Did China import metals from Africa in the Late Bronze Age?

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Did China import metals from Africa in the Bronze Age?

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Abstract

The origins of the copper, tin and lead for China's rich Bronze Age cultures is a major topic in archaeological research, with significant contributions being made by archaeological fieldwork, archaeometallurgical investigations, and geochemical considerations. Here, we investigate a recent claim that a major part of Shang period metalwork was made with metals from Africa, imported together with the necessary know-how to produce tin bronze. A brief review about the current status of lead isotopic study on Shang period bronze artefacts is first provided, clarifying a few key issues involved in this discussion. We then show that there is no archaeological or isotopic basis for bulk metal transfer between Africa and China during the Shang period, and that the copper and lead in Shang bronze with a strongly radiogenic signature was not likely to be from Africa. We call for collaborative interdisciplinary research to address the vexing question of the Shang period's metal sources, focussing on smelting sites in geologically defined potential source regions and casting workshops identified in a number of Shang settlements.

Key word Lead isotopes, highly radiogenic lead, Shang bronze, Provenance

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INTRODUCTION

Most major Bronze Age civilizations developed in the catchments of large rivers sustaining a high population density through intensive agriculture. These areas, however, almost always are devoid of mineral resources which are typically exposed only in mountainous areas, remote from the centres of agricultural civilization. Thus, these centres were dependent on distant areas to provide their strategically important metals, primarily copper, tin and gold, but also lead and silver.

Substantive research has identified major copper sources for Egypt, Mesopotamia and the Indus Valley civilizations (Rothenberg 1988; Weisgerber 1980; Hauptmann 2007; Hoffman and Miller 2014). Depending on geological circumstances and geopolitical conditions, different and changing sources of metal have been used, and the study of these early supply routes and communications is a core element of archaeometallurgical research.

The same is true for the Bronze Age cultures in China and their copious need for copper, tin and lead to produce vast quantities of ritually important vessels, but also weapons and other implements. Extensive programmes of metal analysis have shown that ancient bronze casters in China utilized a range of metal sources in different regions and periods, with distinct trace element and lead isotope signatures (see Cui and Wu 2008; Jin 2008; Chen et al. 2009, 2016; Pollard et al. 2017). Among these, Shang period bronzes dated between the 16th and 11th centuries BCE stand out by their highly distinctive isotopic and chemical compositions. Identifying the geological source(s) of this metal is a long-standing issue in Chinese archaeology, which has attracted considerable research interest from many scholars of various disciplinary backgrounds. A recent article by Sun et al. (2016) is a new but unconvincing attempt to answer this question. It not only claims that '*the Yin-Shang people may have learned bronze technology elsewhere and brought it to China*' (Sun et al. 2016, 5), but also concludes that '*both the Yin-Shang and the Sanxingdui bronzes were obtained in Africa, bearing the highly radiogenic lead isotopic signatures of Africa's Archean cratons. Alternatively, some ancient people might have come to China from Africa, carrying tin and/or bronzes with them*' (Sun et al. 2016, 6). These hypotheses are undoubtedly bold and eye-catching, but unfortunately are also fundamentally flawed. In this paper, we offer a brief summary of currently available research on highly radiogenic lead found in ancient Shang

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bronzes, clarifying a few key issues which were misinterpreted by Sun et al. (2016) and discuss some thoughts on how to progress this research in the future.

PROVENANCE OF SHANG PERIOD BRONZES

The Shang period was a major section of the Bronze Age in China and can be generally divided into the Early Shang/Erligang period (16^{th}-14^{th} century BCE), the Middle Shang/transitional period (14^{th}-13^{th} century BCE) and the Late Shang (Yin)/Anyang period (13^{th}-11^{th} century BCE) (Institute of Archaeology, CASS 2003; Liu and Chen 2012; Tang 2001). The core region of the Shang culture was in the Central Plains of China (the lower reaches of Yellow River), but its cultural influences can be identified by the distribution of ‘Shang style’ bronze vessels and other objects in a fairly large area including the middle range of the Yangtze River, the Huai River basin, the Shandong peninsula, the Chengdu plain, the Hanzhong area, and the Loess Plateau (Liu and Chen 2012). The identification of metal source(s) of this period has been one of the major issues for archaeologists, since it reveals not only the interregional relationship and trading pattern of this period but also potentially explains the change of political landscape. However, for decades, the provenance of Shang bronze has troubled many researchers due to its peculiar lead isotope signature.

The first application of lead isotope analysis to Shang period bronze was carried out by Zhengyao Jin who identified 4 out of 14 samples from Yinxu (the capital of the Late Shang) as having highly radiogenic lead isotope ratios ($^{206}Pb/^{204}Pb>20$ and $^{207}Pb/^{206}Pb<0.80$), very different from most known Chinese lead deposits (Jin 1987). He proposed that the raw materials for casting bronzes in Yinxu came from Yunnan in southwest China despite its fairly long distance away from

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the Central Plains. Triggered by this pioneering work, a number of teams have contributed to this research, and have published the lead isotope ratios of more than 500 Shang bronze artefacts. Approximately half of them show highly radiogenic lead isotope ratios (see reviews by Chen 2010; Cui and Wu 2008; Jin 2008 and references therein).

The interests of geochemists were also caught since no ore deposit with the same chemical and isotopic characteristics has been identified so far within the modern territory of China (Peng 1996; Sun et al. 2016; Zhu and Chang 2002). The highly radiogenic lead in Shang bronze artefacts is isotopically unique. They are both highly uranogenic ($^{206}Pb/^{204}Pb>20$) and thorogenic ($^{208}Pb/^{204}Pb>40$), and generally plot along a line with a high slope in the $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram. This general linear trend was usually interpreted as an isochron line indicating the age of radiogenic lead source (Sun et al. 2016; Zhu and Chang 2002) but some scholars also argued it could be fictional and formed via mixing highly radiogenic lead and normal lead from different sources (Chang et al. 2003; Saito et al. 2002). The characteristics of highly radiogenic lead in Shang bronze distinguish it from most known lead deposits and bronze artefacts worldwide. Based on theoretical geochemical considerations, a number of candidate regions including southwest China (Jin 2008), the Qinling area (Saito et al. 2002), and the Middle-Lower reach of the Yangtze River (Peng et al. 1999) have been proposed (also see Zhu and Chang 2002). However, a specific ore deposit with lead isotope signature matching Shang artefacts has not yet been identified.

Two important points should be drawn from the previous studies (also see Jin 2008, 33-47; Zhu and Chang 2002). Firstly, the ore source(s) we are looking for should contain both copper and lead. The bronze alloys of Shang commonly contain over 2 wt% lead, which distinguish them from the copper alloys used by the cultures in the Eurasian Steppe (Hsu et al. 2016; Pollard et al.

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2017). Considering these lead rich artefacts commonly have highly radiogenic lead isotope ratios, the source we are looking for should be plumbiferous. Furthermore, several artefacts with low lead content (<1 wt%) and malachite samples from various sites also show similar lead isotope ratios, suggesting the source of the highly radiogenic lead in the alloy is indeed a copper ore with variable lead content. Zhu and Chang (2002) have pointed out that copper deposits containing highly radiogenic lead are not rare in China but almost all of them contains less than 50 ppm Pb. Thus, they cannot be the source for the relatively lead-rich Shang bronze artefacts. On the other hand, Cu-Pb polymetallic deposits with lead isotope signatures similar to the Shang bronze artefacts are quite rare (Chang et al. 2003).

Secondly, it is important to note that bronze artefacts with highly radiogenic lead only appeared in significant numbers during the Shang period (Figure 1). Fifty eight analysed artefacts from the pre-Shang Erlitou site (19^{st} -16^{th} century BCE) show no highly radiogenic lead isotope ratios while the one analysed artefact from this site dated to the Shang period (5^{th} stage) contains highly radiogenic lead (Jin et al. 1998). During the Early Shang period, bronze artefacts with highly radiogenic lead appeared in Zhengzhou and Yanshi Shang cities in the Central Plains (Jin 2008, 26; Tian 2013; Peng et al. 1997) and Panlongcheng Shang city in the Middle Yangtze River (Jin et al. 1987; Peng et al. 2001; Sun et al. 2001), while in Yuanqu Shang city in southern Shanxi, fourteen analyses only revealed one artefact of this type (Cui et al. 2012). For the Middle-Late Shang period, they were identified in Anyang in the Central Plains (Jin 2008; Liu 2015; Tian et al. 2010; Peng et al. 1997), Yulin in northern Shaanxi (Liu 2015), Chenggu and Yangxian in Hanzhong area (Jin 2008, 132-147), Xinyang and Zhumadian in Southern Henan (Liu et al. 2016; Xiao et al. 2016), Sanxingdui in the Chengdu plain (Jin et al. 1995), Xin'gan and Wucheng in Jiangxi (Jin et

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al. 1994; Peng et al. 1997), and Ningxiang in Hunan province (Ma et al. 2016). The analyses of collections in the Arthur M. Sackler Museum in Washington D.C. (Barnes et al. 1987) and in the Sen-oku Hakuko Kan in Kyoto (Hirao et al. 1998) also show a significant proportion of Late Shang bronze artefacts with this isotopic signature. At the end of the Shang period, the highly radiogenic lead isotope ratios quickly disappeared in the Central Plains (see Jin 2008, 33-46), while in the relatively remote sites as Jinsha in the Chengdu plain and Tanheli in Ningxiang, the use of bronze with highly radiogenic lead continued into the Late Shang-Early Western Zhou period (11^{th}-10^{th} century BC) (Jin et al. 2004; Ma et al. 2016). It is important to note that although regions such as the Chengdu plain, Hanzhong and northern Shaanxi were not likely under the direct control of the Shang political power and might have developed their own metallurgical industries, they had cultural connections with people in the Central Plains (e.g. Chen et al. 2016; Falkenhausen 2003; Rawson 2017). Shang-period China was home to a multitude of metallurgical traditions, connected through a complex network of metal exchange and trade (see e.g. Chen et al. 2009; 2016). If it is assumed that just one source provided all metals with this unique isotopic signature (Jin 2008, 175), then this source was predominantly exploited during the Shang period and its products circulated in a vast area across north, south and southwest China, penetrating political boundaries. Its quick decline at the end of the Shang period might indicate that by then, the source was exhausted or otherwise lost, possibly due to the change in political landscape and long-distance trade organisation.

Figure 1 Map showing Shang sites where bronze artefacts with highly radiogenic lead isotope ratios were published. They spread across a fairly large area but have cultural connections with each other indicated by the Shang-style bronze ritual vessels.

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The paper by Sun et al. in 2016 makes a new attempt to address the provenance problem of highly radiogenic lead in Shang bronze artefacts. The core conclusion of Sun et al. (2016, 6) is that the bronze from Yinxu/Anyang and Sanxingdui with highly radiogenic lead isotope signature was brought in from Africa, together with some technological know-how of bronze metallurgy. They argued that ore deposits in China are isotopically incompatible with the bronze artefacts with this peculiar isotopic signature while the tin ingots, prills and bronze artefacts from Southern Africa published by Molofsky et al. (2014) match them well both in terms of isotopic composition and isochron age (Sun et al. 2016, 5). We find this argument is misleading and flawed both isotopically and archaeologically.

The difference between Shang bronze and southern African bronze, copper and tin

Sun et al. (2016) misrepresent the lead isotope data published by Molofsky et al. (2014). The highly radiogenic lead in southern African bronze was from tin ore rather than copper or lead ore. As stated by Sun et al. themselves (2016, 4), the lead content of tin ore is generally lower than that of copper ore and usually in the range of 10-500 ppm (see also Gale and Stos-Gale 2000; Molofsky et al. 2014), and in most ancient bronzes, the concentration of copper is much higher than that of tin. Therefore, the lead isotopic signature of tin is normally masked even by just alloying with copper. Only in cases where the copper has an exceptionally low lead content while the tin has highly radiogenic lead isotope ratios and a relatively high lead concentrations, the lead isotope data of tin bronze can be used to address the source of tin. The bronze artefacts, tin ingots and tin prills published by Molofsky et al. (2014) are one such exceptional case. Even though they plot along the isochron line of c. 2.0 Ga and scattered to the highly radiogenic end ($^{206}Pb/^{204}Pb$ up to 90), the local copper ore and metallic copper generally have common lead isotope ratios and

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more importantly very low lead content (<100 ppm) (Molofsky et al. 2014, 448) (Figure 2a). The reason that the bronze artefacts spread along an isochron line and extend to the highly radiogenic end is mainly that tin, containing highly radiogenic lead, was added to a lead-poor copper; the resulting lead contents of these artefacts are generally less than 500 ppm (Figure 2a). Consequently, both isochron age of 2.0 Ga and the high $^{206}Pb/^{204}Pb$ ratio are the signature of the local tin deposit and have nothing to do with the source of copper or lead (Molofsky et al. 2014, 448). In contrast, as it has been clarified previously, the source of highly radiogenic lead in the Shang period is a copper-lead deposit. Figure 2a shows that although the Yinxu and Sanxingdui artefacts have $^{206}Pb/^{204}Pb$ ratios similar to some southern African bronzes, their lead contents are significantly higher. Meyers et al. (1987, 555-557) and Pollard et al. (2017) made similar plots with larger data sets of Shang bronzes and showed the same pattern. Additionally, the $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ diagram shows that southern African bronze and copper have lower $^{208}Pb/^{204}Pb$ than Shang period bronze in the radiogenic end (Figure 2b), indicating that although the source in southern Africa may have a similar isochron age as the Shang bronze, its source was more depleted of thorium. In summary, the characteristics of the published southern African copper deposits and bronze are quite different from the Shang bronzes and do not support the claim that they were from the same source.

Figure 2. a) $^{206}Pb/^{204}Pb$-Pb wt% plot for southern African copper (red open square), bronze (purple open square) and Shang bronzes from Yinxu (blue dots) and Sanxingdui (orange dots). Shang bronze is generally more radiogenic than southern African copper and much richer in lead than southern African copper and bronze. b): $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ diagrams for Shang bronze, Southern African copper and bronze. The southern African bronzes are less thorogenic than highly radiogenic Shang bronze ($^{206}Pb/^{204}Pb>20$). The Shang bronze data is from Jin et al. (1987), Tian et al. (2012) and Jin et al. (1995), provided as online supplementary material by Sun et al. 2016. Only samples published with chemical data were used. The analytical errors of both TIMS and MC-ICP-MS are smaller than the symbols.

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Bronze from Egypt and surrounding regions do not have the Shang radiogenic signature

Secondly, most of the Shang sites are dated to the second half of the second millennium BC, and so far there is no archaeological or isotopic evidence showing any form of bulk metal transfer between China and Africa during this period. In fact there is no evidence for the production or use of metals in southern Africa before 200 AD (Killick 2014). Ancient Egyptians in North Africa commonly used bronze during the 2nd millennium BC. However, regardless of Sun et al.'s (2016, 6-7) speculation that the ancient Egyptians might have used ores from Archean Cratons with highly radiogenic lead, analyses of New Kingdom Egyptian bronze artefacts shows no highly radiogenic lead isotope signatures, and generally low lead content (Cowell 1986; Ogden 2000; Stos-Gale et al. 1995; Rademakers et al. 2017) (Figure 3). The analyses of casting remains, lead artefacts, kohl and glasses also reveal no highly radiogenic lead isotope ratios (Rademakers et al. 2017; Shortland 2006; Stos-Gale et al. 1995) (Figure 3a). The argument of Sun et al. (2016, 7) that the highly radiogenic lead isotope signature in Egyptian artefacts was eliminated in the later recycling practice is not valid since the majority of these artefacts are dated to the New Kingdom of ancient Egypt (contemporary with the Shang period) or to earlier periods. Preliminary analyses of galena and haematite from the Eastern Desert of Egypt and Egyptian burials by Gale and Stos-Gale (1981) does show two galena and one haematite (all from burial) samples containing highly radiogenic lead. However, in comparison to the Shang bronze, they plot in the lower area in both $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ diagrams (Figure 3a-b).

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Figure 3 a: $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ diagram of Shang artefacts and Egyptian artefacts, galena and haematite. Most Egyptian samples are not highly radiogenic. Two galena and one haematite from burials have high $^{206}Pb/^{204}Pb$ but lower $^{207}Pb/^{204}Pb$ ratio than Shang artefacts. b: $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ diagram of Shang artefacts and Egyptian artefacts, galena and haematite. The highly radiogenic Egyptian galena and haematite samples are less thorogenic than the Shang artefacts. c: $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ Shang artefacts, Sinai ores, slag and copper, and Afghanistan copper ore and slag. Afghanistan lead slags are not as radiogenic as Shang artefacts. Some Sinai copper and Afghanistan copper slag have high $^{206}Pb/^{204}Pb$ but lower $^{207}Pb/^{204}Pb$ ratio than Shang artefacts. d: $^{208}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ diagram of Shang artefacts, Sinai ores, slag and copper, and Afghanistan copper ore and slag. The Sinai samples are less thorogenic than the Shang artefacts while the Afghanistan copper slags are more thorogenic than the Shang artefacts. The Egyptian data are from Rademakers et al. 2017, Shortland et al. (2006), and Stos-Gale et al. (1995). The Sinai data are from Abdel-Motelib et al. (2012) and Rehren and Pernicka (2014). The Afghanistan data are from Thomalsky et al. (2015). The analytical errors of both TIMS and MC-ICP-MS are smaller than the symbols.

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Even if a copper-lead deposit with isotope composition similar to the Shang bronze is identified in Egypt in the future, it is still highly unlikely that the long-distance movement of copper and lead with this unique lead isotope signature during the Bronze Age did not leave any evidence at its “source” nor anywhere along its “trading route” through some of the archaeologically best-studied regions on Earth. Until now, the published analytical data from regions surrounding Egypt such as Wadi Arabah (e.g. Hauptmann 1992; Hauptmann 2007; Gale et al. 1990), the Arabian Peninsula (e.g. Begemann et al. 2010; Weeks et al. 1997; Weeks 2004), Eastern Mediterranean (e.g. Stos-Gale 2000; Stos-Gale and Gale 2010; also see the online database OXALID), Mesopotamia (e.g. Begemann and Schmitt-Strecker 2009; Begemann et al. 2010) and Anatolia (e.g. Sayre et al. 2001; Yener et al. 1991) do not show a significant proportion of Bronze Age artefacts with both high lead content and highly radiogenic lead isotope ratios. In the Sinai Peninsula, some copper artefacts, slags and ores with high $^{206}Pb/^{204}Pb$ ratios were identified but they are nearly lead-free copper, having lower $^{207}Pb/^{204}Pb$ values (Figure 3c) and are much less thorogenic than the Shang bronzes ($^{208}Pb/^{204}Pb<40$) (Figure 3d) (Abdel-Motelib et al. 2012; Rehren and Pernicka 2014). Recent work in Afghanistan revealed ore and smelting slag with highly radiogenic lead isotope signatures, indicating some highly radiogenic lead and copper might have been smelted there (not in Africa) (Thomalsky et al. 2015). However, the lead-rich slags only have $^{206}Pb/^{204}Pb$ ratios up to 20.211, still much less radiogenic than Shang artefacts (Figure 3c). The copper slags, though having high $^{206}Pb/^{204}Pb$ ratios, contain little lead and are plotting generally beneath the Shang artefacts at the radiogenic end in the $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ diagram(Figure 3c). In addition, they are even more thorogenic than the Shang artefacts (Figure 3d). Considering China is the only region so far that has revealed abundant lead-rich bronze artefacts with highly radiogenic lead isotope ratios in the second millennium BC, it is reasonable to consider its source was inside rather than outside of modern-day China.

Bronze metallurgy did develop in pre-Shang China

Thirdly, a large number of incorrect notions about early metallurgy in China in Sun et al. (2016) greatly undermine the quality of that paper and caused a number of wrong conclusions to be reached. First, they stated that bronze technology appeared “suddenly” in the Central Plains of China during the Yin-Shang period (Sun et al. 2016: 1). They also claimed that, while arsenical bronze appeared in Mesopotamia and Europe prior to tin bronze, it has not been reported in China (Sun et al. 2016: 5). Thus, in their opinion, the Yin-Shang people had to learn the bronze technology somewhere outside China. Contrary to these assertions, the Shang metallurgy developed from a rich earlier Chinese metallurgical tradition. Here is not the place to review early Chinese metallurgy in full; a brief summary has to suffice. Yin-Shang refers to the Late Shang period with its capital at Anyang, while the Erlitou and Early Shang cultures with their core area in Central Henan are its predecessor (see Bagley 1999; Liu and Chen 2012, 284; Thorp 2006). Linduff and Mei (2009) have provided a thorough review about the development of early metallurgy in China. Solid evidence of tin bronze use appeared in the Central Plains no later than

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the Erlitou period (19th-16th century BC), notably without highly radiogenic lead. By this time, the technology of using piece-mould casting to manufacture bronze ritual vessels, widely accepted as a hallmark of Chinese Bronze technology had already been mastered by metal workers in the Central Plains (Lian et al. 2011; Mei 2009). In the following Erligang period, this technology greatly developed and a significant number of fine bronze ritual vessels have been excavated at sites not only in the Central Plains (e.g. Zhengzhou Shang city in Henan) but also in south China (e.g. Panlongcheng Shang city in Hubei) (Bagley 1977; Bagley 1999). Similar bronze ritual vessels and piece-mould casting technology were, however, not identified in contemporary Egypt (Odgen 2000).

The later Yin-Shang period (Late Shang) with its capital site at Anyang witnessed the peak of manufacturing bronze ritual vessels but by no means the earliest stage of substantial bronze production. It is clear that the typological style of bronze artefacts found at Anyang and many other Late Shang sites is rooted in the early Shang and Erlitou styles, with their decorative patterns becoming finer and frequently with high reliefs (Bagley 1999; Thorp 1985). In this period the piece mould casting gradually developed into a more complex form and the manufacturing of one ritual vessel can sometimes involve dozens of pieces of moulds sectioned both horizontally and vertically (e.g. Bagley 1987; Li 2007; Liu 2009). Abundant archaeological evidence has confirmed that bronze technology did not appear "suddenly" in the Yin-Shang period but evolved gradually within China.

The discussion about the origin of the Erlitou bronze technology is out of the scope of this paper; suffice it to say that there is on-going debate among scholars about how the impetus from the Eurasian Steppe influenced the development of metallurgy in the Central Plains (see the

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reviews by Li 2005; Linduff and Mei 2009; Liu et al. 2016; Mei et al. 2015). Therefore, it is rather alarming to read the statement that '*The majority of archaeologists in China strongly insist …… [that] bronze technology was developed independently in China*'. Even more disturbing is the following claim that "*No arsenic bronze has ever been reported in China*" (Sun et al. 2016: 5), which totally ignores the fact that the use of arsenical copper or 'arsenic bronze' during the second millennium BC has been widely identified in Xinjiang, the Hexi corridor, the Hanzhong area, South China and the Central Plains (e.g. Chen et al. 2009; Jin 2000; Liang et al. 2005; Qian et al. 2000; Wang et al. 2013) and recent studies have even identified a number of arsenical production sites in the Hexi corridor and Guanzhong Plain (e.g. Chen et al. 2017; Li et al. 2015). The fragmented review about 'ancient bronze in China' in Sun et al. (2016: 5) not only neglects many important cultures and sites, but more notably, lacks a clear and correct understanding of the most recent research progress in this field and its academic significance (Mei et al. 2015).

SOME THOUGHTS FOR FUTURE INVESTIGATION

After reviewing major problems of the proposed African origin of Yin-Shang bronze metallurgy, we provide some brief thoughts for future investigation, stressing that archaeologists and geologists have to work together to solve this problem. As far as the published data is concerned, the source of Shang bronze still remains unknown. More geological investigations on ore deposits in those potential regions predicted by geochemical models are certainly important, including deposits that are too small to be of modern economic significance but rich enough to sustain Bronze Age exploitation. However, the geological deposits investigated today may not be the same as the ore used three thousand years ago. Even if the same deposits were exploited,

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continuous human mining activities might have completely destroyed earlier mines or fully consumed their shallower parts. A similar situation has been postulated for the famous lead-silver ore deposit of Laurion in Greece, with large amounts of Bronze Age copper metal matching the lead isotope signature of this deposit (Gale et al. 2009), although there is little evidence of copper minerals at Laurion today[1].

In order to really tackle this problem, we suggest that not only more ore analyses are needed from small but rich occurrences outside the modern large-scale ore prospects, but that much more attention should be paid to archaeological survey and excavation of Shang period copper and lead smelting sites in the aforementioned geochemical potential regions. Due to the bulky nature of ores, they were not likely to be smelted too far away from the mines. These sites are typically littered with smelting slags, which are durable in the depositional process and retain the lead isotopic signature of their products (e.g. Baron et al. 2014). Thus, if the Shang people indeed used ore from any of these mines, it should be expected to find smelting sites with slag containing highly radiogenic lead similar to the Shang artefacts. A large number of smelting sites which can be generally dated to the Shang period have been identified in Zhongtiao Mountain, southern Shanxi (Li 2012), the Middle Range of the Yangtze River (Cui 2016), and the Guanzhong Plain (Chen et al. 2017). The analysis of slag and ore samples from these sites will provide new evidence for this argument in the near future.

Additionally, any finds of raw metals and refining slag from foundries in settlement sites should also be analysed, since they can reveal information about raw materials before they entered the complex mixing and recycling process and help us to better define the isochron age of the original

[1] As one of the reviewers pointed out, a minor amount of lead or leaded copper with Laurion isotope signature may have "infected" large amounts of copper alloys.

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source and further narrow down the search area. In our opinion, only with the archaeological evidence of Shang period smelting and processing of copper and lead with highly radiogenic signatures, can we make meaningful suggestions for the original Shang metal sources.

CONCLUSION

The Shang period was a major section in the Bronze Age of China and the origin of its metal resources is an essential question to be asked. However, the complexity of this question does not allow it to be answered via a single investigation method. Sun et al. (2016) tried to address this problem through geochemical approaches but failed to correctly use the data from southern Africa and to incorporate the available relevant archaeological and archaeometallurgical information. On the other hand, lead isotopic data are also often used in the archaeological literature in an inappropriate manner due to the lack of basic understanding about its geological meaning. In our opinion, the best way to avoid such situation is building a solid cooperative relationship among researchers from different backgrounds, and ensuring that such interdisciplinary papers are reviewed by experts from all involved fields before being published.

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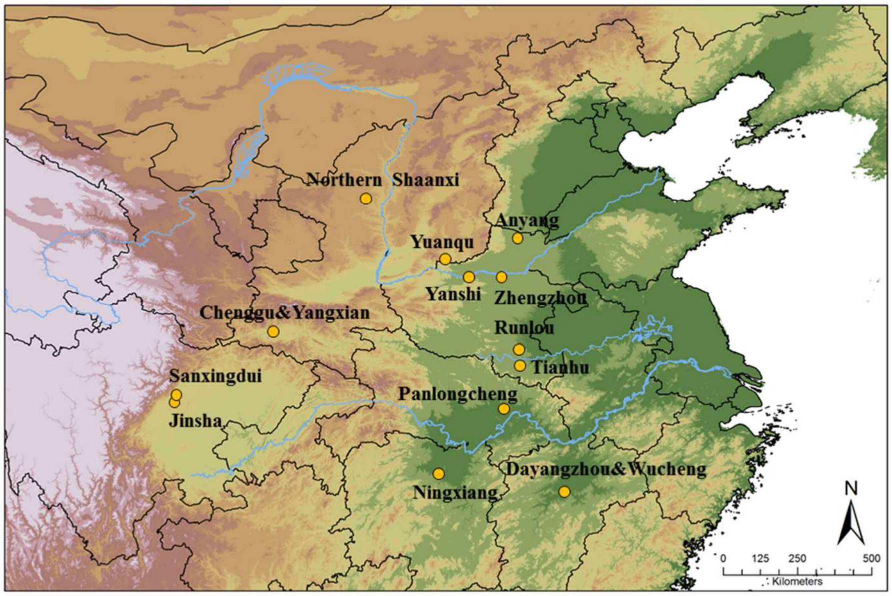

Figure 1 Map showing Shang sites where bronze artefacts with highly radiogenic lead isotope ratios were published. They spread across a fairly large area but have cultural connections with each other indicated by the Shang-style bronze ritual vessels.

279x170mm (96 x 96 DPI)

Review

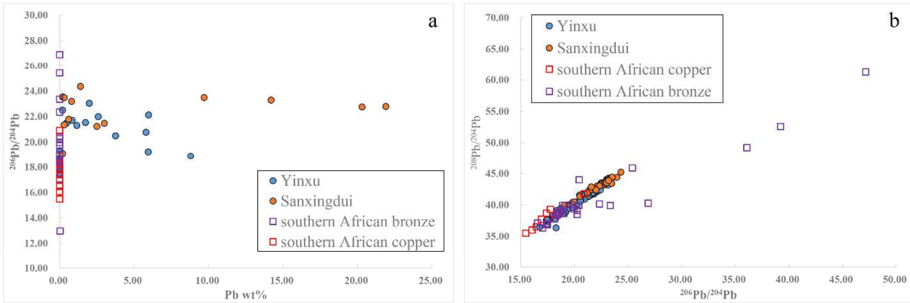

Figure 2. a) 206Pb/204Pb-Pb wt% plot for southern African copper (red open square), bronze (purple open square) and Shang bronzes from Yinxu (blue dots) and Sanxingdui (orange dots). Shang bronze is generally more radiogenic than southern African copper and much richer in lead than southern African copper and bronze. b): 208Pb/204Pb-206Pb/204Pb diagrams for Shang bronze, Southern African copper and bronze. The southern African bronzes are less thorogenic than highly radiogenic Shang bronze (206Pb/204Pb>20). The Shang bronze data is from Jin et al. (1987), Tian et al. (2012) and Jin et al. (1995), provided as online supplementary material by Sun et al. 2016. Only samples published with chemical data were used. The analytical errors of both TIMS and MC-ICP-MS are smaller than the symbols.

399x150mm (300 x 300 DPI)

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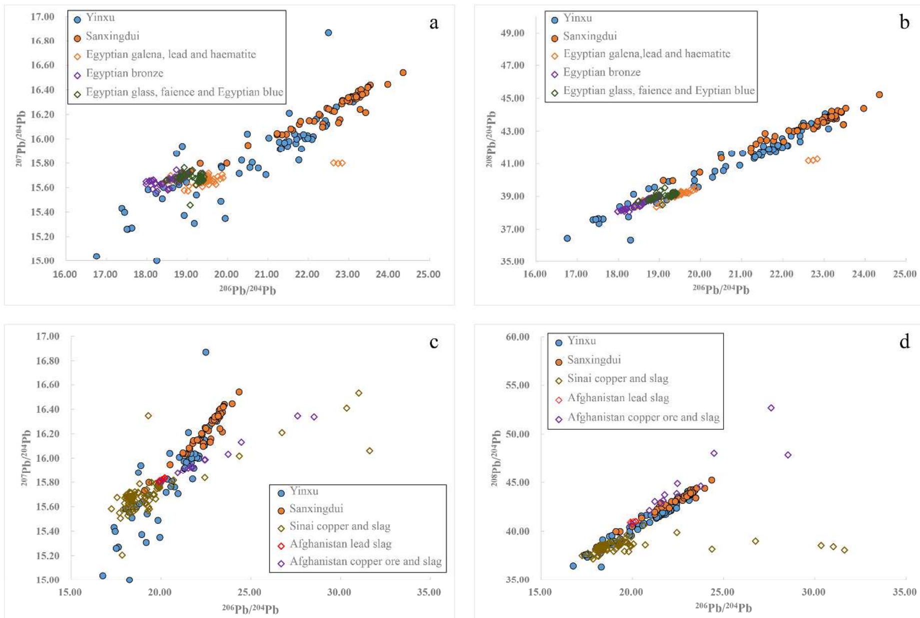

Figure 3 a: 207Pb/204Pb-206Pb/204Pb diagram of Shang artefacts and Egyptian artefacts, galena and haematite. Most Egyptian samples are not highly radiogenic. Two galena and one haematite from burials have high 206Pb/204Pb but lower 207Pb/204Pb ratio than Shang artefacts. b: 208Pb/204Pb-206Pb/204Pb diagram of Shang artefacts and Egyptian artefacts, galena and haematite. The highly radiogenic Egyptian galena and haematite samples are less thorogenic than the Shang artefacts. c: 207Pb/204Pb-206Pb/204Pb Shang artefacts, Sinai ores, slag and copper, and Afghanistan copper ore and slag. Afghanistan lead slags are not as radiogenic as Shang artefacts. Some Sinai copper and Afghanistan copper slag have high 206Pb/204Pb but lower 207Pb/204Pb ratio than Shang artefacts. d: 208Pb/204Pb-206Pb/204Pb diagram of Shang artefacts, Sinai ores, slag and copper, and Afghanistan copper ore and slag. The Sinai samples are less thorogenic than the Shang artefacts while the Afghanistan copper slags are more thorogenic than the Shang artefacts. The Egyptian data are from Rademakers et al. 2017, Shortland et al. (2006), and Stos-Gale et al. (1995). The Sinai data are from Abdel-Motelib et al. (2012) and Rehren and Pernicka (2014). The Afghanistan data are from Thomalsky et al. (2015). The analytical errors of both TIMS and MC-ICP-MS are smaller than the symbols.

399x299mm (300 x 300 DPI)