Abstracts

GENERAL

Liu, S., Sun, Z., Zhang, J., Lin, J., Chen, K., Chen, J., Cui, J. & Mei, J. (2025). 50 years of bronze provenance studies: A perspective from China. *Journal of Archaeological Science* 180, 106272. doi:10.1016/j.jas.2025.106272

This review summarizes the current state of bronze provenance studies in China, highlighting both recent trends and challenges. The first section addresses the issues surrounding highly radiogenic lead (HRL) from the Shang period. This section also emphasises two critical questions: the metal(s) with which HRL is associated, and the meaning of its isochron-like trend line. The second section focuses on the growing body of publications on lead isotope analysis of Chinese bronzes, particularly the synchronic alteration of lead isotope features across vast regions over two millennia. Additionally, this section reviews specific spatial-temporal units, which have generated significant research in recent years and may reveal distinct metal circulation systems. The following sections consider the provenance of copper and tin, essential components in the production of bronze artefacts, but often overlooked in provenance studies. Methodological challenges are discussed, with a particular emphasis on the widely used trace element analysis technique. Finally, the review offers a brief discussion on model-informed provenance investigations, reflecting a global trend in the field, which is expected to have a substantial impact on the study of Chinese materials.

Vigorelli, L., Salvemini, F., Marcucci, G., Cucini, C., Di Martino, D. & Riccardi, M. P. (2025). High resolution neutron tomography as a non-invasive tool for the study of a filigree from the medieval Chiaravalle Cross. *Archaeological and Anthropological Sciences* 17(7), 138. doi:10.1007/s12520-025-02254-y

The Chiaravalle Cross, an ancient Italian processional cross from Chiaravalle Abbey (near Milan, Italy), is a jewellery masterpiece, richly decorated with precious metals applied by combining different metalworking techniques like chiseling, engraving, and gilding with lamination and amalgams. In particular, a golden filigree adorns the entire cross. A very small portion of this filigree was made available for analyses, after the restoration in 2016. The filigree has a multi-component structure, made of drawn and twisted silver wires, soldered and finally gilded. A neutron tomography imaging experiment allowed a three-dimensional structure of the ancient golden decoration to be compared with the two-dimensional results obtained by a previous SEM investigation, demonstrating the potential of non-invasive techniques in understanding the manufacturing technique.

Rippa, M., Fenelli, P., Di Meo, A. & Trojsi, G. (2025). Active thermography for the analysis and conservation of Roman lead pipes at the Baia Archaeological Park. *Journal of Cultural Heritage* 74, 257–264. doi:10.1016/j.culher.2025.06.019

The conservation and study of ancient cultural heritage artifacts, particularly those that have been buried or weathered over time, present considerable challenges. Among these artifacts, Roman lead pipes (*fistulae plumbeae*) require non-destructive methods to assess their condition and reveal hidden details. This study explores the application of Active Thermography (AT) as a non-destructive method for analysing these artifacts, focusing on three distinct thermal stimulation techniques: hot air, long light pulse, and short light pulse. The analysis was conducted on three *fistulae plumbeae* from the Baia Archaeological Park, including a detailed case study on the Pisones *fistula*. Advanced thermal data processing techniques, such as Maximum Thermal Gradient, Thermal Recovery, and Principal Component Thermography, were employed to assess the conservation state of these pipes. The findings demonstrate that AT effectively identifies areas of deterioration, encrustations, and impurity accumulation. It also provides insights into the impact of restoration interventions. This pioneering research highlights the potential of infrared thermography for the non-destructive analysis of Roman lead pipes and underscores the broader applicability of thermal imaging technologies in cultural heritage conservation.

Albarède, F., Blichert-Toft, J. & Pinto, M. (2025). Salt, silver, and gold: Early innovations in precious metal refining. *Heritage Science* 13(1). doi:10.1038/s40494-025-01895-5

This study explores Egyptian and Persian silver artifacts from the Louvre Museum to trace the origins and development of gold and silver refining methods. While conventional theories attribute the emergence of gold parting through salt cementation to Lydia in the Iron Age, our findings indicate that this technique was already in use during the Middle Bronze Age. Lead isotope and elemental analyses reveal two distinct silver sources: (1) Aegean silver, characterised by positive lead model ages, and (2) silver extracted from gold cementation, distinguished by mantle-derived lead with future Pb model ages. The results demonstrate that ancient Egyptian and Middle Eastern metallurgists employed salt-based refining processes, utilising chalk as a reactive medium to enhance silver recovery. This evidence overturns the long-standing belief that the Lydians pioneered gold parting, showing instead that the process was well established over a millennium earlier.

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Sabatini, B. & Allanore, A. (2025). A novel application of X-ray computed tomography towards the characterisation and interpretation of phase formations, mineral parageneses, and internal features in ancient copper slag from Tepe Hissar, Iran. *PLOS One* 20(11), e0336603. doi:10.1371/journal.pone.0336603

A selection of metallurgical slag artifacts from the Early Bronze Age site of Tepe Hissar, Iran, were characterised using CT, XRF, XRD, optical microscopy, and and SEM-EDS. The CT scans were used to identify regions of interest and internal features for sectioning, including pores, high-density inclusions, and differences in slag density and porosity distribution. The scans revealed internal features and patterns; however, contiguous metal-rich regions and thick surface minerals masked some features and misrepresented others. This study demonstrates how CT enables the identification and collection of salient diagnostic information from slag artifacts before sectioning, providing a preview of internal features and a volumetric 3D record of each artifact. After studying the 3D images, the artifacts were precisely sectioned and examined using optical microscopy, SEM-EDS, and XRD, revealing primary pyrometallurgical phases and secondary mineralisations, stratified slag layers, leaching channels, and internal microenvironments. Secondary precipitates and mineral parageneses within these environments are discussed, referencing the archaeological record, soil salinity, and Pourbaix diagrams. An explanation for the presence of speiss in some slag artifacts from Hissar is also detailed.

BRITAIN AND IRELAND

Loveluck, C. P., Millett, M. J., Chenery, S., Chenery, C., Ferraby, R., French, C., Langdon, C, Moore, F. E., Pears, B., Scaife, R. & Toms, P. (2025). Aldborough and the metals economy of northern England, c. AD 345–1700: A new post-Roman narrative. *Antiquity* 99(407), 1320–1340. doi:10.15184/aqy.2025.10175

Increasing interdisciplinary analysis of geoarchaeological records, including sediment and ice cores, permits finer-scale contextual interpretations of the history of anthropogenic environmental impacts. In an interdisciplinary approach to economic history, the authors examine metal pollutants in a sediment core from the Roman metal-producing centre of Aldborough, North Yorkshire, combining this record with textual and archaeological evidence from the region. Finding that fluctuations in pollution correspond with sociopolitical events, pandemics and recorded trends in British metal production *c.* AD 1100–1700, the authors extend the analysis to earlier periods lacking written records, providing a new post-Roman economic narrative for northern England.

EUROPE

Grygiel, M. & Kędzierski, A. (2023). A gold coin from Jastrzębniki, Kalisz district (PL). On the late Celtic coinage in North-Central Europe. *Praehistorische Zeitschrift* 98(2), 729–749. doi:10.1515/pz-2023-2011

Attempts were made in several locations in Central Europe to continue minting in gold, following the Celtic Boii tradition which began to fade after the collapse of the Bohemian-Moravian *oppida* at the turn of the LT D1/D2 phases (ca. 60/50 BC). The main center for the continuation of this activity was in the lands of the Pannonian Boii, in the Bratislava area, and probably in the Bratislava *oppidum* itself. This paper focuses on three other minting centers which were established north of the Carpathians and Sudetes among the northern barbarians and which imitated late Boii gold coins: one in the Tyniec group near Kraków, and two in the main Przeworsk culture settlement zones on the middle Prosna River near Kalisz and in Kuyavia. These northern mints, undoubtedly operated by experienced Celtic minters, recycled extremely popular shell staters with solar and lunar motifs that were reintroduced into circulation with a renewed stamp or after having been legalized by adding small additional marks. They also issued various small coins made of electrum alloys, significantly varying in weight (mostly about 1/8 of a Boii stater), with an abstract knob-and-rib ornamentation reminiscent of the motifs featuring on the later coins minted at the *oppida* in Staré Hradisko (Moravia) and Bratislava. The nominally gold coins issued in the Oder and Vistula basins must have provided the equivalent in supra-regional prestige exchange, which is indicated by their extensive circulation zone. One of the reasons for the disappearance of the local minting traditions among the northern barbarian elites might have been the massive influx of Roman coinage into the Central European Barbaricum in the second century AD.

Wardas-Lasoń, M., Tabaszewski, W., Materna, M. & Garbacz-Klempka, A. (2025). Contents of deposits from the archaeological site of Sobolów in Bochnia—a contribution to prehistoric foundry activity. *Archaeometry* 67(5), 1081–1097. doi:10.1111/arcm.13071

In the Sobolów area, three hoards of the Hallstatt period were discovered, containing ornaments, waste and scrap of tin-lead-bronze alloys, with iron objects in close proximity, possibly indicating the existence of a foundry workshop. They were accompanied by glass beads, an indicator of the settlement of the Lusatian EB-Ha Culture, found together with amber beads, and fragments of composite bracelets made of narrow 'scapes' tightly clamped on a wooden hoop. Macro- and micro- light microscopy, chemical composition analysis by XRF and, for the glass bead, SEM with X-ray microanalysis were used.

Ioannides, D., Georgakopoulou, M., Boyd, M. J., Renfrew, C. & Rehren, T. (2025). Copper smelting on Dhaskalio, Keros: Redefining early Cycladic metallurgy and metalworking. *Journal of Archaeological Science: Reports* 65, 105228. doi:10.1016/j.jasrep.2025.105228

The island of Keros, situated in the middle of the Cyclades in the Aegean Sea, Greece, hosted the world's earliest maritime sanctuary, dating to the Early Cycladic (EC) II and III periods. Just off the west coast of Keros, the islet of Dhaskalio accommodated an important EC complex associated with the sanctuary. One of the principal productive activities within the complex was metalworking and another was obsidian blade production, evidence for which was ubiquitous. Past analytical studies have shown that the metallurgical remains from the summit of Dhaskalio are overwhelmingly consistent with secondary copperworking activities, with arsenical copper being the predominant alloy. Excavations carried out in 2016–2018 revealed that metallurgical processes were spread almost across the entire built-up area. Workshop remains indicative of different technical processes associated with copper and lead metallurgy were uncovered, with key findings in areas below the summit, and the NE periphery of Dhaskalio toward the sea. The finds, which included slags, copper and lead spills, metallurgical ceramics, and baking, surpass in numbers and variety anything known from settlement contexts of the same period in the Cyclades, thus confirming Dhaskalio as a major metalworking centre for the Early Bronze Age Aegean. This paper reports on the analytical examination of slag and mineral samples from the new excavations. The results provide a comprehensive characterisation of the metallurgical processes conducted at the settlement while aiming to explore their longevity and potential spatial functional distinctions within the site.

De Falco, M., Aurino, P., Cavazzuti, C., Lucarelli, C., Canovaro, C., Lugli, F., Sperduti, A., Cecconi, V., Angelini, I., Artioli, G. & Cipriani, A. (2025). A multi-analytical approach to unveil early Bronze Age population dynamics and metal exchange networks at the foot of Mount Vesuvius. *Scientific Reports* 15(1), 19492. doi:10.1038/s41598-025-03024-5

The trajectories of human and object mobility in the 3rd and 2nd millennia BC have long been a significant area of inquiry within prehistoric archaeology and over the past decade; aDNA and isotope analyses revealed a complex pattern of human migration, cultural admixture and exchange routes. While Northern Italy is clearly involved in this phenomenon, there remains a significant gap for the south of the country, generally considered peripheral to major exchange networks in this phase. Recently, two large cemeteries have been discovered in the hinterland of Mount Vesuvius (Acerra, Italy). They have yielded unprecedented numbers of exotic metal objects dating to 2400–1800 BC. Such items are extremely rare in Southern Italy, displaying typologies more commonly found across Northern Italy and Central Europe. Archaeological, bioanthropological and geochemical methods were applied to material from the cemeteries. Pb isotope analyses and metal artifact distribution modeling revealed long-distance terrestrial and maritime connections to Northern Italy, Continental Europe and the Western Mediterranean. Conversely, Sr isotope data indicate that these prestigious and exotic objects were deposited within a context of low human mobility. By integrating investigations into both metal and human mobility, this study emphasises the extent and complexity of the exchange network in Southern Italy around 2000 BC.

Nowak, K., Stos-Gale, Z. A., Bartz, W., Maciejewski, M., Gackowski, J., Karasiński, J., Kuźbik, R., Purowski, T., Sobieraj, J., Hoffmann, M., Badura, B. & Stolarczyk, T. (2025). Metallurgy in first-millennium BC Poland: Insights from metal production, trade networks and landscape archaeology. *Antiquity* 99(407), e41. doi:10.15184/aqy.2025.10128

Multidisciplinary methods permit the first archaeometallurgical study of artefacts from five key first-millennium BC settlements in Poland: Grzybiany, Wicina, Kamieniec, Tarławki and Mołtajny. This project fills a lacuna in our understanding of technical ceramics, metal provenance and the role of settlements in the cultural landscape.

Gassmann, G. & Schwab, R. (2025). New evidence for early pig iron production and refining technology on the foothills of the Swabian mountains, Germany. *Archaeological and Anthropological Sciences* 17(8), 176. doi:10.1007/s12520-025-02288-2

The investigation is focused on the remains of an iron smelting site in South-West Germany of the 11th to 13th centuries AD. Within the scope of a pilot study, scientific analyses of smelting debris revealed lumps of pig iron, finery slag and early blast furnace calcium-alumina-silicate slag, as well as wrought iron with relicts of cast iron within the microstructure. This new evidence for early indirect process technology is concordant with results of contemporary sites in South-West Germany, and fits in seamlessly with current European research on medieval ferrous metallurgy. The results of a High Medieval smelting site near Ohmenhausen presented here are one of the first hints of a deliberate finery process for that early period of a modified proto-blast furnace technology.

Berger, D., Matta, V., Ialongo, N., Nørgaard, H. W., Salis, G., Brauns, M., Holst, M. K. & Vandkilde, H. (2025). Multiproxy analysis unwraps origin and fabrication biographies of Sardinian figurines: On the trail of metal-driven interaction and mixing practices in the early first millennium BCE. *PLOS One* 20(9), e0328268. doi:10.1371/journal.pone.0328268

This article presents a multiproxy investigation of metal samples obtained from 48 Nuragic figurines (so-called *bronzetti*) and three copper bun ingots from three prominent Sardinian sanctuaries and one unidentified site, dating to the late Nuragic period of the early first millennium BCE. The investigation integrates conventional trace-elemental and lead isotope analyses with copper, tin, and osmium isotope measurements, which allows for a more reliable identification of the original metal sources used in the production of the objects (copper from the Iglesiente-Sulcis district in southwest Sardinia, with the Sa Duchessa mine as the most likely supplier; in addition, copper from the Alcudia valley or the Linares district in the Iberian Peninsula). The combination of analytical proxies reveals the mixing of copper from these distinct regions, while ruling out the exploitation of Sardinian tin resources. Osmium isotope ratios confirm the use of Sardinian copper and exclude the alloying of local lead with imported copper. These results shed light on local metallurgical practices and

distribution strategies in Nuragic Sardinia, but also on Sardinia's broader role and position in the Mediterranean world during the transition from the Late Bronze Age to the Early Iron Age.

Petean, I., Peţan, A., Pop, H., Avram, S. E., Tudoran, L. B. & Borodi, G. (2025). Nondestructive investigations of tin-rich bronze mirrors discovered in Dacian sites from Salaj county – Romania. *Journal of Archaeological Science: Reports* 67, 105424. doi:10.1016/j.jasrep.2025.105424

Mirrors were a sign of power and wealth in antiquity, having an important role in wedding and funeral rituals. Bronze mirrors were commonly manufactured in the Roman and Hellenistic worlds (tin content of up to 26 wt%). Roman and Greek mirrors are often found in Dacian sites, either through commerce or as spoils of war. The present article is focused on the non-destructive analysis of unusual white bronze mirror fragments discovered in Dacian sites in Salaj County, Romania, which appeared to have been produced by casting. SEM-EDS analysis reveals bronze with high tin amounts and small amounts of lead. Elemental maps reveal tin-rich grains identified by XRD as intermetallic compound Cu_6Sn_5 and copper-rich grains identified as $Cu_{41}Sn_{11}$. Casting such thin-walled specimens causes rapid cooling, which doesn't allow for the proper crystallisation of Cu_3Sn through the eutectoid reaction, thereby maintaining the $Cu_{41}Sn_{11}$ structure. Thus, these mirrors have brittle structures due to the development of intermetallic compounds, which enable proper abrasion polishing using ancient methods. Atomic Force Microscopy reveals that Cu_6Sn_5 grains are more affected by the polishing action, inducing a roughness of 55.7 to 60.2 nm, while mirrors having more $Cu_{41}Sn_{11}$ have smoother surfaces with a roughness of about 21.7–36.8 nm. Both cases ensure a clear mirror lustre with a silvery aspect, making these mirrors appreciated for their quality. Unfortunately, such brittle intermetallic compounds make these mirrors break like glass, a fact demonstrated by their fragmentary condition. These findings suggest a deliberate technological choice aimed at enhancing reflectivity by using tin-rich alloys, despite their mechanical fragility. Comparative data from Celtic contexts suggest the possibility of shared metallurgical knowledge and similar alloying practices across Late Iron Age Europe. The absence of Greco-Roman parallels and the archaeological contexts point to local production, contributing to a revised understanding of Dacian metallurgy as innovative and regionally integrated.

Boutoille, L. (2025). First evidence of lost-wax casting in the Earlier Bronze Age of South-Eastern Spain: The silver bangle from El Argar, Grave 292. *Oxford Journal of Archaeology* 45, 50–67. doi:10.1111/ojoa.70005

In 1884, one of the burials discovered at El Argar, the eponymous site of the El Argar culture, revealed the remains of a woman wearing an unusual silver bangle. This ornament appears to be the first evidence of a silver object produced by lost-wax casting in Bronze Age Iberia and, to date, in Western Europe. It demonstrates that El Argar metalworking technology was probably more complex and innovative than previously thought, opening up new perspectives on the organisation of metalwork production and the degree of craft specialisation in the earlier Bronze Age of south-eastern Spain.

NEAR EAST

Habibzadeh, M., Oudbashi, O., Naseri, R. & Bahadori, S. (2025). Archaeometallurgical investigation of the copper-based artifacts from Lahsavareh Iron Age II-III cemetery, southwestern Iran. *Journal of Archaeological Science: Reports* 65, 105186. doi:10.1016/j.jasrep.2025.105186

A group of metal artifacts recently excavated from the Lahsavareh Iron Age II-III cemetery in southwestern Iran (dating to the late Middle Elamite to Neo-Elamite period) was analysed to investigate metalworking techniques and alloy composition. Nineteen artifacts were studied using µ-XRF, SEM-EDS, and metallography techniques. The analyses revealed that the artifacts were primarily made from a binary tin bronze alloy with varying tin content, while arsenic and lead were present in significant quantities in only a few artifacts. Microscopic observations and microanalytical studies indicate that the artifacts were produced through different levels of thermo-mechanical processes, with copper sulfide ores used to obtain copper. The results of this interdisciplinary study offer new insights into the material culture of the Iron Age II-III on the Iranian Plateau and provide a comparative analysis of the history and evolution of copper-based metallurgy in the region during the first half of the first millennium BCE.

Güder, Ü., Yavaş, A., Demirel Gökalp, Z., Taşan, C. C. & Raabe, D. (2025). From crucible steel to the battlefield: Investigating a unique early Medieval arrowhead from Anatolia. *Metallography, Microstructure, and Analysis* 14(4), 663–674. doi:10.1007/s13632-025-01216-z

A three-bladed arrowhead with a needle-type tang was recovered during the excavations of the lower city church of Byzantine Stronghold Amorium in central Anatolia and has been analysed. Coins discovered in the same context date the arrowhead to the Middle Byzantine period (ninth–tenth century CE). Metallography (OM, SEM), SEM-EDS and EBSD techniques were used to examine samples taken from the head and the tang sections of the arrowhead. It was found to be made of manganese-alloyed crucible steel (0.4–1% Mn), shaped through warm forging cycles and selectively quenched and tempered to enhance its mechanical properties. The hardened head, likely designed for armour penetration, along with the potential watered surface pattern (*firind*), suggests that the arrowhead functioned both as a weapon and as a prestige symbol. Historical sources and archaeometallurgical evidence link the arrowhead to mounted Turkic archers in the Abbasid army during the 838 CE Sack of Amorium. The arrowhead was revealed to be the earliest crucible steel find and the only example of such an object manufactured from crucible steel discovered in medieval Anatolian excavations.

Finn-Kandel, D. M. & Yahalom-Mack, N. (2025). Copper for the early oxhide ingots: An Egyptian source? *Journal of Archaeological Science: Reports* 66, 105268. doi:10.1016/j.jasrep.2025.105268

The provenance of a group of Late Minoan IB copper oxhide ingots found on Crete remains a mystery in Mediterranean archaeometallurgical research. The distinctive isotopic signature of the Late Minoan IB Cretan ingots points to an ore source

from the Neoproterozoic or early Cambrian eras, effectively excluding most of the well-documented copper sources within the Mediterranean region. Using a blend of legacy geochemical data, historical evidence, and archaeological findings, we argue that the yet-to-be-defined 'Old Copper' signature derives from the Arabian-Nubian Shield. Based on this interpretation, we suggest that copper from the Red Sea region was traded via Egypt to the Late Minoan IB Minoan palaces in the form of oxhide ingots. This interpretation sheds light on the development of the Minoan-Egypt trade at the beginning of the Late Bronze Age.

Bukowski, K., Pieńkowska, A., Woronko, B., Moska, P., Kiersnowski, H., Piestrzyński, A. & Al-Ghafri, W. A. H. S. (2025). Archaeometallurgy in Northern Oman—diachronic copper production on a smelting site in Wadi al-Salh. *Archaeometry* 67(6), 1692–1711. doi:10.1111/arcm.70015

Archaeometallurgical studies at the Salh site in northern Oman have provided new data on copper technology in the Bronze Age and Islamic periods. Archaeological results indicate that it may have functioned seasonally. Slag analyses have shown possible technological changes over the centuries. Smelting was carried out under reducing conditions, using oxidized copper ores from weathering zone deposits. The scale of copper production at Salh was relatively small in both periods, but – due to its strategic location near important trade routes, the site could have functioned as part of a short-range as well as long-range mercantile network.

Eshel, T., Groman-Yaroslavski, I., Shochat, H., Harlavan, Y. & Bar, S. (2025). A 7th century BCE hacksilber hoard from Mras ed-Din: Metrology, functional analysis, lead isotopes and historical implications. *Archaeological and Anthropological Sciences* 17(9), 177. doi:10.1007/s12520-025-02274-8

A silver hoard from Mras ed-Din in the region of Samaria is published here for the first time. Dating to the 7th century BCE, the hoard comprises six large silver cut-ingots – also known as *hacksilber*. The study includes metrological, chemical and isotopic analysis. In addition, for the first time, functional analysis has been applied to hoarded cut-silver items. Results show that the cut-ingots conform to a series of shekel-based weight standards, making this the only known Levantine hoard to clearly adhere to the local weight system. Detailed examination of the cut characteristics and other visible features allows the reconstruction of the segmentation process used to produce the *hacksilber*. This process involved heating, fine-chiseling, segmentation with a larger chisel, and hacking. Some cut ingots have rounded corners, suggesting use as currency. Chemical and isotopic analyses indicate that most of the silver originated from Laurion, Greece. These findings suggest that Mras ed-Din, located in the former territory of the destroyed Kingdom of Israel, was influenced by and possibly integrated into the economic sphere of the Kingdom of Judah.

Cordivari, B. W. & Aras, O. (2025). Copper alloying practices of Urartian metalwork: Results of pXRF analysis from Ayanis, Yukarı Anzaf, and Çavuştepe (Türkiye). *Journal of Archaeological Science: Reports* 67, 105417. doi:10.1016/j.jasrep.2025.105417

Copper alloy metalwork of the Iron Age Urartian kingdom (9th-7th centuries BCE) is famous for its high degree of sophistication and skill. The results of ED-pXRF analysis of 73 Urartian copper alloy objects, primarily from the fortresses of Ayanis, Yukarı Anzaf and Çavuştepe in eastern Türkiye are presented. Material dating to the reigns of three different Urartian kings between the 9th and 7th centuries BCE is included in order to assess and compare alloying strategies across object types, sites, and time periods. The results indicate that the majority of the objects are bronze alloys (Cu-Sn), but there are also a range of other alloys represented (eg. Cu-Zn-Sn). Cu-Sn alloys appear to have been chosen for objects worked by hammering, such as shields, likely due to their hardness. Cast objects frequently included Pb or Zn in addition to Sn, probably to facilitate easier casting. Arrowheads are enriched in As and Sb, consistent with the use of a *fahlore* raw material source different from the other artifact classes. These correlations are present in objects from different sites and time periods, suggesting that alloying practices were shared between craftspeople throughout the kingdom.

Kakavand, M., Rafiei-Alavi, B., Emami, M. & Kehl, M. (2025). Evidence of early bronze age metallurgy from the ancient sites of the Varzaneh plain (Isfahan), considering mineralogical, chemical, and provenance studies. *METALLA* 29(1), 3–32. doi:10.46586/metalla.v29.2025.i1.3-32

The Varzaneh Plain is rich in ancient sites from various periods, from the Early Bronze Age II (2700–2200 BC) to the Islamic middle centuries. Among the 268 sites surveyed, 79 contained slag and metal fragments, indicating metal smelting activities in this region. Two sites from the Early Bronze Age yielded significant evidence of slag, crucibles, metal objects, and litharge. This period marks a peak of prosperity for the Varzaneh Plain, contrasting with the relative decline of nearby ancient sites such as Sialk and Arisman. The analysis of metal materials from the investigations, using a polarizing light microscope (with reflected light), XRF, and SEM-EDX, revealed that the metal smelting used copper sulphide deposits as raw resources. XRF scanning shows the presence of As, Ni, Pb, and Ag as accessory elements. These results, along with the lead isotope test, provide strong evidence for the connection between the metal products of the Varzaneh Plain and the mines of Nakhlak (Pb-Zn-Ag) in the vicinity of the Anarak City and Darhand copper sources in the Karkas Mountain area.

ASIA

Ren, W., Liu, R., Li, Y., Tang, X., Han, R., Jin, F., Huan, L. & Pollard, M. (2025). High tin or high lead: Distinctive alloying practices of the pastoral Yuhuangmiao culture in Northeast China during the first millennium BCE. *Archaeometry* 67(4), 1040–1056. doi:10.1111/arcm.13068

The Jundushan cemetery, located on the northern boundary of present-day Beijing, lies between the Yan and Taihang mountains linking northern and central China and therefore provides an opportunity to examine evidence of interactions between pastoralism and agriculture around the early half of the first millennium BCE. This paper aims to illustrate the local metallurgical development, exemplified by the key metal assemblage discovered at the Jundushan cemetery of the Yuhuangmiao culture. The new alloying and lead isotopic analyses of 39 bronzes reveal a series of changes in both the metallurgical practice and metal supply networks. Jundunshan bronze is characterised by the use of both high-tin and high-lead bronzes. It is suggested that tin played an essential role. Two different alloying processes are proposed, one with almost pure copper being alloyed by pure tin, the other with pure copper combining with a specific tin-lead mixture (Sn: Pb ≈ 45:55). Lead isotopic data reveal a clear change during the transition between the mid and late stages of Jundushan. The major type of lead used in the last stage at Jundushan (*c.* 6th–5th century BCE) does not appear to have been widely circulated in the states of central China, which indicates locally sourced lead. The new data bridge an important gap in our knowledge of the metallurgical practice and flow of metal around the early first millennium BCE in northeastern China, a region where agriculturalists and pastoralists interacted.

Sun, T., Chen, W., Liu, F., Li, Y., Zhang, G. & Li, Y. (2025). Iron smelting techniques in eastern Sichuan province, China: scientific analysis of smelting remains excavated from the Chengba site. *Archaeological and Anthropological Sciences* 17(7), 151. doi:10.1007/s12520-025-02264-w

The Chengba site is the only city site from the Han Dynasty (202 BCE–CE 220) discovered in eastern Sichuan Province. Being the administrative centre of "Dangqu County" during the Han Dynasty, the site has been found to contain urban features, cemetery areas and smelting areas amongst other specialised districts. The large quantities of smelting-related remains recently unearthed from Chengba were investigated by archaeological and scientific analysis. Results suggest that bloomery smelting technology was used at Chengba during the Han Dynasty, and that the site was under the jurisdiction of the "Dangqu Tieguan" (government-controlled offices responsible for iron smelting and production activities, called Tieguan) as recorded in historical documents. The bloomery smelting technology used in Chengba notably differs from the pig-iron smelting common on the Central Plains and the Chengdu Plain during the Han Dynasty, which was likely a result of eastern Sichuan's combined social needs, local traditions, and economic condition. The Han Dynasty smelting remains and ironware objects recovered from Chengba certainly provide new materials and perspectives for the studies of the smelting technologies and the social developments in eastern Sichuan during the Han Dynasty.

Gao, J., Xu, X., Li, C., Hao, N., Lang, J., Han, H. & Wang, Q. (2025). Technology, inhabitants and ritual traditions revealed by scientific analyses of Eastern Zhou bronze artefacts from the Lu state, Qufu, China. *Journal of Archaeological Science* 180, 106309. doi:10.1016/j.jas.2025.106309

Bronze ritual vessels played a crucial role in Chinese civilisation during the Chinese Bronze Age. However, bronze artefacts from the Lu state, one of the vassal states which fully implemented the Rites of Zhou, have rarely been scientifically analysed. This study presents the metallographic and elemental results as well as the lead isotope ratios in 67 bronze artefacts excavated from three burial complexes in Qufu, the capital of the Lu state (8th–3rd century BCE). The results suggest that craftsmen understood the effect of alloy compositions on the mechanical properties of the objects and skillfully produced forged, thin-walled vessels with low lead contents for ritual purposes. Furthermore, by integrating lead isotope data with archaeological contexts, the similarities and differences in lead isotope ratios between bronze artefacts belonging to different genders, social strata and vassal states are revealed, as well as diachronic changes in metal circulation networks. This offers a new perspective for understanding the social and cultural changes during the Eastern Zhou period.

Patro, A. K., Venkatesh, K., Prajapati, S., Talapaneni, T., Singh, P. K. & Lavakumar, A. (2025). Beyond the blade: A microstructural investigation of an ancient Indian steel sword. *Metallography, Microstructure, and Analysis* 14(4), 734–746. doi:10.1007/s13632-025-01226-x

This study investigates a fourteenth-century sword from Kondapalli, India, revealing advanced ancient Indian metallurgical practices associated with crucible steels like Wootz. Optical emission spectrometry confirmed the blade as hypereutectoid steel (1.02 wt.% C), enriched with elements such as Si, Ni, P, and V. Multi-scale characterisation (XRD, SEM, EPMA, and optical microscopy) revealed ferrite-cementite microstructures with distinct cementite bands aligned with micro voids containing silica-rich slag. Elemental segregation around these features suggests deliberate thermomechanical processing. The blade exhibited high hardness (~550–625 HV), while the ferritic hilt remained significantly softer (~158 HV), indicating functional material differentiation. The granular cementite morphology and selective coarsening, likely influenced by alloying elements, point to repeated forging cycles. These findings highlight sophisticated forging temperature utilisation, deformation, and cooling, underscoring the metallurgical expertise of ancient Indian blacksmiths in optimizing performance through structural and compositional control.

Sun, S., Wei, G., Huang, H. & Zhang, R. (2025). Craftsmanship and resource networks: Analysing bronze production and metal materials circulation in the lower Yinghe river region from the 5th to the 1st century BCE. *Journal of Archaeological Science: Reports* 66, 105286. doi:10.1016/j.jasrep.2025.105286

Bronzes excavated from the lower Yinghe River region, dating from the 5th century BCE to the 1st century BCE were examined to investigate their alloy technology and the metal circulation networks. Chemical composition and metallographic analyses

of newly unearthed bronzes from Fuyang City reveal that the artifacts are predominantly tin bronze and lead–tin bronze, with stable alloy proportions. Lead isotope analyses indicate that these bronzes employed diverse sources of copper and lead, revealing both differences and commonalities in the circulation of metal resources compared with bronzes from other regions, and possibly reflecting the influence of political conditions and policies. Furthermore, trace element analyses support the conclusion that the primary metal materials originated from the middle and lower reaches of the Yangtze River as well as the Xiaoqinling region. The study demonstrates that the lower Yinghe River functioned as an important hub connecting the Jianghuai and Central Plains regions from the Eastern Zhou through the Western Han periods, thereby facilitating interregional resource exchange and cultural integration, and providing a valuable perspective on ancient metallurgical technology and regional trade networks.

Kumar, V., Chauhan, A. S., Verma, N., Patel, R. K. & Bhatnagar, M. K. (2025). Archaeometallurgical investigations and computed tomography of excavated ancient copper hoards in the Ganaga-Yamuna valley archaeological site. *Archaeometry*. doi:10.1111/arcm.70012

The Ganga-Yamuna Valley in India has long been a site of archaeological significance. Numerous ancient copper hoards discovered over the years which have been the subject of an intense study, as they offer a unique window into the metallurgical practices and trade networks of the region's past civilisations. The study employed EDXRF, FESEM-EDAX, and ICP-MS, including CT scanning, to explore the copper metallurgy, casting technology, alloy composition, and the types of ores used in the ancient copper hoards. The hoard of the Ganeshpur assemblage was manufactured with pure copper (up to 98%) with the presence of Pb, Si, Co, Ni, and Fe as trace elements. Ca, Cr, Al, Sn, and Au were also reported as traceable impurities. The higher values of oxygen in SEM results are reflected in the microstructures by the formation of copper(I) oxide (Cuprite, Cu_2O). Carbon is also identified as a component of malachite, the green corrosion patina. Trace elements analysis indicate that cuprite was smelted from raw ores containing copper, iron, and sulphite. The lost wax casting method was used for casting the objects in the ancient period, demonstrated by the results of non-invasive medical CT. Correlating with archaeological references, previous excavations, and the results of the present study, it is suggested that the copper hoards of the Ganeshpur assemblage of the Ganga-Yamuna River valley may also be contemporary with the OCP period.

Bayarkhuu, N. (2025). The development of copper metallurgy in ancient Mongolia: The current state of knowledge. *Journal of Archaeological Science: Reports* 66, 105333. doi:10.1016/j.jasrep.2025.105333

Metallurgy played a pivotal role in the technological and economic development of nomadic societies, with gold, silver, copper, bronze, and iron used to produce a diverse range of artefacts. These objects – including tools, weapons, ceremonial items, chariot and horse fittings, and jewellery – offer valuable insights into trade and exchange networks that connected modern Mongolian territories with neighbouring regions. Despite the growing interest from international scholars and research teams in Mongolian archaeology, archaeometallurgical studies remain underrepresented in Western-language publications. This article addresses this gap by presenting the current state of knowledge on the emergence of copper-based metallurgy in Mongolia. Using the *chaîne opératoire* approach, we synthesise key research findings on Bronze Age copper metallurgy, including a refined chronology of the Mongolian Bronze Age, an updated distribution map of copper mines, production debris (including mining, smelting, and casting), metal products, and a summary of the cultural and ritual significance of ancient metalworking in Mongolia. By consolidating these studies, we propose future research directions that promise to yield new discoveries, thereby contributing to the rapidly expanding field of Archaeometry research in Mongolia.

Harris, A., Cabral, R., De Iorio, M., Krajaejun, P. & Kwa, C. G. (2025). Currents of currency: utilising die studies to trace Rising Sun/*Srivatsa* coin distribution in first-millennium AD Southeast Asia. *Antiquity* 99(406), 1030–1048. doi:10.15184/aqy.2025.77

First minted by polities in north-central Myanmar as early as the 4th century AD, silver coins bearing Rising Sun and *Srivatsa* motifs have been found in numerous archaeological contexts across Southeast Asia from Vietnam to Bangladesh. Strong standardisation in the design of these coins highlights patterns of trade and cultural interaction across this region that are otherwise underexplored. Here, the authors draw on a dataset of 245 coins from museums in Cambodia, Vietnam, Thailand and Myanmar, identifying die links that support trade routes between widely disparate areas, and illuminating the utility of die studies in counteracting the illicit trafficking of antiquities.

Craddock, P. (2025). From India to Ireland: A diversity of possible tin sources considered. *Indian Journal of History of Science* 60(3), 245–259. doi:10.1007/s43539-025-00172-5

As any study of copper alloys from the Bronze Age onwards reveals, tin was of some importance, both technically and economically. It was believed that there were just a few sources of the metal in production in the Old World in antiquity, supplying not only local needs but also the civilisations of the Mediterranean, Middle East, Iran and India. These include sources in the south-west of Britain, Central Europe, the north-west of Iberia, and Central and South-East Asia. If this was indeed the case then there must have been long and complex trade routes and exchange mechanisms, speculation about which has fascinated antiquarians and archaeologists for centuries. This situation arises largely because these known sources have been extensively worked in more recent times and thus are familiar and universally accepted. However, there are also many other geological occurrences of tin which may or may not have been worked in the past. These are of interest because they are often very much closer to early cultures than the major accepted sources. The archaeological evidence for early tin workings is poor as most, but not all, were dug in placer deposits of sand and gravel, leaving little permanent evidence beyond largely anonymous, often enigmatic trenches. The ores can be beneficiated to a very high grade and the smelting processes could operate at relatively low temperatures and thus leave little permanent debris. There are also problems of perception and accepted knowledge. Some sources which may well have been used in the past have been ignored whilst conversely other often very minor geological occurrences are

quoted as major sources, because it is believed that tin must have been produced in that locality in the past. This paper will examine some of these putative sources in detail, emphasising the difficulties that arise in trying to establish if or when they are likely to have been in production in the past. The reasons for their present status as likely producers in the past or not are also discussed.

AFRICA

Stephens, J., Mathur, R., Powell, W. & Killick, D. (2025). Complementary use of lead isotopes, tin isotopes, and trace elements to infer the sources of tin in bronzes from Southern Africa, ca. 1200–1800 CE. *Journal of Archaeological Method and Theory* 33(1), 6. doi:10.1007/s10816-025-09732-6

In this paper, we investigate the sources of tin in 153 tin and bronze samples from southern Africa, dated between 1200 and 1800 CE, by integrating lead isotope, tin isotope, and trace element measurements. Our data show that tin from the prehistoric tin mines at Rooiberg (South Africa) was transported more than 900 km. We also present evidence of tin production from other sources, probably pegmatites, within the Bushveld Large Igneous Province of South Africa. Although many of the bronzes analysed are from archaeological sites in present Zimbabwe, we have found no definite evidence so far for exploitation of tin sources within Zimbabwe.

Killick, D., Stephens, J., Katongo, M., Chirikure, S., Mathur, R. & Powell, W. (2025). The central cemetery at Ingombe Ilede, Zambia: Chronology and connections. *Journal of World Prehistory* 38(2), 12. doi:10.1007/s10963-025-09194-4

Ingombe Ilede is located just north of the Zambezi River, and has often been seen as a trading station connected to Central Africa, the Zimbabwe Plateau and the Indian Ocean. Discussion of the richly appointed burials in its Central Cemetery has been hindered by uncertainty over their ages. In this article, we report four new radiocarbon dates from Ingombe Ilede and six new dates from sites in northern Zimbabwe which are relevant to a wider understanding of Ingombe Ilede and its connections. These ten dates are all on organic fiber cores within copper and bronze jewellery, for which we also report chemical compositions, lead isotope ratios, and (for bronzes) tin isotopic ratios. We show that the richer burials in the Central Cemetery were interred no earlier than the mid-15th century. By this time copper from the Central African Copperbelt, 500–700 km north of the Zambezi, had been transported into northern Zimbabwe for at least two centuries, as had tin from the Bushveld Large Igneous Province 900–1000 km south of the Zambezi. The rich burials at Ingombe Ilede represent a late phase of a long-standing trade in copper from the Copperbelt to the Zimbabwean plateau.

Bettenay, L. & Ross, J. (2025). The economics of late Bronze Age gold mining by the Egyptian New Kingdom in Nubia. *Journal of Archaeological Science* 184, 106420. doi:10.1016/j.jas.2025.106420

This paper provides the first quantitative estimates of the profitability (in the sense of reward for effort) of gold mining in Antiquity. We have developed and assessed four models for New Kingdom gold mining in Nubia, during this period of peak gold production. These are: mining from oxidised lodes, proximal alluvial placer deposits in desert wadis, alluvial placer deposits along the Nile, and alluvial clast mining. The last refers to selective extraction of gold-bearing clasts ("quartz chunks") from wadi alluvium. We examine two variants: proximal to the source lodes and distal in larger catchments. Daily worker productivity has been estimated for each step in the *chaîne opératoire* using parameters drawn from: records of 19th century miners in isolated locations and reliant on simple technologies; modern artisanal miners; recent observations in Nubia and along the Nile; and limited experimentation. Gold production in each model is standardised to a 50-day expedition of 50 people. Under our base-case parameters all models, except for distal clast mining, are profitable: they produce more gold than is required to pay the workers. The main factor is the low cost of labour in New Kingdom Egypt, when priced in gold. However, only the placer models can generate large returns within realistic modelling parameters, because their free gold particles can be simply recovered by screening and washing. In contrast, lode and clast mining methods must allocate most of the workforce to crushing and grinding ore to liberate gold before recovery. Clast mining is further disadvantaged by barren sediment dilution and is only viable in small catchments close to source lodes. New Kingdom Egypt expanded into previously unmined areas of Nubia and along the Nile and therefore enjoyed "first-mover" status over large areas of richly endowed goldfields. By analogy with virgin goldfields in Australia and California, where substantial placer gold dominated earliest production, they had access to numerous unworked deposits with grades perhaps significantly higher than assumed in our models. A surge in New Kingdom gold production was likely, followed by an inevitable decline after depletion of best resources.

Babalola, A. B., Meghna, D., Rademakers, F. W., Cissé, M., Degryse, P. & Rehren, T. (2025). Leaded copper crescent-shaped objects and a brass ring from Medieval Gao, Mali. *METALLA*, 29(1), 33–55. doi:10.46586/metalla.v29.2025.i1.33-55

Copper-related metal artefacts and ingots are prominent metal objects of the Trans-Saharan trade route, providing a nexus between producers and consumers, often separated by vast distances. The role of Gao in southern Mali as a major transit point of this trade is archaeologically and historically well-established within the framework of other Medieval trade towns. However, the study of Gao's metallurgical heritage is not fully explored and is full of potential. Of particular interest are the hundreds of crescent-shaped metal objects which are found across different parts of Gao, but not encountered elsewhere. We present a pilot study on five crescent fragments and one brass ring from Medieval Gao, offering new compositional and isotopic data. It is unlikely that these objects were re-melted or recycled, given the

frequent presence of sulphide inclusions in them. The results show that the crescent-shaped objects are heavily leaded copper and retain their as-cast texture, making functional use unlikely. Their composition is either due to a possible mixing of lead and copper metal, or the smelting of multi-metallic ores where different batch compositions result in different concentrations in lead, antimony and arsenic within the dominant copper metal. The lead isotope data, presented here for the first time, confirm general statements made earlier for a similar set of artefacts from Gao, arguing that the metal is isotopically consistent with lead ores from Tunisia as well as being similar to several artefacts from Nigeria, in particular Igbo Ukwu. In the absence of a comprehensive database of regional copper ore data and the long-distance trade of lead across the Sahara, a firm assignment of geological origin of the metal from Gao's crescent-shaped objects remains elusive.

AMERICAS

Bennekom, J. van, Pelsdonk, J., d'Imporzano, P., Archangel, S., Biemond, D. J., Langh, R. van & Davies, G. R. (2025). Historical narratives: Was Dutch Admiral Piet Heyn's silver basin made from "treasure fleet" silver? *Journal of Cultural Heritage* 74, 12–21. doi:10.1016/j.culher.2025.05.002

According to folklore, a basin was made with silver from the 1628 Spanish treasure fleet. Both historical and analytical research was undertaken to establish if this is true. The basin's chemistry has been compared to contemporary silver objects from European and the American sources. It is concluded that the basin is produced from silver of both European and Mexican origin, comparable to silver prevalent in the Netherlands in the 17th century. Although part of the silver could have originated from the treasure fleet, the most probable conclusion is that an American provenance is false and was invented to give more significance to the basin.

Maia, R. R., Lauria, E., Sales, V., Souza, P. P. de, Neiva, A. C., Beneduce, F., Rodrigues, D. L. & Landgraf, F. J. (2025). Titanium and vanadium in slag inclusions from the Ipanema and Sardinha sites, Brazil (XVI and XIX centuries). *Metallography, Microstructure, and Analysis* 14(4), 706–718. doi:10.1007/s13632-025-01217-y

Several ironmaking initiatives were conducted in colonial and imperial Brazil, using either direct or indirect wrought iron processes, based on a magnetitic ore occurring 100 km west of São Paulo which includes 2.5% titanium oxide and 0.5% vanadium oxide. The Sardinha iron mill lasted from 1590 to 1620, while the Ipanema ironworks operated blast furnaces from 1818 to 1926. The microstructures of the objects associated with those two sites were analysed using optical microscopy and SEM. Iron bars and slag samples were also investigated by SEM–EDS and XRF. The paper discusses whether the slag inclusion compositions can be used to discriminate between iron bars produced by the direct or indirect processes, as there is evidence that slag inclusions from bloomery type processes showed higher titanium oxide contents, whereas wrought iron bars produced by the indirect process contained slag inclusions with higher vanadium contents.

Carrizo, P. S. (2025). Copper medal or replica of a biphasic seal of King Alfonso XI of Castile and Leon: Characterisation and archaeometallurgical study. *Metallography, Microstructure, and Analysis* 14(4), 755–763. doi:10.1007/s13632-025-01228-9

A cooperative study was made of a medal (or replica) depicting King Alonso of Castile (1311–1350 AD). Composition studies revealed that it is a quaternary bronze alloyed with lead (Cu-Sn-Zn-Pb). Metallographic studies carried out on the edge and on acetate replicas indicated plastic deformation structures, revealing some of the manufacturing processes.

Río, J. del, Cruz, P., Gómez-Paccard, M., Palencia-Ortas, A., Puente-Borque, M., Pavón-Carrasco, F. J. & Marsh, E. (2025). The first archaeomagnetic age at Tiwanaku and implications for dating Andean metallurgical furnaces. *Archaeometry*. doi:10.1111/arcm70046

This paper presents the first archaeomagnetic dating at Tiwanaku (Andean Altiplano). We compared the geomagnetic field values recorded by a metallurgical furnace against an updated SHAWQ2k-SH global model and a regional intensity curve, both of which include, for the first time, high-quality intensity data from the Southern Hemisphere. Results place the furnace's last use between 450–740 CE, while the decorated ceramic chronology at the site further constrains it to 570–740 CE, with maximum probability during the mid-late 600s. This marks a significant methodological advance for Andean archaeometallurgy, addressing challenges posed by thermoluminescence and radiocarbon dating in the region.

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