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Crafting Innovation: The Emergence and Evolution of Tin Bronze Metallurgy on the Prehistoric Iranian Plateau

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Abstract: The production of metal artefacts using tin bronze appeared on the Iranian Plateau in the 3rd millennium BCE (Early and Middle Bronze Age). This technique became common during the 2nd millennium BCE (Late Bronze Age to Iron Age I) and emerged as the primary copper-based metallurgical technology during the 1st millennium BCE (Iron Age II and III). According to existing research, the spread of tin bronze artefacts on the Iranian Plateau during the 3rd to 1st millennia BCE is known from only a limited number of archaeometallurgical studies. However, recent years have seen a growing number of archaeometallurgical and laboratory investigations aimed at understanding tin bronze production during the Bronze and Iron Ages (3rd to 1st millennia BCE). These studies have provided new insights into copper-based metallurgy of the period, revealing a shift from impure copper/arsenical copper to tin bronze in western and south-western Iran during the 3rd millennium BCE, the widespread use of tin bronze in western, northern, and central Iran during the 2nd millennium BCE, and, ultimately, the adoption of tin bronze as the predominant copper alloy across much of the Iranian Plateau during the 1st millennium BCE. Nonetheless, eastern Iran has yielded only a limited number of tin bronze artefacts from Iron Age II–III and the Achaemenid period.

Keywords: Iranian Plateau, Ancient Metallurgy, Bronze Age, Iron Age, Arsenical Copper, Tin Bronze, Alloying

Résumé : La production d'objets métalliques en bronze à l'étain est apparue sur le plateau iranien au III^e^ millénaire avant notre ère (âge du Bronze ancien et moyen). Cette technique s'est généralisée au cours du II^e^ millénaire avant notre ère (âge du Bronze final à l'âge du Fer I) et s'est imposée comme la principale méthode métallurgique à base de cuivre au cours du I^er^ millénaire avant notre ère (âge du Fer II et III). Selon les recherches existantes, la diffusion des objets en bronze à l'étain sur le plateau iranien au cours des II^e^ et I^er^ millénaires avant notre ère n'est connue que grâce à un nombre limité d'études archéométallurgiques. Cependant, ces dernières années ont vu se multiplier les recherches archéométallurgiques et les études en laboratoire visant à comprendre la production de bronze à l'étain pendant l'âge du Bronze et l'âge du Fer (III^e^ au I^er^ millénaire avant notre ère). Ces études ont apporté de nouvelles connaissances sur la métallurgie à base de cuivre de cette période, révélant un passage du cuivre impur/cuivre arsenié au bronze à l'étain dans l'ouest et le sud-ouest de l'Iran au cours du III^e^ millénaire avant notre ère, l'utilisation répandue du bronze à l'étain dans l'ouest, le nord et le centre de l'Iran au cours du II^e^ millénaire avant notre ère et, finalement, l'adoption du bronze à l'étain comme alliage de cuivre prédominant dans une grande partie du plateau iranien au cours du I^er^ millénaire avant notre ère. Néanmoins, l'est de l'Iran n'a livré qu'un nombre limité d'artefacts en bronze à l'étain datant de l'âge du Fer II-III et de la période achéménide.
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Mots clés : plateau Iranien, ancienne métallurgie, âge, du Bronze, cuivre arsenié, bronze à l'étain, alliage.

For a long period, the Iranian Plateau has been considered one of the pioneering regions in the early development of metallurgy in the prehistoric world, alongside the Caucasus and Anatolia (Thornton, 2009a). This is due to over 10,000 years of evidence for copper-based metallurgy, including mining, smelting, and manufacturing. The process began in the Middle Neolithic period with the shaping of small native copper fragments. It progressed to the melting of native copper and the smelting of various copper ores during the Chalcolithic era. This led to the production of copper and arsenical copper, followed by the emergence and spread of tin bronze during the Bronze and Iron Ages, respectively (Pigott, 1999; 2004; Thornton, 2009a; Helwing, 2013). Furthermore, the Iranian Plateau is rich in metal resources and polymetallic ores, a factor that likely contributed to the early appearance of diverse copper alloy technologies in antiquity (Thornton, 2009a; Weeks, 2013).

At the beginning of the 21st century, our knowledge of prehistoric copper-based metallurgy on the Iranian Plateau was limited to the findings of a few archaeological excavations and laboratory analyses conducted during the second half of the 20th century (Wertime, 1968, 1973; Moorey, 1969 and 1982; Vatandoost-Haghighi, 1977; Pigott et al., 1982; Fleming and Swann, 1993; Pigott, 1999). In recent years, however, archaeological excavations and scientific analyses have shed new light on early copper-based metallurgy on the Iranian Plateau, particularly concerning the emergence and spread of tin bronze metallurgy.

For several decades, the following questions were raised, yet clear answers remained elusive:

– When did tin bronze technology first emerge and develop on the Iranian Plateau?

– Which region(s) did tin bronze technology originate from, and how did it spread across the Iranian Plateau?

– Where were the ore sources located that supplied copper and tin for the production of tin bronze in prehistoric times?

– Where were the early tin bronze artefacts produced (i.e. workshops) on the Iranian Plateau?

Although these main questions, along with several others, have not yet been answered satisfactorily, and some remain entirely unresolved, recent archaeological and archaeometallurgical studies, particularly over the past two decades, have shed light on several key issues.

In recent years, a comprehensive effort has been made to understand the rise and development of tin bronze metallurgy in antiquity, particularly with a focus on the Near East and Western Asia. This has involved close attention to archaeological finds, analytical results, and geological information (Pigott, 2004, 2011 and 2021). One notable recent study was published by Cuénod et al. (2015), focusing on the available analytical data for more than 5,000 copper-based artefacts from Iran and neighbouring regions. Although this work represented a significant contribution to the field, it primarily involved the evaluation and assessment of analytical data from Iranian artefacts, many of which had both clear and uncertain provenance. In contrast, this chapter aims to provide a comprehensive overview of tin bronze metallurgy on the Iranian Plateau during the Bronze and Iron Ages, as well as the Achaemenid period (3rd to 1st millennium BCE; see table 1), based on the analysis of artefacts with well-documented provenance. It also places emphasis on more recently analysed artefacts, although the available analytical and archaeological data may still be insufficient to fully address some of the outstanding questions in this field.

EARLY COPPER METALLURGY: AN OVERVIEW OF PRE-BRONZE DEVELOPMENTS

The earliest evidence of copper metalworking on the Iranian Plateau (fig. 1) is a rolled bead made of native copper from the Neolithic site of Ali Kosh in western Iran, dated to the late 8th/early 7th millennium BCE (Smith, 1969). However, the widespread adoption of copper use occurred much later, in the early to mid-6th millennium BCE, when small native copper tools and ornaments became commonly used in late Neolithic villages across various parts of the Iranian Plateau (fig. 1), including Tappeh Yahya in southern Iran, Tappeh Sialk in central Iran, Tal-e Mushki in the Fars region, Tappeh Sang-e Chakhmaq in northeastern Iran, Chogha Sefid and Chogha Sabz in western Iran, Tappeh Zagheh in north-central Iran, and Hotu Cave in northern Iran (Thornton, 2009a; Helwing, 2013, p. 112). These findings indicate that native copper metallurgy was widespread during the late Neolithic period.

Regarding manufacturing technology, recent analyses of copper artefacts from late Neolithic and transitional Chalcolithic sites in the Fars region demonstrate that these artefacts were produced from native copper containing trace impurities, probably shaped through cold hammering and annealing (Weeks, 2008). Furthermore, geochemical analysis of Neolithic native copper artefacts from Fars suggests that copper sources in Talmesi, central Iran, may have supplied the raw materials (Begemann and Schmitt-Strecker, 2009).

Archaeometallurgical studies indicate intensive copper production in the central Iranian Plateau during the Chalcolithic period (c. 5500–3000 BCE), especially throughout the 4th millennium BCE, as evidenced at sites such as Tal-i Iblis, Tappeh Hissar, and Arisman (Pigott,

	Period	Sub-period	Date (BCE)
3rd millennium BCE	Bronze Age (BA)	Early Bronze Age (EBA)	c. 3000-2500
		Middle Bronze Age (MBA)	c. 2500-2000
2nd millennium BCE		Late Bronze Age (LBA)	c. 2000-1500
	Iron Age (IA)	Iron Age I (IA I)	c. 1500-1000
1st millennium BCE		Iron Age II (IA II)	c. 1000-800
		Iron Age III (IA III)	c. 800-600
	Achaemenid	-	c. 550-330

Table 1 – The prehistoric and historic periods of the Iranian Plateau from the 3rd to the 1st millennium BCE, including their sub-periods and corresponding dates.

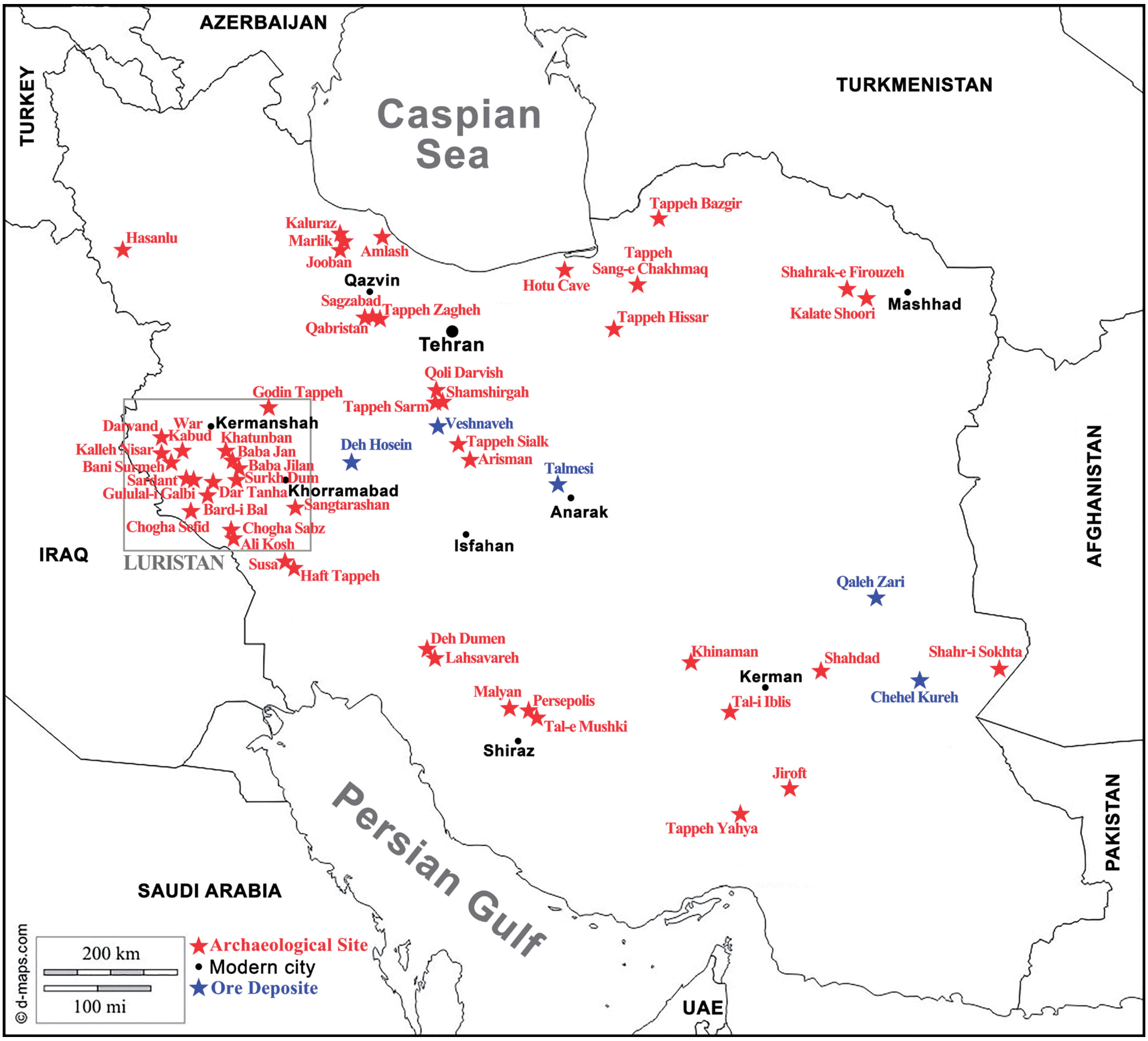

Fig. 1 – Map of modern Iran showing the locations of archaeological sites, modern cities and ore deposits mentioned in the text.

2004; Thornton, 2009a). Excavations at Chalcolithic settlements reveal the emergence and development of copper ore smelting. The earliest evidence of metal smelting on the Iranian Plateau is found at the Chalcolithic site of Tal-i Iblis in south-eastern Iran, located near the rich copper ore deposits of the Kerman region. This site contains a large-scale copper smelting area featuring numerous slagged crucibles, malachite (copper ore) fragments, and charcoal dated to various levels of the Chalcolithic period (Caldwell, 1968; Frame, 2004). Although some scholars have argued that this early copper-working site might reflect only the melting of native copper, the presence of materials related to copper ore smelting, along with precise dating of different occupation levels (Voigt and Dyson, 1992, p. 143–146), demonstrates early copper smelting activity comparable to that of Anatolia and Mesopotamia, dating to the late 6th and early 5th millennia BCE (Thornton, 2009a).

While early Chalcolithic copper smelting primarily produced impure copper, evidence for arsenical copper production also appears towards the end of the 5th millennium BCE (Thornton, 2009a and 2010). Early arsenical copper artefacts have been found in late 5th millennium BCE layers at sites such as Susa, Tappeh Yahya, and Tappeh Hissar (Benoit, 2004; Thornton, 2009b; 2010). However, the current data remain insufficient to fully understand the transition from shaping and melting native copper to smelting copper ores and producing arsenical copper (Thornton, 2009a). By the beginning of the 4th millennium BCE, copper-based metallurgy became clearer, with large-scale copper smelting and copper, possibly arsenical copper, production evidenced at early 4th millennium BCE levels at sites including Susa, Qabristan, Tappeh Hissar, Tappeh Yahya, and Tappeh Sialk (Majidzadeh, 1979 and 1989; Chegini et al., 2000; Benoit, 2004; Thornton, 2009b and 2010).

Moreover, late Chalcolithic copper metallurgy (4th millennium BCE) included the co-smelting of sulfidic copper ores and likely deliberate arsenical copper production, as observed at Tappeh Hissar, Tappeh Yahya, and Arisman (Thornton et al., 2002; Thornton, 2009b; Vatandoust et al., 2011). The presence of speiss slags dating from the late 4th to early 3rd millennium BCE further confirms intentional arsenical copper production in the late Chalcolithic to Early Bronze Age (EBA) of the Iranian Plateau (Thornton et al., 2009; Rehren et al., 2012).

TIN BRONZE, ARSENICAL COPPER, AND IMPURE COPPER: A SUMMARY

Before presenting the archaeological evidence for prehistoric tin bronze metallurgy in Iran, it is essential to clarify what is meant by 'tin bronze' and to distinguish it from other ancient copper-based materials such as impure copper and arsenical copper. These distinctions are crucial for assessing the technological choices made by ancient metalworkers and for understanding the broader context of alloying practices in early metallurgical traditions.

Tin bronze refers to an intentional alloy of copper with tin, typically containing > 1 wt% of tin, although some experts believe that the intentional alloy should contain > 2–3 wt% of tin (Pigott, 2004; Oudbashi et al., 2012). At these levels, tin significantly alters the mechanical and physical properties of copper, improving hardness, strength, and casting performance (Scott, 1991). It also affects the corrosion resistance property of copper, although it may not have been the case for prehistoric metalworkers (Scott, 2002). Although minor amounts of tin can occur naturally in some copper ores, these do not usually produce alloys with significantly enhanced material properties and are therefore generally considered unintentional or accidental. The presence of tin at trace levels can nevertheless be useful as a fingerprint for provenance studies (Pollard and Bray, 2014; Pernicka, 2014). By contrast, copper-based artefacts with consistent tin contents in the range of 1–15 wt% are widely interpreted as the result of deliberate alloying in the prehistoric context, indicating a high degree of metallurgical knowledge (Oudbashi et al., 2012).

From a modern metallurgical viewpoint, binary tin bronze alloys are classified as low-tin and high-tin according to their tin concentration, with low-tin bronzes containing c. < 15 wt% tin, while high-tin alloys contain tin between c. 15 and 35 wt% (Scott, 1991; Meeks, 1993; Ingo et al., 2002; Saraiva et al., 2022). This classification is based on the highest limit of tin solubility in copper under equilibrium conditions: 15.8 wt% (Saunders and Miodownik, 1994; Park et al., 2009). The difference between modern metallurgy and the prehistoric definition of tin bronze lies in archaeologists classifying tin bronzes with around 1–5 wt% tin as low-tin, artefacts with around 6–12 wt% tin as medium-tin bronze, and high-tin bronzes as those with higher tin content. This is a general definition and varies between cultures and regions. Accordingly, this chapter will adopt the classification more familiar to archaeologists, although modern metallurgical terms and definitions will sometimes be used when necessary.

The early tin bronze artefacts are made of alloys with tin content < 15 wt%, often exhibiting variable tin concentrations. This variability may result from the use of uncontrolled alloying methods. Various procedures for producing tin bronze alloys in ancient times have been proposed and discussed in the literature (Pigott, 2004; Rovira et al., 2009; Figueiredo et al., 2010; Murillo-Barroso et al., 2010; Valério et al., 2013; Erb-Satullo et al., 2015; Farci et al., 2017; Rademakers and Farci, 2018; Berger et al., 2019):

– Co-smelting of copper and tin ores: This method involves smelting copper and tin ores together in a single process, allowing tin to alloy with copper during the initial extraction from the ore.

– Cementation of metallic copper with cassiterite: In this process, metallic copper is heated in the presence of cassiterite (tin oxide), causing tin to diffuse into the copper and form a tin bronze alloy.

– Use of a complex Sn-bearing copper ore for smelting: Some copper ores naturally contain tin within their mineral composition; smelting such complex ores can produce tin bronze directly without adding separate tin sources.

– Metal recycling or re-melting of broken metallic pieces: This method involves melting down existing tin bronze artefacts or scrap metal, mixing them to produce new tin bronze items, which may result in variable tin concentrations.

– Melting of metallic copper and tin together in the crucible: This deliberate alloying technique entails combining pure metallic copper and metallic tin and melting them together to produce tin bronze with controlled tin content.

Apart from the final method, which may have allowed ancient metalworkers to control the Cu/Sn ratio precisely in the finished products, it was likely relatively difficult to regulate the tin content in the final metal (artefact or ingot). However, direct alloying of metallic copper and tin appears to have been unlikely in early tin bronzes, with these early examples produced using entirely uncontrolled methods.

To fully appreciate the significance of tin bronze, it is important to compare it with two other categories: impure copper and arsenical copper. Impure copper typically refers to copper containing a range of minor elements (< 1 wt%) such as iron, nickel, antimony, tin, lead, or arsenic, introduced unintentionally through the smelting of polymetallic ores. These trace elements may slightly influence the working properties of the metal (Junk, 2003; Atzeni; 2005), but were not deliberately added. As such, impure copper does not reflect conscious alloying choices and is generally regarded as a-product of early, less refined metallurgical processes.

Arsenical copper, by contrast, occupies an important place in early metallurgical traditions and is often viewed as a precursor to tin bronze (Coghlan, 1975; Lechtman and Klein, 1999; Lechtman, 1996). It contains deliberately or semi-deliberately introduced arsenic, usually through the smelting of arsenic-rich copper ores or, in some cases, by adding specific arsenic-bearing minerals to the smelt (Lechtman and Klein, 1999). Arsenical copper improves upon the mechanical properties of pure copper, increasing hardness and reducing casting porosity (Junk, 2003). However, its production posed health risks due to the toxic fumes released during smelting and working (Martin, 2017; González-Fernández et al., 2018). Despite these challenges, arsenical copper was widespread in early metallurgy, including in Iran, and often coexisted with early tin bronze traditions (Thornton, 2009a).

According to the literature, an arsenic content of less than 2 wt% may indicate that it entered the composition as an impurity from As-bearing copper ores such as tennantite, $(Cu,Fe)_{12}As_4S_{13}$ (Grey Copper), and this can be considered an accidental alloy (Coghlan, 1975). At higher arsenic contents, Coghlan (1975) also suggested that intentional alloying may have occurred through three metallurgical procedures:

– Contemporaneous smelting of copper oxide ores with realgar (As_4S_4) or orpiment (As_2S_3).

– Use of ores with high arsenic content, such as arsenopyrite or tennantite, mixed with copper sulphides.

– Adding realgar or orpiment directly to the melt during smelting.

Furthermore, Boscher (2016) suggested and discussed the following methods for producing arsenical copper (or arsenical bronze), noting that true alloying in the modern sense occurs only in the last two processes:

– Reduction of copper arsenates.

– Co-smelting of copper oxides with copper sulfarsenides.

– Co-smelting of copper oxides with iron arsenides or sulfarsenides.

– Adding copper arsenides or arsenates to molten copper.

– Use of speiss (a metallurgical by-product rich in arsenic and other metals).

Thornton et al. (2009) and Rehren et al. (2012) also suggest that speiss (an iron-arsenide alloy) is a quasi-metallic material, usually formed as an accidental by-product of copper or lead smelting, as observed in analyses of materials from Arisman and Tappeh Hissar. They propose that speiss was deliberately produced to provide arsenic as an alloying component for arsenical copper.

Furthermore, a high content of lead could be another aspect of the composition of ancient copper-based alloys. Lead may have entered the composition accidentally, due to the presence of significant amounts of lead in the smelted ores, or intentionally, by adding lead to the melt or smelting lead-bearing copper ores (Scott, 1991; Valério et al., 2012). Due to the immiscibility of lead in copper, a mixture of copper with lead does not produce a true alloy; for this reason, copper alloys with high lead content are referred to as leaded copper, leaded tin bronze, etc. (Scott, 1991). Generally, prehistoric copper-based artefacts from Iran contain very low levels of lead, and lead played no specific role in the prehistoric copper metallurgy of the region (Oudbashi, 2019a; 2019b). However, leaded copper-based artefacts become significantly more common during the Persian (pre-Islamic historic) and Islamic periods, due to lead's beneficial effect on the fluidity of the melt for casting purposes (Oudbashi et al. 2023a; 2025).

The technological and logistical requirements for producing tin bronze were significantly more demanding than those for impure or arsenical copper. Unlike arsenic, which could be introduced through naturally occurring copper ores, tin typically had to be sourced separately, often from distant regions, and intentionally combined with copper. Notably, there is some evidence of ore sources bearing both copper and tin, such as the ancient mine of Deh Hosein in western Iran (Nazafati ,2006), which was used for early tin bronzes. However, tin bronze technology primarily relied on the use of separate copper and tin sources. This process required knowledge of tin minerals such as cassiterite, control over smelting and alloying techniques, and likely the existence of exchange networks or organised procurement strategies. In this sense, the consistent appearance of tin bronze artefacts in the archaeological record reflects not only an awareness of its material advantages but also deliberate technological planning.

The motivations for producing tin bronze in prehistoric Iran and elsewhere were likely diverse and multifaceted. From a functional perspective, tin bronze offered significantly superior hardness and workability compared to impure or arsenical copper (Coghlan , 1975; Scott, 1991). These enhanced mechanical properties made tin bronze an ideal material for manufacturing a wide range of tools, weapons, and utilitarian artefacts that required greater durability and efficiency. Additionally, tin bronze's improved casting properties allowed for more complex and refined shapes, which may have contributed to its widespread adoption. Beyond practical advantages, the production and possession of tin bronze artefacts may also have held social or symbolic significance, potentially reflecting status or specialised craft knowledge within prehistoric communities. Thus, the emergence of tin bronze technology was driven not only by technical improvements but also by broader cultural and economic factors that encouraged the deliberate and sustained use of this alloy.

THIRD MILLENNIUM BCE: EARLY TIN BRONZES

Western and South-western Iran

Thanks to excavations and archaeometallurgical studies, copper-based metallurgy in western and south-western Iran during the late 4th to 3rd millennium BCE is now relatively well understood, particularly owing to recent archaeometallurgical research.

One of the earliest archaeometallurgical studies in southwestern Iran was the analytical research conducted on artefacts excavated from Susa (Tallon, 1987). Susa is one of the few settlements to show a notable presence of tin bronze as early as the early 3rd millennium BCE. Although the number of tin bronze artefacts dating to the first quarter of the 3rd millennium BCE is very limited, their quantity increases significantly during the second quarter (Berthoud et al., 1982; Tallon, 1987). Thanks to the large-scale metal collections excavated from the Chalcolithic and Bronze Age (Proto-Elamite to Old Elamite) levels of Susa (Susa I to Susa V, mid-6th to early 2nd millennia BCE), chemical analyses of numerous artefacts have provided a partially clear picture of the emergence and development of copper-based metallurgy in the prehistoric Susiana Plain (Berthoud et al., 1982; Malfoy and Menu, 1987). The results indicate that intermediate arsenical copper (As < 5 wt%) was utilised throughout these periods. The transition from arsenic to tin as the principal alloying element (whether deliberate or accidental) coincides with the first appearance of true tin bronzes during the Susa IVa period, c. 2500 BCE. High-tin bronzes began to appear during the Susa V period, c. 2100–1900 BCE (Malfoy and Menu, 1987, also see De Ryck et al., 2003, p. 265, figs. 5 and 6). One challenge in analysing the Susa copper-based artefacts is that, although a considerable number of artefacts (479 in total) have been examined, the dating of this analysed collection requires careful revision (Tallon, 1987). Nevertheless, based on the available dating, it is clear that early tin bronzes appeared at the beginning of the Middle Bronze Age (MBA) or Old Elamite period in Susa (Malfoy and Menu, 1987).

Large-scale archaeological excavations in Luristan, western Iran, conducted by the Belgian Archaeological Mission in Iran (BAMI) during the 1960s and 1970s, led to the discovery of a significant collection of ritual bronze artefacts from Early to Middle Bronze Age graveyards, dated to the late 4th and 3rd millennia BCE. These artefacts include, for example, vessels, weapons, and ornaments, which were found in graves at several excavated sites in the Pusht-i Kuh region, including Kalleh Nisar, Bani Surmeh, Dar Tanha, Mehr War Kabud (War Kabud), Gululal-i Galbi, Sardant, and Darvand (Haerinck and Overlaet, 2006, 2008 and 2010). The chemical analysis of a series of these excavated artefacts revealed a highly significant aspect of copper-based metallurgy in western Iran: the early production of tin bronze. Analysis of a substantial number of copper-based artefacts from Early to Middle Bronze Age sites in the Pusht-i Kuh region showed that, among 58 artefacts dated to the 3rd millennium BCE, 19 were made of tin bronze, 30 were composed of arsenical copper, and 9 consisted of impure copper with tin and arsenic contents < 1 wt% (Begemann et al., 2008). In addition, a group of artefacts from various stratigraphic levels of Kalleh Nisar, specifically, Area A-I (c. 3200–2800/2700 BCE), Area A-II (c. 2150–2000 BCE), and Area C (c. 2950–2300 BCE), were analysed by Fleming et al. (2005). The results revealed that 24 out of 41 artefacts were made of tin bronze (> 1 wt% tin), although arsenic content was not reported, preventing identification of potential arsenical copper artefacts. Notably, all 5 artefacts analysed from Area A-I were made of tin bronze, while 15 out of 19 artefacts from Area C and 4 out of 17 from Area A-II were also made of tin bronze. These findings indicate that the earliest known use of tin bronze for artefact production in the region appears in the assemblage from Area A-I of the Kalleh Nisar Bronze Age cemetery in Luristan, dated to approximately 3200–2800/2700 BCE (Fleming et al., 2005; Begemann et al., 2008).

Another important archaeological site excavated in western Iran is Godin Tappeh, situated on the north-eastern fringes of ancient Luristan. The site was excavated between 1965 and 1973 by T. Cuyler Young Jr., under the auspices of the Royal Ontario Museum in Toronto (Young Jr., 1969; Youn Jr. and Levine, 1974), and its occupational sequence spans from the Neolithic to the Iron Age. A comprehensive archaeometallurgical study has been conducted on the copper-based artefacts recovered from Godin Tappeh, revealing the evolution and transformation of copper-based metallurgy across different levels and periods of the site (Frame, 2010). Chemical analyses of 35 copper-based artefacts dated to the late 4th to 3rd millennium BCE, from archaeological levels VI:1, IV, III, III:6, III:5, and III:4, indicate that only 7 of these artefacts were made of tin bronze. In contrast, 3 artefacts were composed of impure copper, and the majority, 25 artefacts, were manufactured from arsenical copper.

Recent excavations at the Bronze Age cemetery of Deh Dumen in south-western Iran have resulted in the discovery of numerous metal vessels and ritual artefacts within the end of the early to the middle Bronze Age graves, dated to the mid-3rd millennium BCE (Miszkiewicz et al., 2022). Chemical analysis of eight vessels revealed that tin bronze was the predominant alloy used in their production. However, arsenical copper was also identified, most notably in the large metal discs placed at the bases of two tin bronze vessels (Oudbashi et al., 2016; Oudbashi and Naseri, 2017).

Figure 2a presents a bivariate scatter plot of tin versus arsenic concentrations in 103 analysed artefacts from the Pusht-i Kuh region (including Bani Surmeh, Kalleh Nisar, Dar Tanha, Mehr War Kabud, Sardant, Gululal-i Galbi, and Darvand), as well as from Godin Tappeh and Deh Dumen. It is important to note that the analytical data from the artefacts of Susa were excluded from this plot due to concerns regarding the accuracy of their dating, although a similar plot for Susa was previously produced by De Ryck et al. (2003).

The scatter plot displays tin and arsenic contents ranging from approximately 0–10 wt% for tin and 0–4 wt% for arsenic. One notable exception is an artefact from Godin Tappeh, which exhibits an unusually high arsenic content exceeding 8 wt%. Based on their chemical composition, the artefacts can be categorised as follows: impure copper (n=10), arsenical copper (n = 60), tin bronze (n = 25), and tin bronze with arsenic > 1 wt% (n = 8). The artefacts from the Pusht-i Kuh sites have been dated to the Early and Middle Bronze Age. As mentioned above, several artefacts with high tin content originate from Kalleh

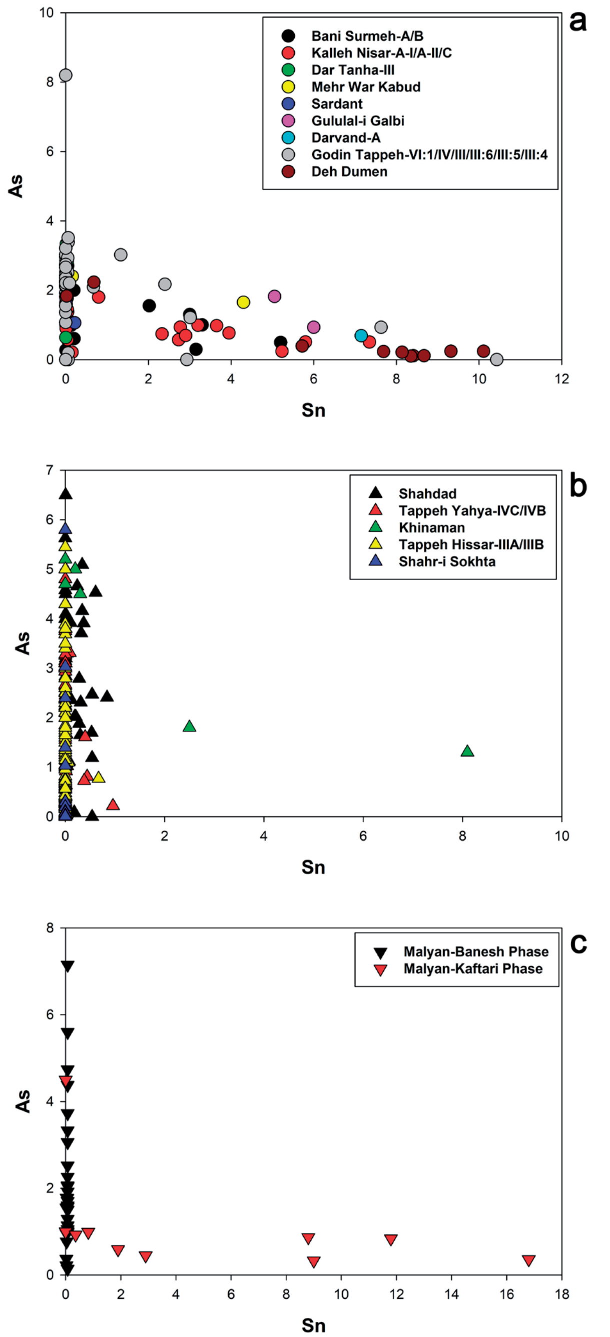

Fig. 2 – Three bivariate scatter plots of tin (Sn) versus arsenic (As) in the composition of analysed copper-based artefacts from the Iranian Plateau, dated to the Early and Middle Bronze Age: a) data from 103 artefacts from the Pusht-i Kuh region of Luristan, Godin Tappeh, and Deh Dumen in western and south-western Iran, 3rd millennium BCE; b) data from 216 artefacts from eastern Iran, 3rd millennium BCE; c) data from 40 artefacts from Malyan in south-central Iran, late 4th to 3rd/early 2nd millennium BCE.

Nisar Areas A-I and C, and are dated to the early 3rd millennium BCE. The Deh Dumen artefacts, dated to the mid-3rd millennium BCE, were predominantly made of tin bronze. These findings suggest that both tin bronze and arsenical copper were used concurrently in western and south-western Iran during the 3rd millennium BCE. However, tin bronze appears to have become more prevalent by the mid-3rd millennium BCE, corresponding to the onset of the Middle Bronze Age.

Eastern Iran

Excavations at various Early and Middle Bronze Age archaeological sites in eastern Iran have uncovered numerous copper-based artefacts, along with evidence of copper smelting technologies. The sites that have been analysed, Shahdad, Khinaman, Tappeh Yahya, Tappeh Hissar, and Shahr-i Sokhta, provide valuable insights into the development and characteristics of copper-based metallurgy in this region (Curtis, 1988; Thornton et al., 2002; Hauptmann et al., 2003; Thornton, 2009b; Meier, 2015).

The well-known Bronze Age site of Shahr-i Sokhta, located in Sistan and dating to the late 4th to 3rd millennia BCE, represents a large-scale prehistoric urban settlement in eastern Iran. Extensive excavations at the site have uncovered both copper smelting evidence and numerous copper-based artefacts. Analytical studies of ores, slags, and metal artefacts from the Early Bronze Age (c. 2700–2500 BCE) indicate that co-smelting of complex copper ores, both oxidic and sulphidic, within crucibles was the primary metallurgical process at that time. Two copper sources located to the west and north-west of the site, Qaleh Zari and Chehel Kureh, may have supplied the raw materials (Hauptmann et al., 2003). The analysis of 21 metal artefacts—including copper prills, lumps, ingots, and tools—revealed variable arsenic contents, reflecting the production of arsenical copper alongside impure copper. Notably, no tin was identified or measured in any of the samples (Helmig, 1986).

Similarly, the chemical analysis of numerous metal artefacts from Tappeh Yahya has provided a comprehensive picture of copper-based metallurgy in south-eastern Iran (Vatandoost-Haghighi, 1977; Thornton et al., 2002; Meier, 2011). These artefacts, dating to the late Chalcolithic and Bronze Age from levels IVC and IVB (3rd millennium BCE), showed no evidence of tin bronze. Instead, arsenic appears to have been the principal alloying element in most artefacts (Thornton et al., 2002; Meier, 2011).

In Shahdad, another significant Bronze Age site in eastern Iran, metallurgical workshops and copper-based artefacts further illuminate copper production during the 3rd millennium BCE. Although comprehensive analytical studies of the metallurgical materials from Shahdad remain limited, available data suggest that arsenical copper was the dominant alloying technology during this period (Vatandoost-Haghighi, 1977; Meier, 2015; 2011; Oudbashi et al., 2017). Altogether, these analytical studies consistently indicate that tin bronze metallurgy was not practiced during the Bronze Age in the eastern regions of Iran. Across the 3rd and 2nd millennia BCE, no clear evidence of tin bronze has been found in the eastern parts of the Lut Desert. In contrast, arsenical copper appears to have been the prevailing alloy in this region (Thornton et al., 2002; Hauptmann et al., 2003; Meier, 2011; 2015; 2019). Nevertheless, two copper artefacts containing tin

(2.5 and 8.1 wt% Sn) have been reported from Khinaman (also known as Khenaman), a Bronze Age cemetery in the Lut Desert associated with the Shahdad civilization (Curtis, 1988; Maxwell-Hyslop, 1988).

The lack of analytical data concerning copper-based metallurgy during the 3rd millennium BCE in north-eastern Iran has left this region largely unexplored in terms of understanding the potential emergence of tin bronze. However, recent limited analyses of copper-based artefacts from the early to middle Bronze Age site of Kalate Shoori, located near Neyshabur, have provided some insight. The results indicate that arsenical copper was the predominant material used in the production of copper-based artefacts at this site (Basafa et al., 2021).

Figure 2b presents a scatter plot of tin (Sn) versus arsenic (As) content in 216 analysed artefacts recovered from the sites of Shahdad, Khinaman, Tappeh Yahya, Shahr-i Sokhta, and Tappeh Hissar. It is noteworthy that artefacts from Shahdad, Tappeh Hissar, Shahr-i Sokhta, and Tappeh Yahya all display a wide range of arsenic concentrations, varying from up to 8 wt%, while their tin content remains below 1 wt%, detected only in trace amounts. The plot clearly illustrates that the vast majority of these artefacts were produced using either impure copper (Sn and As < 1 wt%) or arsenical copper (As > 1 wt%). Remarkably, only two artefacts from Khinaman, out of the 216 analysed, are identified as tin bronzes (Sn > 1 wt%).

Central and South-central Iran

This region, bounded by the southern edge of the Alborz Mountains to the north and the southern reaches of the Fars region to the south, encompasses a vast area with a rich copper-based metallurgical history predating the Bronze Age. Geographically, it roughly includes the central desert and the modern provinces of Fars, Isfahan, and Yazd. Numerous archaeometallurgical studies have revealed the existence of significant copper and arsenical copper production centres at sites such as Tappeh Sialk and Arisman (Ghirshman, 1938; Chegini et al., 2000; Nezafati and Pernicka, 2006; Nezafati et al., 2008; Nokandeh, 2010; Vatandoust et al., 2011; Rehren et al., 2012). While these investigations have uncovered various aspects of copper-based metallurgy in central and south-central Iran, they primarily focus on materials from the 5th to 4th millennia BCE, and only limited evidence points to the continuity of arsenical copper production into the early 3rd millennium BCE. One exceptional case is a tin bronze pin from Sialk III5 (mid-4th millennium BCE), reportedly made of tin bronze (Halm, 1939, p. 206–207). However, the analytical methodology and results are unclear, and the dating of this artefact is considered questionable and in need of reassessment (Helwing, 2021). Furthermore, the absence of Bronze Age levels (c. 2900–1500 BCE) in many key archaeological sites in central Iran, such as Tappeh Sialk and Arisman (Shaikh Baikloo Islam et al., 2016), has resulted in a significant gap in our understanding of copper-based metallurgical practices in the region during this period.

The only analysed site in south-central Iran is Malyan. Excavations at Malyan, a significant archaeological site located in the Kur River Basin of central Fars and identified as ancient Anshan, the highland capital of Elam (Sumner, 2003), have revealed evidence of metallurgical activities dating back to the Banesh phase (c. 3400–2800 BCE) and the Kaftari phase (c. 2200–1600 BCE). Evidence for copper smelting derives from Operation Banesh-TUV, Levels 2–3, where slag, metal fragments, and furnace remains were found in domestic contexts. Additionally, some buildings excavated in Operation Banesh-ABC also yielded indications of copper smelting (Pigott et al., 2003a). Chemical analyses of 30 artefacts showed that the copper contained arsenic, lead, and, in one instance, antimony (Pigott et al., 2003a). Furthermore, ten artefacts dated to the Kaftari phase underwent chemical compositional analysis (Pigott et al., 2003b). PIXE analysis revealed that six of these artefacts are made of tin bronze, with tin detected in varying amounts; two artefacts are composed of arsenical copper, and the remainder are impure copper. The tin bronze artefacts from the Kaftari phase constitute the earliest evidence of bronze metallurgy in south-central Iran (see fig. 2c).

2ND MILLENNIUM BCE: DEVELOPMENT OF TIN BRONZE METALLURGY

Western and South-western Iran

In contrast to the more extensively studied copper-based metallurgy of the 3rd millennium BCE, investigations into metallurgical practices during the 2nd millennium BCE in western Iran and Luristan remain comparatively limited. Nevertheless, the majority of copper-based artefacts analysed from Godin Tappeh are dated to the 3rd millennium BCE. More specifically, analysis of 18 copper-based artefacts from the 2nd millennium BCE levels at Godin Tappeh (Periods III:2 and Post III:2) revealed that 13 of these artefacts are composed of tin bronze, while the remaining five consist of arsenical and impure copper (Frame, 2010). Notably, tin bronze artefacts are far more prevalent in Period III:2 (1900–1600 BCE), with 12 out of 14 analysed pieces made from this alloy, compared to only one out of four in the subsequent Post III:2 period (1600–1400 BCE). This pattern suggests a greater reliance on tin bronze during the earlier part of the 2nd millennium BCE at Godin Tappeh, with a possible decline in its use during the later centuries of this era.

Analytical studies of artefacts from Susa are largely confined to the end of the 3rd millennium BCE, with only a limited number of items from the Susa V phase (late 3rd to early 2nd millennium BCE) having been analysed and interpreted (De Ryck et al., 2003). These artefacts have been discussed previously in conjunction with the broader 3rd millennium BCE collection from the site.

Beyond Susa itself, metallurgical investigations at the Middle Elamite site of Haft Tappeh, located near Susa and dating to the 14th century BCE—a period slightly after the close of the Bronze Age in the Iranian Plateau—have provided further insights. Haft Tappeh, identified as the capital of the Elamite king Tepti Ahar, was extensively excavated, revealing substantial evidence of copper production and metallurgy within its industrial sector. This evidence includes a furnace, crucibles, ingots, slags, and various metal artefacts (Negahban, 1991). A comprehensive multi-analytical study of the metal artefacts, ingots/prills, and slags from Haft Tappeh indicated that metallurgical activities there were characterised by small-scale production of copper and tin bronze items. These were manufactured from sulphidic copper raw materials through a two-stage smelting process, including roasting of the ores to produce matte and smelting matte to produce metallic copper. The first stage yielded a copper matte, which was subsequently refined to produce copper ingots/prills with reduced impurity levels. The coexistence of tin bronze and impure copper artefacts suggests that copper was likely produced using this two-stage smelting technique, followed by an uncontrolled alloying method, probably cementation, to introduce tin (Vatandoost-Haghighi, 1977; Oudbashi et al., 2019; Oudbashi and Mishmastnehi, 2020).

Figure 3a presents a bivariate scatter plot of tin (Sn) versus arsenic (As) concentrations in the composition of analysed artefacts and ingots from the sites of Godin Tappeh and Haft Tappeh. Among the 33 artefacts analysed from Haft Tappeh, 12 were identified as tin bronze, exhibiting a variable range of tin content. However, only two of these artefacts contain arsenic levels exceeding 1 wt%, indicating that arsenic was not a predominant alloying component in the majority of the tin bronzes from this site. Additionally, analysis of the Haft Tappeh ingots revealed that four contain tin in significant quantities (> 1 wt%), further supporting the presence and utilisation of tin bronze at the site. As previously discussed, the artefacts from Godin Tappeh similarly demonstrate a predominance of tin bronze during the 2nd millennium BCE, with 13 out of 18 artefacts from this period composed of tin bronze. This collective data strongly suggests that tin bronze had become the primary copper-based alloy used in western and south-western Iran during the 2nd millennium BCE. Nonetheless, there is also evidence of continued, albeit less frequent, use of low-arsenical copper and arsenical tin bronze. In particular, several tin bronze artefacts from both sites, especially those from Godin Tappeh, display arsenic levels above 1 wt%, indicating either deliberate alloying with arsenic or the use of arsenic-rich copper sources. This combination of alloying practices reflects a period of technological transition and experimentation in regional metallurgical traditions.

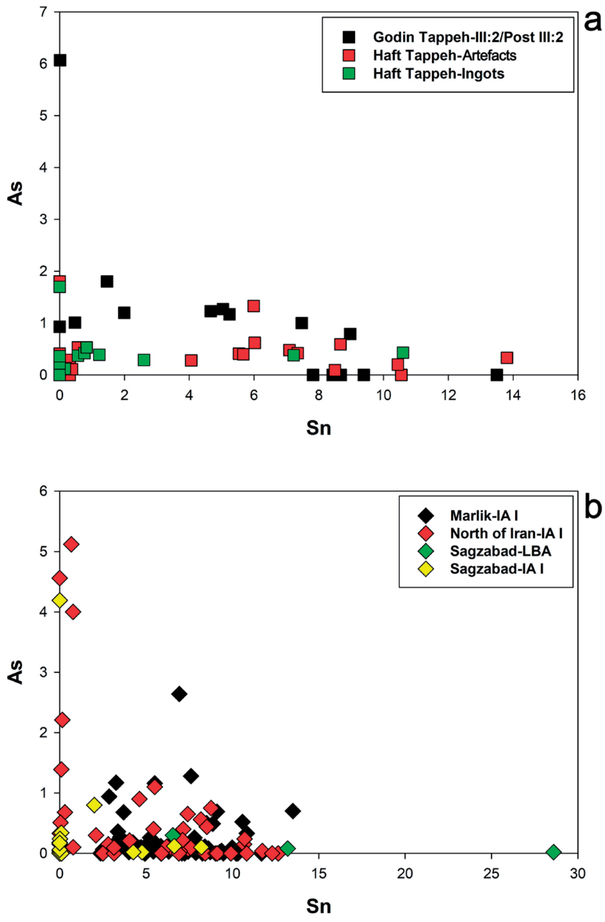

Fig. 3 – Two bivariate scatter plots of Sn versus As in the composition of copper-based artefacts from the Late Bronze Age and Iron Age I in the Iranian Plateau: a) data from 33 artefacts and 26 ingots/prills from Haft Tappeh, and 18 artefacts from Godin Tappeh in western and south-western Iran, 2nd millennium BCE; b) data from 128 copper-based artefacts from northern Iran, 2nd millennium BCE.

Northern Iran

Although northern Iran and the southern littoral of the Caspian Sea are rich in archaeological sites and cultural remains dating to the 2nd millennium BCE, the majority of excavated and documented settlements in the region pertain to the Iron Age I (IA I), approximately dated to 1400–1000 BCE. Notable among these are the excavations carried out by Iranian archaeologists at Marlik and Kaluraz (Hakemi, 1968; Negahban, 1996), as well as investigations conducted by Japanese missions in the Deylamān district and the Gorgan Plain (Sugimura 2008). Despite the archaeological richness of this area, archaeometallurgical research has been relatively limited, with analytical work primarily focused on artefacts from Marlik, c. 1400–1000 BCE, and a number of artefac recovered from other sites in northern Iran. These include Kaluraz, 1400–1000 BCE, Amlash, 1200–1000 BCE, Jooban (or Joobon), 1200–900 BCE, and a broader group of artefacts attributed generally to the southern Caspian region, 1200–1000 BCE (Vatandoost-Haghighi, 1977; Oudbashi and Hessari, 2017).

These findings indicate that tin bronze metallurgy was the dominant copper-based technological tradition in northern Iran during the latter half of the 2nd millennium BCE. The use of arsenical copper appears to have been rare, although the occurrence of arsenic in some tin bronzes implies either intentional combination or the influence of arsenic-bearing copper ores. This technological preference aligns with broader metallurgical trends observed in western/south-western Iran during the same period.

Sagzabad represents another significant site in the study of copper-based metallurgy during the 2nd millennium BCE in northern Iran. Situated in the Qazvin Plain, the site encompasses occupational phases dating to the Late Bronze Age (LBA) and the Iron Age I (IA I), spanning the 2nd and 1st millennia BCE (Negahban, 1973 and 1977; Malek Shahmirzadi, 1977).

Figure 3b presents a scatter plot of tin (Sn) versus arsenic (As) content based on the compositional analysis of 128 copper-based artefacts from these northern Iranian sites, dated to the 2nd millennium BCE. The results show that tin bronze was the predominant alloy, with 81 artefacts identified as tin bronze (Sn > 1 wt%). In contrast, only 8 artefacts were classified as impure copper (Sn and As < 1 wt%), and 5 as arsenical copper (As > 1 wt% and Sn < 1 wt%). Additionally, 5 artefacts exhibit both elevated tin and arsenic contents, suggesting the use of arsenical tin bronze. Archaeometallurgical analysis of 19 copper-based artefacts recovered from the LBA and IA I levels of Sagzabad has contributed valuable information regarding the technological choices made by the inhabitants. Of the analysed artefacts, 10 were identified as being composed of impure copper: Sn and As < 1 wt%; while 8 were made of tin bronze: Sn > 1 wt%. Additionally, one artefact from the IA I context was found to be composed of arsenical copper: As > 1 wt% (Mortazavi et al., 2011; Oudbashi et al., 2021a; see here fig. 3b).

Eastern Iran

Many of the 3rd millennium BCE settlements in eastern Iran were abandoned in the 2nd millennium BCE, as is observable at Shahdad and Shahr-i Sokhta, or continued only for a short time at the beginning of the 2nd millennium BCE, such as at Tappeh Hissar (Thornton, 2009b). Nevertheless, archaeological evidence reveals copper-based metalworking in both north-eastern and south-eastern Iran during the Late Bronze Age. The large number of copper-based artefacts discovered at Tappeh Bazgir, including more than 700 items of varying dimensions and forms, constitutes one of the most important metallurgical assemblages in north-eastern Iran, dating to the Late Bronze Age, 1800–1700 BCE (Nokandeh et al., 2006). The metal artefacts from this site have previously been analysed, although detailed chemical data have yet to be published. Nevertheless, chemical analysis of 171 copper-based artefacts revealed that, apart from two tin bronze buttons, all of the analysed items were likely made of arsenical copper alloy (Lorenz, 2008). Additionally, a published report on a few artefacts from Tappeh Bazgir confirmed the use of arsenical copper in their production (Moslehi et al., 2014). The discovery of a large-scale hoard of copper-based artefacts at Tappeh Bazgir, situated on the western borders of Khorasan, highlights the significance of the region—and of north-eastern Iran more broadly—in copper metallurgy during the Late Bronze Age.

Another recently excavated Late Bronze Age site in north-eastern Iran is Shahrak-e Firouzeh, located near Neyshabur. This site represents a Late Bronze Age settlement in Khorasan and demonstrates connections with the prominent cultures of the 2nd millennium BCE in Greater Khorasan and Central Asia, including the Bactria-Margiana Archaeological Complex/Greater Khorasan Civilisation (BMAC/GKC), dated to c. 2100–1700 BCE (Basafa, 2016; 2022). Analysis of a group of copper-based artefacts from the site revealed that 8 out of 23 artefacts were made of low-arsenical copper, while only 2 were identified as low-tin bronze (Oudbashi et al., 2020). The remaining artefacts were composed of impure copper. Furthermore, copper-based artefacts from Level IIIC of Tappeh Hissar (c. 2100–1700 BCE) exhibited a similar alloy composition pattern, with impure copper and arsenical copper being the predominant materials, and only one artefact identified as tin bronze (Thornton, 2009b; see here fig. 4a).

Tappeh Yahya is the only archaeological site in south-eastern Iran that remained occupied during the 2nd and even into the 1st millennium BCE. Excavation of Level IVA (c. 1800–1400 BCE) revealed a substantial collection of metal artefacts, of which 33 have been analysed (Thornton et al., 2002). The chemical data confirmed that impure copper and arsenical copper were the predominant materials, while seven tin bronze artefacts (with > 1 t% tin) were identified among the 33 analysed items (fig. 4b).

Central Iran

This region is confined to the central desert and its surrounding areas, and, as mentioned previously, reveals rich archaeological discoveries from the 5th to 3rd millennium BCE. However, the absence of Bronze Age (c. 2900–1500 BCE) levels in many well-known archaeological sites in north-central and central Iran has resulted in a gap in our knowledge of copper-based metallurgy in this region. Nevertheless, a recent archaeometallurgical study at Qoli Darvish, near Qom, has revealed some interesting aspects of copper-based metallurgy in central Iran during the 2nd millennium BCE (Nezafati and Stöllner, 2017). Four metal artefacts dating to the beginning of the 2nd millennium BCE (Late Bronze Age) were analysed, and the results showed a variety of compositions: one impure copper, two arsenical copper, and one tin bronze artefact. This suggests the parallel use of arsenical copper and tin bronze at the site, although the small number of analysed artefacts does not provide a comprehensive view of copper-based metallurgy in the central Iranian Plateau during the 2nd millennium BCE (fig. 4c). These artefacts, along with those from the Tappeh Sarm Iron Age site (discussed later), show some correlation with the Veshnaveh copper source, located to the south of these sites (Nezafati and Stöllner, 2017).

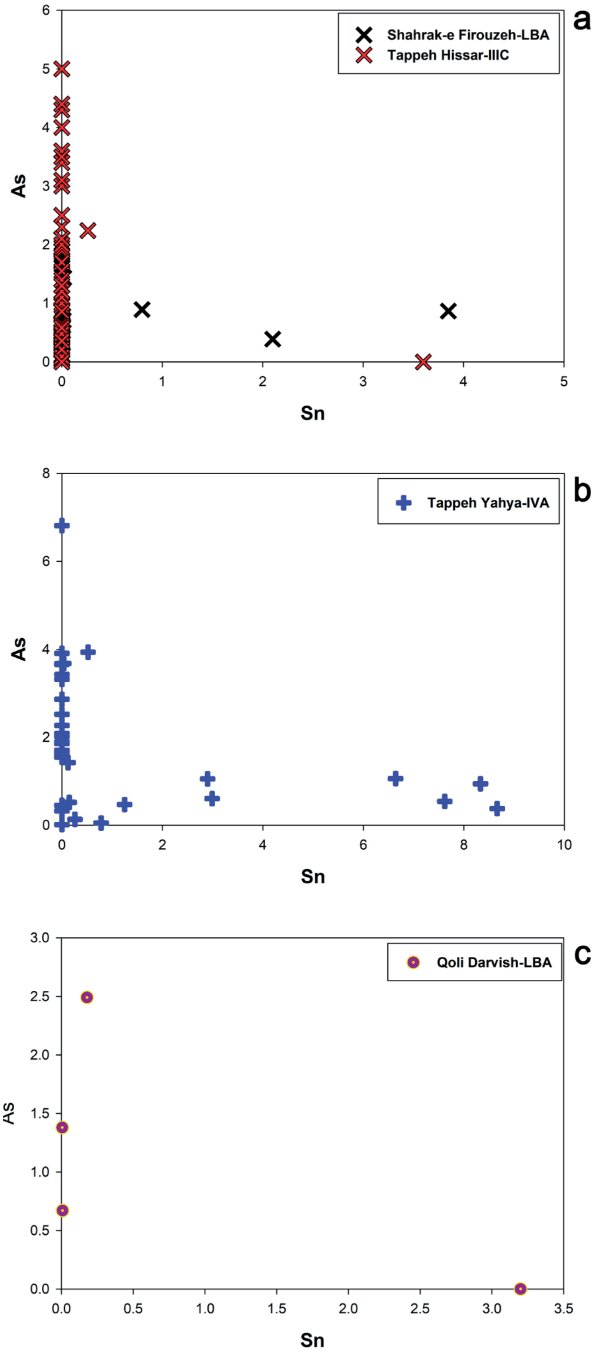

Fig. 4 – Three bivariate scatter plots of Sn versus As in the composition of copper-based artefacts from the Late Bronze Age and Iron Age I in the Iranian Plateau: a) data from 23 artefacts from Shahrak-e Firouzeh and 54 from Level IIIC at Tappeh Hissar in north-eastern Iran, 2nd millennium BCE; b) data from 33 artefacts from Level IVA at Tappeh Yahya in eastern Iran, 2nd millennium BCE; c) data from 4 artefacts from Qoli Darvish in central Iran, 2nd millennium BCE.

1ST MILLENNIUM BCE: TIN BRONZE AS THE PREDOMINANT ALLOY

Western Iran

One of the most striking phenomena in the Iron Age of western Iran is the unusually large quantity of bronzes produced in the Luristan region, including artefacts deposited especially in cemeteries and graves (Moorey, 1982; Overlaet, 2005; Pigott, 2009). These are among the best-known categories of archaeological finds in Near Eastern art and archaeology (Muscarella, 1988; Moorey, 1982 and 1969). They include a series of decorative and ritual bronze artefacts of a specific local style, dating from Iron Age II (IA II) and Iron Age III (IA III) c. 1000–600 BCE, of the Iranian Plateau (Overlaet, 2004 and 2005). Indeed, very few bronzes come from controlled excavations in the Luristan region, and most were collected through large-scale illegal excavations carried out by local people from the late 1920s onwards. Only a few excavations in Luristan yielded examples of these bronzes before the 2000s: the most significant were Erich F. Schmidt's single campaign at the sanctuary site of Surkh Dum in Pish-i Kuh in 1938 (Schmidt et al., 1989) and Louis Vanden Berghe's fifteen campaigns, all at cemetery sites in Pusht-i Kuh, between 1965 and 1979 (Haerinck and Overlaet, 2004). Additionally, Iranian archaeologists have excavated about half a dozen more bronzes from the cemetery site of Khatunban in Pish-i Kuh (Haerinck et al., 2004). The only other settlement site excavated in Luristan, Baba Jan in Pish-i Kuh, about 60 km north of Surkh Dum, yielded a Janus-headed tube and perhaps a zoomorphic pin (Muscarella, 1988).

Interestingly, recent archaeological excavations in Pish-i Kuh of Luristan have led to the discovery of an Iron Age II–III sanctuary and a significant number of Luristan Bronzes at Sangtarashan, near Khorramabad (Oudbashi et al., 2013; Malekzadeh et al., 2017). Furthermore, the excavation of Baba Jilan uncovered an Iron Age II–III cemetery in the north of Pish-i Kuh with some examples of Luristan bronzes as well as other bronze artefacts (Hasanpur et al., 2015).

Both the Sangtarashan and Baba Jilan collections were subjected to archaeometallurgical studies to understand the chemical composition, provenance, and manufacturing techniques used to produce the Luristan Bronzes (Oudbashi and Davami, 2014; Oudbashi and Hasanpour, 2018; Oudbashi et al., 2021b and 2021c). Furthermore, a group of artefacts from earlier excavations in Luristan have also been analysed, for example, artefacts from the two Iron Age graveyards of War Kabud and Bard-i Bal (Pish-i Kuh), and Godin Tappeh (Fleming et al., 2005 and 2006; Frame, 2010). Figure 5a shows a bivariate scatter plot of Sn versus As in the composition of 131 analysed artefacts from western Iran (Luristan). Almost all artefacts are made of tin bronze with variable tin content, while six artefacts from Godin Tappeh show arsenical copper and impure copper.

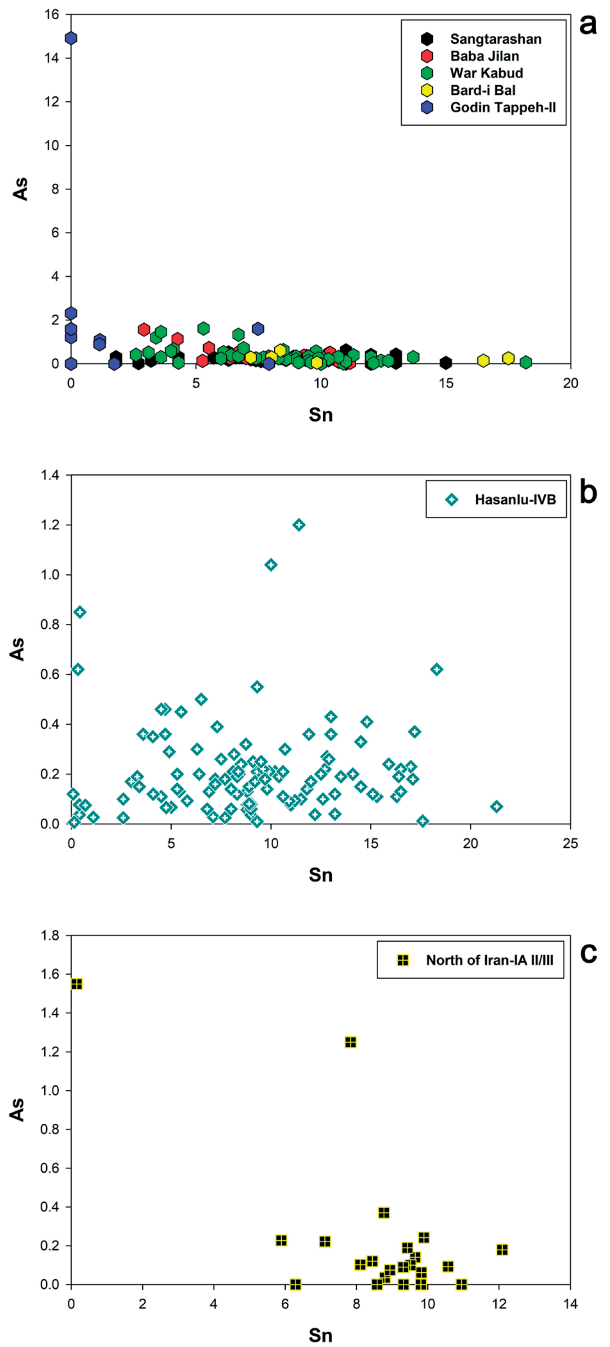

Fig. 5 – Three bivariate scatter plots of Sn versus As in the composition of copper-based artefacts from the Iron Age II–III in the Iranian Plateau: a) data from 131 artefacts from western Iran, 1st millennium BCE; b) data from 112 artefacts from Hasanlu in north-western Iran, 1st millennium BCE; c) data from 22 artefacts from northern Iran, 1st millennium BCE.

North-western Iran

Although many copper-based artefacts were discovered from the Iron Age II and III sites of north-western Iran (Muscarella, 1988), only artefacts from Hasanlu have been subjected to a comprehensive archaeometallurgical study (Fleming et al., 2011). In total, 112 artefacts from the Hasanlu IVB level were analysed, and the results showed that tin bronze was the predominant alloy with variable tin content (1.1–21.3 wt%), while only seven artefacts were made of impure copper. No arsenical copper was detected among the analysed artefacts, but two tin bronzes showed a comparatively higher concentration of arsenic (1.04 and 1.2 wt%; fig. 5b).

Northern Iran

Northern Iran, including the southern littoral of the Caspian Sea (especially modern Gilan), was settled in Iron Age II–III, and many Iron Age cemeteries and sites have been discovered through archaeological excavations (Haerinck, 1988; Khalatbari, 2004a, 2004b and 2004c). Unfortunately, most of the metal finds have not been subjected to archaeometallurgical studies. Analytical work on artefacts excavated from Iron Age II–III sites in northern Iran has been limited to early chemical analyses published by Vatandoost-Haghighi (1977) and Vatandoust (1999). According to analytical data, 20 of 22 analysed artefacts from northern Iran were made of tin bronze, with just one artefact made of arsenical copper, and another made of tin bronze with As > 1 wt% (fig. 5c).

Central Iran

Archaeological excavations related to the 1st millennium BCE in central Iran remain limited, and consequently, the number of analysed copper-based artefacts from this period is also quite small. However, recent excavations at Tappeh Sarm, near Qom, have revealed an Iron Age III cemetery situated near the site of Shamshirgah (Nezafati and Stöllner, 2017). Among the 13 analysed artefacts from this site, 10 were identified as tin bronzes, containing approximately 2 to 12 wt% tin, while the remaining three were made of impure copper. The metallurgical analysis of the Tappeh Sarm artefacts thus confirms the use of tin bronze during Iron Age III in central Iran (fig. 6a).

Eastern and South-central Iran

The only archaeological site in eastern Iran with levels attributed to the 1st millennium BCE is Tappeh Yahya, as Period III dates to the 8th–6th centuries BCE (IA III) and Period II to the Achaemenid period (c. 550–330 BCE) (Thornton et al., 2002). Analysis of three artefacts from Period III showed impure copper and low-arsenical copper, while 13 artefacts from Period II showed the continuity of arsenical copper usage and three examples of tin bronze (fig. 6b). A recent archaeometallurgical study of finds from the Iron Age II/III cemetery of Lahsavareh in south-western/south-central Iran, south-west of the Bronze Age site of Deh Dumen, also revealed the use of tin bronze with variable tin content (1.6–12.1 wt% tin) for producing different types of ritual artefacts (Habibzadeh et al., 2025). Furthermore, a recent study of 14 artefacts discovered at Persepolis (Achaemenid empire) demonstrated tin bronze and leaded tin bronze as the predominant alloys for producing weapons and tools (Oudbashi et al., 2023a).

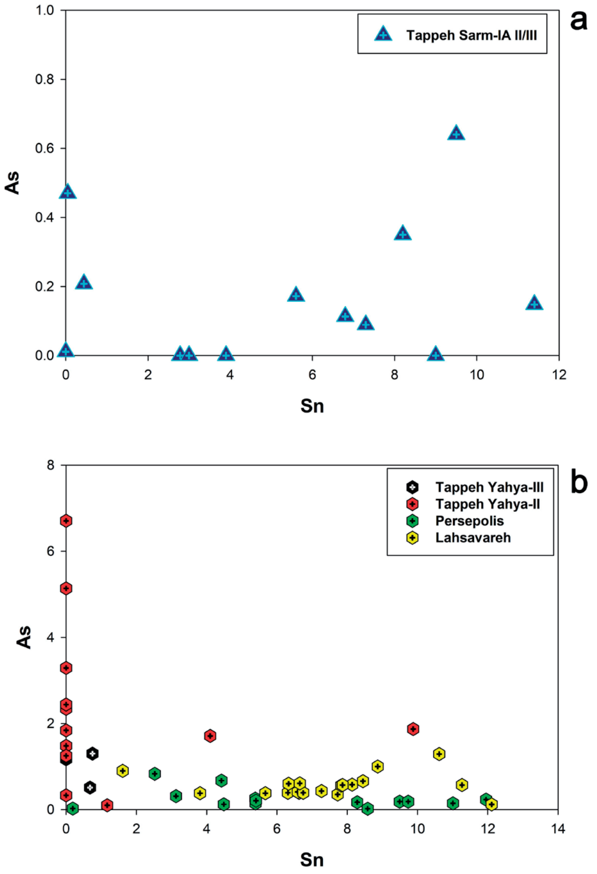

Fig. 6 – Two bivariate scatter plots of Sn versus As in the composition of copper-based artefacts from the Iron Age II–III and the Achaemenid period in the Iranian Plateau: a) data from 13 artefacts from Tappeh Sarm in central Iran, 1st millennium BCE; b) data from 49 artefacts from Levels II and III at Tappeh Yahya, Persepolis, and Lahsavareh in eastern and south-central Iran, 1st millennium BCE.

TIN BRONZE PRODUCTION: A PREHISTORIC EVOLUTION

From Arsenical Copper to Tin Bronze

Figure 7 presents two columnar diagrams illustrating the distribution of tin and arsenic content in the analysed artefacts from the 3rd, 2nd, and 1st millennia BCE. The tin percentage diagram (fig. 7a) and the arsenic percentage diagram (fig. 7b) are based on the results of analyses of 1005 copper-based artefacts (table 2). According to the diagram in figure 7a, it is evident that early tin bronzes from the 3rd millennium BCE contained a lower percentage of tin compared to artefacts from the 2nd and 1st millennia BCE, generally with a tin content between 1 and 11 percent. Most of the artefacts exhibit tin contents ranging from 1–3 and 7–9 wt%. Additionally, the majority of analysed artefacts from the 3rd millennium BCE are made from copper alloys containing less than 1 wt% tin (impure copper and arsenical copper). Furthermore, tin content increases later in the Late Bronze Age and Iron Age I (2nd millennium BCE), with half of the analysed artefacts composed of tin bronze. The distribution of tin content in this period is broader, ranging from 1 to 19 percent. This pattern continues in the Iron Age II and III as well as the Achaemenid period (1st millennium BCE), in which tin bronze artefacts predominate with a higher tin content. In contrast, arsenic content follows a different trend: artefacts with high arsenic content are predominant in the 3rd millennium BCE, with a subsequent decline in later millennia. The highest arsenic content observed across all periods is between 1–3 wt%, and the number of arsenical copper artefacts with elevated arsenic levels diminishes over the three millennia.

The tin content in artefacts dating back to the Bronze and Iron Ages of Iran shows a wide range of compositions, particularly in the later periods. Although some experts suggest a relationship between tin content and artefact function or typology (Moorey, 1994; El Morr and Pernot, 2011), this pattern has not been observed in prehistoric Iranian bronzes. As mentioned earlier, this may be due to the use of uncontrolled alloying methods in early tin bronze production. Various types of artefacts were produced with differing amounts of tin, indicating no clear relationship between alloy composition and typology. This has been particularly evident in Iron Age tin bronze artefacts from western Iran (Oudbashi, 2019a and 2019b; Oudbashi et al., 2021b).

Development of Tin Bronze on the Iranian Plateau

According to the available analytical data, tin bronze technology emerged in western and south-western Iran by at least the middle of the 3rd millennium BCE. Evidence of tin bronze artefacts has been identified in materials excavated from Early to Middle Bronze Age cemeteries in these regions, such as Deh Dumen and Kalleh Nisar. Additionally, tin bronze was also found in artefacts from Susa and Godin Tappeh from the same period. Interestingly, arsenical copper, unalloyed copper, and tin bronze were used concurrently in the region, reflecting a transitional phase from arsenical copper and copper metallurgy to the adoption of tin bronze as a new alloying tradition (fig. 8).

The only studied case of copper-based metallurgy in central Iran is Malyan. Artefacts from the Banesh phase (3400–2800 BCE) are made of impure copper and arsenical copper, while those from the Kaftari phase (2200–1600 BCE) demonstrate a variety of compositions, including tin bronze, arsenical copper, and impure copper. This represents a clear example of the transition from arsenical copper to tin bronze production during the 3rd millennium BCE (Pigott et al., 2003a and 2003b). Artefacts produced at the end of the 4th and beginning of the 3rd millennia BCE show no evidence of tin bronze, whereas those from the end of the 3rd and beginning of the 2nd millennia BCE are increasingly composed of tin bronze alloys with varying tin content (fig. 8).

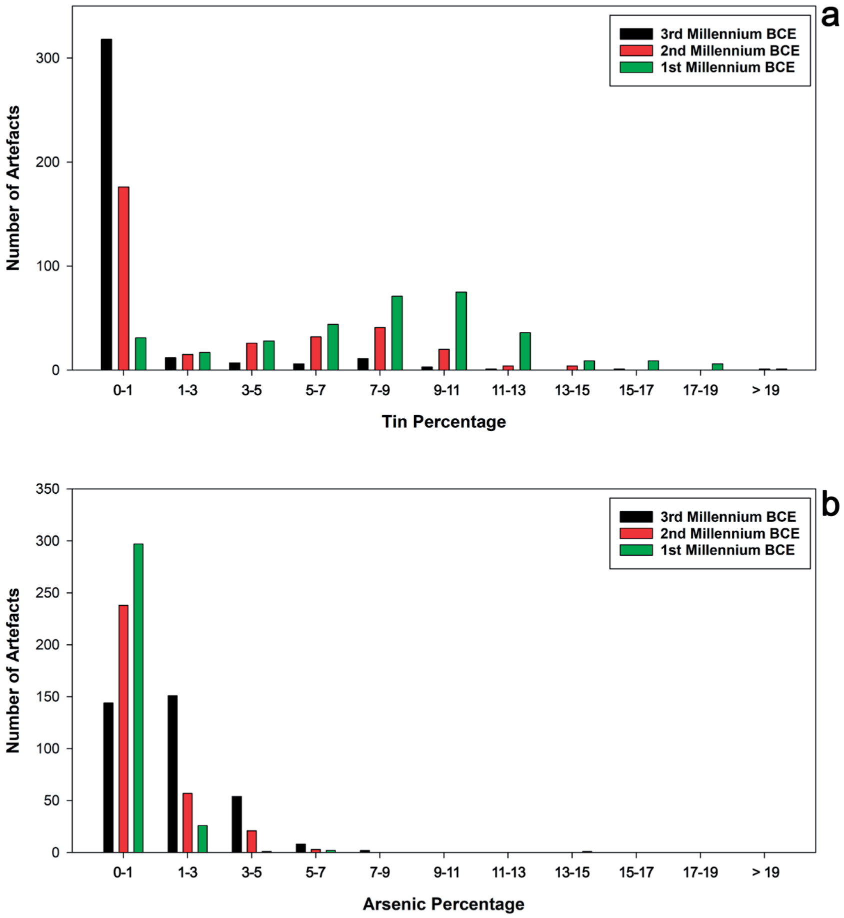

Fig. 7 – Two columnar diagrams showing the distribution of alloying elements in the analysed copper-based artefacts from the prehistoric Iranian Plateau: a) tin content distribution based on the analysis of 1005 artefacts; b) arsenic content distribution based on the analysis of 1005 artefacts.

	Region	Site	Date	Level/ Phase/Area	Analysis Method	No. of Analysed Artefacts	Reference
3rd Millennium BCE	Western and South-western	Kalleh Nisar	3200–2000 BCE	A-I/A-II/C	OES, NAA, PIXE	22	Fleming et al,, 2005; Begemann et al,, 2008
		Bani Surmeh	3rd millennium BCE	A/B	OES, NAA	19	Begemann et al,, 2008
		Dar Tanha	3rd millennium BCE	III	OES, NAA	6	Begemann et al,, 2008
		Mehr War Kabud	3rd millennium BCE	EBA/MBA	OES, NAA	3	Begemann et al,, 2008
		Gululal-i Galbi	3rd millennium BCE	EBA/MBA	OES, NAA	3	Begemann et al,, 2008
		Sardant	3rd millennium BCE	EBA/MBA	OES, NAA	4	Begemann et al,, 2008
		Darvand	3rd millennium BCE	A	OES, NAA	1	Begemann et al,, 2008
		Godin Tappeh	2950–1900 BCE	IV/III/III:6/ III:5/III:4	EPMA	35	Frame, 2010
		Deh Dumen	c. 2500 BCE	EBA/MBA	OES, EDS	10	Oudbashi et al,, 2016; Oudbashi and Naseri, 2017

Table 2 – Details of the archaeological sites and analysed copper-based artefacts from various regions of the Iranian Plateau, dated to the 3rd to 1st millennia BCE. This information is discussed in the manuscript and has also been used to generate graphs and plots.

3rd Millennium BCE	Eastern	Shahdad	2800–2400 BCE	EBA/MBA	AAS, XRF	42	Meier, 2011; Vatan-doost-Haghighi, 1977; Oudbashi et al,, 2017
3rd Millennium BCE	Eastern	Khinaman	c. 2200–2000 BCE	MBA	XRF	12	Curtis, 1988
3rd Millennium BCE	Eastern	Tappeh Yahya	3100–2900/2400–2000 BCE	IVC/IVB	ICP-MS	37	Thornton et al., 2002; Meier, 2011
3rd Millennium BCE	Eastern	Tappeh Hissar	2800–2000 BCE	IIIA/IIIB	PIXE	104	Thronton, 2009b
3rd Millennium BCE	Eastern	Shahr-i Sokhta	2700–2500 BCE	EBA/MBA	-	21	Helmig, 1986
3rd Millennium BCE	Central and south-centrall	Malyan	3400–2800/2200–1600 BCE	Banesh/ Kaftari	PIXE	40	Pigott et al,, 2003a and 2003b
2nd Millennium BCE	Western and South-western	Haft Tappeh	1400 BCE	Middle Elamite	PIXE, AAS	59	Oudbashi et al., 2019; Vatandoost-Haghighi, 1977
2nd Millennium BCE	Western and South-western	Godin Tappeh	1900–1400 BCE	III:2/Post III:2	EPMA	18	Frame, 2010
2nd Millennium BCE	Northern	Marlik	1400–1000 BCE	IA I	ICP-MS, AAS	65	Oudbashi and Hessari, 2017, Vatandoost-Haghighi, 1977
2nd Millennium BCE	Northern	North of Iran-Kaluraz	1400–1000 BCE	IA I	AAS	3	Vatandoost-Haghighi, 1977
2nd Millennium BCE	Northern	North of Iran-Amlash	1200–1000 BCE	IA I	AAS	3	Vatandoost-Haghighi, 1977
2nd Millennium BCE	Northern	North of Iran-Gilan	1200–900 BCE	IA I	AAS	2	Vatandoost-Haghighi, 1977
2nd Millennium BCE	Northern	North of Iran-Jooban	1200–900 BCE	IA I	AAS	1	Vatandoost-Haghighi, 1977
2nd Millennium BCE	Northern	North of Iran-South of the Caspian Sea	1400–900 BCE	IA I	AAS	35	Vatandoost-Haghighi, 1977
2nd Millennium BCE	Northern	Sagzabad	1800–1000 BCE	LBA/IA I	ICP-OES	19	Oudbashi et al., 2021a; Mortazavi et al., 2011
2nd Millennium BCE	Eastern	Shahrak-e Firouzeh	2100–1700 BCE	LBA	ICP-OES	23	Oudbashi et al., 2020
2nd Millennium BCE	Eastern	Tappeh Hissar	2100–1700 BCE	IIIC	PIXE	54	Thornton, 2009b
2nd Millennium BCE	Eastern	Tappeh Yahya	1800–1400 BCE	IVA	ICP-MS	33	Thronton et al,, 2002
2nd Millennium BCE	Central	Qoli Darvish	2000–1500 BCE	LBA	XRF	4	Nezafati and Stöllner,, 2017
1st millennium BCE	Western	Sangtarashan	800–600 BCE	IA III	ICP-OES	46	Oudbashi et al., 2021b
1st millennium BCE	Western	Baba Jilan	800–600 BCE	IA III	ICP-OES	21	Oudbashi and Hasanpour, 2018
1st millennium BCE	Western	War Kabud	800–600 BCE	IA III	PIXE	47	Fleming et al,, 2006
1st millennium BCE	Western	Bard-i Bal	800–600 BCE	IA III	PIXE	6	Fleming et al,, 2005
1st millennium BCE	Western	Godin Tappeh	800–600 BCE	II	EPMA	11	Frame, 2010
1st millennium BCE	North-western	Hasanlu	1050–800 BCE	IVB	PIXE	112	Fleming et al., 2011,; Vatan-doost-Haghighi, 1977
1st millennium BCE	Northern	North of Iran	1000–700 BCE	IA II/III	AAS, EDS, ICP	22	Vatandoost-Haghighi ,1977; Vatandoust, 1999
1st millennium BCE	Central	Tappeh Sarm	1000–600 BCE	IA II/III	XRF	13	Nezafati and Stöllner, 2017
1st millennium BCE	Eastern and south-central	Tappeh Yahya	800–330 BCE	III/II	ICP-MS	16	Thronton et al,, 2002
1st millennium BCE	Eastern and south-central	Lahsavareh	1100–600 BCE	IA II/III	XRF	19	Habibzadeh et al., 2025
1st millennium BCE	Eastern and south-central	Persepolis	550–330 BCE	Achaemenid	ICP-OES	14	Oudbashi et al., 2023a
	Total					**1005**	

Table 2 (continued) – Details of the archaeological sites and analysed copper-based artefacts from various regions of the Iranian Plateau, dated to the 3rd to 1st millennia BCE. This information is discussed in the manuscript and has also been used to generate graphs and plots.

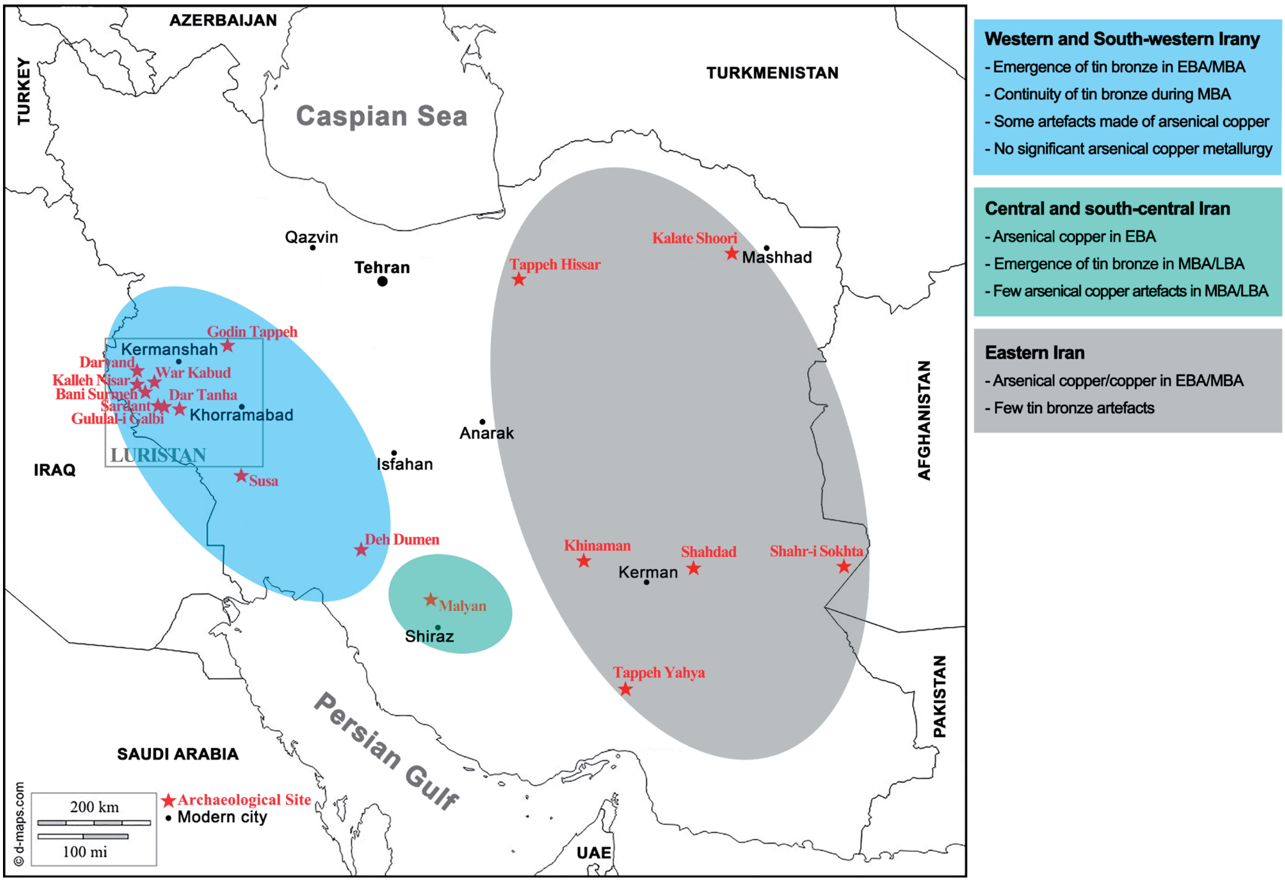

Fig. 8 – Map of modern Iran showing the locations of 3rd-millennium BCE archaeological sites from which copper-based artefacts were analysed, along with information on regional copper-based metallurgy.

Eastern Iran (from north to south) presents a markedly different pattern of copper-based metallurgy in the 3rd millennium BCE. Numerous analysed artefacts and metallurgical materials from well-known archaeological sites—such as Shahdad, Shahr-i Sokhta, Tappeh Yahya, Kalate Shoori, and Tappeh Hissar—show no evidence of tin bronze metallurgy. The only indication of tin bronze comes from two artefacts excavated from the Khinaman cemetery. Notably, Khinaman is a Middle Bronze Age cemetery located on the western fringe of eastern Iran, very close to Malyan and Deh Dumen. The typology of various artefacts from Deh Dumen reveals close connections with both western and eastern sites (Oudbashi et al., 2023b). In particular, similarities between certain metal artefacts from Deh Dumen and those found in Shahdad, Jiroft, or Tappeh Hissar suggest that there were interactions between south-western Iran and the prominent Bronze Age cultures of the eastern Iranian Plateau (Oudbashi et al., 2016 and 2023b). Therefore, while trade in metals between these regions during the 3rd millennium BCE is possible, the lack of tin bronze among the analysed artefacts from Tappeh Hissar and Shahdad highlights the need for further archaeometallurgical studies to better understand the potential connections between western and eastern Iran during this period.

The 2nd millennium BCE also displays a partially similar pattern of copper-based metallurgy to that of the 3rd millennium BCE (fig. 9). The western and south-western archaeological sites show evidence of tin bronze metallurgy, with some examples of impure copper and arsenical copper. However, the proportion of tin bronze compared with arsenical copper increased during the 2nd millennium BCE, and arsenical copper became rare, as seen at Haft Tappeh and Godin Tappeh. Tin content varies in the composition of the analysed artefacts, likely due to the use of uncontrolled alloying processes. These include either the cementation of metallic copper with tin ores or the direct smelting of copper–tin complex ores, as has been observed at Haft Tappeh (Oudbashi and Mishmastnehi, 2020).

Northern Iran also shows tin bronze as the predominant alloy used during the 2nd millennium BCE, although some arsenical copper and impure copper artefacts have also been identified. Tin content varies among the tin bronze artefacts from the region, suggesting that uncontrolled alloying methods were probably applied. The only example of copper-based artefact analysis in central Iran for this period comes from a few artefacts from Qoli Darvish, comprising one tin bronze, one copper, and two arsenical copper artefacts.

Eastern Iran in the 2nd millennium BCE displays a similar pattern to that of the 3rd millennium BCE, with

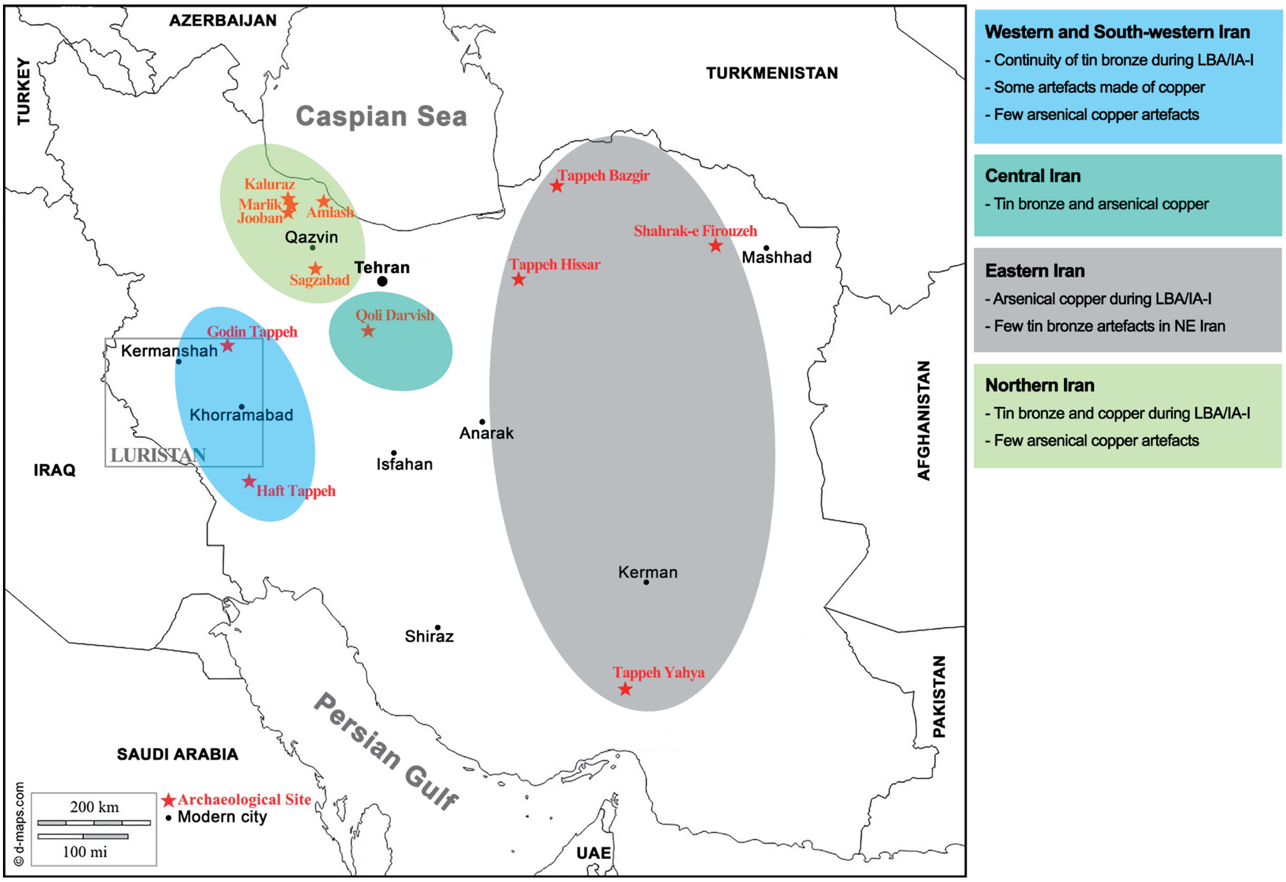

Fig. 9 – Map of modern Iran showing the locations of 2nd millennium BCE archaeological sites from which copper-based artefacts were analysed, along with information on regional copper-based metallurgy.

copper and arsenical copper remaining the predominant metals. However, a few more examples of tin bronze have been identified at Shahrak-e Firouzeh (north-eastern Iran) and Tappeh Yahya (south-eastern Iran). The tin content in these tin bronze artefacts is relatively low (< 10 wt%), similar to that observed in artefacts from western/southwestern Iran in the 3rd millennium BCE, and lower than that in artefacts from later periods, such as the Late Bronze Age and Iron Age. This may be due to the use of direct smelting of tin-bearing copper ores, as has also been observed at the Deh Hosein mine (Nezafati, 2006).

The Iron Age II and III can be considered the era of tin bronze metallurgy on the Iranian Plateau, as tin bronze was the predominant metal used for producing various decorative, ritual, and daily-use artefacts (fig. 10). Iron also emerged during this period, as seen at Hasanlu and in Luristan (Moorey, 1982; Muscarella, 1988; Pigott, 1989). Nevertheless, numerous metal artefacts from Iron Age II–III sites across western, north-western, northern, and central Iran were made of tin bronze. Arsenical copper and impure copper are rare, with only a few examples identified among the analysed artefacts. The only site in south-eastern Iran with Iron Age and Achaemenid levels is Tappeh Yahya. Analysis of artefacts from this site revealed a pattern consistent with that of the 3rd and 2nd millennia BCE in eastern/south-eastern Iran, arsenical copper predominates, with only three tin bronze artefacts identified in the Achaemenid level. This aligns with the earlier copper-based metallurgy of the Bronze Age and Iron Age I at Tappeh Yahya, where copper and arsenical copper were the main alloys. Artefacts from Persepolis were also made of tin bronze, but the available data from the Achaemenid period remain insufficient to form a comprehensive picture of copper-based technology in c. 550–330 BCE on the Iranian Plateau. As Cuénod et al. (2015, p. 44) stated:

> " In western Iran, aside from very early uses in Luristan, the idea of using tin-bronze may have come from the Mesopotamian neighbours, but while more and more objects were made of tin-bronze throughout the third and second millennia BC, it seems possible that the metal kept a valuable status well into the Iron Age: it is indeed only by the late second millennium that almost all copper alloy work is bronze."

The findings of the current study align with their conclusions, although they provide a broader picture of the rise and development of tin bronze metallurgy over three millennia, particularly due to more detailed information from different regions of the Near East, Mesopotamia and the Iranian Plateau. Nevertheless, the origin of tin, as well as the processes and methods of alloying copper with tin, remain unclear. Recent work by Nima Nezafati (2006)

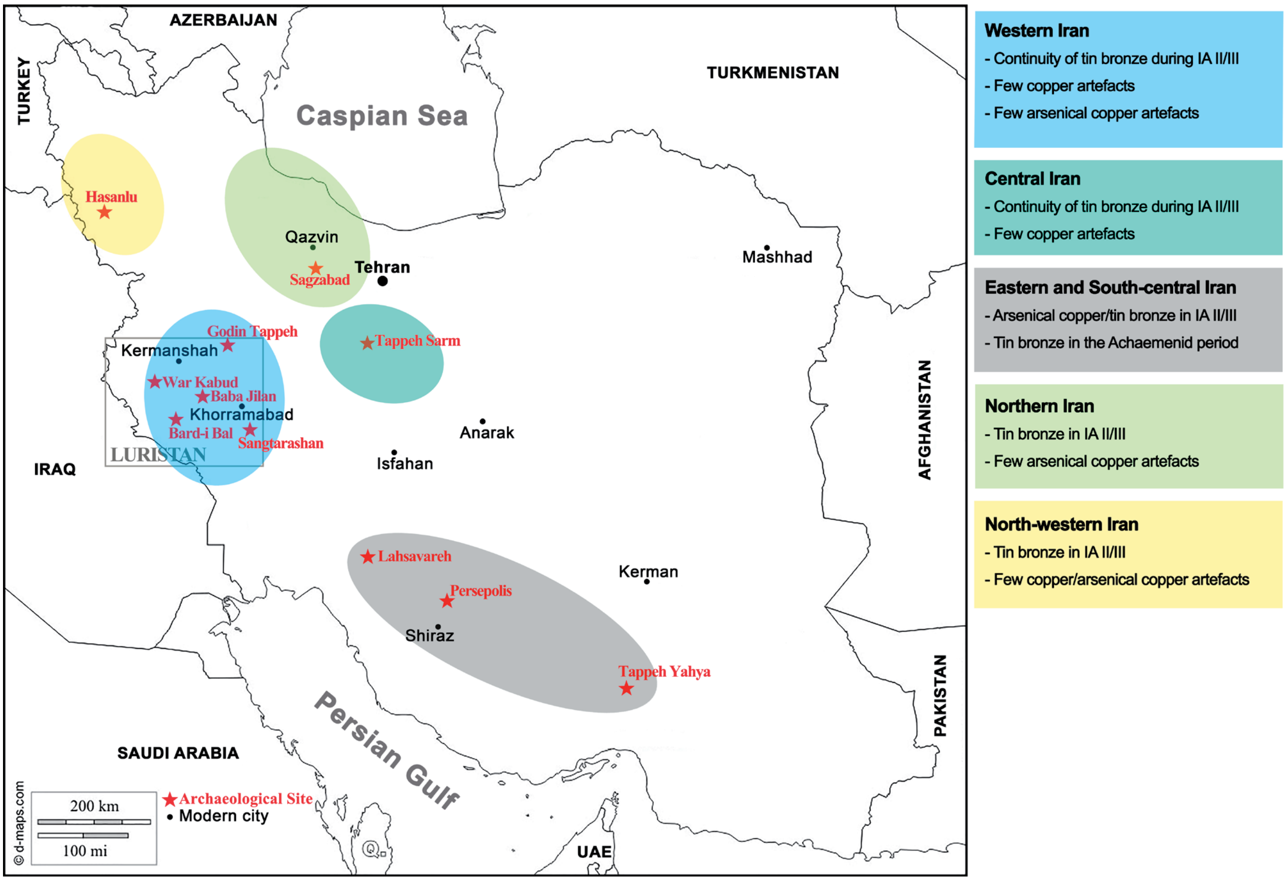

Fig. 10 – Map of modern Iran showing the locations of 1st millennium BCE archaeological sites from which copper-based artefacts were analysed, along with information on regional copper-based metallurgy.

offers some insights into tin supply and tin bronze production on the Iranian Plateau.

CONCLUSIONS

Although the Iranian Plateau is known as one of the pioneering regions in the emergence of early metallurgy in the ancient world, numerous questions about the beginning and development of copper-based metallurgy on the Plateau have not been fully answered. One of the main questions concerns the rise of tin bronze metallurgy in the 3rd millennium BCE and its development in subsequent millennia. Many archaeological excavations on the Iranian Plateau have led to the discovery of numerous copper-based artefacts as well as metallurgical materials, but only a few findings have been studied from an archaeometallurgical viewpoint. Nevertheless, the limited available data can help us shape a general view of the rise and development of tin bronze metallurgy during the Bronze and Iron Ages on the Plateau (3rd–1st millennium BCE). By describing and comparing the data, it has been shown that tin bronze emerged in western and south-western Iran in the middle of the 3rd millennium BCE and that this technology developed and continued in the region. Early examples of tin bronze artefacts were observed alongside arsenical copper and copper artefacts at EBA and MBA archaeological sites in the Zagros Mountains and Khuzestan Plain, while no evidence of tin bronze was found in eastern and central Iran at the same time. By the end of the 3rd millennium BCE, tin bronze had appeared in central Iran. The 2nd millennium BCE (LBA and IA-1) marked the development of tin bronze metallurgy in central and northern Iran, although tin bronze remained a rare material in the eastern half of the Plateau. Finally, tin bronze was the predominant alloy in most regions of the Iranian Plateau during the 1st millennium BCE, including western, north-western, northern, and central Iran, although available data from eastern Iran is insufficient for firm conclusions. Nevertheless, a few artefacts dated to the Achaemenian period are made of tin bronze. Consequently, the transmission from copper/arsenical copper to tin bronze as a new and likely more suitable alloy, with no toxicity and better mechanical properties, on the Iranian Plateau was very slow and took around 2,000 years to become widespread throughout the Plateau, although the western part can be considered the centre of tin bronze technology in prehistoric times.

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