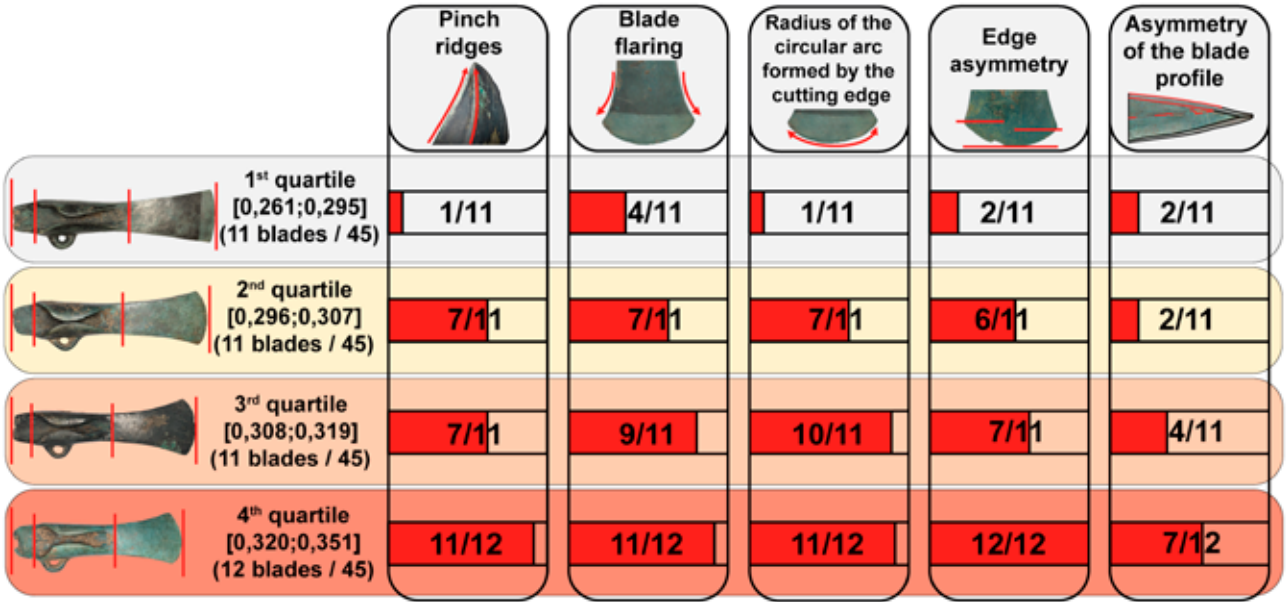


Fig. 16 – Correlation between MWI and morphological criteria related to wear (CAD: T. Enudde).

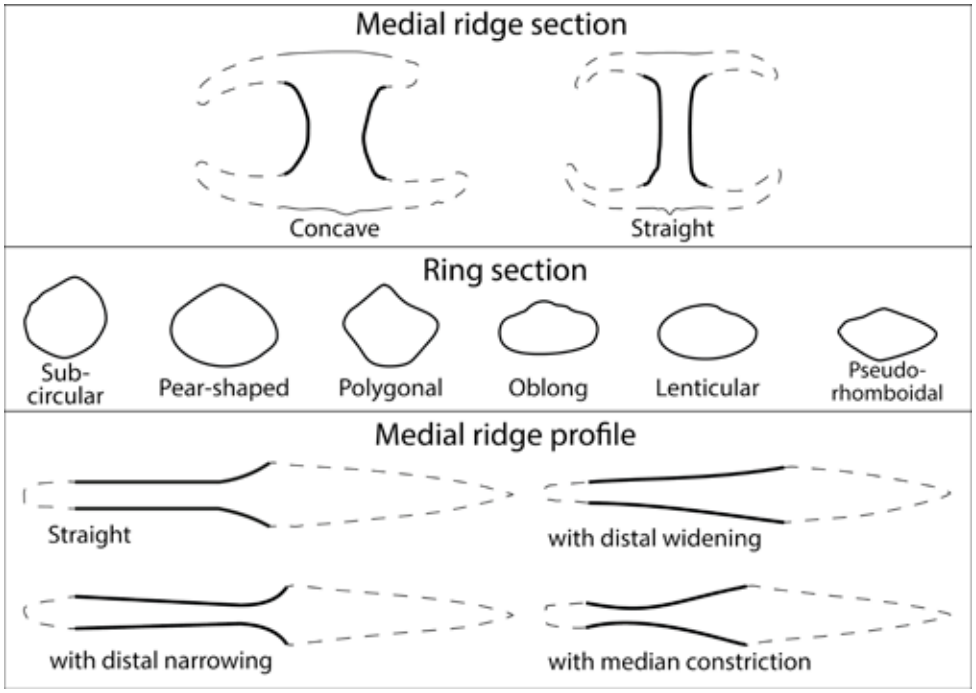


Fig. 17 – New morphological criteria for classifying subterminal winged axe blades (CAD: T. Enudde).

– the section of the ring, which can take on a more rounded shape (sub-circular, pear-shaped, or polygonal) or a flatter shape (oblong, lenticular, or pseudo-rhomboidal);

– the cross-section of the medial ridge, where the faces can be either concave or straight;

– the profile of the medial ridge, which can be straight, with distal widening, with distally narrowing, or with a median constriction.

These features are not evenly represented within the series. The section of the ring (fig. 18) is most commonly pear-shaped. This is followed by polygonal and sub-circular forms, then oblong and pseudo-rhomboidal shapes, with the lenticular form being the least represented. For the cross-section of the medial ridge (fig. 19), the concave shape is overwhelmingly dominant compared to the straight shape. Finally, the profile of the medial ridge (fig. 20) is most frequently with a median constriction or straight, while distal widening and distal narrowing shapes are less common. 3D morphometry has identified six groups of 'twin' blades (14 blades in total), as they exhibit a similarity threshold of 95% or more and an average distance below 360 µm. This strongly suggests that the blades within each group were produced

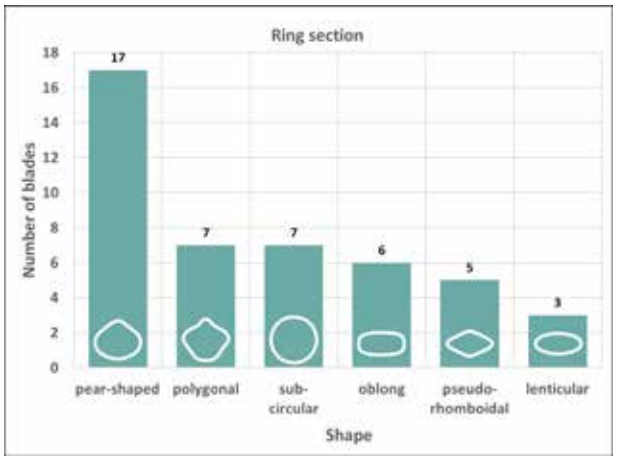


Fig. 18 – Distribution of the different ring section shapes (T. Enudde). Total sample: 45.

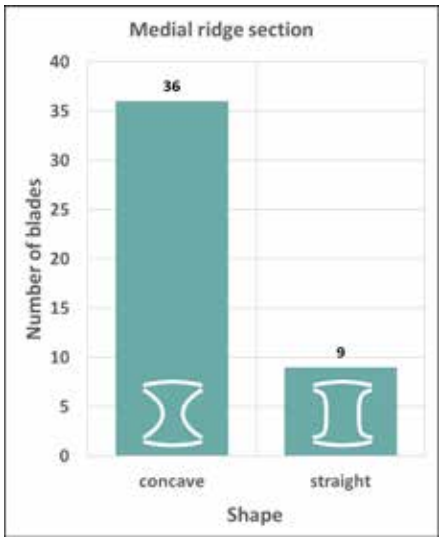


Fig. 19 – Distribution of the different cross-sectional shapes of the medial ridge (T. Enudde). Total sample: 45.

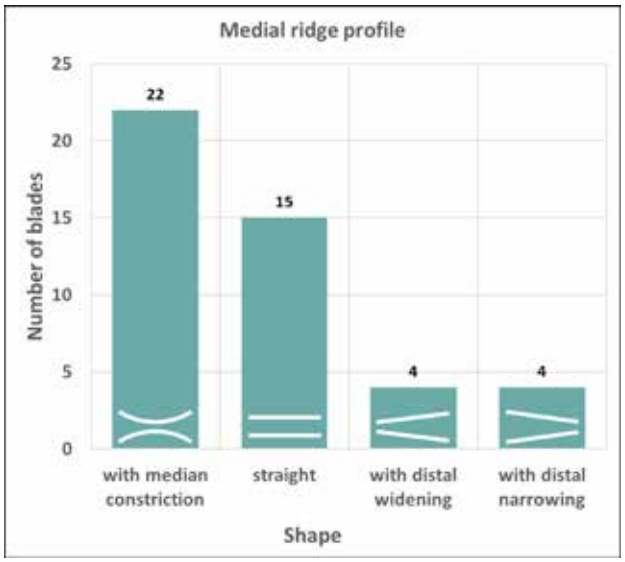


Fig. 20 – Distribution of the different medial ridge profile shapes (T. Enudde). Total sample: 45.

using the same model or more probably cast from the same mould (fig. 21). Morphologically, the profiles of the twin blades identified through 3D morphometry align very well. As theoretically expected, the areas exhibiting variability are:

– the wings, which depend on the shape of the haft and are therefore not significant;

– the top of the blade, which is influenced by the casting and shaping process;

– the cutting edge and the distal part of the blade, which are directly affected by wear;

– the ring of blade 5.1.17, which differs from that of B507 due to an impact.

Although it would be tempting to further refine the grouping of similar blades, we will refrain from doing so at this stage due to the lack of a more diverse comparative corpus. The four twin blades in Group 1 (C62, C63, C66, and C68, all from Jenzat Hoard F28) share a concave-sectioned medial ridge with a distally narrowing profile (the only blades in the corpus exhibiting this feature) and a pear-shaped ring section (fig. 22). A distinct constriction is visible below the distal ends of the wings, aligning with continental models as described by F. Bordas. The two twin blades in Group 2 (A08 from Jenzat Hoard F4 and B219-222 from Jenzat Hoard F17) feature a concave-sectioned medial ridge with a straight profile and a polygonal-sectioned ring (fig. 23). A constriction is also visible beneath the distal ends of the wings, though it is less pronounced than in Group 1. The two twin blades in Group 3 (C69 from Jenzat Hoard F28 and D321 from Jenzat Hoard F55) share a concave-sectioned medial ridge with a straight profile and a pear-shaped ring section (fig. 24). No significant constriction is observed in their outline; however, these two blades display notable differences in the regularization of the top. The two twin blades in Group 4 (B507 from Jenzat Hoard F14 and 5.1.17 from the Charroux hoard) exhibit a concave-sectioned medial ridge with a medially constricted profile and a sub-circular ring section (fig. 25). Once again, the silhouette constriction is minimal. The identification of twin blades from two sites several kilometres apart is a unique occurrence. It is worth recalling that blade 5.1.17 from the Charroux hoard was discovered in 1861 (Tudot, 1861). The two twin blades in Group 5 (C65 from Jenzat Hoard F28 and E378 from Jenzat Hoard F55) have a concave-sectioned medial ridge with a straight profile and a pseudo-rhomboidal ring section (fig. 26). Their silhouette lacks any constriction, a characteristic of Atlantic models according to the observations of F. Bordas. Finally, the two twin blades in Group 6 (B201 from Jenzat Hoard F17 and E58 from Jenzat Hoard F82) possess a straight-sectioned medial ridge with a medially constricted profile and a pear-shaped ring section (fig. 27). No constriction of the silhouette typical of continental models is observed. Based on these findings, it can be determined that the 45 analysed winged axe blades originate from 37 different moulds or models. The full dataset for the 3D morphometry analysis, the mean-distance table, can be found in Annex 2.

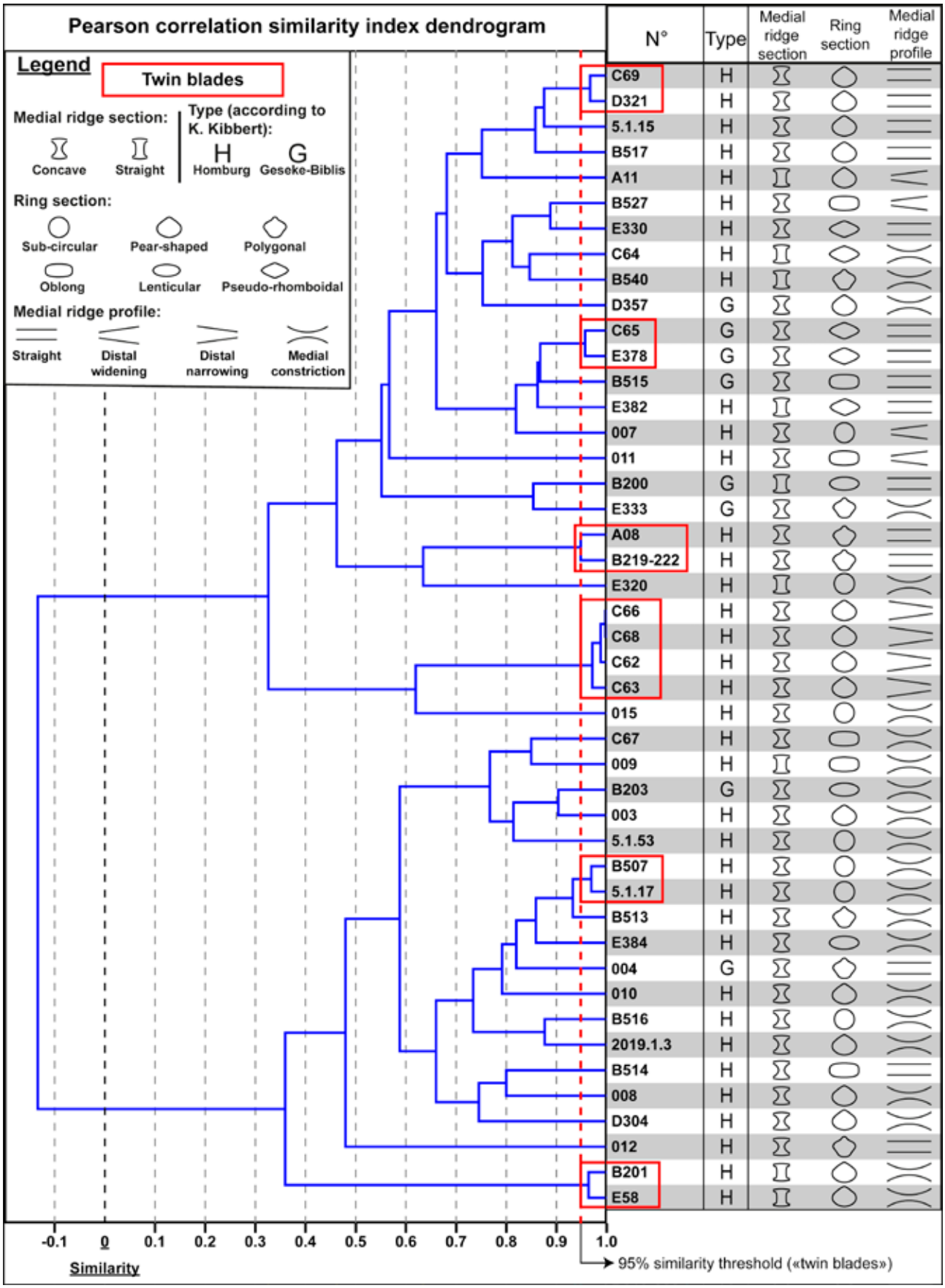


Fig. 21 – Similarity dendrogram of the 45 winged axe blades based on 3D morphometry (T. Enudde).

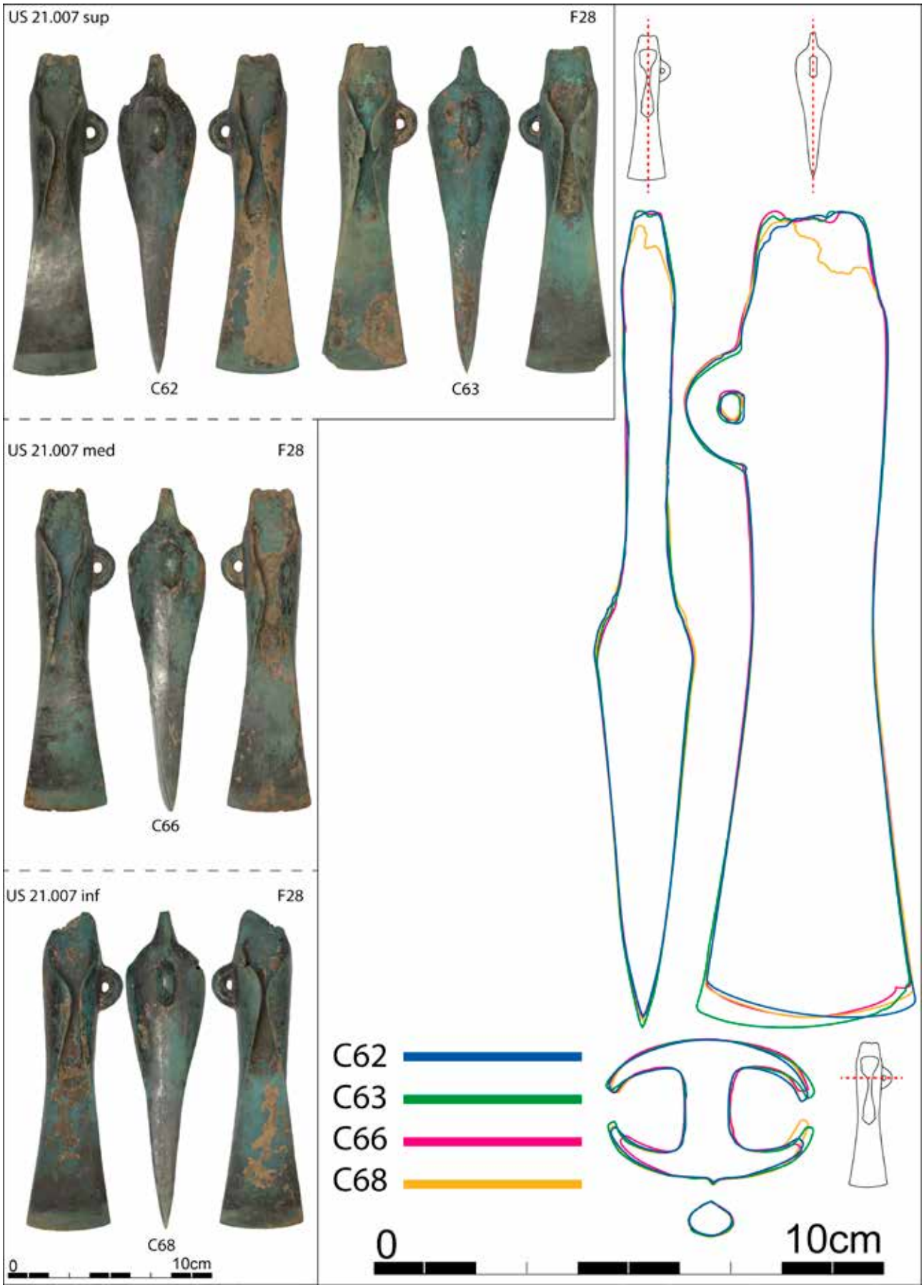


Fig. 22 – Group 1: Superimposed profiles and sections of the four twin blades C62, C63, C66, and C68 from Jenzat Hoard F28 (T. Enudde).

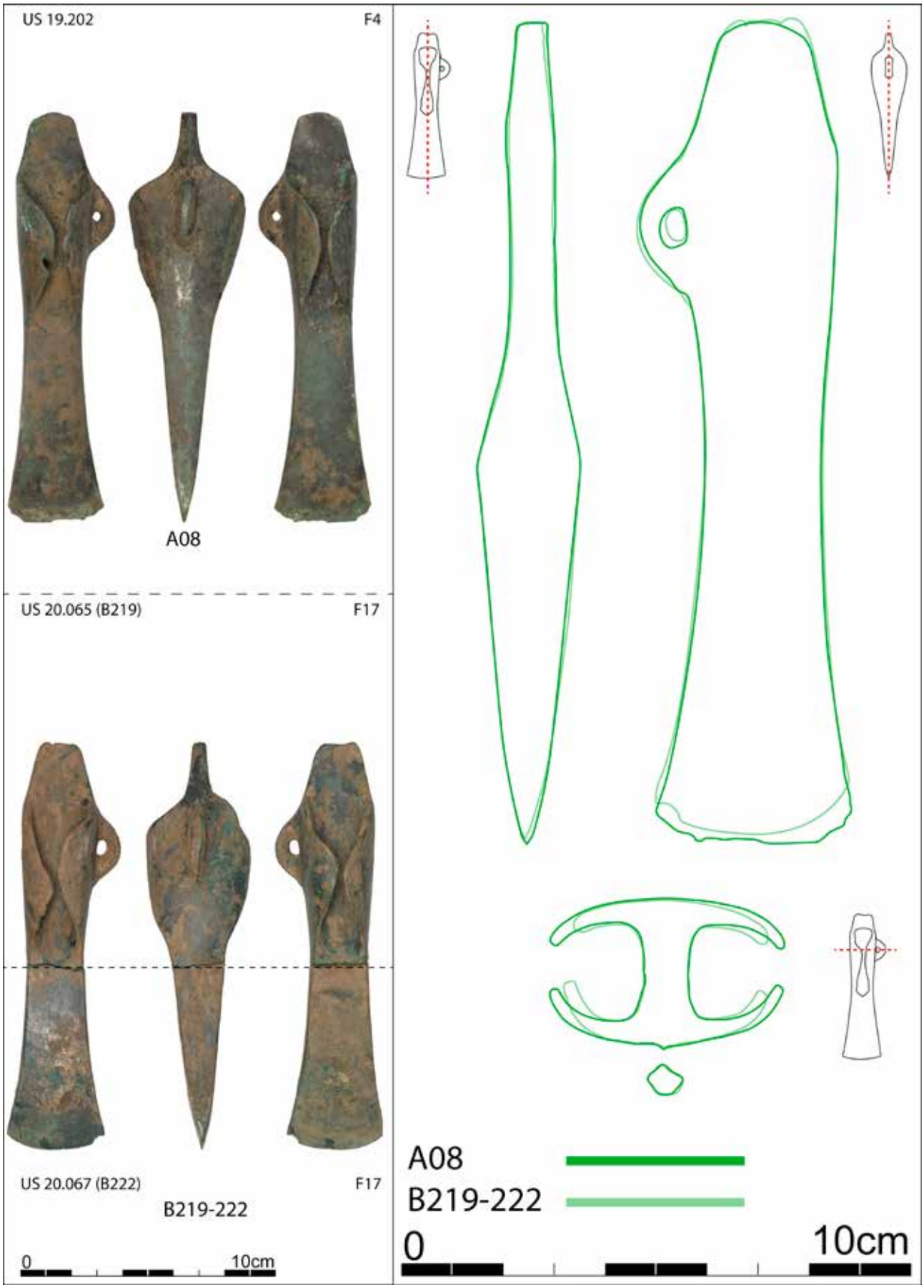


Fig. 23 – Group 2: Superimposed profiles and sections of the twin blades A08 from Jenzat Hoard F4 and B219-222 from Jenzat Hoard F17 (T. Enudde).

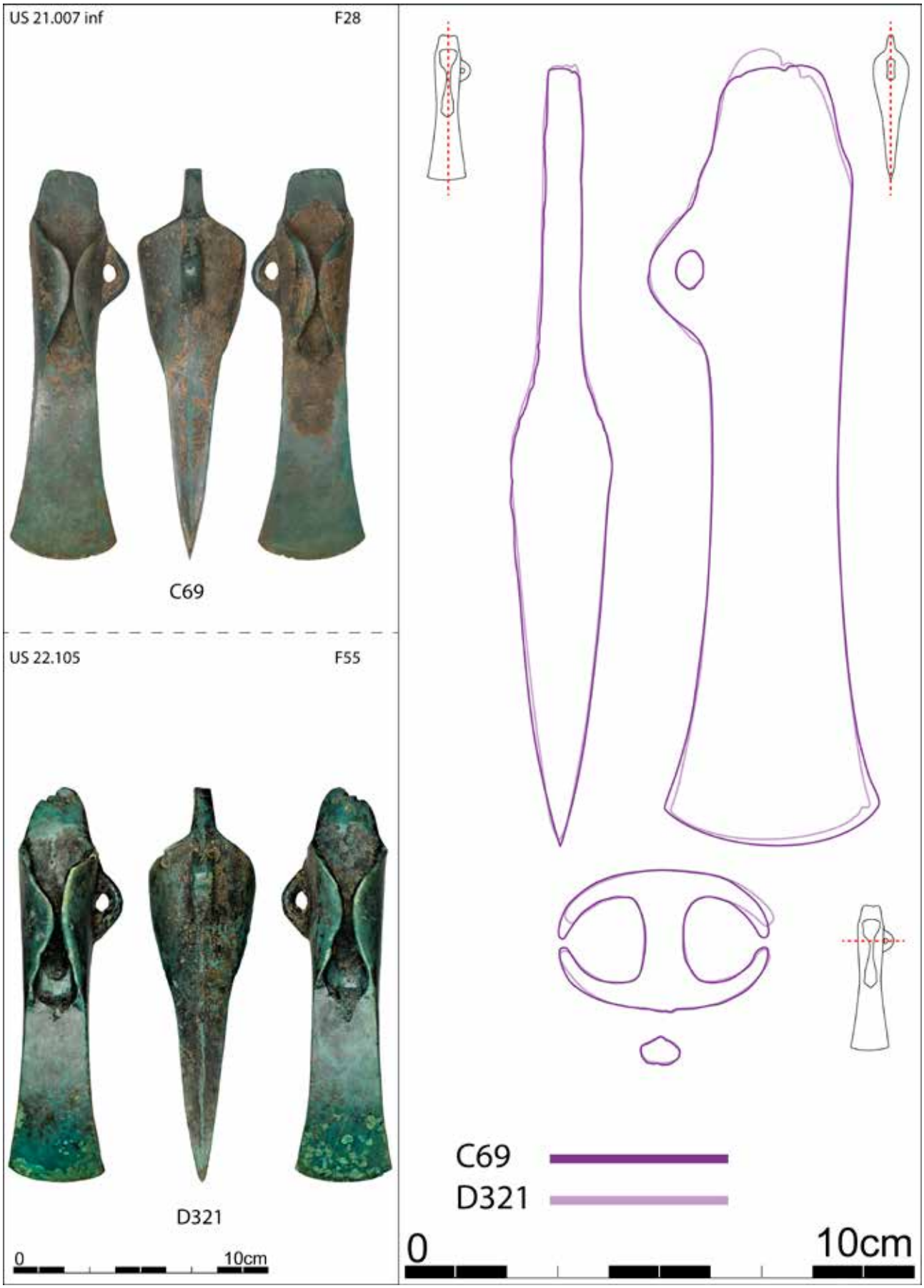


Fig. 24 – Group 3: Superimposed profiles and sections of the twin blades C69 from Jenzat Hoard F28 and D321 from Jenzat Hoard F55 (T. Enudde).

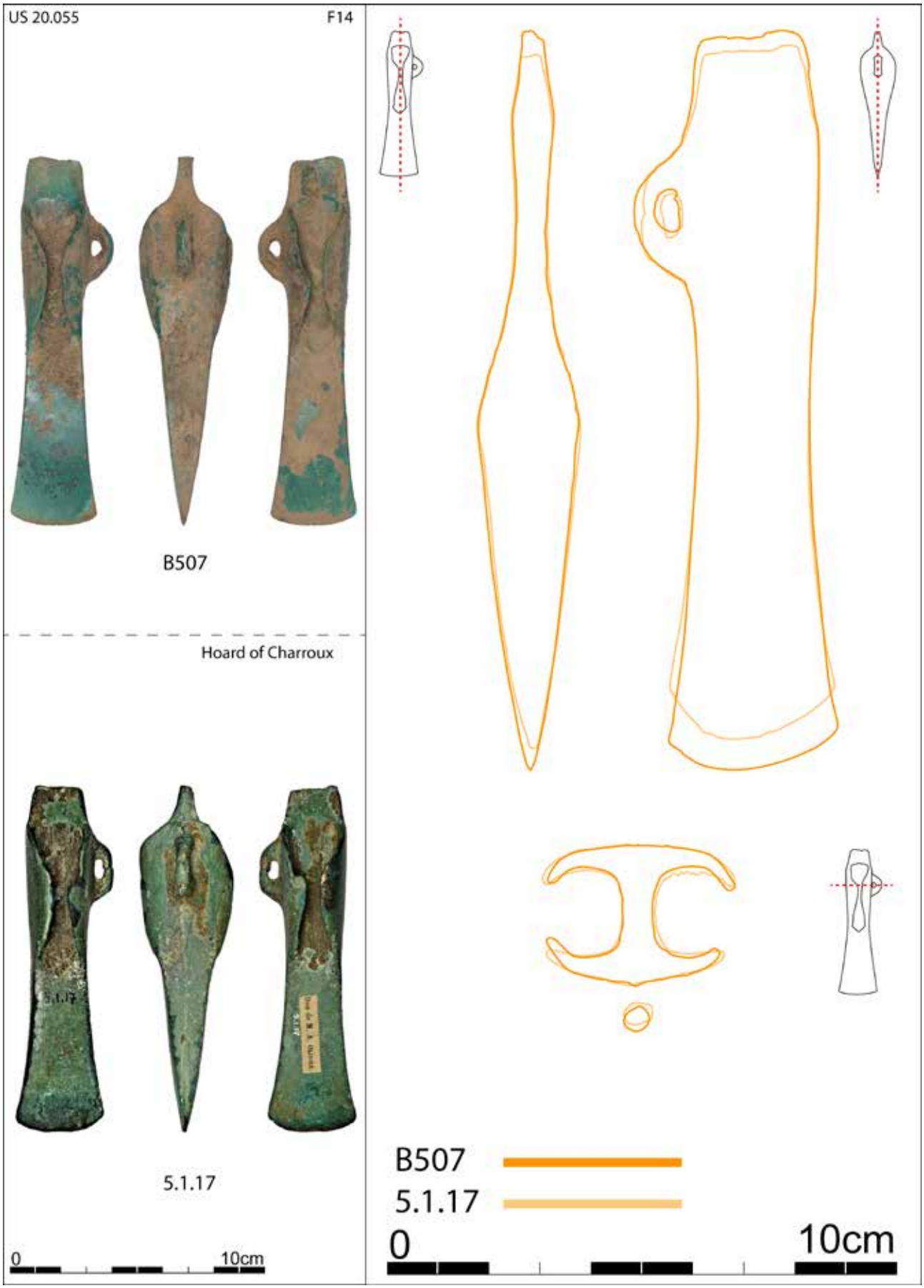


Fig. 25 – Group 4: Superimposed profiles and sections of the twin blades B507 from Jenzat Hoard F14 and 5.1.17 from the hoard of Charroux (T. Enudde).

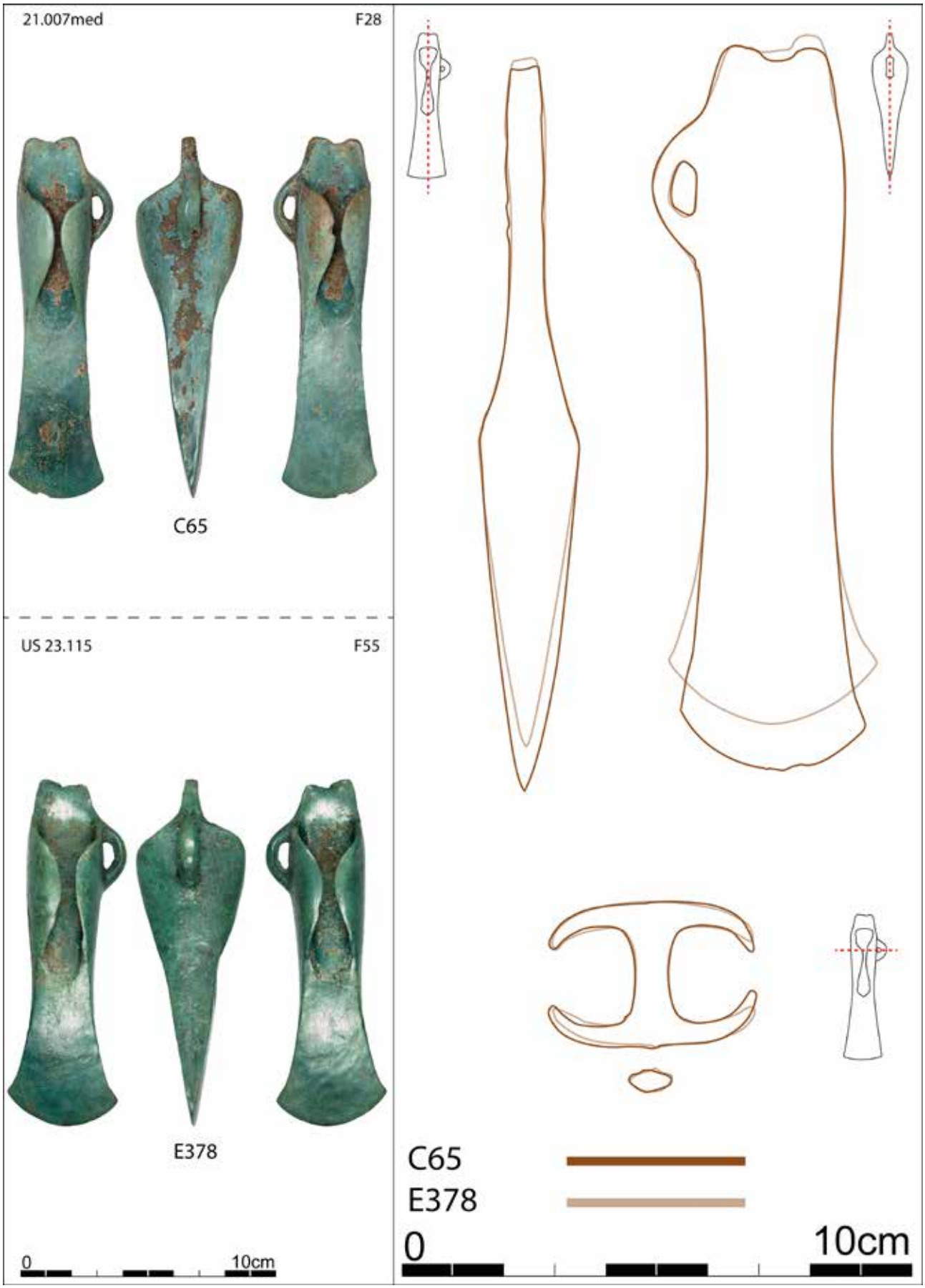


Fig. 26 – Group 5: Superimposed profiles and sections of the twin blades C65 from Jenzat Hoard F28 and E378 from Jenzat Hoard F55 (T. Enudde).

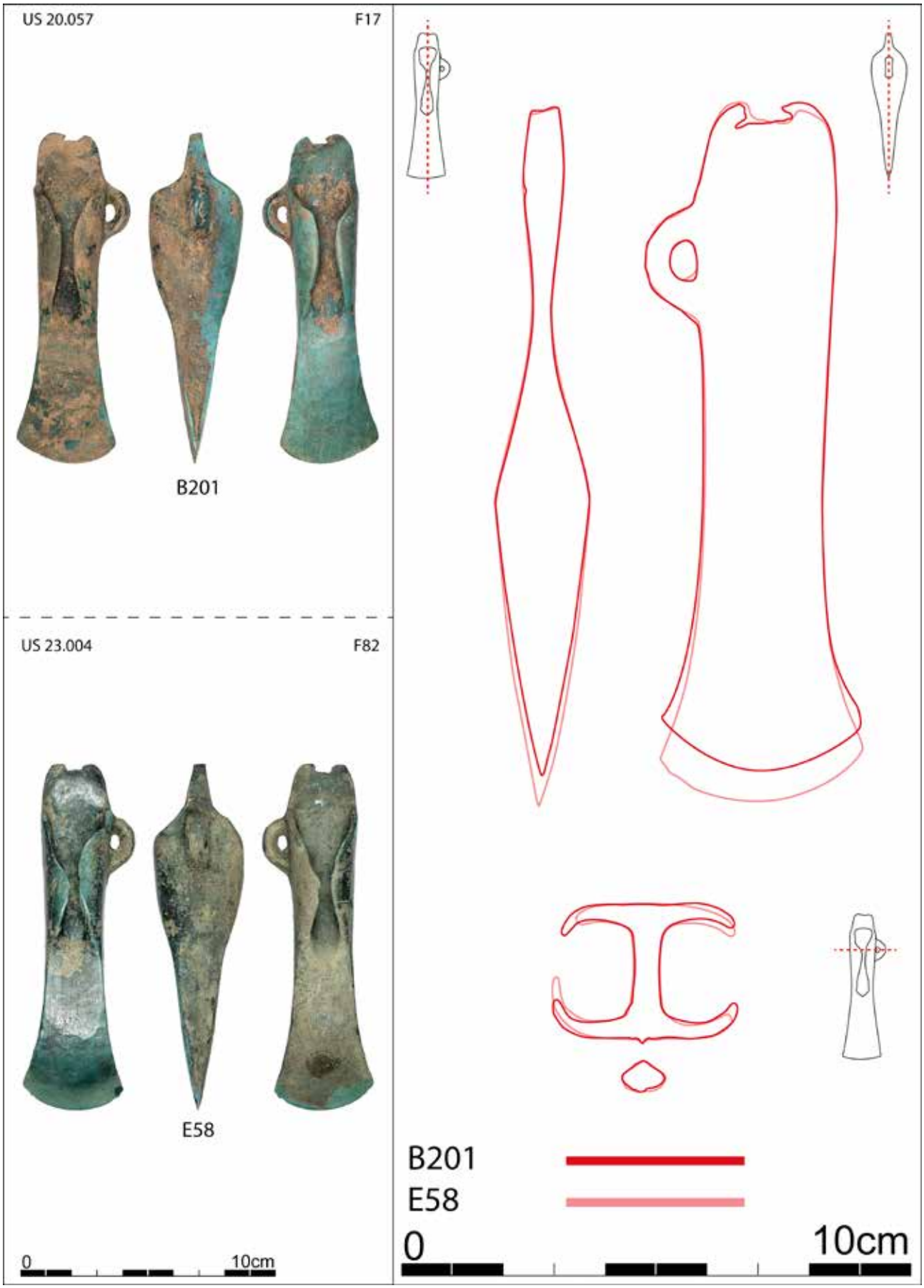


Fig. 27 – Group 6: Superimposed profiles and sections of the twin blades B201 from Jenzat Hoard F17 and E58 from Jenzat Hoard F82 (T. Enudde).

Multi-element analysis: alloying elements

Different alloy types

The study of the main elements considers the tin (Sn) and lead (Pb) content. Given that lead concentrations range from 1.8% to 10.1%, it is highly likely that lead was intentionally added to the alloy (Rychner and Kläntschi, 1995; Mille and Bourgarit, 2000). This hypothesis is supported by the absence of correlation between lead content and the levels of various impurities (fig. 28; Ni/Pb $r^2 = 0.065$; As/Pb $r^2 = 0.16$; Ag/Pb $r^2 = 0.102$; Sb/Pb $r^2 = 0.100$; Bi/Pb $r^2 = 0.177$). Furthermore, this lack of correlation indicates that impurities introduced by lead are negligible compared with those present in copper (the same applies to tin). The overall Sn content (fig. 29) is characterized by an average of 8.4% (median: 8.6%), but the distribution splits into two groups. The first, the majority group, has an average content of 9.0% (median: 8.7%) and includes 35 blades out of 40. The second, much smaller, group shows a significantly lower average of 4.9% (median: 5.2%) and includes only 5 blades out of 40. The overall Pb content (fig. 30) is characterized by an average of 4.7% (median: 4.4%). Here again, the distribution is bimodal. The first, majority, group has an average content of 4.1% (median: 4.1%) and includes 35 blades out of 40. The second, much smaller, group has a higher average of 8.7% (median: 8.3%) and includes 5 blades out of 40. The groups distinguished for each element do not match each other, which complicates the understanding of the variability of the main element contents. The cumulated distribution of the alloying elements content (Sn and Pb) within the series seems to distinguish three different types of alloys. In all cases, these are ternary Cu-Sn-Pb alloys, characterized by varying proportions of these elements. Indeed, the distribution of the cumulative Sn and Pb contents (fig. 31) shows a considerable variability from 6.2% to 21.4%, with an average

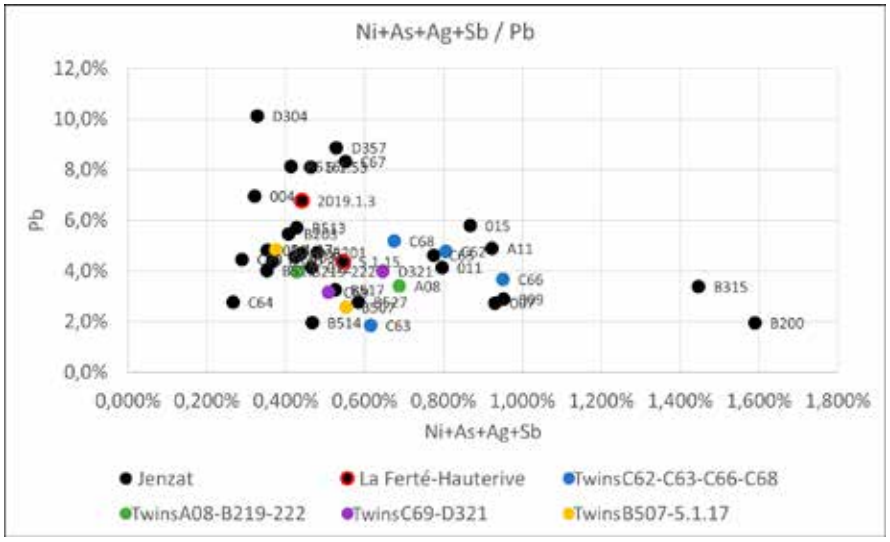


Fig. 28 – Comparison of Pb content and impurity levels in Ni, As, Ag, and Sb (T. Enudde). The graph shows no correlation between the Pb content and the impurities.

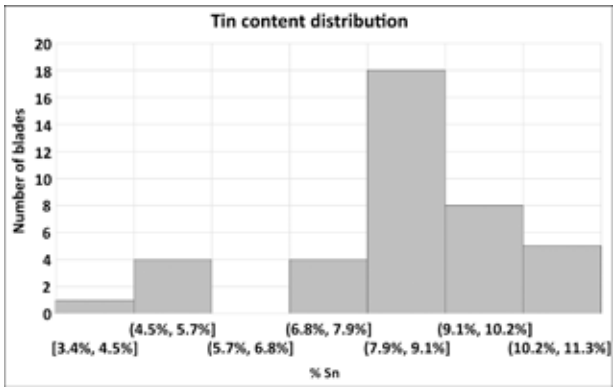


Fig. 29 – Distribution of Sn content showing an uneven bimodal distribution (T. Enudde).

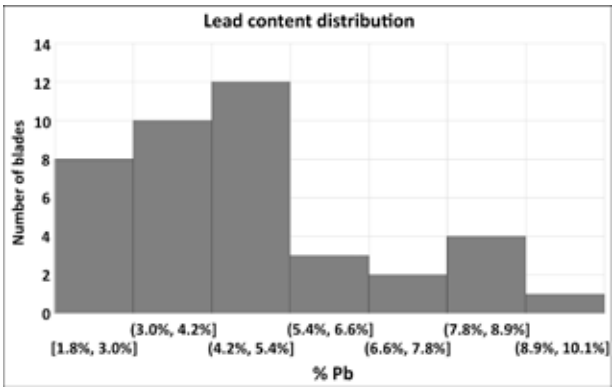


Fig. 30 – Distribution of Pb content showing an uneven bimodal distribution (T. Enudde).

of 13.1 % (median: 13.0 %) . A bivariate tin-lead diagram was plotted to better understand this distribution (fig. 32). This diagram confirms the previously stated trends while clearly distinguishing three types of leaded bronzes:

– type 1, with low alloying levels (4 %–6 % tin and 2 %–4 % lead), includes 5 out of 40 blades;

– type 2, which comprises the majority of the blades (28 out of 40), is characterized by moderately tin-rich bronzes (8 %–10 %) with consistently low lead levels (2 %–6 %);

– type 3 includes the highest lead concentrations (6 %–10 %), and it is also within this group that the highest tin levels are found (8 %–12 %).

Although all three types correspond to leaded bronzes, the observed lead content remains relatively low compared to the concentrations typically found

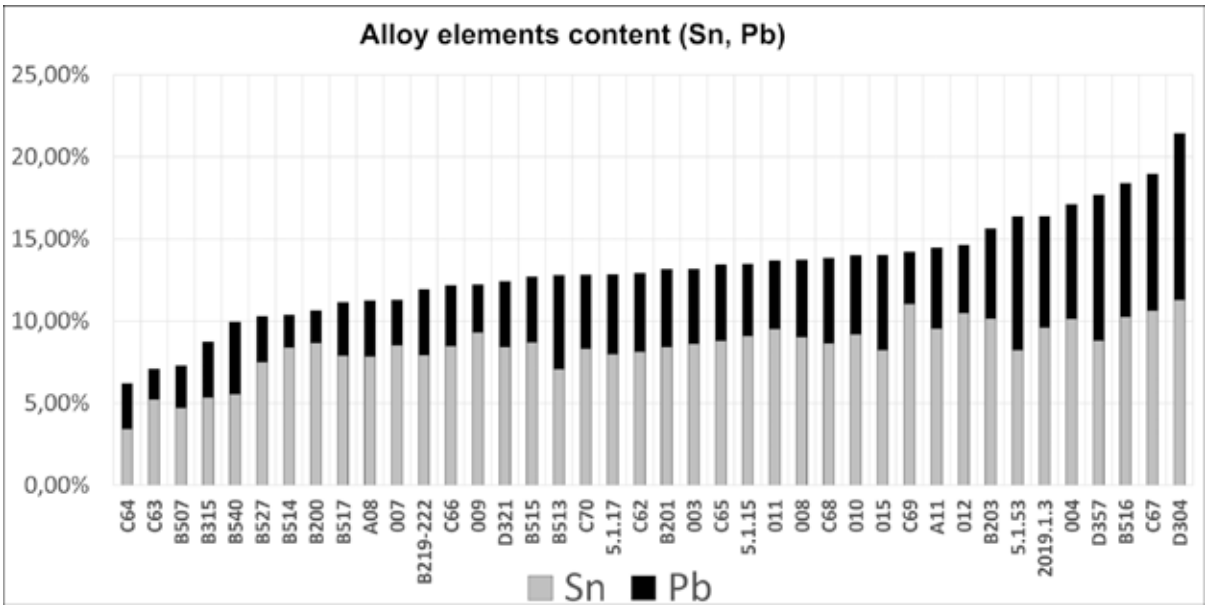


Fig. 31 – Distribution of cumulative alloy element contents within the series (T. Enudde), showing a rather significant variability.

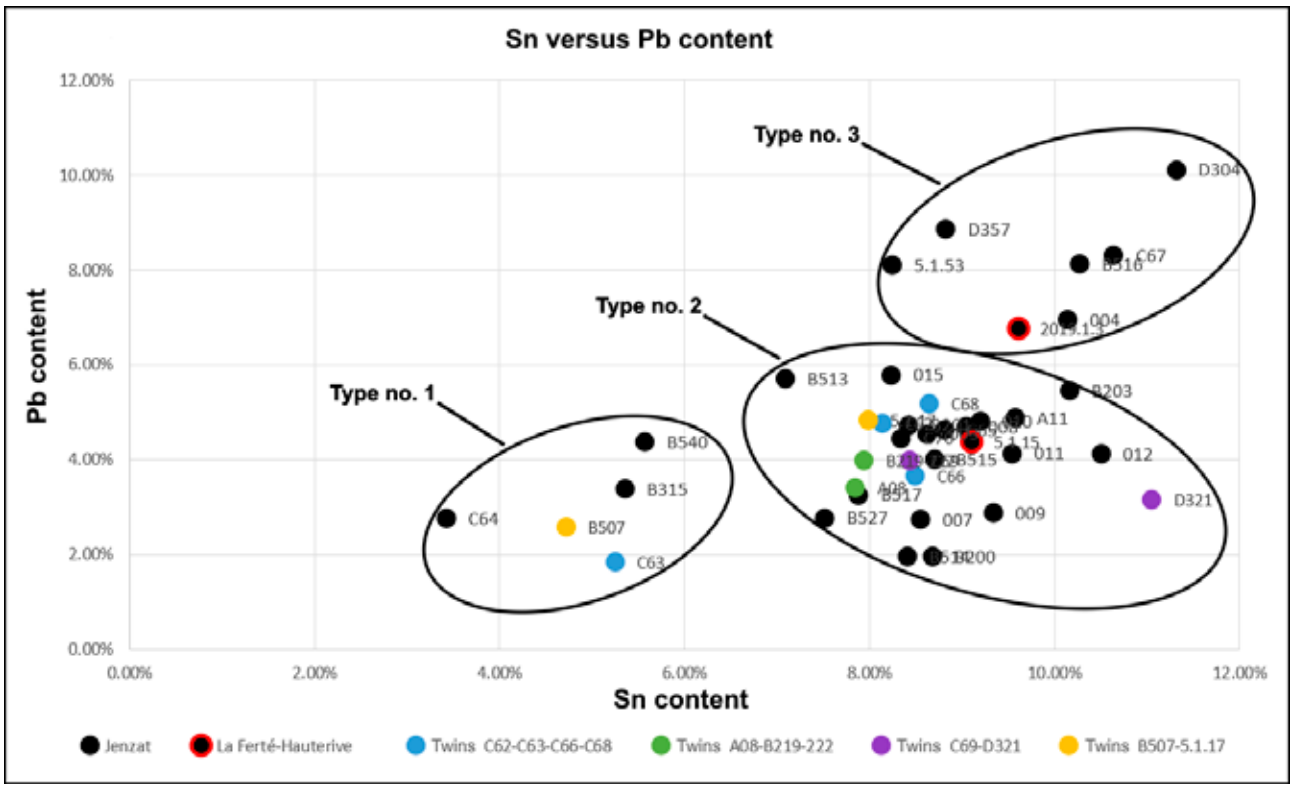


Fig. 32 – Bivariate diagram of Sn and Pb concentrations showing 3 different types of leaded bronzes (T. Enudde).

in Atlantic LBA artefacts from northern and western France (Bourgarit and Mille, 2014; Le Carlier and Révillon, forthcoming).

Same model or mould, different metals?

The most significant result from the distribution of the alloying elements concerns the twin blades: it is noticeable that some of them belong to different alloy types. This observation suggests that there was apparently no strict control over the homogeneity of the alloys used. It implies that a given manufacturer could use different types of alloys to produce multiple copies of an axe blade, or that the same mould was used by multiple manufacturers, using different alloy types. So far, no evidence allows us to select either possibility. A functional hypothesis could also be proposed: these might be identical blades but intended for distinct functions; however, this conjecture appears rather unlikely as no evidence supports it. This raises the issue of who controlled the metal supply: apart from the artisan himself, it may have been the commissioner who provided the metal, or a third party who regulated access to it (fig. 1, model 2). These three hypotheses are not necessarily mutually exclusive: one could easily picture a scenario where both hypotheses coexist in a more complex manner than the methodology employed in this study can capture.

Multi-element analysis: copper impurities

A continental tropism: a likely exploitation of fahlores

The study of trace elements, based on the impurity levels measured in the objects of the series, has allowed us to refine several aspects of metal production, particularly copper. Unlike the alloying elements, the series appears remarkably homogeneous in this regard. The average cumulative impurity level of copper is 0.82 % (median: 0.70 %). Among the 9 elements considered in the study, Fe (average: 0.013 %), Co (average: 0.025 %), Zn (average: 0.012 %), and Bi (average: 0.011 %) show the lowest values (except for a few outliers), while S (average: 0.161 %), Ni (average: 0.126 %), As (average: 0.176 %), Ag (average: 0.079 %), and Sb (average: 0.218 %) present the highest values (fig. 33). The presence of multiple metallic elements in high concentrations (specifically S, Ni, As, Ag, and Sb) most likely indicates the use of sulphidic copper ores of the fahlore type: various copper sulpharsenides and sulphantimonides (Mille and Bourgarit, 2000). However, a mixture with small amounts of another type of ore or the use of recycled metal cannot be entirely ruled out without a much more detailed study.

Some statistical outliers

While the trace element levels in the study are generally remarkably homogeneous, a few exceptions can still be noted:

– blade B517 has an abnormally high Zn content, which could be explained by a difference or error in ore sorting methods;

– blades B507 and B514 have relatively high As and Ag contents, while their Ni and Sb contents are relatively low; additionally, B514 has an exceptionally high S content;

– the twin blades D321 and C69 have exceptionally high Ni contents;

– finally, blades B315 and B200 are outliers regardless of the element considered

Overall, the observed variability is not particularly significant. The presence of a few abnormal contents

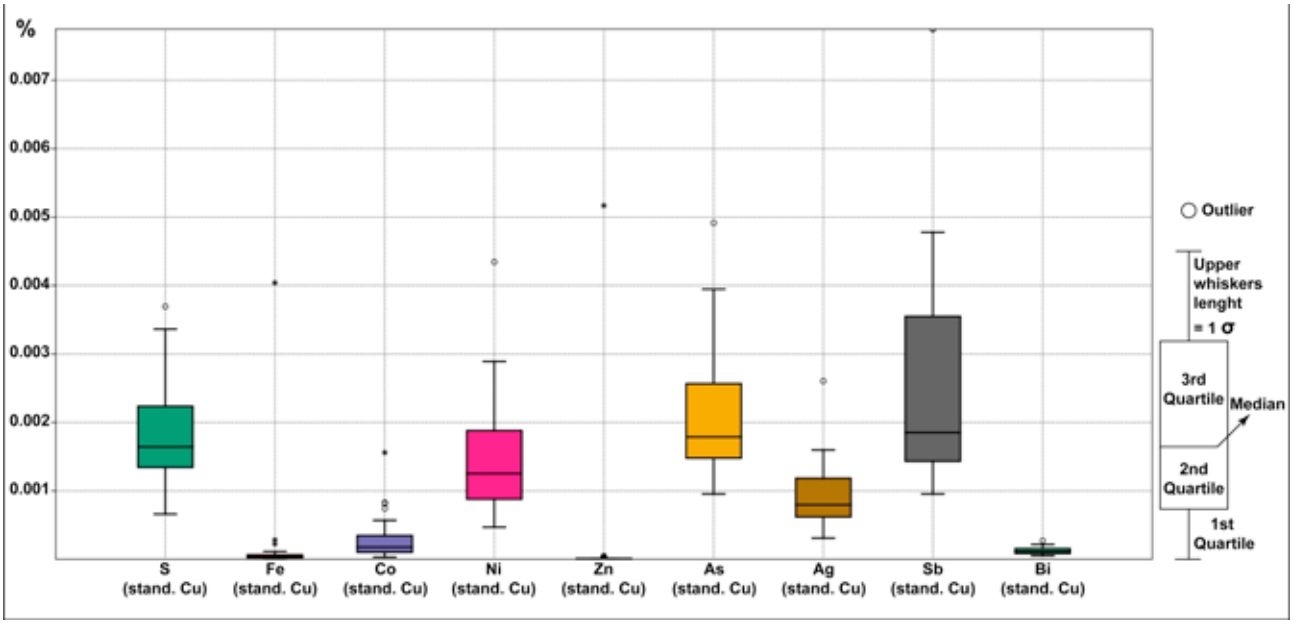


Fig. 33 – Boxplot of the impurities in copper measured with ICP-MS-MS (T. Enudde).

for one or two elements in a small number of objects is expected and can have many causes: objects from a different metallurgical tradition (imported?), 'pollution' of a portion of the local metal stock by the recycling of foreign objects, changes in metal composition over time (Mille and Bourgarit, 2000; Le Carlier de Veslud et al., 2017). The full dataset for multi-element analysis can be found in Annex 3.

DISCUSSION

The issue of copper provenance: a remarkably homogeneous stock

The multi-element analyses of the axe blades in the corpus revealed a remarkable homogeneity in the impurity profile of this metal. The elements with the highest concentrations (S, Ni, As, Ag, and Sb) are typical of the western part of the continental cultures at the end of the Bronze Age. It can thus be assumed that the type of mineralization exploited is similar. The hypothesis of an exploitation of fahlore copper from the Alpine region has been suggested, but without certainty (Rychner and Kläntschi, 1995; Véber, 2009). Isotopic analyses are underway to attempt to address the question of the more precise origin of the raw materials. Moreover, good correlations were found between the concentrations of the main trace elements in the studied objects. This indicates homogeneity in copper supply. The blades showing out-of-norm concentrations for one or two chemical elements do not challenge the overall homogeneity of the series (Mille and Bourgarit, 2000; Le Carlier de Veslud et al., 2015).

Bourbonnais and Sarre-Lorraine: distinct metal circulation areas within the continental domain?

To further clarify the question of how metal stocks were formed, a comparison with a reference corpus was made. The axe blades from Sarre-Lorraine analysed by C. Véber during her doctoral thesis (2009) were selected because they also belong to the western part of the continental cultural area, and the types of deposits exploited seem to match at first glance. Additionally, since these analyses were also carried out at the C2RMF, their comparability is ensured. A Principal Component Analysis was performed by including the copper impurity levels of the axe blades from our series along with those from Sarre-Lorraine (fig. 34). The result shows a notable difference, in terms of both signature and homogeneity. Higher average impurity levels are observed in the Sarre-Lorraine objects, particularly concerning As and Sb. Although comparing the production of an entire region to that of a single site (Jenzat and its surroundings) is relatively irrelevant, this observation still seems valid since each of the hoards from the Lorraine or Saarland corpus shows more variability than the entire set of axe blades from the Jenzat hoards, excluding blades B200, B315 and B514. This variability in trace element concentrations can be attributed to a range of varied and interdependent factors. It may stem from the use of more homogeneous mineral resources in the case of the Bourbonnais axe blades, a more centralized supply and circulation of metal raw materials, or different recycling practices. However, it is not possible to draw definitive conclusions with the current state of research, and it is not excluded that other factors are at play.

A more balanced view of cultural geography at the end of the Bronze Age

These findings lead us to reconsider the sometimes dichotomous vision of Western Europe during the LBA, with the idea of a clear distinction between an Atlantic cultural domain to the west and a continental cultural domain to the east. Indeed, according to this view, these two entities would be distinguished primarily by different areas of metal circulation and distinct technical traditions for alloying (Véber et al., 2003; Véber, 2009; Bourgarit and Mille, 2014; Costa et al., 2020): to the east, copper would be rich in impurities (1.6% for Sarre-Lorraine and up to 2.5% in Switzerland), alloyed with tin and a smaller content of lead (averages of 8.5% and 2.8%, respectively), while to the west, copper would contain fewer impurities (0.4% on average) and would be alloyed heavily with tin and lead (averages of 11% and 7%, respectively). The concentrations of Pb in the objects from Atlantic France sometimes exceed 20%, making the role of Pb in this space a real question. Both technical and economic interests may be mentioned. At the cost of the degradation of the metal's mechanical properties, adding Pb greatly improves the castability of the alloy during the casting process while lowering the copper quantity to be used (Mille, 2017). Our observations significantly nuance this dualistic model. In fact, contrary to what seems to be observed in the Paris Basin (Véber et al., 2003; Bourgarit and Mille, 2014), they highlight a transitional phenomenon rather than a clear-cut boundary between the two cultural domains, with copper impurity levels and alloy types intermediate between those found in the east and west. The multi-element analyses of the axe blades from southern Bourbonnais reveal hybrid characteristics:

– the average cumulative impurity content for the axe blades is 0.823%, which is twice as much as in the Atlantic domain, but half as much as in Sarre-Lorraine and three times less than in Switzerland;

– the average tin content is 8.4%, and the average lead content is 4.7%. The tin content is comparable to that of the western continental domain and therefore lower than in the Atlantic domain. On the other hand, the lead content is significantly higher than in the east and noticeably lower than in the west. This indicator, associated with a probable use of fahlores, still points towards a slight continental tropism.

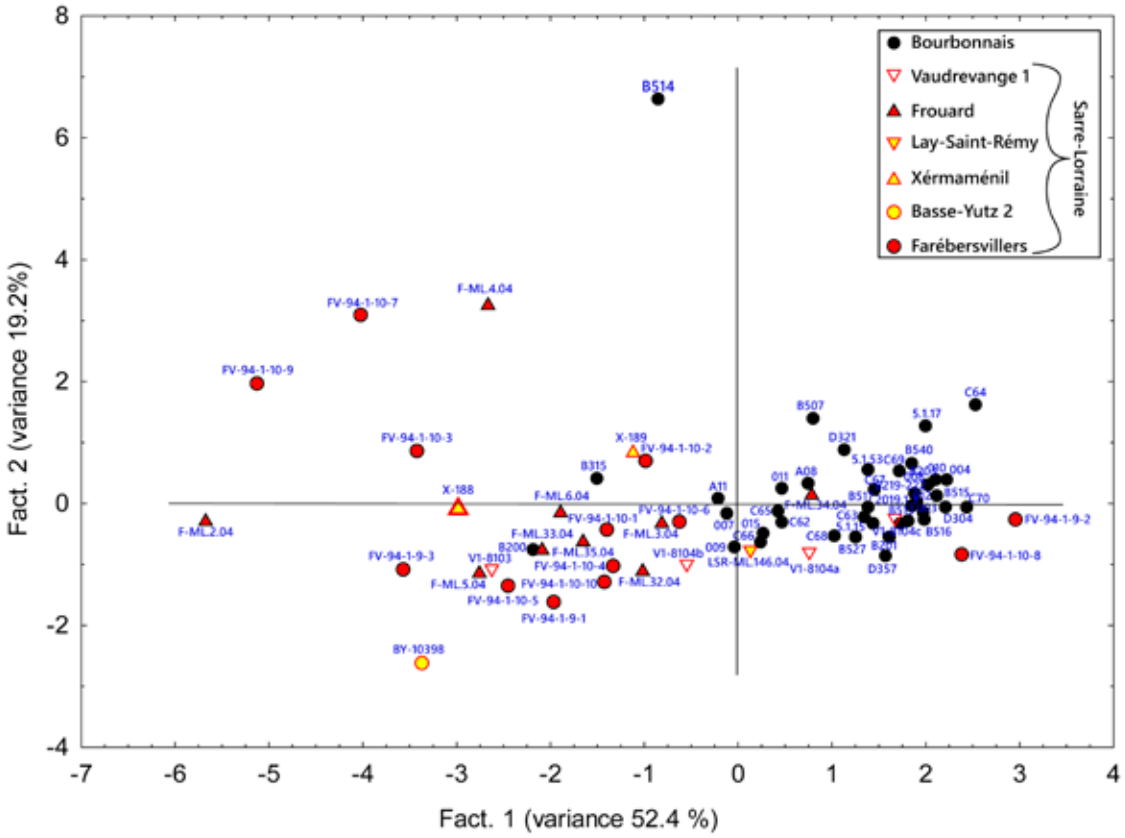


Fig. 34 – Principal Component Analysis results comparing the copper impurity levels of axe blades from Bourbonnais and Sarre-Lorraine (T. Enudde).

These observations depict a complex and nuanced pattern. The specific characteristics of our study area could suggest that it is a distinct metal circulation space, but this could also be an indication of an east-west gradient. The characteristics of the metal used would thus reflect the geographical position of Bourbonnais, at the junction of cultural domains whose borders may not be truly distinct. Furthermore, this complexity is further reinforced by the presence at Jenzat of the C70 blade of the Meldreth type, considered typically Atlantic or even British. However, the elemental analysis results for this object fit perfectly within the rest of the series: nothing suggests that the metal used came from a different circulation zone than the rest of the corpus. The hypothesis of local production is further strengthened by the discovery of a mould valve used to create comparable models at Jenzat in the F2 assemblage, as shown by the 3D model virtually reconstructed from the mould's cavity (fig. 35). These observations now allow us to seriously consider the existence of local production for this model, which is mainly found within the Atlantic area.

3D morphometry as the basis for a comprehensive typology of subterminal winged axe blades

The combination of technological and morphometric approaches has demonstrated the obsolescence of K. Kibbert's (1984) precise classification of axe blades based on the shape of the top. It has also highlighted the indistinct association of blades belonging to the Homburg and Geseke-Biblis types: this underscores the need to make the morphological silhouette criterion, which distinguishes the two categories, more objective. Our approach has also allowed us to identify, among the characteristics of the axe blades, those that do not vary with post-casting operations or the degree of wear. It is based on these characteristics that it seems relevant to classify winged axe blades. These include:

– proximal thickness at the ring;
– distal thickness at the ring;
– minimal blade thickness;
– proximal blade width;
– distance between the proximal edge of the wings and the ring;
– ring dimensions (height and length);
– median body width;
– wing length

However, the size of the studied corpus and its unique origin make it relatively risky to develop a new typology without further expanding the sample. In general, the groups formed by 3D morphometry are difficult to interpret in the absence of a comparison corpus: this is currently a work in progress in the framework of an ongoing PhD thesis. It is impossible to know whether they distinguish real sets or mere micro-divisions within a homoge-



Fig. 35 – Right valve of the axe blade mould of the Meldreth 041 type from Jenzat Hoard F2 and virtual reconstruction of the corresponding blade (T. Enudde).

neous population. It is precisely this remarkable homogeneity that raises questions and deserves to be addressed.

A regional and standardized production?

The study of the variation coefficients of the different dimensions reveals a fairly high degree of standardization (fig. 36). The proximal thickness at the ring, the distal thickness at the ring, the minimal blade thickness, and the proximal blade width show the lowest variation coefficients. They range between 0% and 5%, indicating a very high standardization of these dimensions (Birch and Martinón-Torres, 2019). The ring length, the ring height, the wing length, the wing width, the blade length, the total length, and the edge width have intermediate variation coefficients, ranging from 5% to 10%. It is worth noting that the wing width is directly influenced by the post-casting shaping process: it relates to the attachment of the blade to the handle and is therefore not significant in terms of standardization. Additionally, the total length, blade length, and edge width are all subject to the effects of wear; they are therefore not significant either. Particularly for the latter, the measured variation coefficient is artificially increased due to wear. Nevertheless, variation coefficients between 5% and 10% still indicate a relatively high degree of standardization, especially when considering the aforementioned biases. The top's length, the distance between the top and the ring, and the thickness of the medial ridge (measured at the centre of the ring) have the highest variation coefficients, between 10% and 19%. The top's length is directly dependent on a regularization operation and the possibility of a break during the removal of the casting cone; it is therefore not significant in terms of production standardization. However, high variability in the other dimensions suggests a certain discriminating potential in typological terms. It is important to note that a variation coefficient between 10% and 19% still does not indicate a lack of standard. It is observed that when excluding dimensions modified either post-casting or during the object's life, we obtain overall very low variation coefficients. Specifically, the dimensions of the object's outer contours are the least variable. In the absence of a comparison corpus, it is not possible to determine whether this standardization is a characteristic specific to the winged axe blades of Bourbonnais or if it is a general trend shared by all objects of this type. This issue will also be addressed in the ongoing PhD thesis that follows the study presented in this paper.

Controlling the metal stocks

The thriving metal production in the LBA reflects the dependence of societies on the use of this material. Consequently, controlling the supply of bronze becomes a major issue for communities. The way this control is exercised may have significant societal implications. Although our study does not allow us to definitively choose among the three hypotheses mentioned earlier (fig. 1: copper supply controlled, 1: by the manufacturer; 2: by the commissioner; 3: by a third entity, possibly a social elite for whom this activity constitutes an important economic lever), it provides some avenues for further

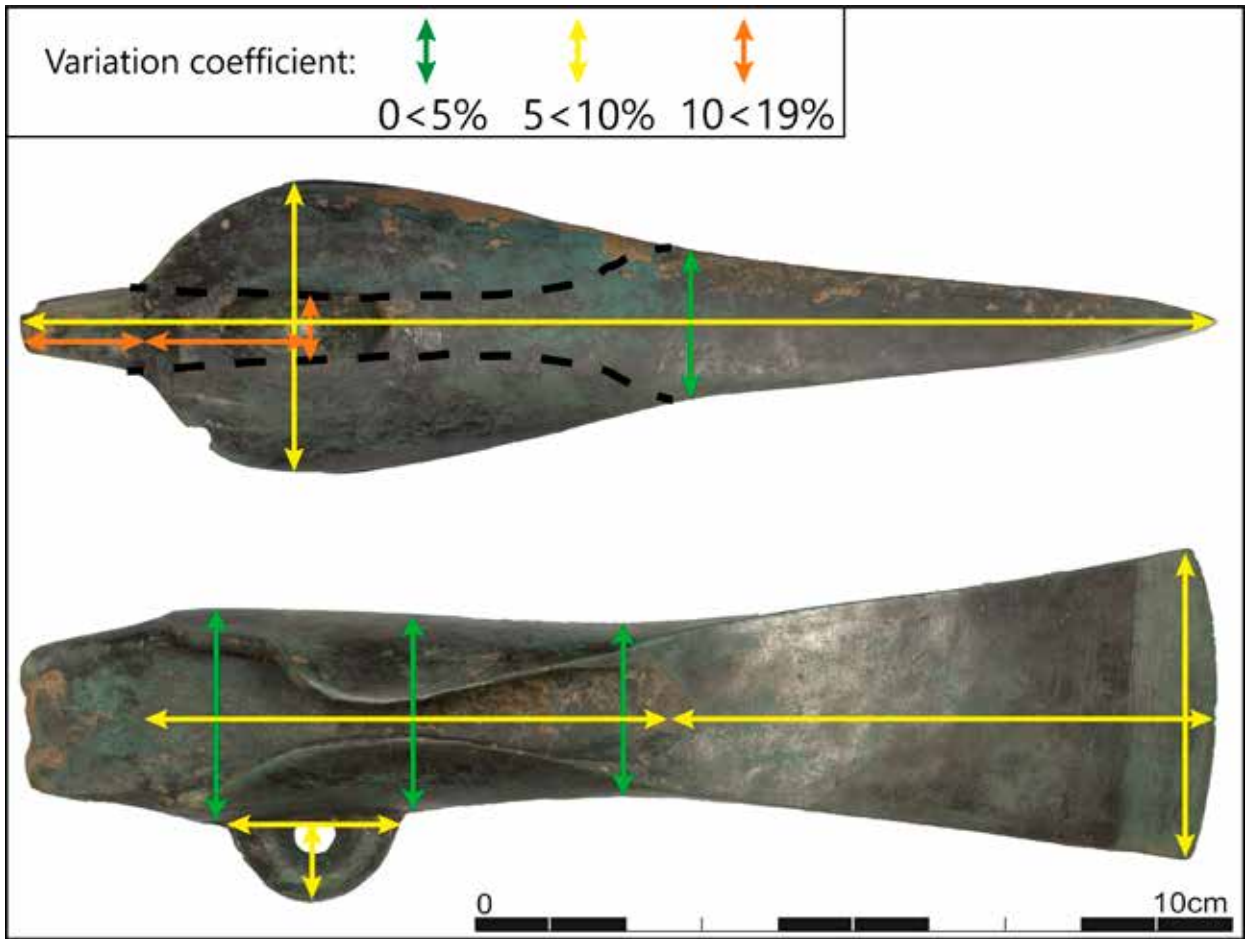


Fig. 36 – Coefficients of variation of the different parts of the winged axe blades studied (T. Enudde).

reflection. The first hypothesis seems the least convincing. Indeed, the Principal Component Analysis (PCA) of the trace elements content highlights a complete lack of correlation between twin blades and the copper impurity content (fig. 37). In this case one would expect the opposite result. While this observation alone is insufficient to disprove the hypothesis, it does constitute a counterargument. The high degree of standardization in production combined with the heterogeneity of supply seems more consistent with the second model (copper supply controlled by the commissioner). But we are confronted with the impossibility of definitively identifying objects from different commissioners. This limitation significantly reduces the scope of the approach, which would need to be supplemented by further analysis and prevents us from making a definitive conclusion regarding the hypotheses about copper supply control. The overall homogeneity of the studied corpus, regardless of the twin blades (and thus the potential manufacturer), leaves open the possibility of supply control being exercised either by the commissioner or by a third entity like a social elite. Exploring these avenues would require studying a larger and broader corpus. On the other hand, the study of the wear level of the twin mould blades identified by 3D morphometry allows for a better understanding of the hoarding practices at the Jenzat site and its surroundings.

Comparative wear of twin blades as a framework for interpreting intra-site hoarding practices and their chronology

The arrhythmic nature of metal hoarding across different chronological horizons of the LBA is already documented in Western Europe (Milcent, 2012). Therefore, it is conceivable that at an even smaller chronological scale, this episodic nature of metal hoarding might also occur. The observations made by cross-referencing the wear degree of the different twin blades indeed allow us to propose the hypothesis of a synchronous or quasi-synchronous hoarding at the site and its surroundings. Indeed, it is observed that, based on 3D morphometry, twin blades consistently have very similar Morphometrical Wear Index values (MWI). Experimental references are lacking to assess the rate at which such objects wear out. However, it seems reasonable to consider a period of a few years at most (Roberts and Ottaway, 2003; Dolfini and Crellin, 2016; Dolfini et al., 2023). Therefore, it is likely that blades from the same mould or the same model but from different hoards, if they have a similar wear degree, were hoarded within a relatively short time span. The fact that within each group of twin blades, a very similar or even identical wear degree is displayed between the twins further supports this hypothesis; perhaps even more deci-

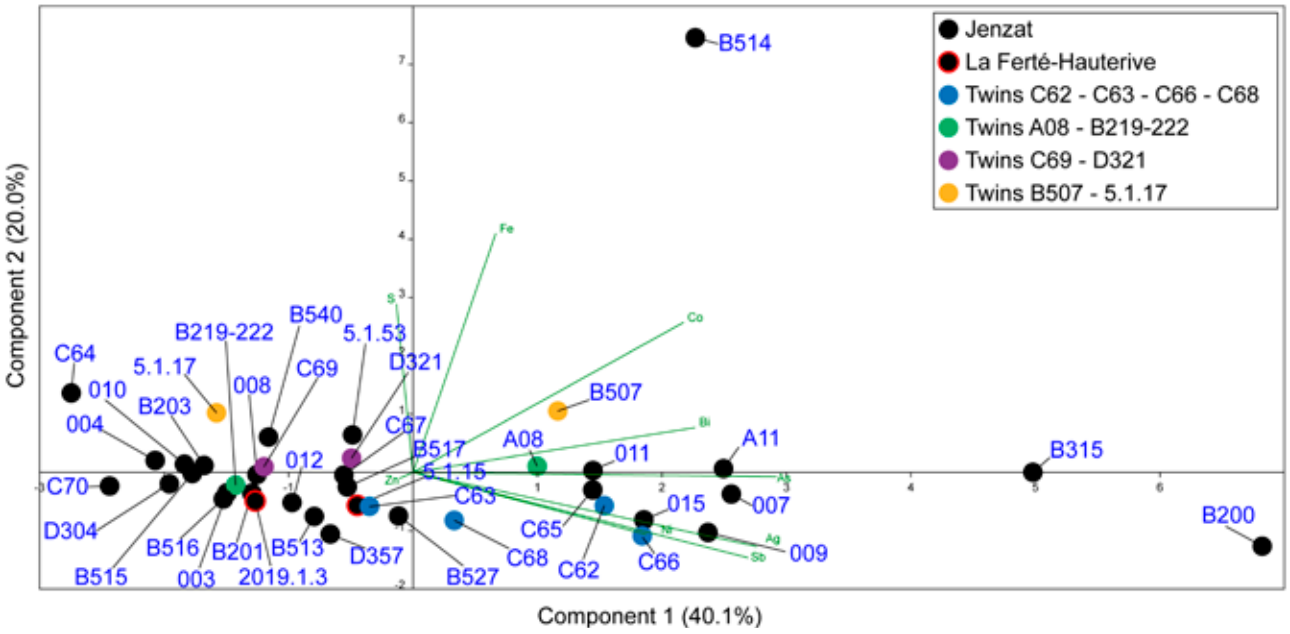


Fig. 37 – Principal Component Analysis result (Principal Component 1 – Principal Component 2) of copper impurity levels highlighting the twin blades (T. Enudde).

sive is the complete absence of the opposite case, that is twin blades of extremely different MWI. Of course, this leaves open the possibility for the hypothesis where twin blades are cast roughly at the same time, but one is used and hoarded right away while the other is kept unused, and only after a long period of time is used and then hoarded. There are several issues with this scenario however: first, this process should theoretically allow for twin blades with noticeably different MWIs to be found, yet this has not been observed; second, such a "random" process resulting in consistent observations in 8 different occurrences is unlikely. The only 'exception' concerns the group of twin blades no. 5, consisting of blades C65 and E378, which have slightly different MWIs. They are still relatively close, with less than a quartile equivalent of a difference, and are qualitatively at the same general wear stage. In the event that bronze moulds were used to cast the Jenzat axe blades, this would also be consistent with the theoretical lifespan of these moulds, which would become unusable after several dozen castings (Mohen, 1973; Mohen and Walter, 1998; Webley and Adams, 2016). These moulds form the clear majority of known examples for the winged axe blades west of the Rhine (Cordier, 1962; Briard and Verron, 1976; Kibbert, 1984); stone moulds exist, but they are fewer and seem to be mostly limited to the Alpine region (Cordier, 1962). No clay examples have been documented so far. However, it is suggested in the literature that Bronze Age metal moulds were primarily dedicated to the mass production of wax models rather than metal casting; see, for example, Mille, 2017, p. 444. In any case, it is possible to hypothesize a close contemporaneity of the F4 and F17 hoards of Jenzat, the F14 hoard of Jenzat with the Charroux hoard, and the F28 and F55 hoards of Jenzat. When reasoning in terms of "hoarding areas", we can estimate that the Charroux hoard, the trios F28 – F14 – F17, F55 – F57 – F58, as well as the two hoards F3 and F4 of Jenzat were buried almost synchronously (fig. 38). However, this is a hypothesis that would need to be supported by other chronological elements.

CONCLUSION

The study of the axe blades from the Bourbonnais highlights the value of an interdisciplinary approach combining techno-functional analysis, 3D morphometry, and multi-element metal analyses, particularly in a context where the discovery setting is well documented. Even when the geological context is favourable for the good preservation of objects, the absence of precise or reliable data concerning old or illicit finds remains a major obstacle to interpretation. The integration of new three-dimensional morpho-typological criteria has allowed for an objective characterization of the winged axe blades of the LBA 3. This provides the prospect of revising their general classification. The morphological standardization and homogeneity of the blades in the corpus suggest a marked degree of specialization, as well as a strong proximity of the discovery sites (primarily Jenzat) to the places of production, likely local. The composition analyses also support the idea of specific production sites within the Bourbonnais, as they reveal alloys with a signature that is hybrid between what is known in the Atlantic area on one hand, and the continental area on the other. In contrast, the twin blades show no conclusive similarity in metal supply, suggesting that their manufac-

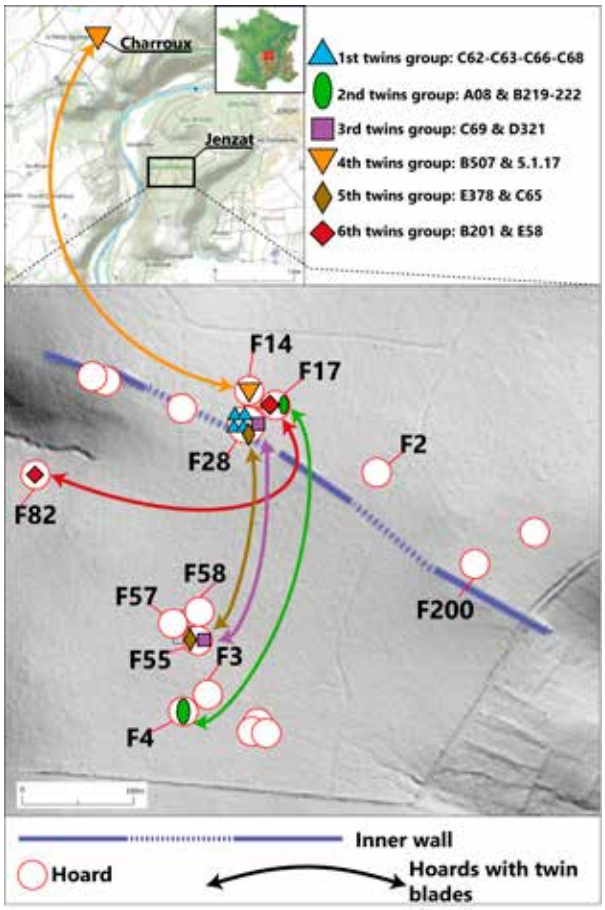


Fig. 38 – Location of twin axe blades between hoards from Jenzat and Charroux (T. Enudde).

turers did not control their supply and were dependent either on an authority managing the influx of metal or, more likely, on commissioners who could entrust a stock of metal to the bronze artisan for (re-)casting (models 2 and 3 of fig. 1). These observations also raise questions about the mobility of artisans and the organization of tasks within the production sites (possibly temporary) necessary for casting the axe blades. Again, only through a broader-scale study can these questions be definitively addressed. The identification of an east-west gradient without a clear separation strongly invites a reconsideration of the model of a dichotomy between the Atlantic and continental cultural spheres. The new data on hoarding practices, combined with a better chronological resolution, allow us to envision that these hoards were formed over a very short period, possibly even simultaneously, suggesting different dynamics of management and accumulation than those traditionally considered in ritualistic hypotheses, which emphasize the recurrence of hoarding actions.

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No.	Weight (g)	Lenght of the top (cm)	Ring to proximal wing edge distance (cm)	Ring height (cm)	Ring lenght (cm)	Total lenght (cm)	Edge width (cm)	Wings lenght (cm)	Blade lenght (cm)	Outer socket ø (cm)	Inner socket ø (cm)	Socket depth (cm)	Thickness at the ring's distal end (cm)	Thickness at the ring's proximal end (cm)	Minimal thickness (cm)	Width at the ring (cm)	Width at the blade's proximal end (cm)	Medial ridge thickness at the ring (cm)	
003	398	2,5	1,7	0,9	2,6	15,5	4,2	6,1	6,9	n/c	n/c	n/c	2,5	2,7	2,1	4,2	2,2	0,7	
004	469	1,9	1,7	1,0	2,5	15,3	4,0	5,5	7,9	n/c	n/c	n/c	2,5	2,5	2,2	4,4	1,9	0,9	
007	389	1,4	1,6	0,9	2,3	14,9	3,6	5,5	8,0	n/c	n/c	n/c	2,7	3,0	2,4	3,6	2,0	0,7	
008	398	2,0	1,9	1,0	2,4	15,2	3,9	5,2	8,0	n/c	n/c	n/c	2,6	2,8	2,3	3,5	2,2	0,5	
009	436	2,0	1.7	0.9	2.6	15.4	3.9	6.6	6.8	n/c	n/c	n/c	2.7	2.8	2.2	4,0	2.2	0.7	
010	388	1.9	2.5	1,0	2.7	14.9	3.5	5.5	7.5	n/c	n/c	n/c	2.6	2.8	2.3	3.9	2,0	0.6	
011	505	1.6	1.7	0.8	1.9	14.2	4.5	6.1	6.5	n/c	n/c	n/c	3.2	3.2	2.6	4.2	1.9	0.8	
012	425	2.2	2.5	0.8	2.5	15.2	3.8	6.2	6.8	n/c	n/c	n/c	2.6	3,0	2.1	4.2	2.3	0.9	
015	398	1.1	2.1	1.1	2.9	14.2	3.9	6.6	6.5	n/c	n/c	n/c	2.7	2.9	2.3	4,0	2.2	0.4	
2019.1.3	355	1.6	2.5	1,0	2.6	14.1	3.5	6.1	6.4	n/c	n/c	n/c	2.5	2.7	2.1	3.8	2,0	0.5	
5.1.15	447	1.6	2.4	1,0	2.9	13.7	4.4	5.2	6.9	n/c	n/c	n/c	2.7	3.1	2.5	4.1	2,0	0.8	
5.1.17	349	1.4	1.9	0.9	2.9	13.6	3.5	5.3	6.9	n/c	n/c	n/c	2.5	2.7	2.2	3.4	2	0.6	
5.1.53	476	1.6	1.9	1	2.9	15.3	3.7	5.7	8	n/c	n/c	n/c	2.4	2.7	2.2	3.9	2.3	0.6	
A08	445	2	2.2	1	2.8	16.1	3.8	6	8.1	n/c	n/c	n/c	2.7	2.9	2.3	4.6	2	0.8	
A11	344	0.8	2	1.2	2.6	12.3	4.2	5.9	5.6	n/c	n/c	n/c	2.8	3.1	2.5	3.7	2.1	0.7	
B200	407	1.8	2.2	0.7	2	14	4.1	6.4	5.8	n/c	n/c	n/c	2.6	2.8	2.4	4.2	2.2	0.6	
B201	324	1.7	1.6	1.1	2.6	13.1	3.9	5.5	5.9	n/c	n/c	n/c	2.5	2.8	2.3	3.7	2	0.5	
B203	391	2	2.2	0.9	2.6	14.3	4.3	6	6.3	n/c	n/c	n/c	2.3	2.5	2.1	4.1	2.2	0.6	
B219-B222	468	2.1	2.2	1	2.9	16	3.8	6	7.9	n/c	n/c	n/c	2.7	2.9	2.3	4	2.1	0.8	
B315	231	n/a	n/c	n/a	n/a	8.5	5	n/a	6.5	n/c	n/c	n/c	n/a	n/c	2.4	n/a	1.8	n/a	
B507	356	1.8	1.9	1	2.9	14.5	3.4	5.3	7.4	n/c	n/c	n/c	2.5	2.7	2.2	3.7	2.1	0.6	
B513	379	1.5	1.7	1	2.5	14.3	4	5.4	7.4	n/c	n/c	n/c	2.6	2.7	2.2	3.8	1.9	0.6	
B514	413	1.5	2.1	1	2.3	14.3	4.4	5.8	7	n/c	n/c	n/c	2.6	2.8	2.2	3.9	2.1	0.6	
B515	453	1.7	1.5	0.9	2.9	15.3	4.4	5.8	7.8	n/c	n/c	n/c	2.8	2.8	2.4	4.6	2	0.8	
B516	336	1.7	2	0.9	2.7	14.2	3.7	5.8	6.7	n/c	n/c	n/c	2.5	2.8	2.2	3.7	1.8	0.4	
B517	420	1.8	2.4	1	2.5	15.6	3.4	5.9	7.9	n/c	n/c	n/c	2.8	3.1	2.4	3.7	2	0.8	
B527	422	1.6	1.9	0.8	2.6	15	4.3	7.1	6.3	n/c	n/c	n/c	2.8	3.1	2.4	4.3	2.1	0.7	
B540	480	1.6	1.6	1	2.5	15.2	4.2	6.5	7.1	n/c	n/c	n/c	2.8	3	2.5	4.1	1.9	0.7	
C62	469	1.8	2.1	1.1	2.5	15.8	4.2	6.3	7.7	n/c	n/c	n/c	2.6	2.9	2.4	3.9	2	0.9	
C63	450	1.8	2.1	1.1	2.5	15.9	4.2	6.3	7.8	n/c	n/c	n/c	2.6	2.9	2.4	4.1	2.1	0.9	
C64	407	1.8	1.8	1.1	2.6	16	4	6.2	8	n/c	n/c	n/c	2.8	2.9	2.4	4.4	2	0.5	
C65	418	1.4	1.5	0.8	2.7	14.2	3.7	5.7	7.1	n/c	n/c	n/c	2.8	2.8	2.5	4.2	1.9	0.7	
C66	470	1.8	2.1	1.2	2.5	15.8	4.1	6.3	7.7	n/c	n/c	n/c	2.7	2.9	2.4	3.9	2.1	0.9	
C67	436	1.9	2	0.9	2.7	14.7	4.4	6.5	6.3	n/c	n/c	n/c	2.6	2.8	2.1	4	2	0.8	
C68	482	1.6	2.1	1.1	2.5	15.7	4.2	6.3	7.8	n/c	n/c	n/c	2.6	2.9	2.4	3.9	2	0.9	
C69	489	1.7	2.3	1.1	2.9	15.3	4.2	5.7	7.9	n/c	n/c	n/c	2.7	3	2.5	4.2	2	0.7	
C70 (socketed)	243	n/c	n/c	0.8	1.8	11.9	5.7	n/c	n/c	3.8	2.7	7.7	2.5	n/c	2.1	2.8	n/c	n/c	
D304	354	2.1	2.4	1	2.4	14.7	3.8	6.2	6.4	n/c	n/c	n/c	2.7	2.9	2.3	3.7	1.9	0.4	
D321	453	2	2.3	1.1	2.9	15.5	3.9	5.7	7.8	n/c	n/c	n/c	2.7	3.1	2.5	4.2	2	0.7	
D357	462	1.7	1.7	1.2	2.7	17	3.8	7.7	7.6	n/c	n/c	n/c	2.8	2.9	2.5	4	2.1	0.6	
E320	445	1.7	1.5	1	2.9	16.3	4	6.3	8.3	n/c	n/c	n/c	2.7	2.9	2.3	4.2	2.3	0.7	
E330	465	1.8	2.1	1	2.8	15.5	4	6.2	7.5	n/c	n/c	n/c	2.9	3.1	2.4	4.5	2.2	0.7	
E333	441	1.8	2.5	1	2.6	15.5	3.8	6.4	7.3	n/c	n/c	n/c	2.7	2.8	2.5	3.9	2.1	0.7	
E378	389	1.6	1.5	1	2.9	13.5	4.3	5.7	6.2	n/c	n/c	n/c	2.9	2.8	2.4	4.2	1.9	0.7	
E382	436	1.5	1.5	1.1	2.9	14.8	3.8	5.7	7.6	n/c	n/c	n/c	2.8	2.8	2.3	4.2	2.1	0.5	
E384	350	2.7	1.9	1.1	2.1	15.4	3.4	5.6	7.1	n/c	n/c	n/c	2.6	2.9	2	3.8	2	0.7	
E58	352	1.7	1.5	1.1	2.3	13.7	4	5.5	6.5	n/c	n/c	n/c	2.6	2.8	2.3	3.6	2	0.5	
Average mean	415	2,0	1,8	1,0	2,4	15,4	4,1	5,8	7,7				2,6	2,9	2,2	4,0	2,0	0,7	Winged axe blades only
Standard deviation	43	0,2	0,2	0,0	0,2	0,6	0,2	0,3	0,4				0,1	0,2	0,1	0,2	0,0	0,1	
Variation coefficient	10 %	8,2%	8,2%	1,8%	7,1%	4,0%	5,2%	5,3%	5,5%				2,9%	5,7%	5,5%	4,7%	1,8%	14,3%	

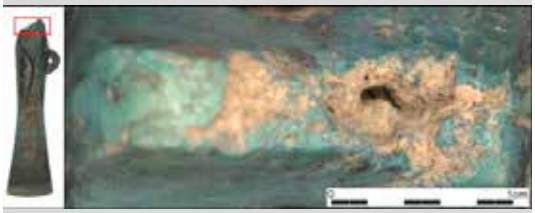
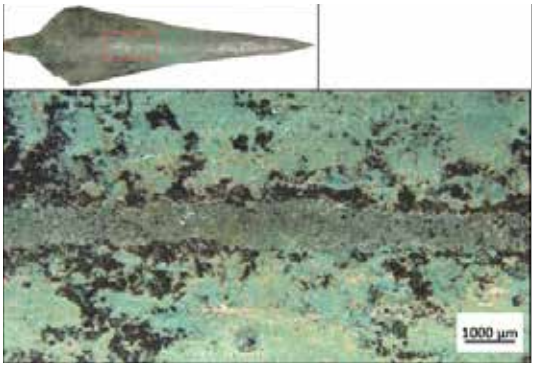
Annex 1 – Morphometric data of the 47 axe blades studied (46 winged and one socketed).

Mean distance matrice (µm)	C62	C63	C64	C65	C66	C67	C68	C69	A08	A11	B200	B201	B203	B219-222	B507	B513	B514	B515	B516	B517	B527	B540	D304	D321	D357	003	004	007	008	009	010	011	012	015	5.1.15	5.1.17	5.1.53	2019.1.3	E58	E320	E330	E333	E378	E382	E384
C62	0	140	690	990	140	910	130	800	640	930	780	1060	1010	620	1000	940	780	810	1240	810	710	900	750	790	990	1050	980	1020	810	740	880	1410	820	710	1043	1110	1000	1140	1020	840	690	700	1000	860	1070
C63	140	0	770	1040	170	880	170	840	650	980	850	1080	990	660	970	910	770	860	1180	860	750	980	750	840	1040	1040	940	1080	800	750	860	1450	800	740	1090	1070	1020	1090	1020	870	760	780	1030	900	1020
C64	650	730	0	660	660	990	650	740	700	740	600	840	1140	590	960	990	850	630	1150	780	550	490	780	780	690	1140	1210	720	900	690	800	1290	1000	710	910	1150	980	1210	840	670	520	740	690	620	1260
C65	950	990	640	0	940	1120	940	620	770	550	800	740	1340	660	930	930	930	460	1160	700	630	570	860	740	800	1250	1160	510	870	920	740	1190	1130	1090	590	1030	1110	1270	720	780	590	850	320	390	1210
C66	130	170	710	1000	0	980	90	780	660	910	820	1120	1100	650	1070	1020	860	820	1300	800	690	910	810	770	960	1130	1040	1050	870	810	940	1360	870	720	1020	1190	1090	1210	1090	910	690	740	1000	900	1150
C67	830	790	970	1110	890	0	860	1030	680	1280	950	1130	690	720	730	620	740	960	1050	1100	1080	1000	1000	980	1400	540	720	1050	840	440	740	1760	470	1060	1260	760	690	970	1020	650	980	910	1150	880	750
C68	130	170	710	1010	90	960	0	780	650	920	820	1130	1090	640	1070	1010	860	830	1300	810	710	900	810	770	970	1110	1040	1060	880	790	940	1360	850	730	1030	1190	1070	1210	1090	880	690	740	1010	900	1140
C69	780	830	800	700	760	1150	750	0	720	600	780	1110	1260	640	930	1110	800	700	1420	560	660	800	880	800	1230	1150	800	1230	1030	860	1120	910	960	410	1060	1040	1280	1060	910	560	600	820	670	1200
A08	610	610	690	770	620	690	610	680	0	870	880	1010	1040	210	810	830	700	630	1200	620	650	800	800	660	1150	880	800	820	660	640	680	1300	1010	980	860	890	950	1180	920	650	500	830	790	590	980
A11	920	960	760	630	900	1350	900	600	880	0	890	940	1390	750	1050	1120	940	750	1170	760	640	840	840	720	780	1450	1340	690	940	1090	920	1110	1220	1010	530	1180	1310	1200	980	1040	620	850	700	820	1250
B200	590	660	460	670	620	890	620	600	770	690	0	880	930	660	870	680	660	1130	750	590	540	770	650	720	1010	1130	630	810	580	810	1280	880	700	820	1020	820	1040	850	560	570	410	770	620	1090
B201	1030	1020	820	740	1080	1120	1080	1020	1030	900	1030	0	1240	960	810	800	900	880	1180	1010	1000	1000	640	1160	1100	1200	1110	730	920	650	890	1960	1770	1250	1010	1100	890	1080	1030	240	870	1060	1120	740	780	1110
B203	970	950	1080	1230	1060	650	1040	1190	1000	1290	930	1140	0	1000	670	640	660	1190	910	1330	1150	1220	930	1250	1480	520	800	1200	930	650	890	1960	690	1070	1430	700	630	1020	850	1120	910	1260	1060	730
B219-222	610	650	600	680	630	740	630	620	220	750	800	960	1050	0	810	850	710	550	1210	580	570	690	800	610	1030	960	920	750	700	670	680	1210	680	950	780	940	930	1210	890	610	360	770	700	540	1010
B507	920	890	930	870	1000	710	1000	870	810	990	880	760	660	810	0	410	430	960	610	1040	940	1160	580	1060	1300	610	570	820	540	660	350	1780	750	970	1010	280	580	640	600	740	1010	890	900	750	650
B513	850	820	940	860	920	590	920	960	810	1010	870	750	810	660	410	0	500	880	670	1030	960	1120	610	1060	1300	580	550	820	630	540	480	1780	680	970	1070	390	730	580	640	730	1010	870	860	780	530
B514	750	740	810	840	820	720	820	780	680	880	740	810	660	680	450	570	0	880	800	880	800	1030	520	870	1140	760	760	820	510	600	550	1630	620	770	970	600	780	610	710	670	810	720	890	710	630
B515	840	870	650	470	840	1020	850	710	690	770	910	890	1360	590	1050	1000	1010	0	1340	650	690	610	1020	740	960	1210	1090	680	950	890	830	1170	1060	1180	800	1150	1120	1440	850	790	580	960	530	510	1310
B516	1200	1140	1100	1130	1260	1000	1260	1310	1200	1100	1130	610	890	1190	600	670	760	1270	0	1440	1180	1420	680	1460	1350	990	970	1050	980	890	750	2040	1140	990	1380	640	960	580	650	1070	1320	1270	1100	1130	880
B517	780	820	800	710	760	1140	760	540	630	750	860	1170	1330	560	1050	1100	880	620	1470	0	540	790	920	520	1040	1300	1120	830	820	1030	940	1000	920	1050	590	1150	1210	1340	1100	940	480	740	700	760	1190
B527	700	730	560	610	670	1110	690	620	680	630	660	1030	1160	560	950	990	820	620	1210	540	0	670	810	680	710	1240	1220	730	860	830	900	1020	940	740	700	1090	1100	1180	1020	820	460	770	620	700	1180
B540	870	950	490	590	860	1090	850	700	780	740	690	1020	1320	640	1190	1180	1080	600	1470	700	660	0	1090	700	640	1260	1370	720	1100	830	1000	1110	1140	1030	740	1510	1350	1540	980	660	470	700	660	580	1480
D304	700	690	720	790	760	980	760	850	780	810	820	610	900	750	590	680	510	870	720	930	790	1030	0	970	1050	1040	940	870	750	540	1630	830	660	970	710	1050	630	600	850	870	860	760	770	680
D321	750	800	820	780	720	1090	710	230	680	710	820	1240	1290	620	1030	1180	880	710	1530	530	690	780	980	0	1000	1190	1110	860	730	1030	930	1150	840	1010	480	1130	1000	1400	1170	920	570	590	900	720	1270
D357	1010	1060	680	860	970	1440	970	900	1160	780	930	1150	1610	1010	1340	1390	1260	950	1460	1040	750	650	1180	980	0	1570	1620	940	1350	1100	1210	1050	1520	890	890	1550	1350	1560	1180	1050	830	980	950	930	1710
003	930	920	1100	1190	1010	1520	990	1080	840	1330	1030	1160	510	900	610	580	720	1100	1220	1200	1210	1020	1060	1510	0	580	1130	830	620	760	1940	640	1120	1330	620	560	900	980	810	1120	950	1240	940	820
004	900	860	1190	1110	950	700	940	1060	800	1290	1140	1050	800	920	580	560	750	1010	980	1110	1210	1340	930	1040	1570	570	0	1000	760	770	650	1880	730	1270	1180	560	740	920	880	930	1200	1050	1130	930	850
007	850	900	670	490	850	1020	850	560	740	520	710	710	1260	660	800	840	810	580	1040	690	650	690	790	650	850	1150	990	0	760	830	650	1300	1000	980	610	890	1020	1120	650	800	650	760	570	510	1080
008	740	730	840	790	790	820	790	660	640	890	860	870	910	660	540	670	500	800	990	810	830	1030	460	700	1220	870	760	800	0	720	510	1640	640	830	820	600	820	830	780	850	780	780	610	720
009	660	660	680	920	730	450	710	900	640	1010	660	890	700	650	700	590	610	830	940	980	810	830	760	930	1080	650	800	850	740	0	670	1560	610	780	1120	770	670	920	850	510	770	710	950	730	870
010	810	790	770	720	880	720	870	780	670	890	890	650	910	660	360	510	570	780	760	930	870	990	550	870	1170	780	650	700	530	640	0	1610	800	970	900	440	730	860	560	700	870	860	730	630	720
011	1340	1390	1250	1190	1300	1750	1300	1050	1310	1090	1320	1710	1920	1200	1750	1790	1610	1120	2050	990	1010	1110	1630	1090	980	1930	1820	1330	1660	1550	1600	0	1650	1540	1000	1870	1720	2020	1700	1480	970	1230	1260	1320	2010
012	750	730	950	1030	800	450	770	850	560	1120	890	1190	690	620	750	720	610	890	1190	900	920	1050	860	790	1410	1680	740	1050	650	610	760	1610	0	1030	1070	760	820	870	1090	700	860	830	1060	810	670
015	710	740	720	1120	720	1150	720	1000	1060	1030	830	1080	1120	980	1080	1080	840	1110	1100	1110	760	1030	760	1090	810	1280	1370	1080	960	830	1090	1590	1080	0	1220	1250	1220	1000	1080	1000	940	860	1130	1030	1220
5.1.15	1010	1060	940	640	990	1360	990	400	880	540	940	1180	1500	790	1070	1210	1000	780	1460	610	710	870	990	480	880	1470	1280	830	870	1220	960	1040	1120	1150	0	1170	1280	1380	1130	1090	690	830	770	830	1310
5.1.17	1010	970	1090	980	1080	710	1080	970	870	1100	1020	860	680	890	270	400	580	1050	650	1130	1050	1290	700	1050	1440	600	550	930	600	720	410	1850	730	1100	1080	0	650	670	740	870	1110	1010	1010	870	610
5.1.53	890	910	950	1120	970	700	950	930	940	1240	840	1090	650	900	600	760	750	1060	1010	1160	1070	1020	1050	890	1330	570	750	1040	820	660	750	1810	820	1100	1190	690	0	1090	910	660	1020	780	1170	860	1110
2019.1.3	1080	1030	1120	1120	1150	910	1150	1220	1120	1080	1040	850	650	1130	620	610	590	1220	590	1330	1130	1420	620	1370	1360	920	940	1080	840	850	770	1990	860	920	1310	660	1090	0	790	1090	1240	1050	1100	1100	560
E58	980	970	800	720	1040	1010	1040	960	950	930	1000	240	1130	900	670	690	790	850	710	1120	1000	970	610	1100	1130	1040	930	680	820	840	550	1770	1140	1000	1040	780	950	950	0	790	1020	1060	730	690	1040
E320	810	850	670	820	860	690	840	820	650	1000	760	910	980	600	800	820	770	780	1150	940	840	660	930	850	1040	880	990	830	870	530	740	1510	820	950	1030	950	700	1270	800	0	690	760	890	620	1130
E330	690	760	560	650	690	1020	690	570	510	630	730	1030	1180	360	1020	1060	940	990	1350	510	480	580	910	590	880	1210	1230	770	910	820	880	990	920	920	710	1170	1070	1330	1000	730	0	720	680	630	1250
E333	670	750	690	790	690	940	690	580	810	780	510	1060	940	720	940	990	740	770	1360	750	760	650	880	590	870	1020	1110	790	810	750	860	1320	860	810	830	1060	840	1100	1010	700	660	0	930	740	1100
E378	980	1020	670	320	960	1180	980	780	800	660	970	750	1390	690	980	960	1020	500	1160	720	680	630	870	880	880	1340	1200	590	920	960	780	1230	1210	1120	750	1090	1210	1300	730	840	1040	0	470	1250
E382	810	860	590	400	840	910	840	590	720	820	780	1160	510	820	870	820	510	1170	720	690	580	860	660	910	1020	1000	550	720	740	660	1330	940	1020	750	940	890	1270	690	610	570	840	480	0	1190
E384	1000	950	1150	1020	1070	660	1060	1100	900	1110	1080	960	700	910	610	550	600	1050	870	1160	1130	1320	660	1200	1520	810	820	1030	710	800	620	1930	640	1130	1210	570	1060	540	900	950	1140	1030	1020	980	0

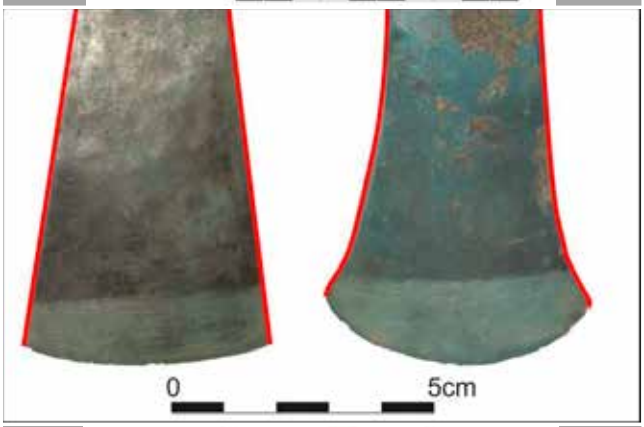
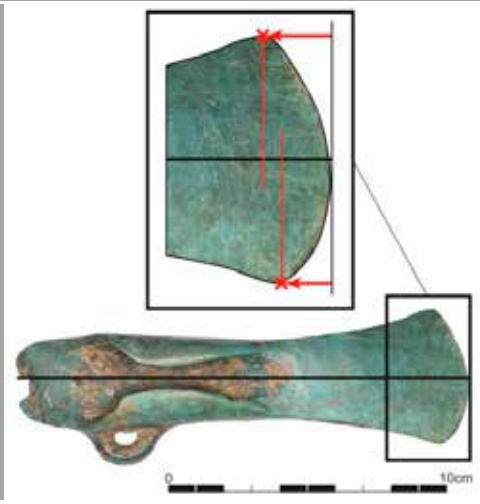
Annex 2 – 3D Morphometry mean-distance matrix of the 45 intact winged axe blades studied.

No.	Cu	Sn	Pb	S	Fe	Co	Ni	Zn	As	Ag	Sb	Bi
003	86.30%	8.60%	4.50%	0.13%	0.00%	0.01%	0.09%	0.00%	0.14%	0.05%	0.14%	0.01%
004	82.40%	10.10%	7.00%	0.19%	0.00%	0.01%	0.07%	0.00%	0.10%	0.05%	0.10%	0.01%
007	87.60%	8.60%	2.70%	0.14%	0.00%	0.05%	0.19%	0.00%	0.25%	0.12%	0.37%	0.02%
008	85.60%	9.00%	4.70%	0.16%	0.01%	0.01%	0.09%	0.00%	0.16%	0.06%	0.13%	0.01%
009	86.70%	9.30%	2.90%	0.08%	0.00%	0.04%	0.22%	0.00%	0.26%	0.11%	0.36%	0.02%
010	85.40%	9.20%	4.80%	0.19%	0.00%	0.01%	0.09%	0.00%	0.11%	0.05%	0.11%	0.01%
011	85.30%	9.50%	4.10%	0.19%	0.01%	0.04%	0.14%	0.00%	0.25%	0.10%	0.31%	0.01%
012	84.70%	10.50%	4.10%	0.15%	0.00%	0.01%	0.11%	0.00%	0.14%	0.07%	0.16%	0.01%
015	84.90%	8.20%	5.80%	0.11%	0.00%	0.03%	0.17%	0.00%	0.24%	0.11%	0.35%	0.02%
2019.1.3	83.10%	9.60%	6.80%	0.11%	0.00%	0.01%	0.11%	0.00%	0.12%	0.06%	0.15%	0.01%
5.1.15	85.80%	9.10%	4.40%	0.11%	0.00%	0.02%	0.13%	0.00%	0.14%	0.08%	0.21%	0.01%
5.1.17	86.50%	8.00%	4.80%	0.29%	0.01%	0.01%	0.07%	0.00%	0.15%	0.05%	0.10%	0.01%
5.1.53	82.90%	8.20%	8.10%	0.19%	0.00%	0.05%	0.12%	0.00%	0.18%	0.06%	0.11%	0.01%
A08	87.80%	7.80%	3.40%	0.18%	0.01%	0.02%	0.10%	0.00%	0.20%	0.09%	0.30%	0.02%
A11	84.40%	9.60%	4.90%	0.13%	0.02%	0.07%	0.22%	0.00%	0.26%	0.11%	0.34%	0.01%
B200	87.50%	8.70%	1.90%	0.14%	0.01%	0.07%	0.25%	0.00%	0.43%	0.23%	0.68%	0.02%
B201	86.30%	8.40%	4.70%	0.07%	0.00%	0.02%	0.11%	0.00%	0.12%	0.08%	0.17%	0.01%
B203	83.80%	10.20%	5.50%	0.18%	0.01%	0.01%	0.07%	0.00%	0.13%	0.05%	0.15%	0.01%
B219-222	87.50%	7.90%	4.00%	0.15%	0.00%	0.01%	0.09%	0.00%	0.12%	0.07%	0.16%	0.01%
B315	89.50%	5.40%	3.40%	0.24%	0.02%	0.07%	0.26%	0.00%	0.35%	0.14%	0.69%	0.01%
B507	91.80%	4.70%	2.60%	0.31%	0.00%	0.00%	0.05%	0.00%	0.24%	0.12%	0.15%	0.03%
B513	86.70%	7.10%	5.70%	0.10%	0.00%	0.01%	0.07%	0.00%	0.13%	0.07%	0.16%	0.01%
B514	88.40%	8.40%	2.00%	0.29%	0.36%	0.14%	0.08%	0.00%	0.23%	0.06%	0.10%	0.02%
B515	86.80%	8.70%	4.00%	0.15%	0.00%	0.01%	0.06%	0.00%	0.11%	0.05%	0.13%	0.01%
B516	81.10%	10.30%	8.10%	0.12%	0.00%	0.01%	0.08%	0.00%	0.12%	0.06%	0.15%	0.01%
B517	87.70%	7.90%	3.30%	0.12%	0.01%	0.03%	0.11%	0.45%	0.16%	0.07%	0.20%	0.01%
B527	89.00%	7.50%	2.80%	0.08%	0.00%	0.02%	0.11%	0.00%	0.16%	0.08%	0.23%	0.01%
B540	89.50%	5.60%	4.40%	0.20%	0.00%	0.01%	0.04%	0.00%	0.16%	0.05%	0.12%	0.01%
C62	86.10%	8.10%	4.80%	0.13%	0.00%	0.03%	0.14%	0.00%	0.23%	0.12%	0.32%	0.01%
C63	92.10%	5.20%	1.80%	0.15%	0.00%	0.02%	0.14%	0.00%	0.17%	0.08%	0.21%	0.01%
C64	93.20%	3.40%	2.80%	0.34%	0.00%	0.00%	0.06%	0.00%	0.09%	0.03%	0.09%	0.01%
C65	85.60%	8.80%	4.60%	0.13%	0.01%	0.04%	0.16%	0.00%	0.21%	0.09%	0.32%	0.02%
C66	86.70%	8.50%	3.70%	0.12%	0.00%	0.03%	0.20%	0.00%	0.22%	0.11%	0.41%	0.01%
C67	80.30%	10.60%	8.30%	0.18%	0.01%	0.02%	0.15%	0.00%	0.18%	0.07%	0.16%	0.01%
C68	85.40%	8.60%	5.20%	0.10%	0.00%	0.02%	0.14%	0.00%	0.17%	0.10%	0.26%	0.01%
C69	85.00%	11.10%	3.20%	0.23%	0.00%	0.01%	0.18%	0.00%	0.14%	0.05%	0.14%	0.01%
C70	86.80%	8.30%	4.50%	0.13%	0.00%	0.00%	0.05%	0.00%	0.11%	0.04%	0.09%	0.01%
D304	78.10%	11.30%	10.10%	0.13%	0.00%	0.01%	0.06%	0.00%	0.11%	0.05%	0.11%	0.01%
D321	86.60%	8.40%	4.00%	0.27%	0.01%	0.02%	0.38%	0.00%	0.14%	0.04%	0.09%	0.01%
D357	81.70%	8.80%	8.90%	0.05%	0.00%	0.02%	0.10%	0.00%	0.14%	0.09%	0.21%	0.01%

Annex 3 – Multi-element analyses results (partial) of 40 axe blades studied (39 winged and one socketed).

Trace description	Picture	Interpretation
Bent-down casting sprues on the top of the blade (here on blade B201 from hoard F17 of Jenzat, photo T. Enudde)		Removal of the casting cone and hammering down of the casting sprues
Unevenly shaped proximal extremity with clear signs of mechanical fracture (here on blade C68 from hoard F28 of Jenzat, photo: T. Enudde)		Breakage of the top of the blade during the removal of the casting cone and the bending of the sprues
Thin line (around 1 mm wide) with no relief, visible only due to differential oxidation (here on the upper face of blade C63 from hoard F28 of Jenzat, photo: T. Enudde)		Flattening of the mould seam line by hammering and fine polishing
Thin, irregularly shaped piece of metal protruding from the mould seam line inside the ring (here on the ring of blade A11 from hoard F3 of Jenzat photo: T. Enudde)		Incomplete flashing removal, probably due to the difficulty and/or uselessness of reaching the medial face of the ring
Contiguous, oval-shaped concavities on the surface of the blade (here on the right side face of blade B514 from hoard F14 of Jenzat photo: T. Enudde)		Hammering traces

Annex 4 – Description, illustration, and interpretation of the traces attributed to the shaping phase.

Trace description	Picture	Interpretation
Difference of the radius of the arcs formed by the cutting edges of different blades (here, a comparison between blades C62, at the top, from hoard F28 of Jenzat, and B514, at the bottom, from hoard F14 of Jenzat, photo: T. Enudde)		The radius of the arc formed by the cutting edge decreases as wear increases : this is likely due to the deformation induced by edge maintenance through resharpening and hammering.
Flaring of the of the sides of the blade (here, comparison between blade C62 -which is not flared at all - on the left, from hoard F28 of Jenzat, and B515 - which shows flaring - on the right, from hoard F14 of Jenzat, photo: T. Enudde)		This is corollary of the previous feature (the cutting edge arc radius) and due to edge maintenance as well.
Asymmetrical cutting edge (here on blade B201 from hoard F17 of Jenzat, photo: T. Enudde)		This trace suggests more advanced wear than a rounded but symmetrical edge.

Annex 5 – Description, illustration, and interpretation of the traces attributed to use, wear, and maintenance.

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Isotopic and elemental analyses of north-western French Bronze Age metal hoards

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Abstract: The north-west of France is one of the regions of Europe with the greatest number of Bronze Age metal hoards. This leads to the presence of several tens of thousands of whole or fragmented deposited objects. The region has no major copper deposits. The metal had to be imported from the various copper-producing regions of Europe. Over the last fifteen years, an analytical study has been carried out on these objects, leading to the production of more than 2,000 elemental chemical analyses obtained by ICP-OES and more than fifty lead isotope analyses realised by MC-ICP-MS. Analyses show that in the early Middle Bronze Age, copper was supplied from Wales. The spread of this metal seems to have been confined to the regions bordering the Atlantic and the English Channel/North Sea. From the second Middle Bronze Age onwards, the trades change radically, with copper possibly coming from the Iberian Peninsula and Austria. These networks seem to remain in place during the first phase of the Final Bronze Age. With the second period of the Final Bronze Age, the copper supply diversified. This can be seen from the elemental analyses. Unfortunately, it is not possible to identify the origin of the copper in objects from this period because of their high lead content, probably added deliberately to the alloy. Fragments of copper ingots are rare but do exist. Their isotopic analysis could indicate a Central European origin. At the end of the Final Bronze Age, the diversity of metal composition was even greater, reflecting the increasing complexity of the networks. The many fragments of copper ingots found in the deposits suggest a range of origins, from the western Alps to central Europe, as well as the Mediterranean regions.

Keywords: North-West France, Bronze Age, metal hoard, elemental analysis, lead isotope analysis, copper supply, ancient supply network.

Résumé : Le nord-ouest de la France est l'une des régions d'Europe où il y a le plus grand nombre de dépôts métalliques terrestres de l'âge du Bronze. Cela conduit à la présence de plusieurs dizaines de milliers d'objets entiers ou fragmentés ainsi déposés. Or, cette région ne possède pas de grands gisements de cuivre. Le métal ainsi immobilisé a dû être alors importé des différentes régions productrices de cuivre européennes. Depuis une quinzaine d'années, une étude est menée sur l'analyse des objets des dépôts de cette région conduisant à la production de plus de 2 000 analyses chimiques élémentaires obtenues par ICP-OES et plus de cinquante analyses isotopiques du plomb produites par MC-ICP-MS. Les analyses révèlent qu'au début du Bronze moyen, l'alimentation en cuivre se fait depuis le Pays de Galles, plus précisément depuis la mine de Great Orme. La diffusion de ce métal semble cantonnée aux régions attenantes au domaine atlantique et celles limitrophes à la Manche/Mer du Nord. Plus au sud, le long de la façade atlantique, dans la région aquitaine, le métal du dépôt de Martillac, tout en ayant la signature du métal de Great Orme, semble être mélangé avec du cuivre d'une autre région productrice, dont l'origine n'a pas encore été déterminée. À partir de la seconde période du Bronze moyen, les circuits changent radicalement avec du cuivre pouvant provenir d'une part de la péninsule ibérique (région de Huelva) ou d'Italie (Vlasugana) ainsi que de l'Autriche, notamment le domaine minier de Mitterberg. De plus, il est fort probablement que du métal provenant du secteur minier de Great Orme ait encore été utilisé à cette période, soit qu'il s'agisse de recyclage de métaux de la période précédente, soit que du métal ait été importé depuis le Pays de Galles, cette mine étant encore en activité à cette période. Ces réseaux semblent rester en place au cours de la première phase du Bronze final. Avec la deuxième période du Bronze final, l'alimentation en cuivre se diversifie. Cela transparaît à travers les analyses élémentaires. Ainsi, l'analyse d'objets de plusieurs dépôts du nord-ouest permet de mettre en évidence cinq signatures différentes, basées sur les compositions élémentaires qui peuvent traduire autant d'origines du cuivre différentes. À cette période, les objets produits contiennent du plomb dans l'alliage, parfois en forte teneur, ce que laisse penser que ce plomb est un ajout. Il est donc impossible de tracer l'origine du cuivre de ces objets en réalisant des analyses isotopiques. La particularité de certains de ces dépôts, c'est la présence de lingots barres très riches en plomb, dont des parallèles peuvent être trouvés avec des lingots présents dans les régions d'Europe centrale, bien que ceux-ci ne sont pas tout à fait similaires. Les fragments de lingots de cuivre sont rares dans ces dépôts mais ils existent cependant. Leur analyse isotopique pourrait traduire une origine d'Europe centrale. À la fin du Bronze final, la diversité de composition du métal est encore plus grande traduisant une complexification dans les réseaux. Les analyses élémentaires montrent sept signatures chimiques différentes. Ces objets contiennent tous du plomb dans l'alliage. Leur analyse isotopique montre bien qu'ils sont composés par des mélanges de métaux de différentes origines. Heureusement, de nombreux fragments de lingots de

cuivre sont présents dans les dépôts et permettent de proposer des origines pour ce métal. Ces origines sont très diverses allant des Alpes occidentales à l'Europe centrale (Slovaquie) en passant par le sud des Alpes italiennes. Du cuivre des régions méditerranéennes depuis Chypre, l'Espagne (Huelva), le sud de la France, et peut-être la Sardaigne, pourrait également avoir alimenté le nord-ouest de la France. Ainsi, à l'instar des autres études menées en Europe à partir des analyses élémentaires et isotopiques sur les objets des dépôts métalliques, les réseaux d'échange se complexifient à travers l'Europe, au fur et à mesure que l'on avance dans l'âge du Bronze. La poursuite des recherches est essentielle pour saisir l'ampleur et la chronologie des activités minières de cuivre au cours des différentes périodes historiques dans les cordillères Bétiques.

Mots clés : France du Nord-Ouest, âge du Bronze, dépôts métalliques, analyses chimiques élémentaires, analyses isotopiques du plomb, réseau d'échanges.

The Bronze Age is characterised by the use of bronze alloys, although these appeared earlier in Eastern Europe, probably during the Chalcolithic period. While the use of this alloy developed slowly during the Early Bronze Age, offsetting that of arsenic or non-arsenic copper, from the Middle Bronze Age onwards its increasingly important use can be seen in the many artefacts that make up terrestrial metal hoards. Of course, the metal recovered in this way only represents a fraction of the metal in circulation, but its chemical composition can still be considered partially representative of the metal stocks built up during each period in a defined region. All regions across Europe seem to have participated in this phenomenon, to a greater or lesser extent, even those without copper or tin ores. With the spread of metallurgy, metal trading networks were set up throughout Europe, as copper and tin ore deposits were unevenly distributed across the continent. These metal masses may have been transported over considerable distances across the continent, as studies of several European regions have shown, combining typological studies of the objects and elemental chemical and isotopic analyses of the lead in them (Ling et al., 2013; 2014; 2023; Pernicka et al., 2016; Melheim et al., 2018; Kmosek et al., 2020; Berger et al. 2022; Nowak et al., 2023; Bruyère et al., 2024). Western Europe has remained on the sidelines of these regional studies, and this work should contribute to a better understanding of the movement of metal masses towards the western extremity of Europe.

In the north-west of France, a very large number of Bronze Age metal objects have been discovered, mainly in terrestrial hoards (Briard, 1965; Milcent, 2012; Nordez, 2019; Bordas, 2023), but also in riverbeds (Mélin, 2011) and in graves (Nicolas, 2016), as well as isolated finds without any known context (Gandois, 2018). In the latter case, it was mainly flat axeheads that were found, most of which can probably be attributed to the Chalcolithic period, although a minority could be linked to the more recent Bronze Age. The main question that arises in this western region concerns the copper origin. Armorican deposits contain some evidence of copper, but most occurrences encountered are not recognised as significant deposits by modern geologists, except perhaps one sector located in the northern department of Finistère (Marcoux, 2017). However, while some areas may have been rich enough to be considered as small deposits, allowing for the production of artefacts in the earliest periods, it is clear that, at some point, given the size of the mass of metal needed for all the known artefacts, copper in metallic form has to have been imported from other regions of France or Europe.

The long-distance transport of masses of metal is still relatively unclear, particularly as regards their nature: primary-type copper ingots, secondary-type alloy ingots or objects. The presence of fragments of copper ingots in the metal hoards indicates that the raw material may have circulated in this form. This is particularly true of the Late Bronze Age, where copper ingots were numerous in hoards (Bordas, 2023). Secondary-type ingots of lead bronze alloys have also been found in Late Bronze Age deposits in western France (Boulud-Gazo et al., 2022), suggesting that these may also have travelled. The discovery of Bronze Age shipwrecks containing objects such as weapons and ornaments, in addition to ingots, shows that finished objects produced in distant regions also circulated (Berger et al., 2022). The circulation of the ornaments between the Atlantic and continental domains has also been demonstrated through elemental chemical analyses (Couderc et al., 2021). The movement of metal in these various forms, and perhaps from several different sources, might suggest that it is difficult, if not impossible, to obtain chemical and isotopic signatures that would enable us to characterise regional artefact production. What's more, exchange networks vary in space and time, further complicating the situation. Nevertheless, as other studies have already demonstrated (Gavranović et al., 2022; Ling et al., 2023), analyses carried out on statistically significant corpus make it possible to detect chemical signatures specific to a region for a defined period.

This is the approach that was initiated in western France as part of a program that began more than 15 years ago. The study presented here concerns the stages of the Bronze Age for which most of the metal objects have been found in hoards. The Early Bronze Age period is not covered. For the Early Bronze Age in north-western France, metal objects have been found in tombs and do not seem to reflect a massive production. From MBA1 onwards, various types of objects were deposited in hoards. This phenomenon continued into the Early Iron Age, albeit in varying forms and to various extents. The starting hypothesis is that, from MBA1 onwards, the quantity of metal buried is so great that new metal is needed to produce new objects in quantity. It should be remembered that north-western France is the region of France, if not Europe, with the greatest richness of metal contained in hoards. As the Armorican Massif does not seem to be rich enough in copper to produce all

these objects, it must have been necessary to bring in new copper from one or more copper-mining regions in Europe. Through an elementary analysis of the bronze objects and copper ingots found in the hoards, we will attempt to trace the origin of the copper.

CONTEXT OF THE BRONZE AGE IN NORTH-WESTERN FRANCE

The area covered by this study is a part of medio-Atlantic Europe, whose various definitions are based on the frequency of appearance and associations of types of metal production and specific cultural features (Milcent, 2012). Today, the existence of a cultural Atlantic Europe domain is no longer debated, but its limits and the internal dynamics that drive it still are (Bordas, 2023). For Milcent (2012), Atlantic Europe can be seen as "the image of a living, fairly fluid mechanism based mainly on the circulation of goods, people and ideas along the Atlantic coasts and within the lower basins of the main rivers that flow into them, on a scale that goes beyond community frameworks." As with the delimitation of territories, chronological limits are based essentially on the typology of bronze objects most often found in metal hoards from the Middle Bronze Age onwards, as well as their frequency of appearance and association.

The typology of the cultural artefacts reveals connections with the surrounding regions, providing an initial overview of the networks that developed during the Bronze Age (Milcent, 2012; Nordez, 2019; Bordas, 2023). Most of the known Bronze Age metal objects from north-western France come from non-funerary hoards. The nature and interpretation of these contexts remain open to debate, between economic needs (founders' reserves) and ritual practices. The typology of hoards based on the frequency of functional categories of objects, as well as their state of fragmentation, shows that the composition of hoards is not random and becomes increasingly complex over time (Bordas, 2023). There could therefore be an analytical bias towards this phenomenon. However, as we shall see below, this diversity is of little importance in the study of compositions when a sufficient number of chemical analyses are taken into account.

COPPER RESOURCES IN THE ARMORICAN MASSIF

The geological context of north-western France corresponds, for a very large part of the territory, to the Armorican Massif, whose latest major tectonic movements occurred during the Hercynian orogeny (400–300 Ma; Ballèvre et al., 2009). The terrain currently visible therefore corresponds to an ancient, now-eroded mountain belt, with numerous gold, tin, and lead deposits, but very little copper (fig. 1; Marcoux, 2017). Nevertheless, copper occurrences were observed by geologists at various points in Brittany in the early 19th century (Kerforne, 1926) and then later during intensive geological surveys between the 1960s and 1990s by the BRGM (Bureau de recherches géologiques et minières, the French Geological Survey, Orléans). These are essentially polymetallic sulphide mineralisations of the BGPC (Blende-Galena-Pyrite-Chalcopyrite) type. Chalcopyrite is usually speckled with other minerals but may also be present as veinlets (Pierrot et al., 1973; 1975). Fahlore could be also observed. Meteoric alteration zones are generally non-existent due to the acidity of the soils and the high rainfall. However, a few sectors did show some covellite and, much more rarely, malachite (Robert, 1970; Chauris et al., 1976). The quantities of these oxidised minerals are quite small. However, it is very difficult to determine the exact quantity of copper minerals in these deposits, as the descriptions made by geologists are often vague, using terms such as 'rich', 'rare', and 'very rare'. In a region where copper is rare, one sector may be described as 'rich' because it is exceptional in the regional context, although it is not a major deposit. Six sectors may nevertheless have contained copper in sufficient quantities to enable small-scale copper-mining operations to be carried out. Unfortunately, three sectors were intensively mined in modern times, destroying any areas that might have shown signs of earlier mining: Lanmeur (Finistère) for associated tin (Robert, 1970), and Huelgoat (Finistère), and, to a lesser extent, Trémuson (Côtes-d'Armor) for galena (Chauris et al., 1976). A fourth sector (Carnoët, Finistère) is currently under archaeological investigation; here, a very small copper mine was exploited in the 18th century (Mulot, 1984), and it is possible that some malachite may still be found. Unfortunately, for the moment no archaeological evidence of prehistoric mining has been found and no prehistoric mining tools have been discovered in connection with possible copper mining.

SAMPLING METHODOLOGY TO IDENTIFY THE CHEMICAL AND ISOTOPIC SIGNATURES OF METAL STOCKS

The objects analysed in this project, which focuses on western France, come exclusively from land-based metal hoards (table 1). In fact, analyses of metal from a casting workshop would make it possible to certify the working of a particular type of metal in a given region. However, workshops such as Aubervilliers (Melin et al., 2020) and Fort-Harrouard in the Paris region, or Montélimar in the Rhône valley (Néré et al., 2023) do not exist in the west. The two workshops recognised so far are at Mez Notariou on the island of Ouessant (Finistère), where the contexts are complex and no analysis has yet been carried out, and at Saint-Avé in Morbihan (unpublished), where no fragmentary metal waste has been found. At the latter site, only a few objects were collected in a pit in the workshop, in

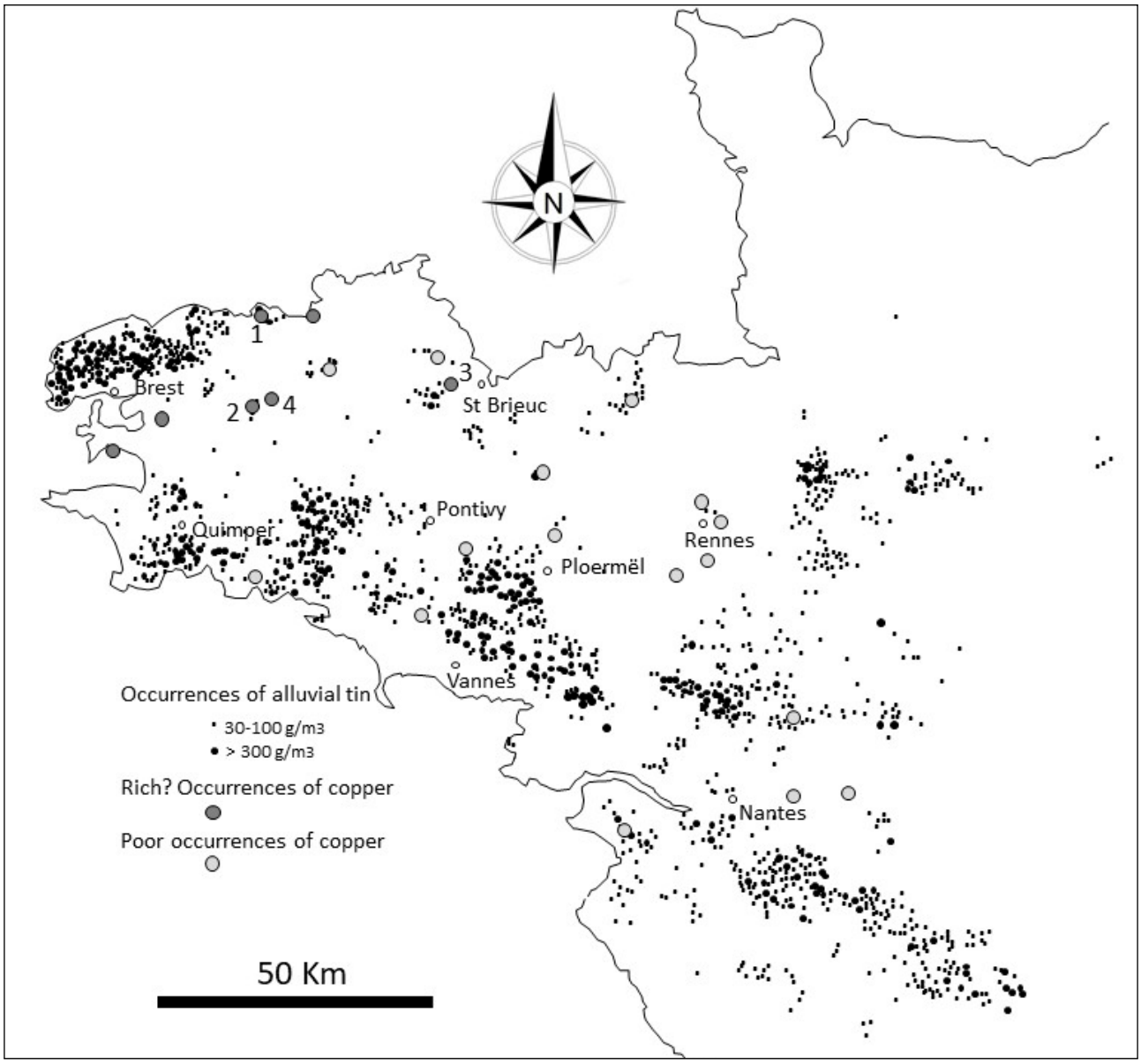


Fig. 1 – Distribution map of alluvial cassiterite (Guigues et Devismes, 1969) and copper occurrences in the Armorican Massif (data from Marcoux 2017). 1: Lanmeur; 2: Huelgoat; 3: Trémuson; 4: Carnoët.

what might have been a terrestrial metal hoard identified at the time as a foundry reserve. Analyses have not yet been carried out, however.

To establish a regional signature (or more than one), the study has therefore focused on objects found in terrestrial metal hoards. The hoards taken into account in the study largely correspond to those recently discovered, for which the context is known and the integrity is respected (table 1). Hoards found in the past, in the nineteenth century, were part of private collections where mixing may have occurred, particularly when they were passed on to heirs. Thus, for a long time, Armorican-type socketed axes were placed at the very end of the Bronze Age, whereas it is now known that they were produced during the Early Iron Age. Lengthy historiographical investigations have brought this to light (Gomez de Soto, 2014), and elementary chemical analyses have finally demonstrated it (Le Carlier de Veslud et al., 2018). However, some older hoards have been analysed. These are the eponymous hoards, such as those at Tréboul, Rosnoën and Saint-Brieuc-des-Iffs. Knowledge of the accurate context of these deposits is essential if the analyses are to be correctly interpreted in terms of chronology. Once the signatures for each period are known, it is then possible to follow any continuities in the use of the objects in subsequent periods.

The sampling, which is statistically representative, focuses on several types of objects where possible. For some periods, for example, no copper ingots are known to exist in the deposits. Sampling is concentrated on finished objects with an a priori ‘regional’ typological affinity. For hoards with a wide variety of objects, all functional categories are taken into account in the sampling.

Hoard	Department	Period	Nb. elementary analyses	Nb. analyses in annexes	Nb. isotopic analyses	Nb. analyses in annexes	Comments
Tréboul	29	MBAa1	77	77	5	5	
Martillac	33	MBAa1	14	14	5	5	
Boisgervilly	35	MBAa2	13	13	5	5	
Boulay-Morin	27	MBAa2	10	10	5	5	
Saint-Thois	29	MBAa2	30	30	0	0	
Heucqueville	27	MBAa2	41	41	0	0	
Saint-Germain d'Esteuil	33	MBAa2	6	6	3	3	
Malassis-copper ingots	36	MBAa2	19	19	10	10	
Malassis objects	36	MBAa2	27	27	5	5	
Rosnoën	29	LBAa1	12	12	5	5	
Saint-Brieuc-des-Ifs	35	LBAa2	26	26	6	6	
Plérin	*22*	*LBAa2*	*27*	*0*	*0*	*0*	*in a forthcoming publication*
Soullans	*85*	*LBAa2*	*73*	*0*	*11*	*0*	*in a forthcoming publication*
Saint-Sauveur	*50*	*LBAa3b*	*20*	*0*	*2*	*2*	*Gandois and al., 2019*
Mérézel	*56*	*LBAa3b*	*139*	*0*	*14*	*0*	*in a forthcoming publication*
Lanhuron	*29*	*LBAa3b*	*25*	*0*	*13*	*0*	*in a forthcoming publication*

Table 1 – List of hoards analysed in this study, including the number of elemental analyses carried out on deposit objects and the number of those shown in table 2, as well as the number of isotopic analyses and the number of those shown in table 3. Hoards written in italics correspond to those whose analyses were used to produce the diagrams. These analyses are either already published, or will be in another submitted publication.

On the other hand, many sampled objects are foundry waste, such as feeders or crucible bottoms, which are probably less likely to have been transported over long distances than other objects, such as ornaments. Primary copper ingots also help to identify these signatures, because if they are present in the region concerned, it means that some of them were potentially used to produce objects. Isotopic analysis of the lead contained in these ingots allows us to put forward hypotheses as to their origin, and to see whether they come from one or more producing regions. Numerous analyses of objects from north-western France have revealed consistent levels of the main trace elements (silver Ag, arsenic As, nickel Ni, and antimony Sb) over a given period, defining regional chemical signatures (Le Carlier de Veslud et al., 2017; 2018; Le Carlier de Veslud and Le Bannier, 2018). In addition, other elements such as iron (Fe), cobalt (Co), and bismuth (Bi) can also be identified. These vary from period to period, indicating changes in metal supply. These materials constitute stocks of metals for the production of objects of regional typology.

Putting these results into perspective with those obtained for other regions helps to sketch out the geographical contours of these regional signatures, for each major period of the Bronze Age. These regions supplied by the same sources could be very vast, or even correspond more or less to the boundaries of cultural domains (Véber et al., 2003). Assuming that the copper supply in these distant regions came from different sources, the objects produced in these regions would have different chemical compositions. It is therefore important to know the chemical and isotopic signature of objects from the same period in several given regions, on the assumption that they were produced there, and to compare them.

ANALYSIS METHODS

Numerous elementary chemical analyses were carried out between the 1960s and 1990s in Rennes (Giot et al., 1975; Bourhis and Briard, 1979, Briard and Bourhis, 1984). These analyses made it possible to identify the nature of the alloys making up the objects and to observe possible differences between the different periods. However, the number of analyses is too small and the sampling is often too disparate, making it difficult to identify the signatures. In addition, since these analyses were carried out using an arc spectrometer, they lack the precision required to identify different signatures. As a result, these older analyses were not used at all in this programme, which only uses analyses carried out in Rennes over the last fifteen years.

Samples were taken with a micro-drill from the sound metal after stripping of the weathered surface layer, enabling more than 40 mg of metal to be taken, leaving a surface impact of around 1 mm. The quantity of metal sampled is important for the representativeness of the analysis. In fact, metals can have a small chemical variability. This may be due to segregation caused by the slow cooling of a thick object. It may also be due to the presence of lead 'balls'. These metallic atoms tend not to associate with the copper atoms in the alloy and tend to gather in masses of varying size depending on the lead content of the alloy and the cooling rate of the moulded object. Thus, with 40 mg of material sampled, sampling is less sensitive to these analytical biases than with smaller samples. Analyses carried out on several zones of the same object have shown that this type of sampling enables us to see that trace element levels are more or less the same throughout the object (Le Carlier de Veslud and Le Bannier, 2018).

Elemental compositions of major (Cu, Sn, Pb) and trace (Ag, As, Bi, Co, Fe, Ni, Sb, Zn) elements of the samples taken were obtained at the Archéosciences laboratory in Rennes by ICP-OES (Inductively Coupled Plasma - Optical Emission Spectrometry; Ultima Expert). The analysis protocol is based on that of Mille and Bourgarit (2000) and is fully described in Aranda et al. (2013). Alloying elements are given in percentages (calculated from concentration in mg/l), and trace elements in ppm (10,000 ppm = 1%). The machine was calibrated using 22 standards with a wide concentration range for each element, giving a negligible measurement error. The uncertainties are mainly a result of laboratory manipulations. The uncertainties are 1.6% for tin and lead, and 2.2% for copper and all trace elements. An international standard (Br 207) of known composition was analysed at the same time as the samples to verify that there was no machine deviation during the analysis sessions, and from one session to the next.

In accordance with the results from the whole elemental analysis of alloy and typology, some objects were chosen to measure the Pb isotopic ratios. Priority is given to copper ingots, when they exist, because they have the isotopic ratios of the ores from which they are extracted. According to the period, bronze objects have one or more basic elemental chemical compositions. Where several groups can be defined on the basis of their elemental composition, isotopic analyses are carried out, as far as possible, on bronze objects in each group, and even better on copper ingots. This program has not yet been fully achieved due to a lack of funds to carry out these expensive analyses. In each group, when they exist, objects with a 'regional' typology have been chosen as a priority in order to identify a signature that could be representative of a local production of objects.

'Classic' bronze objects, which do not contain lead in the alloy, are also analysed as a priority. Contents of several percent can be interpreted as lead additions, changing the isotopic signature of objects and making it impossible to trace the copper ore. But we also have to be careful with these wrongly substantiated interpretations. Thus, at the Great Orme mine, it was found that lead, in the form of PbS galena, accompanied copper mineralisation (especially malachite) in the deposit (Williams, 2023). As it was impossible to completely separate the galena from the copper-bearing minerals because the minerals were so intertwined, it was this combination that was introduced into the smelting furnace. The copper produced, which may contain a few percent lead, has the isotopic signature of galena rather than malachite. Lead isotope analyses are also carried out on lead-rich objects. The aim is to trace lead additions to objects if these appear to be evidence, or to recognise signatures representative of lead-rich copper deposits. In the case of the MBA1 objects from the Great Orme mine, the origin of the leaded copper was not too difficult to identify. This is not the case with the Late Bronze Age artefacts, which have much higher lead contents and diverse elemental chemical signatures. In the latter case, there are probably mixtures of copper sources and perhaps additions of lead.

Lead isotope analyses have been initiated and realised in SEDISOR/GEO-OCEAN in Brest, Finistère. Approximately 10 mg of sample powder was dissolved in Teflon beakers in a mixture of HNO_3 (^{14}N) and HCl (^{10}N) *(aqua regia)* at an elevated temperature (100 °C) for 36 hours. After evaporation, the solid residues were recovered in ^{1}N HNO_3 and the Pb was separated on a column using the protocol described by Gale (1996). Measurements of Pb isotopic compositions were carried out by MC-ICP-MS Neptune (Thermo Scientific) at the Pôle de Spectrométrie Océan in Brest. The Pb isotope ratios were corrected for instrumental bias and isotopic fractionation using White's Tl method (White et al., 2000) and the NIST SRM 981 measurement for all three samples. The reproducibility of the measurements is of the order of 0.002 (2 σ) for $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ and 0.005 (2 σ) for $^{208}Pb/^{204}Pb$. These three isotope ratios are taken into account in the search for copper sources by comparing the values of the objects analysed in this study with those of mineralised domains in Europe, known to have been exploited in ancient times, or showing strong suspicion of exploitation. As all the domains have been tested, if they are not mentioned in the following paragraphs, it is because they do not correspond to the isotopic values of the objects analysed. To simplify reading, the diagrams only show the domains that may correspond to the objects. The domains taken into account correspond to major domains actually known (table 2). The validity of the isotopic signatures of these areas varies from one to another. While some mining sectors are well known in terms of mining archaeology, such as the Great Orme, Ross Island and Mitterberg mines, other sectors are less well understood. For example, Sardinia and Romania are known through the analysis of mineralisation sampled by geologists. We don't really know whether they were mined in ancient times. Another interpretation problem concerns the high isotopic variability of certain areas. For example, Slovakia has a very high isotopic variability, which often leads to this region being proposed as a potential source. Similarly, the overlap in the isotopic diagrams of several mining areas raises the question of the validity of this method alone. It is then necessary to compare these isotopic data with the elemental chemical compositions, which can help to discriminate between sources. Finally, there are mineralised areas that are not yet known, or have not been sufficiently analysed. These include veins in the Pyrenees and Vosges mountains for example.

Finally, propositions made in this work are no more than hypotheses. Only the comparison with archaeological data (typological affinities of metal objects, but also of other materials such as ceramics and lithics) can help to confirm these hypotheses. The essential contribution of this analytical approach is to be able to say where copper does not come from.

Ross Island	Rohl and Needham, 1998
Copa Hill	Rohl and Needham, 1998
Great Orme	Williams, 2023
centre and south west Sardinia	Begemann et al., 2001; Boni and Köppel, 1985
North and north-west Sardinia	Stos-Gale et al., 1997; Begemann et al., 2001
France Cabrières	Pranges and Amber, 2005
France Queyras (included. Saint Véran)	Artioli et al., 2014
Slovakia	Schreiner, 2007; Andras et al., 2010
Spain Jaén	Marcoux, 1998; Klein et al., 2009
Spain Huelva	Marcoux, 1998; Klein et al., 2009
Spain Asturies	Huelga-Suarez et al., 2012
Italia Vlasugana	Artioli et al., 2014
Italia south Toscane	Artioli et al., 2014
Italia South Alps AATV	Artioli et al., 2014
Cyprus	Stos-Gale and Gale, 1994
Austria Tyrol	Höppner et al., 2005
Austria Mitterberg	Pernicka et al., 2016
Romania Baia Mare	Marcoux et al., 2002
Romania Apuseni	Marcoux et al., 2002

Table 2 – Copper-mining domains known by isotopic analyses, used to compare with isotopic analyses obtained on Bronze Age objects and ingots studied in this work.

RESULTS FOR EACH BRONZE AGE PERIOD

First stage of Middle Bronze Age (MBA1/ Bz B): Tréboul horizon (1550–1450 BC)

The discovery of the Tréboul hoard (fig. 2) has enabled us to group some bronze objects, found in the deposit or on their own. Briard (1965) listed a number of these objects, mainly located in Brittany. He then noted a greater density of objects to the west of Brittany. In 1990 the Tréboul horizon was updated with the addition of discoveries and the revision of older ones (Briard, 1990). The group then grew to around thirty ensembles and over forty individual objects. This shows that its influence is more extensive than previously thought, extending right up to the limits of Upper Brittany. To the south, along the Atlantic coast, it is difficult to pinpoint the limits of dispersion of this type of object. It should be noted that long-flanged axeheads are found in the Médoc (Lagarde-Cardona, 2012) and Vendée (Pautreau, 1979), though also in Brittany, but palstaves come from Brittany, Normandy and the mid-western region (Nordez, 2019). Two hoards were analysed for this period. These include a part of the Tréboul hoard (Finistère), and some axes from the Martillac hoard (Gironde).

For the Tréboul hoard, which contains 142 objects, seventy-seven objects were analysed for elemental chemistry (table 3). These include twenty-four fragments of undetermined axes, ten flanged axes, three palstaves, eight fragments of spearheads, two sword heads, seventeen fragments of sword blades, two fragments of daggers, two rivets, seven masselottes and two floor castings. Five lead isotope analyses were also carried out (table 3): a flanged axe, a fragment of an axe, two fragments of sword edge and a masselotte. For the Martillac hoard (fig. 2), 14 flanged axes were analysed for elemental chemistry (table 2), and 5 of them were analysed for isotopy (table 4).

The elemental chemical composition of all objects is identical with objects made of 'classic' bronze (lead content up to 0,1 %) and others of lead-rich bronze of up to 15.3 % Pb (average at 0,58 %; table 3). The tin content (2.37 to 18.09 %, average at 10.66 %) varied for all the objects with no influence from the lead content. As for trace elements, the composition is identical between classic bronze and lead bronze objects. There is a clear positive correlation between As and Ni (fig. 3). Similarly, isotopic compositions were identical between the two groups (table 3). The presence of lead did not influence the isotope ratio values. The axes from the Martillac hoard contain less lead (up to 0.54 %, average 0.15 %) and tin (4.05 to 12.14 %, average at 7.59 %) than the objects from Tréboul. While the Ag, As, and Ni contents are approximately identical between the two hoards, the Sb content shows a very clear difference, with a much higher content in the axes from Martillac than in the objects from Tréboul. This would seem to indicate a probable different origin for the copper.

With regard to isotopic analyses (table 4), the $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios of the objects from Tréboul are all compatible with only two areas of production: the Great Orme mine and the Slovakia deposits (fig. 4). These objects show a very strong typological affinity with objects from the Acton Park horizon in the British Isles. The comparison of elemental and isotopic chemical compositions shows also a real correspondence (Williams and Le Carlier de Veslud, 2019). According to recent results, the copper in the 'Acton Park' type objects comes from the Great Orme mine. Indeed, it appears, judging from the similarity of chemical and isotopic compositions, that this metal was also used to produce the MBAa1 artefacts from the north-west of France. The higher or lower amount of lead is linked to the presence of galena veinlets within the deposit intersecting the cop-

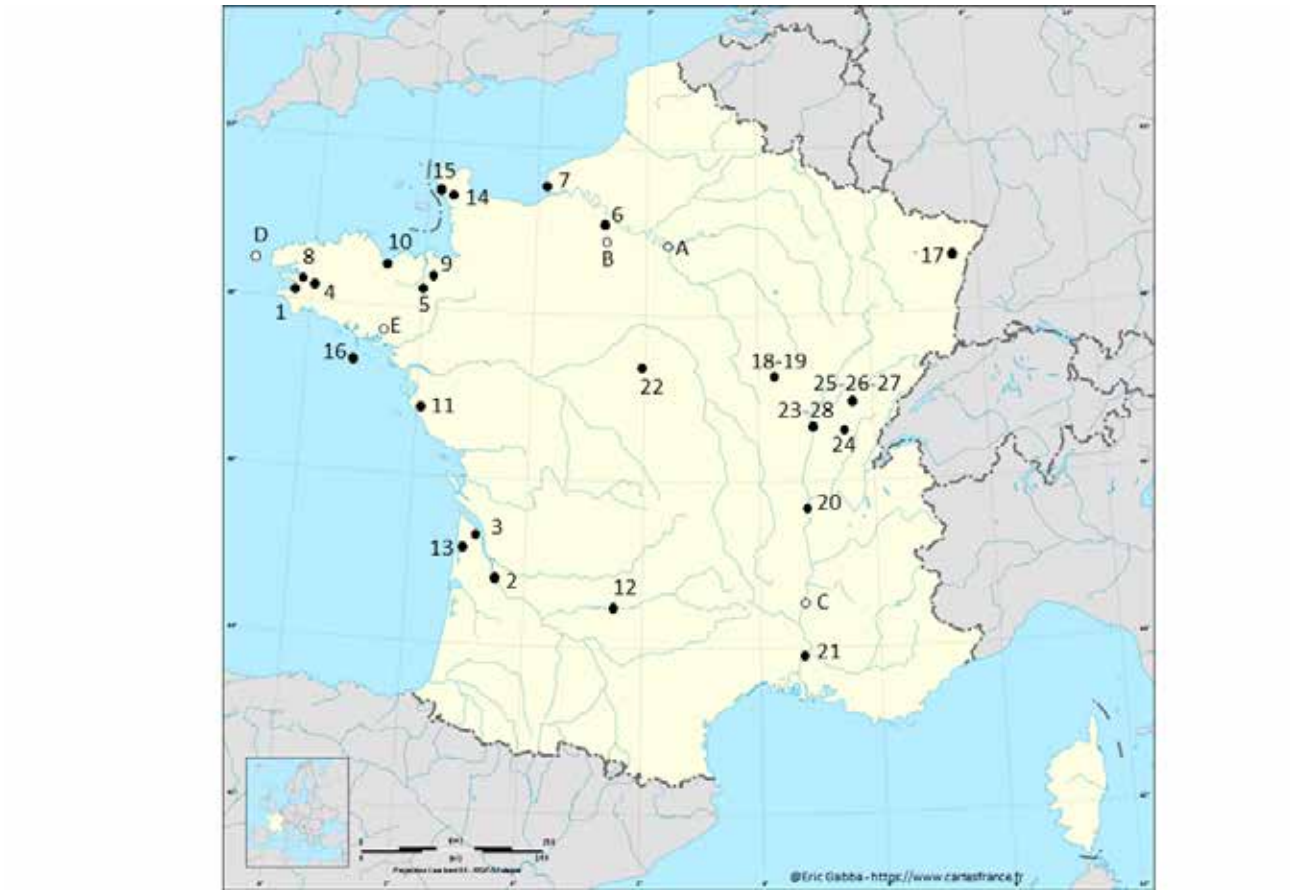


Fig. 2 – Location map of sites mentioned in text. *Atlantic hoards*: 1: Tréboul (MBA1); 2: Martillac (MBA1); 3:Saint-Germain-d'Esteuil (MBA2); 4: Saint-Thois (MBA2); 5: Boisgervilly (MBA2); 6: Boulay-Morin (MBA2); 7: Heucqueville (MBA2); 8: Rosnoën (LBA1); 9: Saint-Brieuc-des-Iffs (LBA2); 10: Plérin (LBA2); 11: Soullans (LBA2); 12: Saint-Sulpice (LBA2); 13: Hourtin (LBA3a); 14: Saint-Sauveur-Le-Vicomte (LBA3b); 15: Surtainville (LBA3b); 16: Mérézel (LBA3b). *Other location hoards*: 17: North-East (Hochfelden); 18: Centre-East (Granges-Sous-Grignon); 19: Centre-East (Vic-de-Chassenay); 20: Rhone valley (Ternay); 21: South (Monfrin-Romanès); 22: Malassis; 23: Centre-East (Ouroux-sur-Saône); 24: Centre-East (Lons-Le-Saunier); 25: Centre-East (Saizenay); 26: Centre East (Thézy); 27: Centre East (Prétin); 28: Centre East (Chalon-sur-Saône). *Workshops* : A: Aubervilliers; B: Fort-Harrouard; C: Montélimar; D: Mez Notariou; E: Saint-Avé. .

per deposit which may have been used in the composition of the charge in the smelting furnaces, hence the similarity of the isotopic compositions. It is therefore not a deliberate addition (Williams, 2023).

Concerning the axes from Martillac, for the three isotopic ratios, one object corresponds to the Tyrol domain or Slovakia, while the other four objects correspond to the Great Orme domain (fig. 4). These four compositions are slightly offset from those of the Tréboul objects while being aligned in the direction of the object located in the Tyrol or Slovakia domains. One possible hypothesis is that the Martillac axes may have been produced using a mixture of copper from two different sources, the main contribution being copper from the Great Orme, the other possibly being represented by Tyrol or Slovakia. This hypothesis needs to be confirmed by further analysis of objects from the Médoc.

Elemental analysis of artefacts of the same chronology from other French regions (the Rhône Valley, southern France, Burgundy and Alsace; fig. 2) shows that artefacts from Alsace (Ag content average at 1,037 ppm, As at 5,464 ppm, Ni at 17,482 ppm and Sb at 3,333 ppm) have a very different chemical composition (fig. 3). Similarly, artefacts from the south of France (Ag content average at 170 ppm, As at 1,097 ppm, Ni at 268 ppm and Sb at 204 ppm), from the Rhône Valley (Ag content average at 87 ppm, As at 1,012 ppm, Ni at 446 ppm and Sb at 53 ppm; Delrieu et al., 2015) and from Burgundy (Ag content average at 129 ppm, As at 1,652 ppm, Ni at 843 ppm and Sb at 172 ppm; Forel 2009) have a chemical composition similar to each other but different from that of the north-west and Alsace. Finally, the analysis of the artefacts of Tréboul shows that the spread of this metal seems to have involved only the regions close to the Atlantic/North Sea coast, as also reflected in A. Williams's research (2023).

Table 3 (right page) – Elemental compositions of Tréboul (MBA1), Martillac (MBA1), Boisgervilly (MBA2), Boulay-Morin (MBA2), Saint-Thois (MBA2), Heucqueville (MBA2), Saint-Germain-d'Esteuil (MBA2), Malassis (MBA2), Rosnoën (LBA1) and Saint-Brieuc-des-Iffs (LBA2) hoard artefacts.

Dépôt	Dpt	Period	Lab analysis #	Ech #	Type	Cu	Pb	Sn	Ag	As	Bi	Co	Fe	Ni	Sb	Zn
						(%)	(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
Tréboul	29	MBAa1	Ren-000822	49 5 16/22	axe (frgt)	83,04	0,11	14,11	395	16992	555	295	289	8243	154	476
Tréboul	29	MBAa1	Ren-000823	49 5 16/23	axe (frgt)	86,52	0,93	11,44	311	6450	571	171	111	2679	298	508
Tréboul	29	MBAa1	Ren-000824	49 5 16/21	axe (frgt)	87,04	0,80	11,04	338	6442	538	207	433	2399	279	458
Tréboul	29	MBAa1	Ren-000825	49 5 16/1	axe (frgt)	84,66	1,30	12,55	397	7774	552	270	2213	3033	144	488
Tréboul	29	MBAa1	Ren-000826	49 5 89	sword blade	93,07	0,06	5,73	326	7395	591	81	241	2089	187	528
Tréboul	29	MBAa1	Ren-000827	49 5 17/4	spear head	87,37	0,08	10,59	368	8378	556	265	6510	2769	236	513
Tréboul	29	MBAa1	Ren-000828	49 5 16/11	axe (frgt)	80,73	1,40	16,49	368	7927	503	240	608	3569	159	454
Tréboul	29	MBAa1	Ren-000829	49 5 16/9	axe (frgt)	88,86	0,16	9,86	208	2652	555	727	5195	1150	112	497
Tréboul	29	MBAa1	Ren-000830	49 5 16/15	axe (frgt)	88,40	0,37	10,21	313	5808	539	177	397	2188	322	486
Tréboul	29	MBAa1	Ren-000831	49 5 16/4	axe (frgt)	80,08	6,49	12,23	383	7067	510	193	378	2930	145	435
Tréboul	29	MBAa1	Ren-000832	49 5 16/8	axe (frgt)	83,18	3,83	11,53	374	7540	535	335	1305	3813	172	573
Tréboul	29	MBAa1	Ren-000833	49 5 16/19	axe (frgt)	81,82	6,45	10,52	385	7243	528	118	260	2948	154	476
Tréboul	29	MBAa1	Ren-000834	49 5 16/14	axe (frgt)	86,14	0,07	11,98	482	12455	546	142	363	3430	111	499
Tréboul	29	MBAa1	Ren-000835	49 5 16/3	axe (frgt)	88,36	0,41	10,07	345	6438	537	216	809	2592	161	485
Tréboul	29	MBAa1	Ren-000836	49 5 16/20	axe (frgt)	82,78	0,42	14,60	343	13935	534	211	347	5977	130	489
Tréboul	29	MBAa1	Ren-000837	49 5 16/16	axe (frgt)	79,91	1,19	18,09	253	5161	495	14	94	1497	113	429
Tréboul	29	MBAa1	Ren-000838	49 5 16/6	axe (frgt)	86,83	1,05	10,95	330	6693	539	216	533	2770	206	475
Tréboul	29	MBAa1	Ren-000839	49 5 101/5	masselotte	87,42	0,12	11,51	307	6022	539	122	600	1420	105	455
Tréboul	29	MBAa1	Ren-000840	49 5 101/3	masselotte	89,15	0,46	8,86	349	7440	537	316	3058	2929	178	509
Tréboul	29	MBAa1	Ren-000841	49 5 88	sword blade	90,12	0,28	8,76	298	4310	581	164	465	1762	305	499
Tréboul	29	MBAa1	Ren-000842	49 5 18	spear head	82,23	0,19	16,57	304	5137	517	176	702	1827	981	432
Tréboul	29	MBAa1	Ren-000843	49 5 93	sword blade	90,42	0,28	8,36	318	4522	546	179	1044	1825	444	504
Tréboul	29	MBAa1	Ren-000844	49 5 44	dagger base	88,85	0,07	10,53	175	2455	539	110	776	863	85	471
Tréboul	29	MBAa1	Ren-000845	49 5 95	sword blade	89,93	0,58	8,47	314	5765	547	135	604	2160	134	483
Tréboul	29	MBAa1	Ren-000846	49 5 17/2	spear head	92,18	0,05	5,46	379	8139	562	584	8696	4065	164	534
Tréboul	29	MBAa1	Ren-000847	49 5 73	dagger base	88,02	0,45	10,42	292	5889	559	230	570	2736	236	534
Tréboul	29	MBAa1	Ren-000848	49 5 57	sword blade	90,37	0,00	9,27	40	1198	630	118	208	448	416	517
Tréboul	29	MBAa1	Ren-000849	49 5 70/8	Rivet	90,07	0,33	8,61	192	5056	576	184	1209	1940	114	550
Tréboul	29	MBAa1	Ren-000850	49 5 101/1	masselotte	85,65	3,26	9,80	611	5535	542	166	1204	3690	585	522
Tréboul	29	MBAa1	Ren-000851	49 5 86/1	sword head	83,57	1,45	13,83	706	5503	544	184	1420	2600	151	486
Tréboul	29	MBAa1	Ren-000852	49 5 62	sword blade	87,28	0,00	11,61	718	5247	551	227	1566	2129	164	547
Tréboul	29	MBAa1	Ren-000853	49 5 28	spear head	88,69	0,21	9,99	949	5536	565	227	459	2106	709	538
Tréboul	29	MBAa1	Ren-000854	49 5 101/2	masselotte	87,89	1,09	9,98	494	5394	547	202	752	2221	322	512
Tréboul	29	MBAa1	Ren-000855	49 5 61	sword blade	84,68	3,13	11,01	832	5812	524	234	986	2742	176	494
Tréboul	29	MBAa1	Ren-000856	49 5 6	long flanged axe	86,36	1,08	11,41	360	5649	536	246	1268	2625	279	527
Tréboul	29	MBAa1	Ren-000857	49 5 101/4	masselotte	87,29	1,03	10,60	632	5488	545	193	723	2412	298	543
Tréboul	29	MBAa1	Ren-000858	49 5 70/9	Rivet	83,61	0,88	14,48	589	5152	515	125	34	3043	320	503
Tréboul	29	MBAa1	Ren-000859	49 5 101/8	masselotte	92,99	0,24	2,37	100	1953	558	983	38783	942	0	659
Tréboul	29	MBAa1	Ren-000860	49 5 24	spear head	87,92	0,00	10,97	904	6342	536	114	850	1659	79	545
Tréboul	29	MBAa1	Ren-000861	49 5 101/7	masselotte	87,14	1,34	10,46	509	5531	534	205	270	2597	336	543
Tréboul	29	MBAa1	Ren-000862	49 5 22	spear head	88,85	0,47	9,84	517	3958	558	203	545	1709	382	514
Tréboul	29	MBAa1	Ren-000863	49 5 83	sword head	88,91	0,16	9,72	475	5738	533	261	2121	2111	304	538
Tréboul	29	MBAa1	Ren-000864	49 5 25	spear head	82,74	2,72	13,09	1030	7347	505	365	1993	2614	218	463
Tréboul	29	MBAa1	Ren-000865	49 5 63	sword blade	91,31	0,00	7,80	902	3607	570	115	644	1227	1342	512
Tréboul	29	MBAa1	Ren-000866	49 5 21	spear head	84,22	4,91	9,80	697	5792	538	170	567	2297	231	495
Tréboul	29	MBAa1	Ren-000867	49 5 48	sword blade	89,51	0,15	9,54	67	3591	527	353	1140	1652	258	525
Tréboul	29	MBAa1	Ren-000868	49 5 8	long flanged axe	84,62	3,40	11,21	105	3812	566	179	455	1602	474	506
Tréboul	29	MBAa1	Ren-000869	49 5 101/6	masselotte	91,22	0,02	7,91	426	4418	568	139	306	1889	189	533
Tréboul	29	MBAa1	Ren-000870	49 5 101/9	masselotte	84,99	0,63	13,25	344	5719	524	188	1611	2106	327	514
Tréboul	29	MBAa1	Ren-000871	49 5 67	sword blade	88,66	0,00	10,45	351	4467	540	153	730	1442	663	499
Tréboul	29	MBAa1	Ren-000872	49 5 58	sword blade	91,30	0,10	7,50	315	6171	547	185	1467	1653	276	421
Tréboul	29	MBAa1	Ren-000873	49 5 16/34	axe (frgt)	75,78	15,31	7,85	377	6888	477	16	35	2278	204	328
Tréboul	29	MBAa1	Ren-000874	49 5 10	long flanged axe	85,48	1,01	11,89	382	8045	548	274	3525	2697	321	436
Tréboul	29	MBAa1	Ren-000875	49 5 56	sword blade	91,50	0,37	7,35	271	4294	551	181	344	1450	300	416
Tréboul	29	MBAa1	Ren-000876	49 5 53	sword blade	88,44	0,72	9,05	324	6853	569	373	6285	2851	256	449
Tréboul	29	MBAa1	Ren-000877	49 5 16/28	axe (frgt)	80,29	3,02	15,37	300	7194	520	218	989	3367	211	411
Tréboul	29	MBAa1	Ren-000878	49 5 14b	palstave	89,61	0,17	8,83	376	8193	539	131	896	3093	232	431
Tréboul	29	MBAa1	Ren-000879	49 5 9	long flanged axe	87,68	0,94	9,83	398	8117	546	366	2045	3182	322	448
Tréboul	29	MBAa1	Ren-000880	49 5 14a	palstave	89,73	0,13	8,77	387	8595	571	127	384	3029	221	446
Tréboul	29	MBAa1	Ren-000881	49 5 3	long flanged axe	87,88	0,48	10,43	348	6959	545	186	940	2317	407	405
Tréboul	29	MBAa1	Ren-000882	49 5 16/2	axe (frgt)	87,48	1,40	9,99	311	6102	536	223	1092	2399	201	402
Tréboul	29	MBAa1	Ren-000883	49 5 15	palstave	92,10	0,75	4,91	434	10436	586	688	3458	6067	234	461
Tréboul	29	MBAa1	Ren-000884	49 5 54	sword blade	89,60	0,34	8,94	420	6136	545	190	1009	2044	374	441
Tréboul	29	MBAa1	Ren-000885	49 5 16/7	axe (frgt)	85,54	2,08	11,14	360	7391	547	200	666	2709	232	408
Tréboul	29	MBAa1	Ren-000886	49 5 52	sword blade	89,18	0,59	9,15	303	6161	561	156	933	2053	216	416
Tréboul	29	MBAa1	Ren-000887	49 5 16/17	axe (frgt)	80,52	4,64	13,49	294	6965	498	367	1674	3054	216	379
Tréboul	29	MBAa1	Ren-000888	49 5 16/18	axe (frgt)	89,53	0,31	9,12	295	6095	569	149	204	2125	541	427
Tréboul	29	MBAa1	Ren-000889	49 5 5	long flanged axe	85,90	1,13	11,86	382	6469	528	152	451	2206	524	408
Tréboul	29	MBAa1	Ren-000890	49 5 49	sword blade	86,80	0,61	11,37	312	6804	556	193	1285	2432	225	408
Tréboul	29	MBAa1	Ren-000891	49 5 4	long flanged axe	87,88	0,31	10,68	354	6376	564	187	772	2079	466	428
Tréboul	29	MBAa1	Ren-000892	49 5 90	sword blade	85,58	1,47	11,79	342	7002	542	194	106	2762	230	416
Tréboul	29	MBAa1	Ren-000893	49 5 7	long flanged axe	82,98	3,34	12,08	391	7880	551	557	3362	2623	265	420
Tréboul	29	MBAa1	Ren-000894	49 5 16/5	axe (frgt)	84,32	1,98	12,51	322	6906	516	189	640	2664	202	386
Tréboul	29	MBAa1	Ren-000895	49 5 16/10	axe (frgt)	86,95	2,05	9,82	333	6388	533	226	764	2844	303	397
Tréboul	29	MBAa1	Ren-000896	49 5 13	long flanged axe	88,98	0,42	9,58	324	5129	559	277	1188	1874	403	442
Tréboul	29	MBAa1	Ren-000897	49 5 2	long flanged axe	86,75	0,64	11,36	369	6951	559	206	1192	2411	371	511
Tréboul	29	MBAa1	Ren-000898	49 5 16/12	axe (frgt)	82,21	0,31	16,12	293	6834	517	206	2068	2890	217	501
minimum						75,78	0,00	2,37	40	1198	477	14	34	448	0	328
maximum						93,07	15,31	18,09	1030	16992	630	983	38783	8243	1342	659
médiane						87,37	0,58	10,46	351	6171	545	193	772	2411	232	486

Dépôt	Dpt	Period	Lab analysis #	Ech #	Type	Cu	Pb	Sn	Ag	As	Bi	Co	Fe	Ni	Sb	Zn
						(%)	(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
Martillac	33	MBAa1	Ren-001524	mart 10	long flanged axe	90,25	0,09	8,40	166	5867	719	224	148	3707	1009	749
Martillac	33	MBAa1	Ren-001525	mart 24	long flanged axe	91,78	0,06	5,68	129	9287	794	765	165	9919	2863	942
Martillac	33	MBAa1	Ren-001526	mart 9	long flanged axe	91,04	0,03	7,85	85	4871	687	33	79	3952	411	742
Martillac	33	MBAa1	Ren-001527	mart 6	long flanged axe	90,48	0,16	7,88	161	7301	795	300	209	4401	859	744
Martillac	33	MBAa1	Ren-001528	mart 13	long flanged axe	89,85	0,54	8,47	239	5352	723	219	149	3267	700	744
Martillac	33	MBAa1	Ren-001529	mart 3	long flanged axe	91,55	0,24	6,97	191	6036	760	216	253	3095	1033	763
Martillac	33	MBAa1	Ren-001530	mart 5	long flanged axe	90,06	0,15	8,09	3740	6459	737	206	241	3679	1171	779
Martillac	33	MBAa1	Ren-001531	mart 18	long flanged axe	91,12	0,14	7,19	240	7583	774	259	372	4052	1439	792
Martillac	33	MBAa1	Ren-001532	mart 19	long flanged axe	90,14	0,24	8,76	275	2733	590	295	423	2613	836	747
Martillac	33	MBAa1	Ren-001533	mart 7	long flanged axe	92,18	0,07	5,22	203	12733	869	357	271	7208	2862	758
Martillac	33	MBAa1	Ren-001534	mart 15	long flanged axe	86,30	0,16	12,14	224	6946	683	306	338	3843	1020	618
Martillac	33	MBAa1	Ren-001535	mart 21	long flanged axe	93,21	0,10	4,05	161	14464	959	432	395	7476	1669	869
Martillac	33	MBAa1	Ren-001536	mart 1	long flanged axe	90,74	0,25	7,81	287	5552	670	118	291	2895	1479	703
Martillac	33	MBAa1	Ren-001537	mart 2	long flanged axe	90,07	0,07	7,70	163	10334	893	409	95	7111	1885	748
minimum						86,30	0,03	4,05	85	2733	590	33	79	2613	411	618
maximum						93,21	0,54	12,14	3740	14464	959	765	423	9919	2863	942
médiane						90,61	0,15	7,83	197	6702	748	277	247	3898	1102	748
Boisgervilly	35	MBAa2	ren-000774	1	palstave	81,95	0,08	16,65	190	4555	524	295	884	5728	746	338
Boisgervilly	35	MBAa2	ren-000775	2	palstave	82,95	0,19	15,79	289	3758	552	305	586	3823	1075	354
Boisgervilly	35	MBAa2	ren-000776	3	palstave	83,99	0,22	14,72	690	2523	528	217	2182	3663	483	377
Boisgervilly	35	MBAa2	ren-000777	4	palstave	86,24	0,01	12,85	125	1948	510	367	1812	3552	404	271
Boisgervilly	35	MBAa2	ren-000778	5	palstave	82,96	0,15	15,78	220	3852	548	357	362	4622	808	336
Boisgervilly	35	MBAa2	ren-000779	6	palstave	81,52	0,09	16,66	186	6000	526	412	1503	7479	918	325
Boisgervilly	35	MBAa2	ren-000780	7	palstave	83,68	0,13	15,25	203	2924	523	287	552	3902	691	327
Boisgervilly	35	MBAa2	ren-000781	8	palstave	79,79	0,06	18,86	155	3249	501	379	2491	5265	485	305
Boisgervilly	35	MBAa2	ren-000782	9	palstave	82,31	0,14	16,27	231	4560	557	360	621	5058	1077	324
Boisgervilly	35	MBAa2	ren-000783	10	palstave	81,17	0,12	17,22	201	5861	545	386	995	5634	949	344
Boisgervilly	35	MBAa2	ren-000784	11	palstave	81,63	0,13	17,13	226	4196	546	309	109	4239	1123	297
Boisgervilly	35	MBAa2	ren-000785	12	palstave	83,29	0,12	14,77	214	6174	541	572	1301	8274	845	326
Boisgervilly	35	MBAa2	ren-000786	13	palstave	82,47	0,32	16,05	248	4233	563	329	518	4424	913	310
minimum						79,79	0,01	12,85	125	1948	501	217	109	3552	3552	404
maximum						86,24	0,32	18,86	690	6174	563	572	2491	8274	8274	1123
médiane						82,47	0,13	16,05	214	4196	541	357	884	4622	4622	845
Boulay-Morin	27	MBAa2	ren-000678	3471	palstave	85,69	0,02	13,99	113	1071	587	55	0	520	351	506
Boulay-Morin	27	MBAa2	ren-000679	3472	palstave	88,47	0,14	9,72	222	4050	613	541	2968	6147	1543	624
Boulay-Morin	27	MBAa2	ren-000680	3473	palstave	80,80	0,13	17,71	235	3158	621	274	630	6730	1461	575
Boulay-Morin	27	MBAa2	ren-000681	3474	palstave	80,12	0,15	18,51	243	3009	548	396	983	5495	1095	431
Boulay-Morin	27	MBAa2	ren-000682	3475	palstave	85,35	0,07	13,48	212	2536	599	175	301	4626	2078	518
Boulay-Morin	27	MBAa2	ren-000683	3476	palstave	85,44	0,15	13,30	233	3464	579	174	0	5226	1266	521
Boulay-Morin	27	MBAa2	ren-000684	3477	palstave	79,83	0,35	18,86	341	2689	589	275	622	3470	914	677
Boulay-Morin	27	MBAa2	ren-000685	3478	palstave	82,64	0,16	16,04	319	2851	543	211	381	5345	1378	542
Boulay-Morin	27	MBAa2	ren-000686	3479	palstave	81,30	0,25	16,46	273	4478	568	331	3955	8307	1282	689
Boulay-Morin	27	MBAa2	ren-000687	3482	palstave	80,44	1,42	17,07	256	2977	548	262	9	4662	1003	953
minimum						79,83	0,02	9,72	113	1071	543	55	0	520	351	431
maximum						88,47	1,42	18,86	341	4478	621	541	3955	8307	2078	953
médiane						81,97	0,15	16,25	239	2993	583	268	502	5286	1274	559
Saint-Thois	29	MBAa2	ren-000505	ST8	palstave	81,72	0,17	16,96	92	2285	551	294	326	5900	1336	672
Saint-Thois	29	MBAa2	ren-000506	ST12	palstave	87,79	0,03	11,24	29	1930	558	748	183	4765	506	686
Saint-Thois	29	MBAa2	ren-000507	ST30	palstave	82,55	0,05	15,30	43	6098	518	560	4329	8063	747	678
Saint-Thois	29	MBAa2	ren-000508	ST40	palstave	88,41	0,07	10,81	25	2123	557	188	540	2505	466	632
Saint-Thois	29	MBAa2	ren-000509	ST43a	palstave	84,17	0,16	14,92	83	1365	574	246	383	3110	1059	696
Saint-Thois	29	MBAa2	ren-000510	ST43b	palstave	84,32	0,15	14,75	65	1330	568	255	674	3115	1015	802
Saint-Thois	29	MBAa2	ren-000511	ST44	palstave	88,23	0,08	9,78	40	11473	611	169	97	4954	986	743
Saint-Thois	29	MBAa2	ren-000512	ST48	palstave	81,68	3,70	13,72	747	1937	712	179	601	3160	903	767
Saint-Thois	29	MBAa2	ren-000513	ST53	palstave	84,10	0,07	14,69	38	2446	553	245	86	6258	1062	677
Saint-Thois	29	MBAa2	ren-000514	ST54a	palstave	85,43	0,80	12,73	135	2027	681	318	315	4599	1485	855
Saint-Thois	29	MBAa2	ren-000515	ST54b	palstave	86,03	0,80	12,15	254	1951	670	311	324	4489	1411	803
Saint-Thois	29	MBAa2	ren-000516	ST74	palstave	83,87	0,14	14,91	65	2366	544	321	341	5340	1047	792
Saint-Thois	29	MBAa2	ren-000517	ST77	palstave	83,13	0,17	15,42	226	2560	588	361	364	6562	1391	732
Saint-Thois	29	MBAa2	ren-000518	ST83	palstave	85,05	0,06	13,76	39	2148	556	240	1391	5500	709	671
Saint-Thois	29	MBAa2	ren-000519	ST93a	palstave	81,02	0,15	17,59	134	2818	546	318	367	6083	1403	679
Saint-Thois	29	MBAa2	ren-000520	ST93b	palstave	82,23	0,15	16,33	159	2827	545	341	979	5879	1449	683
Saint-Thois	29	MBAa2	ren-000521	ST99	palstave	86,64	0,13	11,50	133	2745	569	301	1200	10799	756	739
Saint-Thois	29	MBAa2	ren-000522	ST107	palstave	85,09	0,43	13,52	195	1919	553	246	401	4135	1375	735
Saint-Thois	29	MBAa2	ren-000523	ST114a	palstave	83,57	0,19	15,09	187	2770	566	256	81	5560	1365	666
Saint-Thois	29	MBAa2	ren-000524	ST114b	palstave	84,20	0,18	14,51	123	2619	553	258	132	5520	1294	679
Saint-Thois	29	MBAa2	ren-000525	ST118	palstave	85,21	0,10	13,37	113	2646	565	251	558	6588	1618	787
Saint-Thois	29	MBAa2	ren-000526	ST127	palstave	84,58	0,10	14,18	74	2401	575	303	244	5788	1333	699
Saint-Thois	29	MBAa2	ren-000527	ST137	palstave	83,15	0,09	15,51	94	2679	542	354	433	6474	1218	671
Saint-Thois	29	MBAa2	ren-000528	ST138	palstave	81,96	0,17	16,75	55	2362	560	283	282	5242	1646	724
Saint-Thois	29	MBAa2	ren-000529	ST143a	palstave	85,41	0,08	13,03	39	3505	537	286	343	7638	1779	685
Saint-Thois	29	MBAa2	ren-000530	ST143b	palstave	85,52	0,08	12,95	39	3310	555	286	289	7669	1726	690
Saint-Thois	29	MBAa2	ren-000531	ST149	palstave	86,96	0,11	11,32	23	4283	562	619	1625	7314	865	829
Saint-Thois	29	MBAa2	ren-000532	ST150	palstave	83,26	0,14	15,25	59	2438	551	426	1174	6541	1495	765
Saint-Thois	29	MBAa2	ren-000533	ST151	palstave	85,58	0,10	13,37	20	3044	545	239	564	3045	1356	684
Saint-Thois	29	MBAa2	ren-000534	ST152	palstave	87,13	0,41	11,53	77	2631	569	290	327	3322	1324	743
minimum						81,02	0,03	9,78	20	1330	518	169	81	2505	466	632
maximum						88,41	3,70	17,59	747	11473	712	748	4329	10799	1779	855
médiane						84,45	0,14	13,97	75	2503	557	288	365	5540	1328	698

Dépôt	Dpt	Period	Lab analysis #	Ech #	Type	Cu	Pb	Sn	Ag	As	Bi	Co	Fe	Ni	Sb	Zn
						(%)	(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
Heucqueville	27	MBAa2	Ren-001061	R Hqvil 2524-25	palstave	77,78	0,03	21,67	55	227	487	640	1 923	828	522	498
Heucqueville	27	MBAa2	Ren-001062	R Hqvil 2524-26	palstave	86,30	0,06	12,50	173	3 024	517	648	806	4 908	782	547
Heucqueville	27	MBAa2	Ren-001063	R Hqvil 2524-27	palstave	87,76	0,13	10,78	337	3 226	541	775	1 052	6 112	788	576
Heucqueville	27	MBAa2	Ren-001064	R Hqvil 2524-28	palstave	80,19	0,34	17,92	424	3 917	550	816	2 677	5 175	997	915
Heucqueville	27	MBAa2	Ren-001065	R Hqvil 2524-29	palstave	85,04	0,03	13,59	162	2 792	519	924	1 832	5 899	746	570
Heucqueville	27	MBAa2	Ren-001066	R Hqvil 2524-30	palstave	78,89	0,47	19,62	316	2 446	524	573	1 192	3 923	745	572
Heucqueville	27	MBAa2	Ren-001067	R Hqvil 2524-31	palstave	83,07	0,04	15,61	88	2 780	515	679	1 259	5 965	956	533
Heucqueville	27	MBAa2	Ren-001068	R Hqvil 2524-32	palstave	85,61	0,22	13,02	323	3 519	527	632	431	4 609	933	565
Heucqueville	27	MBAa2	Ren-001069	R Hqvil 2524-33	palstave	84,79	0,31	13,61	171	4 012	531	670	618	5 285	1 096	558
Heucqueville	27	MBAa2	Ren-001070	R Hqvil 2524-34	palstave	82,60	0,13	15,98	183	3 536	505	828	1 152	4 801	1 295	531
Heucqueville	27	MBAa2	Ren-001071	R Hqvil 2524-35	palstave	89,42	0,06	9,41	109	2 759	537	728	1 061	4 608	750	594
Heucqueville	27	MBAa2	Ren-001072	R Hqvil 2524-36	palstave	84,04	0,14	14,50	140	3 831	534	618	619	5 906	1 021	576
Heucqueville	27	MBAa2	Ren-001073	R Hqvil 2524-37	palstave	84,05	0,08	14,62	186	3 564	538	672	390	5 688	968	559
Heucqueville	27	MBAa2	Ren-001074	R Hqvil 2524-38	palstave	82,75	0,10	15,64	112	4 520	510	773	1 357	6 344	981	534
Heucqueville	27	MBAa2	Ren-001075	R Hqvil 2524-39	palstave	84,14	0,02	14,19	84	4 757	499	924	2 260	6 734	597	578
Heucqueville	27	MBAa2	Ren-001076	R Hqvil 2524-40	palstave	86,03	0,02	12,99	39	2 944	528	536	423	3 389	1 185	527
Heucqueville	27	MBAa2	Ren-001077	R Hqvil 2524-41	palstave	84,82	0,05	14,33	78	2 264	495	583	131	3 378	550	553
Heucqueville	27	MBAa2	Ren-001078	R Hqvil 2524-42	palstave	83,04	0,01	15,66	61	2 760	472	219	1 415	6 953	362	672
Heucqueville	27	MBAa2	Ren-001079	R Hqvil 2524-24	palstave	89,08	0,08	9,73	206	3 057	558	395	778	5 190	556	407
Heucqueville	27	MBAa2	Ren-001080	R Hqvil 2524-23	palstave	88,00	0,04	10,52	111	3 290	538	588	724	8 138	595	388
Heucqueville	27	MBAa2	Ren-001081	R Hqvil 2524-21	palstave	84,30	0,12	14,40	205	4 076	540	376	1 064	4 029	1 016	402
Heucqueville	27	MBAa2	Ren-001082	R Hqvil 2524-21	palstave	86,95	0,26	10,93	446	3 428	560	351	8 459	3 770	1 133	459
Heucqueville	27	MBAa2	Ren-001083	R Hqvil 2524-20	palstave	85,81	0,19	12,65	258	5 405	531	394	174	5 368	979	370
Heucqueville	27	MBAa2	Ren-001084	R Hqvil 2524-19	palstave	81,72	0,11	16,91	197	4 179	520	356	1 104	4 999	771	375
Heucqueville	27	MBAa2	Ren-001085	R Hqvil 2524-18	palstave	83,92	0,19	14,67	201	4 456	548	303	567	4 766	1 044	399
Heucqueville	27	MBAa2	Ren-001086	R Hqvil 2524-17	palstave	85,16	0,08	9,96	121	2 349	541	263	39 434	4 166	700	412
Heucqueville	27	MBAa2	Ren-001087	R Hqvil 2524-16	palstave	90,64	0,31	8,11	130	2 458	539	217	821	4 274	608	424
Heucqueville	27	MBAa2	Ren-001088	R Hqvil 2524-15	palstave	85,97	0,12	12,49	272	3 948	543	421	1 776	5 639	1 247	416
Heucqueville	27	MBAa2	Ren-001089	R Hqvil 2524-14	palstave	82,81	0,08	15,74	199	4 057	534	344	1 043	6 168	1 010	421
Heucqueville	27	MBAa2	Ren-001090	R Hqvil 2524-13	palstave	83,41	0,13	15,22	237	3 780	483	294	1 311	4 781	1 134	382
Heucqueville	27	MBAa2	Ren-001091	R Hqvil 2524-11	palstave	82,48	0,19	16,29	282	3 542	478	233	319	4 463	690	454
Heucqueville	27	MBAa2	Ren-001092	R Hqvil 2524-10	palstave	83,44	0,74	15,00	419	1 959	486	220	1 695	2 505	443	481
Heucqueville	27	MBAa2	Ren-001093	R Hqvil 2524-9	palstave	80,26	0,28	18,55	435	2 247	479	301	1 331	2 940	908	468
Heucqueville	27	MBAa2	Ren-001094	R Hqvil 2524-8	palstave	84,95	0,05	13,37	124	7 646	512	659	1 274	5 125	629	393
Heucqueville	27	MBAa2	Ren-001095	R Hqvil 2524-7	palstave	84,10	0,11	14,49	236	4 413	504	432	891	5 086	919	395
Heucqueville	27	MBAa2	Ren-001096	R Hqvil 2524-6	palstave	84,12	0,07	14,45	122	4 226	486	365	1 320	5 975	631	386
Heucqueville	27	MBAa2	Ren-001097	R Hqvil 2524-5	palstave	79,47	0,24	18,88	227	4 565	491	336	1 008	6 148	955	374
Heucqueville	27	MBAa2	Ren-001098	R Hqvil 2524-4	palstave	80,50	0,11	18,38	125	3 160	483	258	823	4 195	590	380
Heucqueville	27	MBAa2	Ren-001099	R Hqvil 2524-3	palstave	87,03	0,10	11,38	169	5 023	526	390	1 494	6 103	754	420
Heucqueville	27	MBAa2	Ren-001100	R Hqvil 2524-2	palstave	88,03	0,09	10,58	130	3 373	542	303	2 410	5 126	621	435
Heucqueville	27	MBAa2	Ren-001101	R Hqvil 2524-1	palstave	82,98	0,07	14,59	110	7 695	508	615	6 583	6 946	751	437
minimum						77,78	0,01	8,11	39	227	472	217	131	828	362	370
maximum						90,64	0,74	21,67	446	7695	560	924	39434	8138	1295	915
médiane						84,12	0,11	14,45	173	3536	524	432	1104	5125	782	459
St Germain-d'Esteuil	33	MBAa2	Ren-001537	St G-ES 28	axe	81,21	2,74	15,17	366	1795	576	152	543	3430	1006	911
St Germain-d'Esteuil	33	MBAa2	Ren-001538	St G-ES 25	axe	83,16	0,10	15,89	225	1314	614	135	442	3594	1211	1023
St Germain-d'Esteuil	33	MBAa2	Ren-001539	St G-ES 23	axe	84,13	0,23	14,79	282	1657	642	125	405	3522	1202	621
St Germain-d'Esteuil	33	MBAa2	Ren-001540	St G-ES 27	axe	80,95	2,90	15,29	365	1730	565	151	514	3404	981	915
St Germain-d'Esteuil	33	MBAa2	Ren-001541	St G-ES 26	axe	86,32	0,13	12,61	187	2255	560	99	361	4613	658	696
St Germain-d'Esteuil	33	MBAa2	Ren-001542	St G-Es 22	axe	83,62	0,39	15,21	576	1098	649	113	451	3195	794	937
minimum						80,95	0,10	12,61	187	1098	560	99	361	3195	658	621
maximum						86,32	2,90	15,89	576	2255	649	152	543	4613	1211	1023
médiane						83,39	0,31	15,19	324	1693	595	130	446	3476	993	913
Malassis	36	MBAa2	Ren-000978	36R 208	ingot	96,58	0,04	0,83	422	505	865	578	15 441	344	3 213	4 000
Malassis	36	MBAa2	Ren-000979	36R 232	ingot	97,99	0,04	0,09	369	179	790	356	15 064	338	413	1 280
Malassis	36	MBAa2	Ren-000980	36R 236	ingot	96,24	0,12	1,52	902	799	895	696	12 488	299	1 524	3 590
Malassis	36	MBAa2	Ren-000981	36R 214	ingot	97,93	0,03	0,46	538	211	783	479	7 247	175	732	5 709
Malassis	36	MBAa2	Ren-000982	36R 215	ingot	98,80	0,03	0,02	137	200	597	141	9 430	271	47	675
Malassis	36	MBAa2	Ren-000983	36R 228	ingot	97,92	0,03	0,62	671	555	894	614	6 155	200	1 481	3 675
Malassis	36	MBAa2	Ren-000984	36R 206	ingot	94,64	0,04	0,02	104	12 312	586	524	13 855	24 584	392	677
Malassis	36	MBAa2	Ren-000985	36R 210	ingot	98,28	0,11	0,20	325	1 126	1 754	487	8 100	354	284	1 610
Malassis	36	MBAa2	Ren-000986	36R 217	ingot	97,46	0,03	0,05	261	123	723	378	21 503	278	133	1 184
Malassis	36	MBAa2	Ren-000987	36R 233	ingot	99,27	0,03	0,34	498	115	746	96	1 031	157	110	839
Malassis	36	MBAa2	Ren-000988	36R 209	ingot	98,45	0,10	0,49	793	527	791	540	3 459	178	74	3 220
Malassis	36	MBAa2	Ren-000989	36R 229	ingot	98,81	0,02	0,02	118	98	594	79	9 223	738	40	668
Malassis	36	MBAa2	Ren-000990	36R 213	ingot	98,18	0,02	0,12	397	201	606	473	13 408	221	221	1 306
Malassis	36	MBAa2	Ren-000991	36R 240	ingot	96,73	0,28	0,02	109	1 928	582	293	20 278	5 248	588	644
Malassis	36	MBAa2	Ren-000992	36R 211	ingot	98,54	0,02	0,02	95	2 807	582	169	6 401	3 344	121	633
Malassis	36	MBAa2	Ren-000993	36R 221	ingot	98,59	0,03	0,55	469	765	798	97	2 048	282	1 463	2 429
Malassis	36	MBAa2	Ren-000994	36R 212	ingot	98,77	0,04	0,25	434	687	833	560	4 709	198	906	1 088
Malassis	36	MBAa2	Ren-000995	36R 207	ingot	97,37	0,17	0,19	490	15 254	834	792	3 162	212	162	1 780
Malassis	36	MBAa2	Ren-000996	36R 219	ingot	97,07	0,08	2,14	827	486	713	471	2 958	164	57	1 407
Malassis	36	MBAa2	Ren-000997	36R 13	palstave	87,11	0,11	11,59	230	3 095	569	378	1 481	4 518	1 158	547
Malassis	36	MBAa2	Ren-000998	36R 41	palstave	91,43	0,24	7,07	302	1 456	620	492	3 829	4 302	754	907
Malassis	36	MBAa2	Ren-000999	36R 160	bracelet	89,03	0,12	9,07	230	3 829	573	268	2 571	4 835	5 006	534
Malassis	36	MBAa2	Ren-001000	36R 129	bracelet	85,74	0,10	13,16	208	2 319	535	279	497	4 675	906	507

Table 3 (continued, left and right) – Elemental compositions of Tréboul (MBA1), Martillac (MBA1), Boisgervilly (MBA2), Boulay-Morin (MBA2), Saint-Thois (MBA2), Heucqueville (MBA2), Saint-Germain-d'Esteuil (MBA2), Malassis (MBA2), Rosnoën (LBA1) and Saint-Brieuc-des-Iffs (LBA2) hoard artefacts.

Dépôt	Dpt	Period	Lab analysis #	Ech #	Type	Cu	Pb	Sn	Ag	As	Bi	Co	Fe	Ni	Sb	Zn
						(%)	(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
Malassis	36	MBAa2	Ren-001001	36R 151	bracelet	83,58	0,09	15,79	167	757	517	153	561	2 426	396	486
Malassis	36	MBAa2	Ren-001002	36R 253	masselotte	88,93	0,09	10,10	217	2 004	545	307	538	4 017	717	547
Malassis	36	MBAa2	Ren-001003	36R 198	bar ingot	83,27	0,09	15,48	378	1 522	547	312	5 058	2 549	428	732
Malassis	36	MBAa2	Ren-001004	36R 12	palstave	89,69	0,11	9,63	181	419	547	69	437	3 175	359	532
Malassis	36	MBAa2	Ren-001005	36R 57	sword blade	85,66	0,03	13,04	204	2 976	536	458	618	6 388	980	498
Malassis	36	MBAa2	Ren-001006	36R 34	long flanged axe	81,25	0,04	14,50	143	3 404	506	520	25 986	10 531	498	501
Malassis	36	MBAa2	Ren-001007	36R 42	palstave	91,28	0,23	7,60	318	1 490	616	274	1 432	3 228	648	837
Malassis	36	MBAa2	Ren-001008	36R 255	masselotte	87,85	0,14	11,01	241	2 223	550	269	408	4 741	1 082	537
Malassis	36	MBAa2	Ren-001009	36R 197	bar ingot	86,28	0,23	12,64	296	1 554	557	199	383	3 991	963	511
Malassis	36	MBAa2	Ren-001010	36R 54	sword blade	85,33	0,09	13,45	216	2 519	533	314	411	5 797	963	503
Malassis	36	MBAa2	Ren-001011	36R 247	ingot	89,75	0,14	0,01	193	21 681	570	1 216	40 837	32 122	3 631	715
Malassis	36	MBAa2	Ren-001012	36R 238	ingot	98,66	0,09	0,01	308	144	610	199	9 411	374	41	1 376
Malassis	36	MBAa2	Ren-001013	36R 234	ingot	98,51	0,09	0,03	390	195	827	181	10 092	251	370	1 391
Malassis	36	MBAa2	Ren-001014	36R 239	ingot	98,91	0,01	0,01	95	1 292	556	94	4 663	3 423	63	545
Malassis	36	MBAa2	Ren-001015	36R 231	ingot	97,81	0,30	0,19	365	4 035	742	1 867	7 080	239	491	2 173
Malassis	36	MBAa2	Ren-001016	36R 205	bar ingot	95,22	0,69	0,15	417	1 003	1 028	443	29 047	364	1 364	5 687
Malassis	36	MBAa2	Ren-001017	36R 241	ingot	94,24	0,01	0,09	113	6 143	549	2 067	25 422	20 933	829	547
Malassis	36	MBAa2	Ren-001018	36R 4	palstave	86,74	0,25	11,49	260	6 376	586	1 311	640	4 491	851	663
Malassis	36	MBAa2	Ren-001019	36R 196	bar ingot	80,73	0,19	18,18	251	1 679	526	417	333	4 287	865	596
Malassis	36	MBAa2	Ren-001020	36R 167	bracelet	85,97	0,10	12,86	193	2 153	547	382	892	5 068	844	621
Malassis	36	MBAa2	Ren-001021	36R 127	bracelet	85,99	0,17	12,85	289	1 857	544	463	883	4 172	1 052	678
Malassis	36	MBAa2	Ren-001022	36R 223	foundry waste	81,37	0,13	17,26	211	2 732	519	454	653	5 819	1 412	583
Malassis	36	MBAa2	Ren-001023	36R 1	palstave	81,10	0,13	17,34	230	2 708	532	455	2 637	5 757	1 370	606
minimum						80,73	0,01	0,01	95	98	506	69	333	157	40	486
maximum						99,27	2,90	18,18	902	21681	1754	2067	40837	32122	5006	5709
médiane						89,75	0,10	7,60	282	1554	586	314	2637	3404	794	715
Rosnoën	29	LBAa1	ren-000688	49.1.14	rapier	88,04	0,13	11,21	419	1309	691	231	0	2333	609	644
Rosnoën	29	LBAa1	ren-000689	49.1.19	rapier	85,14	0,11	13,91	440	1583	661	215	1555	2207	748	924
Rosnoën	29	LBAa1	ren-000690	49.1.20	sword	88,20	0,23	10,69	569	1632	913	359	219	2201	768	2100
Rosnoën	29	LBAa1	ren-000691	49.1.22	sword	87,17	0,24	11,88	653	1621	811	275	265	2114	753	606
Rosnoën	29	LBAa1	ren-000692	49.1.16	rapier	86,35	0,14	12,67	445	2151	695	203	0	3330	994	546
Rosnoën	29	LBAa1	ren-000693	49.1.1	socketed hammer	73,34	0,21	25,82	504	1644	595	202	0	2004	1036	390
Rosnoën	29	LBAa1	ren-000694	49.1.24	sword	87,61	0,18	11,50	718	1322	751	352	579	1705	916	750
Rosnoën	29	LBAa1	ren-000695	????	rapier	86,03	0,04	13,59	172	793	598	81	0	928	432	409
Rosnoën	29	LBAa1	ren-000696	49.1.29	sword	86,55	0,08	12,74	383	1808	631	231	355	1663	599	635
Rosnoën	29	LBAa1	ren-000697	49.1.21	sword	86,99	0,22	12,10	633	1463	822	241	636	1587	859	685
Rosnoën	29	LBAa1	ren-000698	49.1.9	palstave	85,27	0,22	13,69	705	1546	828	397	1322	1799	864	706
Rosnoën	29	LBAa1	ren-000699	49.1.8	palstave	84,87	0,19	13,03	459	2103	686	241	11038	2953	1019	527
minimum						73,34	0,04	10,69	172	793	595	81	0	928	432	390
maximum						88,20	0,24	25,82	718	2151	913	397	11038	3330	1036	2100
médiane						86,45	0,19	12,71	482	1602	693	236	310	2059	813	640
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002071	St-Brieuc 73918-A2	ingot	97,41	0,41	0,20	1324	2720	378	976	11054	288	641	4009
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002072	St-Brc 10	palstave	75,16	12,35	8,41	4240	4763	300	302	111	2242	7368	526
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002073	St-Brc 3	palstave	67,94	18,90	7,97	4551	5151	294	178	107	1273	7576	476
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002074	St-Brc 8	palstave	89,55	1,73	3,27	12462	17960	467	124	194	1308	18272	638
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002075	St-Brc 16	palstave	75,93	7,61	13,25	3928	4403	318	341	264	2048	6075	587
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002076	St-Brc 5	palstave	71,39	17,74	5,91	4762	4627	320	333	275	1786	7204	683
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002077	St-Brc 31	winged axe	85,73	0,19	12,28	405	1730	332	3156	6484	2585	448	1603
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002078	St-Brc 7	palstave	86,11	3,41	7,10	5986	6761	356	368	2140	2255	9393	676
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002079	St-Brc 23	palstave	88,44	1,51	7,67	5408	5569	358	210	83	1662	7845	694
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002080	St-Brc 73918-B6	masselotte	87,87	2,34	7,40	4701	4917	329	376	470	1997	7228	680
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002081	St Brc 49	sword blade	89,20	0,54	7,82	6605	7291	393	202	199	1805	10603	723
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002082	St Brc 73918-B2	masselotte	81,93	8,12	7,28	6615	7089	360	275	168	1807	10737	482
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002083	St Brc 22	palstave	88,85	2,16	6,54	6449	7173	381	196	224	2086	9753	596
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002084	St Brc 20	palstave	85,13	6,17	6,55	5657	6690	374	202	381	797	7899	720
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002085	St-Brc 73918-B5	masselotte	66,03	25,07	6,75	3596	3127	310	351	1662	966	5824	1979
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002086	St-Brc 4	palstave	87,30	2,66	8,00	5684	5741	380	267	158	1952	8933	562
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002087	St-Brc 33	winged axe	91,45	0,46	5,72	4942	6076	356	1265	2291	2682	7834	729
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002088	St-Brc 52	sword blade	90,18	0,31	3,07	15178	20138	561	43	114	1719	23880	536
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002089	St-Brc A	palstave	91,33	0,43	2,42	12039	16990	461	75	83	671	24674	573
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002090	St-Brc 73918-A5	masselotte	87,16	4,47	5,22	7598	8127	399	271	113	2173	12544	578
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002091	St Brc 24	palstave	67,20	24,43	6,14	3782	4572	278	271	161	1889	7046	560
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002092	St-Brc 54	sword blade	85,96	4,38	7,93	4480	4749	375	595	397	1897	7085	689
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002093	St-Brc 50	sword blade	89,14	1,16	6,48	7767	9978	417	311	444	1816	12740	615
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002094	St-Brc 73918-B3	masselotte	87,58	3,64	4,59	9819	11346	441	219	256	1225	17061	633
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002095	St-Brc 46	sword handle	81,86	10,04	3,67	9346	12873	421	271	69	1325	16288	583
Saint-brieuc-des-Iffs	35	LBAa2	Ren-002096	St-Brc 30	winged axe	83,19	4,17	8,70	9678	12569	415	352	202	1811	15518	670
minimum						66,03	0,19	0,20	405	1730	278	43	69	288	448	476
maximum						97,41	25,07	13,25	15178	20138	561	3156	11054	2682	24674	4009
médiane						86,63	3,53	6,65	5670	6383	374	273	213	1809	8416	636

Table 3 (end) – Elemental compositions of Tréboul (MBA1), Martillac (MBA1), Boisgervilly (MBA2), Boulay-Morin (MBA2), Saint-Thois (MBA2), Heucqueville (MBA2), Saint-Germain-d'Esteuil (MBA2), Malassis (MBA2), Rosnoën (LBA1) and Saint-Brieuc-des-Iffs (LBA2) hoard artefacts.

	ID sample	206Pb/204Pb	207Pb/204Pb	208Pb/204Pb
MBAa1	2 σ	0,001	0,001	0,002
Tréboul	49 5 8	18,317	15,627	38,352
Tréboul	49 5 16/3	18,327	15,628	38,356
Tréboul	49 5 89	18,741	15,653	38,466
Tréboul	49 5 93	18,337	15,634	38,377
Tréboul	49 5 101/1	18,316	15,625	38,347
MBAa1	2 σ	0,0005	0,0005	0,0015
Martillac	mart 10	18,4420	15,6553	38,4581
Martillac	mart 6	18,4189	15,6485	38,4342
Martillac	mart 13	18,3487	15,6374	38,3884
Martillac	mart 5	18,4070	15,6458	38,4199
Martillac	mart 21	18,7753	15,7054	38,6887
MBAa2	2 σ	0,0005	0,0005	0,0015
Boisgervilly	BG1	18,1745	15,6648	38,4119
Boisgervilly	BG3	18,1699	15,6575	38,4110
Boisgervilly	BG5	18,1516	15,6548	38,3714
Boisgervilly	BG7	18,1799	15,6618	38,4037
Boisgervilly	BG8	18,2594	15,5455	38,4321
MBAa2	2 σ	0,0005	0,0005	0,0015
Boulay-Morin	3479	18,2283	15,6651	38,4435
Boulay-Morin	3477	18,0752	15,6544	38,3061
Boulay-Morin	3473	18,0066	15,6489	38,2361
Boulay-Morin	3474	18,1542	15,6568	38,3955
Boulay-Morin	3471	18,3566	15,6706	38,5329
MBAa2	2 σ	0,0005	0,0005	0,0015
St Germain-d'Esteuil	SG 25	18,0751	15,6529	38,2954
St Germain-d'Esteuil	SG 23	18,1302	15,6539	38,3644
St Germain-d'Esteuil	SG 27	18,6262	15,6691	38,7785
MBAa2	2 σ	0,0005	0,0005	0,0015
Malassis-ingot	36 R 214	17,9070	15,6396	38,1371
Malassis-ingot	36 R 234	18,0103	15,6434	38,2493
Malassis-ingot	36 R 206	20,8292	15,7911	40,4465
Malassis-ingot	36 R 207	18,1838	15,6568	38,4318
Malassis-ingot	36 R 208	17,9185	15,6338	38,1318
Malassis-ingot	36 R 221	17,8460	15,3326	37,2708
Malassis-ingot	36 R 232	18,0050	15,6493	38,2563
Malassis-ingot	36 R 210	18,1182	15,6509	38,3653
Malassis-ingot	36 R 217	18,0052	15,6445	38,2534
Malassis-ingot	36 R 240	19,7551	15,7432	39,6809
Malassis	36 R 41	18,0549	15,6517	38,2908
Malassis	36 R 54	18,0931	15,6609	38,3405
Malassis	36 R 197	18,1844	15,6586	38,4301
Malassis	36 R 205	17,9014	15,6445	38,1407
Malassis	36 R 12	18,1349	15,6572	38,3779
LBAa1	2 σ	0,0005	0,0005	0,0015
Rosnoën	49.1.1	18,2177	15,6612	38,4437
Rosnoën	49.1.8	18,1779	15,6642	38,4260
Rosnoën	49.1.16	18,1850	15,6706	38,4484
Rosnoën	49.1.20	18,1927	15,6657	38,4442
Rosnoën	49.1.21	18,1754	15,6629	38,4236
LBAa2	2 σ	0,0005	0,0005	0,0015
Saint-brieuc-des-Iffs	St Brieuc 49	18,285	15,650	38,423
Saint-brieuc-des-Iffs	St Brieuc 23	18,364	15,640	38,426
Saint-brieuc-des-Iffs	St Brieuc 10	18,484	15,634	38,460
Saint-brieuc-des-Iffs	St Brieuc A	18,389	15,642	38,444
Saint-brieuc-des-Iffs	St Brieuc 3	18,436	15,638	38,447
Saint-brieuc-des-Iffs	St Brieuc 8	18,367	15,651	38,472
recent LBAa3	2 σ	0,0005	0,0005	0,0015
St Sauveur	lingot 1	18,1602	15,6356	38,2793
St Sauveur	lingot 2	18,2152	15,6311	38,2424

Table 4 – Lead isotope compositions of Tréboul (MBA1), Martillac (MBA1), Boisgervilly (MBA2), Boulay-Morin (MBA2), Saint-Germain-d'Esteuil (MBA2), Rosnoën (LBA1), Saint-Brieuc-des-Iffs (LBA2) and Saint-Sauveur (LBA3b) hoard artefacts.

Second stage of Middle Bronze Age (MBA2/Bz C): Moutiers horizon (1450–1300 BC)

Metal from the Middle Bronze Age 2 in north-western France is known from the very large number of hoards made up either solely of ornaments or solely of axes, or, much more rarely, of assemblages of various objects, essentially associating axes with other elements of ornaments or weaponry (Boulud-Gazo et al., 2017). The axes are palstaves of various types – Breton, Norman, and Central-Western and long-flanged type without a stop-ridge in Vendée and Aquitaine areas, which are scattered in the regions of the same name. A total of 450 hoards have been identified in these regions, with a total of 3,148 objects inventoried (Nordez, 2019) with tin contents ranging from 9 % to 15 % (average 12 %). This number is largely underestimated because many hoards have gone unreported for decades. These types of axes can be recognised in much more distant regions, in central-eastern France for example, or even in the south, suggesting that objects were moved over long distances (Gabillot and Quentinet, 2023). However, local copies are always possible.

6 deposits were analysed as part of this study (fig. 2). These are the hoards at Boisgervilly (35), composed entirely of palstaves, for which 13 elemental chemical analyses were carried out and 5 isotopic analyses; Boulay-Morin (27), also composed of palstaves (10 elemental chemical analyses and 5 isotopic analyses); Saint-Thois (29), for which 30 palstaves were analysed for elemental chemistry; Heucqueville (27), where all 31 palstaves were analysed for elemental chemistry; Saint-Germain-d'Esteuil (33), where only 6 axes were analysed for elemental chemistry and 3 for isotopes; and finally the Malassis hoard (18). The latter hoard, considered to be slightly later, is located in central France and contains objects with typological attributions from the Atlantic and continental domains. Unlike the typical MBAa2 hoards mentioned above, this type of complex hoard includes a wide variety of objects, and also, very interestingly for research into copper sources, fragments of copper ingots. Elemental analysis of the axes shows a very high compositional homogeneity for most of the Atlantic seaboard, from Normandy to the Médoc, with a classical bronze composition (table 3). Compositional homoge-

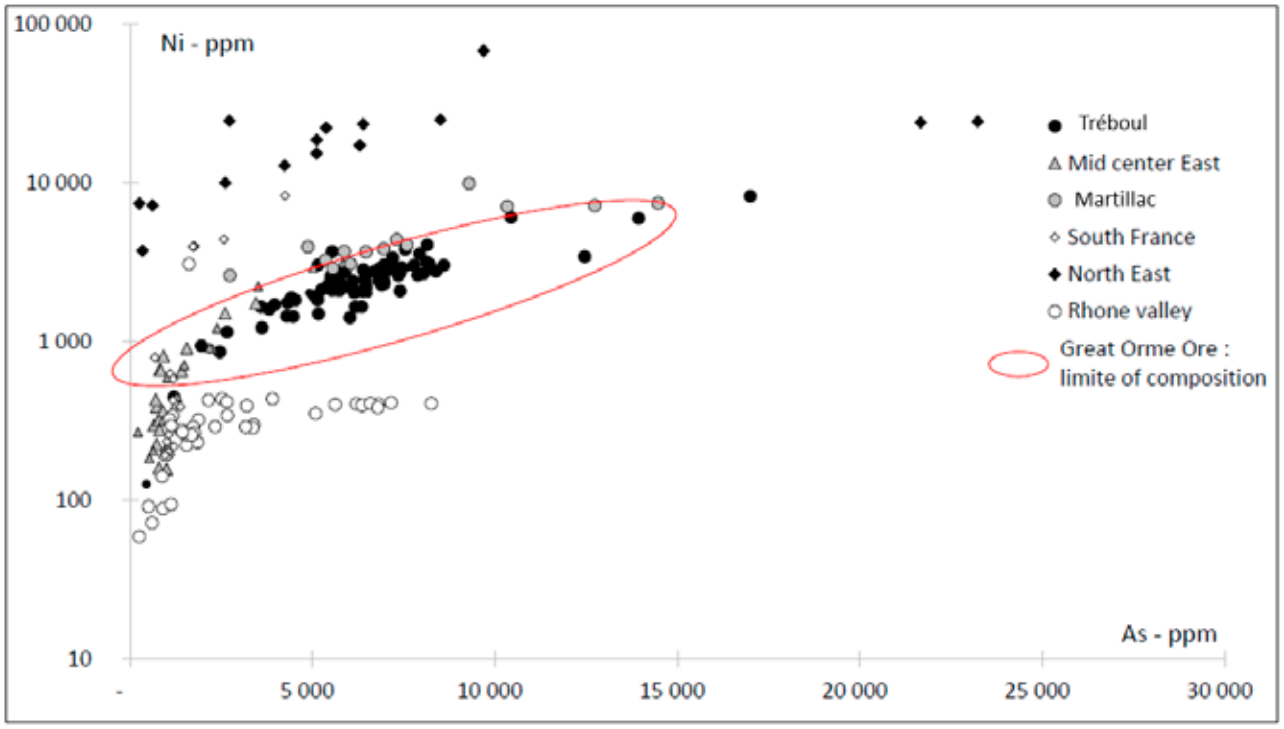


Fig. 3 – Comparison of Ni and As contents of Tréboul and Martillac hoard artefacts with that of Rhône valley (unpublished data), Mid-Centre-East (Gabillot, 2021), North-East (unpublished data), South (unpublished data) artefacts from hoards, and with Great Orme ore compositions.

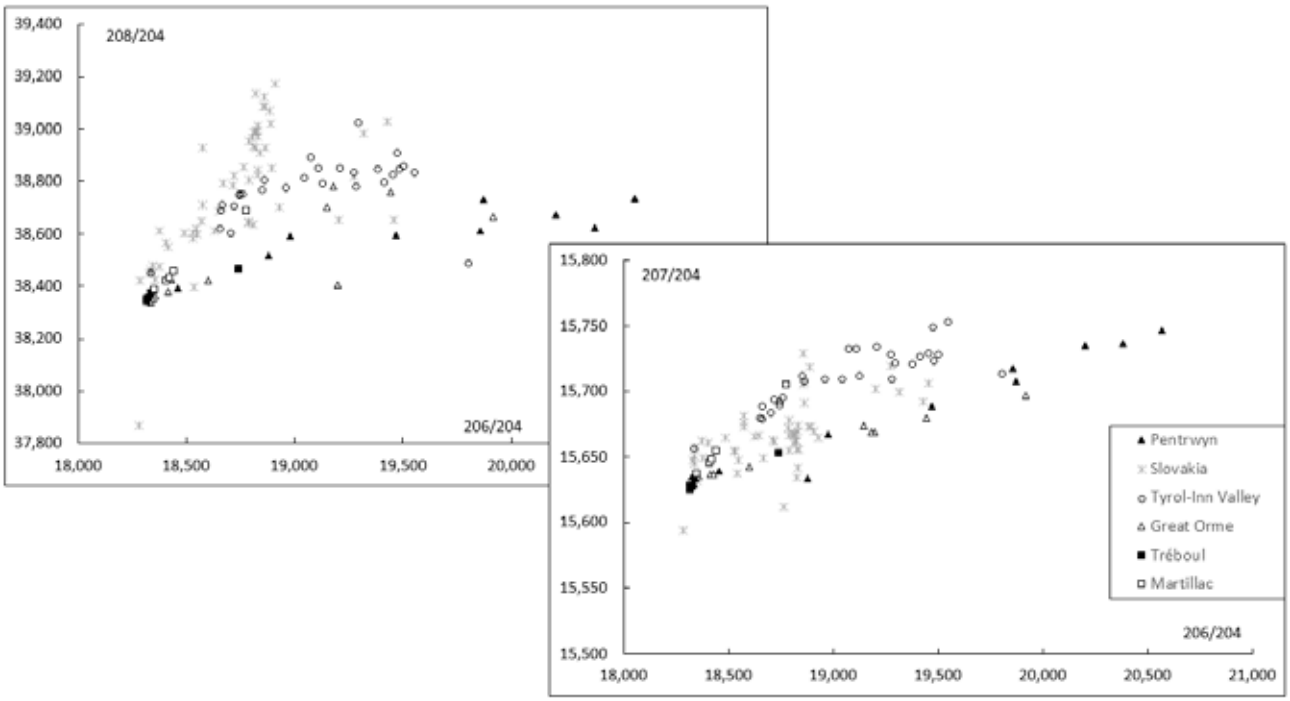


Fig. 4 – Lead isotopes diagrams for Tréboul and Martillac hoards artefacts, compared to Great Orme, Slovakia and Tyrol (Inn Valley) copper ore domain values.

neity is also high relative to that of the axes from the Burgundy and Franche-Comté hoards, particularly in terms of trace element contents. Overall, the Malassis hoard shows the same variation in elemental composition as the hoards mentioned above (fig. 5). Only a few objects and ingots have much lower levels of As, Ni and Sb (Briard et al., 1969).

This composition seems quite different from that of the previous period for north-western France (fig. 6). The average Ni content is higher in MBA2 (5,111 ppm) than in MBA1 (2,399 ppm). The same applies to Sb (1,056 ppm in MBA2 compared with 232 ppm in MBA1). By contrast, the average As content is higher in MBA1 (6,161 ppm) than in MBA2 (2,868 ppm). This observation suggests a radical change in the origin of the imported metal. However, some MBA2 axes from the northwest show sometimes a chemical composition identical to objects from the previous MBA1 period, and show a difference from axes from eastern and central France. The compositions of the axes from Burgundy and the centre of France are similar and do not come close at all to the composition of MBA1. It is, therefore, possible to imagine that copper from the Great Orme mining area was still being used in part of north-western France in MBAa2, or that objects from MBA1 were being recycled in large numbers in this region. On the other hand, all the axes from hoards found in the northern part of France, in the west and east, show a very clear difference in composition from the artefacts from the south of France (fig. 6). In particular, these objects have a high average Ag content (1,599 ppm) and low Ni (815 ppm) and As (1,153 ppm). Isotopic analyses were carried out on axes from north-western France, south-west France (Saint-Germain d'Esteuil) and central France (Malassis) (table 4). Unfortunately, the axes from eastern France have not yet been analysed.

Comparison of the isotopic compositions of the north-western axes with the signatures of major copper-mining areas in Europe suggests that the origin of

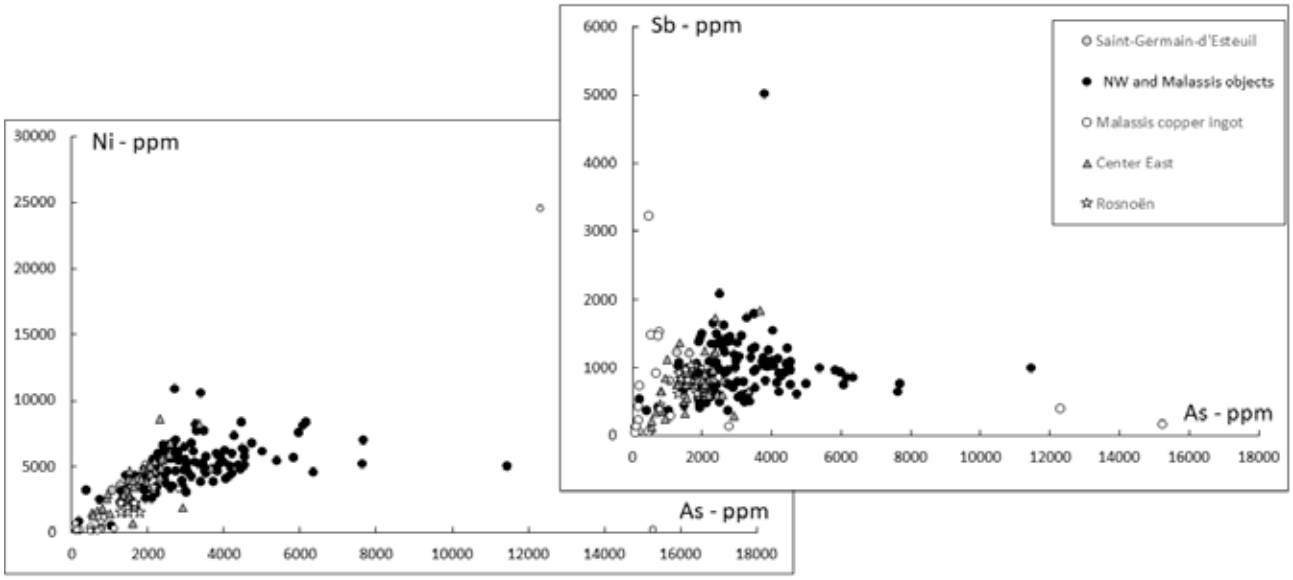


Fig. 5 – As/Ni and As/Sb diagrams for MBA2 and LBA1 north-West and MBA2 Médoc hoard artefacts compared to MBA2 Malassis artefacts and copper ingots, and MBA2 Centre-East hoard artefacts..

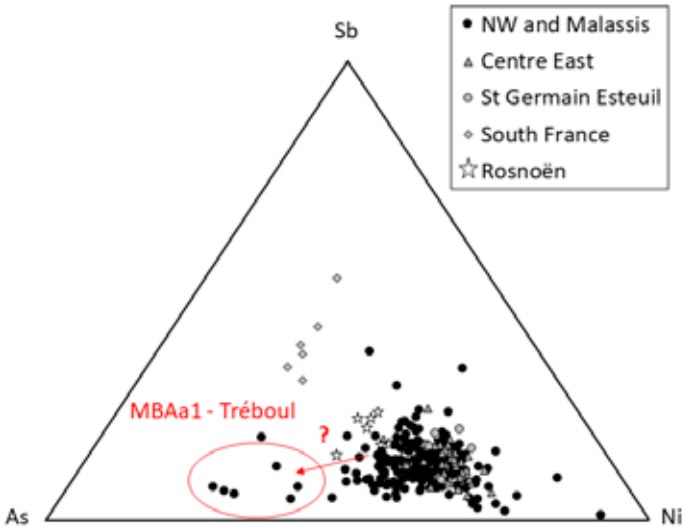


Fig. 6 – Ternary As/Ni/Sb diagram for MBA2 and LBA1 north-West and MBA2 Médoc hoard artefacts compared to MBA2 Malassis, South and Centre-East hoard artefacts, and MBA1 Tréboul artefacts.

the copper could be Spain (Huelva), in the first approach. However, the signatures of the Malassis copper ingots seem to point to Spain (Huelva) and/or Italy (Valsugana), on the one hand, and to Austria, with the district of Mitterberg, on the other (fig. 7a and b). The objects do not have the signature of the ingots but lie on a straight line connecting the points representing the ingots located in the three mentioned districts. The hypothesis of the use of copper from the Great Orme mine could perhaps be confirmed because some analyses seem to point toward the Great Orme isotopic domain from the alignment of points.

First stage of Late Bronze (LBA1/Bz D–Ha A1): Rosnoën horizon (1275–1140/1125 BC)

With the beginning of the Final Bronze Age, the typology and number of hoards changed radically. The Rosnoën group comprises barely fifteen or so assemblages and a few isolated objects in Brittany. Most of them are located in central-western Brittany. A few groups are located in Ille-et-Vilaine and swords are thrown at the mouth of the Loire (Nallier and Le Goffic, 2008). The type of palstave changed, as did the type of hoard, in which the artefacts are varied and partially fragmented.

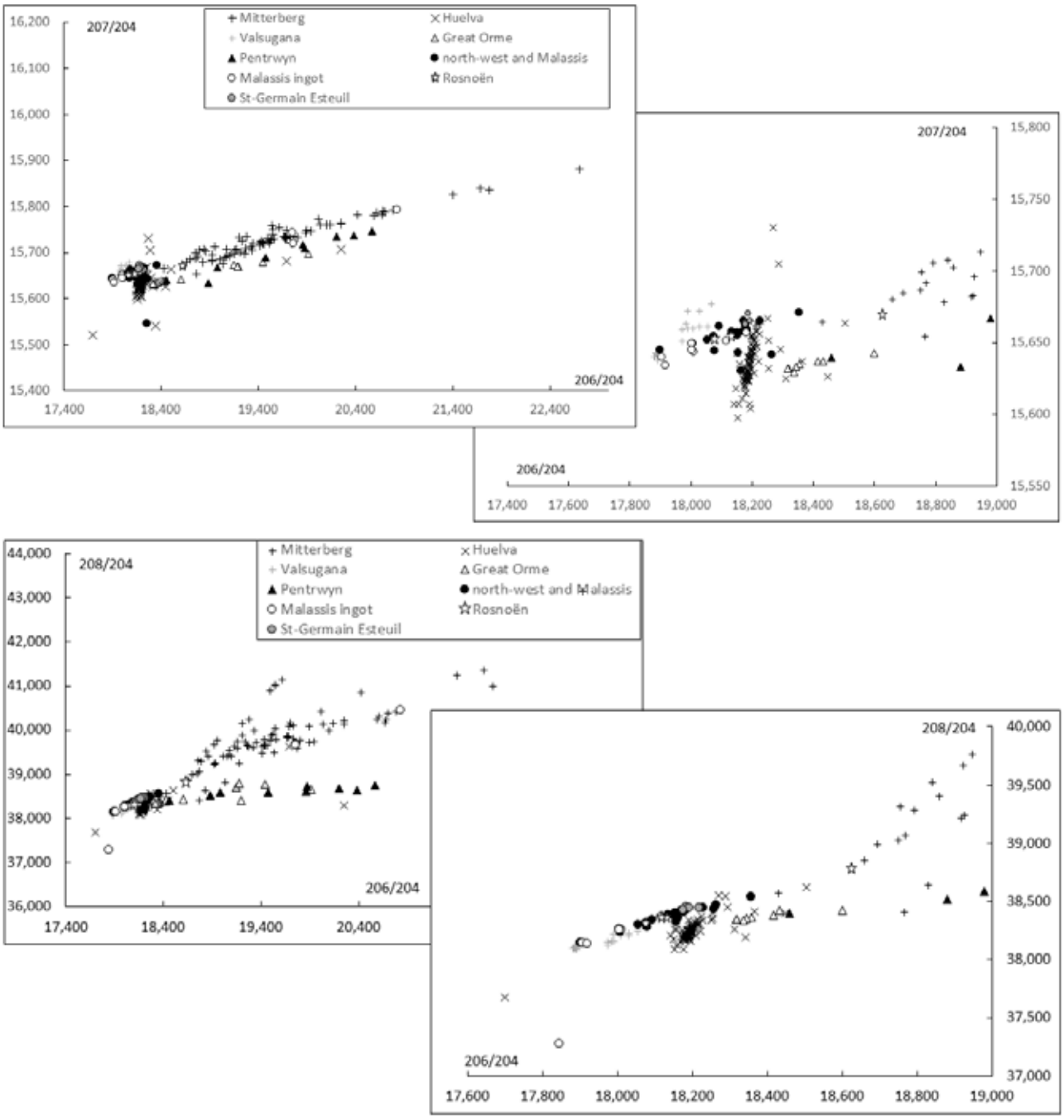


Fig. 7 – Lead isotopes diagrams for MBA2 and LBA1 North-West and Médoc hoards artefacts, compared to Mitterberg, Valsugana and Huelva copper ore domain values..

The number of hoards as well as the number of artefacts per hoard is also much lower. Palstaves, known as 'Rosnoën' axes, become more massive and have a right-angled stop-ridge.

The eponymous deposit of Penavern in Rosnoën (fig. 2) was discovered in 1944 and partially acquired by P.-R. Giot for the Penmarc'h museum. J. Briard described this lot in his thesis in 1965. Since then, the deposit has been better documented (Nallier and Le Goffic, 2008). Some of the objects dispersed among the family of the discoverer have been examined. The hoard contains 88 items, including whole swords, rapiers, daggers, spear points, axes, triangular scrapers, and at least one socketed hammer. 12 elemental analyses were carried out for this hoard (table 3). 5 isotopic analyses were also produced (table 4).

The chemical and isotopic compositions of the axes are identical to those of the other objects in the hoard (average content of Ag at 508 ppm, As at 1,581 ppm, Ni at 2,069 ppm and Sb at 800 ppm) and are almost identical to those of the previous period (figs. 5, 6, and 7). While the typology of the axes has changed, as have the methods of deposition, the copper supply circuits seem to remain the same as before. However, given the limited number of analyses carried out for this period, these results should not be considered definitive.

Second stage of the Late Bronze Age (LBA2/ Ha A2–Ha B1): Saint-Brieuc-des-Iffs horizon (1140/1125–950 BC)

In Late Bronze Age 2, there are more hoards than LBAa1, but far fewer than in MBAa2. The artefacts in hoards are numerous, often several dozen specimens, up to 200 artefacts. The artefacts are most often fragmented. Axes are represented by massive palstaves, also known as 'Rosnoën' type axes because they are fairly identical to the previous period (Briard and Verron, 1976).

Four hoards were analysed in this study (fig. 2). Firstly, there are the two hoards at Soullans (Vendée; Boulud-Gazo et al., 2022), objects from the unpublished Plérin hoard (Côtes-d'Armor) and part of the Saint-Brieuc-des-Iffs hoard (Ille-et-Viliane). A wide variety of objects are collected in these hoards, and it would be tedious to make an inventory of them here. However, there are a number of special features. The Soullans hoards contain bar-shaped alloy ingots. This type of ingot was also found in the Bougues hoard at Saint-Sulpice (Lot; Milcent et al., 2022). The largest objects from these hoards were analysed for elemental chemistry (82 analyses, mainly of bar-shaped alloy ingots, copper ingots, fragments of swords, axes, and bouterolles). The Plérin hoard contains reniform type bracelets that point to the continental domain, particularly in eastern France (Eluère, 1975). 27 objects were analysed for elemental chemistry for the Plérin hoard. These were mainly massive palstaves with a right-angled stop-ridge, but also fragments of swords and javelins, bracelets, and casting wastes. The Saint-Brieuc-des-Iffs hoard contains continental-type ornaments (Briard and Onnée, 1972). Unfortunately, the latter was not sampled due to its fragility. Only the most massive objects were selected, i.e. massive palstaves with a right-angled stop-ridge, winged axes, casting wastes, and sword fragments, for a total of 27 elemental chemical analyses (table 3) and 6 isotopic analyses (table 4).

What is special about this period is the nature of the alloy, which contains lead (from 0.08 % to 48,47 %, with an average of 5,32 %) in addition to copper and tin. A comparison of the composition of these palstaves with that of axes from the previous period, all defined as 'Rosnoën' type axes, shows a clear difference in elemental and isotopic composition between these two populations. The LBAa2 axes contain lead, while the LBAa1 axes do not (fig. 8). Similarly, the levels of the four main trace elements (Ag, As, Ni and Sb) do not correspond at all (fig. 8; see contents in previous paragraph for LBA1 and

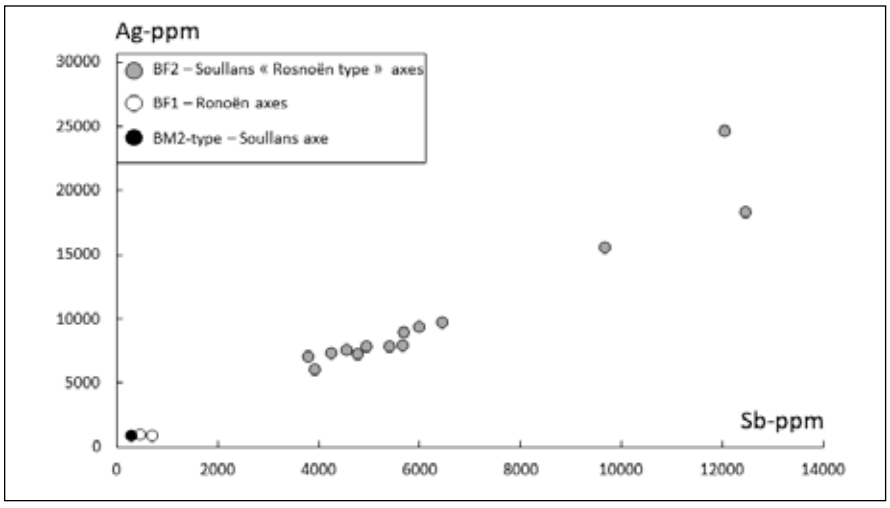


Fig. 8 – Comparison of Ag and Sb contents of MBA2 type palstave and of Rosnoën type axes of LBA2 Soullans hoards, with LBA1 Rosnoën type axes.

below for LBAa2). The isotope ratios are also different. This leads us to believe that the origin of the metal changes completely between the LBAa1 and LBAa2, in north-western France, whereas the typology of certain objects remains more or less identical.

Another case study highlights the late use of axes produced in earlier periods. For example, a Breton palstave from the MBAa2 period, found in an LBAa2 hoard in Vendée (Boulud-Gazo et al., 2022), has the chemical and isotopic composition of objects from this earlier period.

Nevertheless, objects from the Atlantic seaboard seem to be made from copper of several different origins (fig. 9). The copper may come from:

1) copper ingots; poor in Ag (about 300 ppm) Ni (120–230 ppm) and Sb (140–210 ppm) and with a little richness in As (2,500–5,800 ppm);

2) a type of alloy, somewhat poor in As (300–2000 ppm), Sb (200–1,200 ppm), Ni (100–1,000 ppm), and Ag (less than 1,000 ppm), mainly represented by a part of Pb-rich bar ingots (2.5–48.5 %) and some artefacts from Soullans hoards;

3) another type of alloy rich in As (1,000–8,000 ppm), with a low content in Ni (100–1,500 ppm) with moderate to high content in Sb (2,500–12,500 ppm) and Ag (1,000–7,000 ppm), represented by the other part of Pb-rich bar ingots and some artefacts from Soullans hoards, and some artefacts from Saint-Brieuc-des-Iffs and Plérin;

4) another one very rich in As (8,000–20,000 ppm), Sb (12,500–25,000 ppm) and Ag (7,000–15,000 ppm), and somewhat rich in Ni (700–2,500 ppm), represented by some artefacts of Soullans and Saint-Brieuc-des-Iffs hoards, with chemical characteristics which can be observed in artefacts from Wilburton Step in England (Williams, 2023);

5) finally, an alloy very rich in As (3,000–10,000 ppm) and Ni (2,000–6,000 ppm) and rich in Sb (6,000–12,000 ppm) and Ag (4,000–7,000 ppm). This chemical composition is particularly represented in the Plérin hoard. This type of metal is recognised in Switzerland (Rychner and Kläntschi, 1993) and could have an Alpine origin. The origin could also be Slovakia because of the presence of an Ni-rich ore district (Nøorgard et al., 2021).

The mixture of sources can also be seen in the isotopic analyses, with the points representing the analyses of alloy artefacts aligned on a mixing line (fig. 10). The very high lead content in the bar ingots suggests that lead was added to the alloy. Comparing the isotopic compositions of LBAa2 objects with copper deposits is not meaningful. Comparing these isotopic compositions with European lead deposits does not provide any information either (fig. 10). In fact, several artefacts correspond to these compositions: the Armorican Massif (Marcoux, 1986), the British Isles (Rohl, 1996), and Western Germany (Bode, 2008).

The isotopic analysis of one of the two copper ingots from the Soullans hoards seems to indicate an origin from Slovakia or the Great Orme (fig. 11). However, a comparison of the elemental compositions of the LBAa2 objects with those of the MBAa1 objects, the copper of which almost certainly came from the Great Orme, shows that these two groups of objects do not have the same elemental composition at all: the MBAa1 objects are much less rich in Sb. So Great Orme copper couldn't be the source. The same situation was observed for copper ingots from the Hourtin deposit (Médoc; fig. 2), dated to the following period (Couderc et al., 2021). An isolated point could also refer to a closer ore, located in the western French Alps (fig. 11).

End of the Late Bronze Age (LBA3/Ha B2-B3): Vénat horizon (900-800 BC)

In the recent Late Bronze Age 3, there are an extremely large number of metal hoards, with a wide variety of numerous objects (weapons, ornaments, tools, ornaments

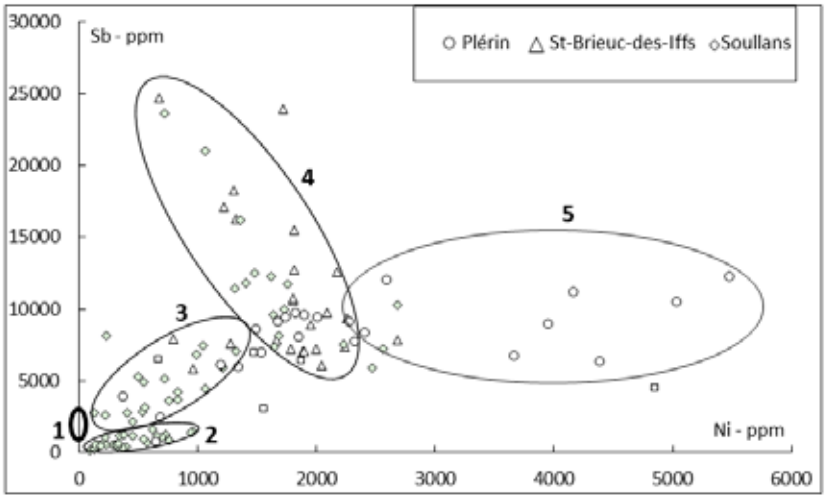


Fig. 9 – Binary diagram Ni/Sb showing the fifth type of elemental compositions observed in North-West LBA2 hoard artefacts.

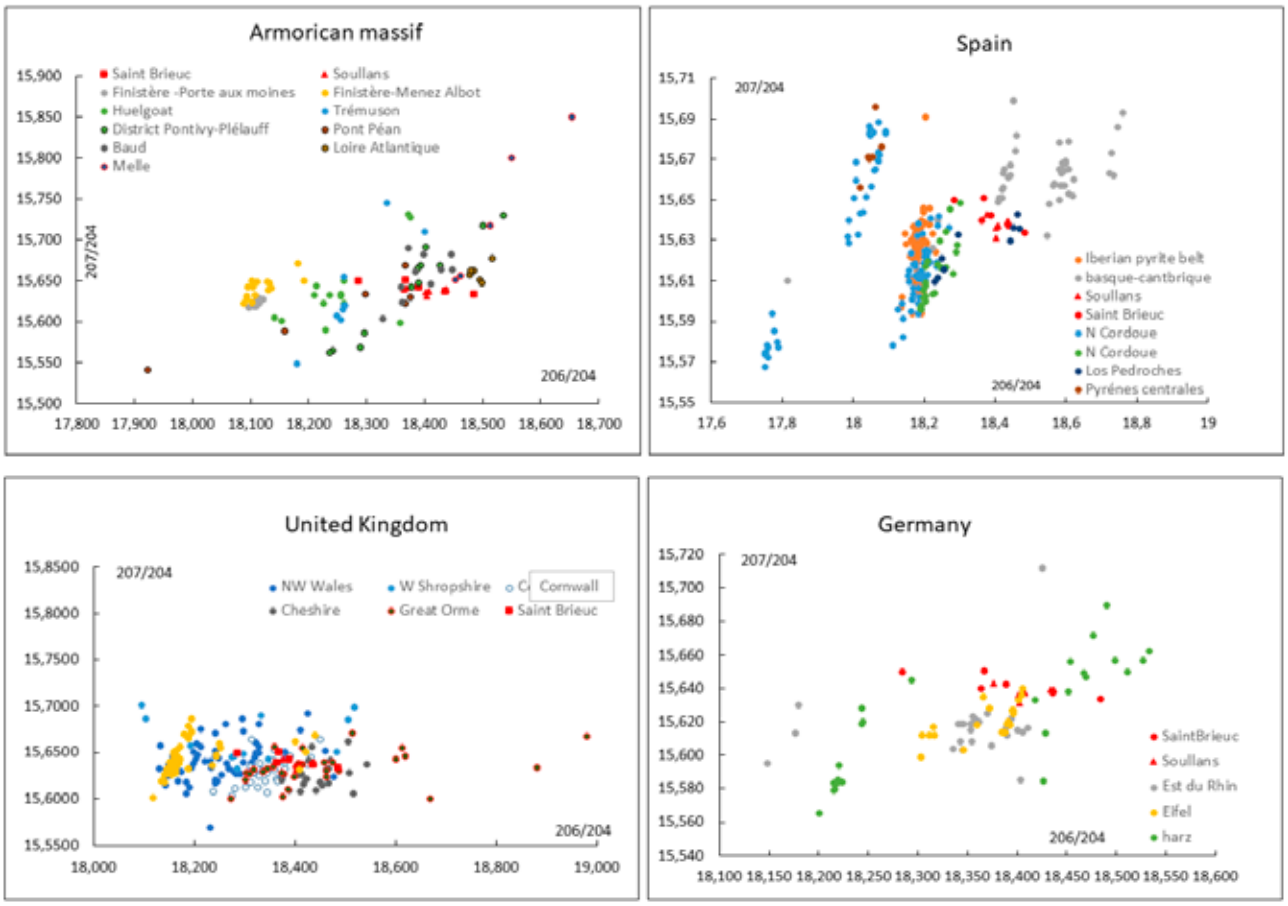


Fig. 10 – Lead isotopes diagrams for LBA2 North-West hoards artefacts, compared to lead deposits form Armorican massif, Spain, Germany and United Kingdom.

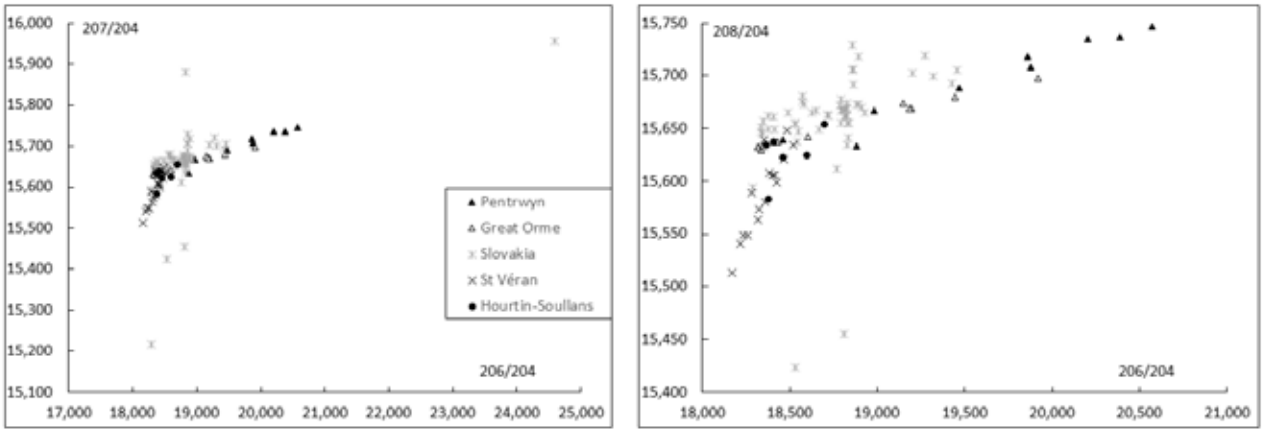


Fig. 11 – Lead isotopes diagrams for LBA2 and LBA3a North-West hoards copper ingots, compared to copper deposits form Great Orme, Saint-Véran and Slovakia.

of carts, care tools, casting wastes, etc…), most often fragmented, including fragments of copper ingots (Milcent, 2012; Bordas, 2023). There are more located close to the sea in particular, but some are placed in the centre of Brittany (Fily and Boulud-Gazo, 2009).

Three hoards were analysed for this study (fig. 2). The first, Le-Bois-de-l'Enfer hoard at Saint-Sauveur-Le-Vicomte (Manche), is made entirely of copper ingots. The 20 elemental analyses have already been published (Gandois et al., 2019). Two isotopic analyses have been carried out since then (table 3). Elemental analyses of the Surtainville hoard have also been published (Le Carlier de Veslud et al., 2018). The Mérézel hoard (Bordas, 2019; 2023) in the commune of Le Palais at Belle-Île (Morbihan) was recently analysed. A total of 91 elemental chemical analyses and 15 isotopic analyses were obtained.

Elemental chemical analyses of artefacts from Mérézel show a wide range of compositions suggesting various sources of copper. It should be noted that the majority of objects have lead in the alloy up to 23 % (table 5). Various composition groups have been identified, but perhaps some groups could be brought together in the future with new analyses.

1) The first group, which includes the largest number of objects in the hoard (87), as well as the largest number of copper ingot fragments (29), has low contents of Ag (130–2,300 ppm), As (100–1,500 ppm), Ni (100–1,300 ppm), and somewhat high contents of Sb (300–6,700 ppm). It is also in this group that objects of Atlantic typology are present in greater numbers.

2) The second group consists of just 8 objects, including one copper ingot. It is characterised by very high contents of Ag (1,700–22,600 ppm) and As (2,000–25,600 ppm), low contents of Ni (200–2,500 ppm), and extremely high contents of Sb (10,000 to 107,000 ppm).

3) The third group comprises 7 objects. It is characterised by low contents of Ag (900–1,700 ppm) and As (1,000–3,300 ppm), low contents of Ni (400–2,800 ppm), and high to very high contents of Sb (6,700–35,200 ppm).

4) The fourth group is made up of 3 objects and is mainly characterised by a very high Ag content (2,000–16,000 ppm), a low As content (1,100–1,500 ppm), and a high to very high Sb content (6,000–34,700 ppm). Ni content varies from low to high (100–6,200 ppm).

5) The fifth consists of 5 objects including 2 ingots. It is characterised by low to high contents of Ag (80–1,200 ppm), high contents of As (4,000–8,000 ppm), low contents of Ni (400–1,200 ppm), and fairly high contents of Sb (1,600–3,800 ppm).

6) The sixth group consists of only two objects, including a fragment of ingot. It is very low in Ni (200–300 ppm), low to high in Ag (300–1,200 ppm), high in As (4,200–7,300 ppm), and very high in Sb (7,000–44,000 ppm).

7) The seventh group is composed only of a fragment of a copper ingot. It is characterised by a high content of Ag (2,652 ppm) and Sb (3,246 ppm) and a low content of As (124 ppm) and Ni (529 ppm).

It's worth noting that at this period, metal did not only travel in the form of ingots, but manufactured objects were probably also part of the trade. However, the presence of copper ingots in almost all chemical categories, combined with the fact that most of the objects have a regional typology, suggests that the metal travelled mainly in the form of copper ingots. The large number of hoards made up entirely of ingots provides further support for this hypothesis.

A comparison of the elemental compositions of objects of the recent Late Bronze Age 3 with those of Late Bronze Age 2 shows similarities for some objects, suggesting continuity in the supply of copper from the same sources (fig. 12). Comparison with objects from the east of France (fig. 13) shows that the copper supplying the Atlantic domain is significantly different from that supplying the continental domain (Véber, 2009).

As we have seen from the elemental analyses of bronze objects, copper ingots show a very wide variation in composition, which is confirmed by isotopic analyses (fig. 14a and b), implying multiple supplies throughout Europe. Three ingots show a compatibility with Spain (Huelva). A majority of ingots show correspondence with Slovakia. However, some of these also have a positive link with the Great Orme, Saint-Véran, the Italian Alps (Alto-Adige Trentino Veneto AATV), and Cabrières. One ingot is also compatible with an Austrian origin (Mitterberg). Finally, two or even three ingots could come from Cyprus (Kalavassos). Sardinia in the north-west has a small isotopic proximity, but this origin is less evident. Given this diversity, it is difficult to propose reliable sources of copper at this stage. A comparison of elemental chemistry with copper produced in these different sectors will certainly enable us to refine our knowledge of these sources.

DISCUSSION

This study provides an initial overview of the supply of copper during the Bronze Age in north-western France. The origins of copper ore have been determined or pro-

			Cu (%)	Pb (%)	Sn (%)	Ag (ppm)	As (ppm)	Bi (ppm)	Co (ppm)	Fe (ppm)	Ni (ppm)	Sb (ppm)	Zn (ppm)
Group 1	87 objects	min	58,97	0,07	2,72	135	95	212	0	52	102	314	0
Group 1	87 objects	*max*	*94,44*	*37,79*	*19,42*	*2256*	*1499*	*362*	*96*	*3789*	*1296*	*6674*	*853*
Group 1	87 objects	**median**	**86,33**	**3,26**	**9,88**	**772**	**1014**	**295**	**24**	**268**	**685**	**2963**	**613**
Group 2	8 objects	min	68,02	1,91	0,02	1737	2085	279	0	98	225	9820	121
Group 2	8 objects	*max*	*92,07*	*23,47*	*11,13*	*22590*	*25091*	*1352*	*483*	*1040*	*2464*	*107023*	*1150*
Group 2	8 objects	**median**	**75,31**	**12,78**	**8,47**	**2866**	**5132**	**304**	**81**	**135**	**811**	**13057**	**636**
Group 3	7 objects	min	65,04	0,48	8,20	866	937	252	13	81	402	6705	206
Group 3	7 objects	*max*	*87,56*	*22,83*	*13,04*	*1731*	*3309*	*422*	*54*	*3212*	*2772*	*35230*	*721*
Group 3	7 objects	**median**	**86,83**	**3,36**	**10,00**	**1174**	**2184**	**298**	**31**	**500**	**1122**	**9210**	**609**
Group 4	3 objects	min	67,71	3,11	7,53	2019	1159	241	10	79	98	5997	524
Group 4	3 objects	*max*	*86,28*	*22,82*	*7,94*	*16214*	*1492*	*376*	*61*	*2949*	*6188*	*34753*	*785*
Group 4	3 objects	**median**	**85,10**	**4,53**	**7,63**	**14403**	**1301**	**324**	**35**	**1314**	**1810**	**6031**	**746**
Group 5	5 objects	min	76,50	0,09	0,01	76	4135	285	0	37	375	1595	176
Group 5	5 objects	*max*	*97,49*	*9,18*	*14,01*	*1209*	*8002*	*509*	*138*	*257*	*1206*	*3748*	*671*
Group 5	5 objects	**median**	**95,50**	**1,14**	**3,11**	**464**	**5034**	**348**	**0**	**45**	**413**	**1977**	**579**
Group 6	2 objects	analysis	98,06	0,87	0,07	264	4221	317	0	532	284	7111	260
Group 6	2 objects	analysis	90,31	2,14	3,52	1176	7349	348	11	120	174	44086	665
Group 7	1 object	analysis	98,40	0,18	0,08	2652	124	305	0	308	529	3246	726

Table 5 – Minimum and maximum values, and median values for each group of elemental composition for LBA3b Mérézel hoard.

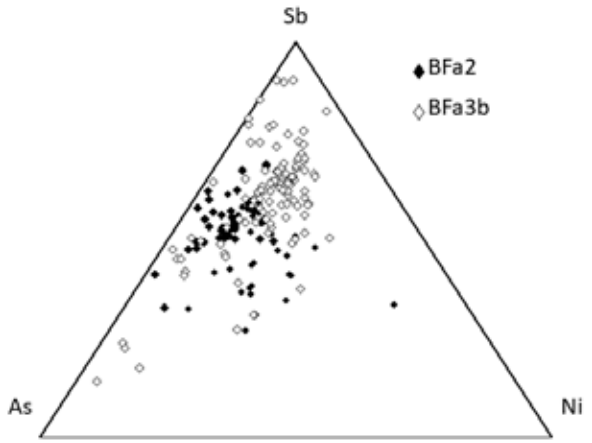


Fig. 12 – Ternary As/Ni/Sb diagram for North-West LBA3b hoard artefacts compared to that LBA2 North-West hoard artefacts.

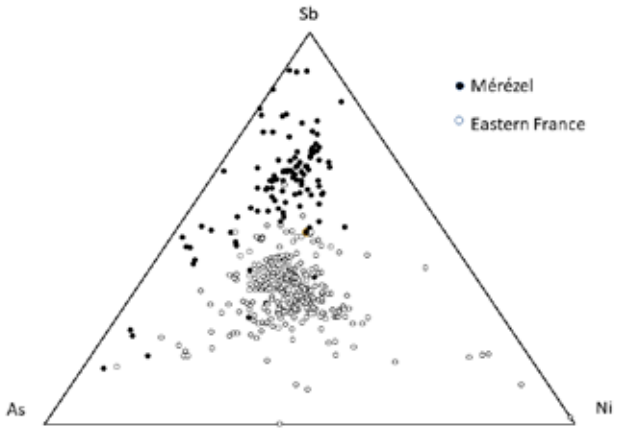


Fig. 13 – Ternary As/Ni/Sb diagram for North-West LBA3b hoard artefacts compared to that LBA2b North-East hoard artefacts.

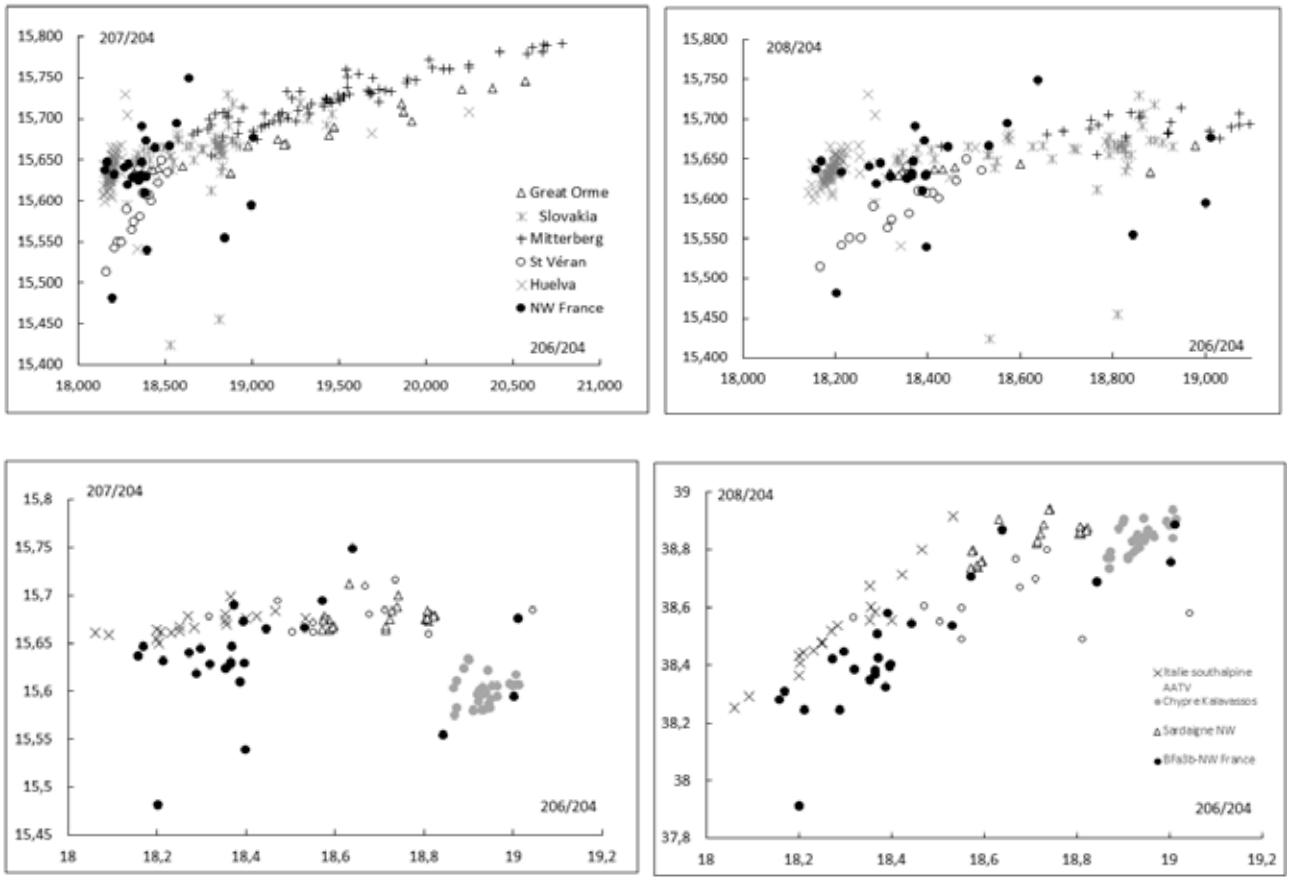


Fig. 14 – Lead isotopes diagrams for LBA3a North-West hoards copper ingots, compared to copper deposits form Great Orme, Slovakia, Mitterberg, Saint-Véran, Huelva, Italia southalpine AATV, Cyprus Kalavassos, Parys Moutain, Sardinia NW..

posed for the production of objects from several periods. This has been made possible by a large series of elemental and isotopic analyses that have already identified regional signatures, corresponding to metal stocks that vary in time and space. Although the metal analysed comes from metal hoards in which the objects may have a distant provenance, the focus of the analyses on regionally typical objects, foundry waste, and copper ingots makes it possible to identify the signatures of these stocks of metals used in the region concerned. Nevertheless, the exhaustive sampling enables us to approach the supply networks and their evolution for the first time.

These analyses suggest that the metal stocks in circulation were not the same in the Atlantic, Continental,

and Mediterranean areas, although the nature of these differences has yet to be clarified. This statement needs to be qualified because when analyses reveal a high degree of homogeneity in chemical signatures over a large geographical area, this can be interpreted as indicating the intense circulation of raw materials and artefacts within a very extensive geographical zone, without making it possible to trace the exchange networks more precisely. These results also show that stocks of metals of different origins appear to be present in the same hoards, highlighting the diversity of copper sources. They show too that the nature and origin of copper change over time.

For the Middle Bronze Age 1, copper seems to have come from Atlantic areas, and the copper most probably comes from the Great Orme mine in Wales. The analytical data concur with the typological observations, i.e. the objects from the Tréboul horizon show typological similarities to those from Acton Park. Williams (2023) has shown that copper supplies from the Great Orme are not confined to north-west France. Copper supply networks extend along the coasts of the English Channel and the North Sea, even as far as Sweden. This copper also seems to be distributed on the Aquitaine coast, which, however, also seems to be supplied by a second source. Comparison with other French regions seems to show that these networks were not able to penetrate significantly into the territory, although objects linked to the Tréboul horizon have been recognised as far as the Alps (Gabillot et al., 2023). The study of this period is not yet complete, and we now need to identify the limits to the circulation of this metal within France.

From the Middle Bronze Age 2 onwards, the supply of metal became much more important, with various sources, some of them probably very distant.

In the Middle Bronze Age 2, despite the very high chemical homogeneity of the bronze axes in the hoards, analyses show that they are made up of a mixture of copper of at least two origins: one probably from the south, with a potential Spanish origin (Huelva) or Italian (AATV); the other from the east, with metal from the large Mitterberg production area. A third source could be considered, taking into account the metal from the Great Orme. This metal could correspond either to the re-use of objects from the previous period made in the region or to newly imported metal, as the Great Orme mine was still in operation at this time. Despite a possible partial continuity of copper supply with the previous period, the analyses show a fairly drastic change in metal supply trades. The provenance of copper from Austria is consistent with the expansion of the tumuli culture. Although the north-west of France shows few artefacts linked to this culture, it would seem that the raw metal, probably in the form of ingots, spread further west into the Atlantic region. The similarity of the elemental chemical and isotopic compositions of the objects from the hoards from central and central-eastern France to those in the west also supports this hypothesis. The Spanish influence, in terms of copper supply, can also be seen as an expansion, northwards along the Atlantic coast, of a possible supply from the south in Aquitaine in the previous period.

For the Late Bronze Age 1, only one deposit, from Finistère, has been analysed. Consequently, very little information is available to support discussion of the origin and expansion of the metal supply. However, elemental chemical and isotopic analyses show a close similarity between objects from this period and those from the previous period, suggesting continuity in terms of metal supply, whereas the method of deposition of objects is changing in the hoards, and the number of these is decreasing drastically. Are we confronted with a lack of metal in the Atlantic domain, or are we simply facing cultural changes?

For the Late Bronze Age 2, the situation seems to have changed considerably in terms of copper supply networks. Chemical and isotopic analyses show several metal compositions that may correspond to as many sources. Because of the presence of lead in alloys, it is currently difficult to know the origin of most copper sources. However, the very high content of lead suggests that it may have come from a separate source. Nevertheless, elemental analyses have revealed groups of compositions that differ from those of copper ingots. Two sources of metal are used in the composition of heavily leaded bar ingots. The search for a typological match for these objects leads us to Eastern Europe, and in particular Slovakia, where this type of material has also been recognised, although the objects' shape is not quite identical (Boulud-Gazo et al., 2022). Elemental chemical analyses may also lead us eastwards due to the very high nickel content of some alloys. Austria, with the Mitterberg sector, could be a potential source, as well as ores located in Slovakia. Finally, the presence of a Klentice-type sword handle in the Late Bronze Age 3a Hourtin hoard (Couderc et al., 2021), which may have originated in this sector, is a further factor supporting the hypothesis that this region of Eastern Europe was the source of some of the copper. The chemical proximity of objects from north-west France to those from the Wilburton horizon in England raises questions. The large island has numerous lead deposits that could have supplied the continent with lead-rich alloys. Unfortunately, isotopic analyses cannot distinguish between several regions containing lead deposits in Western Europe. Finally, from the Late Bronze Age 2 onwards, we can see that the network supplying copper to north-western France became more complex and spread over greater distances.

For the Late Bronze Age 3b, the mixture of metals from different sources seems to be even greater. This can be seen in the elemental analyses of bronze objects and copper ingots. Isotopic analyses of the copper ingots seem to indicate sources of copper of different origins, ranging from the western and eastern Alps to central Europe. Origins in Mediterranean regions such as Cyprus, Sardinia, southern Spain, and southern France are also assumed. This southern origin can be compared with the fact that most of the copper ingots found in metallic hoards in north-western France are located on the south coast of the peninsula, from Finistère to Pays de la Loire (Bordas, 2023). The link between Mediterranean countries is also evident in the typology of the objects. Objects with typological affin-

ities to Nuragic pieces have been observed in north-western hoards. By contrast, occurrences have been found in Sardinia (Bordas, 2023). Similarly, a Huelva-type sword was brought up from the bottom of the English Channel off Normandy (oral communication H. Gandois), also showing a link with Spain. A link between the Iberian Peninsula and the Nordic countries has also been demonstrated by isotope analyses (Ling et al., 2013). Finally, the link with the regions of north-east France, and beyond with western Germany, is known through the presence in north-western hoards of objects of oriental typology such as sickles, tintinnabuli, or bracelets, of the Vandrevanges type in particular. The movement of metal objects also contributed to long-distance exchanges. The use of these metals of different origins leads to the production of regional objects whose chemical and elemental signatures correspond mainly to mixtures. As in the previous period, metal stocks are being built up.

To sum up, although this region is located at the end of the continent, it seems that it has always been part of a network for the exchange of goods toward Europe. Perhaps the numerous tin deposits in Brittany encouraged these exchanges. The region also faces Cornwall, which has the largest tin reserves in Europe, and which probably supplied the whole of Europe with this metal (Williams et al., 2025). The north-west of France probably played a major role in the transport of goods, including metals, which probably led to the development of a significant regional metallurgy.

CONCLUDING PERSPECTIVES

The programme developed in north-western France is far from complete. A great amount of work remains to be done on objects from the Chalcolithic period and the Early Bronze Age. Numerous chemical and isotopic analyses are still needed to try to identify the many sources of copper used during the Middle and Late Bronze Age.

A greater number of analyses taken into account in this way can highlight chemical signatures that differ to a greater or lesser extent depending on the period under consideration. This makes it possible to see potential continuities in the supply of metal or real ruptures. For the north-west, it would therefore be interesting to analyse MBAa1 objects further to the east of the Armorican peninsula, but also further towards the centre of France, in order to determine the distances over which Welsh copper may have spread. In the same way, it would be necessary to develop the database for the LBA1 period, covering the whole of the Armorican peninsula and even further east. While objects from this period seem to have a composition very close to that of the previous period, at least for the few objects analysed so far, it is also possible that it corresponds to a transition period to the next period, LBAa2, which presents a very clear difference in chemical and isotopic composition from MBAa2. It would also be desirable to be able to analyse all of the rare fragments of copper ingots found in hoards from this period in order to better identify the potential sources of the copper. Finally, for the last period, which corresponds to LBA3b, because of the extensive mixing of metals in the production of bronze objects, the focus should also be on copper ingots, of which there are fortunately many, but which alone have the signature of the ores.

However, these results encourage us to continue this analytical approach with quantitatively significant series that are strategically sampled from a functional, geographical and typochronological point of view. Combined with isotopic analyses of lead, copper, and iron, these data are contributing to discussions on the movement of metal masses across France and, more broadly, across Europe during the Bronze Age.

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26

DEWA 2023 – FROM MINE TO OBJECT

DIALOGUES BETWEEN EASTERN AND WESTERN ARCHAEOMETALLURGY

(3RD-1ST MILLENNIUM BC)

Actes de la séance conjointe de la Société préhistorique française
et de l'Association pour la promotion des recherches sur l'âge du bronze
Saint-Germain-en Laye, 22-24 novembre 2023

Archaeometallurgy (of non-ferrous alloys) is a discipline which encompasses the entire field of ancient metallurgy, from the extraction of metals from their ores to the present state of archaeological objects, and has been rapidly expanding over the last two decades. Considerable progress in advancing the field is enhancing our knowledge, whether about ore extraction and mining activities, production processes (from ore to metal) or artefact transformation (from metal to finished product), as well as the lifecycle of metallic products (from finished products to their current status and location).

This structuring of archaeometallurgical research has been accompanied by several bulkheads: researchers are often specialists in one step of the chaîne opératoire, a type of approach, a category of scientific analysis, a specific material or a particular geographic area or time period. It makes for research compartmentalized between different approaches such as mining archaeology, archaeometry, technology and archaeology on one hand, and, for example, between Europe and the Near East on the other. Although interdisciplinarity, which is now the norm, relativize this observation, the various specialists often have difficulty gathering and exchanging ideas due to their disparate methods, training, research traditions and questions.

Otherwise, it seems that archaeometallurgical research is developing in parallel in Europe and in the Near East, with relatively few bridges between these two regions, although some researchers navigate between these very different chrono-cultural, technical, environmental, and socio-political contexts.

This is why, in the framework of this conference, we wanted to create a dialogue between these two worlds. Our objective was to provoke a disciplinary, methodological, geographical, and chronological decompartmentalization to bring together researchers who are rarely in contact despite the complementarity of their approaches. We hope, in the long run, that this approach will allow us to strengthen ties, weave collaborations, and create an interdisciplinary research group on archaeometallurgy in the entire Old World.

The conference was organized around four axes, making four main sessions:

1. Mining and ore extraction activities
2. Tools, actors and production loci: specialization and organization
3. The production process (chaînes opératoires), from metal to finished product
4. Exchanges and uses of metallic objects: from archaeological contexts to the laboratory

This conference was part of a series of meetings organised by the Société préhistorique française (SPF), in conjunction with the Association pour la promotion des recherches sur l'âge du Bronze (Aprab).

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