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Hanzhong bronzes and highly radiogenic lead in Shang period China

Kunlong Chen[a,b,*], Jianjun Mei[a,c], Thilo Rehren[b,d], Siran Liu[a], Wei Yang[e], Marcos Martinón-Torres[f], Congcang Zhao[g], Yoshimitsu Hirao[h], Jianli Chen[i], Yu Liu[j]

[a] Institute of Historical Metallurgy and Materials, University of Science and Technology Beijing, Beijing, 100083, China
[b] UCL Institute of Archaeology, London, WC1H 0PY, UK
[c] Needham Research Institute, Cambridge, CB3 9AF, UK
[d] Science and Technology in Archaeology and Culture Research Center, The Cyprus Institute, Nicosia, Cyprus
[e] Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, 100029, China
[f] Department of Archaeology, University of Cambridge, Cambridge, CB2 3ER, UK
[g] School of Cultural Heritage, Northwest University, Xi'an, 710069, China
[h] Faculty of Humanities, Beppu University, Beppu, 874-8501, Japan
[i] School of Archaeology and Museology, Peking University, Beijing, 100080, China
[j] Institute of Archaeology, Chinese Academy of Social Sciences, Beijing, 100710, China

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ABSTRACT

For decades, the origin of the bronzes with distinct highly radiogenic lead isotopic ratios in Shang period China has been a puzzle. This paper presents new lead isotope data for bronze objects from the Hanzhong region, one of the key regional bronze cultures during Shang period China. On the basis of a synthetical investigation of the typological, chemical and lead isotopic features of Hanzhong bronzes and their relations to other regional bronze cultures, we propose the Qinling area as a potential region of origin for the metals containing highly radiogenic lead used by several contemporaneous but culturally/politically distinct entities across a vast territory. Taking into account both archaeological and geological evidence, this working hypothesis draws attention not merely to the geological provenance of metal resources, but also to the mechanisms of metal production and circulation as well as broader social-economic dynamics.

1. Introduction

The production of splendidly cast bronzes, one of the most prominent features characterising China's early civilisations (Chang, 1986: 365–7) reached its zenith during the middle and late Shang period (ca. 1300-1046 BCE). To support the large-scale production of ritually important vessels, weapons and other implements, copper, tin and lead had to be exploited in ore-rich mountainous regions, remote from the centres of Shang civilisation, and transported to the Central Plain in the lower reaches of the Yellow River (Yue and Liu, 2006), the metropolitan region of the Shang polity (Fig. 1). The circulation of these key resources and products must have resulted in complex trans-cultural inter-regional interactions, which in turn played a significant role in shaping the developmental trajectory of the early states in Bronze Age China (Liu and Chen, 2012: 369–81).

Seeking to identify the geological origins and supply routes of raw metals, and the circulation patterns of the finished bronzes, chemical and/or isotopic analyses have therefore been a core topic of archaeometallurgical research in China, as in many other regions in the world (e.g. Peng et al., 1999, Jin, 2008, see also Pollard et al., 2015, Radivojević et al., 2018 for most recent reviews on methodology). However, the distinctive highly radiogenic lead (HRL) isotopic composition of many Shang period bronzes has puzzled scholars from various disciplinary backgrounds, and become a long-standing issue in Chinese archaeology since it was first identified in the 1980s.

Over the last few years, another round of discussion on this question has attracted interest from a broad academic community (e.g. Sun et al., 2016; Jin et al., 2017; Liu et al., 2018a; Liu et al., 2018b). While the mysterious HRL metal and its geological origin still lies at the heart of the debate, a promising new tendency have emerged paying more attention to general archaeological contexts and questions (Jin et al., 2017; Liu et al., 2018b). In this paper we report new analytical data, briefly review previous studies, propose a potential geographic region of origin for the HRL metal, and discuss the implications of this new model, thus moving towards a new understanding of bronze metallurgy and its social-economic contexts in Bronze Age China.

* Corresponding author. Institute of Historical Metallurgy and Materials, University of Science and Technology Beijing, Beijing, 100083, China.
E-mail address: kunlong.chen@ustb.edu.cn (K. Chen).

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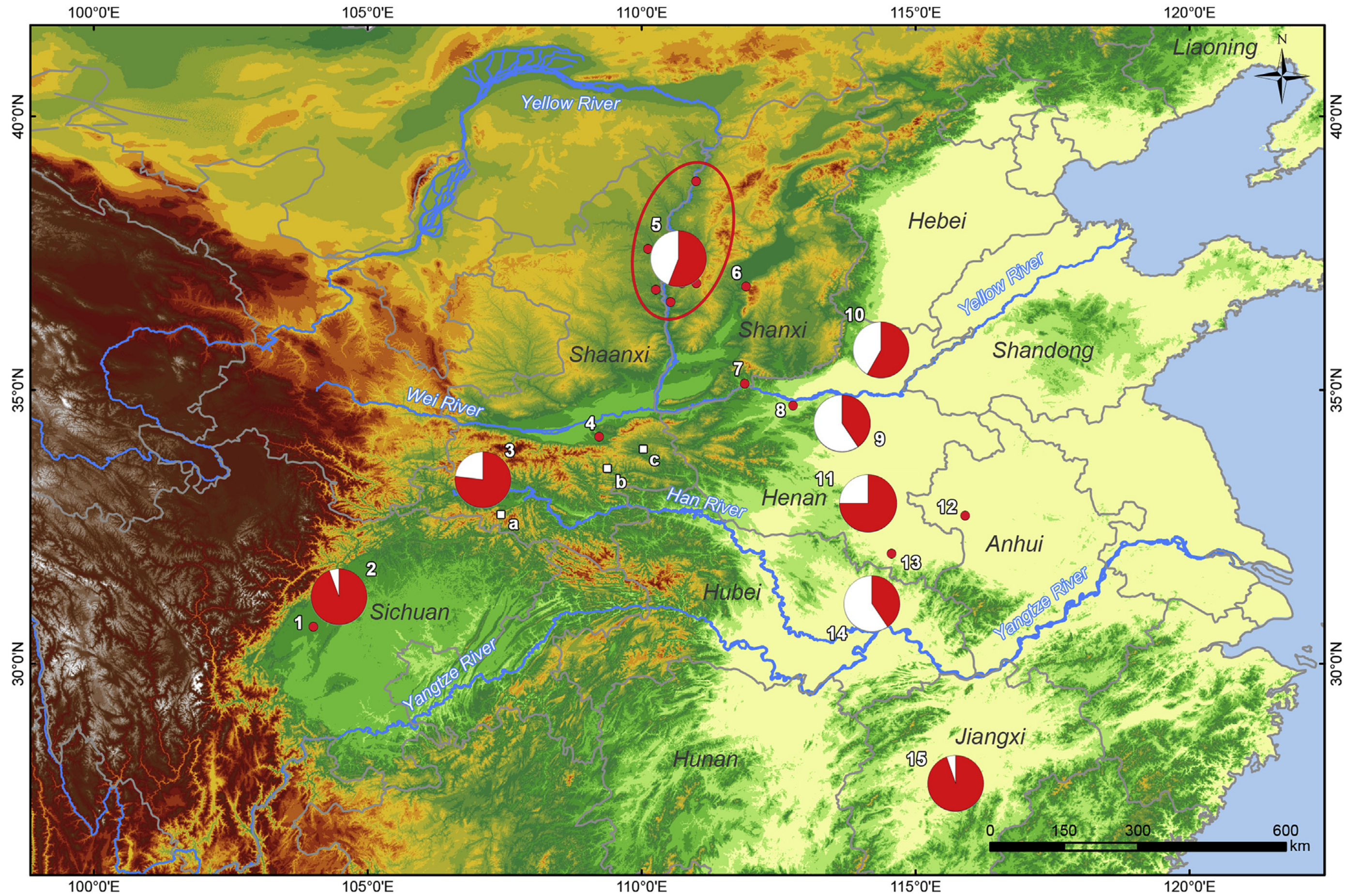

Fig. 1. Map showing the sites/regions yielding HRL bronzes (red dots) and ore deposits mentioned in the text (white square). Pie charts show the proportion of HRL bronzes among the analysed samples from the major Shang sites/areas (1. Jinsha; 2. Sanxingdui (n = 53); 3. Hanzhong (n = 115); 4. Huaizhenfang; 5. Northern Shaanxi and Shanxi (n = 195); 6. Lingshi Jingjie; 7. Yuanqu; 8. Yanshi; 9. Zhengzhou (n = 37); 10. Anyang (n = 67); 11. Runlou (n = 20); 12. Taijiasi; 13. Luoshan; 14. Panlongchen (n = 37); 15. Dayangzhou (n = 19); a. Mayuan; b. Mujiazhuang; c. Luonan). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2. The Hanzhong bronzes

The Hanzhong basin, situated in southwestern Shaanxi, is located on the upper reaches of the Han River, surrounded by the Qinling mountain range to the north and the Daba-Micang Mountains to the south. The basin has geographic connections reaching southwest to the Chengdu Plain, north to the Wei River valley and south to the Middle Yangtze region, making it an important centre for communication networks between various parts of China (Fig. 1). Since the 1950s, dozens of ancient bronze hoards or caches have been found around the confluence of the Han and Xushui Rivers (e.g. Duan, 1963; Tang et al., 1980; Chai et al., 2005), forming the so-called Hanzhong bronze group, also known as the 'Chengyang bronze group', after the two counties of Chenggu and Yangxian in the eastern part of the basin (Zhao, 1996). The total assemblage of Hanzhong bronzes comprises more than 700 objects from 33 caches at 19 different sites. The bigger caches/hoards, such as Longtou, Sucun and Machang (Chen et al., 2016: online supplement 1), often contain stylistically mixed but chronologically similar assemblages of bronze artefacts (Zhao, 2006; Sun, 2011). The whole bronze assemblage includes hundreds of weapons and *Yang* discs, dozens of ritual vessels, masks, *Zhang* sceptres, sickle-shaped objects, and a few tools and ornaments (Fig. 2) (Cao, 2006; Zhao, 2006). As a group, these bronzes, often found accidentally by farmers, have been assigned to the "Baoshan Culture", which takes its name from the only properly excavated site in the region, contemporary with the Shang culture of the Central Plain (XDWX, 2002: 176–9). Typological studies suggest an approximate date ranging from the Upper Erligang to the late Anyang (Yinxu) periods, spanning the fourteenth to eleventh centuries BCE (Cao, 2006; Zhao, 2006), although some pieces in the group may be dated to the Western Zhou period (e.g. Li, 2007; von Falkenhausen, 2011).

Previous research has revealed two notable features of the Hanzhong bronzes. On the one hand, the whole assemblage shows remarkable stylistic/typological diversity, comprising various groups of products that are typologically attributable to distinct regions, including the Shang metropolitan areas in the Central Plain (Fig. 2: Sub-group A), the Wei River valley in the north of the Qinling Mountains (Fig. 2: Sub-group B), and the middle-lower Yangtze River Valley (Fig. 2: Sub-group C) (e.g. Cao, 2006, Chen, 2010a: 117–23, von Falkenhausen, 2011, Chen et al., 2016). On the other hand, the close correlations among the indigenous archaeological culture, stylistically local items (sickle-shaped objects, *Zhang* sceptres and socketed axes, Fig. 2: Sub-group D) and their characteristic metal compositions (mainly unalloyed copper and the "natural alloys" containing arsenic, antimony and nickel), suggests the existence of indigenous metalwork in the Hanzhong region during the Shang period (Chen et al., 2009; Chen, 2010a: 104–9, Chen et al., 2016).

Jin et al. (2006) reported lead isotopic results for 31 Hanzhong bronze objects, and suggested the region as a foothold in the "northern route" through which the polities of Central Plain contacted those in the Sichuan Basin, which is relevant to the exploitation of metallic resources in the regions further southwest, where the provinces of

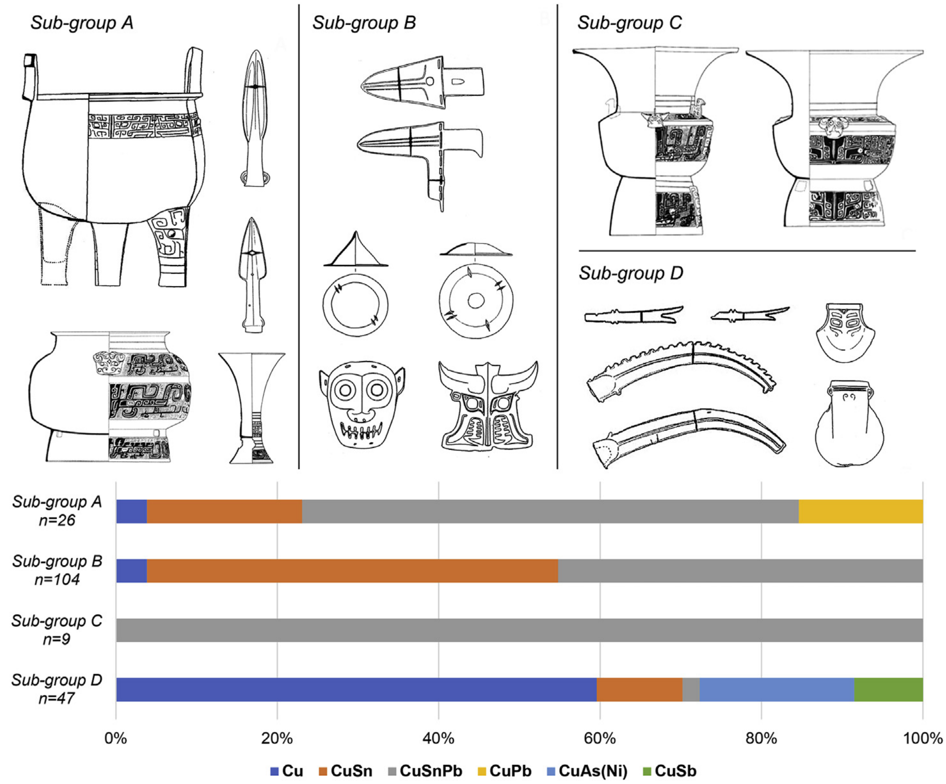

Fig. 2. Examples of Hanzhong bronzes (upper) and their alloy types (lower) showing the typological/cultural and material diversity of the assemblage (drawings are reproduced from Cao, 2006 and Zhao, 2006, chemical data are from Chen, 2010a).

Yunnan, Guizhou and Sichuan meet.

3. Materials, methods and analytical results

This paper presents new lead isotope data for 84 samples from 72 objects among the Hanzhong bronzes. The objects sampled cover a good range of various typologies, chronology and aforementioned sub-groups, and therefore are considered to be representative of the entire group (Fig. 2). The lead isotope composition of our samples was analysed utilizing a Thermo Electron Corporation MAT262 Surface Ionization Mass Spectrometer (TIMS) at Beppu University in Japan.

The results are presented in Table S1 in the Supplementary materials as three isotopic ratios with ^{204}Pb as the denominator, together with the methods of sample preparation and measurement. The table also shows lead isotope data published by Jin et al. (2006), lead concentrations, and the alloy types following the conventional threshold of 2 wt% for alloys classification. Detailed results and descriptions of chemical compositional analysis can be found in Chen et al. (2009), Chen (2010a) and Chen et al. (2016: supplementary material S2). In total, lead isotopic data for 115 samples from 104 bronze objects from Hanzhong are now available for discussion, 87 of which are complemented by elemental composition.

The lead isotope compositions of the Hanzhong bronzes span a broad range, from 17.531 to 23.853 for ^{206}Pb/^{204}Pb, 15.452 to 16.507 for ^{207}Pb/^{204}Pb and 38.104 to 44.681 for ^{208}Pb/^{204}Pb. Among them, more than three quarters of the samples (88 of 115) are highly radiogenic, defined here as ^{206}Pb/^{204}Pb $\geq$ 20 and ^{208}Pb/^{204}Pb $\geq$ 40 (Jin, 2008: 292–302, Liu et al., 2018b). Though there is concern that possible contamination from the burial environment may alter the lead isotope composition of the patina in base metal with low lead content (e.g. Snoek et al., 1999; Gale and Stos-Gale, 2000), the non-clustered distribution of the lead isotope ratios and the good agreement with published data suggest lead contamination from the burial environment was negligible. Therefore, the results are considered robust and taken to represent the base metal of the objects.

Lead concentration is a major concern when using lead isotope analysis to investigate the provenance of copper-based metals in antiquity (Gale and Stos-Gale, 1982). While the contribution of traces of lead in tin and its influence on the lead isotope composition are generally negligible (Gale and Stos-Gale, 2000; Molofsky, 2009), it is crucial to ascertain whether the measured isotopes from one specific object are derived from traces of lead within the copper, or from the lead added during the alloying process (Gale and Stos-Gale, 1982; Pollard and Bray, 2015). This issue appears to be even more significant in Bronze Age China, given the prevalence of leaded tin bronze (taken here as Pb $\geq$ 2 wt%) among hundreds of chemically analysed objects. Although deciding how much lead in copper-based alloys can signify the deliberate addition of lead is complicated, several scholars have tentatively suggested that a concentration of 1 wt% Pb is sufficient to indicate the addition of lead, and the isotope signature will be dominated by the lead source (Zhu and Chang, 2002; Jin, 2008: 41, Liu et al., 2018b). As shown in the Supplementary materials (as well in Fig. 3:b), very few samples (only 3 of 86) have a lead concentration between 1 and 2 wt%, which might suggest that the lead could have been introduced in different ways: those with a lower concentration of lead tend to be the result of impurity from the copper ore, and those with higher concentrations tend to be from intentional addition.

Fig. 3:a plots a lead isotope ratio against inverse lead chemical concentration as recently proposed by Pollard and Bray (2015). Theoretically, the mixing lines of two components would become linear in the chart and can be used to illustrate the controlling component (copper or lead in this case) of the isotope data. We also plot the data with two isotope ratios grouped by different lead contents for comparison (Fig. 3:b). There is no clear linear correlation between 1/Pb (1000 ppm^{-1}) and the lead isotope ratio (^{206}Pb/^{204}Pb) (Fig. 3:a), as many of the plots are horizontally squeezed into a very narrow area around 1/Pb $\approx$ 0 due to their relatively high lead contents, but vertically scattered over a broad range of lead isotope values. Fig. 3:b is also

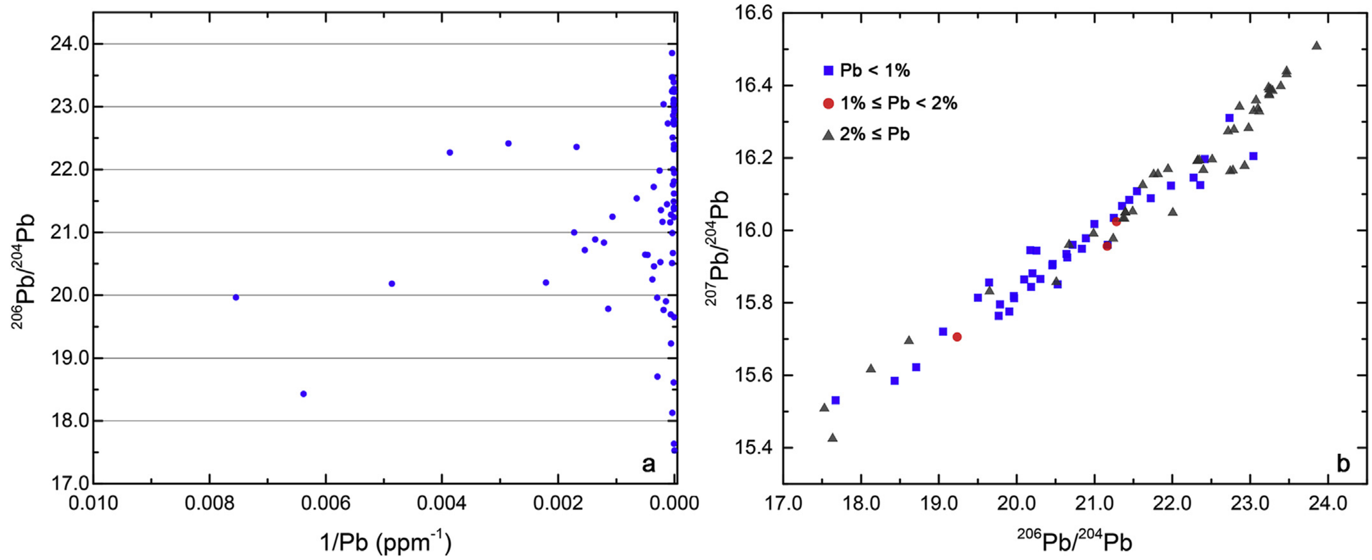

Fig. 3. (a) A plot of Hanzhong bronzes data, showing 1/Pb against lead isotope ratio ^{206}Pb/^{204}Pb. (b) A ^{207}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb diagram for Hanzhong bronzes showing the distribution of lead isotope ratios of artefacts with different lead contents.

characterised by the substantial overlap of the isotope ratios despite their various lead concentrations. These patterns, revealed by both isotopic and elemental compositions, suggest that the copper (indicated by the low lead samples) and lead (as shown by the high lead ones) used to cast most of the Hanzhong bronzes have a similar HRL isotope signature, although it is interesting to see that a considerable number of lead-rich samples (Pb ≥ 2%) seem to be more radiogenic than the rest (^{206}Pb/^{204}Pb > 23).

As mentioned above, typological diagnosis and chemical analyses have differentiated four sub-groups among the assemblage of Hanzhong bronzes, implying diverse origins from distinct regional bronze cultures (e.g. von Falkenhausen, 2011; Chen et al., 2016). When the data are classified by these sub-groups and plotted, as in Fig. 4, it is surprising to see that the lead isotopic composition of samples from different sub-groups again substantially overlap and are hardly distinguishable. That is to say, even though objects assigned to distinct sub-groups were most likely fabricated in various regions and cultural/political contexts, the raw metals used (copper and/or lead), especially the ones that have HRL isotope composition, seem to have originated from a common source. This observation is very significant for our understanding of metal sources and their circulation networks.

4. Discussion

4.1. The highly radiogenic lead metal in Shang period bronzes

Since the pioneering work of Jin Zhengyao in the early 1980s (Jin, 2004), for decades the provenance of the metals for the HRL Shang bronzes has puzzled researchers. More than 60% of the analysed Shang period bronzes (n > 800) were found to have distinctive highly radiogenic lead isotopic compositions, ^{206}Pb/^{204}Pb ≥ 20 and ^{208}Pb/^{204}Pb ≥ 40, which distinguish them from most known lead deposits and bronze artefacts worldwide (Zhu and Chang, 2002; Jin, 2008; Sun et al., 2016; Liu et al., 2018b). Their occurrence is geographically widespread across a vast area of several million km^2 in China, and involves most of the major regional cultures of the Shang

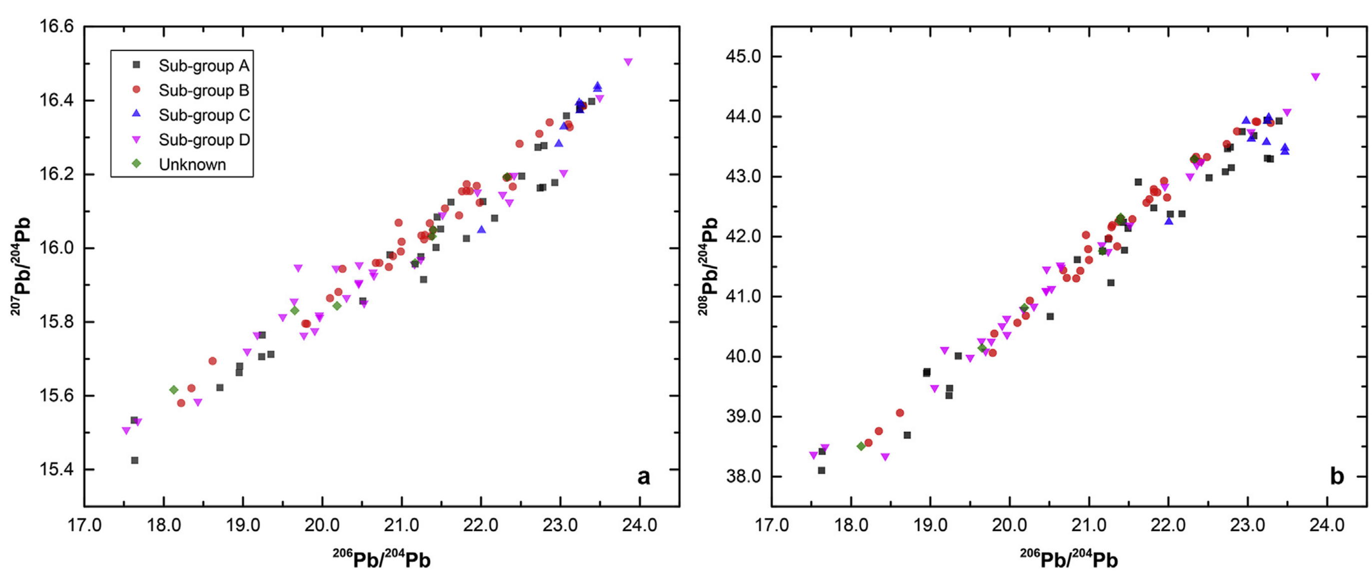

Fig. 4. Plots of lead isotope ratios of Hanzhong bronzes showing the overlap of objects from distinct sub-group, especially at the highly radiogenic region (^{206}Pb/^{204}Pb ≥ 20).

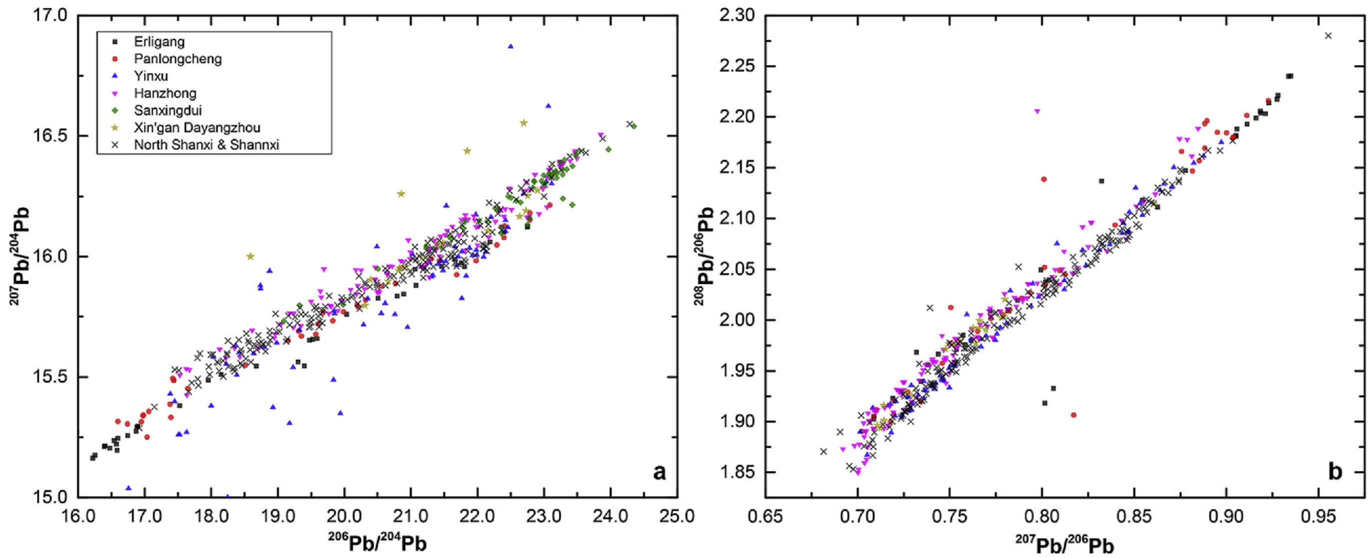

Fig. 5. Plots of lead isotope ratios of major Shang period bronze assemblages including Hanzhong. Note the large proportion of HRL values and the substantial overlapping of the artefacts from various sites/regions. (see Supplementary material for the sources of data used).

period (Fig. 1). The HRL bronzes from different regions are hardly differentiated from each other by their lead isotope ratios (Fig. 5), despite their remarkable typological/cultural variety (e.g. Bagley, 1999).

Another interesting point is that the chemical compositions of HRL bronzes cover various copper alloys with distinct lead concentrations. On the one hand, since most of the HRL bronzes contain a significant amount of lead (> 2 wt%) that determines lead isotope ratios of the measured objects, the source should be plumbiferous. On the other hand, some artefacts with low lead content (< 1 wt%) and malachite samples from various sites also show similar lead isotope ratios (Jin, 2008: 39–43), suggesting that the HRL in the alloy could have derived from copper ore as well. The same uncorrelated patterns between lead concentration and isotope ratios have been observed from our results of Hanzhong bronzes as indicated in Fig. 3.

It is also important to note that the widespread appearance of HRL bronzes is chronologically restricted to approximately 300 years between the Upper Erligang (early-middle Shang period) and the Yinxu Phase III (ca. 1450-1150 BCE) (Figs. 6 and 7). Despite forming the majority of Shang period objects, HRL bronzes are rarely found among bronzes from the pre-Shang Erlitou or the Zhou periods (Jin, 2008). HRL bronze first appears in early Shang cities at Zhengzhou and Yanshi in Henan (Peng et al., 1999; Jin, 2008; Tian, 2013), Yuanqu in Shanxi (Cui et al., 2012) and Panlongcheng in the Middle Yangtze River (Peng et al., 1999). It is subsequently identified in almost every major bronze group dating to the middle-late Shang period, such as Anyang (Yinxu) in Henan (Jin, 2008), northern Shanxi and Shaanxi (Cao, 2014; Liu, 2015), Sanxingdui in Sichuan (Jin et al., 1995) and Xin'gan Dayangzhou in Jiangxi (Jin et al., 1994). A significant proportion (~60%) of the collections of Shang bronzes in the Arthur M. Sackler Museum in Washington D.C. and the Sen-oku Hakuko Kan in Kyoto also have this distinctive isotopic signature (Barnes et al., 1987; Hirao et al., 1998). Towards the end of the Shang period, HRL bronze rather quickly disappeared except for the continued presence at the site of Jinsha in Sichuan, where it persisted for around another one hundred years (Jin et al., 2004).

In our view, two important observations can be derived from previous research. Firstly, the fact that the HRL bronzes are relatively tightly circumscribed chronologically, but widespread geographically (covering a vast territory around 3 million km^2), indicates that it is most likely that a single source region provided the HRL metal for many distinct regional bronze cultures in China during the Shang Period (e.g. Jin et al., 2017; Liu et al., 2018b). Secondly, the various lead concentrations of HRL bronzes, from lead-free unalloyed copper to alloys containing dozens of percent of lead, suggest the source would have

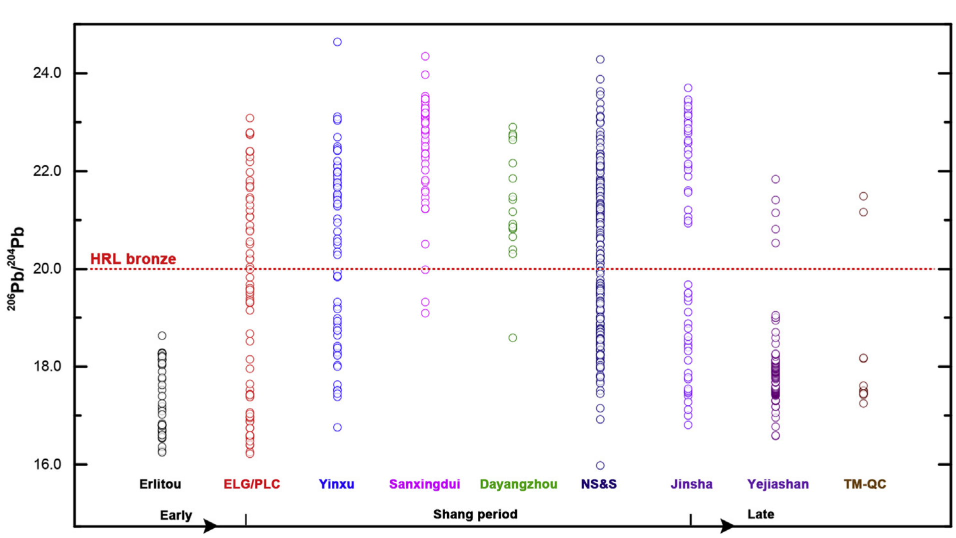

Fig. 6. Plots of $^{206}Pb/^{204}Pb$ ratios of objects from different sites/regions showing that the uses of HRL bronzes are almost completely limited to the Shang period. (ELG/PLC = Erligang and Panlongcheng, NS&S = North Shanxi and Shaanxi, TM-QC = Tianma Qucun). Note that the few objects with HRL signatures from the Yejiashan and Tianma-Qucun sites of the Western Zhou period are typologically dated to the Shang period. (see online Supplementary Material for sources of data used).

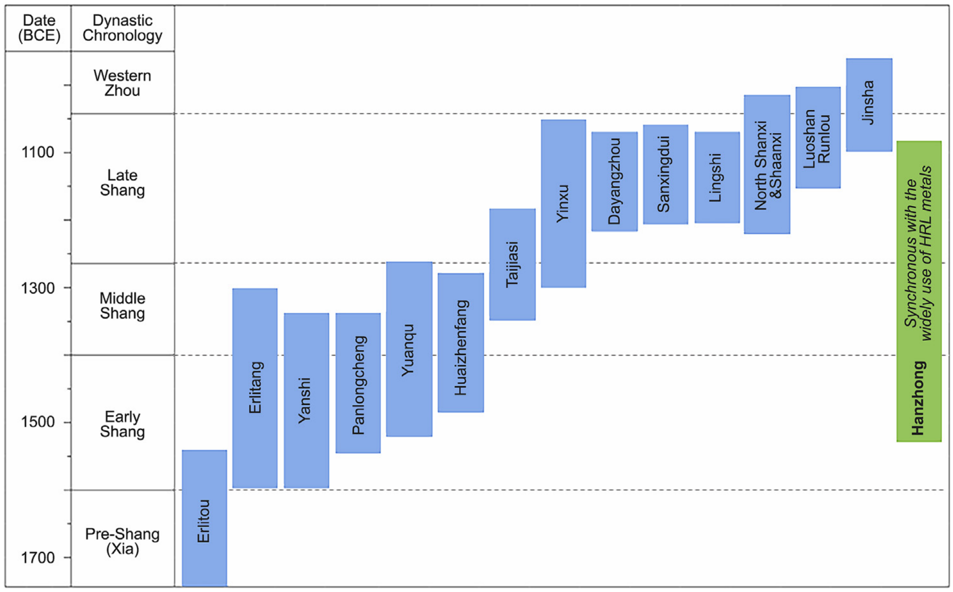

Fig. 7. Schematic diagram showing the relative chronology of the sites/regions mentioned in the text. Note the date of the whole assemblage of Hanzhong bronzes is in essence synchronous with the wide appearance of HRL objects.

supplied both copper and lead during its period of exploitation (e.g. Jin, 2008: 33–47, Tian, 2013; Liu et al., 2018b).

Theoretically, it is possible that more than one source of HRL was exploited during the Shang period, as recently proposed by Liu et al. (2018a). However, it needs to be noted that metal sources for Shang bronzes should not only have high $^{206}Pb/^{204}Pb$ ratio (highly uranogenic) but also old isochron age and high $^{208}Pb/^{204}Pb$ ratio (highly thorogenic). Even though there are a number of copper and lead deposits in China which also have highly radiogenic lead isotopic ratio (in terms of $^{206}Pb/^{204}Pb$ ratio), none of them can meet all aforementioned features of the Shang bronzes (Jin et al., 2017 Fig. 3). In light of this, the source for Shang bronze is geologically quite unusual. Additionally, considering the rather 'sharp' chronological beginning and end of the use of HRL in such a vast geographically and culturally diverse territory, current evidence tends to be more consistent with the assumption of a single source or source region. With multiple sources, each potentially with their own geological, political and economic constraints, we might expect more variability in terms of the chronology. Liu et al. (2018a) note that HRL signatures are found in some pigments and glass after the Shang period (but so far not in metal objects) and use this as key evidence to argue for multiple sources of HRL for the Shang bronzes. However, there are obvious risks when assuming that the parameters affecting the supply of non-metals in the post-Shang period can be so easily applied to Shang-period metals. Thus, on balance, we favour the hypothesis of a single source.

Discussion of the geographic location of this source, however, is difficult and controversial. Jin Zhengyao first proposed that the raw materials for casting HRL bronzes in Yinxu came from Yunnan, and developed the hypothesis of the "southwest origin" of HRL metal in a series of papers on the materials from Zhenghzou (Erligang), Sanxingdui and Xin'gan Dayangzhou (e.g. Jin, 2008; Tian, 2013; Jin et al., 2017). Although this suggestion has been supported by geologists (Zhu and Chang, 2002), the lack of archaeological evidence for contacts between Yunnan and central China during the Shang period has raised serious questions from archaeologists. Considering the geographic intermediate position of the Qinling Mountains, Saito et al. (2002) suggested the region as another possible source of HRL, but provided no isotopic and archaeological evidence. A number of other regions, including Jiangxi, Hunan (Peng et al., 1999, Zhu and Chang, 2002), the minor Qinling area in Henan, Qingchenzi in Liaoning (Zhu and Chang, 2002) and even Africa (Sun et al., 2016), have been proposed by other scholars. None of them is so far conclusive and fits the archaeological evidence and existing analytical results (see also Chen, 2010b; Jin et al., 2017; Liu et al., 2018b for detailed review). The geological source of the HRL Shang bronzes therefore remains unknown.

4.2. The implications of the new data from Hanzhong

The lead isotope analysis, together with the systematic typological and technological research, presented in this paper throws new light on the discussion of HRL bronzes of Shang period China. As shown in Fig. 5, the results of our analysis are consistent with previous studies, and the lead isotope ratios of Hanzhong bronzes are hardly differentiable from other major Shang period bronze groups. More importantly, a substantial part of the group of typologically and chemically distinctive objects, such as sickle-shaped objects and *Zhang* sceptres (Sub-group D in Fig. 2) are found to be made of HRL metal as well (mostly unalloyed copper, Figs. 3 and 4). Since it is widely accepted that these objects are characteristic products of the Hanzhong community (e.g. Cao, 2006; Zhao, 2006; Chen et al., 2009; von Falkenhausen, 2011; Chen et al., 2016), a tight interrelationship between Hanzhong's local metallurgical industry and the HRL source is therefore upheld by both archaeological, technological and isotopic evidence. It is interesting to see that all of the four samples from the repairing patches of different vessels (No. HZ029, 102, 105, 116) also have HRL composition, even though one sample from the main (repaired) body (HZ104) is common lead (see Supplementary Table S1). These repair patches are most likely to have been added to the vessels when they were used in Hanzhong (Chen, 2010a: 97–99), and further testify to the HRL signature of local metalwork.

The Qinling area, where the Hanzhong Basin is located, is a well-known metallogenic region of multimetallic ore deposit clusters (e.g. Qi and Hou, 2005; Ren et al., 2007). The rich mineral resources in the region have long been used by the ancient communities there. Several ancient mining pits for turquoise and hundreds of hammer stones have recently been discovered in the area centred at the conjunction of the Xiyu and Luo Rivers in Luonan County (Li et al., 2016). Pottery sherds found in the mining pits were assigned to archaeological cultures ranging from the Neolithic to the Late Bronze Age, consistent with the absolute dates of 2030-500 BCE obtained from eight radiocarbon dates (samples of bone and charcoal, four of each) (Xian, 2016: 76–80). It is suggested that the Luonan region is a potential source of the turquoise industry at Erlitou, the key site of the Early Bronze Age in the Central Plain (Xian et al., 2018). This research provides crucial evidence for the early exploration and exploitation of mineral resources in the Qinling region, even though ancient copper/lead mining and smelting sites in this area are yet to be identified.

It is also important to point out that the dates of the Hanzhong bronzes, and the Baoshan archaeological culture to which they have been assigned, span from the Upper Erligang to the Yinxu Phase III (Cao, 2006; Zhao, 2006), which is virtually synchronous with the period when HRL bronzes were widespread (see Fig. 7). The Jinsha site, which has yielded the only later HRL bronze group dated to the early Western Zhou (Jin et al., 2004), is located in the Sichuan Plain, hence not very far from Hanzhang, and exhibits a close relationship with the Baoshan culture (XDWX, 2002).

Based on the aforementioned observations, here we propose the Qinling area as a potential source region for the geological and geographical origin of the Shang period HRL bronzes. According to this proposal, polymetallic resources (copper and lead) exploited by the local communities in Hanzhong would have supplied the raw metals for many bronze industries in different regions during the Shang period in China, as indicated by their shared and highly characteristic lead isotope signature and the archaeologically evidenced trans-cultural correlations (e.g. von Falkenhausen, 2011; Chen et al., 2016). The implications of this new hypothesis are briefly outlined below.

4.3. Social-economic landscape in Shang period China: a metallurgical perspective

The early Shang period, when the HRL bronzes first came into use, witnessed the wide adoption of bronze metallurgy in China, especially spreading south-eastward (Bagley, 1999; Wang, 2014). The increasing expansion of scale of production in the Shang metropolitan areas would have undoubtedly increased demand for raw metals, which subsequently facilitated interregional connections and established routes of exchange between the ore-rich mountainous areas and the regional centres where the raw metals were accumulated and worked into artefacts. It has been stated repeatedly by specialists in Bronze Age China archaeology that acquisition of metals for elites would has been an essential motive for the well-formulated “Erligang Expansion” during the early Shang period (e.g. Bagley, 1999; Wang, 2014; Liu and Chen, 2003: 131–45).

Demonstrated as a crucial nodal point in the exchange network since the Erligang period, the local communities of Hanzhong would have been stimulated by external influences and reacted by taking advantage of the natural landscapes and resources (Chen et al., 2016). As von Falkenhausen (2011: 435) has insightfully pointed out, “whatever bronze manufacturing went on in the upper Han River Basin should be viewed in conjunction with the exploitation of the copper-ore resources of the Qinling Mountains”. Considering the ore-rich geology and ample fuel supplies of the mountainous area, and the relatively underdeveloped state of agriculture as evidenced by the finds from the Baoshan site (XDWX, 2002: 180), it would have been a rational choice for this region to specialise in the primary production of metals (mining and smelting) and to exchange their metals with cultures in other regions that excelled at other productive activities. These kinds of interaction dynamics have been considered to have occurred regularly in Bronze Age China, as illustrated by the production and exchange of salt (von Falkenhausen, 2006; Liu and Chen, 2012: 273–90). The intermediate geographic position of the Qingling Mountains and navigable water routes along the Han River would have been crucial in promoting the proposed exchange.

During the Yinxu period, the Hanzhong region continuously participated in a trans-cultural interaction network connecting many regions. While the control of the Shang state seemed to retreat to Anyang and surrounding areas (Li, 1990), regional bronze industries across the vast territory of south China prospered, as exemplified by the spectacular and distinctive artefacts from Jiangxi, Sichuan and Hunan (Kane, 1974; Bagley, 1999; Xu, 2008; Steinke, 2014). With the engagement of these newly established regional centres, the simplified “core-periphery” tributary model (Liu and Chen, 2003: 133–40), even if it reflects the situation during the early Shang period, must have given way to a more complex multiple-directional exchange network. Importing copper and lead from specialised mining/smelting communities in Hanzhong through the existing routes would have been more cost-effective than producing them locally, even for some regions where ores were available. The increasing interactions with other regional bronze cultures in turn explain why bronzes of various styles and manufacturing origins (secondary production) were gathered in Hanzhong (Li, 2007; Chen, 2010a; von Falkenhausen, 2011; Chen et al., 2016). This pattern of economic specialisation (i.e. production for exchange and import across cultural and geographic boundaries) is predicted by Ricardo's Law of Comparative Advantage, and has been demonstrated previously for copper production and exchange in the Bronze Age Alps (Shennan, 1999).

It is also worth noting that the decrease in HRL bronzes in the Central Plain coincided with the rise of the Zhou in the Wei River valley towards the late Yinxu period. The dramatic change of the political landscape would have undoubtedly affected and potentially limited the multiple-direction exchange network connecting many regional powers of various political standings. Several scholars have already correlated the sudden disappearance of bronzes in Hanzhong with the conquest of Shang, although whether the local communities were allies of the Zhou is still controversial (e.g. Li, 1997; von Falkenhausen, 2011; Sun, 2011).

5. Concluding remarks

Until direct evidence of metallurgical production, such as mining pits, furnaces, slag and other technological remains dated to the Shang period, is identified in the region, the proposed Qinling area as an origin of the Shang period HRL bronzes should remain as a working hypothesis. However, the significance of this paper is not merely in demarcating the potential geological ore source, but, more importantly, in aligning the archaeological and scientific data into a coherent historical narrative. Even though we are unable to confirm the exact geographical/geological origin of the metal with the evidence available, the proposed model of a single specialised source supplying a number of culturally distinctive regional bronze industries itself is sufficiently intriguing and meaningful to further our understanding of Shang period China. Instead of being just an unsolved mystery surrounding the exact geographical/geological origin of HRL, the subject is shown here to be an excellent case in point for the discussion of regional relationships and the wider social-economic landscape in Shang period China.

While the provenance of ancient artefacts and the location of primary production remains will undoubtedly continue to be one of the primary goals of our research, cautious research has to continue to explore the archaeological/historical dynamics outlined by the existing evidence. Solid cooperative relationships among researchers from diverse backgrounds are undoubtedly crucial for further work on bronze metallurgy in Shang China, given the interdisciplinary nature of archaeological research.

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Appendix A. Supplementary data

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