Hanzhong bronzes and the highly radiogenic lead in Shang period 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 constituted a research puzzle. This paper presents new lead isotope data of bronze objects from Hanzhong, representing 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 the 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 is expected to draw attention not only 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.

Keywords:

Lead isotopes; provenance; Shang; China; bronze; highly radiogenic lead; regional specialisation; multiple-direction exchange.

Highlights:

- New lead isotope results from a key regional bronze culture of Shang period China.
- The Qinling region is proposed as a source of the mysterious highly radiogenic lead in Shang period bronzes.
- Regional specialisation and a multiple-direction interregional exchange are shown in Bronze Age China
- A new understanding of ancient metallurgy in broader social-economic contexts is offered.

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 core and metropolitan region of the Shang polity (Figure 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 just 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. After looking at the data collected by the authors, Ernst Pernicka (2013, personal communication) even joked that archaeological scientists would have given up the lead isotope method if they had started with the Shang period bronzes.

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 sit in the heart of the debate, we begin to see a promising new tendency 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 and discuss the implications of this new model, thus moving towards a new understanding of bronze metallurgy and its social-economic context in Bronze Age China.

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 (Figure 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 (Figure 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 from the fourteenth to the 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 stylistical/typological diversity, comprising various groups of products that are typologically attributable to distinct regions, including the Shang metropolitan areas in the Central Plain (Figure 2: Sub-group A), the Wei River valley in the north of the Qinling Mountains (Figure 2: Sub-group B), and the middle-lower Yangtze River Valley (Figure 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 correlation among the indigenous archaeological culture, stylistically local items (sickle-shaped objects, *Zhang* sceptres and socketed axes, Figure 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 of 31 Hanzhong bronze objects and suggested the region as a foothold in the "northern route" through which the Central Plain polities contacted those in the Sichuan Basin, which is relevant to the exploitation of metallic resources in the regions further southwest, the bordering area of Yunnan, Guizhou and Sichuan provinces.

3. Materials, methods and analytical results

This paper presents new lead isotope data of 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 thought to be representative of the entire group (Figure 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 2wt% for alloys classification. Detailed results and description 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 of 115 samples of 104 bronze objects from Hanzhong are now available for discussion, with 87 of them being complemented with their 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 from 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 applying lead isotope analysis for the provenance of copper-based metals in antiquity (Gale and Stos-Gale, 1982). While the contribution of lead from 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). The issue appears 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 it is complicated to decide how much lead in copper-based alloys can signify deliberate addition of lead, several scholars have tentatively suggested that a concentration of 1 wt% Pb is sufficient to indicate addition of lead, and for the isotope signature being dominated by the lead source (Zhu and Chang, 2002, Jin, 2008: 41, Liu, et al., 2018b).

Figure 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 (Figure 3:b). There is no clear linear correlation between 1/Pb (1000 ppm^{-1}) and the lead isotope ratio ($^{206}Pb/^{204}Pb$) (Figure 3:a), as many of the plots are horizontally squeezed in 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. Figure 3:b is also 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 similar HRL isotope signature, although it is interesting to see that a considerable number of lead-rich samples (Pb $\geq$ 2%) seem to be more radiogenic than the rest ($^{206}Pb/^{204}Pb$ > 23).

As mentioned before, typological diagnosis and chemical analyses have differentiated four sub-groups among the assemblage of Hanzhong bronzes, implying their 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 in Figure 4, it is surprising to see that lead isotopic composition of samples from different sub-groups again substantially overlap with each other 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 material 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 from various disciplines. More than 60% of the analysed Shang period bronzes (n>800) were found to have distinctive highly radiogenic lead isotopic compositions, $^{206}Pb/^{204}Pb \geq 20$ and $^{208}Pb/^{204}Pb \geq 40$, 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 in a vast area of several million km^2 in China and involves most of the major Shang period regional cultures (Figure 1). The HRL bronzes identified in different regions are hardly differentiated from each other by their lead isotope ratios (Figure 5), despite their remarkable typological/cultural varieties (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, as most of the HRL bronzes contain a significant amount of lead (> 2 wt%) that dominates lead isotope ratios of the measured objects, the source should be plumbiferous. On the other hand, some artefacts with low lead contents (< 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 Figure 3.

It is also important to note that the wide appearance of HRL bronzes is chronologically limited to approximately 300 years between the Upper Erligang (early-middle Shang period) and the Yinxu Phase III (ca. 1450-1150 BCE) (Figure 6, Figure 7). Despite forming the majority of Shang period objects, HRL bronzes are hardly found among bronzes from the pre-Shang Erlitou and the later 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), and 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 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 indicates that it is most likely that a single source region had 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 percent of lead, suggest the source would have supplied both copper and lead during its 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 China, as recently proposed by Liu, et al. (2018a). However, according to the lead isotope data for lead and copper ores from China (Jin, et al., Figure 3), radiogenic lead is rather rare and only several mineral deposits including the ones in north-east Yunnan, Qinling and Zhongtiao Mountains are reported to yield metalliferous ores with lead isotopic values as high as Shang bronzes. Considering the rather 'sharp' chronological beginning and end of use of HRL in such a vast geographically and culturally diverse territory, current evidence tends to be more consistent with the asumption of a single source or source region. With more 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.

Talking about the geographic location of this source, however, becomes 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 the following 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 the 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, but none of them is so far conclusive and sometimes conflicts with 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 has therefore remained 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 Figure 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 typologically and chemically distinctive objects such as sickle-shaped objects and *Zhang* sceptres (Sub-group D in Figure 2) are found to be made of HRL metal as well (mostly unalloyed copper, Figure 3, Figure 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) has 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 would further testify 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 Mujiazhuang copper deposit in the Zhashan area of the south Qinling Orogenic Belt, about 200 km to the northeast of Hanzhong, had been identified to have highly radiogenic lead isotopic compositions (see Supplementary Table S2 for detailed analytical results) (Zhu, et al., 2006). To the south of the basin, the Pb-Zn deposit in Mayuan has been classified as Mississippi Valley Type (MVT), which tends to have more radiogenic and varied lead isotope signatures (Liu, et al., 2015), even though the published data for this deposit were not highly radiogenic.

The rich mineral resources in the region have long been noticed and 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 date 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 date of 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 Figure 7). The Jinsha site, which has yielded the only later HRL bronze group dated to early Western Zhou (Jin, et al., 2004), is located in the Sichuan Plain, hence not very far from Hanzhang and showing a close relationship with the Baoshan culture (XDWX, 2002).

Based on the aforementioned observations, here we propose the Qinling area as a potential target area to locate 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 widespread adoption of bronze metallurgy in China, especially south-eastward (Bagley, 1999, Wang, 2014). The increasing expansion of production scale in the Shang metropolitan areas would have undoubtedly increased demand for raw materials such as metals, which subsequently facilitated the 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 pronounced repeatedly by specialists in Bronze Age China archaeology that acquisition of metals for the 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 of the exchange network since the Erligang period, the local communities of Hanzhong would have been stimulated by the external influence and reacted to it 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 from 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 which excelled at other productive activities. This kind of dynamics of interaction has 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), reginal bronze industries across the vast territory in 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 was the case during the early Shang period, must have given way to a more complex multiple-direction exchange network. Importing copper and lead from specialised mining/smelting communities in Hanzhong through the existing connection 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 manufacture 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 Bronze Age Alps (Shennan, 1999).

It is also worth noting that the decrease of 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 engaged with 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 has been 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 only 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 for furthering our understanding of Shang period China. Instead of being just an unsolved mystery pertaining to 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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Figure Captions

Figure 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)*

Figure 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 2010)*

Figure 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*

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

Figure 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)*

Figure 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)*

Figure 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.*