Multiple metallurgies in Medieval Tamdult, a mining, smelting and caravan town in Southern Morocco

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ABSTRACT: The medieval era Islamic settlement of Tamdult in Southern Morocco is at the centre of an archaeological mining-metallurgical landscape with strong evidence for the production and working of lead, silver, copper and brass. Here, we provide an overview of the various metallurgies identified and discuss their likely common origin from a sulfidic complex lead-zinc-copper ore mineralisation, leading to two distinct primary products: silver pellets and brass ingots. The presence of ancient mining traces, multiple locales of copper and lead smelting, fragments of litharge, numerous pellet moulds with silver traces, and various types of ore, slag, crucibles and moulds linked to brass making, constitutes the most comprehensive inter-connected set of chaînes opératoires for copper, brass, lead and silver production in north-western Africa. The initial results presented here allow key aspects of the raw material procurement and processing to be reconstructed, and to identify remaining gaps in our understanding and documentation of medieval metal production on the western fringes of the Sahara.

KEYWORDS: Polymetallic, Archaeometallurgy, Lead, Silver, Copper, Zinc, Brass, Smelting, Africa, Morocco

Introduction

Tamdult in Southern Morocco is amongst the earliest centres of commerce and industry in Islamic North-West Africa. It is first mentioned by the Abbasid geographer and historian Ya'qubi at the end of the 9th century CE as a small fortified town and site of silver deposits, dependent upon the metropolis and trading centre of Sijilmasa, *c.* 500 km to the North-East (Levtzion and Hopkins 2000, 22; Messier and Miller 2015, Chap. 1; Erbati *et al.* 2020, 13-43). At this earliest point, the locality is described as primarily inhabited by Berber populations referred to as the 'Banu Tarja'. In the 11th century, Tamdult is described by Al-Bakri as a fortress with abundant water and numerous date palm plantations (as cited in Rosenberger 1970, 120), stating that "its wall was of stones and of mud-bricks, pierced only by the four gateways situated around the town" (as cited in Rosenberger 1970, 118-119). From this time, Tamdult also seemingly functioned as an entrepôt on the earliest trans-Saharan trade routes between Sijilmasa (Morocco) and Audaghust (Mauritania), on which West African commodities, including gold and ivory, were exchanged for copper and other products (Al-Bakri 1859, 302). There is very limited documentary evidence providing insight into Tamdult's history during the 12th and 13th centuries (see Handaine 2008, 19-21, 52-53). Tamdult's later history is better attested if no less certain. Al-Watwat, who died in 1318–1319, confidently asserted that Tamdult was still extant in his time (Rosenberger 1970, 128). However, it appears likely that it experienced significant change around this time, with even full abandonment being a possibility. Justinard (1933) cited traditions that internal disputes within the town led to its destruction, or that it was destroyed due to its heretical or heterodox religious practices. A more prosaic explanation may be that population shifted in response to either a climatic crisis or well-documented

Submitted: 24.07.2025; Accepted: 25.05.2026; Published online: 28.06.2026

ISSN 0142-3304 (print)
ISSN 2755-0249 (online)

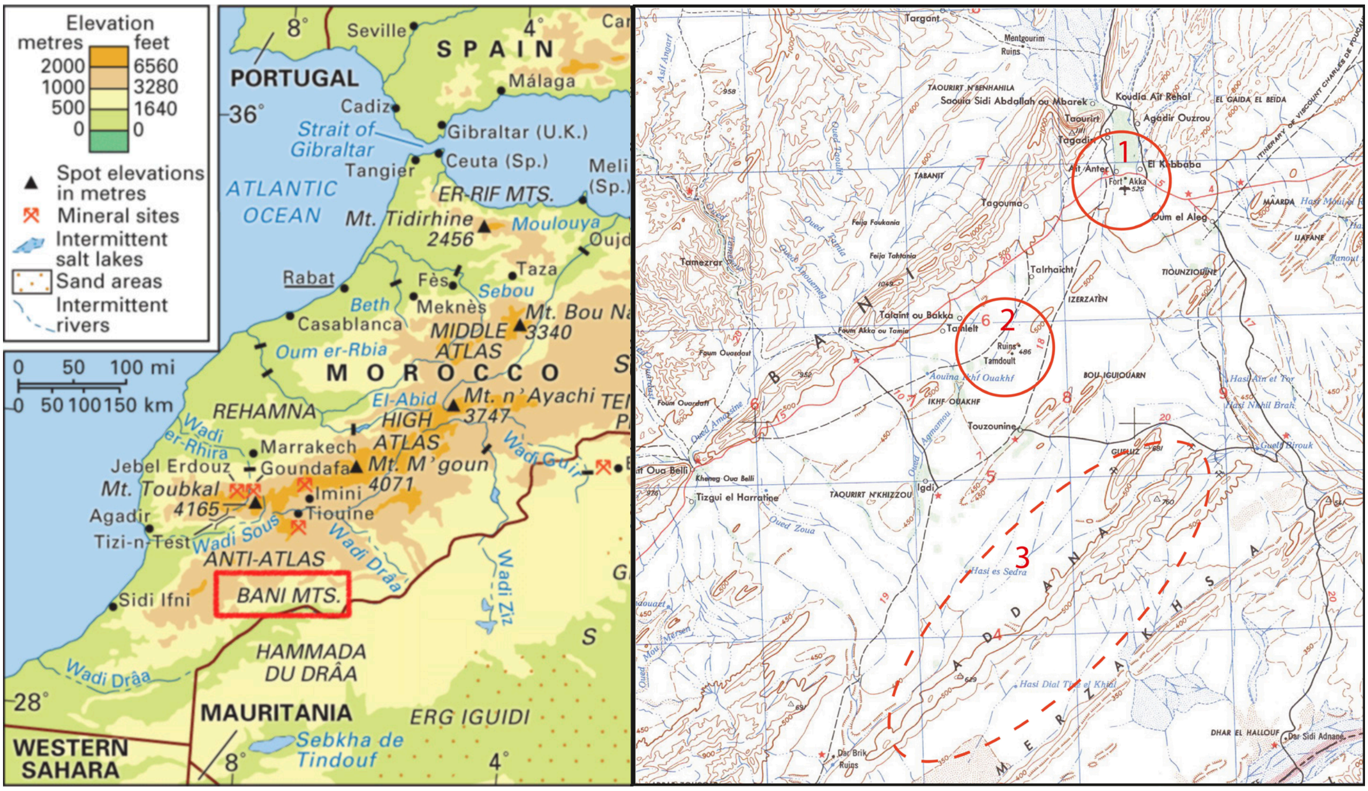

Figure 1: The site of Tamdult located within the wider North-West African context (Bani Mountains, red box in left image). Right: 1: the town of Akka; 2: Tamdult ruins focused on in this paper; 3, dashed line: Djebel Addana mountain range where historic silver mining took place (base-map sources: left, Encyclopædia Britannica, Atlas Mountains, https://www.britannica.com/place/Atlas-Mountains#/media/1/41302/199 (accessed: 20 June 2026); right, Institut National de l'Information Géographique et Forestière)(IGN 1953).

political shifts and warfare in the zone during the 1350s CE (Handaine 2008, 94-106). Today, the prominent ruins some 13 km South-west from the modern town of Akka are widely associated with the remains of medieval Tamdult, while the town of Akka itself also features medieval period remains (Fig. 1).

Numerous localities in the Maghreb, on the Sahara's North-western fringes, played important roles in the trans-Saharan trade landscapes, provisioning caravans for long-distance trade and participating in the commerce in West African gold (see *e.g.* Erbati *et al.* 2020; Fenwick *et al.* 2022). Several of them were not just trade centres but associated with the production of copper which then was shipped South to West Africa, or silver which was traded North. Tamdult's dual role in both silver and copper production (El Ouad *et al.* 2023) makes it a fascinating combination of trade hub, multiple metal production site and agricultural settlement. As Rosenberger (1970, 118-126) already noted in the first major historical publication on the site, Tamdult was at once a citadel, a centre of metal production and commercial entrepôt, and a focus of oasis agriculture.

Initial archaeological work at Tamdult was undertaken in the 1990s under the auspices of the Moroccan-French project 'La naissance de la ville islamique au Maroc (Nakur, Aghmat, Tamdult)' (Cressier 2004; Cressier and González-Villaescusa 2025). Since 2018, the study of this polymetallurgical centre has been a key focus of the Jbel Bani Archaeological Project, set up between the Moroccan Institut National des Sciences de l'Archéologie et du Patrimoine (INSAP) and the Sainsbury Research Unit, University of East Anglia, and in collaboration with the Cyprus Institute and its A. G. Leventis Chair in Archaeological Sciences (see Bokbot *et al.* in press; Nixon *et al.* submitted). Several projects over the last few decades have highlighted Tamdult's metallurgical prowess and the technical advancement of its craftspeople (Rosenberger 1970; Cressier 2004; El Ouad *et al.* 2023), and detailed studies are still ongoing. This paper provides an overview of the interconnected metallurgies in medieval Tamdult based on our recent excavations and surveys and ongoing multi-institutional research reconstructing its various metallurgical technologies.

Historical Metallurgy: Medieval Evidence

From the earliest historical references to Tamdult, a key feature of the descriptions is its metallurgy. The 9th century CE description by Ya'qubi states that "around it there are deposits of gold and silver. It [the gold] is found like plants and it is said the wind blows it away" (Levtzion and Hopkins 2000, 22). An important aspect of Ya'qubi's description is his reference to the ownership of Tamdult by Yahya b Idris Al-Alawi of the Idrisid dynasty (788–974 CE). No explicit reference is made to ownership of Tamdult's silver mines, but the importance of silver to the Idrisid dynasty's coinage presents a clear metallurgical basis for Idrisid links to Tamdult. Al-Bakri's 11th century description of Tamdult also refers to its nearby mines rich in silver (Levtzion and Hopkins 2000, 22, 73). While Islamic dynastic coinage has been found at Tamdult, including of the Almoravids (1050s–1147 CE) and Almohads (1121–1269 CE), no dirhams have yet emerged struck in the name of Tamdult. Rosenberger (1970, 126) suggested that this is due to the absence of a sovereign or ultimate political power at Tamdult; thus, it had no prerogative to strike coins. In this context he refers also to the possibility instead of the circulation of silver as ingots or jewellery. Notably, neither copper nor iron are mentioned in any of the known historical sources relating to Tamdult (see Handaine 2008), let alone the making of brass.

Brass plays a significant role in Islamic metalwork and has been widely traded across the Sahara and beyond. The evocatively named 'Lost Caravan' of Ma'aden Ijafen (Monod 1969) with its thousands of brass ingots is a striking example of the scale and importance of this trade. However, the only historical reference to copper production in the wider region is given by Al-Bakri in the 11th century, who mentions it being produced near Igli (about 100 km North of Tamdult) and then exported to West Africa (Levtzion and Hopkins 2000, 69). The new evidence recovered through our excavations now dramatically changes this picture, with effectively the entire *chaîne opératoire* of brass making being represented at Tamdult.

Brief mining geological setting

The region from Akka through to the Djebel Addana district is known for its long mining history (Rosenberger 1970, 105-112; Cressier 2004; El Ouad *et al.* 2023) and continues to attract interest for its significant economic potential, particularly for lead, silver, copper and zinc mineralisations (El Ouad *et al.* 2024; 2025). Situated in the western Anti-Atlas metallogenic province, multiple hydrothermal deposits are hosted in metamorphosed and heavily folded Ordovician sandstone, typically forming WNW-ESE trending veins with primary sulfide (massive galena, minor chalcopyrite and pyrite) and supergene carbonate (smithonite, malachite, azurite, and cerussite) ore minerals. The gangue minerals include columnar quartz, calcite, siderite and secondary limonite and occasionally manganese minerals. Individual ore bodies in the Bou-Oudadene deposit are said to range from 10 to 100 metres (El Ouad *et al.* 2025), but smaller ore bodies and mineralisations would also have been of potential value for pre-modern mining and smelting operations.

Archaeological setting

The principal site which has been identified with the historically documented Tamdult features a fortified hilltop settlement, overlooking a surrounding landscape of industrial sites, walled settlements, Islamic necropoleis, and irrigation networks for a large agricultural hinterland, 13 km from the town of Akka (Fig. 1; Bokbot *et al.* in press; Nixon *et al.* submitted; see also Cressier and González-Villaescusa 2025). With no current or sub-modern occupation in this area, and due to the low sediment build-up of the desert environment, the archaeological remains are highly visible in the landscape, enabling significant surface recording and mapping. The immediate archaeological landscape surrounding and associated with the central site complex stretches along the valley adjoining the Jbel Bani mountains for around 10 km, including in the direction of the modern town of Akka. While the evolution of the broader settlement landscape of historic Tamdult remains an open research question – including its association with the town of Akka, where also Medieval era remains are located – it is already very clear that several metallurgical industries of Tamdult can be principally associated with it.

The core of the site complex of Tamdult consists of a tell site straddling an inselberg, of around ca 25 ha, arranged North-East to South-West along the length of the inselberg (see Fig. 2, 3). The height of this inselberg above the wadi floor has been measured at 25 m. The archaeological deposits of the 'tell' are not uniform, including that at its highest point bedrock is present near the surface; elsewhere, it is estimated a stratigraphy of up to 3–4 m exists at points across the site (see also below on excavated stratigraphy to date). At its summit are two fortified enclosures in mud-brick and stone, certainly at least partly of medieval origin and including potentially 16th or 17th century Saadian construction additions, though remaining unconfirmed in date. Within one of these forts is a later monumental shrine associated with Sidi Shanawil (Boum 2010). Between the two forts is an area of shallow stratigraphy and exposed bedrock, including the partially buried remains of a mosque. The flanks of the tell are covered with mounded areas of wall-collapse that appear to consistently relate to mud-built structures with stone foundations. The ground immediately surrounding the tell also features a range

Figure 2: Drone photography of the tell complex of Tamdult and immediate surrounding area seen from the North (Photo: J. Wexler).

of stone and mud-built buildings and larger enclosures, including on the North-west side where they extend for a certain distance into the valley floor. To the North-east and South-west of the tell are large walled Islamic cemeteries with scores of standing uninscribed grave stelae, while to the South-east is a further smaller, unwalled cemetery, overlapping with the metallurgical features and surface presence of slag remains.

While extensive metalworking is visible across the site and its hinterland, no silver deposits are known in the immediate vicinity of the town itself. Historic and geological research by Rosenberger (1970, 105-112) strongly suggests that the ancient sources of Tamdult's silver were in fact located over 20 km away, within the range of hills known as the Djebel Addana (see Fig. 1). This has been borne out both by Rosenberger's and later physical investigation of this area, but also by elementary toponomy, as, etymologically, Djebel Addana signifies in Arabic 'the mountain of the miners'. These mines indeed continued to be exploited until recent times.

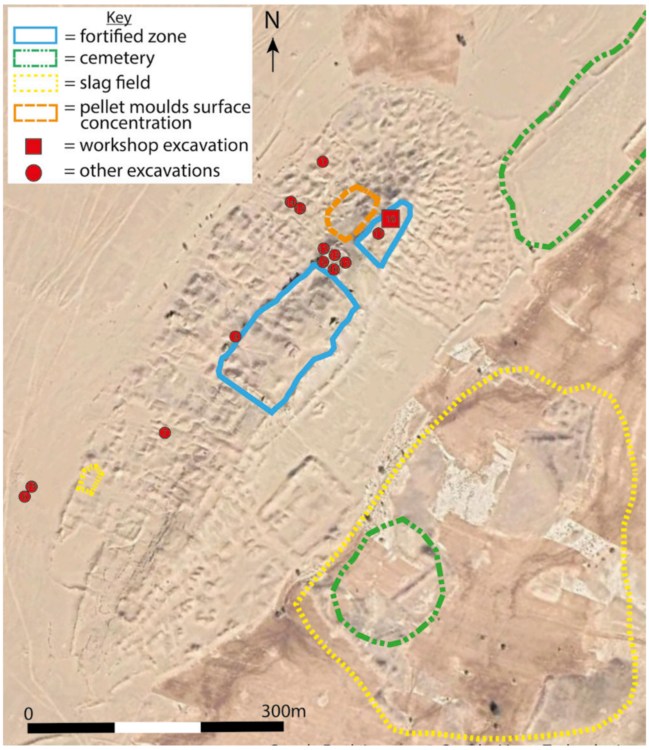

Figure 3: Satellite image of central area of ruins at tell Tamdult, with key features and excavation locations annotated.

Overall, the site and surrounding landscape of Tamdult presents itself as a near-ideal archaeological context for exploring metallurgy. Its excellent preservation combines with a desert landscape with no recent overlying occupation and limited sediment build-up, meaning the relics of metal production are well preserved within the landscape for surface investigation and to inform targeted subsurface exploration. Combining remains of primary and secondary or urban metallurgy, such conditions are a major advantage from a research perspective, providing a fascinating case study of an individual

Figure 4: Survey in the industrial zone immediately South-east of the main mound site of Tamdult.

mining and metal-producing town, where the history, culture and production geography of this industry can be explored. It additionally occupies a key cultural and geographical niche within a Maghrebian and North-western African context, enabling an important exploration of historic Islamic and global medieval metal production and broader exchange networks. Thus, the remains of Tamdult provide a hugely important opportunity for refining our understanding of the history of Islamic metallurgy on a wider scale, to shed additional light on multiple aspects of this industry and its interconnected *chaînes opératoires*.

In February 2018, a pilot field season was conducted, followed by two further field seasons in 2019 and 2020; originally planned further fieldwork in 2021 and 2022 was not possible due to Covid-19. The most recent field season took place in late 2023, adding significant further evidence of widespread metallurgical remains in and around Tamdult. During these field seasons, up to 2 m of deposits were excavated across the site, revealing and recording an archaeological sequence associated with building remains and including *in situ* metallurgy-related features and metallurgical debris (see Fig. 3 for excavation locations; Bokbot *et al.* in press, Nixon *et al.* submitted). Four radiocarbon dates have been secured from the main site within the complex of Tamdult, and one from the nearby site of Talraicht, situated in the valley at 10 km distance in the direction of Akka. These were all carbonised date stones (*Phoenix Dactylifera*) and dated at the SUERC AMS Laboratory (Glasgow, UK). The samples from the main site at Tamdult have a date range of cal 1233–1430 CE, with the sample from Talraicht also falling within this range; full details will be published in a forthcoming paper (Nixon *et al.* submitted). These dates complement Almoravid period (1056–1147) and Almohad period (1121–1269) coins from the site and are important in providing compelling

Figure 5: Excavations underway in the metalworking complex within the northernmost fortified hilltop area of Tamdult (unit S18).

evidence for Tamdult's ongoing occupation likely into at least the 14th century, at a period when the historical records are less certain. In light of the historical sources referring to Tamdult back to the 9th century CE, given the still limited excavations from various sectors of the site and from the wider site landscape, including the town of Akka, it is presumed that 12th century and earlier deposits from Tamdult remain unexcavated.

Throughout the last few years, intensive laboratory-based analysis, particularly of the metallurgy samples, has been ongoing. So far, we have identified evidence for two main and distinct metallurgical activities, namely lead smelting and silver extraction by cupellation, and copper smelting and brass making by cementation.

Multiple metallurgies at Tamdult

We have tentatively identified a broad separation of discrete metallurgical activity areas across Tamdult and its hinterland (Fig. 3, 4; see also Cressier 2004; El Ouad *et al.* 2023). West of the tell, and at some distance, several slag clusters were identified in the flat broad wadi areas. Visual inspection identified these slag clusters as predominantly tapped glassy cupriferous smelting slags, likely rich in lead oxide. Their situation within the main wadi, and the lack of stratified excavations, makes it difficult to assign specific dates to them; this will form part of future research. Immediately East/South-east of the tell, better preserved and more densely clustered, is an area of slag mounds consisting predominantly of lead-rich glassy red to brown-black slag with fewer obvious flow textures, and generally fewer visible green corrosion specks than seen on the slags from further West. Their appearance indicates that these, too, are smelting slag, but likely related to lead (silver) metallurgy. Within

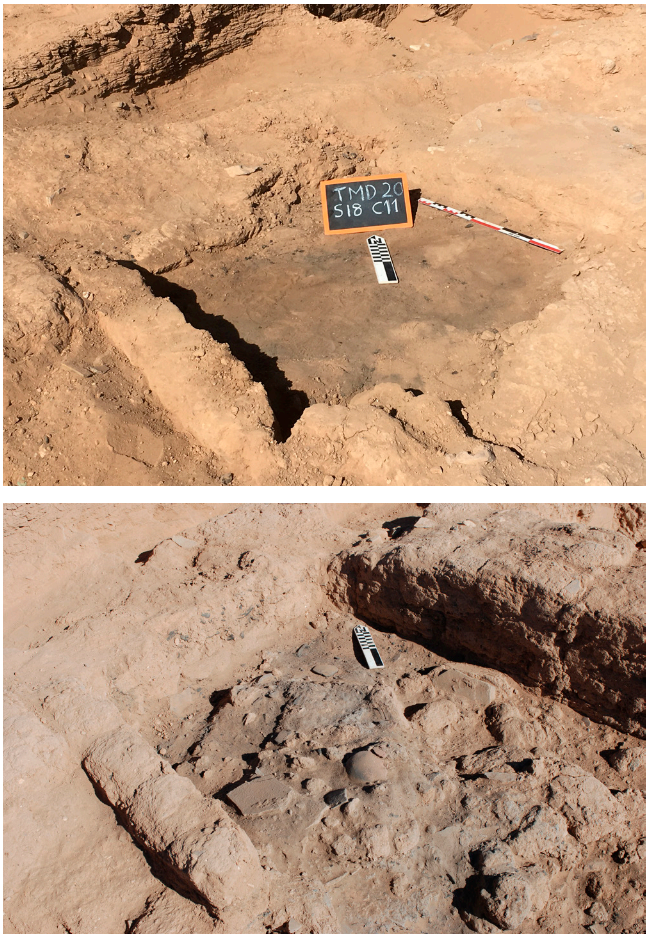

Figure 6: Hearth area with surrounding structure in the upper levels of S18, in the northernmost area of the fortified zone on top of the hill at Tamdult. The excavation revealed remains of a furnace for copper working in upper levels (see Fig. 7). The top image shows an early stage of excavation, the bottom one a later stage with structures visible. Full illustrations will be published in Nixon et al. (submitted).

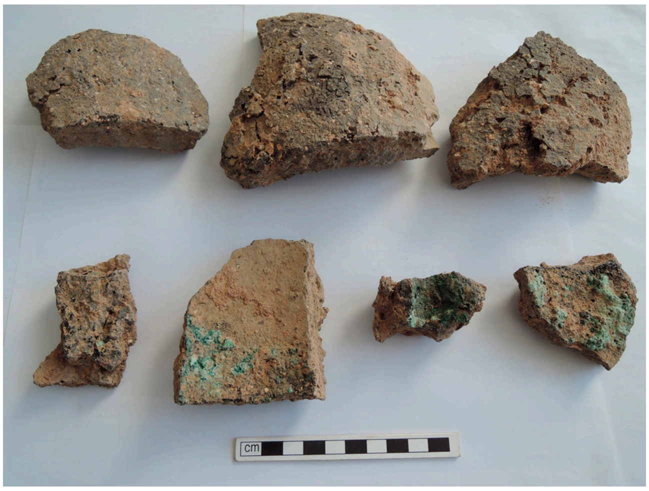

Figure 7: Fragments of tuyere pipe associated with excavated copper-working furnace remains from S18 (see Fig. 6).

the actual hill site, and therefore in a more urban setting, a mostly random scatter of different remains of metallurgy prevails. The only clear spatial pattern is formed by numerous fragments of pellet moulds which mainly occur in a relatively well-defined strip from the base of the northernmost fortified area down the North-western slope. Within the northernmost fortified hilltop area, remains of a metallurgical workshop were found (unit S18, Figs. 5–7). Elsewhere, slags and different types of crucibles, visually linked to copper metallurgy by their green corrosion stains, are found more widely along the North-western facing slope, and particularly in the South-west corner near the foot of the tell, but also on top of the hill in the northernmost fortified area. Fragments of several large finger or bar ingot moulds were found in the settled area, and a fragment of at least one small brass ingot was recovered as a surface find, together with several other finds of raw metal. This material sits alongside the significant quantities of fragments of metal objects found across the site surface, including for example small items of silver and copper jewellery. Field analysis by pXRF showed that several of the crucible types and the ingot moulds are rich in zinc, indicating their potential link to the production and processing of brass. Fragments of zinc ore found at several places on the site further support this hypothesis.

Here, we summarise the current state of our research based on a combination of visual observation and pXRF analysis in the field, and of ongoing more detailed research using metallographic and scanning electron microscopy with energy-dispersive spectrometry and further pXRF analysis in the laboratory. Details of operating conditions, sample numbers and individual results will be provided in a series of specialised publications currently being written; this overview serves to introduce the site as a major multi-metallurgical centre and outlines the essence of our observations to date.

Lead-Silver: Preliminary insights

Usually, the production of silver from argentiferous lead-rich ores consists of multiple steps, beginning with the mining of the ore and its smelting to produce metallic lead or bullion containing the silver, as well as slag. The subsequent extraction of silver from the bullion requires cupellation, producing fine silver and lead oxide or litharge as a waste or by-product. The silver would then be cast into ingots or pellets for onward trade, or processed into coins or other finished objects in a mint or jeweller's workshop. Tamdult presents the nearly complete *chaîne opératoire* for silver pellet production.

Lead-rich ore fragments are relatively rare but have been found scattered across the site; they seldom exceed five to ten centimetres in maximum dimension. They are coarse-grained, visually identifying them as hydrother-

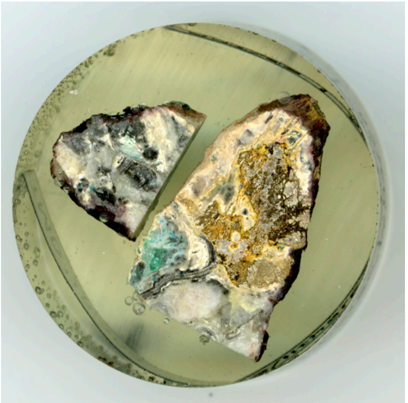

Figure 8: Polished block of lead-rich ore. Diameter of block: 3 cm.

Figure 9: Galena samples from fieldwork at Tamdult.

mal gangue ore with galena, sphalerite, calcite and minor amounts of other minerals, as well as columnar quartz (Fig. 8, 9). Numerous columnar quartz crystals are also scattered across some of the smelting sites. Overall, the ore and gangue mineralogy is consistent with the mineralogy given for the Djebel Addana district (El Ouad *et al.* 2025).

The most obvious metallurgical find group is slag, which occurs in distinct mounds of up to several meters diameter and standing about 50 to 100 cm above the wadi floor East/South-east of the site, as well as in isolated finds scattered across the tell (Fig. 10; see also Fig. 4). Individual fragments are rarely exceeding five centimetres in maximum dimension. Visually, the slags are generally glassy to dull microcrystalline, with a flow texture indicative of a highly viscous melt. Their colour ranges from dark red to nearly black; many fragments have small white quartz inclusions. Some slag fragments are attached to furnace wall remains, and a few have lead metal inclusions or trapped lead 'flows' attached to them.

The studied slags can be classified into two groups, based on their macroscopic and microscopic characteristics (Fig. 11). Type 1 slags are black/grey and often

Figure 10: One of multiple small slag heaps in the wadi floor in the area to the East/South-east of the Tamdult tell. The hammer in the foreground is 30 cm long.

dull on the exterior surface, with few green corrosion products. Microscopically, these slags range from completely crystalline to a glassier matrix with large clusters of crystalline growth throughout. In most of these slags, there are visible unreacted gangue minerals, mostly quartz.

Type 2 slags are very glassy, red and/or black in colour. Microscopically they are highly vitrified, with visible layers of different colours (schlieren) and a clear fluidal texture. Some of the slags in this group do have some crystalline growth, but this is limited to small clusters and unreacted gangue minerals, such as residual quartz grains.

Overall, the slags are very low in copper, consistently having less than 1 wt% CuO and predominantly even below 0.5 wt% (Table 1). The concentration in ZnO is similarly low, indicating that the ore did not contain much sphalerite; in contrast, the FeO content, averaging around 9 wt% but with a wide range from *c.* 5 to *c.* 12 wt% and an exceptionally high value of 17.5 wt%, is consistent with the reported occurrence of siderite and limonite with the galena (El Ouad *et al.* 2025).

As expected, remains of silver production and processing are much rarer. Crucial finds here include litharge, more precisely cupellation hearth material (CHM, Fig. 12); so far, only four fragments have been identified. They are characterised by a high specific gravity, a reddish colour in the fresh cut and the typical off-white corrosion of

Table 1: Average composition of lead slags type 1 and 2. Average of SEM-EDS analyses of ten individual samples, reported in wt%.

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	CuO	ZnO	PbO
N=10	1.3	3.5	8.4	39.9	0.4	2.1	16.4	0.5	0.5	8.7	0.3	0.4	17.7

lead-rich material. Particularly diagnostic is the 'fin' of almost pure litharge forming a circle on top of the hearth material, marking the edge of the final silver regulus (see *e.g.* Rehren and Klappauf 1995; Cohen *et al.* 2009, Fig. 5). Of these fragments, only one allows a tentative reconstruction of its original dimensions (Fig. 12a). Assuming that the fragment represents the full radius would indicate a minimum hearth diameter of at least 15 cm and a diameter of the resulting regulus of around 8 cm. Allowing for an average thickness of the regulus of 1 cm, consistent with the 'fin' of pure lead oxide visible in the profile (Fig. 12b), would give a volume of around 50 cm^3 and a silver mass of around 500 g, consistent with a relatively large-scale production rather than what a town's silversmith would be processing.

The pellet moulds are more frequent, occurring mainly in a narrow band reaching from the base of the northernmost fortified area on the hilltop down the northwestern slope. Visual inspection on site of a large amount of pellet moulds showed them to be all more or less similar in their principal form (Fig. 13) and mostly broken into relatively small pieces with just a few cups preserved in each. Few edge pieces survived, making it difficult to estimate the original plate size / number of cups or wells per plate. The wells range in diameter from 12 to 15 mm (at the top of the mould, they taper down a few mm towards the bottom), and range in depth from 6 to 12 mm, with a round shape and hemispherical bottom. There is also significant variability in the thickness of the bottom part (from the bottom of the well to the bottom of the mould), ranging from 4 to 15 mm. This data suggests that there was not much standardisation in the forming stage of the production. Use traces are inconspicuous and include slight surface vitrification both at the top and bottom, indicating exposure to high temperatures.

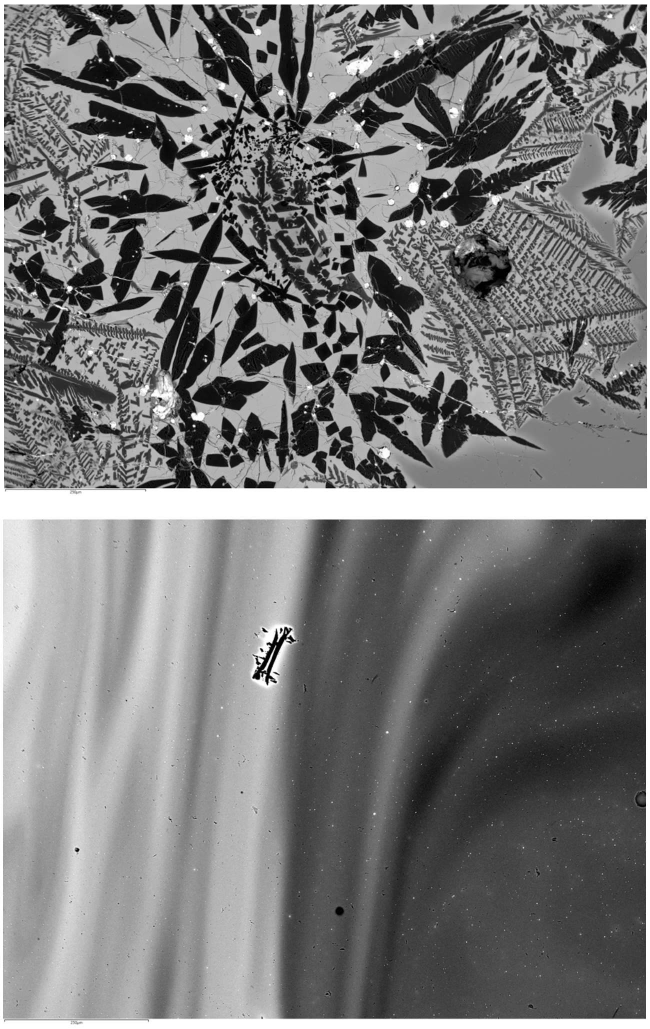

Figure 11: Type 1 slag (top, TMD 19 46c) and Type 2 slag (bottom, TMD 19 45b). SEM-BSE images, width of view c. 1 mm.

The pellet moulds are an unmistakable sign for silver processing, as confirmed by the occasional presence of silver droplets discovered in the wells or cups, both by XRF and in the cross sections (Fig. 14). Their shape

Figure 12: (a) Fragment of Cupellation Hearth Material (CHM). The cut surface reveals the typical structure of such material (Rehren and Klappauf 1995); the silver button would have formed on the upper left side, surrounded by a rim or fin of pure litharge. Length of cut surface c. 7 cm. (b) Mounted cross section through the rim of the CHM. The litharge crystals (top of section, deep red) penetrate the original hearth material (off-white). Diameter of block: 3 cm.

Figure 13: Pellet mould fragments from Tamdult

is highly characteristic for their function and can be traced back to Celtic contexts in Europe, where they are commonly referred to as coin moulds (*e.g.* Heinrichs and Rehren 1996, and literature therein). They have been attested elsewhere from Islamic contexts, such as in northern Morocco (Fentress *et al.* 2022) or in Mali for the production of gold blanks (Nixon *et al.* 2011). The ceramic analysis showed that the craftspeople were carefully selecting a highly refractory clay to manufacture these moulds, quite distinct from the calcareous clay used for domestic pottery. Accordingly, the thermal impact on the pellet mould ceramic is modest, despite an expected operating temperature of around 950 to 1,000 °C to fully melt the silver alloy.

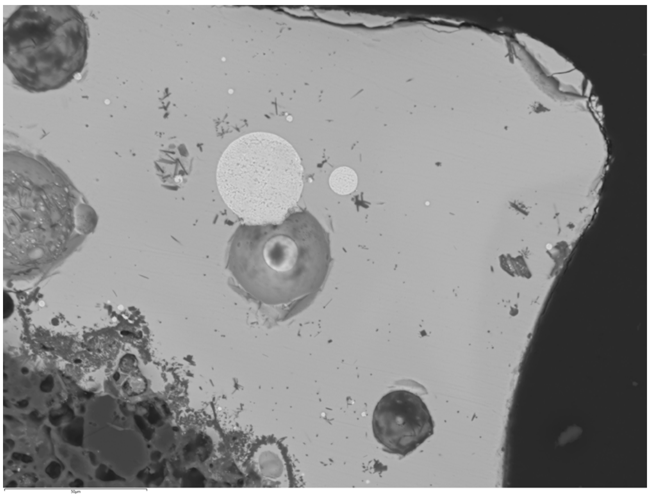

Figure 14: Cross section of a pellet mould section, with metallic silver prill (centre) trapped in the vitrified inner surface of the cup. SEM-BSE image, width of view c. 0.25 mm.

Copper and brass

The first essential raw material for brass production is metallic copper. We assume that copper was smelted in the wadi west of Tamdult, where numerous large slag scatters are still visible. Their chemical composition and general appearance are very similar to the lead slags to the East/South-east of the settlement. However, they show a higher presence of copper staining and copper-rich matte inclusions and have slightly elevated zinc and copper contents. Research is ongoing to develop criteria to link these slags reliably to either lead or copper smelting, bearing in mind that also both metals could have been smelted in the same furnace, and only separated during the tapping and cooling stage of the process.

Raw metallic copper is present among the finds as prills in some of the lead-rich slags, and as isolated irregular spills and flows (Fig. 15). The composition of four of the raw metal flows ranges from 75 to 95 wt% copper,

Figure 15: Selection of lead (far left) and various copper-based raw metal finds collected in and around Tamdult. Note the end piece of a small finger ingot on the far right. Length of ingot c. 1.5 cm.

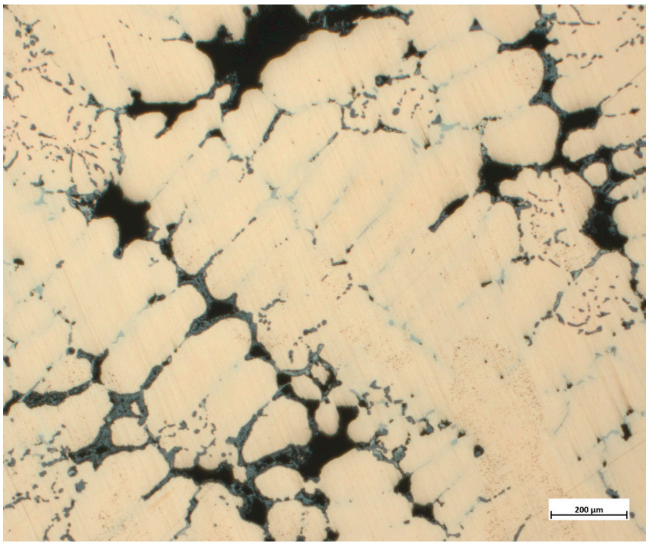

Figure 16: Micrograph of a copper alloy with around 5 wt% zinc, 4 wt% arsenic, 2 wt% iron and 0.5 wt% lead, as well as some sulfur. Note the as-cast dendritic texture with the enrichment of alloying elements in the grain boundaries. Sample TMD 23-703, reflected light.

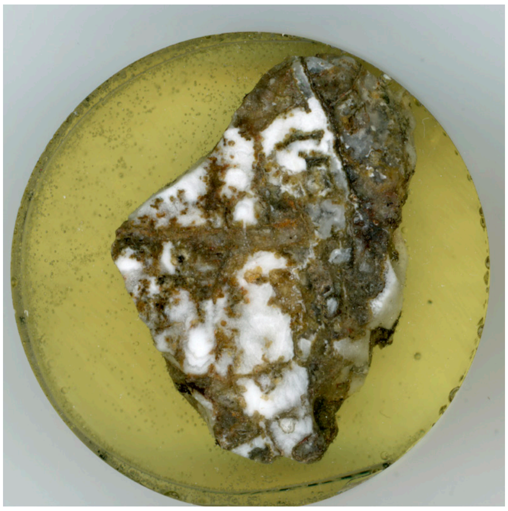

Figure 17: Zinc ore fragment TMD 23-657, mounted as polished block. Diameter of block: 3 cm.

with the balance to 100 wt% consisting of up to 11 wt% zinc, up to *c.* 4.5 wt% each arsenic and iron, and highly variable lead content, from less than 1 wt% up to nearly 20 wt%. All samples have frequent sulfide inclusions (Fig. 16).

Numerous zinc-rich ore fragments were found scattered across the surface of the mound (Fig. 17). Their zinc content reaches from 20 to more than 70 wt% ZnO, with additional major oxides present being MgO, CaO, MnO, FeO, PbO and SiO_2. While the composition of the roughly walnut-sized fragments varies widely from piece to piece, it is noteworthy that they are generally very low in copper (< 1 wt%) and sulfur (<0.5 wt%). Accordingly,

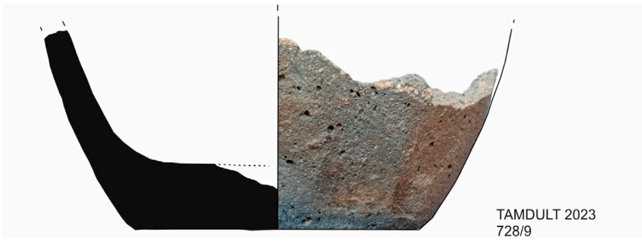

Figure 18: Brass-making crucible, photo (right) and profile drawing (left). Base diameter is c. 12 cm (Illustration: Y. Gutiérrez).

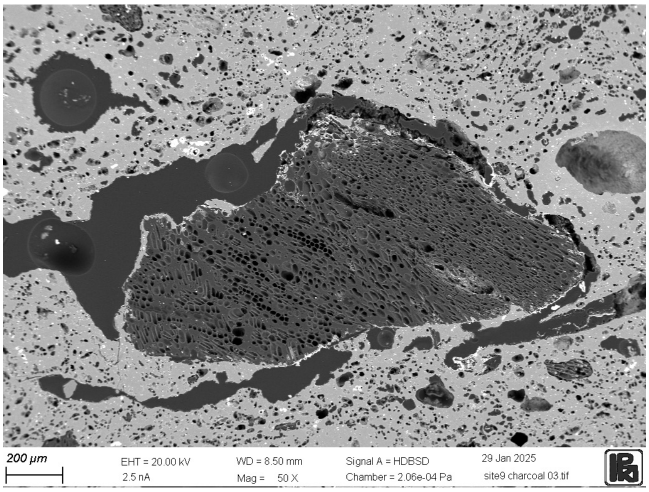

Figure 19: Charcoal temper in brass cementation crucible from Tamdult. SEM-BSE image, 50x magnification.

the main zinc minerals are carbonates, while silica is present as quartz crystals rather than zinc silicate.

Crucial evidence for actual brass making is provided by numerous crucible fragments, found scattered across the site. They are typically grey to light lilac in colour, with wall thicknesses ranging from 1 to 2.5 cm (Fig. 18). In many instances, the crucibles have a second, outer layer of a different clay, often more iron-rich and/or with more coarse rock and mineral inclusions. Their outer surfaces are often covered by a thin fuel ash glaze, while the inside is either completely ‘dry’, *i.e.* without recognisable metallurgical traces, or covered with green corrosion products and/or a rust-brown residue. Notably, pXRF analysis in the field showed a persistent occurrence of zinc content on the ‘dry’ inner surfaces, and often also throughout the body matrix and on the outside of the crucible fragments. SEM-EDS analyses of multiple cross sections identified in the majority of analysed finds a highly refractory ceramic composition, with around 27 to 29 wt% Al_2O_3, 5 to 10 wt% FeO, around 3 wt% K_2O and less than 2 wt% each of MgO, TiO_2 and CaO. Notably, several of the crucibles are tempered with charcoal dust (Fig. 19), ensuring a highly reducing atmosphere within the fabric (Freestone and

Tite 1986) and preventing the oxidation of zinc vapour during the cementation process. A few crucibles are heavily tempered with rock fragments and are richer in CaO and FeO, reaching up to 15 wt% of each, and have only around 20 to 22 wt% Al_2O_3. In cross section, most fragments show a clear gradient in their zinc content, decreasing from several wt% ZnO near the inner surface to levels below the detection limit of the SEM-EDS system near the outside; the fuel ash glaze, however, was often rich in ZnO. The scarcity of copper in many of the 'dry' crucibles is notable. The rust-brown residue preserved on the inside of numerous crucible fragments is rich in secondary iron hydroxides and held together by a vitrified siliceous matrix rich in calcium oxide and sometimes manganese oxide, with minor amounts of lead and copper. This composition is consistent with the composition of the analysed zinc ore fragments minus the zinc content and therefore could represent the residue of a cementation process whereby the zinc ore was mixed with charcoal and heated in the presence of copper metal. During the process, the zinc carbonate would first decompose to zinc oxide which then would be reduced to zinc metal vapour, before being absorbed by the copper metal to form brass. Under these conditions, some of the iron in the ore was reduced to iron metal, which is now almost fully corroded, giving rise to the brown appearance of the residue.

The further processing of the raw brass is indicated by the presence of several fragments of ingot moulds with characteristic trapezoid or V-shaped cross sections and very smooth surfaces (Fig. 20). The largest fragments have a height of the internal channel of around 2 cm and a preserved length exceeding 17 cm. Fragments of smaller moulds also exist, indicating the production of different sizes of ingots. Upon pXRF analysis, their inner surfaces were found to be very rich in zinc, linking them to the production of brass ingots similar in shape to the small ingot fragment found on site.

Figure 20: Fragments of ingot moulds recorded at Tamdult used to produce long brass ingots. The one on the left has a V-shaped cross-section, the one at the top a trapezoid section.

Figure 21: Ancient mining traces following the outcrop of an ore vein, c. 15 km due North of Tamdult (29°25'54" N, 8°18'34" W).

Discussion

The metallurgical assemblage from Tamdult covers the key elements of two closely connected *chaînes opératoires*; one for lead smelting and silver production by cupellation, and another one for copper smelting and brass making by cementation. Individual elements of these sequences are also known from various sites elsewhere, such as the contemporary silver smelting sites of Imiter (Milot *et al.* 2018) and Sijilmasa further North in Morocco (Baron *et al.* 2020), or the prehistoric copper smelting further South in Mauritania (Courcier *et al.* 2019). However, the degree of completeness and coexistence of these two specialised metallurgies make the site of Tamdult a particularly important case study to explore historic Islamic metallurgical production in its complexity and interconnectedness.

Beginning from the mining of the ore, our survey of the landscape around Tamdult has identified several lead and copper mineral outcrops, some with traces of ancient mining (Fig. 21). Geological and archaeological fieldwork is ongoing to narrow down the type of ore exploited, and the period of mining activity. Given the overall situation, it is reasonable to assume that at least some of these mines are contemporary with the metallurgical activity at Tamdult.

Following the extraction at the ancient mine, the ore would have been further prepared for smelting through crushing and enrichment in metalliferous material. This beneficiation step could have taken place at or near the mines, or nearer to the smelting sites. It is unknown at present whether different outcrops were exploited for copper, lead-silver, and zinc ore, respectively, or whether a single mine provided a multi-metallic ore that was beneficiated into different smelting charges. The occurrence of columnar quartz crystals among the smelting debris near Tamdult points to the processing of some of the ore near the site.

After the mining and potentially beneficiation of the ore, its smelting evidently took place near to and within the wider settlement. Both clay to build the furnaces and wood to use as fuel for the smelting would have been available in the wider landscape surrounding Tamdult. Depending on the degree of mechanical separation of lead and copper ore, the two metals could have been smelted in separate furnaces. However, even a joint smelting of a mixed lead-copper ore would have been feasible, as was the case for instance in the contemporary smelting operation at the Huneberg/Rammelsberg in North-Central Germany (Asmus 2012; 2014). There, a single furnace produced both lead and copper metal, which were separated during tapping (Asmus 2014, 135). Since lead and copper do not form an alloy like copper and tin do but remain mostly separate liquids in the molten stage and during cooling solidify sequentially, it is relatively easy to separate the two metals even when smelted in a single operation.

The final steps, producing highly valuable commodities, would have taken place within the well-protected environment of the walled hilltop settlement. Accordingly, we have three different categories of material in the archaeological record that cover the different steps of the high-temperature processes: slags and furnace wall fragments from smelting the ores, with scatters of slag heaps both to the West and East/South-east of the settlement, an array of crucible fragments and some cupellation remains linked to brass making and silver refining, and finally fragments of pellet and ingot moulds for silver and brass, respectively. Based on our current thinking, we discuss the two technologies separately for lead/silver and copper/brass in more detail below, in their respective sequences of production.

Lead-silver production

The dark red to black slags are the visually most apparent metallurgical remains; their shape reflects the viscous nature of lead- and lime-rich silicate melts, while their colour difference mostly reflects different degrees of vitrification or crystallisation; compositionally, they fall in a very narrow range with no major distinction between the suspected lead and lead-copper slags. Visually similar slags are known from a number of early medieval and early Islamic metallurgical sites, from western and central Europe (Rehren *et al.* 1993) to Merv and Akhsiket in Central Asia (own unpublished data). Their technological interpretation, however, is an open question; in Dortmund (Germany), they have been tentatively linked to brass making, while in Central Asia, they are more generally related to copper metallurgy.

While the lead-rich composition of the slag points towards the smelting of argentiferous lead as the main metal, the composition of the matte and metal inclusions indicate the extraction of copper as a further accompanying metal. To extract the silver, the lead metal underwent cupellation as evidenced by the fragments of cupellation hearth material discovered on site. The pure silver was then processed into pellets as indicated by the numerous pellet mould fragments found on site. We do not know the amount of silver in the lead bullion; however, it is reasonable to assume that it was less than 1 wt%. Accordingly, for each kilogram of silver produced there would have been at least 100 kg pure litharge (PbO), or at least 150 kg cupellation hearth material, that is ash soaked with litharge to facilitate the clean mechanical separation of lead oxide and silver metal during cupellation. Considering this, it is remarkable that only very few fragments of cupellation hearth material were found at Tamdult; this could indicate that the bulk of it was recycled into the primary smelting charge, together with fresh sulfidic lead ore (*e.g.*, Cohen *et al.* 2009, 468-469).

The selection of highly refractory alumina-rich and non-calcareous clay for the production of the pellet moulds minimised the vitrification of the ceramic even at the high operating temperatures needed to melt the silver metal, and in the presence of strong fluxes such as lime from the fuel ash and lead oxide from residual lead metal within the freshly cupelled silver. The source of this kaolin-rich clay has not yet been identified, but clearly differs from the highly calcareous and less alumina-rich clay source exploited for the production of domestic pottery. There are not large enough fragments to reconstruct the original shape of the pellet mould trays; however, we assume that they were heated indirectly, with the hot air flowing from a separate firebox to heat the moulds. Such furnaces were well established during this period, but no physical evidence for such a complex furnace structure has been found yet.

Copper and brass production

Similar to the evidence for lead-silver production, dark glassy slags are the main evidence we have for the smelting of copper. It is important to see the very close compositional and mineralogical similarity between the slags which we interpret as lead-silver related and those that we associate with copper production; this similarity indicates that the ore and gangue were likely coming from the same deposit, with a significant overlap between lead and copper minerals, and smelted following the same furnace charge recipe. It is only the frequent presence of copper-lead matte among the slags from the area west of Tamdult and the slightly elevated copper and zinc levels in the slag itself that point to them being copper-related. This interpretation is further supported by the finds of small copper items, particularly several flows of raw copper, and a fragment of a small brass ingot. Two of the metal flows are raw copper with less than 0.2 wt% zinc, while three have zinc values between 4.5 and 11 wt%. They all share the same range of minor and trace elements, indicating that the brass was most likely made by cementation using the raw copper as starting material.

The presence of brass cementation crucibles is of major importance for our understanding of the complexity of the interconnected metallurgies at Tamdult; the strongly reducing conditions evidenced by the presence of (now corroded) metallic iron in the crucible slag, and the deep penetration of zinc as metallic vapour into the crucible fabric are the main arguments to support our interpretation. The high degree of fragmentation of the crucibles prevents a reconstruction of their original size and shape; of particular interest is the apparent absence of a formal lid or cover for these crucibles, which parallels the early medieval European brass cementation crucibles from Dortmund (Rehren *et al.* 1993). In Europe, lidded crucibles are a later development, culminating in the early modern vessels from Zwickau in SE Germany (Martinón-Torres and Rehren 2002).

Finds of ingot mould fragments of various sizes with intentionally smoothened inner surfaces rich in zinc oxide support the understanding that at least a significant part of the brass produced at Tamdult left the site as trade ingots. The ingot fragment from Tamdult has a relatively low zinc content of only around 11 wt% zinc but relatively high arsenic, of around 2 wt%, in line with the arsenic content observed in the raw copper flows. It remains to be seen whether this is a characteristic feature of this metal which could facilitate its recognition elsewhere.

Future research will have to determine the likely scale and duration of copper and brass production at and around Tamdult and explore potential destinations for the finished metal ingots. Trade in copper-based metal across the Sahel and sub-Saharan West Africa has been extensive and is subject to numerous studies (*e.g.*, Willet and Sayre 2006; Garenne-Marot and Mille 2007; Garenne-Marot 2009; Babalola *et al.* 2025, and references therein). The exact shapes and dimensions of the ingot moulds from Tamdult differ, but in particular the trapezoid ones resemble the cross sections of the famous ingots recovered by Monod from the 'Lost Caravan', as recently published by Garenne-Marot (2017, 191). Work is ongoing to determine the lead isotope signature of the metal from Tamdult, in an attempt to position it within the growing corpus of provenance studies for West African copper work (Willet and Sayre 2006; Skowronek *et al.* 2023; Babalola *et al.* 2025). Here, the significance of Tamdult lies in the fact that it has been identified as a primary production centre rather than a transhipment place, adding a rare fixed starting point to our evolving picture of the flow of copper.

Conclusions

Several seasons of fieldwork and laboratory analyses on selected archaeometallurgical finds have begun to paint a vivid picture of a thriving and diverse metallurgical activity in medieval era Tamdult. The remains of extensive and widely dispersed lead and copper smelting, set within a complex metalliferous mining landscape, have been mapped and will be further analysed in conjunction with the study of the range of urban remains of silver production and brass cementation. There is strong evidence for cupellation and the regular production of silver pellets, while brass was being made in cementation crucibles, for the production of long thin brass ingots.

The early stages, from the mining to the smelting, of the two metallurgies were closely connected, potentially one and the same. The craftspeople were mining a complex sulfidic ore rich in lead and copper, with relatively little iron and very little zinc. Minor amounts of arsenic and antimony in the ore were associated with silver, sufficient to make the mining, beneficiation and smelting of this ore a worthwhile sustained activity, as frequently mentioned in the medieval sources about Tamdult.

As our ongoing research is showing, the silver metallurgy for which Tamdult has been known for nearly a millennium is part of a wider metallurgical landscape. Evidence for brass cementation includes the presence of small amounts of copper metal and

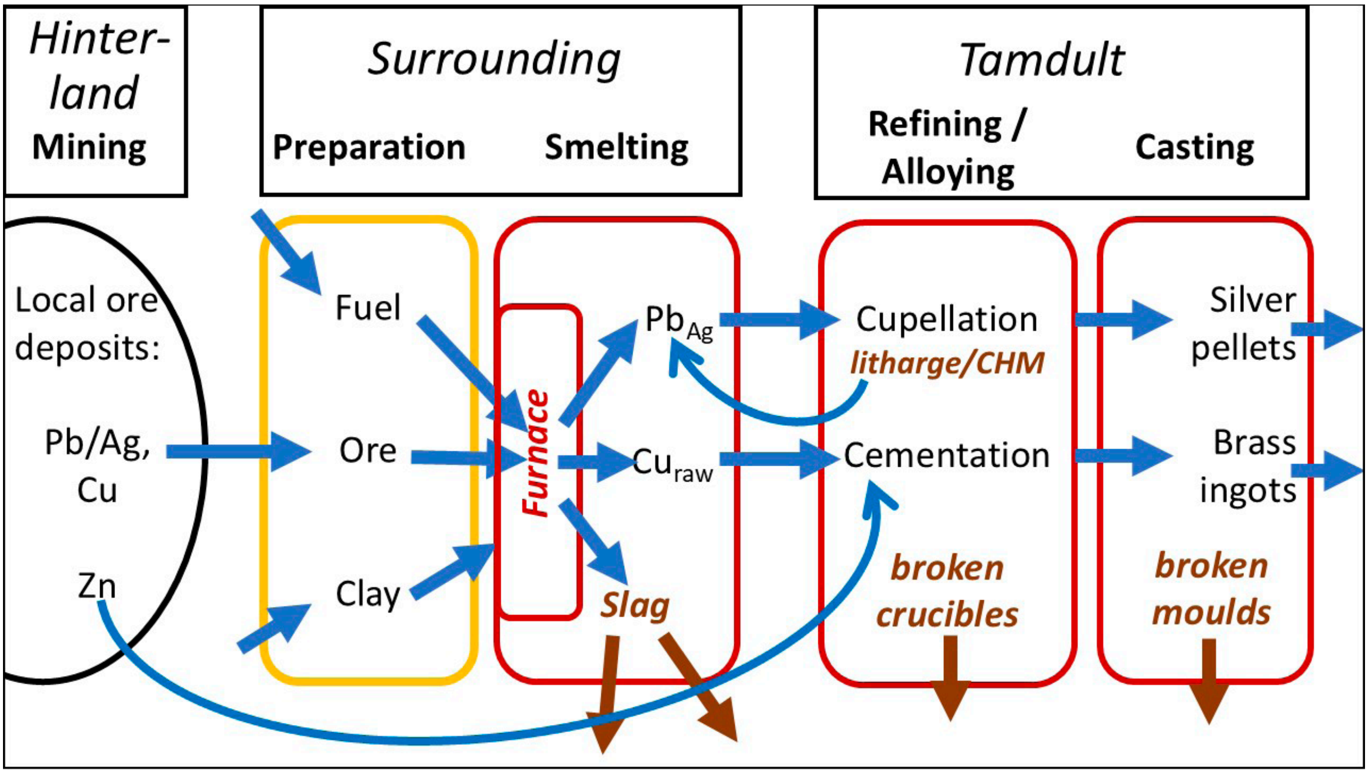

Figure 22: Overview schematic of the two main chaînes opératoires for silver and brass making, respectively, at Tamdult. Raw material inputs are in dark yellow, high-temperature processes in red, material flow in blue, and waste material in brown. CHM = cupellation hearth material.

matte inclusions in some of the lead-rich slags, strongly pointing to the possibility that more copper-rich parts of the ore were smelted for copper metal. Initial fieldwork observations point to a spatial separation of potential copper smelting and lead/silver smelting. The very similar slag compositions tie the two metallurgies clearly together, and their actual relationship is subject to ongoing research. Surface finds of copper metal include flows of unrefined raw copper with varying amounts of lead, arsenic and zinc. The strongest evidence for the production of brass comes from the presence of fragments of zinc-rich ore, of numerous crucibles rich in zinc oxide, of ingot mould fragments with zinc oxide on the surface that was in contact with the metal, and of small fragments of brass ingots. The crucibles are made from a relatively coarse ceramic, often with alumina-rich rock fragment inclusions and in many instances with an outer layer of additional ceramic. During the cementation process, zinc-rich vapour penetrated deep into the fabric, with zinc concentrations in the ceramic exceeding five weight percent near the inner surface. The residual material in the crucibles is rich in iron, with minor amounts of lead and occasionally copper. The microscopic study showed that at the end of the process the iron was often originally present as metallic prills, demonstrating the strongly reducing conditions within these crucibles, even though the prills are now corroded to iron hydroxide. The ingot moulds have trapezoid and V-shaped cross sections with maximum dimensions of about 2 cm in cross-section; due to the fragmentation of the moulds their original lengths are unknown, but certainly exceeded 20 cm.

Taken together, the research so far enables us to sketch a general outline for the closely connected productions of copper/brass and lead/silver at Tamdult (Fig. 22). It is quite possible that the two processes were running as one up to the smelting furnaces; it is even possible that lead and copper were smelted together and only separated in the final tapping of the metal from the furnaces. After this, the lead bullion and raw copper would be processed in two very different processes, namely cupellation for silver extraction, and cementation to make brass ingots, respectively. Despite relatively rich historical sources, it is impossible to more than speculate about details of the organisation and the craftspeople behind these operations. We also have only limited understanding of who had control over craftspeople and their production; whether for example these operations were controlled by trade guilds, by a central authority, or some other body. Clearly, much more work is needed to untangle the spatial arrangements between the different steps, and to more closely date the various operations.

Notably absent from the metallurgical evidence so far is any slag related to iron smelting or smithing, despite the indisputable need for iron and steel for tools for mining and agriculture, for arms and armour, and a raft of domestic and craft uses. This may be due to the limited amount of excavation conducted on site, and our ongoing surveys aim to mitigate this. Alternatively, there could be two reasons to explain this separation as an intentional aspect of the spatial organisation of the metallurgy in Tamdult. On the one hand, fire wood and charcoal would have been valuable in this desert landscape, despite the relative abundance of biomass in the oasis. If this was indeed a concern, then the use of fuel could have been prioritised for the smelting of the higher value metals lead/silver and copper/brass, while iron smelting and smithing would have been done elsewhere, where there was less competition for fuel resources. Alternatively, the main concern could have been the level of control over the metals produced, with the most expensive silver being produced near to and within the fortified settlement, with raw copper being smelted somewhat further away to the west of the site, but the value-generating brass cementation and ingot casting still conducted within the settlement. This would have ensured that the local administration had tight control over the production and distribution of these economically strategic metals, while keeping the initial smelting of the ore outside the settlement.

Data availability statement

The data is in the repositories of the A. G. Leventis Archaeological Materials Science Laboratories and stored according to the Cyprus Institute's Data Management Policy.

Acknowledgments

The fieldwork at Tamdult has taken place within the remit of the Jbel Bani Archaeological Project and has been supported and authorised by the Institut National des Sciences de l'Archéologie et du Patrimoine (INSAP), under the wider guardianship of the Moroccan Ministry of Culture and Communication. Support for the fieldwork has also been provided by the Governor of the Tata Region and the Communes of Akka and Tizunine, of whom various members of the community participated in and delivered the fieldwork programme, as well as providing general support and welcome to the project team.

Funding

Funding for fieldwork at Tamdult has been provided by the Max Van Berchem Foundation, the Society for Libyan Studies, the British Institute in Eastern Africa, the Centre Jacques Berque, Rabat, and IAMS, the Institute for Archaeo-Metallurgical Studies. Support from the A. G. Leventis Foundation for the laboratories at the Cyprus Institute is gratefully acknowledged, without which this research would not have been possible. This publication is one of the outputs of the A. G. Leventis Chair in Archaeological Sciences at the Cyprus Institute.

Competing Interest

The authors declare no competing interests.

References

Al-Bakri (1859). *Description de l'Afrique septentrionale / par El-Bekri; traduite par Mac Guckin de Slane*. Paris: Impr. Impériale.

Asmus, B. (2012). *Medieval Copper Smelting in the Harz Mountains, Germany*. Bochum: Deutsches Bergbau-Museum Bochum (Montanregion Harz 10).

Asmus, B. (2014). Theophilus und die mittelalterliche Verhüttungstechnologie. *Der Anschnitt* 66, 126–140.

Baron, S., Souhassou, M. & Fauvelle, F.-X. (2020). Medieval Silver Production around Sijilmâsa, Morocco. *Archaeometry* 62, 593–611. https://doi.org/10.1111/arcm.12546

Babalola, A. B., Desai, M., Rademakers, F., Cisse, M. Degryse, P. & Rehren, Th. (2025). Leaded Copper Crescent-Shaped Objects and a Brass Ring from Medieval Gao, Mali. *Metalla* 29, 33–55. https://doi.org/10.46586/metalla.v29.2025.i1.33-55

Bokbot, Y., Nixon, S., Saghir, M., Rehren, Th., Wexler, J., De Juan Ares, J., Cáceres, Y., El Mehdaoui, R., Bravin, A., Ouakrim, Z. & Benattia, H. (In press). Jbel Bani Projet Archéologique (province de Tata, Maroc): campagnes de terrain 2018-2020 et résultats de recherche intermédiaires. *Bulletin d'Archéologie Marocaine* (BAM).

Boum, A. (2010). From 'Little Jerusalems' to the Promised Land: Zionism, Moroccan nationalism, and rural Jewish emigration. *The Journal of North African Studies* 15, 51–69. https://doi.org/10.1080/13629380902745876

Cohen, C., Rehren, Th. & Van Buren, M. (2009). When the wind blows: environmental adaptability in current day silver production within the Bolivian Andes. In: J.-F. Moreau, R. Auger, J. Chabot (Eds.), *Proceedings ISA 2006 – 36th International Symposium on Archaeometry* (pp. 465–475). Quebec: CELAT, University Laval.

Courcier, A., Essaid, E., Abdoullah Ould Bagga, M., Celauro, A. & Maass, A. (2019). La métallurgie du cuivre dans la région de l'Inchiri, en Mauritanie au cours de l'Holocène récent. Etat de la recherche à la lumière des nouvelles recherches menées par le projet franco-mauritanien CUPRUM. In: *Les annales de l'IMRS (Institut Mauritanien de Recherche Scientifique)*. SAGEP

Cressier, P. (2004). Du Sud au Nord du Sahara: la question de Tamdult (Maroc). In: A. Bazzana & H. Bocoum (Eds.), *Du nord au sud du Sahara. Cinquante ans d'archéologie française en Afrique de l'Ouest et au Maghreb* (pp.275–284), Paris: Bilan et perspectives. Sépia.

Cressier, P. & González-Villaescusa, R. (2025). A Look Back at the Irrigated Areas of the Medieval Town of Tāmdult (Morocco). *Land* 15, 69. https://doi.org/10.3390/land15010069

El Ouad, Z., Souhassou, M. & Ikenne, M. (2023). Métallurgie Ancienne du site de Tamdûlt, Anti-Atlas Marocain: Contexte Géologique et Minier. *Journal of African Archaeology* 21, 201–212. https://doi.org/10.1163/21915784-bja10031

El Ouad, Z., Souhassou, M., Ikenne, M., Hibti, M., Said, I., El Hassan, A., Moundi, Y., Madi, A. & Karfal, A. (2024). Geology and mineralogy of Pb-Ag-Cu veins of the Central Plateau Deposits of the Jbel Addana District (Western Anti-Atlas, Morocco). *SEG 2024 Conference: Sustainable Mineral Exploration and Development, Namibia*.

El Ouad, Z., Jabbour, M., Souhassou, M., Ikenne, M., Belfoul, M. A., Hibti, M., Said, I., Nathwani, Ch., Moundi, Y., Madi, A. & Karfal, A. (2025). Mineralogical data and structural contol of Pb-Fe-Zn-Cu mineralizations of the Bou-Oudadene deposit (Jbel Addana District, Western Anti-Atlas, Morocco): implications for mineral exploration. In: E. Anderson & G. Graham (Eds.) *Mineral Resources for Our Ever-Changing World* (Vol. 1, pp. 297–300), 18th SGA Biennial Meeting 2025.

Erbati, E., Fauvelle, F-X. & Mensan, R. (2020). *Sijilmâsa, cité islamique du Maroc médiéval: recherches archéologiques maro-co-française 2011-2016*. Rabat: INSAP (« Vesam » 9).

Fentress, E., Fenwick, C. & Limane, H. (2022). Urban life in early Islamic Morocco: new light from the excavations at Walīla (Roman Volubilis). *Archaeology International* 25, 111–131. https://doi.org/10.14324/111.444.ai.2022.08

Fenwick, C., Sterry, M., Mattingly, D. J., Rayne, L. & Bokbot, Y. (2022). A Medieval boom in the North-west Sahara: Evolving oasis landscapes in the Wadi Draa, Morocco (c. 700–1500 AD). *Journal of Islamic Archaeology* 8, 139–165. https://doi.org/10.1558/jia.20440

Freestone, I. C. & Tite, M. S. (1986). Refractories in the ancient and preindustrial world. In: W. D. Kingery & E. Lense (Eds.) *High-Technology Ceramics – Past, Present, and Future* (pp. 35–63). Westerville, Ohio: American Ceramic Society.

Garenne Marot, L. (2009). 'Fils à double tête' and copper-based ingots: copper money-objects at the time of the Sahelian Empires of Ancient Ghana and Mali. In: C. Eagleton, H. Fuller & J. Perkins, (Eds.) *Money in Africa* (pp. 1–8). London: British Museum (British Museum Research Publications 171).

Garenne Marot, L. (2017). Cuivre. In: A. Livingstone Smith, E. Cornelissen, O. Gosselain, & S. MacEachern (Eds.) *Manuel de terrain en Archéologie africaine* (pp. 190–196). Tervuren: Musée royal de l'Afrique centrale.

Garenne Marot, L. & Mille, B. (2007). Copper-based metal in the Inland Niger delta: metal and technology at the time of the Empire of Mali. In: S. La Niece, D. Hook, P. Craddock (Eds.) *Metals and Mines. Studies in Archaeometallurgy* (pp. 159–169). London: Archetype.

Handaine, M. (2008). *Tamedoult: Histoire d'un Carrefour de la civilisation maroco-touarégue*. Rabat: Editions & Impressions Bouregreg.

Heinrichs, J. & Rehren, Th. (1996). Keltische Münzschrötlingsformen aus Bonn - Naturwissenschaftlich-numismatischer Vorbericht und historische Interpretation. *Metalla* 3, 83–100.

IGN (1953). Institut National de l'Information Géographique et Forestière (France) – *no. LXXX, TATA region*.

Justinard, L. (1933). *Notes sur l'histoire du Sous au XVIe siècle. I – Sidi Ahmed ou Moussa. II – Carnet d'un lieutenant d'Al Mansour*. Paris: Honoré Champion (Archives Marocaines 29)

Levtzion, N. & Hopkins, J. (Eds.). (2000). *Corpus of Early Arabic Sources for West African History*. Princeton: Markus Wiener.

Martinón-Torres, M. & Rehren, Th. (2002). Agricola and Zwickau: theory and practice of Renaissance brass production in SE Germany. *Historical Metallurgy* 36, 95–111.

Messier, R. & Miller, J. (2015). *The Last Civilized place. Sijilmasa and its Saharan Destiny*. Austin, Texas: University of Texas Press. https://doi.org/10.7560/766655

Milot, J., Baron, S. & Poitrasson, F. (2018). Potential use of Fe isotopes for ancient non-ferrous metals tracing through the example of a lead-silver production site (Imiter mine, Anti-Atlas, Morocco). *Journal of Archaeological Science* 98, 22–33. https://doi.org/10.1016/j.jas.2018.07.004

Monod, Th. (1969). Le Ma'den Ijafen: une épave caravanière ancienne dans la Majabat al-Koubra. In: *Actes, 1er Colloque Internationale d'Archéologie Africaine*. Fort Lamy: Institut national tchadien des sciences humaines.

Nixon, S., Rehren, Th. & Guerra, M. F. (2011). New light on the early Islamic West African gold trade: coin moulds from Tadmekka, Mali. *Antiquity* 85, 1353–1368. https://doi.org/10.1017/S0003598X00062104

Nixon, S., Bokbot, Y. , Saghir, M., Rehren, Th., Wexler, J., De Juan Ares, J., Bigoulimen, A., Cáceres, Y., Hachami, H., El Mehdaoui, R., Bravin, A., Ouakrim, Z. & Benattia, H. (Submitted). *The Jbel Bani Archaeological Project (Tata Province, Morocco): fieldwork seasons 2018, 2019, 2020, 2023 and interim research results*.

Rehren, Th. & Klappauf, L. (1995). … ut oleum aquis – Vom Schwimmen des Silbers auf Bleiglaette. *Metalla* 2, 19–28.

Rehren, Th., Lietz, E., Hauptmann, A. & Deutmann, K. H. (1993). Schlacken und Tiegel aus dem Adlerturm in Dortmund: Zeugen einer mittelalterlichen Messingproduktion. In: H. Steuer & U. Zimmermann (Eds.) *Montanarchäologie in Europa* (pp. 303–314). Sigmaringen: Thorbeke (Archäologie und Geschichte - Freiburger Forschungen zum ersten Jahrtausend in Südwestdeutschland 4).

Rosenberger, B. (1970). Tamdult: Cité minière et caravanière presaharienne, IX-XIVe S., *Hesperis Tamuda* 11,103–139.

Skowronek, T. B., DeCorse, C. R., Denk, R., Birr, S. D., Kingsley, S., Cook, G. D., Benito Dominguez, A. M., Clifford, B., Barker, A., Otero, J. S. & Moreira, V. C. (2023). German brass for Benin bronzes: Geochemical analysis insights into the early Atlantic trade. *PLoS ONE* 18(4), e0283415. https://doi.org/10.1371/journal.pone.0283415

Willet, F. & Sayre, E. V. (2006). Lead isotopes in West African copper alloys. *Journal of African Archaeology* 4, 55–90. https://doi.org/10.3213/1612-1651-10063

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