archaeometry

*Archaeometry* **60**, 1 (2018) 105–117 doi: 10.1111/arcm.12352

# DID CHINA IMPORT METALS FROM AFRICA IN THE BRONZE AGE?*

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*The origins of the copper, tin and lead for China's rich Bronze Age cultures are 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 the greater part of the Shang-period metalwork was made using metals from Africa, imported together with the necessary know-how to produce tin bronze. A brief review of the current status of lead isotopic study on Shang-period bronze artefacts is provided first, clarifying a few key issues involved in this discussion. It is then shown 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 is not likely to be from Africa. We call for collaborative interdisciplinary research to address the vexing question of the Shang period's metal sources, focusing on smelting sites in geologically defined potential source regions and casting workshops identified at a number of Shang settlements.*

*KEYWORDS:* LEAD ISOTOPES, HIGHLY RADIOGENIC LEAD, SHANG BRONZE, PROVENANCE

## INTRODUCTION

Most major Bronze Age civilizations developed in the catchments of large rivers that were sustaining a high population density through intensive agriculture. These areas, however, are almost always 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

*Received 1 February 2017; accepted 9 August 2017
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the Indus Valley civilizations (Weisgerber 1980; Rothenberg 1988; 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 need to import copper, tin and lead to produce not only 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 Chen *et al*. 2009, 2016; Pollard *et al*. 2017). Among these, Shang-period bronzes dated between the 16th and 11th centuries BCE stand out due to their highly distinctive isotopic and chemical compositions. The identification of 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 paper 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 it 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 bronzes, clarifying a few key issues that were misinterpreted by Sun *et al*. (2016), and discuss some thoughts on how to progress this research in the future.

## THE PROVENANCE OF SHANG-PERIOD BRONZES

The Shang period was a major element of the Bronze Age in China and can generally be divided into the Early Shang/Erligang period (16th–14th centuries BCE), the Middle Shang/transitional period (14th–13th centuries BCE) and the Late (Yin) Shang/Anyang period (13th–11th centuries BCE) (Tang 2001; Institute of Archaeology, CASS 2003; Liu and Chen 2012). The core region of the Shang culture was in the Central Plains of China (the lower reaches of the Yellow River), but its cultural influences can be identified by the distribution of 'Shang-style' bronze vessels and other objects over 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 the metal source(s) of this period has been one of the major issues for archaeologists, since it reveals not only the inter-regional relationship and trading pattern of this period but also it potentially explains the change of political landscape. However, for decades, the provenance of Shang bronze has troubled many researchers due to its distinctive 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 ($^{206}\text{Pb}/^{204}\text{Pb} > 20$ and $^{207}\text{Pb}/^{206}\text{Pb} < 0.80$), 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 south-west China. 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 Cui and Wu 2008; Jin 2008; Chen 2015 and references therein).

Geochemists were also intrigued by these results, since no ore deposit with the same chemical and isotopic characteristics has been identified so far within the modern territory of China (Peng *et al*. 1997; Zhu and Chang 2002; Sun *et al*. 2016). 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 on a $^{207}$Pb/$^{204}$Pb versus $^{206}$Pb/$^{204}$Pb diagram. This general linear trend has usually been interpreted as an isochron line indicating the age of the radiogenic lead source (Zhu and Chang 2002; Sun *et al*. 2016), but some scholars have also argued that it could be fictional, and formed via mixing highly radiogenic lead and normal lead from different sources (Saito *et al*. 2002; Chang *et al*. 2003). The characteristics of highly radiogenic lead in Shang bronze distinguish it from most known lead deposits and bronze artefacts worldwide. On the basis of theoretical geochemical considerations, a number of candidate regions including south-west China (Jin 2008), the Qinling area (Saito *et al*. 2002) and the Middle-to-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 a lead isotope signature matching Shang artefacts has not yet been identified.

Two important points should be drawn from the previous studies (also see Zhu and Chang 2002; Jin 2008, 33–47). First, 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 distinguishes them from the copper alloys used by the cultures in the Eurasian Steppe (Hsu *et al*. 2016; Pollard *et al*. 2017). Considering that these lead-rich artefacts commonly have highly radiogenic lead isotope ratios, the source that we are looking for should be plumbiferous. Furthermore, several artefacts with low lead contents (< 1 wt%) and malachite samples from various sites also show similar lead isotope ratios, suggesting that 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 although copper deposits containing highly radiogenic lead are not rare in China, almost all of them contain 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 those of the Shang bronze artefacts are quite rare (Chang *et al*. 2003).

Second, it is important to note that bronze artefacts with highly radiogenic lead only appear in significant numbers during the Shang period (Fig. 1). Fifty-eight analysed artefacts from the pre-Shang Erlitou site (19th–16th centuries BCE) show no highly radiogenic lead isotope ratios, while the one analysed artefact from this site dated to the Shang period (fifth stage) contains highly radiogenic lead (Jin *et al*. 1998). During the Early Shang period, bronze artefacts with highly radiogenic lead appeared in the Shang cities in Zhengzhou and Yanshi in the Central Plains (Peng *et al*. 1997; Jin 2008, 26; Tian 2013) and Panlongcheng Shang city in the Middle Yangtze River (Jin 1987; Peng *et al*. 2001; Sun *et al*. 2001), while in Yuanqu Shang city in southern Shanxi, 14 analyses only revealed one artefact of this type (Cui *et al*. 2012). For the Middle-to-Late Shang period, they were identified in Anyang in the Central Plains (Peng *et al*. 1997; Jin 2008; Tian *et al*. 2010; Liu 2015), Yulin in northern Shaanxi (Liu 2015), Chenggu and Yangxian in the Hanzhong area (Jin 2008, 132–47), 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 al*. 1994; Peng *et al*. 1997) and Ningxiang in Hunan province (Ma *et al*. 2016). Analyses of collections in the Arthur M. Sackler Museum in Washington, DC (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

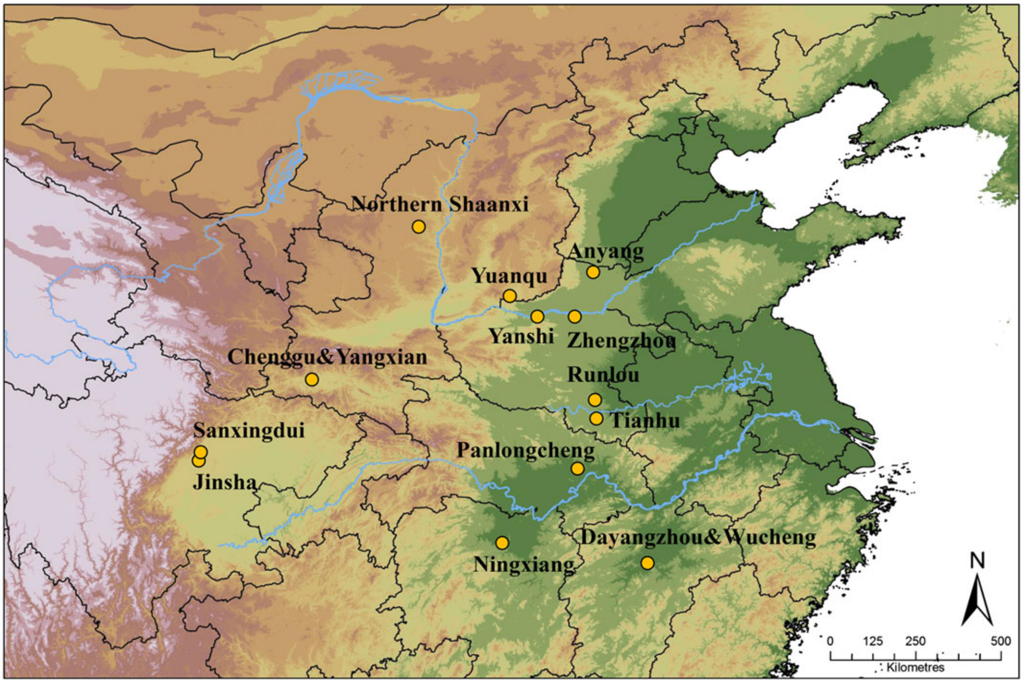

Figure 1 *A map showing Shang sites where bronze artefacts with highly radiogenic lead isotope ratios have been published. [Colour figure can be viewed at wileyonlinelibrary.com]*

the Shang period, the highly radiogenic lead isotope ratios rapidly disappeared in the Central Plains (see Jin 2008, 33–46), while at relatively remote sites such 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 (11th–10th centuries 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 probably not under the direct control of Shang political power and might have developed their own metallurgical industries, they had cultural connections with people in the Central Plains (e.g., von Falkenhausen 2001; Chen *et al*. 2016; 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 of the metals with this unique isotopic signature (Jin 2008, 175), this source was predominantly exploited during the Shang period and its products circulated over a vast area across north, south and south-west China, penetrating political boundaries. Its rapid decline at the end of the Shang period might indicate that by then, the source was exhausted or otherwise lost, possibly due to a change in the political landscape and in the organization of long-distance trade.

## SHANG BRONZE FROM AFRICA?

The paper by Sun *et al*. (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 a highly radiogenic lead isotope signature was brought in from Africa, together with some technological know-how concerning bronze metallurgy. They argue that ore deposits in China are isotopically incompatible with the bronze artefacts that have this distinctive 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, however, find this argument is misleading and flawed.

### *The difference between Shang bronze and Southern African bronze, copper and tin*

The highly radiogenic lead in Southern African bronze was from tin ore rather than copper or lead ore. As stated by Sun *et al*. (2016, 4) themselves, 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 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 can the lead isotope ratios of tin bronze be used to address the source of the 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 ~2.0 Ga and are scattered at 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, more importantly, very low lead contents ($<$ 100 ppm) (Molofsky *et al*. 2014, 448) (Fig. 2 (a)). Consequently, both the isochron age of 2.0 Ga and the high $^{206}$Pb/$^{204}$Pb ratio are the signature of the local tin deposit, and the resulting lead contents of bronze are less than 500 ppm (Fig. 2 (a)) (Molofsky *et al*. 2014, 448). In contrast, as has been clarified previously, the source of the highly radiogenic lead in the Shang period is a copper–lead deposit. Figure 2 (a) shows that although the Yinxu and Sanxingdui artefacts have $^{206}$Pb/$^{204}$Pb ratios similar to those of some Southern African bronzes, their lead contents are significantly higher. Meyers *et al*. (1987, 555–7), and Pollard *et al*. (2017) constructed similar plots with larger data sets of Shang bronzes and showed the same pattern.

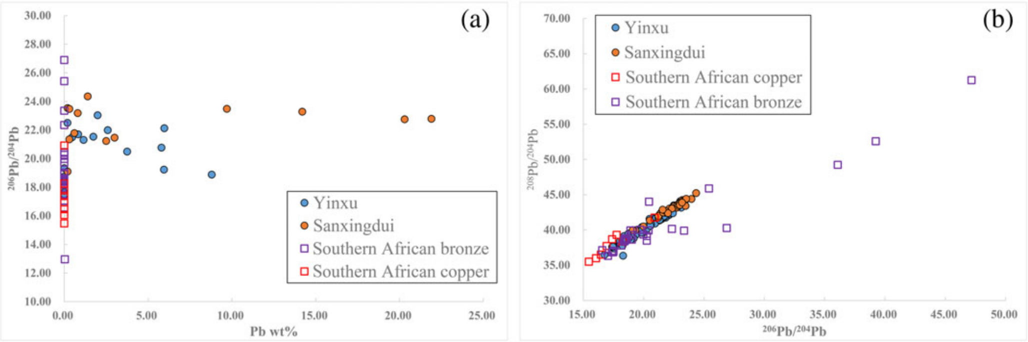

Figure 2 *(a) A plot of $^{206}$Pb/$^{204}$Pb versus Pb wt% for Southern African copper, bronze and Shang bronzes from Yinxu and Sanxingdui. Shang bronze is generally more radiogenic than Southern African copper and much richer in lead than Southern African copper and bronze. (b) A $^{208}$Pb/$^{204}$Pb versus $^{206}$Pb/$^{204}$Pb diagram for Shang bronze, Southern African copper and bronze. The Southern African bronzes are less thorogenic than the 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. [Colour figure can be viewed at wileyonlinelibrary.com]*

Additionally, the $^{208}$Pb/$^{204}$Pb versus $^{206}$Pb/$^{204}$Pb diagram shows that Southern African bronze and copper have lower $^{208}$Pb/$^{204}$Pb values than Shang-period bronze at the radiogenic end (Fig. 2 (b)), indicating that although the source in Southern Africa may have an isochron age similar to that of the Shang bronze, it is more depleted in 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.

### *Bronze from Egypt and the surrounding regions does not have the Shang radiogenic signature*

Second, 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 AD 200 (Killick 2014). Ancient Egyptians in North Africa used bronze during the second 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 show no highly radiogenic lead isotope signatures, and generally low lead contents (Cowell 1986; Stos-Gale *et al.* 1995; Ogden 2000; Rademakers *et al.* 2017) (Fig. 3). The analyses of casting remains, lead artefacts, kohl and glasses also reveal no highly radiogenic lead isotope ratios (Stos-Gale *et al.* 1995; Shortland 2006; Rademakers *et al.* 2017) (Fig. 3 (a)). 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 hematite from the Eastern Desert of Egypt and Egyptian burials by Stos-Gale and Gale (1981) does show two galena and one hematite (all from burial) samples containing highly radiogenic lead. However, in comparison to Shang bronze, they plot in the lower area in both $^{207}$Pb/$^{204}$Pb versus $^{206}$Pb/$^{204}$Pb and $^{208}$Pb/$^{204}$Pb versus $^{206}$Pb/$^{204}$Pb diagrams (Figs 3 (a) and 3 (b)).

Additionally, it is 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 anywhere along its 'trading route'. Until now, the published analytical data from regions surrounding Egypt, such as Wadi Arabah (e.g., Gale *et al.* 1990; Hauptmann *et al.* 1992; Hauptmann 2007), the Arabian Peninsula (e.g., Weeks 1999; Weeks 2003; Begemann *et al.* 2010), the Eastern Mediterranean (e.g., Stos-Gale 2000; Stos-Gale and Gale 2010; see also the online OXALID database), 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 a 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 have been identified, but they are almost lead-free copper, having lower $^{207}$Pb/$^{204}$Pb values (Fig. 3 (c)) and they are much less thorogenic than the Shang bronzes ($^{208}$Pb/$^{204}$Pb $< 40$) (Fig. 3 (d)) (Abdel-Motelib *et al.* 2012; Rehren and Pernicka 2014). Recent work in Afghanistan has revealed ore and smelting slag with highly radiogenic lead isotope signatures (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 (Fig. 3 (c)). The copper slags, though having high $^{206}$Pb/$^{204}$Pb ratios, contain little lead and generally plot beneath the Shang artefacts at the radiogenic end (Fig. 3 (c)). In addition, they are even more thorogenic than the Shang artefacts (Fig. 3 (d)). If we consider that

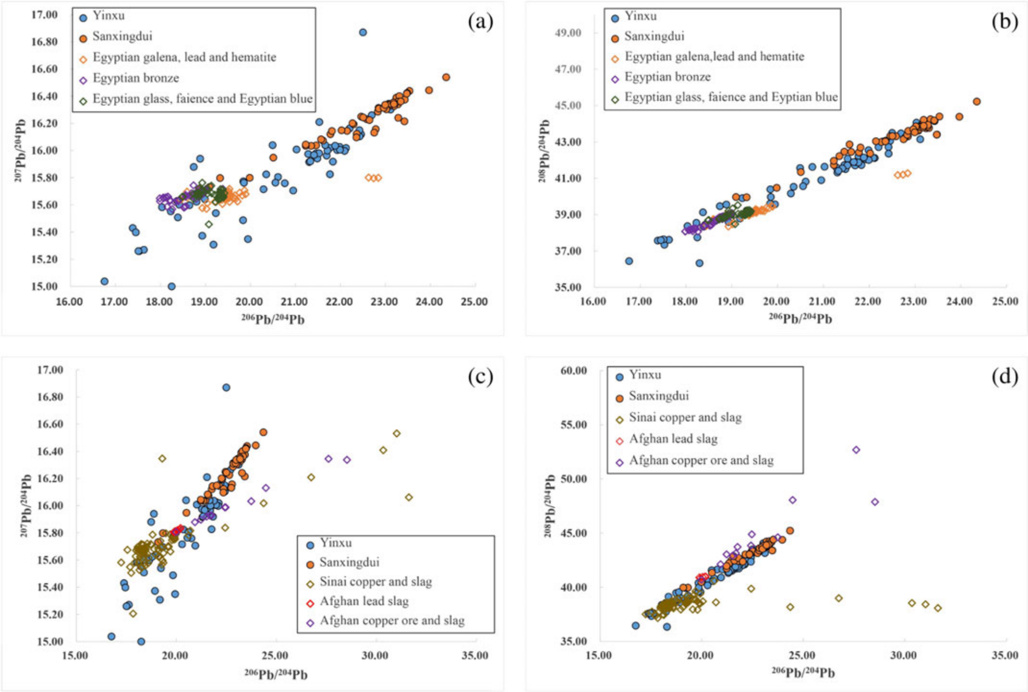

Figure 3 *(a) A $^{207}$Pb/$^{204}$Pb versus $^{206}$Pb/$^{204}$Pb diagram for Shang artefacts and Egyptian artefacts, galena and hematite. Most Egyptian samples are not highly radiogenic. Two galena and one hematite from burials have high $^{206}$Pb/$^{204}$Pb ratios but lower $^{207}$Pb/$^{204}$Pb ratios than Shang artefacts. (b) A $^{208}$Pb/$^{204}$Pb versus $^{206}$Pb/$^{204}$Pb diagram for Shang artefacts and Egyptian artefacts, galena and hematite. The highly radiogenic Egyptian galena and hematite samples are less thorogenic than the Shang artefacts. (c) A $^{207}$Pb/$^{204}$Pb versus $^{206}$Pb/$^{204}$Pb diagram for Shang artefacts, Sinai ores, slag and copper, and Afghan copper ore and slag. Afghan lead slags are not as radiogenic as Shang artefacts. Some Sinai copper and Afghan copper slags have high $^{206}$Pb/$^{204}$Pb ratios but lower $^{207}$Pb/$^{204}$Pb ratios than Shang artefacts. (d) A $^{208}$Pb/$^{204}$Pb versus $^{206}$Pb/$^{204}$Pb diagram for Shang artefacts, Sinai ores, slag and copper, and Afghan copper ore and slag. The Sinai samples are less thorogenic than the Shang artefacts, while the Afghan 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 Afghan data are from Thomalsky et al. (2015). The analytical errors of both TIMS and MC-ICP–MS are smaller than the symbols. [Colour figure can be viewed at wileyonlinelibrary.com]*

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 that its source was probably inside rather than outside modern-day China.

## *Bronze metallurgy did develop before the Yin-Shang period*

Third, a large number of incorrect notions about early metallurgy in China in Sun *et al*. (2016) greatly undermine the quality of that paper and have caused a number of wrong conclusions to be reached. First, the authors state that bronze technology appeared ‘suddenly’ in the Central Plains of China during the Yin-Shang period (Sun *et al*. 2016, 1). They also claim 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 about bronze technology somewhere outside China. Contrary to these assertions, the Shang metallurgy developed from a rich earlier Chinese metallurgical tradition. This 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 Erligang cultures, with their core area in central Henan, are its predecessor (see Bagley 1999; Liu and Chen 2012, 284). Linduff and Mei (2009) have provided a thorough review of the development of early metallurgy in China. Solid evidence of the use of tin bronze appears in the Central Plains no later than the Erlitou period (19th–16th centuries 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 metalworkers in the Central Plains (Mei 2009; Lian *et al.* 2011). In the following Erligang period, this technology developed considerably and a significant number of fine bronze ritual vessels have been excavated at sites not only in the Central Plains but also in South China (Bagley 1977, 1999). Similar bronze ritual vessels and piece-mould casting technology have not, however, been identified in contemporary Egypt (Odgen 2000).

The later Yin-Shang period (Late Shang), with its capital site at Anyang, witnessed the peak of the manufacture of 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 (Thorp 1985; Bagley 1999). 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.

Discussion of the origin of the Erlitou bronze technology is beyond the scope of this paper; suffice it to say that there is ongoing debate among scholars about how the impetus from the Eurasian Steppe influenced the development of metallurgy in the Central Plains (see the reviews by Li 2005; Linduff and Mei 2009; Mei *et al.* 2015; Liu *et al.* 2016). 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., Jin 2000; Qian *et al.* 2000; Liang *et al.* 2005; Chen *et al.* 2009; Wang *et al.* 2013) and recent studies have even identified a number of arsenical copper production sites in the Hexi corridor and in the Guanzhong Plain (e.g., Li *et al.* 2015; Chen *et al.* 2018). 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. More geological investigations on ore deposits in those potential regions predicted by geochemical models are certainly important. However, it should be noted that some deposits that are too small to be of modern economic significance could be rich enough to sustain Bronze Age exploitation. They may sometimes be ignored by modern geological investigations or fully consumed by continuous human mining activities. 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 are more ore analyses needed from small but rich occurrences outside the modern large-scale ore prospects, but that much more attention should be paid to the 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, we should expect to find smelting sites with slag containing highly radiogenic lead similar to that in the Shang artefacts. A large number of smelting sites generally dated to the Shang period have been identified at Zhongtiao Mountain, southern Shanxi (Li 2011), in the Middle Range of the Yangtze River (Cui 2016) and on the Guanzhong Plain (Chen *et al*. 2018). 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 at 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 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 element of the Bronze Age in China and the origin of its metal resources is an essential question that needs to be asked. However, the complexity of this question does not allow it to be answered via a single method of investigation. 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 a basic understanding about their geological meaning. In our opinion, the best way to avoid such a situation is to build a solid cooperative relationship among researchers from different backgrounds, and to ensure that such interdisciplinary papers are reviewed by experts from all involved fields before being published.

## ACKNOWLEDGMENTS

We thank Dr Wei Yang from Institute of Geology and Geophysics, Chinese Academy of Science for useful discussions. We appreciate the help from Professor Zhengyao Jin from University of Science and Technology China and Dr. Jianfeng Cui from Peking University in the revision stage

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

of this paper. Our thanks also go to Professor Mark Pollard, Dr Frederik Rademakers, Dr Wugan Luo, Dr Jianyu Liu, Dr Brett Kaufman, Dr Hongjiao Ma, Professor Yanxiang Li and Professor Wei Qian for exchanging ideas with us. K.C. acknowledge the Newton International Fellowship awarded by the British Academy and the hosting of UCL Institute of Archaeology. Comments from three anonymous reviewers helped to improve the paper; any remaining shortcomings and errors are ours. This research is supported by China Postdoctoral Science Foundation (No. 2016M591065), National Natural Science Foundation of China (No. 51304020, No. 51704023) and National Administration of Cultural Heritage (No. 2014220).

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