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

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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, metals 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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