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ORIGINAL PAPER

Sources of Western Zhou lead: a new understanding of Chinese Bronze Age supply networks

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Abstract
Bronze vessels are the hallmark of the Chinese Bronze Age, and the formation of the Western Zhou's (1046–772 BC) extensive metallurgical network has been the subject of much scholarly interest. However, what remains unclear is the dynamic circulation of metal within the Zhou realm and its connections with neighbouring regions. Here, the authors utilise published lead isotope data from artefacts and ore bodies to elucidate important spatial-temporal changes in metal supply. While the early Western Zhou demonstrate centralised control over metal resources (primarily lead) taken from its previous Shang Dynasty (1250–1046 BC) as well as from new mining regions in the Yangtze River basin, a major change occurred from the mid-Western Zhou onward, when metal sources in the Yangtze River basin were increasingly exploited, resulting in a shift in bronze-producing system to regional powers. These findings regarding metal circulation broaden our understanding of processes contributing to Zhou politics and the economy, as well as the relationships between the constituent parts of the Zhou realm in addition to neighbouring communities.

Keywords Chinese Bronze Age · Western Zhou · Lead isotope geochemistry · Provenance · Bronze metallurgy

Introduction

During its rule, Bronze Age China's Western Zhou dynasty (1046–771 BC) forged an extensive network by which raw metal and products circulated throughout its realm (Feng 2018 and references therein). The Zhou royal house in the Wei River valley encouraged family members and allies to establish colonies in the Yellow and Yangtze River basins (Fig. 1). Transmitted texts and bronze inscriptions provide some evidence of the circulation of metal through the process of warfare, gift-giving, trade, and marriage between both the Zhou colonies and the Zhou and neighbouring non-Zhou communities, known historically as Jing, Chu, and Huaiyi (IA CASS 1984–1994; Yi 2011: 139–49; Yang 2005). However, the textual evidence sheds little light on the question of whether the Zhou people secured routes to transport various metal resources from foreign regions, particularly metalliferous districts in the Yangtze area, where abundant Bronze Age production remains have been found in recent years (Cui 2016).

The Western Zhou polity is here defined as the region under the control of the Zhou royal house. This includes both the territory that the court administered directly, as well as land governed by the rulers of regional states from the royal Ji lineage or other clans. Archaeological finds, transmitted texts, and vessel inscriptions suggest that these states' lands and tenants were bequeathed by the Zhou king in exchange for their submission, which they demonstrated through tribute and military aide (IA CASS 2004: 197–99). Interpretations of the relationship between the Zhou realm's constituent parts have been the subject of much discussion. One theory holds that all regional states were controlled entirely by the Zhou king, even if they were given a high degree of freedom in managing their own affairs (Zhao 1990: 206–219 & 321–28). Alternatively, it has been suggested that the Zhou king was simply the head of an equal alliance between states (of which the Zhou was one) (Tian 1992: 385–415). Similarly, political control is suggested to have been concentrated in the sites of the Zhouyuan, as well as Fenghao and Chengzhou

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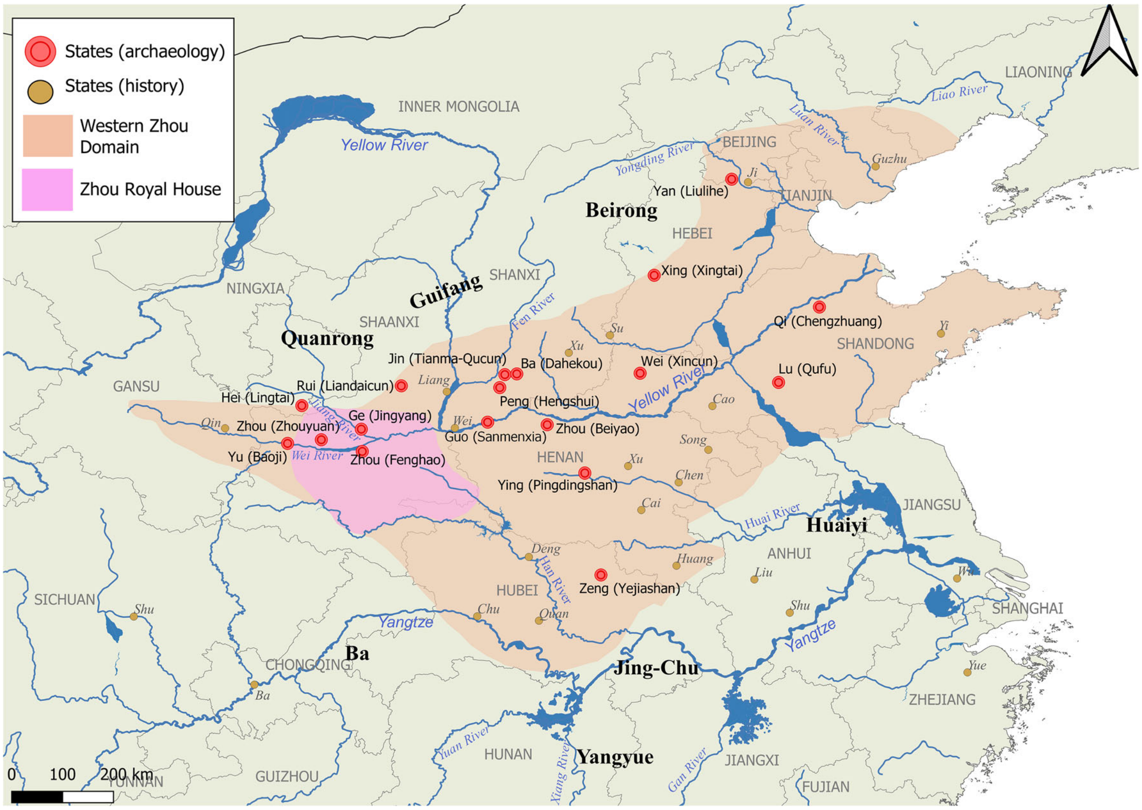

Fig. 1 The Western Zhou states. The borders of the Zhou royal house and its domain are based on historical and archaeological data, and the locations of groups outside the Zhou realm are indicated generally, as textual records to link specific sites with these groups are lacking

(Hsu 1984: 86–87; Xu 2017: 476), but it has also been argued that these sites served various administrative, diplomatic, and ritual functions that the Zhou used to manage relations with the regional states (Khayutina 2008). In this model, centralised control over the regional states was attempted but rarely achieved, particularly towards the end of the Western Zhou period (Khayutina 2010; Shelach-Lavi 2015: 266).

Outside of the Zhou realm were peoples with whom the Zhou had complicated relations, oscillating between hostile and collaborative (Zhu 1988). Expansion of the polity involved migration of Zhou people, as well as the integration of non-Zhou groups into the Zhou lineage and ritual systems through marriage, with military conquest also playing a role (Li 2006: 49–58; Falkenhausen 2006: 244; Khayutina 2017; Rawson 2019). In some cases, these outside groups already sharing common social and cultural features with the Zhou, which facilitated their integration into the Zhou polity (Khayutina 2017: 112). Despite this, archaeological finds presently indicate that areas north and south of the Yangtze River, as well as north of the Zhou realm, remained outside of archaeologically visible Zhou networks (Rawson 2019: 6), indicating that they were politically autonomous.

Within Western Zhou society, bronze occupied a unique position, being the material of choice for huge cast vessels that were central to the Zhou ritual system. This system both reflected and underpinned constructs of clan, lineage, and ancestor worship (Shelach-Lavi 2015: 278–80). The bronzes were also presented on major social occasions, such as marriages (Khayutina 2014), as well as by the Zhou to rulers of regional states and outside groups (Khayutina 2010). Consequently, much research has been dedicated to identifying metal sources for these bronze vessels and other artefacts. In recent years, understanding of the Zhou metallurgical network, predominantly based on textual sources and stylistic typologies (e.g. Rawson 1990; Shaughnessy 1991; Sun 2017), has been complemented and sometimes revised by chemical analyses. Most recently, Li et al. (2020a, b) examined the copper used in bronze artefacts, finding that the regional states had some access to independent copper sources that they used to make low-quality objects, whereas high-quality bronze vessels excavated from these states as well as the metropolitan Zhou area shared similar chemical characteristics, indicating centralised control over the casting of such items.

A method that illuminates another aspect of bronze industry is lead isotope geochemistry (e.g. Cui & Wu 2008; Jin et al. 2017), which has allowed researchers to trace the lead used as an alloy in bronze vessels—as opposed to the copper—and shed new light on the dynamic circulation of both raw metal and finished metal artefacts. Although promising, most studies have relied on limited artefact assemblages or incomplete reference databases to compare the archaeological metal, as most lead isotope data for Zhou metal artefacts are not published alongside artefacts' chemical compositions (an exception is Yejiashan). This issue hinders the exploration of the copper used in bronze.

This study compares published lead isotope values for an unparalleled number of Western Zhou artefacts ($n = 758$) against a comprehensive ore reference database recently compiled by Hsu and Sabatini (2019) to provide a new reading of late Chinese Bronze Age geopolitics. Specifically, we examine diachronic changes in the lead supply network, identify potential raw material sources, and compare variation in lead-use between the Zhou states, as well as between these states and groups on their peripheries.

Lead isotope research and database

Lead isotope research on Western Zhou bronzes specifically was relatively sparse before the early 2000s. In 1988, Barnes et al. examined lead isotope compositions of approximately 400 unprovenanced Shang and Zhou bronze vessels from the Arthur M. Sackler Collections, of which 127 dated to the Western Zhou. They found that styles of vessel mainly excavated from the Zhou heartland in the Wei River valley formed a separate cluster from Shang and Eastern Zhou bronzes. In 2000, Jin et al. analysed bronzes excavated from the Jin state cemetery at Tianma-Qucun, identifying three isotopic groups among early Western Zhou objects: two were classed as 'common lead' ($^{206}Pb/^{204}Pb \approx 17.5–18.5$) and one as 'highly radiogenic lead' ($^{206}Pb/^{204}Pb > 19$). Similar methods have been applied to the bronze assemblages from Liulihe and Baoji (Cui & Wu 2008:40). In these studies, however, the little lead isotope data available for Chinese ore deposits mean that they essentially describe isotopic patterns with little reference to geological sources.

Over the last decade, an increasing amount of lead isotope data have been published, allowing researchers to link metalwork to ore sources, trace metal circulation, establish possible trade networks, and theorise production structures. For instance, Yu et al.'s (2016) study of the early Western Zhou Zeng state at Yejiashan highlights two major sources of lead: one with $^{206}Pb/^{204}Pb$ around 18–18.2 and the other around 17.6, with the former supposedly from the middle and lower Yangtze and the latter from the eastern Qinling. Comparing inscriptions on the vessels led the study to conclude that the Zhou states' bronze production was centralised in the royal foundries.

Despite recent advances, a coherent picture of the supply network throughout Western Zhou territory is lacking, as most studies have been regional case studies. Furthermore, the majority of these provenance bronzes use lead isotope data from ores. These often include a substantial amount of poor-quality legacy data, generally lacking any record of experimental details, including the effect of mass bias, the reproducibility of NBS-981 lead standard, and measurement errors. It has been shown that measurements of ore samples taken before the year 2000 often have high experimental errors (~ 0.5%) and are thus unsuitable for determining provenance (Hsu & Sabatini 2019: S1 Appendix). For instance, legacy data for three prehistoric mining areas in the Yangtze River basin exhibit large variations in their isotopic values (Fig. 2), as opposed to the tighter clusters of new measurements. This demonstrates that individual mines' isotopic arrays in old data overlap, meaning that the provenance of metal objects is considerably more ambiguous. Critical selection of published data is therefore crucial for determining geologic sources of archaeological metal.

To this end, we have assembled a large number of lead isotope values for excavated Western Zhou bronze artefacts to compare against a comprehensive ore reference database compiled by Hsu and Sabatini (2019). For bronze artefacts, we collected all available isotopic ratios to cover as large a geographic extent as possible, while ore data were selected to comprise mainly galena samples from after the year 2000, when new instruments and analytical protocols were developed, allowing for more precise lead isotopic measurements. We also include materials from immediately before and after the Western Zhou to better characterise the Zhou metal network in the broader context of Bronze Age metallurgy. All lead isotope data used in this paper are accessible via the online supplementary material (OSM) and the Harvard Dataverse repository (see Hsu and Sabatini 2019 for details). Artefacts include materials from Anyang (Yinxu IV phase [$n = 34$]), the Zhou states (Zhouyuan [$n = 35$], Beiyao [$n = 17$], Tianma-Qucun [$n = 204$], Yejiashan [$n = 164$], Liulihe [$n = 28$], Baoji [$n = 51$], Hengshui [$n = 18$], Dahekou [$n = 6$], Sanmenxia [$n = 20$]) and communities outside the Zhou realm (Xiajiadian [$n = 85$], Shigudun [$n = 12$], Tanheli [$n = 47$], and Gaoshaji [$n = 73$]). The ritual vessel, which occupies approximately 55% of the data set, is the most abundant grave good in the majority of the Zhou cemeteries. The exceptions are Baoji and Liulihe sites, where the artefacts are mainly weaponry and chariot fittings. Meanwhile, the object types sampled at Zhouyuan and Beiyao have not been reported. Although some sites are represented by markedly fewer samples than others, this reflects the largest number of high-quality lead isotope data published to date. The ores are mostly galena samples from major lead-zinc metallogenic districts that are geographically or archaeologically relevant (Fig. 3). For the Middle–Lower Yangtze River Metallogenic Belt (MLYMB), other non-lead minerals are also included (see OSM1), as this province hosts more than 200 polymetallic copper deposits, and lead was potentially mined alongside copper in the past. Each entry in OSM1 represents one artefact, and, in cases

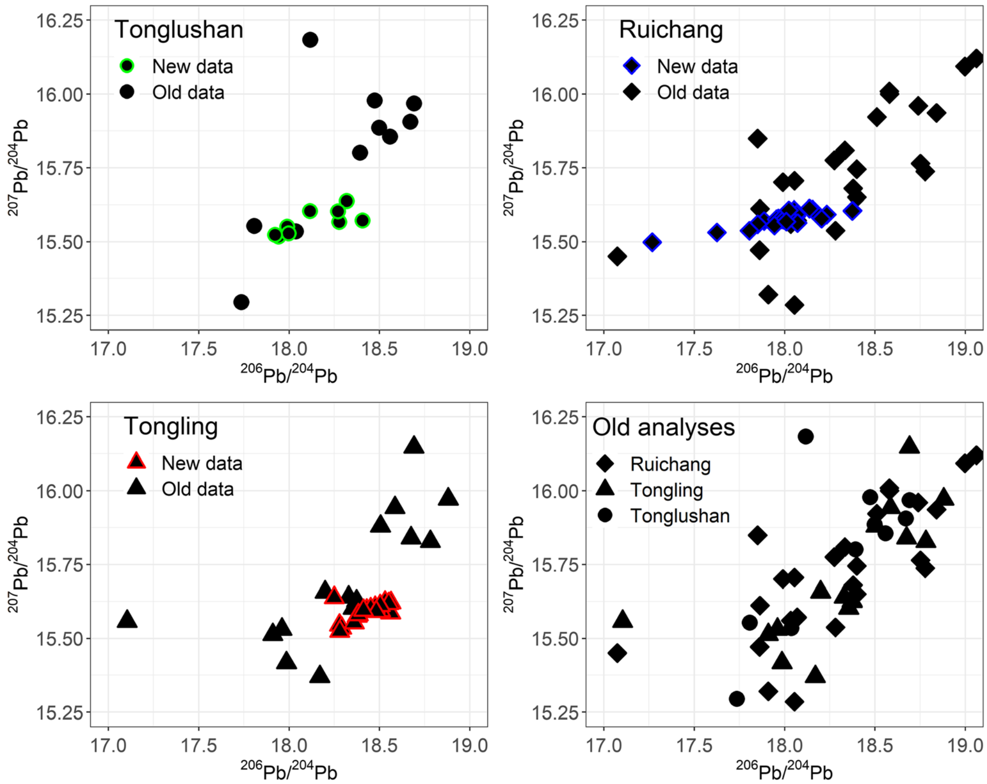

Fig. 2 Comparison of old and new lead isotope data for the same prehistoric mines (see OSM1 for citations)

where multiple measurements were available for one artefact, we have used the average.

Visualisation of data was performed using the open-source programming language R (R core team 2017) with the package ggplot2 (Wickham 2016). The ks package was used for the bivariate kernel estimation that shows the probability contours of data sets Duong (2020). The code for generating these contour plots can be found in OSM2.

Diachronic change in lead sources

To identify changing lead sources or intensive use of multiple sources, the $^{206}Pb/^{204}Pb$ ratios of the bronze assemblages are compared across the late Shang (c. 1250–1046 BC), the early Western Zhou (c. 1046–950 BC), the mid-Western Zhou (c. 950–850 BC), the late Western Zhou (c. 850–771 BC), and the early Spring and Autumn (c. 800–650 BC) periods (cf.

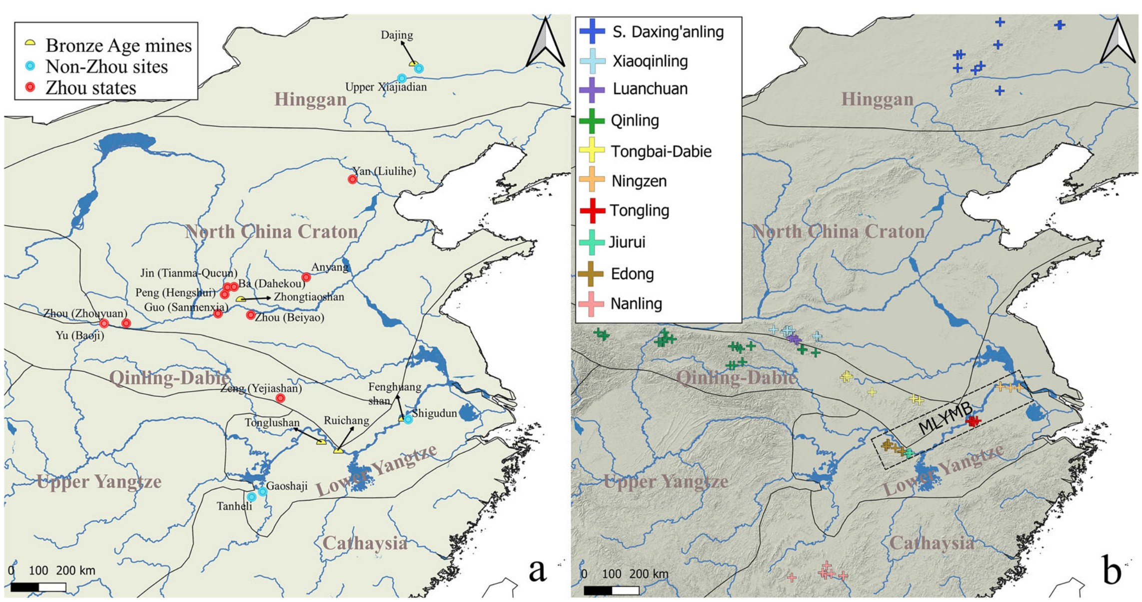

Fig. 3 **a** Bronze assemblages included in this study and **b** relevant metallogenic districts

Pollard et al. 2018: 156–8). Two distinct lead signatures, group I ($^{206}Pb/^{204}Pb \approx 17.4–17.6$) and group II ($^{206}Pb/^{204}Pb \approx 17.9–18.2$), are clear (Fig. 4), with group II becoming more prevalent over time. In the late Shang, group I is most common, and this pattern continues into the early Western Zhou. This agrees with earlier results from Cui & Wu (2008). Starting in the early Western Zhou, the proportion of objects with lead isotope ratios outside of group I increases, while group I objects become less common and virtually disappear by the late Western Zhou. In contrast, group II exhibits the opposite pattern, which is rare in late Shang assemblages but ubiquitous in early Western Zhou ones. This lead then appears constantly into the early spring and autumn, with progressively tighter clustering around $^{206}Pb/^{204}Pb \approx 18$.

The identification of group I and group II lead is primarily based on two observations. Firstly, the kennel density estimation of one isotopic value ($^{206}Pb/^{204}Pb$) explicitly demonstrates the concentration of two types of lead over the periods under study, particularly group I for the late Shang and group II for the early spring and autumn. Although ratios from others intervening periods present a more complex picture with a spread of values between I and II, the general trend of using these two lead sources is the same, as demonstrated in Fig. 5. One striking feature is that the rapid decrease in group I lead, which corresponds to the transition from the early Western Zhou to mid-Western Zhou. Apart from bronze artefacts themselves, metallogenic settings of China could also hint at the origin and occurrence of group I and group II lead. The shift in isotopic composition between these two lead signatures may indicates a move from exploiting Precambrian (c. 700–850 Ma) lead-bearing ores in the North China Craton to Phanerozoic (c. 400–500 Ma) ones in the Lower Yangtze (Fig. 3).

Possible auxiliary sources of lead are evident in the distributions outside of groups I and II. This includes the so-called 'highly radiogenic lead' ($^{206}Pb/^{204}Pb > 19$), which exhibits a negative model age (Fig. 4a). The significance of this anomalous component has been addressed by other authors (e.g. Jin et al. 2017) and is not pursued further in this study. Another unique lead signature is characterised by high $^{206}Pb/^{204}Pb$ values (18.25–19), which generates a young model age (c. 0–400 Ma), typical of lead-bearing deposits from South China, particularly the Upper Yangtze and Cathaysia (Zhu 1995). This high radiogenic lead appears consistently in the early and mid-Western Zhou assemblages. Finally, a number of leaded bronzes fall into an intermediate range between groups I and II, representing either a unique geological source or a mixture of high and low ratio leads.

There are several implications of these isotopic patterns. Firstly, the continuation of group I lead from the late Shang into the early Western Zhou suggests that the Zhou took appreciable amounts of metal from their predecessor. After the Zhou conquest c. 1046 BC, Shang bronzes were distributed throughout the Zhou ruling class and its allies (Hwang 2012). Meanwhile, the Shang foundries might have continued in operation and produced ritual vessels for early Western Zhou elites (Zhang 2019).

Secondly, the sudden rise of group II metal coincides with early Western Zhou military expansion into new territory, which facilitated the transport of exotic goods, possibly including new metal resources (Qiu 1978; Rawson 1999). Indeed, campaigns by the Zhou kings in the lower Ordos region, the eastern Shandong Peninsula, and the middle Yangtze are well documented (Liu 2000). These expeditions probably allowed the Zhou to both plunder raw metal and establish tributary relations to ensure access to metal produced by these communities. Archaeological evidence also demonstrates, however, that metal resources were obtained through peaceful means in the forms of gift-giving at the state level or for marital alliances, as seen at the regional cemeteries of Liulihe, Hengshui, and Yicheng (Khayutina 2014; Sun 2017).

Thirdly, the marked decline in group I metal corresponds to the mid-Western Zhou period, when a major ritual reform took place around the ninth century BC manifesting in new,

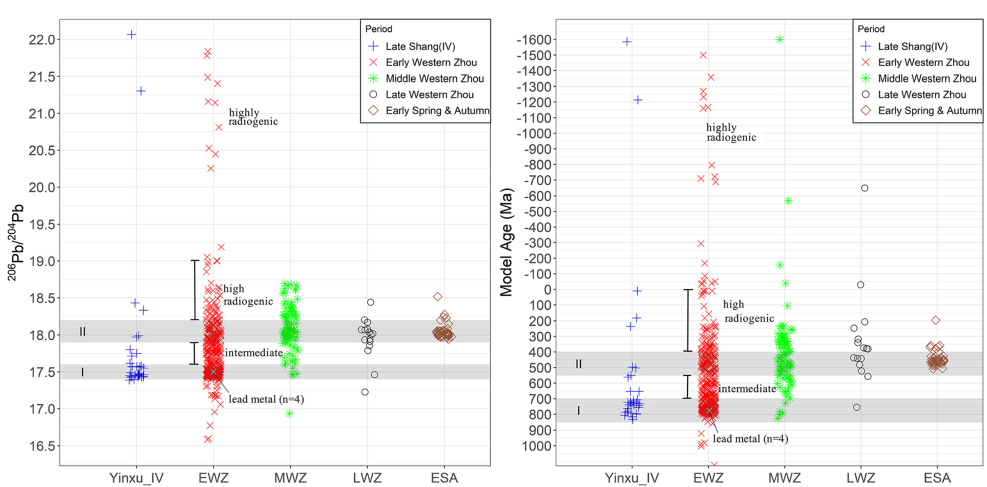

Fig. 4 Chronological change in lead isotope compositions of bronze artefacts by (**a**) isotopic ratio $^{206}Pb/^{204}Pb$ and (**b**) model age

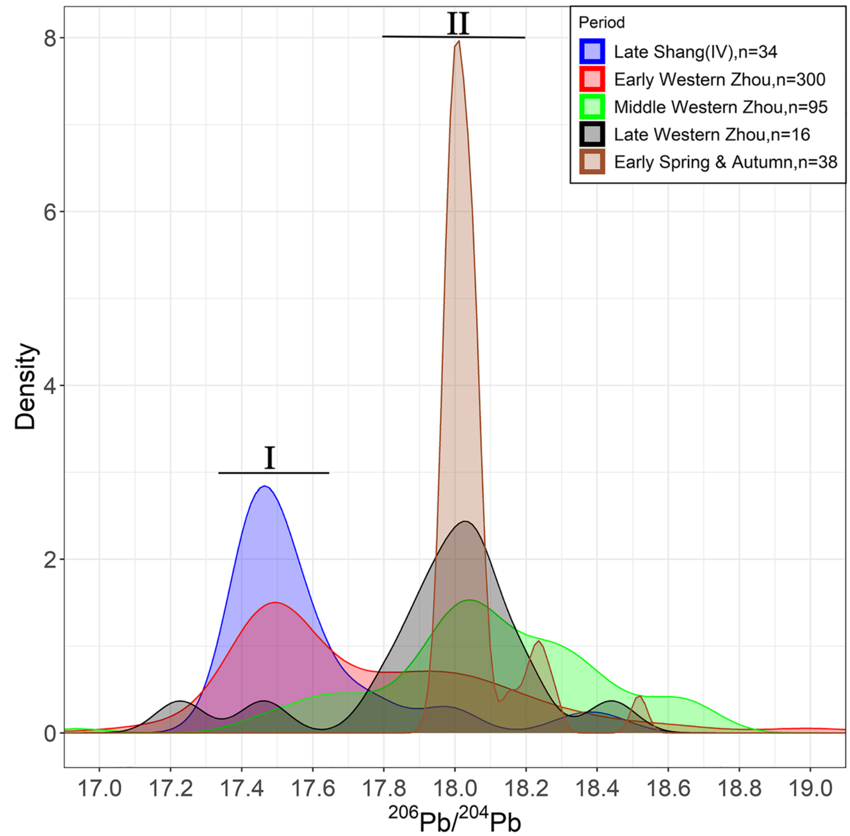

Fig. 5 Kernel density plot of isotopic ratio 206Pb/204Pb of study material. It shows two pronounced peaks identified here as group I and group II lead

standardised forms of bronze vessels (Rawson 2013). This critical change in bronze ritual may indicate a shift in aesthetic tastes from those in line with Shang traditions to Zhou craftsmanship.

Lead sources

The lead isotopic signatures can be compared against those of modern ores from important metallogenic districts to identify potential geological origins. They can be roughly divided into northern and southern districts. The northern ones include the Xiaoqinling, Luanchuan, Tongbai-Dabie, Qinling, and South Daxing'anling areas. The first four areas are of particular interest, as these lead sources are nearest to the metropolitan Zhou and in contrast the South Daxing'anling hosts several mines contemporary with the Western Zhou (Dong 2012). The southern districts comprise Ningzhen, Tongling, Edong, and Jiurui in the MLYMB and Nanling regions of southern Hunan.

Lead isotope values for galena ores from the northern districts are compared against early Western Zhou group I and group II leads with 95% confidence levels in Fig. 6. Due to the Tongbai-Dabie district's complex, multi-stage mineralisation history (Wu & Zheng 2013), its lead displays extremely variable isotopic compositions with consistently lower $^{206}Pb/^{204}Pb$ and higher $^{208}Pb/^{204}Pb$ values than the Zhou bronzes. Some of the ores exhibit anomalously low $^{206}Pb/^{204}Pb$ values (~ 16.5), which are beyond the extent of Fig. 6 a. Likewise, Xiaoqinling and Luanchuan are marked by complex, heterogeneous isotope signatures, which, compared to the bronze artefacts, are depleted in $^{207}Pb/^{204}Pb$ but enriched in $^{208}Pb/^{204}Pb$. Qinling and South Daxing'anling are more radiogenic ($^{206}Pb/^{204}Pb > 18$) than the other districts. While the South Daxing'anling ores do not match the early Western Zhou values, those from Qinling overlap partially with the group II bronzes, some of which have high radiogenic lead. Lead-bearing deposits at Qinling are the only northern candidates for the source of lead in Western Zhou bronzes. The same is evident for the middle and late Western Zhou bronzes, apart from the disappearance of group I lead, which had been the primary source for the early period (Fig. 7).

Despite the absence of archaeological evidence for Bronze Age mining at most mineral deposits in the north, they deserve serious consideration as potential sources for Western Zhou lead. In particular, the Xiaoqinling, Luanchuan, Tongbai-Dabie, and Qinling sources are close to the Zhou heartland and located on tributaries of the Yellow and Yangtze rivers. These rivers could have provided passage for the Zhou's expansion into the southern basin, as suggested by early Western Zhou archaeological remains distributed along the Qinling to Tongbai-Dabie (Fang 2014). Mineral resources were

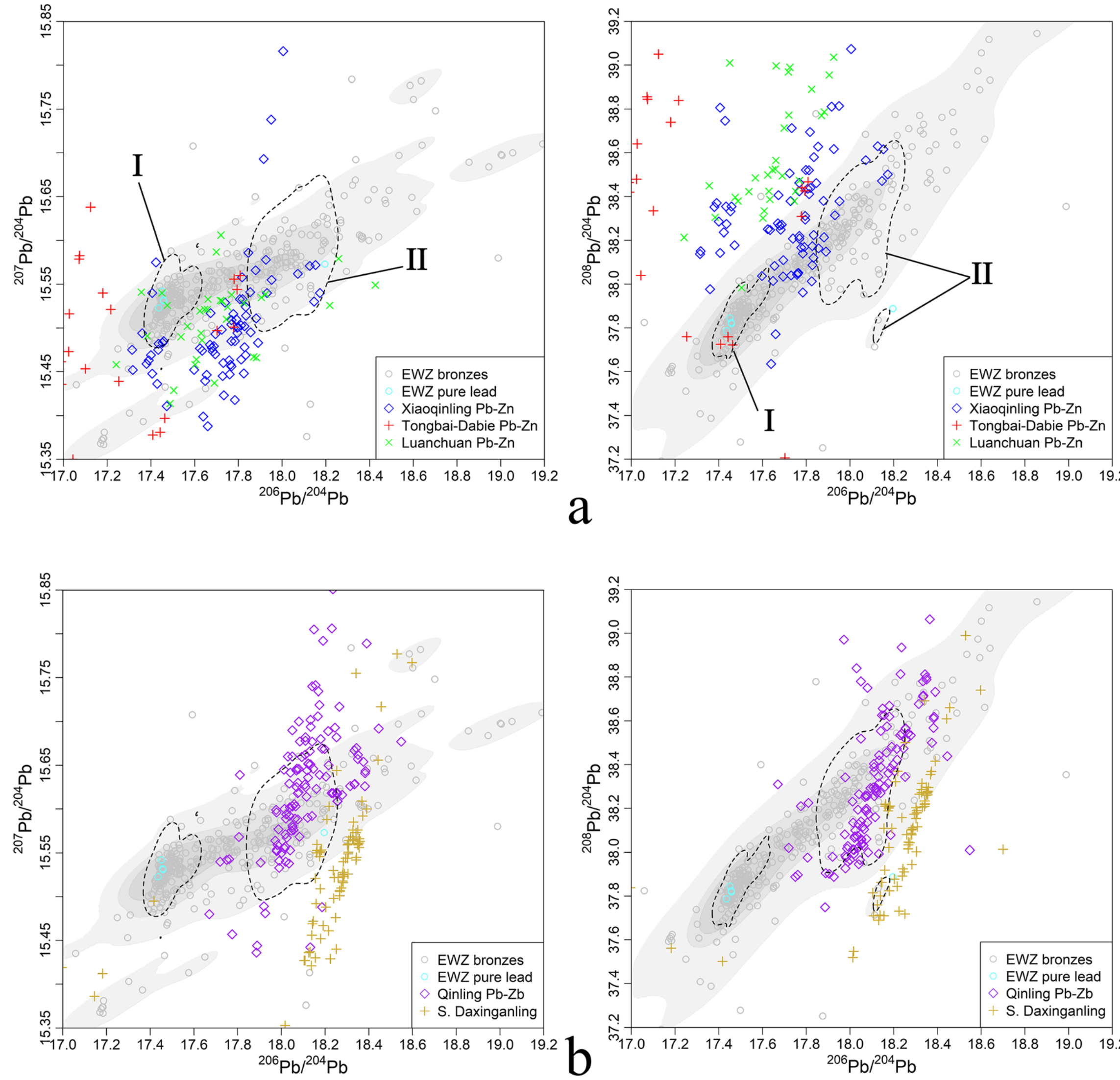

Fig. 6 Lead isotopic ratios of early Western Zhou bronzes against those of northern ore deposits: (**a**) Xiaoqinling, Tongbai-Dabie, and Luanchuan; (**b**) Qinling and South Daxing'anling. Two circular dashed lines indicate the 95% confidence intervals of group I (17.4–17.6) and group II (17.9–18.2) objects. Grey areas represent all bronze artefacts' kernel density distributions at 50%, 75%, and 95% (from dark to light colours)

potentially exploited during the Zhou's colonisation of the area. Inscribed bronze vessels testify to regular military conflict between the Zhou and the Jingchu, Yangyue, and Huaiyi to the south, which led to the Zhou's acquisition of raw metal and metal objects from the middle and lower Yangtze regions (IA CASS 1984–1994). The metal was probably also acquired more diplomatically through mechanisms of exchange and gift-giving, as occurred between the Zhou and regional states (Khayutina 2014; Sun 2017).

The Xiaoqinling, Luanchuan, and Tongbai-Dabie regions are isotopically heterogeneous, and there is no clear match between their ores and the Zhou artefacts. These regions are characterised by galena ores of Precambrian age, similar to the model ages for group I lead, thus it remains a possibility that unanalysed ore bodies in these areas host pockets of radiogenic lead analogous to the group I artefacts. Alternatively, Qinling is a promising source for Western Zhou bronzes with group II and high radiogenic isotope values. There is ample evidence for smelting activity at nearby Laoniupo during the late Shang period, and the raw materials are thought to have come from Qinling (Chen et al. 2017). In addition, local inhabitants began exploiting turquoise mines around 2000 BC, demonstrating that they had the necessary skills and technical knowledge to exploit minerals (Li et al. 2016).

The isotope ratios of southern metallogenic districts are compared to those of the objects in Figs. 8 and 9. The MLYMB has lead isotope compositions consistent with the early Western Zhou data distributed across three distinctive signatures (intermediate, group II, and high radiogenic). Ores from Ningzhen have the lowest ^{206}Pb/^{204}Pb values compared to other districts in the MLYMB, and they clearly match the middle section of the early Western Zhou array. In contrast,

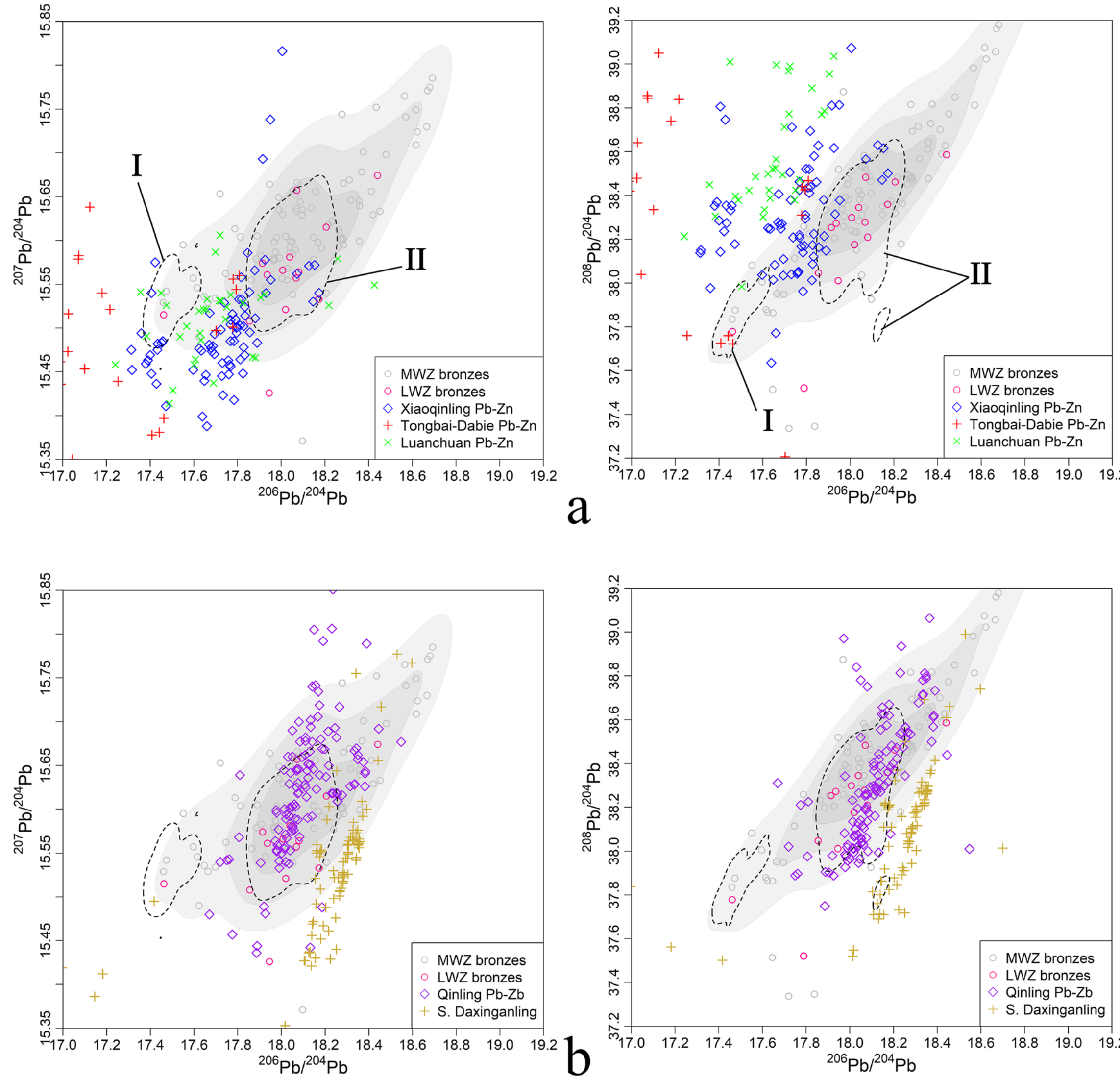

Fig. 7 Lead isotopic ratios of middle and late Western Zhou bronzes against those of northern ore deposits: (**a**) Xiaoqinling, Tongbai-Dabie, and Luanchuan; (**b**) Qinling and South Daxing'anling. Grey areas represent all bronze artefacts' kernel density distributions at 50%, 75%, and 95% (from dark to light colours)

the districts of Edong and Jiurui overlap and fall within the distribution for group II. Ores from Edong in particular are relatively dispersed, intersecting both Jiurui and Tongling values. Finally, ores from Tongling and Nanling exhibit more elevated radiogenic lead values than the other districts, with their isotopic ratios overlap partially with the high radiogenic group from the Western Zhou artefacts (Figs. 8b and 9b). The possible origins of the types of lead mentioned above are listed in Table 1.

Mineral deposits in the MLRYB are known to have been exploited during the Bronze Age, especially in Edong, Jiurui, and Tongling. The Ruichang copper mine at Jiurui was first exploited during the early Shang period, which continued into the Western Zhou (Chen 2014:48). Additionally, the Tonglushan copper mine at Edong was a large-scale mining site active from the late Shang and into the imperial period (post-221 BC) (Chen 2014:48). Several small-scale sites provide evidence of mining activity at Tongling, the earliest of which dates to the Western Zhou (Chen 2014:49). Although these prehistoric mines are thought to have mainly supplied copper, a cluster of lead-bearing deposits with similar isotopic signatures to the copper are located nearby, suggesting the exploitation of lead alongside copper. Ningzhen, on the other hand, is characterised by a relatively older model age, and its isotopic signature corresponds to intermediate values between groups I and II. Although evidence of prehistoric mining in Ningzhen is currently lacking, one well-known early Western Zhou ritual vessel—Yi *hou* Ze *gui*—found in Dantu, Jiangsu, is markedly similar to ones from the metropolitan Zhou area (Li 1985). Based on the isotopic data and archaeological finds, the possibility that Ningzhen was the source for the intermediate-value objects cannot be ruled out.

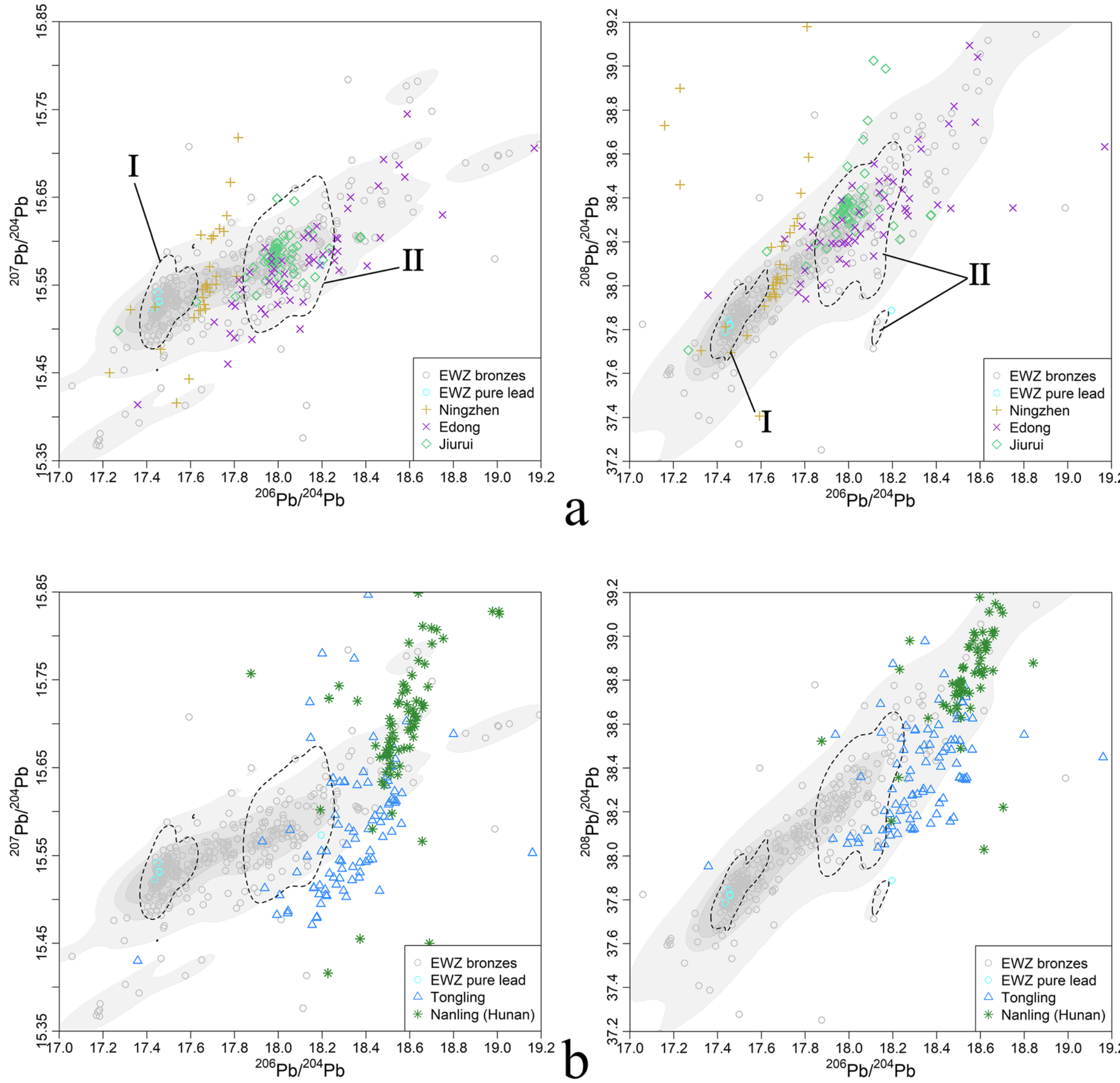

Fig. 8 Lead isotopic ratios of early Western Zhou bronzes against those of southern ore districts: (**a**) Ningzhen, Edong, and Jiurui; (**b**) Tongling and Nanling

In addition to the exploitation of mines in the MLRYB, the presence of high radiogenic lead in some of the Western Zhou bronzes also indicates a source in the Nanling metallogenic belt (Fig. 3), which hosts many large tungsten-tin polymetallic deposits with similar isotopic characteristics. This is important to understanding the reach of Western Zhou metal-trading network, as it reflects an early long-distance connection with the extreme south.

When using lead isotope tracers to provenance archaeological metal, it is important to acknowledge that different metallogenic districts' values can overlap. For instance, even though the Qinling and MLRYB regions are geographically separate, their ore bodies overlap a lot (Hsu & Sabatini 2019: 12), meaning that artefacts falling within the area of overlap cannot be attributed to either source with confidence. Current archaeological evidence supports use of the MLRYB sources; however, the possibility of early exploitation in the Qinling cannot be ruled out. Another issue to consider when interpreting lead isotope analysis results is that ancient metal-workers recycled old bronzes and probably mixed lead from different sources, which prompts the question of whether the intermediate group of isotope values in Western Zhou bronzes reflects a genuine source, like Ningzhen, or a mix of group I and group II leads. The simultaneous decline of intermediate and group I lead from the mid-Western Zhou implies that the intermediate metals were the result of mixing, disappearing when the group I source was no longer used.

Internal and external supplies

The Western Zhou was a sophisticated political institution comprising three spheres: the Zhou royal house, states ruled by the Ji family—the ancestral ruling clan—and states ruled by outsider families. Surprisingly, assemblages from all early Western Zhou states have overlapping isotopic signatures,

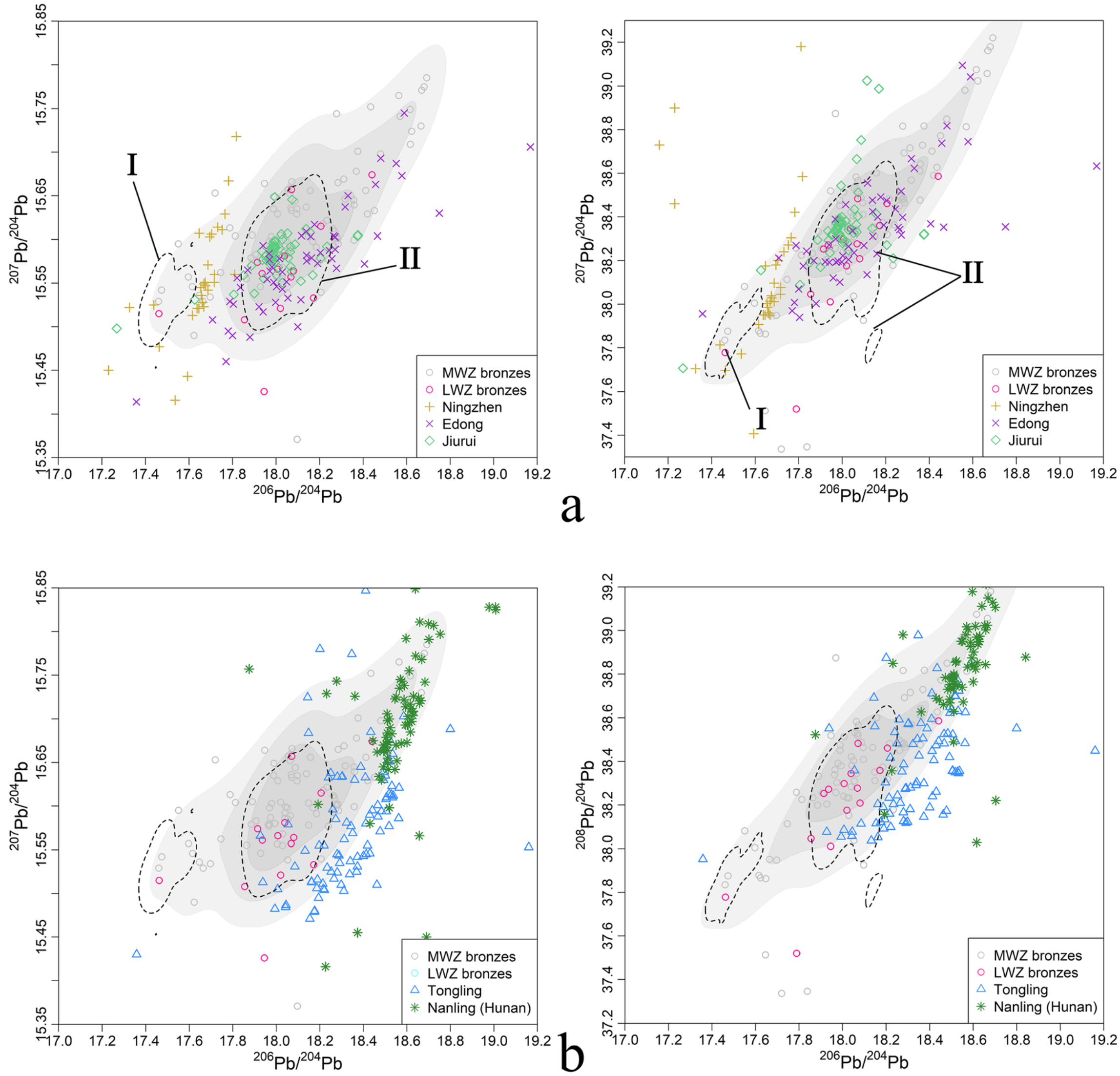

Fig. 9 Lead isotopic ratios of middle and late Western Zhou bronzes against those of southern ore districts: (**a**) Ningzhen, Edong, and Jiurui; (**b**) Tongling and Nanling

regardless of geographic location or political status (Fig. 10a). Furthermore, while group II metal most likely came from sources at Edong and/or Jiurui, which witness the new supply network established by the Zhou, group I's values match those of a furnace/crucible lining from Xiaomintun, a late Shang foundry site at Anyang. The consistency between early Western Zhou bronzes and the late Shang foundry suggests that early Zhou bronze production was largely reliant on the earlier Shang supply network. It has been argued that the early Western Zhou continued to manufacture bronze ritual vessels at the Shang foundries using the same raw material sources and casting techniques (Lei 2008). A late Shang hoard at Anyang was recently discovered containing 293 lead-copper ingots that weighed approximately 3404 kg (Tang et al. 2018). Twelve of the ingots have identical lead isotope signatures (group I) to those from Xiaomintun (Liu et al. 2018). This

Table 1 Summary of possible lead sources

Type	$^{206}Pb/^{204}Pb$	Model age (Ma)	Possible source
Group I	17.4–17.6	700–850	Xiaoqinling, Tongbai-Dabie, Luanchuan
Group II	17.9–18.2	400–500	Edong, Jiurui, Qinling
Intermediate			Ningzhen, mixed sources (groups I and II)
High radiogenic	18.25–19	0–400	Tongling, Nanling

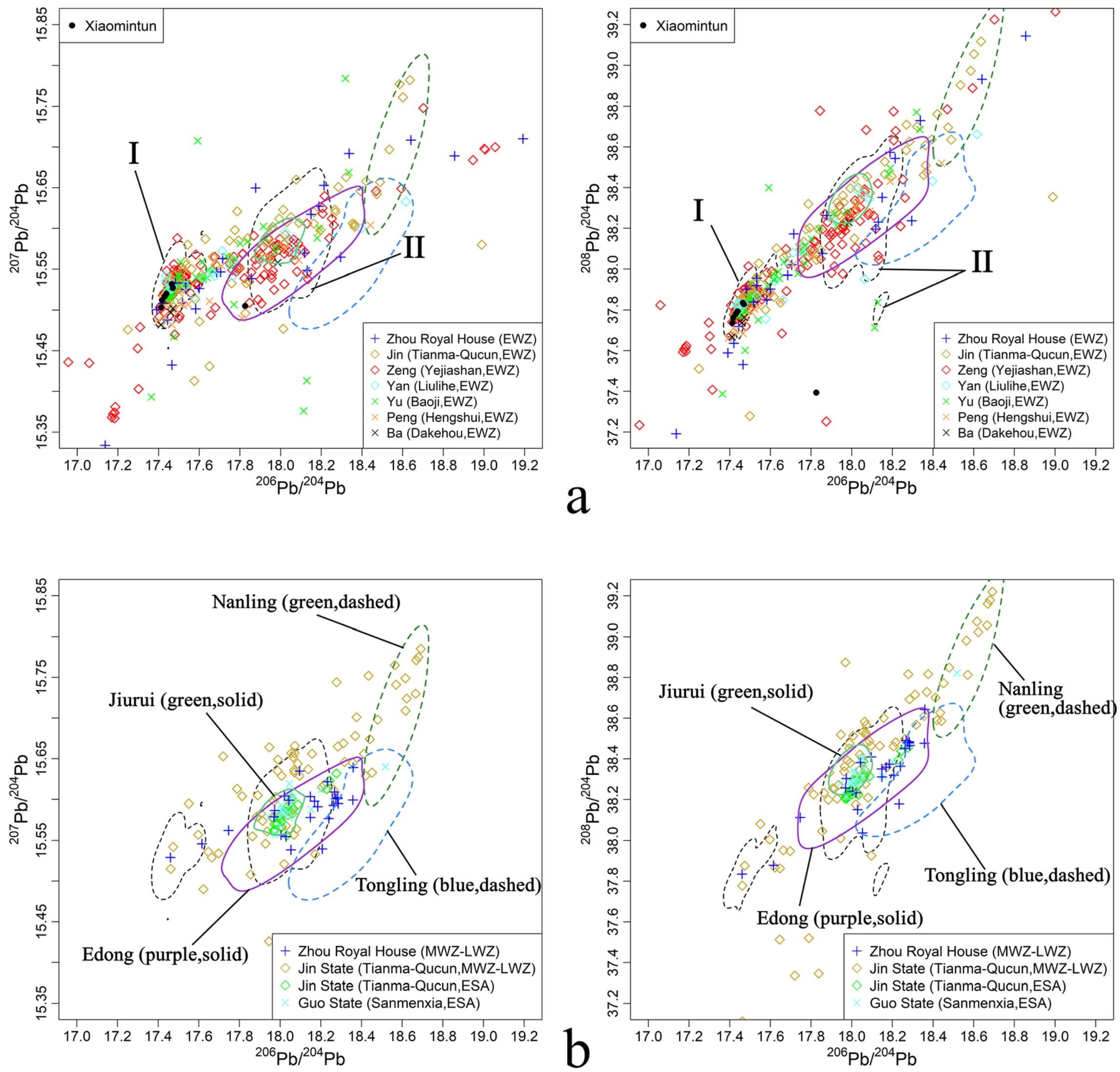

Fig. 10 Lead isotopic ratios of bronzes from different political territories and likely ore sources: (**a**) the royal family, Ji-clan states (Jin, Zeng, and Yan), and non-Ji-clan states (Yu, Peng, and Ba), early Western Zhou; (**b**) the royal family, Ji-clan state (Jin), and non-Ji-clan state (Guo), mid-Western Zhou to early spring and autumn

suggests that Shang metalwork tradition continued to play a key role in the early Western Zhou bronze industry. However, at present, it is difficult to distinguish whether the presence of group I lead is due to the fact that the Zhou took over Shang supply network or simply recycled existing Shang objects and ingots. We can only ascertain that the Zhou managed to combine both Shang (group I) and newly acquired lead sources (group II) to sustain its enormous bronze industry. The use of multiple lead sources is best illustrated by the inscribed bronzes found at the Yejiashan cemetery, where vessels with both Shang and Zhou (Zeng) inscriptions were made using two primary lead sources (Fig. 11). The Shang vessels with group I signatures imply the continuity of Shang metalwork in which existing objects were reused or re-distributed. In contrast, the Shang vessels with group II lead suggest the use of new lead sources to meet demand from the Shang clan in the early Western Zhou. The same holds true for the production of Zeng vessels where both lead sources were used.

The homogeneity of lead isotope compositions across early Western Zhou states is indicative of the centralisation of raw lead materials and regulation of bronze manufacturing by the Zhou royal house. It has been suggested that the Zhou procured valuable metal resources from territories outside their immediate control by establishing dependent regional powers (Yu et al. 2019). The central bronze foundries (e.g. Zhouyuan and Beiyao) acquired metal from these states to cast bronze vessels, which were returned to the regional states. Alternatively, lead may have been transported directly to the regional states in the form of ingots, where chariot fittings and other small bronze objects were made (Lei et al. 1996), in addition to some vessels that imitated the Zhou ritual bronzes (Thote 2014: 35). This is significant for arguments concerning

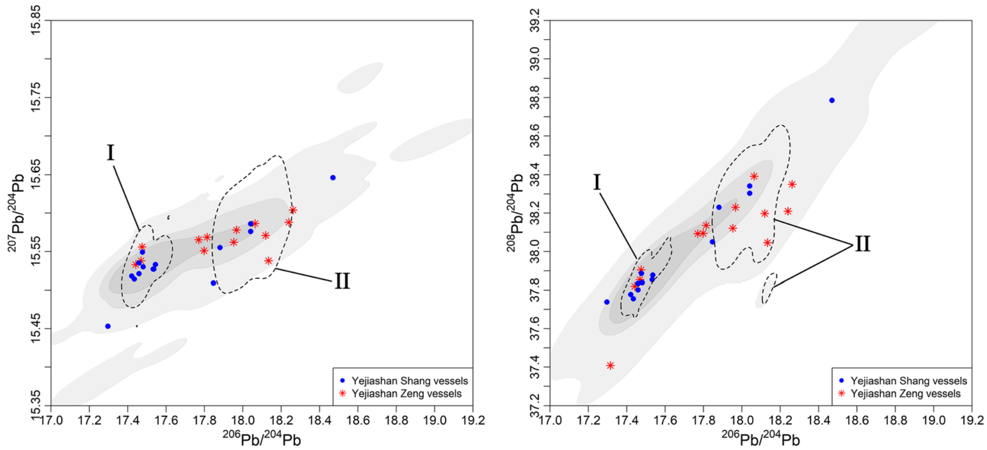

Fig. 11 Comparison between inscribed Shang and Zhou (Zeng clan) vessels from the Yejiashan cemetery

bronze production at the site of Baoji, for instance, where production and trace elements in the copper has been used to suggest that the bronzes were manufactured locally (Li et al. 2020a, b). However, the lead isotopic ratios of objects from Baoji still resemble those of the central Zhou territory, indicating that the same sources for raw lead was used in these objects. This indicates complex procurement and distribution systems existed for raw metal and metal objects, most likely combining an extent of regional autonomy in some cases, while also involving centralised oversight and resource coordination.

Nonetheless, the results of this study show that this narrative is slightly more complex. We argue that metal resources plundered from the Shang (group I lead) were the early Zhou's main metal resource, and the nature of its acquisition allowed the royal house to control its distribution and use (Zhao 2019). These huge metal reserves would have been an important tool for the Zhou ruling class to establish and dominate the new political system defined by bronze ritual vessels. Artefacts with group I lead were therefore sent to regional states to establish links between the central government and local powers. Meanwhile, the Zhou court probably also possessed craftspeople and/or foundries from the sophisticated Shang metalworking system, which surpassed regional workshops in both technological prowess, organisation, and scale. Thus, a system emerged where regional states delivered the necessary raw metal to the metropolitan foundries for the intricate bronze vessels desired for mortuary or ritual events. This network structure then facilitated the introduction of group II lead to the metallurgical system.

In contrast with the Zhou royal house's dominant position in the early Western Zhou metallurgical network, the mid-Western Zhou saw the regional states manage bronze production and metal procurement more actively. The local production of ritual bronzes manifests in the appearance of bronzes with local designs or palaeography of inscriptions most likely produced in regional foundries (Li et al. 2020a, b). At this time, access to the supply of group I metal was probably lost, so the Zhou court came to primarily rely on group II metal from the Yangtze River basin in the south, particularly ore deposits in the Edong and Jiurui areas. Isotopic values of some bronze artefacts from the metropolitan Zhou and the Jin state are spread beyond the major fields of groups I and II, matching the ore signatures of Tongling and Nanling (Fig. 10b). The shift in metal supply and the acquisition of lead as far as south of the Yangtze River basin suggest long-distance connections between the regional states and non-Zhou territories, which allowed regional states greater independence from central control.

New metal resources were probably derived from areas bordering on the Zhou regional states, which is supported by similarities in isotopic signatures of bronzes from the Zhou realm and non-Zhou metal-using cultures. For the early period, lead isotope values for Gaoshaji are fairly consistent with the early Western Zhou data, whereas Tanheli, despite some overlaps with group II, has a broad distribution of values that are different from groups I and II (Fig. 12a). The presence of group I in the Gaoshaji assemblage both implies that Gaoshaji interacted closely with the Zhou states in terms of metal circulation and indicates early Western Zhou expansion into the middle Yangtze. The Upper Xiajiadian assemblage (1000–600 BC) also shares similarities with the Zhou bronzes in terms of group II lead. They also overlap in the more radiogenic area. All this suggests an extensive sphere of Zhou metalwork.

The later periods display a diverse picture of mineral resource exploitation by communities outside the Zhou realm (Fig. 12b). Each assemblage has its own isotopic pattern, and these differ from the Zhou bronzes with group I and group II lead. For instance, objects from Upper Xiajiadian to the Zhou's northeast are represented by relatively elevated $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ values. The Shigudun assemblage on the Yangtze's lower reaches, meanwhile, isotopically resembles the lead signature of local ores at Tongling, and the Gaoshaji bronzes form a tight cluster consistent with the ores from Nanling. The regionalisation of metal procurement coincides with the intensification of local primary metal

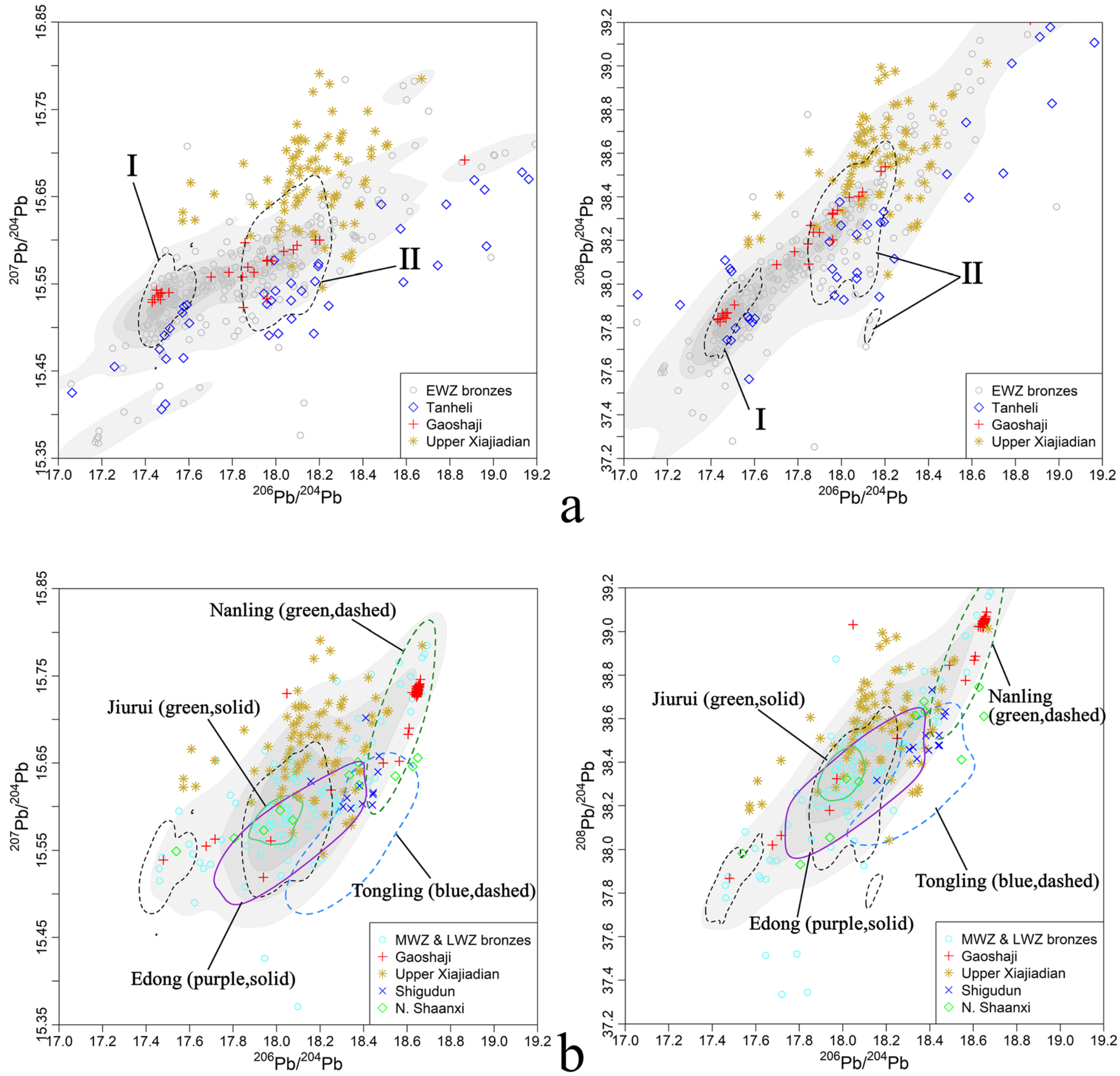

Fig. 12 Lead isotopic ratios of the Zhou states and neighbouring communities: (**a**) early Western Zhou and (**b**) mid to late Western Zhou

production in these regions during the mid-Western Zhou (Li 2016). It is thus probable that the Zhou did not mine and smelt metal directly but developed an extensive network to procure it from neighbouring communities, which they then refined and made into bronze vessels (Li & Cui 2018).

Conclusions

This study outlines diachronic changes in the lead supply of the Western Zhou period and its possible geological origins. We confirm two primary sources of lead that were previously highlighted as potential sources. Group I is the most common lead in late Shang bronze objects, and this pattern continues for the early Western Zhou states; however, group I virtually disappears in the middle and late Western Zhou. There are currently no geological sources that match group I's characteristics, but this type of lead might come from northern China, particularly the mountainous regions of Xiaoqinling and Tongbai-Dabie. These terranes have heterogeneous, variable isotopes and potentially host undiscovered lead-bearing deposits that are isotopically similar to group I. The closest archaeological link for group I are lead-copper ingots and production waste from Anyang. This indicates that the Zhou royal house appropriated the Shang's metal supply network, as well as their bronze-casting infrastructure and/or techniques, which were used to produce ritual bronzes for the Zhou elite. However, by the mid-Western Zhou, group I metal virtually disappeared from bronze assemblages, which coincided with major changes in the Zhou's ritual and sociopolitical environment.

The presence of group II lead in bronze artefacts signifies the acquisition of new metal source(s) under the expanding network of the early Western Zhou. This new metal supply became increasingly important throughout the Western Zhou and dominated metal production in the early spring and autumn period. This sudden change may correlate with intensive warfare and cultural contact between the Zhou and neighbouring communities to the south, which facilitated the influx of metal from these regions. Group II lead probably originated from metallogenic districts in the middle and lower Yangtze basin, particularly ore deposits at Edong and Jiurui, where evidence for Bronze Age mining is ubiquitous. Nonetheless, Qinling might have been also an important source for group II, as its isotopic values overlap with those of Edong and Jiurui. Further fieldwork is required to test this hypothesis.

Bronze artefacts from the early Western Zhou states are isotopically indistinguishable from each other. This reflects a highly centralised metal supply network regulated by the royal house, which enabled the Zhou court to provide regional states with the centrepieces of its ritual system: bronze vessels. By the middle and late Western Zhou, the regional states had gained control over metal supplies, as they developed close socio-political relationships with neighbouring communities to the south, who exploited a variety of local mineral resources. The shift from centralised to local networks of metal circulation reflects the political upheaval also evident in the archaeological record and bronze inscriptions.

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