

Metallurgical strategies at Sanxingdui: bronze production and resource reuse in Late Shang, China

Xiaotian Zeng

University of Science and Technology Beijing

Huiru Lian

University of Science and Technology Beijing

Honglin Ran

Sichuan Provincial Institute of Cultural Relics and Archaeology

Kunlong Chen

kunlong.chen@ustb.edu.cn

University of Science and Technology Beijing

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Abstract

This study investigates the metallurgical traditions and resource circulation of the Sanxingdui culture through alloy compositional and lead isotope ratio analyses of 79 bronze samples from Sanxingdui Pits 1 and 2. The results reveal a predominance of lead-tin bronze characterised by ubiquitous high lead content, while tin levels were more strictly managed, particularly in bronze vessels. All samples exhibit the highly radiogenic lead (HRL) signature characteristic of the Shang period. The persistence of HRL at Sanxingdui after its decline in the Central Plains is consistent with a shift from external procurement towards the internal circulation and reuse of metal. We advance the remelting of earlier HRL bronzes as a working hypothesis to account for this pattern. These findings illuminate how regional polities adapted their metallurgical strategies to shifting geopolitical landscapes.

Introduction

Bronze metallurgy provides a fundamental proxy for understanding the structural complexity and interregional interactions of early civilizations. During the Late Shang period (1320–1040 cal BC), bronze production in China reached its apogee, marked by unprecedented technical sophistication and the systemic use of ritual artefacts (Chang 1983; Ma 1982; Zhu 1995, 2009). Within this context, a fundamental inquiry in Chinese archaeology concerns the relationship between the Shang heartland (centred at Yinxu in Anyang, in the Central Plains) and contemporary regional polities such as Wucheng, Laoniupo and Sanxingdui (Chen 2008; Jin et al. 2009; Dou 2017, 2021; Tian 2021; Wang 2025). Reconstructing the metallurgical traditions of these regional bronze industries is therefore crucial for deciphering the broader landscape of power and material exchange during the Late Shang period.

Among the regional polities, the Sanxingdui site stands as a pre-eminent representative of Bronze Age civilization on the Chengdu Plain, Sichuan. It is situated on the south bank of the Yazi River in Guanghan, Sichuan Province, approximately 40 km northeast of Chengdu (Sichuan sheng wen wu kao gu yan jiu yuan 1999). In the 1980s, two sacrificial pits (Pits 1 and 2) were discovered in the central-southern sector of the ancient Sanxingdui city, yielding more than 1,800 artefacts including bronzes, gold and jades. Recent excavations in 2020 uncovered six additional pits (K3–K8) surrounding the original two, bringing the total number of recovered bronze artefacts to over 2,200 (Ge and Linduff 1990; Li et al. 2023; Sanxingdui yi zhi ji si qu kao gu gong zuo dui 2022). Radiocarbon dating indicates that Pits 1 through 8 were filled concurrently during the Late Shang period (Sanxingdui yi zhi ji si qu kao gu gong zuo dui 2022), marking Sanxingdui as a pivotal site for exploring the metallurgical and cultural dynamics of the region. Although bronze artefacts constitute one of the most substantial and striking categories from these pits, they exhibit significant stylistic and morphological heterogeneity (Fig. 2). Some bronzes closely align with the ritual bronzes of the Shang heartland, while others display distinct local features in their morphology, ornamentation and decorative style (Sichuan sheng wen wu kao gu yan jiu yuan 1999). Based on typology and iconography, current research categorises the Sanxingdui bronzes into two primary groups: local-style bronzes (e.g. bronze trees, masks and figures) and Shang-style vessels such as zun and lei (Sichuan sheng wen wu kao gu yan jiu yuan 1999; Jiang 2006; Zhang 2006). Furthermore,

these distinct categories are suggested to have had different casting sites (Lian et al. 2025). Investigating the production and circulation of Sanxingdui bronzes therefore provides critical evidence for understanding the technological interactions and resource-circulation systems between the Shang core and its contemporary regional polities.

Since the 1980s, extensive scholarship has investigated the Sanxingdui bronzes, focusing on chronology and manufacturing techniques. Analytical studies by Sun (Hao 2005), Zeng (1989, 1991) and others (Cui & Wu 2013; Ma et al. 2012) have demonstrated the compositional diversity of the Sanxingdui bronzes; however, whether alloy selection was systematically differentiated by artefact category remains debated. Furthermore, investigations by Su (Su & Zhu 2023), Hua (Sun & Su 2003) and others (Zeng 1994; Xu 2003, 2008; Guo et al. 2021; Tian et al. 2022) suggest that Sanxingdui metallurgy is rooted in the Central Plains tradition, characterised by the prolific use of casting-on and diverse joining methods.

Beyond these material properties and manufacturing techniques, the provenance of metal sources for the Sanxingdui bronzes remains a primary focus of academic inquiry. Previous research (Jin et al. 1995; Cui and Wu 2013; Li et al. 2023; Ma & Cui 2024) has identified highly radiogenic lead (HRL) signatures across all analysed samples from Sanxingdui. HRL is widely recognised as a distinctive marker of Late Shang (1320–1040 cal BC) metallurgy, yet the mechanisms of its circulation and utilisation remain a central focus of debate (Liu et al. 2025). Current isotopic studies reveal that HRL resources in China exhibit distinct chronological and spatial patterns. HRL bronzes were broadly used from the Upper Erligang period (1460–1400 cal BC) through the Middle–Late Shang periods (1400–1040 cal BC) across both the Central Plains and regional polities, including Hanzhong and Sanxingdui. Following the Yinxu III stage (1200–1080 cal BC), the use of HRL bronzes declined rapidly in the Central Plains and ultimately ceased during the Yinxu IV stage (1090–1040 cal BC). In contrast, HRL usage persisted for approximately another century on the Chengdu Plain, as evidenced at sites such as Sanxingdui and Jinsha (a centre of the Chengdu Plain that emerged after the abandonment of Sanxingdui) (Jin 2008; Chen et al. 2019; Wang et al. 2021; Ma and Cui 2024; Liu et al. 2025).

As a pre-eminent representative of regional bronze civilizations in southwest China, Sanxingdui provides a critical perspective for deciphering shifts in Shang metal-supply networks and the technological interactions among different regional centres. However, the lack of direct archaeological evidence for bronze-casting workshops (e.g. crucibles, furnaces) at Sanxingdui has led to significant debate concerning the provenance of the Sanxingdui bronzes. Li (Li 1988), Shi (Shi 2003) and others argue that all bronzes from Sanxingdui were cast locally; in contrast, scholars such as Jiang (Jiang 2006) and Xu (Xu 2008) contend that the Sanxingdui bronzes have multiple manufacturing locations, based on typological research. Moreover, trace-element analyses of several bronzes suggest the import of raw materials or finished bronzes from other regions (Li et al. 2023). Recent investigations into casting cores (Lian et al. 2025) support a more nuanced view, indicating that bronze objects of different styles were cast at varying sites, while non-vessel objects (e.g. masks, figures) were likely produced locally.

Although the cultural background and technology of Sanxingdui have been widely studied, core issues regarding material characteristics and raw-material provenance remain unresolved. One issue is particularly significant: while highly radiogenic lead (HRL) appears to have declined rapidly in the Central Plains after the Yinxu III stage, it continued to be used at Sanxingdui for nearly another century. This chronological discrepancy raises a central question: did Sanxingdui maintain access to earlier metal-resource networks, or did it develop a distinct strategy of metal procurement, circulation, and use? Recent systematic excavations and associated scientific analyses have provided a clearer chronological context for addressing this question. Within this framework, we present a comprehensive compositional analysis of bronzes from Pits 1 and 2, supplementing the existing corpus with new alloy and lead isotope data. By integrating these datasets, we refine the reconstruction of metallurgical sources and production practices at Sanxingdui, and provide new evidence for understanding the interregional metal-exchange networks of early China.

Materials and methods

To characterise the material composition and raw-material provenance of the Sanxingdui bronzes, this study analysed a total of 79 samples from 50 artefacts recovered from Sanxingdui Pits 1 and 2. In some cases, multiple samples were extracted from the same bronze artefact to compare different components (Supplementary Table S2). The 50 sampled artefacts were selected according to three criteria: (i) the availability of detached fragments or pre-existing break surfaces, allowing sampling without damage to intact objects; (ii) coverage of the full typological range recovered from Pits 1 and 2, including both vessels (*Zun*, *Lei*) and the principal non-vessel categories (trees, masks, human figures, sun-shaped objects and bird decorations); and (iii) where a large or composite object was likely to be compositionally heterogeneous, multiple samples were taken from different components of the same artefact (Table S2).

The present study does not include material from the six pits (K3–K8) excavated in 2019–2020. These bronzes were undergoing conservation and primary publication and were not available for destructive sampling. Our dataset therefore characterises the Pit 1 and Pit 2 assemblages, which remain the largest analytically accessible and most fully published body of Sanxingdui bronzes. We consider the sample broadly representative of the compositional and isotopic range of these two pits, while recognising that incorporating material from K3–K8 is an essential next step that may refine or revise the patterns reported here.

We further note that within-object compositional variability (e.g. lead enrichment in lower-cast portions; Table S3) can be substantial in large castings. Where such variability was observed, our provenance interpretations rely on the lead isotope signal, which is unaffected by elemental segregation, rather than on absolute compositional values; the alloying patterns discussed below should nonetheless be read with this intra-object variability in mind.

Typological classification followed criteria from *The Chinese Bronzes* (Ma 1982) and *The Sacrificial Pits at Sanxingdui* (Sichuan Provincial Institute of Cultural Relics and Archaeology 1999). Based on recent typological studies, the bronzes were divided into two categories: bronze vessels ($n = 31$), including forms such as *Zun* and *Lei*; and non-vessel objects ($n = 48$), comprising bronze trees, masks, human figures, sun-shaped objects and bird decorations (Table S2). All samples were subjected to alloy compositional and lead isotope ratio analyses.

All samples were mounted, ground and polished according to standard metallographic preparation procedures. After carbon coating, major elemental compositions were determined using a Tescan Vega III XMU scanning electron microscope (SEM) equipped with a Bruker XFlash 6|10 energy-dispersive X-ray spectrometer (EDS) at the Institute for Cultural Heritage and History of Science and Technology, University of Science and Technology Beijing (USTB). To minimise the influence of corrosion, uncorroded metal cores or areas with minimal corrosion were targeted for area scanning. Lead isotope ratios were measured using a Thermo Fisher Scientific Neptune Plus MC-ICP-MS at Beijing Kehui Testing Technology Co., Ltd (full analytical methods are given in the online Supplementary Material).

To avoid ambiguity, we specify here the dataset underlying each analysis. The compositional and isotopic results reported in Section 3 (79 samples from 50 objects) derive exclusively from the new analyses generated in this study. For the broader discussion of alloying practice in Section 4 (Figs. 4–5), we combine these with previously published results to form the integrated dataset of 195 data points from 114 objects (Table S4). The lead isotope discussion (Fig. 7a) likewise draws on an integrated dataset that combines our new measurements with previously published lead isotope results, comprising 147 valid data points in total.

Results

Adopting a compositional threshold of 2% for intentional alloying (Wen 1980), the 79 newly analysed samples were classified into four alloy types: unalloyed copper (Cu), lead bronze (Cu-Pb), tin bronze (Cu-Sn) and lead-tin bronze (Cu-Sn-Pb). The bronzes were predominantly lead-tin bronze, accounting for 74 samples (94.9%). Minor categories include two tin bronzes (one containing 1.19% Pb), two lead bronzes (both containing $\sim 0.5\%$ Sn) and a single unalloyed copper sample (containing 1.83% Sn). These results indicate that lead-tin bronze represents the predominant alloying practice in Sanxingdui bronze production, while multiple alloy types coexisted.

Regarding the relationship between alloy composition and typology, no significant correlation was observed between alloy classes and artefact categories: both vessel and non-vessel categories are dominated by lead-tin bronze. Specimen SXD:10 (a branch fragment from a bronze tree) contains 1.83% tin, slightly below the 2% threshold; while this indicates potential impurities or minor alloying, it is classified as unalloyed copper for analytical consistency. However, distinct variations in tin content occur across categories. Bronze vessels are characterised by higher tin contents and a wider range (0.55–15.71%), whereas non-vessel objects show a tighter distribution, clustering primarily between 3%

and 7%. In terms of lead content, both categories display consistently high values, ranging from 0 to 18.91% for non-vessel objects and from 1.19 to 29.12% for bronze vessels; values exceeding 20% are largely associated with ring-foot samples. Although the lead content of bronze vessels displays slightly greater variability, the overall characteristics of the two categories do not differ significantly. Full alloy composition data are provided in Supplementary Table S3 and Fig. S1.

Lead isotope analysis of the 79 bronze samples reveals a consistent signature. Measured ratios fall within 40.0795–45.3677 for $^{208}\text{Pb}/^{204}\text{Pb}$, 15.7401–16.4973 for $^{207}\text{Pb}/^{204}\text{Pb}$, and 19.4621–24.1328 for $^{206}\text{Pb}/^{204}\text{Pb}$. All samples exhibit HRL signatures (characterised by future model ages under the Stacey–Kramers two-stage model, roughly equivalent to $^{206}\text{Pb}/^{204}\text{Pb} > 19$ and $^{208}\text{Pb}/^{204}\text{Pb} > 40$; Faure 1977; Dickin 2018; Liu et al. 2019; Killick et al. 2020), a typical lead resource of the Shang period in China. Given that the lead content of nearly all samples exceeds 1% (except SXD:10 and SXD:51), lead constitutes an intentional alloying element, and the isotopic data therefore reflect the geological characteristics of the lead source. Although the presence of HRL is universal across the Sanxingdui bronzes irrespective of alloy composition, the isotopic distributions exhibit distinct patterns correlated with artefact categories: non-vessel objects show a highly clustered distribution, whereas bronze vessels display a comparatively more dispersed range (Supplementary Table S3; Fig. S2).

Discussion

The alloying process of the Sanxingdui bronzes

Given the typological complexity of the Sanxingdui bronzes, whether distinct technological choices were applied to different artefact types has remained debated. To address this, we systematically synthesised previously published analytical data with our new results, compiling a comprehensive dataset of 195 data points from 114 bronze artefacts (Supplementary Table S4). This expanded dataset enables a more detailed investigation of alloying strategies at Sanxingdui. The results show that, while material diversity exists across both vessel and non-vessel categories, lead-tin bronze (Cu-Sn-Pb) predominates, with the other three alloy types appearing in minor quantities (Fig. 4). This preference aligns with the broader technological characteristics of the Bronze Age in China (Pollard et al. 2019). Sanxingdui bronze vessels exhibit a high degree of uniformity in material selection, with lead-tin bronze accounting for nearly 90% of the category; copper, lead bronze and tin bronze occur in limited proportions and are significantly less frequent than among non-vessel objects. This may imply that the production of Sanxingdui bronze vessels was governed by a more consistent metallurgical recipe.

The selection of alloy composition is a critical indicator of both technical agency and social organisation. It directly influences casting performance and the functionality of the final product, reflecting the depth of craftsmen's material knowledge and the sophistication of production control. Variations in alloying recipes fundamentally affect melt fluidity and the potential for solidification defects (Wen 1980). Comparative analysis of alloy compositions is therefore essential for evaluating craftsmen's metallurgical expertise and the technological sophistication of bronze production during this period.

This study reveals that distinct strategies governed the use of tin and lead in Sanxingdui bronze production. Tin content differs significantly: bronze vessels are characterised by higher and more variable tin levels, whereas non-vessel objects exhibit a tightly clustered distribution. This clustering may imply that non-vessel objects were produced within a relatively short and concentrated period of manufacture. Lead usage, conversely, demonstrates a widespread preference for high content across both categories, with no discernible distinction between them. This finding challenges previous hypotheses (e.g. Sun, in Hao 2005) that associated high lead content exclusively with local-style (primarily non-vessel) objects; instead, our re-evaluation demonstrates that high lead content is a ubiquitous feature of Sanxingdui metallurgy, independent of artefact category. Overall, these patterns suggest a flexible approach to lead addition, contrasting sharply with the strictly controlled use of tin.

These patterns of raw-material utilisation provide new insights into the organisation of production at Sanxingdui. Recent analyses of casting cores indicate that the Sanxingdui bronzes may have been produced at multiple locations (Lian et al. 2025). This supports the interpretation that the stylistic diversity of the bronzes reflects production across multiple interconnected yet relatively independent metallurgical centres. Within this framework, the non-vessel bronzes (e.g. bronze trees, masks) were likely produced within a locally rooted technical tradition. While the manufacturing techniques of these objects reflect considerable metallurgical skill and clear technological linkages with the Central Plains, the present evidence does not allow us to estimate the scale of this production. In particular, the absence of any identified casting installations at Sanxingdui means that the existence of a substantial local production system remains a possibility to be demonstrated rather than an established fact.

Sanxingdui in the exchange network of the Late Shang period

The dynamic circulation of metal resources offers a critical perspective on interregional interaction during the Shang period. A pivotal shift occurred around the Yinxu III stage (1200–1080 cal BC): HRL, a raw material previously ubiquitous across the Shang interaction sphere, vanished rapidly from the material-supply networks of the Central Plains. In contrast, the Chengdu Plain, represented by Sanxingdui, followed a divergent trajectory: the lead isotope ratios of its Late Shang bronzes fall exclusively within the typical HRL range, indicating that this resource continued to be used for nearly another century in the region. Elucidating this spatiotemporal difference in material choice is fundamental to understanding the geopolitical relationship between Sanxingdui and the Central Plains, and to reconstructing the resource strategies and sociopolitical trajectory of the Sanxingdui civilization during the Shang-to-Zhou transition.

Previous isotopic investigations (Jin et al. 1995; Cui and Wu 2013) highlighted the remarkable consistency of the Sanxingdui bronzes' lead isotope data, suggesting a similar source of raw material for casting bronzes of different categories. Notably, the $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of non-vessel objects are tightly concentrated between 22.5 and 23.5, a clustering significantly more pronounced than that of bronze vessels. This was previously interpreted as evidence that these local-style bronzes were produced intensively over a short period. However, these earlier studies were constrained by the lack of a precise

chronological framework, leaving isotopic analyses isolated from the broader historical context of Late Shang metal-exchange networks.

Recently, the excavation of six additional pits and subsequent typological breakthroughs have refined the chronological framework of the Sanxingdui bronzes, offering an opportunity to re-contextualise the use of HRL at Sanxingdui within Bronze Age resource circulation. Several scattered bronze fragments from the six pits (excluding Pits 5 and 6) were successfully rejoined into integral objects, demonstrating clear cross-pit links and implying that the deposition of most pits occurred during a single, synchronous event. Accordingly, Sun (Sun and Peng 2022) argues that the bronze vessels (e.g. *Zun* and *Lei*) are typologically identical to Central Plains counterparts and can be assigned to the Middle Yinxu period (1260–1200 cal BC), coinciding with the peak use of HRL in the Central Plains. In contrast, the dating of non-vessel objects remains ambiguous, as the lack of comparative material from other sites has confined previous assessments to estimating burial dates rather than dates of manufacture.

The key to dating these non-vessel objects lies in the observation that many local-style bronzes show evidence of reworking and composite construction, combining local forms with components that strictly follow Central Plains traditions. The most notable evidence comes from the “slender-bodied *Gu*” and the “*Gu*-shaped *Zun*” elements. A primary example is the bronze altar from Pit 3 (Fig. 6), whose central platform supports four vessels identified as the slender-bodied *Gu* type (Xu et al. 2024), characterised by slender cylindrical bodies, flared mouths and slightly curved bellies adorned with *taotie* and *yunlei* motifs. While the slender-bodied *Gu* appeared as early as the Erligang period (1540–1400 cal BC), the “extremely slender-bodied” variant became popular during the Late Shang and Zhou periods (Ma 1982; Wang 2006; Zhu 2009; Sun 2020; Ning 2024). These four examples show strong morphological affinities with the bronze *gu* from M7:328 at Zhuyangou, Baoji, suggesting a date corresponding to Yinxu Phase III (1200–1080 cal BC) (Ma 1982; Zhang 2004; Zhu 2009; Zhang & Wang 2013; Sichuan sheng wen wu kao gu yan jiu yuan (Sanxingdui yan jiu yuan) & Beijing da xue kao gu wen bo xue yuan 2024). Further resolution is provided by the inverted bird-footed figure with *zun* from Pit 8, which supports a *Gu*-shaped *Zun* on its head, characterised by a long neck and bulging belly decorated with plantain-leaf, *taotie* and dotted-circle patterns (Sichuan sheng wen wu kao gu yan jiu yuan (Sanxingdui yan jiu yuan) and Beijing da xue kao gu wen bo xue yuan 2024). In the Central Plains sequence, the *Gu*-shaped *Zun* emerged later than the standard *gu*, flourishing from the late phase of the Late Shang (1090–1040 cal BC) to the Early Western Zhou (1046–950 BC) (Zhang 2004; Zhu 2009; Zhang and Wang 2013; Sichuan sheng wen wu kao gu yan jiu yuan (Sanxingdui yan jiu yuan) and Beijing da xue kao gu wen bo xue yuan 2024). The presence of this vessel type indicates a date no earlier than Yinxu Phase III for the composite bronzes (Fig. 6).

Although absolute dating remains challenging, the analysis of composite bronzes provides indirect evidence that a significant portion of Sanxingdui bronze production post-dates the primary phase of vessel manufacture (Middle Yinxu). On this basis we posit that the vessels and the non-vessel objects represent distinct chronological periods: the bronze vessels align with the flourishing of similar forms elsewhere, placing them roughly in the Middle Yinxu phase, while the non-vessel objects and composite bronzes likely date to a later period, potentially Yinxu Phase III or subsequent stages.

A clarification of our chronological approach is warranted here. We use the Central Plains / Yinxu periodisation as a reference framework for two specific and limited purposes: first, to provide relative dates for Sanxingdui materials that currently lack independent chronological control, given the absence of a securely dated local typological sequence; and second, as a comparative structure that allows the interaction between the Sanxingdui and Central Plains metallurgical traditions to be examined on a common temporal scale. Adopting this framework does not imply that the Central Plains chronology is fully applicable to a regional context such as Sanxingdui, nor that Sanxingdui followed Central Plains stylistic trajectories in a straightforward manner. The typological correlations underpinning our phase attributions—particularly the dating of non-vessel objects and composite bronzes by morphological comparison—carry substantial uncertainty, and the resolution between adjacent phases (e.g. Yinxu II vs III) is limited. We therefore treat these correlations as provisional, and emphasise that testing them will ultimately require the direct dating of the Sanxingdui materials themselves, which we regard as a necessary direction for future work.

When situated within the context of Shang metal circulation, previous hypotheses face challenges. Ma (Ma and Cui 2024) posited, on isotopic grounds, that Sanxingdui bronze production declined after the Yinxu II stage (1260–1200 cal BC). Chen (Chen et al. 2019) surveyed lead isotope signatures from the Erlitou to Western Zhou periods and proposed the Qinling Mountains as the likely geological source of Shang HRL, explaining the prolonged consumption of HRL in the Sichuan Basin (Sanxingdui and Jinsha) through the spatial accessibility of the Qinling resource domain. However, tested against the chronological framework presented here, these earlier studies reveal contradictions, necessitating a re-evaluation of why Sanxingdui retained access to HRL long after its decline in the Central Plains.

Integrating these chronological insights, we argue that a significant portion of the non-vessel objects must be assigned to the Yinxu III stage or later. Corroborated by casting-core analyses (Lian et al. 2025) that distinguish production loci, these artefacts (e.g. bronze trees and masks) represent a distinct tradition of localised manufacture. The continued use of HRL at Sanxingdui is thus primarily reflected in these local-style, non-vessel objects, which used metal resources that had largely ceased to circulate in the Central Plains by the Yinxu III stage. This raises a critical question: how can the persistence of HRL in late-phase Sanxingdui artefacts be reconciled with its disappearance from the Central Plains system?

To explain this divergence, it is necessary first to consider the geographical and archaeological constraints on metal supply at Sanxingdui. Bordered by the Tibetan Plateau and the western Sichuan Basin, the Chengdu Plain forms a geographically distinct and relatively enclosed region (Liang et al. 2014; Fig. 1a, b). In this environmental and cultural context, the supply of resources may have been more limited than in other regions, and access to metal materials less extensive than in areas such as the Central Plains. Moreover, bronzes have been found only in specific locations, such as the Cangbaobao sacrificial pit and the eight sacrificial pits, with only scattered finds of slag and scraps elsewhere. This distribution suggests that the overall scale of primary bronze production at Sanxingdui was limited.

Against this background, the persistence of HRL in late-phase Sanxingdui bronzes may be explained not only by continued access to external HRL-bearing resources, but also by changes in the way existing metal was managed, circulated, and reused. Given the apparently limited input of new external resources and the small scale of primary production, we propose, as a working hypothesis, that part of the metal used in late-phase Sanxingdui production may have derived from the reuse of earlier HRL bronzes, with remelting offering one plausible mechanism by which the HRL signature could be preserved and transferred to later local-style objects.

Such a strategy would not be unprecedented: the reuse of metal resources via remelting has been attested in studies of metallurgical debris at the Xiaozui and Guoyuanzui sites during the Middle Shang phase (Liu et al. 2023; Hubei sheng wen wu kao gu yan jiu yuan et al. 2024). Similarly, at the Jinsha site, Li (Li et al. 2019) suggested that the HRL signatures observed in artefacts from the Late Shang to Early Western Zhou and into the early Spring and Autumn period may result from the late remelting of earlier bronzes or from stratigraphic mixing. These cases do not provide direct evidence for recycling at Sanxingdui, but they demonstrate that the reuse of earlier metal was a plausible technological and economic response within Shang and post-Shang metallurgical systems.

Contextual support for this hypothesis can also be drawn from the well-documented practice of reworking and composite construction among the Sanxingdui bronzes. Several composite objects deliberately combine local forms with components made in strict accordance with Central Plains conventions—most notably the slender-bodied *Gu* mounted on the Pit 3 altar and the *Gu*-shaped *Zun* supported by the inverted bird-footed figure from Pit 8 (Fig. 6). The recombination of existing bronze elements into new ritual assemblages shows that the curation and modification of finished objects was an established part of Sanxingdui practice. Such object-level reworking is not equivalent to the melt-level recycling we hypothesise; it does, however, indicate a cultural disposition toward the reuse of existing bronze that is at least consistent with, and lends plausibility to, the remelting scenario. We emphasise, however, that the present dataset provides no direct evidence for remelting; this interpretation should therefore be regarded as a hypothesis requiring corroboration from additional lines of archaeological and archaeometric evidence.

While the geological origin of HRL remains elusive, the available evidence suggests that Sanxingdui was initially integrated into a broad resource-exchange network. During the Yinxu III and IV stages, however, this network may have weakened for various reasons, resulting in a relative narrowing of access to metal resources. The continued production of HRL bronzes at Sanxingdui can thus be understood as a manifestation of a shift in resource-use strategies, from reliance on external supply towards internal circulation and reuse. It must nevertheless be acknowledged that no definitive evidence of bronze casting or metallurgical activity has yet been identified within the Sanxingdui site, and further discussion of bronze production and resource circulation therefore remains constrained by the limited evidence, requiring additional archaeological discoveries and analytical research.

Conclusion

By integrating compositional analysis and lead isotope analysis with chronological frameworks, the technological analyses of the Sanxingdui bronzes reveal a complex landscape of production and circulation. In terms of material composition, the bronzes are dominated by lead-tin bronze. With regard to alloying practices, the Sanxingdui bronzes are characterized overall by high lead contents, while the use of tin appears to have been more deliberately controlled, with bronze vessel generally exhibiting higher tin contents. Collectively, the bronze culture of the Chengdu Plain from the late Shang to the Western Zhou period, as represented by the Sanxingdui site, reflects a regional bronze tradition. While absorbing elements of Shang technology, evidenced by the adoption of Central Plains casting traditions, this local industry developed unique characteristics. Compositional and typological evidence analyses further suggest that bronzes of different stylistic groups at Sanxingdui may represent products of at least two distinct bronze casting locations, and that local bronze production may also have taken place. These production practices were likely influenced by bronze-casting traditions originating in the Central Plains, indicating close connections among interregional bronze industries during the late Shang period. At the level of resource circulation, the ubiquitous presence of HRL confirms that Sanxingdui was integrated into the core Shang resource network during its peak. However, a pivotal shift occurred during the Late Yinxu phase. As HRL vanished from the Central Plains, its persistence at Sanxingdui suggests a divergence in resource strategy. In the late Yinxu phase, access to raw materials at Sanxingdui appears to have become more restricted. This resulted in a greater reliance on the reuse of existing metal resources. It also marked a shift in resource-use strategies from external procurement to internal circulation.

This study sheds light on the complexity of regional interactions between Shang and regional civilizations. It not only clarifies the technological choices of Sanxingdui craftsmen but also contributes to a broader understanding of how regional polities adapted their metallurgical strategies in response to shifting geopolitical landscapes in Bronze Age China.

Declarations

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Competing interests The authors declare no competing interests.

Author contributions X. Z.: conceptualisation, performed experimental analysis, drafted the manuscript. H. L.: conceptualisation, provided project supervision, review and editing. H. R.: provided research materials, review and editing. K. C.: conceptualisation, provided project supervision, methodology, review and editing.

Data availability All data generated and analysed during this study are included in this article and its Supplementary Material.

Ethics approval Not applicable.

Geographical coordinates The Sanxingdui site is located in Guanghan, Sichuan Province, China, at approximately 104°11'58"E,30°59'38"N (previously published coordinates) (Guo 2024). The GPS coordinate was obtained from satellite imagery and is considered reliable.

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Figures

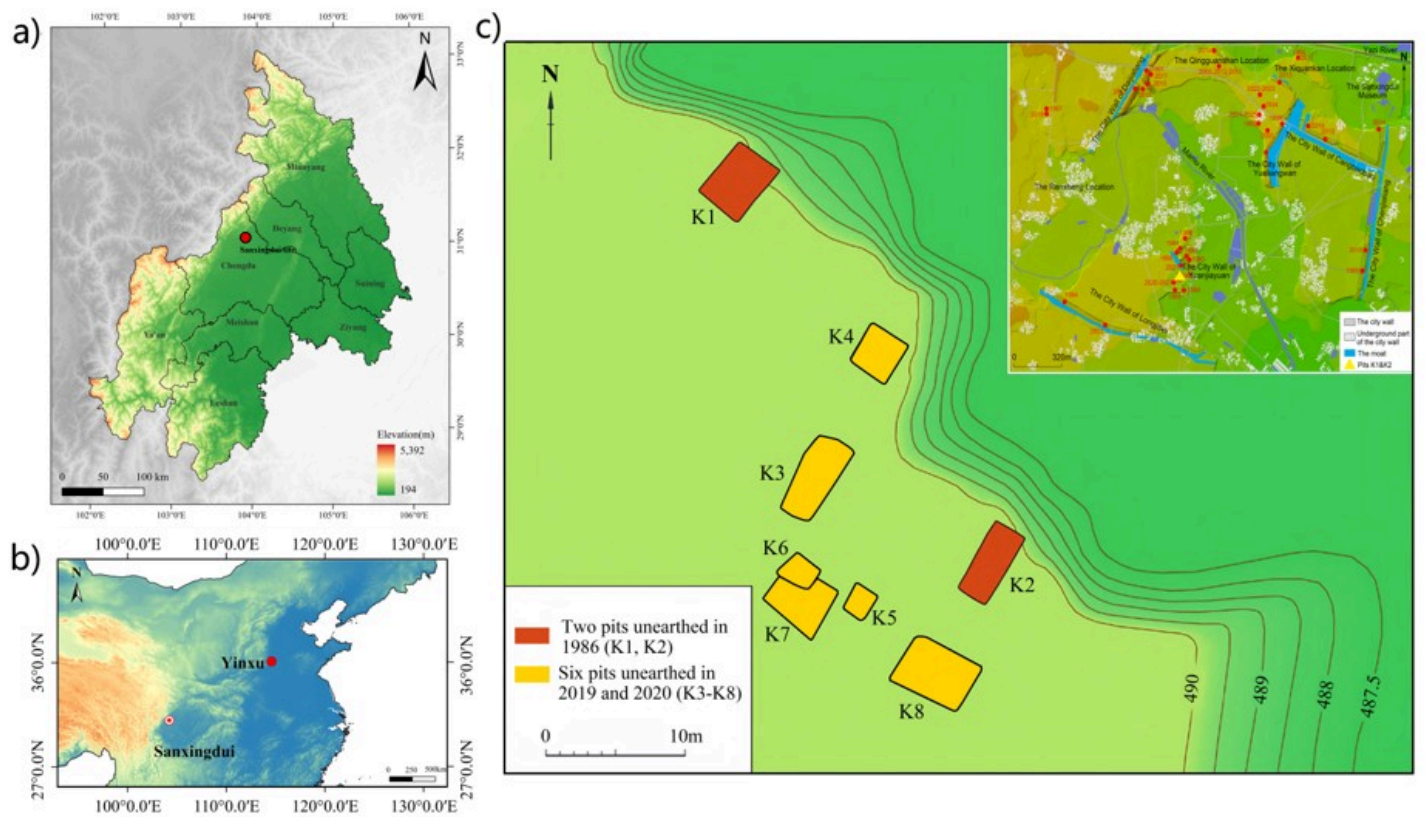


Figure 1

The locations of Pits 1 and 2 at the Sanxingdui site. a). The location of the Sanxingdui site. b). Map of the Sanxingdui site and Yinxu in the Central Plains of China, which is heartland of the Late Shang dynasty. c). Map of the sacrificial areas and the Sanxingdui site (Sanxingdui yi zhi ji si qu kao gu gong zuo dui 2022).)



Figure 2

Representative bronze artefacts from the Sanxingdui site(Lian et al. 2025). a). Large standing bronze figure (Editorial Committee of the Complete Collection of Chinese Bronzes 1994). b). Bronze mask (Editorial Committee of the Complete Collection of Chinese Bronzes 1994). c). Bronze human head (Editorial Committee of the Complete Collection of Chinese Bronzes 1994). d to e). Bronze vessels (Editorial Committee of the Complete Collection of Chinese Bronzes 1994). f). Bronze sacred tree (Sanxingdui Museum)

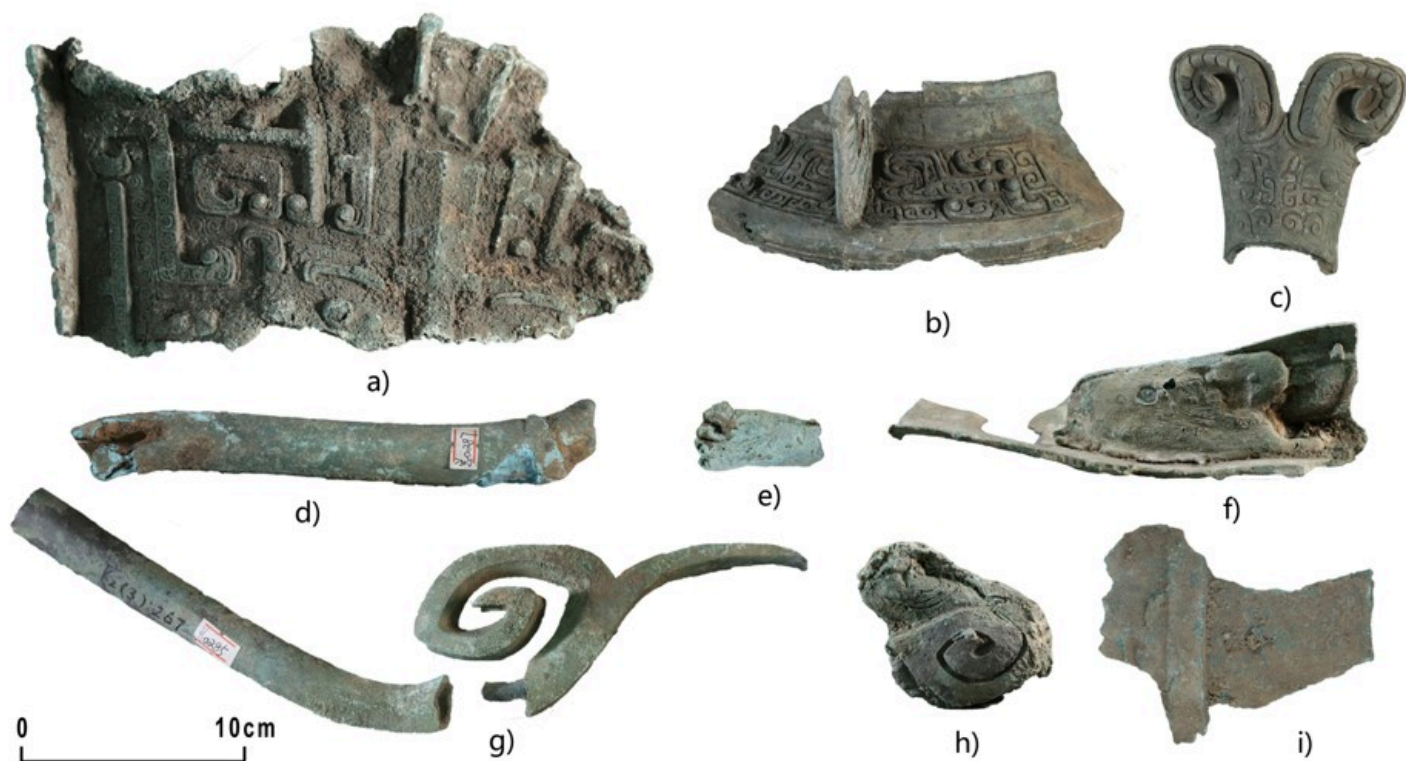


Figure 3

Bronze fragments sampled from the Sanxingdui site. a). The belly of vessel. b). The shoulder of vessel. c). The animal-head decorations on the shoulder of vessel. d & g). Branches of the bronze trees. e). Animal feet. f). The ear of the bronze human head. h). The belly of the bird decoration. i). Flake-like fragment, possibly the base of a non-vessel artefact)

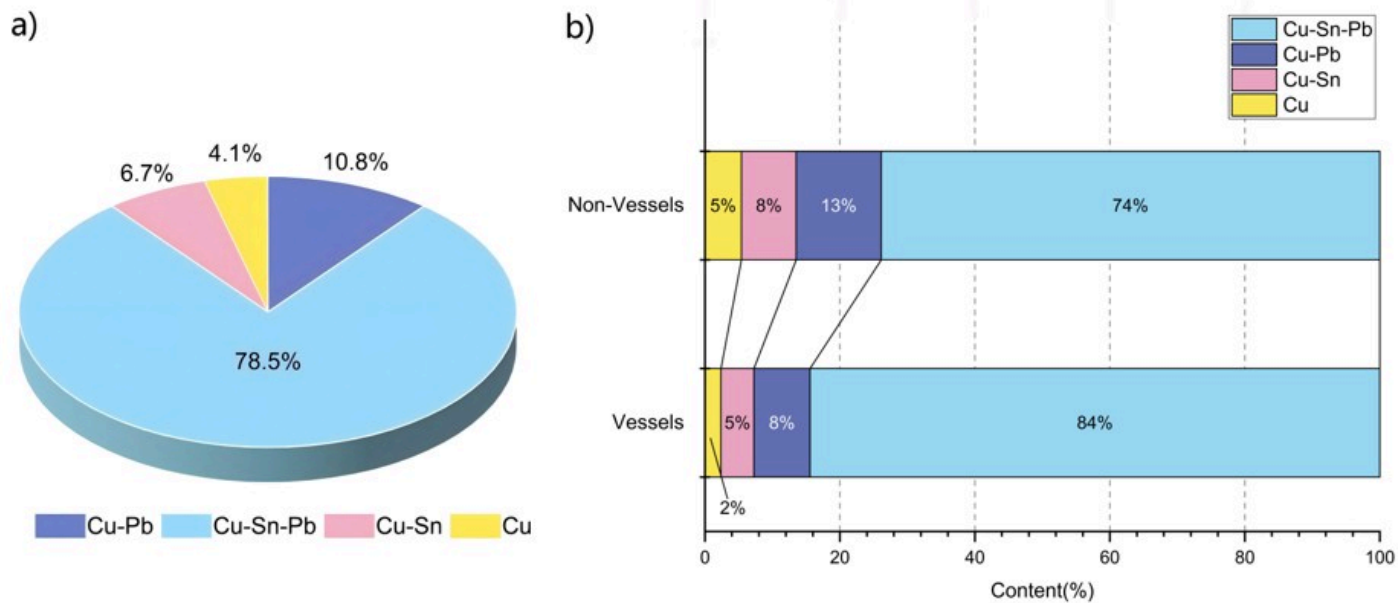


Figure 4

Alloy types for the analyzed Sanxingdui bronzes. a). Pie chart showing the overall distribution of alloy types. b). Stacked bar chart comparing the alloy types between vessel and non-vessel bronze categories.

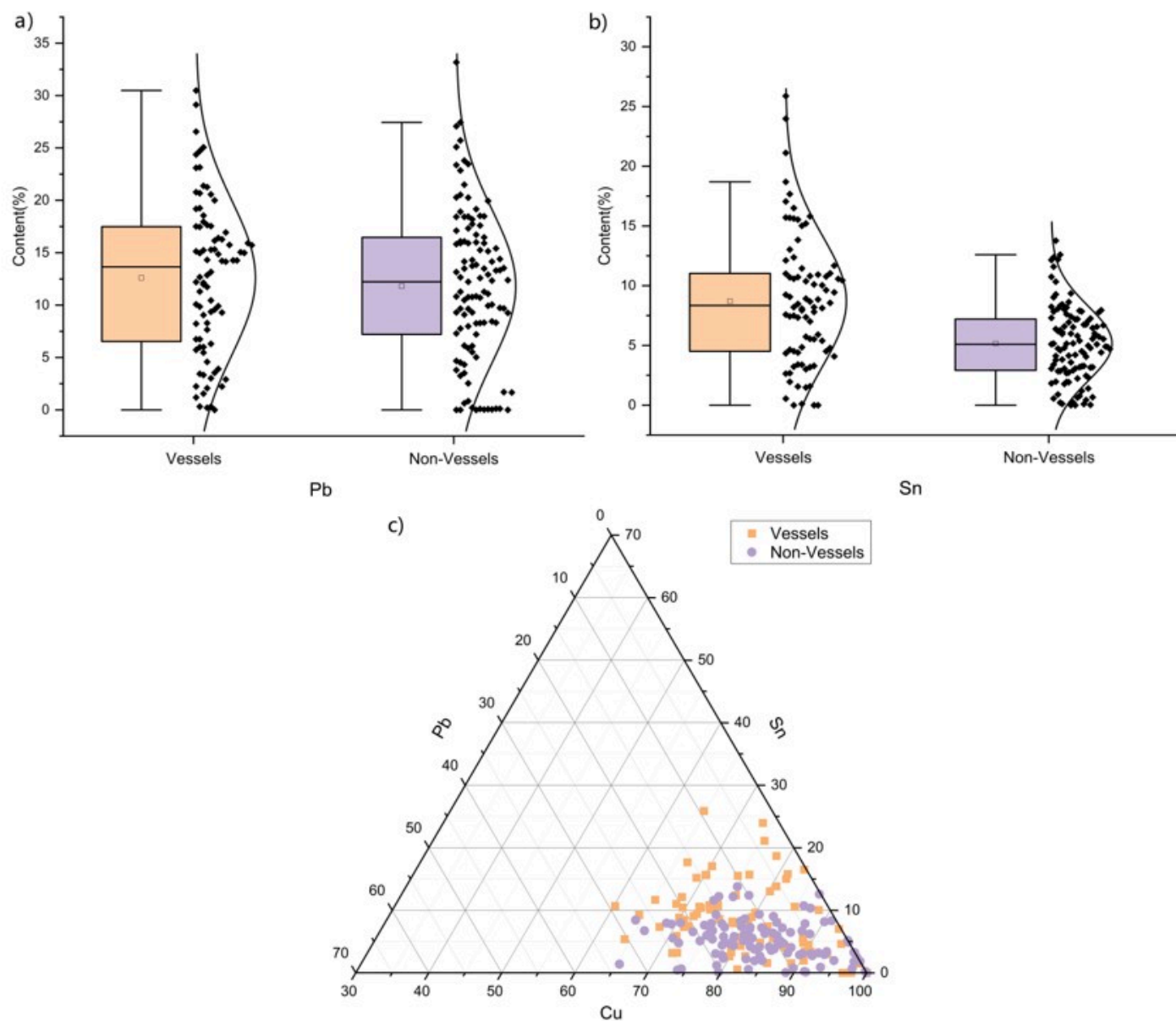


Figure 5

Comparison of Lead (Pb) and Tin (Sn) content in Sanxingdui bronzes. a). Box plot of Pb content for vessel and non-vessel categories. b). Box plot of Sn content for vessel and non-vessel categories. c). Ternary plot (Cu-Sn-Pb) showing the alloy distribution of vessel and non-vessel categories.

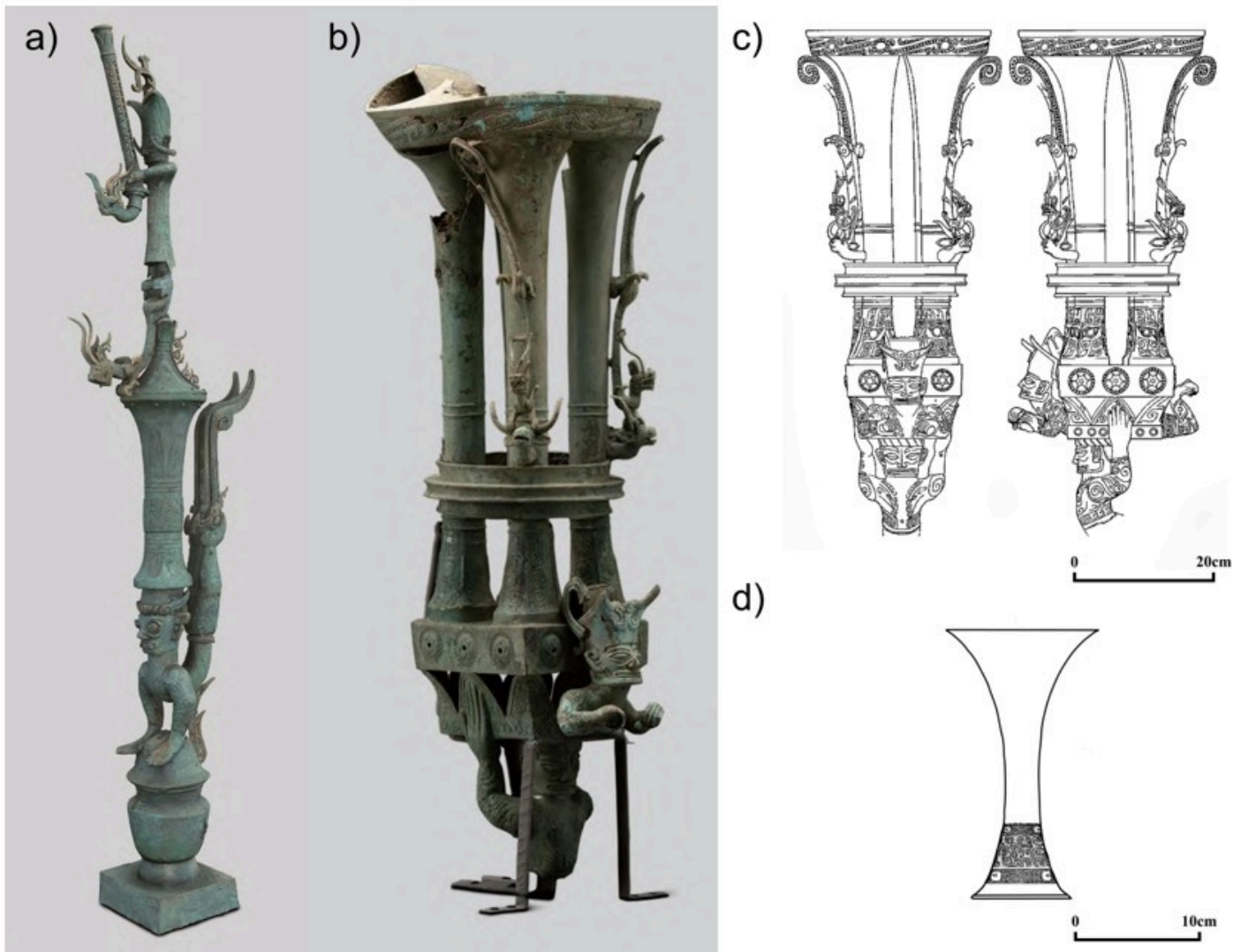


Figure 6

Representative composite bronzes excavated from Sanxingdui. a). Digital reconstruction of the inverted bird-footed figure with a lei-base and zun-top from Pit 8 (Sichuan sheng wen wu kao gu yan jiu yuan (Sanxingdui yan jiu yuan) and Beijing da xue kao gu wen bo xue yuan 2024). b). Photograph of the bronze altar (K3QW:13) from Pit 3 Sichuan sheng wen wu kao gu yan jiu yuan (Sanxingdui yan jiu yuan) and School of cultural heritage and information management Shanghai university 2024). c). Line drawing of the bronze altar (K3QW:13) from Pit 3 (Sichuan sheng wen wu kao gu yan jiu yuan (Sanxingdui yan jiu yuan) and School of cultural heritage and information management Shanghai university 2024). d). Bronze gu excavated from Tomb M7:328 at Zhuyangou, Baoji, for typological comparison (The Baoji Museum 1988).)

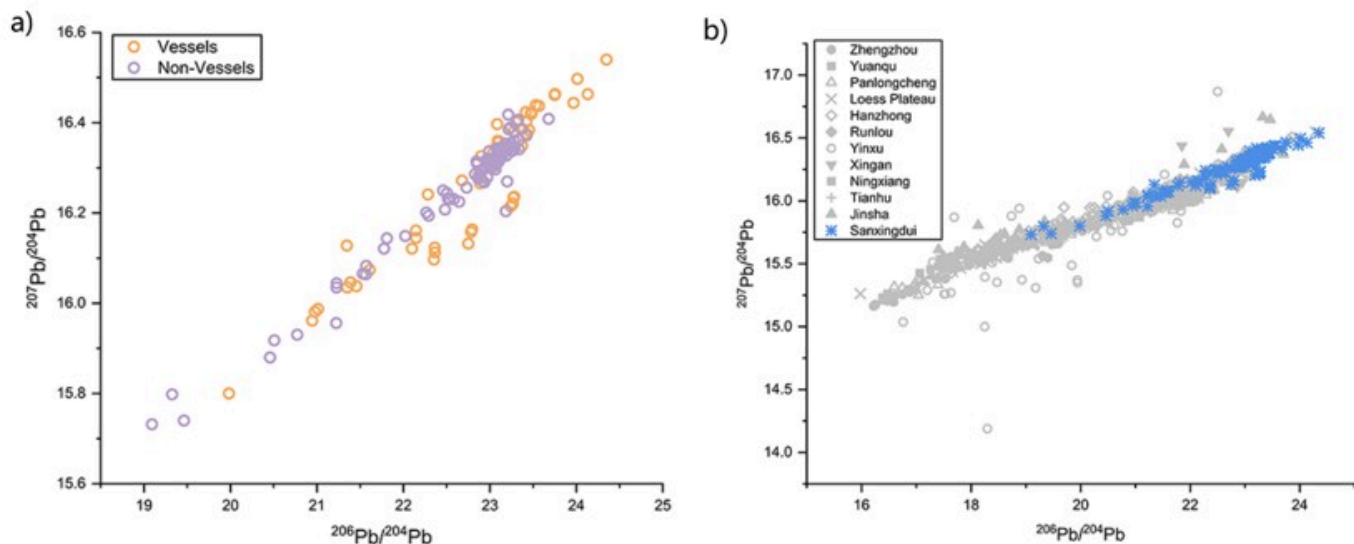


Figure 7

Lead isotope ratio plots. a). Scatter plot of lead isotope ratios for bronze artefacts from Sanxingdui. b). Scatter plot of lead isotope ratios for selected sites dating from the Early Shang to the early Western Zhou period.)

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