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Archaeometallurgical production remains in India: A review

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ABSTRACT

The archaeometallurgical literature on India can be broadly separated into the study of the composition and manufacturing of metal artefacts, the geological provenancing of metal objects primarily using lead isotope abundance ratios, and the study of production technologies as represented by remains related to the smelting and alloying of the metals used; this review covers the latter. Beginning with the early evidence for metallurgical practices in the Indus Valley Civilisation it moves to copper smelting, first in the IVC and then across India. Subsequent sections cover the evidence for bronze working, before summarising the important work on medieval and later zinc and lead-silver production in Western India, and emerging crucible finds in recent excavations across India. The production of iron is ubiquitous, but surprisingly little-studied. Much emphasis is placed on crucible steel research, with northern Telangana a particular region of sustained and fruitful research, and further evidence spread across southern India. Finally, we highlight specific technologies that are particularly understudied, such as gold and silver production and refining, brass making, tin smelting, and the diversity in bloomery iron smelting practices. The importance of long-term, collaborative and in-country based research in order to achieve archaeologically meaningful results is stressed, incorporating theoretical models of data interpretation and social anthropology into the research, highlighting the importance of studies in reverse engineering and *chaîne opératoire*.

1. Introduction

1.1. Crafting a decolonised past

The study of archaeometallurgy in India provides a fascinating window into the technological advancements and cultural exchanges that shaped the subcontinent's history. India's metallurgical heritage, marked by its early and sophisticated practices, dates back to at least the 3rd millennium BCE, followed by significant developments in the production of copper and its alloys, iron and its alloys, zinc, lead, gold & silver (Kenoyer and Miller, 1999; Kenoyer, 2008), tin and mercury. Of them, the working of copper and its alloys has the longest continuous history, beginning with the earliest evidence so far known from the Indus Valley Civilisation (IVC), and continuing today as artisanal traditional practice. Similarly, iron and steel metallurgy have a very deep and long-lasting history, too, with the last indigenous practices surviving well into the 20th century. Archaeological and literary records show that ancient Indian societies excelled in metalworking and participated in extensive trade networks, facilitating the exchange of metallurgical knowledge across regions. This is evident by outstanding masterpieces, such as centuries-old well-preserved iron pillars, or the complex and rich southern Indian bronze castings. Indus Valley craftsmen demonstrated their familiarity with and knowledge of techniques such as lost-wax casting and the use of copper-based alloys in casting from as early as the fifth millennium BCE (Mille, 2017; see also Rose et al., 2023). Comparable practices are documented in Mesopotamia by approximately 2900 BCE, and somewhat later in New Kingdom Egypt (Davey, 2009). Within the IVC, such metallurgical knowledge is exemplified by artefacts including the iconic *Dancing Girl* figurine and other small cast objects dated to the early second millennium BCE (Marshall, 1931; Penniman, 1975).

Over time, casting techniques became increasingly refined and regionally differentiated, giving rise to distinct traditions. In the southern regions of the subcontinent, solid casting methods predominated, whereas northern regions developed a preference for hollow casting, particularly for larger artefacts (Lahiri, 1993; Craddock, 2015).

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By the early historical period, further innovations in copper metallurgy are evident in finds from the Central Ganga Valley, where tin bronze and brass artefacts display significant lead content (3–6 %). The consistent use of lead—an alloying element that enhances castability—suggests a deliberate choice by metalworkers, reflecting an increasingly sophisticated understanding of alloy properties and casting techniques (Rai, 2021).

The production of metal and metal alloys, as well as their refining and casting, can follow many different technological trajectories, as recorded by remnants such as broken crucibles, slags, and furnace remains. Within an anthropology of technology framework, these remnants are unique repositories of valuable archaeological information. However, it can be challenging to determine the specific type of production solely through visual inspection. Noteworthy is the recognition that in particular the earliest alloys can include both, natural alloys formed through the smelting of geologically mixed complex ores, or artificial alloys formed through intentional mixing of two metals as a conscious act to improve the properties of the resulting metal. Often there is lack of evidence to differentiate the two, but it is not impossible. Therefore, it becomes essential to differentiate processes through instrumental analyses that provide insights into the nature of the raw materials, production temperatures, reducing conditions, and the composition of the charge, which in turn facilitates further insights into multiple aspects of past societies, such as the organisation of production, degrees of standardisation and specialisation, developments over time, economic priorities and trade connections, and many more. For a country such as India with its extensive remains of ancient metallurgy (see map Fig. 1), it is crucial to properly classify archaeometallurgical finds and offer standardised data, to facilitate comparisons and overarching interpretations (see Fig. 2).

These studies are not new to India, given her long-standing tradition of incorporating laboratory practices in archaeology. More than a century ago, in 1917 the Archaeological Survey of India established their Chemical Branch along with an assigned archaeological chemist. The primary aim of the branch was to examine, treat and preserve objects post excavation and offer analytical services to the archaeologists when necessary (Lal, 1953; Mujumdar, 1973). The quick expansion of activities was enabled by a permanent position for the use of science in Indian archaeology, two years before the British Museum began scientific investigations on archaeological remains. The 1950s in India saw routine analytical examination of ceramics, metals, and soil, and by the 1970s, archaeological science was regularly helping formulate archaeological

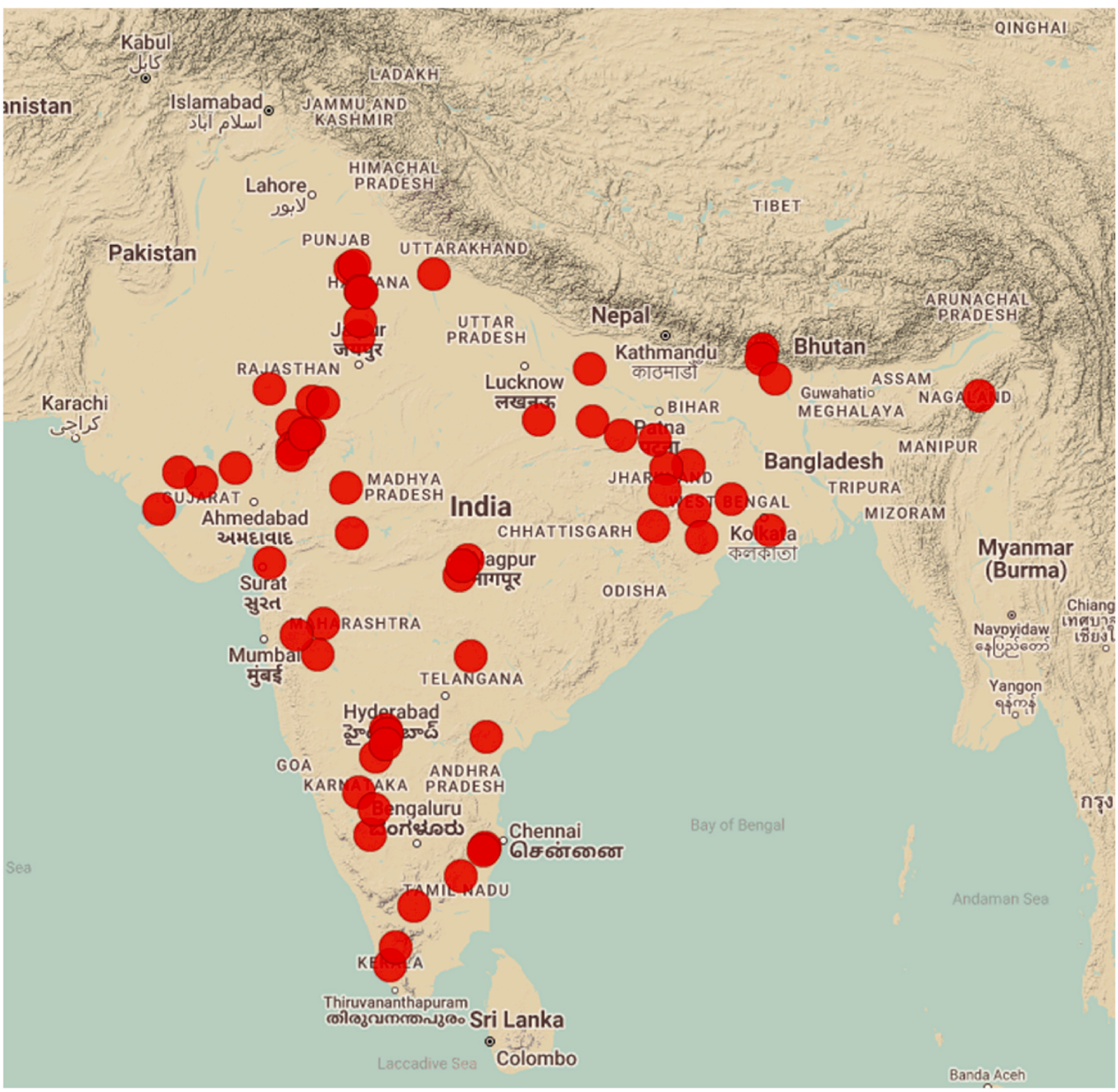

Fig. 1. Locations with archaeometallurgical finds reviewed in this study. The reported and/or analysed production remains are well distributed across India; however, large tracts of land still remain under-studied.

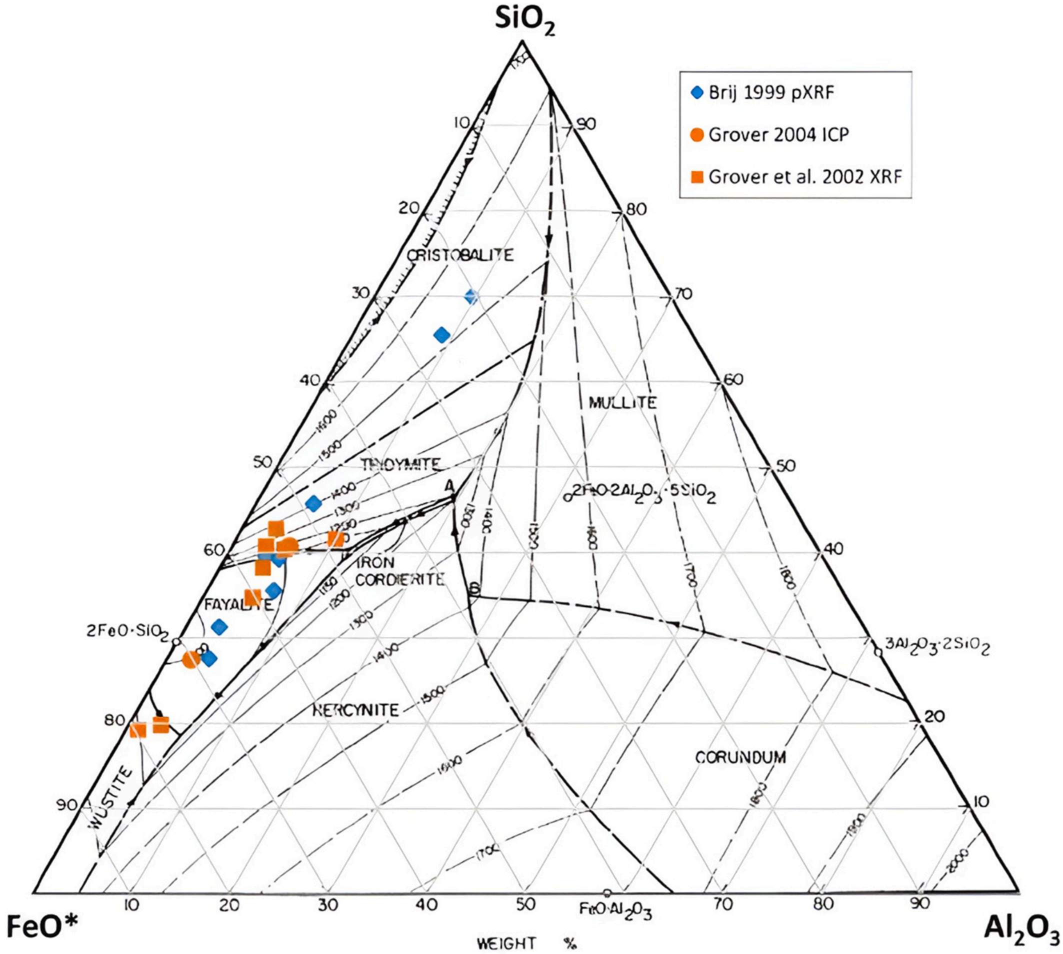

Fig. 2. Projection of slag compositions onto the liquidus surface of the ternary phase diagram FeO – SiO_2 – Al_2O_3, combining all metals with valency 2+ with the dominant FeO. Brij (1999) slags are from iron smelting, while the slags reported by Grover et al. (2002) and Grover (2004) are from copper smelting. Nearly all slag data from Brij (1999) plot into the fayalitic region; only two stand out as being very high in silica, appearing more like molten ceramic contaminated with some slag (for data, see online supplementary material, Table 1). It is noteworthy how the composition of copper slag and iron slag is indistinguishable in this projection, reflecting their very similar bulk composition and melting temperatures.

narratives.

Over the past two decades, archaeological excavations across India have played a pivotal role in reshaping the narrative of the subcontinent's ancient past. Grounded in scientific methodology, these efforts by Indian scholars have contributed to a more decolonised and indigenous understanding of early cultural developments, challenging long-standing imperial models—particularly those asserting Steppe or Iranian origins for the Indo-Aryans (Shinde et al., 2019). Within this broader discourse, archaeometallurgy offers a critical line of evidence, illuminating patterns of metal and craftsperson mobility, the emergence of indigenous smelting technologies, artisanal traditions, and the dynamic interactions between ancient communities and their environments. In doing so, it reinforces a more nuanced and locally rooted understanding of South Asia's shared cultural and technological heritage. Undoubtedly, pioneering Indian institutions in archaeology such as the Deccan College, Maharaja Sayaji Rao University, Banaras Hindu University and others, together with the Archaeological Survey of India have made significant strides in shaping our understanding of India's metallurgical past.

1.2. Trade or production: objectives of this review

Despite these early advances, our understanding of early metallurgical production processes remains limited. Indian archaeometallurgical studies have largely focused on artefact analysis, leaving significant gaps in research on smelting waste and crucible remains. While studies of metals and alloys shed light on alloying elements, provenance, and trade through lead isotope and trace element analyses, they provide limited insight into the technologies of production (Rehren and Pernicka, 2008). Lead isotope analysis (LIA) has emerged as a vital archaeological tool for grouping artefacts of similar lead isotope signatures (e.g., Srinivasan, 1999), and ideally tracing their geological provenance, but its reliability is hindered by factors such as the limited geological variability among ore deposits of similar geological age which complicates source matching (Pollard, 2017), while metal mixing and recycling distort isotopic signatures in artefacts (Brügmann et al., 2016). Similarly, analytical characterisation is often affected by contaminants, particularly in low-lead copper artefacts, leading to potential errors (Hauptmann, 2007). Overall, interpreting LIA data is complex, requiring consideration of mixed sources, contamination, and limited datasets (Pernicka, 1999). Besides its own technical challenges, this approach sidelines the skills of the early craftspeople, their environmental interactions, their understanding of the product, their intentionality, and, to some extent, the artefact's function. Therefore, to study past societies with a human-centred approach, production or processing debris should be prioritised for analysis and then complemented by provenance methods where possible. Groundbreaking publications such as Mujumdar (1973), Biswas (1991) and Agrawal (1971) encouraged slag and crucible analyses, while Biswas (1991) also highlighted the drawbacks of simple ore-artefact correlations. The seminal work of Agrawal (1971) presents a meticulous picture of Harappan copper and related metallurgy, along with the work of Hegde [1965, 1981, 1989, see also (Agrawal, 1971: 120–175)] and many others. India's research tradition in archaeometallurgy has stood the test of time, and is now expanded much beyond the IVC with indigenous craftsmen still carrying forward the traditions well into the 21st century.

Given the vast extent of the country and the existence in it of nearly all antiquarian metals and their alloys, we are in no position to claim to have covered all published work. This is even more true for iron slags which have dominated India's metallurgical landscape from at least the early historical/Megalithic period onwards. This review focuses on production-related evidence and practices, while metal objects and alloys were included only where essential for informed comparison. Our intention is to strike a balance between showing the breadth of research done and of research potential in one of the culturally most fascinating major global regions, exploring technological innovations, regional variations, and the socio-economic impacts of metal production throughout history. We also recognize the modern geographical and political divisions which limit the review of what could be 'shared heritage' and deserves its full attention as such.

Given the heavy emphasis on ore-artefact relationships in much of India's archaeometallurgical study, we turn the focus on production evidence, which we believe will prove most fruitful for reconstructing India's metal production, and with an intent for this review to help lay the foundation for future scholarship in Indian archaeometallurgy.

2. The evidence

2.1. Indus Valley Civilisation (IVC)/Harappa–the beginnings

From either side of the river Indus, Harappan copper metallurgy is mostly known through implements, including a variety of vessels, ornaments, tools and weapons, stamps, seals and figurines. Numerous papers, analytical studies and databases have characterised this Harappan metallurgy and collated metal and alloy-to-ore data through trace element or LIA (Hegde and Ericson, 1985; Yule, 1985; Herman, 1984; Rapp, 1990; Lahiri and Chakrabarti, 1996; Kenoyer and Miller, 1999; Agrawal, 2001; Hoffman and Miller, 2009; Law, 2011, see also the extensive summary in Singh, 2014).

Little is known about pre-Chalcolithic primary metal production in the IVC, although a strong casting tradition is traceable to the Harappan period. Until the Indian archaeological excavations (Hooja, 1988; Hooja and Kumar, 1997; Hegde, 1965 etc.) reopened the discussion, based on the absence of primary production remains it was widely believed that the Harappan copper was imported (e.g., SanaUllah, 1931; Mackay, 1938; Rao, 1985; Kenoyer and Miller, 1999; Hoffman and Miller, 2009; Patel et al., 2014; Hoffman, 2018 etc.). In the last six to seven decades, around the Aravalli region and further south-west (Agrawal et al., 1976; Agrawal, 1984; Raghunandan et al., 1981; Hegde, 1991) namely Rajasthan and Gujarat (Mujumdar and Rajguru, 1962; Grover, 2004), Chalcolithic slags and furnace remains were reported and preliminarily investigated; however, more substantial analytical and chronological efforts are still required to categorise the finds as remains of primary production or of subsequent steps such as metal refining or processing. Only then would a more accurate commentary become possible on the import or home-grown origin of Harappan copper – or both.

Lead isotope studies by Law (2011: 456; 460) strengthen the argument for the local acquisition of copper first put forward by Hegde (1991), teasing out a plausible connection between a handful of IVC copper objects and the Aravalli and Ambaji mines. Law (2011: 448) also added evidence for Harappan lead acquisition from the lead deposits of Jammu and Kashmir in Northern India. For production, the paucity of published and well-dated evidence limits a substantial argument, despite the sporadic studies of copper slag, lacking a systematic methodology, rendering them insufficient to address this fundamental question. In our view, the shortage of production evidence may not be evidence for a shortage of production at all. Both schools of thought – copper import or indiginous IVC smelting – are heavily depended on ore-artefact relationship studies; so far, this is particularly challenging owing to very little lead isotope data from the sub-continent being available yet.

2.2. Variability in IVC copper compositions

Copper hoards from what is now the Indian side of the IVC, of artefacts with various compositions, sometimes with tin, lead, zinc, arsenic, iron or nickel in minor or major quantities (Singh, 2014),[1] show the wide spectrum of copper traditions across IVC cultures and eventually into peninsular India, as seen from the extraordinary Daimabad bronzes (Sali, 1986; Dhavalikar, 1993). What remains to be distinguished is the intentional versus natural alloying. While the former reflects craftspeople's decision and conscious use of different metals, the latter is an incidental result of complex ore compositions and the preferential partitioning behaviour of chalcophile elements (Radivojević et al., 2013). This can be exemplified by the metal compositions from some seventy objects analysed from Lothal (Rao, 1973, 1985; Nautiyal et al., 1981; Hoffman, 2018: 258-9). Of these, five contain around 5 to 15 wt% tin, another four contain tin between 1 and 5 wt%; all others report no tin analysed or found. Of these, two to three unalloyed copper artefacts contain nickel, with one object around 3 wt% nickel, another three objects contain up to 4 wt% lead and one probably a leaded copper with 9 wt% lead. Thus, around 65–70 % of the metal objects from Lothal are technically pure, unalloyed copper, while the others contain a wide range of additional elements. The variability in elements and their concentrations brings us back to the same question again, whether low levels of "alloying" elements in copper are products of complex ore smelting or are intentionally added. At other sites, such as in Surkotada (Joshi, 1990; Kuppuram, 1989: 49–50, Nautiyal et al., 1981), less than 2 wt% arsenic is found in copper artefacts along with some lead and tin. Overall, we are advanced in reconstructing a veritable mosaic of copper alloying in the IVC, with raw copper, arsenical copper, tin bronze and leaded alloys all found and spatially widely dispersed, but still lack the understanding of the processes behind this wide variability.

2.3. Copper production: Harappa and beyond

In the 1960s, Sankalia et al. (1969) and later Hegde (1981; 1991: 15–16) presented evidence of early copper production from six copper working sites in the Aravalli copper belt, an area which also includes Zawar, Dariba and Agucha (see below). The mines were exploited using fire setting to extract malachite and azurite. The Aravalli hills quickly emerged as a Harappan hot-bed for copper and eventually iron metallurgy. Hegde's investigations showed for the first time a production record from the Aravalli copper belt with smelting remains such as furnaces, tuyères and slags, allowing the reconstruction of copper furnaces and stimulating smelting simulations (Hegde, 1991: 11–21). The Ahar-Banas culture (Possehl, 2002), a chalcolithic culture spread from Southern Rajasthan to Western Madhya Pradesh, is host to several chalcolithic copper- and early historical iron-related production sites with remains of slags and furnaces (Shinde and Deshpande, 2015: 48-49). Recent discoveries at Gilund[2] include copper casting mould

[1] Contains a comprehensive list of compositional tables of copper-based artefacts from various sites in the IVC.

[2] Part of the Ahar-Banas culture in western India.

fragments similar to those found at Ahar, along with fragments of vitrified ceramics bearing traces of copper[3] oxide/chloride(?) still attached to the interior wall, as well as a furnace pit containing ash and slag (Hanlon, 2010). While these finds strongly suggest copper-related metallurgical activity, further analytical investigation is needed to confirm linkages to primary copper production.

In Dholavira, the heavily vitrified crucibles with adhering copper-rich slag (Bourgarit et al., 2005) show the processing of copper, arsenical copper, tin-bronze and partly leaded copper. Particularly intriguing about the slags from Dholavira is the presence of a rich matte phase, suggesting they are too impure to be associated with refining processes. Instead, they offer modest but significant indications of possible primary smelting activity. A closer look into Gilund and Dholavira copper production alone may help us reconstruct several pieces of the copper production mosaic in western India, especially in Gilund, which preserves a substantial portion of the *chaîne opératoire* associated with copper production. The residual furnace structures associated with copper metallurgy in the Western Indian Chalcolithic suggest that ingots cooled within the furnaces, which were subsequently broken open to extract the metal (Hegde, 1991: 21). This form of furnace extraction is thought to be compatible with the bun-shaped copper ingots with an uneven bottom and a smooth upper surface documented from excavations at Chalcolithic sites of Lothal, Harappa and Mohenjo-Daro. For instance, a copper ingot from Lothal measured around 10 cm in diameter, 4 cm in height and weighs 1438 gm (Rao, 1973; Hegde, 1991: 21); these ingots and their potentially associated furnace structures offer a vast analytical potential in exploring evidence for primary production.

An exhaustive compilation of slag data appears in Grover (2004), with nearly 200 slag analyses from the literature. The majority of these are from western and north-western India, known for the production of copper, zinc, lead and silver. The slag compositions, primarily determined through XRF and ICP analysis, were scrutinised for precious metals and major and minor oxides. While details on the exact analytical methodology followed are missing, 190 samples from the list are said to be copper and iron slags. Unfortunately, differences in analytical methods and in reporting of results prevent a more detailed assessment of the data, and leaves in many cases open whether the analysed material is copper or iron slag – or something different altogether. Remarkably, the vast majority of copper slags have in the order of ¼ to ½ of a percent of copper, indicating a highly efficient technology of copper extraction on a par with, or even better than, Roman copper smelting in the Old World. Some of the copper slags seem to result from smelting of polymetallic ore deposits, setting them apart from the traditional copper slags based on relatively pure chalcopyrite ore and opening the door to the above-mentioned smelting of 'natural' alloys.

Several of the analytical studies carried out on the Early and Mature Harappan site Binjor, Rajasthan close to the India-Pakistan border, identified copper and precious metal finds along with metallurgical production/processing remains dated to 2341-1691 BCE (Sharma et al., 2020). A slag sample and metal artefact from Binjor were examined using optical and electron microscopy (SEM-EDS), showing phases in the slag such as copper chloride (nantokite), copper oxide, euhedral tin oxide, and various silicate phases, such as alkali and alkaline feldspars, ferromagnesian minerals, and quartz (Manjul et al., 2017). The euhedral tin oxide probably formed during melting of bronze under slightly oxidising conditions, rather than representing the smelting of bronze using cassiterite mineral. Typically, during bronze smelting, the recrystallisation of cassiterite retains the original oval, globular shape morphology of the ore grains, with or without the growth of euhedral tin oxide crystals (Rademakers and Farci, 2018; Rademakers et al., 2018). Clearly, the find merits further investigation. The metal artefact from the site was found to contain 65–70 wt% copper, 20–25 wt% tin, and 7–10 wt% arsenic. The absence of micrographs and detailed descriptions of the analytical areas limits further interpretation, but preliminary evidence suggests the presence of arsenical bronze production; it remains open whether this is from primary smelting of a complex ore, or melting for casting.

Similarly, crucibles from Bhirrana show copper oxide/chloride layer within the crucibles. The broken crucibles were found in a badly damaged artisan's house structure in circular hearths filled with ash and small stones (Rao et al., 2005). The site also yielded a variety of copper finds of Early Harappan, Transitional and Mature Harappan date, and a medieval copper coin hoard along with one silver coin (Rao et al., 2005). A photograph of two crucibles, possibly bases with signs of internal heating, and XRF analyses of copper and copper alloys from Bhirrana were published by Sahu (2013). No further information on the crucibles was given. Elsewhere, the best-preserved crucible fragment/furnace wall fragments from Navinal (Patel et al., 2014) range from around little over 5 cm, while smaller ones are approximately 2–3 cm in length. While these fragments are assigned as crucibles, their similarities with other "copper working waste" shown in the paper raises the probability of these fragments to be furnace wall materials. From the images published by Patel et al. (2014), the fragments appear to be strongly heated internally as their inner contents is either fully molten or molten enough to wet the internal surface of the ceramic. The walls are about 2 cm thick in the biggest and best-preserved fragments, and have white quartz inclusions. At this site, a notable amount of copper slag has also been found, together with other corroded prills and artefacts. Elsewhere, preliminary work on ceramic-rich material associated to melting or casting of copper has come to light from Bagasra, in addition to metallic copper and bronze artefacts (Patel and Ajithprasad, 2015).

Furthermore, a unique account of Percy quoted by Tylecote from Sikkim in Eastern India was compared to western Indian copper production by Bharadwaj (1979)[4]. The account states that copper sulfide ore with gangue is powdered and mixed with dung to form lumps and then roasted in a hearth. The copper oxide is then put with charcoal into a shaft furnace driven by bellows. Slag in small quantities collects over the metal. The resulting copper is impure and is refined during re-melting (Tylecote, 1977; Bharadwaj, 1979: 91; see also the ethnographic report from Nepal by Anfinset, 2011). A similar production process was followed at Singhana in western India, Rajasthan, with some regional variations, such as drying of ore and dung lumps in the sun prior to roasting, and the beneficiated ore goes into a furnace with 3 tuyères and one hole, where a plate of fire clay is placed to stir the metal and tap the slag (Bharadwaj, 1979: 92). Interestingly, iron slags are added as flux in the Sikkimese copper production, probably to initiate slag formation. Much further south of Sikkim, in Eastern Central India, copper smelting/working related finds appear from Baragunda and significant old workings from Singhbhum, both now in Jharkhand.

In the late 1980s and thereafter, some literature appeared in prospective geology and mineral studies (Shankar, 1986; Nagabhushana and Sanjeeva Reddy, 1985; Ravindra et al., 1990; Rao and Naqvi, 1997) listing copper ore deposits across districts of Karnataka in Southern India: Ingaldhal, Kalyadi and Thinthini. Old copper workings were discovered on Belligudda Hill, the main copper-producing area of Ingaldhal with malachite encrustations, wooden log reinforcements and heaps of slags. These were later confirmed as copper slags by Srinivasan (1997) and Srinivasan and Griffiths (1997). Srinivasan (2017) linked the slag finds from Ingaldhal to the Satavahanas, an early historical connection, and those from Kalyadi to be related to direct bronze smelting (Srinivasan, 1997).

[3] Hanlon (2010) mentions copper attached on the interior surface of the crucible. We assume it could actually be copper oxide/chloride or copper rich slag. Even if it was pure copper, it would have transformed to its oxide during weathering.

[4] Bharadwaj (1979) has very little information on instrument type, where mentioned is through wet chemistry.

2.4. Beyond copper

2.4.1. Bronze

A few examples illustrate the potential of more detailed studies, enabling the analyst to identify previously unknown technological processes that are impossible to deduce from the finished metal alone. The study of Kunal crucible slags followed a good multidisciplinary approach using optical microscopy, SEM-EDS and ICP-MS, Micro-XRF and XRD (Kanth et al., 2022). The data shows different degrees of vitrification of the underlying ceramic, dominated by silica, alumina and iron oxide with variable alkali and alkaline earth oxides, and with additional high lead, low to high tin, and some copper oxide from the charge. The authors offer no further technological interpretation of the data; however, their documentation and reporting of the compositional data enables us to make some assumptions. Commonly, copper smelting slag is low or even devoid of typical alloying elements, particularly tin and lead; thus, the presence of a whole range of potential alloying metals in these slags points to the processing of an existing alloy, possibly for recycling, rather than primary smelting of copper. Importantly, the quantified values for metal concentrations such as lead, tin, zinc and copper in the slag or crucible remains cannot be taken as representative of the actual alloy worked in these vessels; the differential preferred oxidation of most alloying elements (lead, tin and zinc) compared to copper enriches these in the slag, while the actual alloy was most likely vastly dominated by copper. As the more noble/less reactive metal, it simply did not oxidise sufficiently to be fully represented in the slag (Kearns et al., 2010, and literature therein). Thus, it is possible to state that these crucibles were most likely used to process a leaded tin bronze, with minor amounts of zinc and arsenic, but nothing beyond this.

There is significant variation in the compositional data of the Kunal copper slags determined using SEM-EDX and XRF, respectively (Kanth et al., 2022). For example, manganese is analysed by XRF but missing in the SEM-EDS data, and the reported values for silicon vary widely between the two methods. Furthermore, the XRD identification of calcite in the granulated slag, confirmed by their very high CaO content in the SEM-EDS data, indicates post-depositional contamination, since calcite is in itself not a high-temperature slag phase. Accordingly, the reported high calcium oxide values are probably not representative of the original slag melt. This study highlights the importance of complementary methods generating interoperable data sets, and the necessity to differentiate between the composition of the original alloys or raw materials, the slags derived from their working, and common post-depositional changes in composition when 'reverse engineering' the original activity of the craftsmen. Overall, based on the data generated in the study, the glassy slag appears to be slag from vitrified ceramic and re-melting leaded tin bronze, with the alloying elements burning out and fusing with the ceramic and fuel ash to form slag. A few SEM-BSE images and phase analyses would add further information to this interesting material. The analyses of prills from the slag, mentioned by the authors to occur across the sample, and images of the tin oxide phases would have been particularly helpful in determining the exact nature of the slag.

Another crucial bronze smelting evidence emerged from Kalyadi in Karnataka (Srinivasan, 1997), where large pieces of slag and abundant tuyère fragments were dated to the late centuries BCE to early centuries CE (Shankar, 1986). In a potentially revolutionary insight in Indian archaeometallurgy, the slags seem to result from primary bronze smelting rather than the commonly practiced alloying of copper and tin, or simple bronze casting. The metal prills are reported to consist of 5 wt % tin and 63–72 wt% copper, with traces of iron, which would typically result from co-smelting or reduction of copper and tin ores; the balance is likely due to corrosion. Such low-tin bronzes have been linked elsewhere to the direct smelting of bronze (Radivojević et al., 2013); the presence of tin in local sources, including Karnataka's alluvial deposits, further supports this interpretation (Srinivasan, 1997). The micrographs of slags showed fayalite lathes with dendritic iron oxide, metallic iron and bronze prills; the first three of these crystal species are all consistent with primary smelting. The presence of tin is remarkable, as it rarely occurs in primary smelting slags; its presence here is therefore highly interesting. Quantitative bulk compositions of the slags would aid in understanding of the production, particularly for a better characterisation of the ore smelted based on gangue components such as quartz, barite, fluorite etc. (see e.g., Tylecote et al., 1989; Chirikure et al., 2010; Berger et al., 2022).

A significant new discovery are several vitrified crucibles excavated at Khanak (Singh et al., 2016; Singh and Singh, 2016) near Tushan/Tosham in Haryana, a potential tin source for ancient India (Murthy and Nagesh Rao, 1990; Kochhar et al., 1999). From the photographs published (Singh et al., 2016: 1–23) we think the crucibles appear to have a diameter of around 3 cm and wall thickness of a little over 1 cm, with quartz inclusions in the ceramic. The images show potential multilayering of low fired clay, potentially indicating repair and reuse. Some slag formation is seen on the inside of the crucible but their heating mode remains to be determined. The slags were dated to the Mature Harappan phase, whereas the crucibles were from both Early and Mature Harappan phases. From the data in Singh and Singh (2016), we see the slags to be very high in tin, high in potash and low in iron oxide, with no calcium oxide reported. The total alkali content is unusually high for slags but still too low for it to be any glass-related production. Slag compositions resemble molten ceramic rather than smelting slags, while the high tin content, the absence of cuprite and the low content of lead indicates potential melting (or smelting?) of metallic tin. However, it must be noted that the strong spectral line L_β of tin is at 3.663 keV, whereas the calcium K_α line is at 3.690 keV, leading to potential mis-interpretations due to this line overlap. Thus, the very high apparent tin oxide content could be due to a peak overlap with calcium, the concentration of which is not reported.

Apart from Haryana, cassiterite ore has been reported from a large number of sites from Hazaribagh, Ranchi and Gaya in the eastern states of Jharkhand and Bihar. Tin smelting was practiced in Bihar up until 1849 (Brown and Dey, 1955: 167; Bharadwaj, 1979: 95). In Bihar, Jharkhand and West Bengal a large number of copper hoard objects have emerged but little work has been done to catalogue them (Chattopadhyay, 2004: 74). Copper smelting was also reported from Darjeeling and Jalpaiguri in West Bengal, and lead-silver smelting in Jharkand and iron smelting in several parts of eastern India (Chattopadhyay, 2004: 21).

2.4.2. Zinc and brass, lead-silver and copper

A review of early metal production in India would be impossible without covering the seminal work in Rajasthan on zinc distillation and silver production, conducted over more than three decades by scholars from the British Museum, Hindustan Zinc Limited and the Department of Archaeology, Maharaja Sayajirao University, Baroda in Vadodara, Gujarat (Mookherjee, 1964; Craddock et al. 1983, 1985, 1989, 2013; Freestone et al. 1985, 1986, 1991; Hegde, 1989; Gandhi et al., 1984; Craddock, 2017). Zawar stands as the world's oldest known production site for metallic zinc through distillation, predating regular zinc production in Europe by around half a millennium, and even the earliest Chinese evidence (Zhou et al., 2012) by several centuries. The robust metallurgical investigations at Zawar, Agucha, and Dariba reveal an advanced understanding of smelting technologies and highlight the ingenuity of metallurgical practices in pre-modern India. These collaborative and interdisciplinary studies, combining detailed archaeological and analytical approaches, provide insights into the processes used for extracting zinc, lead, silver, and copper, showcasing the technological capabilities of dealing also with complex ore bodies. Zinc production is attested mostly through distillation retorts and the scoria in them, left behind from the charge after extraction of the zinc. In contrast, the slags from all three sites relate either to lead-silver smelting or copper production as well as some iron smelting, reflecting the polymetallic nature of the ore.

From the sixteen slag deposits recorded at Zawar alone, slag samples were analysed using AAS and ICP, leading to classification of slags based on their iron oxide content – group I and II (Freestone et al., 1991: 620). The group I slags are linked to earlier production (1st cent BCE to 1st century CE) with more indigenous ore-specific smelting methods; whereas group II slags relate to later periods (6th – 7th century onwards, post 15th century), and are dominated by fayalite (for chronology see: Craddock et al., 1998, see Figs. 3 and 4). The group II slags are characterised by low zinc oxide content; as the iron oxide increases, zinc oxide and to some extent lead oxide drop significantly. This could be due to a more efficient metal extraction, or higher operating temperatures leading to higher evaporation of zinc, or a different charge composition when zinc oxide was removed from the ore to be used separately for zinc smelting by distillation. The earlier furnace slags from Zawar are characterised by high concentrations of MgO and CaO, which drop a little in the later period Zawar slags, whereas in Agucha and Dariba slags they show little variability. The Agucha slags have twice the alumina content of Zawar and Dariba slags, indicating a possible furnace wall contribution. The Dariba slags range from lead-silver smelting, copper and iron smelting, with on average 25 wt% FeO in lead-silver and copper slags, and twice as much in iron smelting slags. The Dariba copper and lead-silver smelting slags can be easily distinguished from binary composition plot between ZnO, BaO and PbO versus MgO, reflecting different ore charges (see Figs. 3 and 4).

The lead-silver smelting slags in Dariba and Agucha contain numerous unreacted residual host rock inclusions such as quartz and phyllite, despite which the authors stress the good separation of liquid lead metal from the slag. While the copper slag system from Dariba is a fully molten system, it is interesting to see that for the more valuable silver production, the craftsmen did not aim for a fully molten slag (Craddock, 2017), even though it is commonly believed that the metal yield increases with a fully molten slag over a partially molten slag. Slags rich in unreacted quartz and rock inclusions are also known in European lead-silver (e.g., Kassianidou, 1992) and copper production (e.g., Pearce et al., 2022; Hauptmann et al., 2022). Beyond silver, lead, copper and zinc, there are also potential hints on bronze working at Dariba, and good potential for exploring brass making in Zawar owing to the presence of zinc rich crusts (Craddock, 2017). For Agucha and Dariba, SEM-EDS quantification of the melt phase of slags alone could give data more suitable for ternary projection, given that the slag contains numerous quartz and host rock inclusions.

2.4.3. Technical insights in iron and steel production

a. Iron

The surviving remains of pre-industrial metallurgy in India are dominated by iron production remains, based on direct smelting of ore to form a bloom which is then processed into iron bars and artefacts. The literature on Indian iron is exhaustive and cannot be possibly covered here in full. Therefore, the focus is on studies that provide compositions of iron production remains and not the metal itself. The earliest iron production in India dates to around 1200 BCE and is understood to have evolved independently in various parts of the country.[5] Steel samples dating to the early centuries CE have been recorded from many archaeological sites in southern India. These samples contained a noticeable carbon content, but carbon was not homogeneously distributed (Sasisekaran and Rao, 2001; Park and Shinde, 2013). The metal is consistent with being bloomery iron and therefore should be referred to as case carburised, where a high carbon rim is formed, or a steely bloom smelted with an irregular carbon content.

The Central Himalayan regions, as well as southern and eastern India, i.e. largely the peninsular regions, show some of the earliest iron production evidence. Extensive reviews on Indian iron highlight regional variation of iron smelting, of cultural contexts of the craftsmen and the processing of the bloom, with ongoing indigenous activity up until the 19th century (Hegde, 1973; Chakrabarti, 1976; Bharadwaj, 1979; Biswas, 1994; Prakash, 2001, 2011; Banerjee, 1965; Tripathi, 2001; Agrawal, 1999; Chattopadhyay, 2004 etc.) Notable archaeological evidence includes the site of Naikund in Maharashtra, where an excavated iron smelting furnace was built by a coiling technique, about 25 cm high with an internal diameter of roughly 30 cm. Two tuyères associated with forced air-blowing (likely via bellows) were found in situ, alongside approximately 40 kg of slag (Deo and Jamkhedkar, 1982; Gogte et al., 1982). Experimental estimates suggested 10–12 kg of iron ore yielded around 3–4.2 kg of useable iron. The ore source, a micaceous hematite quartzite with associated manganese deposits, was located within the proximity of the smelting site, highlighting Naikund's strategic position for both production and regional distribution. More recent analyses from the region are presented in Park and Shinde (2013) and Deshpande et al. (2011). Production evidence of iron smelting from Karnataka (Anantharamu et al., 1999; Buchanan, 1807) is extensive but so far without systematic technical investigation.

Recently, new iron production evidence has emerged from Kerala, found around cist burials (Ambily et al., 2021) and in Wui, Nagaland (Tzudir et al., 2019). The state of Orissa and Chhattisgarh boasts a large number of iron smelting remains with cultural context and smelting continuity up until the 19th century (Tripathy and Garnayak, 2023; Mohanta, 2016; Prakash, 2001) which includes furnace remains, tuyères, metallic iron and slags. More production remains come from Maski in Karnataka (Johansen, 2014) where old furnaces and slags were recovered in great quantities, and from various parts of Tamil Nadu (Rajan 1996; Sasisekaran & Rao, 1999, 2001). In southern India, iron smelting sites can be closely linked to crucible steel production sites (see below); such cases are observed significantly in Telangana, Tamil Nadu, and to some extent in Karnataka. One example is the recently discovered archaeological evidence for both bloomery iron production and crucibles from Kanchipuram district in southern India (Pisipaty, 2018). These crucibles were found together with the slags; however, it remains to be seen whether they are remains of crucible steel production (see below). While iron production evidence keeps emerging, similar to copper, more iron artefacts have been analysed compared to the production waste.

During the analysis of bloomery slags, for the first time evidence of discrete pieces of bloomery cast iron emerged in Telangana (Desai, 2023), whereas evidence for cast iron fragments was already known from Guttur in Tamil Nadu (Sasisekaran and Rao, 2001).[6] It is widely accepted that cast iron can be produced at least accidently in bloomery iron furnaces, but more evidence is needed to call it an intentional utilitarian or large-scale production.

Nearly all analysed slags are low in MnO values, but slags from Dhatwa in western India and a few sites in West Bengal, eastern India show 2–3 wt% MnO, indicating the use of a different ore type. Apart from the one silica-rich sample, all iron slags fall near the so-called Optimum 2 on the FeO-rich end of the compositional range; only two samples fall into the FeO-poor Optimum 1 (Fig. 5; Rehren et al., 2007, Table 2).

Bloomery iron slags from Telangana in south-central India show less variability in FeO content and a strong compositional overlap of slags from various sites, mostly within the fayalitic core region of bloomery iron slags (Fig. 6). Lime, alumina and titania showed the highest variability among the slags. Titania is either extremely low (0.1–0.7 wt%) in some slags, whereas between 1 and 2.9 wt% in more than half of the

[5] A recent publication claiming even earlier iron use in Tamil Nadu is based on artefacts, not on production evidence, and is therefore not covered here.

[6] Microscopic cast iron prills have been observed previously in a variety of metallurgical remains, often highly enriched in phosphorus (e.g., Srinivasan et al. 2011); these are typically related to fuel ash slags and unrelated to the actual metallurgical process (see e.g. Desai et al., 2023a).

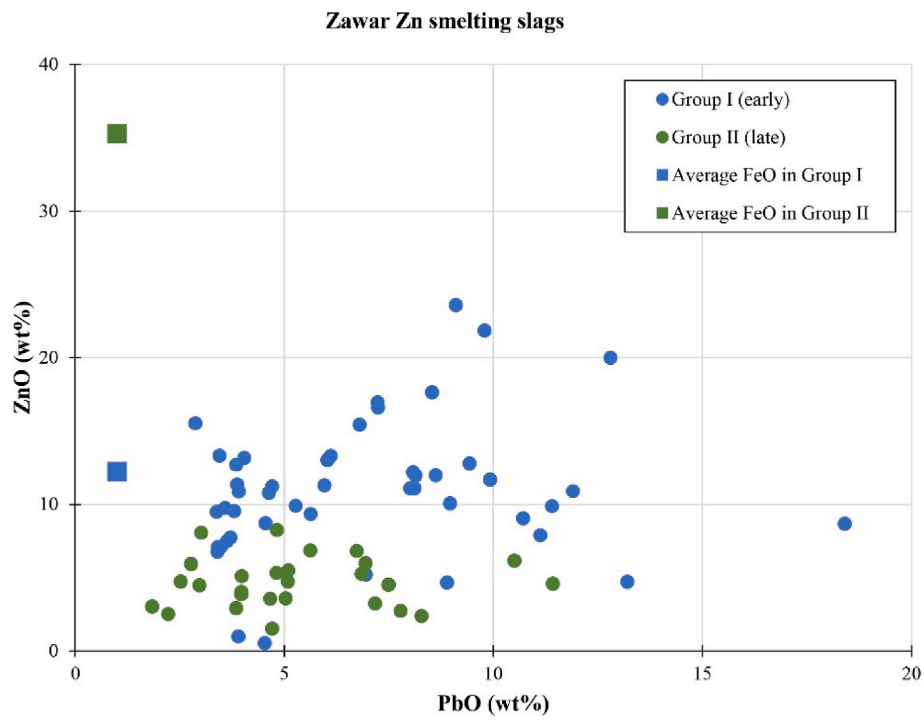

Fig. 3. Graph of Zawar zinc smelting slags from early historical and late medieval production along with their average FeO content. The data published in Freestone et al., (1991); Craddock (2017) illustrate the two types of slags at Zawar, with some overlap. The Group I or early slags likely formed from smelting roasted mixed sphalerite/galena ore to produce zinc oxide at lower temperatures. Higher ZnO and PbO contents in Group I correspond to lower iron oxide content in slags; in contrast with Group II slags (Freestone, 1989; Craddock, 2017 quantified by AAS and ICP-MS).

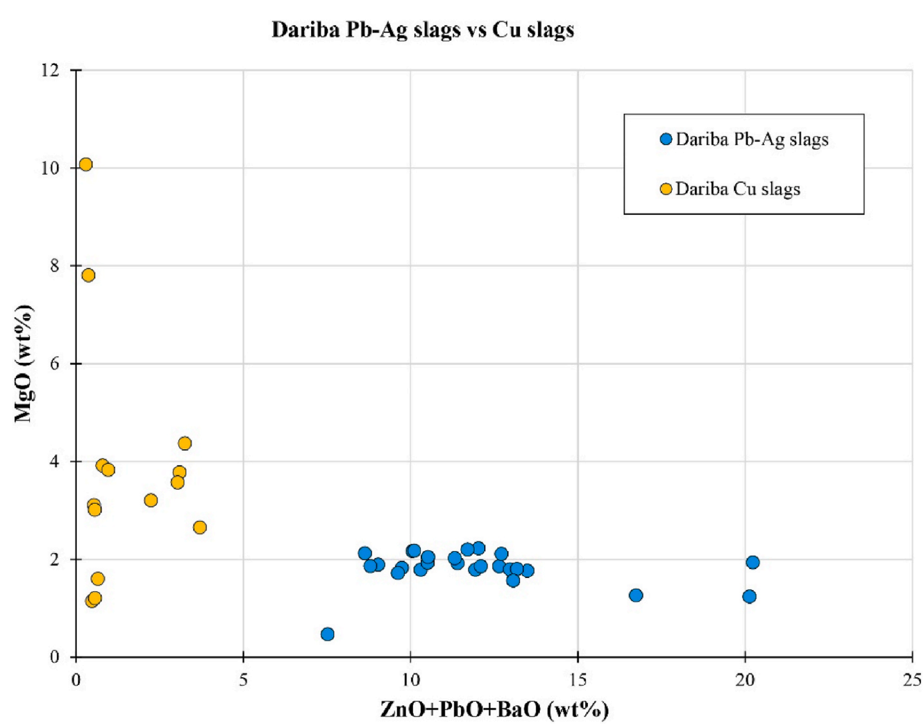

Fig. 4. The two types of slags from Dariba are clearly separated by their composition. Data from Craddock et al. (2013) and Craddock (2017) analysed by ICP-AES. The copper slag has high MgO and low metal oxides, whereas the lead-silver slag has high metal oxide and low MgO slags. The MgO in copper slag can be derived from ore or a fuel ash addition and has a negative correlation with other metal oxides.

analysed samples. Fayalite phase morphology ranged from euhedral to feathery to skeletal and acicular, indicating varying cooling conditions. Alumina-rich slags, with alumina roughly around 8 wt% and above, have alumina-rich phases such as hercynite or leucite or both. Ulvöspinel grows in slags with higher titania content, i.e. circa 1 wt% and above, likely indicating the use of magnetite ore (Ige and Rehren, 2003). However, only a handful of iron smelting slags were studied from Telangana's vast landscape (Desai, 2023). The sample size was

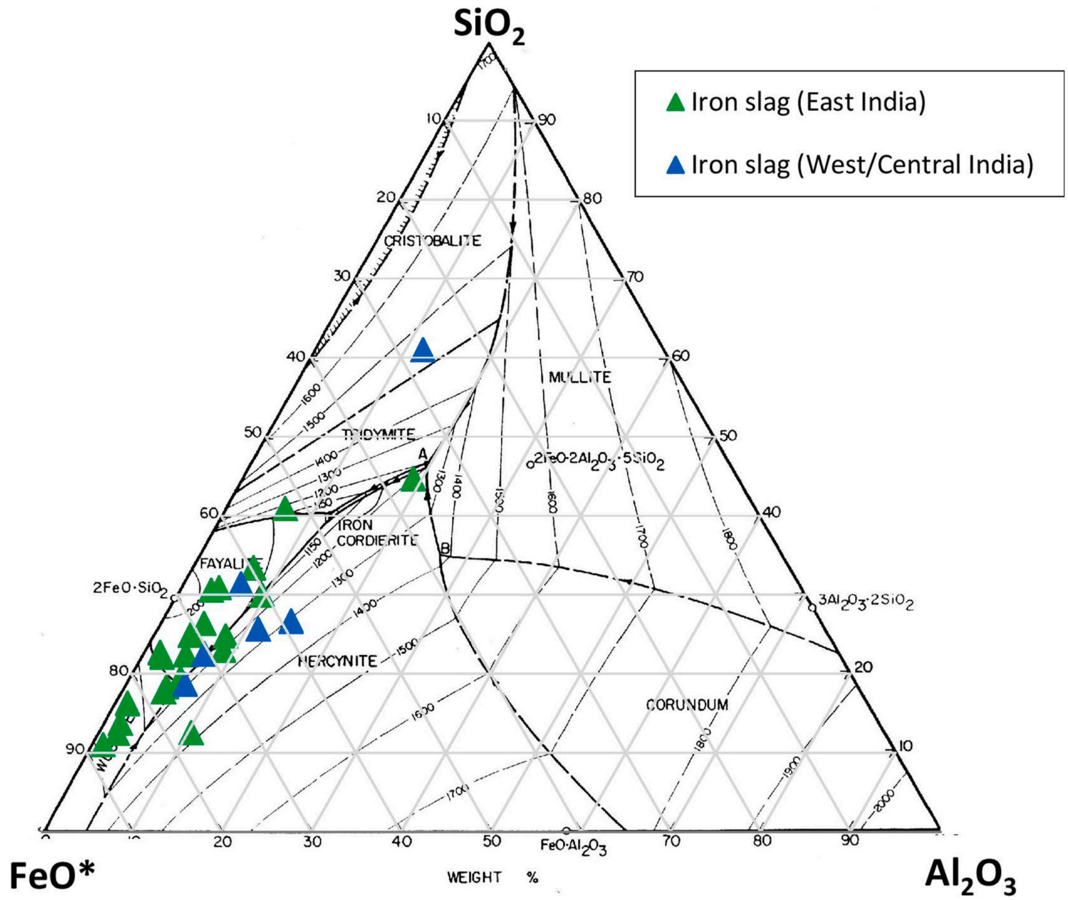

Fig. 5. Iron slags from eastern and western parts of India (see appendix Table 2), from compositional analyses in Chattopadhay (2004: 64–101), Hegde (1991: 46); Bharadwaj (1979: 148); Singh (2004: 600); Gogte et al. (1982) and Mohanta (2016: 81–108). The iron oxide corner contains also CaO and MgO, the silica corner includes titania values, and the alumina corner includes potash values, where reported.

insufficient for grouping or identifying regional variability of raw materials; to the contrary, the data plot into a much more restricted area of the ternary diagram (Fig. 6) than the slags summarised before (Fig. 5). At this stage of the research it is difficult to reconstruct the entire production picture with such limited data, but when blended with oral history through interviews of surviving iron smelters by Jaikishan (2007) and Jaikishan and Balasubramaniam (2007b), the accounts closely matched the analytical observations.

b. Crucible steel production

One of the major marvels of Indian archaeometallurgy is the widespread and large-scale production of crucible steel, known also as wootz, throughout central (Jaikishan, 2007; Jaikishan and Balasubramaniam, 2007a, 2007b); and southern (Srinivasan, 1994; Srinivasan et al., 2009) India. For centuries, its production has attracted the attention of international travellers and scientists (Tavernier, 1676; Mushet, 1805; Voysey, 1832; Lowe, 1995), and to this day provides fertile ground for research (Desai et al., 2023b). Its prominence in the literature and perception on Indian archaeometallurgy allows us to only briefly summarise here the key features of this technologically and economically important industry, while referring the reader to recent more detailed accounts elsewhere (e.g., Bronson, 1986; Craddock, 1998; Srinivasan and Ranganathan, 2004; Jaikishan et al., 2021).

The essence of crucible steel production is the addition of carbon, typically as organic matter, to bloomery iron fragments in closed crucibles. The process leaves very little slag but huge amounts of crucible fragments, discarded once they were broken open to retrieve the wootz ingot. The crucibles are made from local kaolinitic ferruginous clay, heavily tempered with rice husk which further improves the reducing conditions within the crucible (Lowe, 1989) and the refractory properties of the ceramic itself (Freestone and Tite, 1986). What small amount of crucible slag has formed in the process is typically attached to the crucible fragments as a characteristic slag 'fin' (Fig. 7); additionally, lumps of green-glassy fuel ash slag indicate the vast amounts of fuel that would have been needed to operate the furnaces. Crucible steel production is documented across entire landscapes where it forms the backbone of an export-oriented but village-based industry, as for instance in northern Telangana (Jaikishan, 2007). The wide variety of archaeologically documented crucible shapes and sizes, and the dispersed production units allow for a customisation of wootz ingots to suit individual consumers' needs as well as the large-scale production of standardised ingots for international trade (Desai, 2023).

Technologically, there are two main themes; one concerns the actual steel-making process, and the other the preparation of the necessary highly refractory crucibles. The two main steel-making processes being discussed include either carburisation of bloomery iron using organic matter, or the co-fusion of bloomery iron with no or very little carbon with cast iron with up to 4 wt% carbon to obtain crucible steel with around 2 wt% carbon. Written sources are somewhat ambiguous and can be read either way, while direct evidence for cast iron production in India is lacking. There is a possible use of so-called 'crown' material, that is carbon-rich iron formed as a by-product of bloomery iron smelting, as a source for cast iron (Desai, 2023); however, this is unlikely to have been sufficient to sustain a large-scale production, and more research is needed to explore this hypothesis further.

The extraordinarily refractory quality of the crucible bodies, suitable to withstand temperatures in excess of 1400 °C, is due to a combination

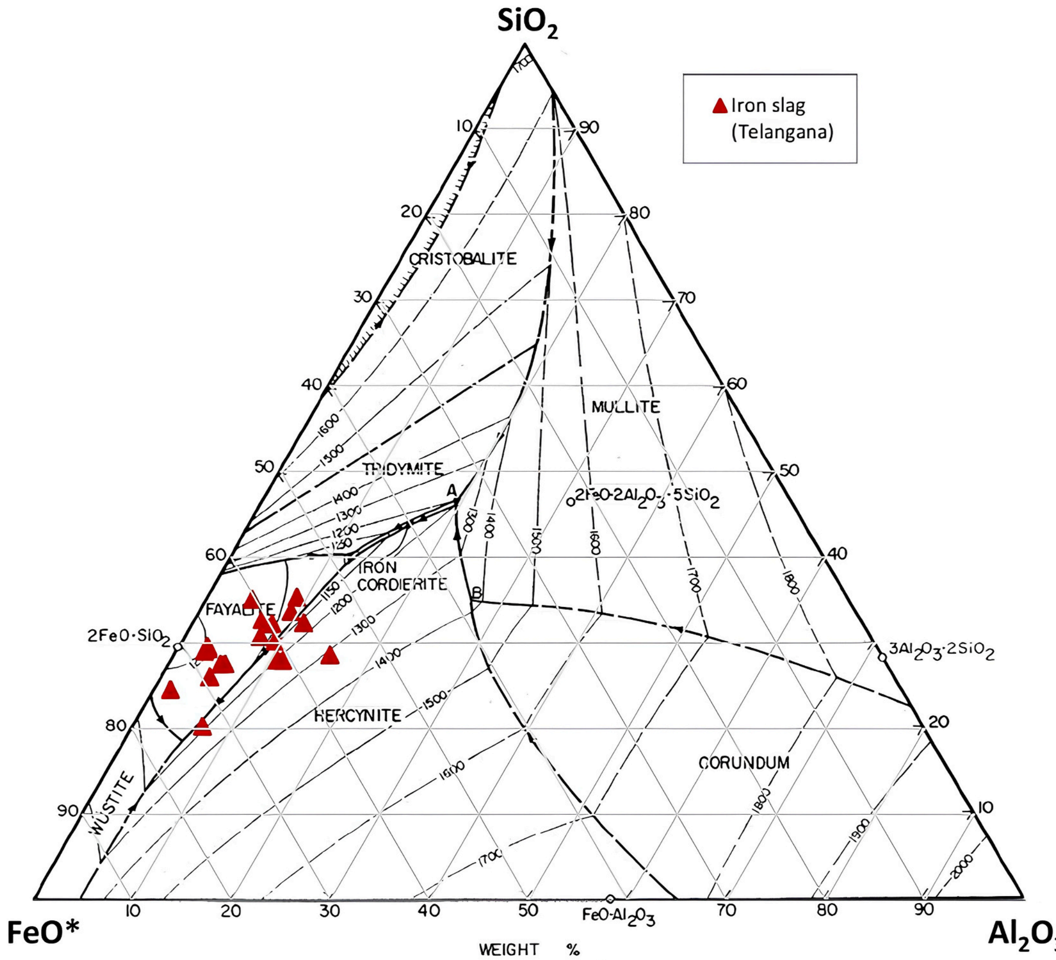

Fig. 6. The majority of the Telangana iron smelting slags (data from Desai, 2023) plot in the core fayalitic region of the FeO – Al_2O_3 – SiO_2 phase diagram. Alumina-rich slags plot in higher temperature range up to nominally 1300 °C into the hercynite phase region, to the right of the fayalite-hercynite eutectic trough.

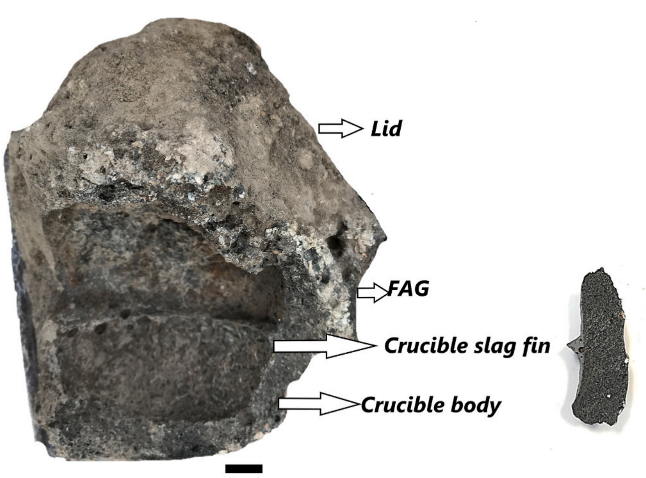

Fig. 7. Typical slag 'fin' in steel-making crucibles from Telangana; front view of the inside (left), cross section (right). The steel ingot solidified in the open space below this slag fin.

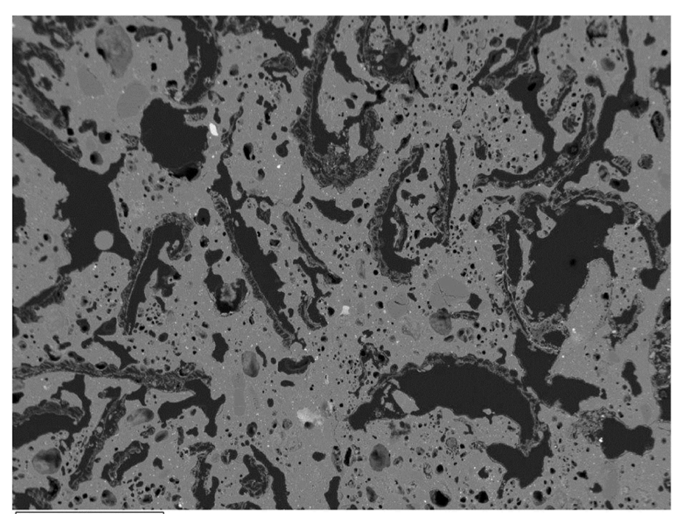

Fig. 8. BSE image of Ind-Gur'19-cru001b at 200x body with disintegrated organic temper, likely rice husk, with basket weave pattern, metallic iron prills and other gas related porosities in a highly vitrified matrix.

of carefully selected clay rich in alumina and tempering with rice husk which under the conditions in the furnace reduces the iron oxide in the clay to iron metal prills, thereby depriving it of the fluxing effect on the siliceous ceramic (Fig. 8; see also: Freestone and Tite, 1986).

Despite the long-standing and wide-ranging research on Indian crucible steel production there are still major research questions to be addressed. The work in Telangana has shown the potential and merit of systematic regional surveys, combining archaeological field evidence with oral history and ethnographic studies (Jaikishan and Balasubramaniam, 2007b; Juleff et al., 2011; Neogi, 2017). Similar large-scale studies in Karnataka, Kerala and Tamil Nadu are likely to reveal further cultural and technological detail and variation in Indian crucible steel production, including identifying a better chronological grasp on the introduction, spread and decline of this emblematic industry.

Generally, the fabrics of the crucible fragments from all the mentioned sites, including Tintani, Machnur, and Kodumanal, visually resemble those of the Mel-Siruvalur (Tamil Nadu), Ghattihosahalli (Karnataka) and Telangana crucibles, being composed of a very black refractory material formed under highly reducing firing conditions. The crucibles have inclusions of white quartz only in the blackish exterior glaze, while the bodies are porous and rich in carbon (Freestone and Tite, 1986; Anantharamu et al., 1999; Craddock, 1998; Lowe, 1990; Balasubramaniam et al., 2007; Juleff et al., 2011; Girbal, 2017). The Kodumanal crucibles, however, were more friable with a thinner black exterior glaze, a characteristic that may be attributed to weathering, given that it came from an early context (Rajan 1996). It should be noted that only 1–2 crucibles from Kodumanal were examined, making the findings preliminary. On the other hand, Tintani and Manchur are close to copper sources and show some copper-related production material (Srinivasan and Griffiths, 1997). In-depth analyses may help in classifying these crucibles. While the Telangana crucibles are thought to be hand-formed (Jaikishan, 2007), the Tintani and Ghattihosahalli crucibles have concentric ridges on fragments suggesting they were wheel-turned (Srinivasan and Griffiths, 1997). Crucible fragments from Tintani, Machnur, and Ghattihosahalli showed diagnostic glassy slag fins along the midsection accompanied by a characteristic honeycomb pattern in the lower half, linking them to crucible steel production (see Fig. 7). Also, the base fragments from Tintani and Machnur displayed prominent black slag linings with the honeycomb pattern and a thick exterior glaze (Srinivasan and Griffiths, 1997).

Comparing the collected evidence, it becomes apparent that the Indian archaeometallurgical record regularly shows specialised high-performance ceramic crucibles for high temperature productions. These crucibles can withstand temperatures exceeding 1400 °C (Fig. 9) without cracking or other deformation. Similarities in crucible making can be seen across all high temperature production sites, whether in Rajasthan, Telangana, Karnataka (see appendix Table 2), or Tamil Nadu. The craftsmen, though spatially separated from each other, show remarkably similar practices of manipulating clays to make thermally resistant crucibles. These studies and finds confirm a pan-Indian tradition of the use of crucible-related technologies with similar understanding of temper, whether it is organic, grog or quartz-based, manipulating ferruginous clay for high temperature production and use of specialised ceramics made by the metal craftsmen. The vegetal temper could range from rice, straws, etc., and the vessels were hand- or wheel-moulded (Srinivasan and Griffiths, 1997; Anantharamu et al., 1999). Most crucibles contained quartz tempering or were made of coarse clay. If the crucibles are made from ferruginous clay and tempered with

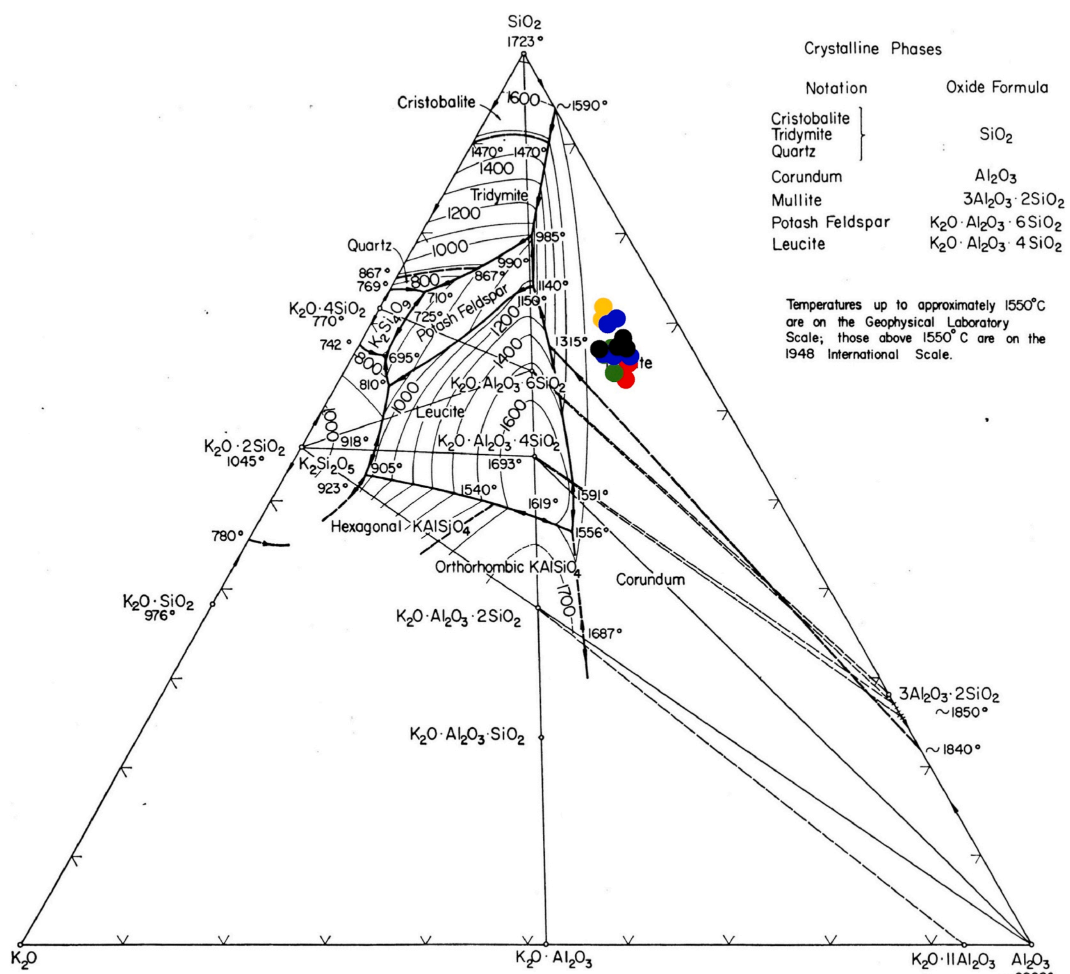

Fig. 9. Projection of crucible steel-making crucible ceramic compositions onto the phase diagram K_2O – Al_2O_3 – SiO_2. The compositions fall into a very high-temperature field, exceeding nominal melting temperatures of 1600 °C. The different colours represent different sites across northern Telangana; note their close compositional similarity. The K_2O* vector combines the sum of Na_2O, K_2O, MgO and CaO. Data of Telangana crucible bodies analysed using SEM-EDS. From Desai (2023).

organic material, they can be fired under reducing conditions at high temperatures without any detrimental role of iron oxide, which is reduced to form metallic iron preventing the crucible from collapsing (Freestone and Tite, 1986).

3. Refining, remelting, casting: technical ceramics

The archaeological evidence for casting operations in India presents considerable interpretative challenges. While numerous Harappan urban sites have yielded metallurgical remains such as furnaces, slags, and vitrified ceramics, these are thought to be more closely associated with casting and other metalworking activities rather than primary smelting (Kenoyer and Miller, 1999; Agrawal, 2000: 37–47). Notably, mould materials are largely absent, with crucible fragments forming the primary evidence for such activities (Agrawal, 2000: 39–40). Casting crucibles have been extensively documented across South Asia, including from sites such as Dariba, Rajasthan, a prominent Mauryan silver-smelting site (Craddock et al., 2013). Analysis of these crucibles revealed traces of copper and tin on vitrified surfaces that had come into contact with molten metal. Despite Dariba's primary exploitation for lead and silver, the absence of tin in the local ore deposits suggests that the crucibles were used for secondary melting and casting operations involving imported bronze. Many of the crucibles were large, with one intact example having a capacity of approximately 150 cm^3, sufficient to hold about 1.2 kg of copper alloy. Vitrification was most intense on the outer convex surfaces, indicating externally fired crucibles resulting in formation of a fuel-ash glaze from the interaction between fuel ash and crucible. The crucibles also featured pronounced nipples on their bases, likely to elevate them above the charcoal—a design characteristic consistent with other early Indian crucibles, such as those found at Chandraketugarh, West Bengal, dating to the 2nd century BCE–2nd century CE (Chattopadhyay, 2004: 143).

In West Bengal, the site of Dihar, which spans the Late Chalcolithic to the Early Historical period, provides further evidence of large-scale metallurgical activity. Excavations uncovered burnt earth patches, slag deposits, copper and iron objects, and thick ashy layers, suggesting intensive firing processes within a large workshop. Deeper in the stratigraphy, broken crucibles and hearth remains were found coated with smelted metal and slag, identified as iron slag. The excavation reports suggest the use of handmade crucibles with sand and cow dung temper. Published images suggest external vitrification and internal melt formation, indicating external firing, while their internal curvature likely facilitated the collection of molten metal (Chattopadhyay et al., 2014). Tilpi, in southern West Bengal was excavated to yield a furnace and eight metal smelting/melting hearths among other finds, such as slag, a metal ingot (or casting waste?) and broken crucible fragments. The SEM-EDS data of the cleaned as-cast metallic lump shows it to be composed of around 24 wt% tin and 76 wt% copper. However, we think the unusually high tin content and the corresponding low copper content is strong indication of corrosion of the object, during which copper was selectively removed. If this were the case, the original values for tin could be lower and higher for copper. The slag from Tipli qualitatively analysed by XRD shows iron oxide, siliceous compounds, ilmenite, sodium-rich felspar etc. Based on the XRD analyses it is difficult to identify it as iron or copper smelting or working slag (Datta et al., 2008). The external shape of the Tilpi crucible is similar to those found in contemporary Senuwar, Bihar in Kushana Period, during the 1st-3rd century CE (Datta et al., 2008).

At Dhulikatta, an Early Historical site in south-central India, a crucible measuring 15 cm in diameter was recovered. It was encrusted with charred wood, leafy material, and mud, with a well-burnt terracotta cake adhered to its concave surface. The internal and external incrustations suggest exposure to intense heat under a substantial pile of wood. Nearby, a square cake containing a solid iron core overlaid with quartz crystals and burnt clay was discovered, offering evidence of domestic-scale iron and steel production (Krishna Sastry, 1983: 153–154). If the discovery from Dhulikatta is indeed a steel-producing crucible, it can potentially push back the chronology for crucible steel production in Telangana by several centuries.

Further south, a single crucible was also uncovered at Idukki in Kerala, a Megalithic/Early Historical site. This handmade crucible had a cup-shaped base and weighed 206.5 g, with a rim diameter of 7.4 cm and a height of 6.5 cm. Thumb impressions on its surface indicate manual shaping. While the external surface exhibited a thin red clay coating with no vitrification, the blackened internal surface displayed signs of thermal alteration. Quartz inclusions are visible in the published images (Sandra et al., 2017). Although the crucible is well-preserved for its age, limited contextual information raises caution in definitively associating it with metallurgical activity.

Together, these findings highlight the diversity of metallurgical practices across India, reflecting variations in crucible design, materials, and production techniques that evolved over time and across regions. Similarly, they constitute an area of huge untapped research potential, given the rich cultural and technological diversity of crucible processes (Bayley and Rehren, 2007).

4. New trends and road forward

Numerous studies (Hegde, 1973, 1991; Bharadwaj, 1979; Anantharamu et al., 1999; Chattopadhyay, 2004; Craddock, 2017; Jaikishan, 2005; Girbal, 2017; Neogi, 2017) have shown considerable success in applying the *chaîne opératoire* concept to the study of ancient metallurgical activities (Schlanger and Sinclair, 1990; Martinón-Torres, 2002: 30) and reverse engineering approaches in Indian archaeometallurgy, including both tangible and intangible elements. These studies gave, just to mention some examples, a significant push to a holistic understanding of copper and iron production at Ahar and elsewhere in western India, Dhatwa iron production, crucible steel production at Ghattihosahalli and in northern Telangana, iron and copper production in eastern India, and zinc and lead-silver production at Zawar. These production reconstructions, which include determination of standardisation, choice of clay and temper, smelting conditions, ore exploitation, product manufacture and use are possible only in sites with large number of finds, and comprehensive analytical programmes. For sites that show single crucibles or a few slags, it is difficult to construct a concrete narrative and research can only show some temporal production evidence.

Overall, this review has shown the long tradition of cutting-edge archaeometallurgical research being conducted within Indian scholarly institutions. During the past few decades, research in Indian archaeometallurgical production has significantly gained momentum and increased archaeological excavations have now shown unexpected finds, such as availability of tin before the 6th century BCE (Upadhyay, 2015) with tin smelting crucibles and bronze-related slags reported from Haryana; previously, tin was thought to be imported from south-east Asia or from Afghanistan (SanaUllah, 1940: 379). Much of this work has been published in well-established Indian journals and a multitude of edited and single-authored books; unfortunately, this limits to some extent the international visibility of this research. A recent study looked at the relationship between papers published in the *Journal of Archaeological Science* discussing material from any given country and the proportion of lead authors for those papers that are based in that country (Rehren, 2025). This study found India with 42 published papers in *JAS*, of which only 10 were first-authored by scholars based in India – placing the country at the lower end of this measure compared to many other countries (Rehren, 2025, Fig. 5). However, as our review has shown, this is a misleading representation of the actual research activity taking place in India, and dedicated research centres such as the National Institute for Advanced Studies in Bengaluru, or several of the prestigious Indian Institutes of Technology, provide fertile ground for research that would deserve to be published internationally. A full bibliometric study of archaeological science research in India is beyond the scope of this review; however, there is clear qualitative evidence for an increasing trend of Indian scholars publishing internationally, and the following paragraphs address research areas that would all be of global relevance and interest.

The seminal work on Zawar-Dariba-Agucha has revealed large-scale evidence for medieval zinc production; further investigation is necessary to explore brass and bronze-related production evidence from these sites, which have all the necessary raw materials. Equally intriguing is the copper-zinc ore exploitation from Bandlamottu close to Agnigundala where the production evidence is rather limited (Heyne, 1814: 108, Ziauddin, 1961) but present, and clearly requires more investigation.

The attestation of a site with metallurgical finds to primary production needs convincing evidence of production debris. In the archaeological record, this is primarily slags, but also remains of ore mining and beneficiation, furnace installations, charcoal pits, and even the associated infrastructure to transport goods in and out in the often-significant quantities required. Particularly in later periods, mining and smelting are often large-scale industries requiring huge numbers of full-time skilled and unskilled workers, leading to the establishment of whole mining-metallurgical landscapes and settlements. An example of such a landscape is the major zinc-producing region in Rajasthan which has attracted research for nearly half a century (Freestone et al., 1986; Craddock et al., 1989; Hegde, 1989 etc.); another one is the crucible steel production landscape in northern Telangana (Jaikishan, 2005, 2007; Juleff et al., 2011). Equally true is the notion that not all sites are as well-studied and richly presented. Environmental and anthropogenic factors often disperse, dilute and destroy the production debris, through reuse as reinforcements or succumbing to modern construction projects, levelling for agriculture or burying through urban developments, as seen very clearly in Telangana where previously huge crucible and slag heaps go missing, buried under roads or otherwise moved and scattered beyond recognition in a span of two decades. There is clearly a sense of urgency in documenting and studying the rich archaeometallurgical heritage of India before the rapid development of the country obliterates it even further.

A remarkable outcome of the compilation by Grover (2004) is the ubiquity of ancient slag heaps across the entire metalliferous landscape of Gujarat and Rajasthan, demonstrating the sheer intensity of past metallurgical activity which is barely documented and even less understood in its technological and cultural detail. The mineralogical and compositional information available shows that iron and copper smelting followed similar principles as in western Asia; however, there are also very interesting 'glassy' slags, probably linked to polymetallic ore exploitation. These are not well documented elsewhere, and bear a major research potential in their own right.

Parallel to copper and casting mould finds at sites such as Gilund, the use of bronze extended across the Harappan landscape all the way into peninsular India. Yet, evidence is limited for the primary production of copper anywhere in Harappa as well as peninsular India, or for the alloying of tin to copper. With the data from Kalyadi, we need to reconsider the possibility of bronze being smelted directly from copper and tin ores without the intermediary steps involving crucibles. The bronze slags from Kalyadi and further provenance of metal objects from southern India underline the need to look for homegrown sources of tin, which remains a lingering question in Indian antiquity. Similarly, old and new excavations from the Eastern part of the country continue to demonstrate strong high-tin bronze related evidence comparable to southern India. Further in peninsular India, data now supports high carbon steel production in Maharashtra and Karnataka as more slags and metal objects are brought to light.

For the time being, it will remain difficult to attempt any reconstructions of gold production (see Allchin, 1962 for gold exploitation in pre-industrial India), with just some possible furnace evidence from Inamgaon (Dhavalikar et al., 1988). An Indian description from the early fourteenth century CE mentions the occurrence of gold in miniature tin ingots, in *Dhatupatti* written by Thakkura Pheru, a medieval Indian treasury operator and then a mint governor. While the text throws no light on the source of the ingots, it opens the possibility that tin and gold were extracted from the same alluvial placer deposits (Dube, 2006). In addition to tin and gold from similar sources, the publication also shows the importance of historical literature in past reconstruction in addition to archaeomaterials research.

India has its own strong literary corpus of alchemical, scientific and metallurgical treatises. Several researchers have used pre-modern and imperial literary records in addition to or separately from archaeological and/or scientific approaches; this has considerable merit in building a holistic narrative of our past. Reporting and translating pre-modern and traditional recipes and incorporating them into building the archaeological science framework is another area of promising research opportunities.

5. Conclusion

More than for most other ancient technologies, laboratory-based analysis is indispensable for a proper understanding and interpretation of archaeometallurgical remains. A simple example is the field identification of slag; mostly, if chalcopyrite is used to smelt copper, the external appearance of iron and copper slags are very much alike and can be only differentiated analytically. Both slags appear in different shades of dark grey to black, with textures well-known from volcanic rocks and iron ores, making their visual identification often ambiguous. Even on initial mineralogical analysis the two metal slag types are very similar, as they are commonly dominated by olivine, mostly fayalite, and free iron oxide. Typically, as visible only in the optical or electron microscope, the formation of matte phases or copper prills is conclusive evidence pointing to the slag's origin from copper smelting. While the overall bulk content of copper can be low, concentrations in the range of 0.1–1 wt% copper are easily determined by common analytical methods, either in the laboratory or even in the field, using the increasingly common handheld XRF instruments. The lack of such basic identifications, however, severely limits the usefulness of any archaeometallurgical assessment, leading to scepticism among field archaeologists and accordingly of fewer samples being made available for instrumental analyses to facilitate technological and cultural studies. Hence, we are operating with only a miniscule fraction of the potentially available data for process reconstructions. This, then, can lead scholars to perceive metal production at a given site as a sporadic activity or even only a suggestive interpretation, when in fact it may have been a sustained, large-scale and complex industry, the study of which would reveal tremendous and often unparalleled insight into the technological skills, levels of organisation, and macro-economic contributions to the societal developments of the craftspeople who left these remains behind.

There is more information contained in the composition of smelting slag beyond the identification of the target metal of the operation. Similar to most magmatic systems, slags follow in their melt formation and crystallisation the predetermined layout of the relevant phase diagrams, particularly their liquidus surfaces. In archaeometallurgy, plotting slag and ceramic compositions into these diagrams is a powerful tool to determine aspects such as the influence of different raw materials to the melt formation process, the operating temperatures, saturation of the melt in particular oxides, and even aspects of furnace batch recipes and fuel to ore ratios (Rehren, 2000; Rehren et al., 2007). A combination of *chaîne opératoire* and reverse engineering approaches offers significant insights based on data from instrumental analyses, potentially complemented by historical texts (Martinón-Torres and Rehren, 2008).

Looking back at the archaeological evidence and critical assessment of the extensive literature on India's archaeometallurgy offered above, a few key points emerge. Firstly, the geological, geographical and ethnographic diversity of India is fully reflected in the richness and complexity of its archaeometallurgical heritage. Its evidence for the production of metallic zinc by downward distillation, the first known regular production of metallic zinc globally by about half a millennium, and of crucible steel making in a wide variety of shapes and sizes of ingots is unique and of global significance. Both technologies have inspired early modern entrepreneurs and scientists in the UK and elsewhere as part of the Industrial Revolution, and in particular crucible steel production continues to fascinate researchers and students alike today. The early metallurgy of the Indus Valley Civilisation is on a par with that of the other great river valley civilisations in Egypt and Mesopotamia, and faces similar challenges of an archaeology focussed more on urban elite centres than rural production sites; accordingly, metal artefacts from Harappan sites are well documented and understood, while the source of the metal remains enigmatic.

Besides these famous sites and regions there are literally countless equally important but less-well known sites with evidence for ancient metallurgy. A vast amount of scattered literature, spanning more than a century, demonstrates that the archaeometallurgy of India is a massive and fertile research field, and still with a huge and largely untapped potential to reveal the past skills and achievements of craftspeople, early metallurgists and the administrative and political elites organising and benefitting from these industries. The importance of metallurgy for cultural and economic development is beyond doubt, whether it is silver for economic development, bronze for religious and mundane artefacts, iron and steel for tools and weapons, of zinc, tin, brass and other metals for a plethora of every-day and specialist applications. Archaeometallurgy therefore is highly relevant for all archaeological research, once it plays to its full potential.

Unsurprisingly, the literature demonstrates that evidence for copper/bronze and iron/steel production is found all over India. Primary production is typically found near ore deposits, often away from urban settlements, while urban metallurgy is mostly secondary: casting and refining metal to produce finished objects. From what is visible today, the main technologies are similar to the metallurgical practice elsewhere; copper smelting based on chalcopyrite and bloomery iron smelting both operating in fayalitic slag systems. However, even from the data available so far, we can already see indications for regional diversity, with different chemical signatures for iron slags in their alumina or manganese content reflecting different ore types. Considering the geological diversity and the many different advanced cultures that evolved over several millennia in what is today's India, future work will surely reveal many more different smelting practices based on the detailed analysis of slags and furnace remains. Besides the choice of ores, ancient smelters would have taken decisions regarding the ore-to-fuel ratio, whether to supply air via bellows, natural draft, or other even more ingenious ways, such as in the wind-powered west-facing furnaces in neighbouring Sri Lanka (Juleff, 1996). Much remains to be discovered!

The literature review has identified a remarkable lack of studies of ancient copper smelting. The geology of India is rich in copper deposits, and throughout history, copper has been widely used. Thus, copper production in India must have been a major area of past technological achievements, cultural diversity and social complexity, one that remains almost completely unknown today. Similarly, there is a huge research potential related to tin and direct bronze smelting, for which we may just begin to see the first indications. Wide open questions concern the making of brass by cementation and/or by direct alloying; while brass objects are not uncommon particularly in the later periods, there is literally no published evidence for the making of this important alloy.

In the same vein, the use of silver for jewellery goes back right to the Harappan period, with major production of silver coins already during the 1st millennium BCE. Nothing, however, is known about the smelting of this silver (and lead, presumably), apart from the work in Zawar and Agucha reported above.

More fundamentally, our review has also shown the importance of well-integrated and archaeologically sound studies combined with competent laboratory-based analyses, leading to well-documented results based on sufficiently large numbers and range of samples. In order to achieve more of these studies, there is a clear need for institutional focus and formal dedication to archaeometallurgical research. India can be rightfully proud of its scientific and technological advances, today and during its millennia of metallurgical achievements and unique traditions. It should be able to support multiple research groups dedicated to the study of this technological heritage, within a framework of interdisciplinary research across the sciences, engineering, arts, humanities and social sciences. Only then can knowledge and expertise be sufficiently accumulated and disciplinary memory build up, enabling a broader field of scholars who cooperate and share practices and data. Compared to many other disciplines, archaeometallurgy is not particularly resource-intensive, and offers rich fruits to those who know to harvest them. We sincerely hope that this review entices more scholars, in India and elsewhere, to dedicate themselves to the study of India's archaeometallurgical heritage, presenting it to the global community.

CRediT authorship contribution statement

Meghna Desai: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Thilo Rehren:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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