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Fighting and burial: the production of bronze weapons in the Shu state based on a case study of Xinghelu cemetery, Chengdu, China

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Abstract

This article discusses the bronze weapons discovered in the Xinghelu cemetery of Chengdu, China in order to study the production of bronze weapons in the Shu state. Metallographic microscopy, inductively coupled plasma atomic emission spectroscopy (ICP-AES) and multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) were used to analyze 56 bronze samples. The results show that normal size weapons contain more lead or tin than the equivalent small weapons. Some normal size weapons were made from the same lead sources as the small ones; others, such as the dagger-axe and scabbards, might be imported products. To match the imported scabbards, swords of comparable size were cast or chosen. Most of the small weapons may have been produced by type, while the variable alloying composition and size for each weapon suggests multiple casting processes.

Keywords: Xinghelu cemetery, The Shu state, Bronze weapons, Elemental compositions, Lead isotope ratios

Introduction

The Chinese Bronze Age featured many types of ritual vessels. In the Central Plains, these vessels were most common during the Shang and Zhou Dynasties [1, 2]; different ritual vessel traditions also existed in other regions. In the southwest part of China, the Shu state (unknown–316 BCE) in the Sichuan Basin was one of the most important political states. This state was characterized by bronze weapons in general, specifically triangle dagger-axes, swords, and spearheads in the shape of willow leaf. These weapons have been found in large numbers and are generally seen as the representative artefacts and focus of study in the archaeology of southwest China [3, 4].

In these three types of weapons, there are two specific categories: normal size and small size weapons. No large size weapons have been discovered yet. The sizes of weapons are classified due to the obvious differences in size, weight, quality, and possible function between them. Classifying the weapons also allows them to be studied separately. Chinese archaeologists agree that the small weapons were clearly much smaller, thinner, and lighter than the normal ones and could not possibly have been used in battle. They are believed to have been specifically made as funerary objects [3, 5, 6]. The relationship between normal and small size weapons, especially how they were produced, has become one of the most intriguing questions in the archaeology of southwest China [2–4]. However, few studies on either small or normal size weapons have been carried out, leaving researchers with many questions. How were the production systems of small weapons and normal size weapons related, for example? Was the alloying composition different? Were they made from different ore sources? Are there relationships between different types of weapons in terms of alloying technique and ore sources?

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This research aims to conduct a systematic scientific analysis on both the small and normal size weapons in order to study the production of weapons in the Shu state. This should give researchers the preliminary clues necessary to begin answering the above questions.

In 2008, during the excavations of Xinghelu cemetery, 56 weapons were found, including both small and normal sized items. By looking at the artifacts found in this cemetery, we can analyze both kinds of weapons. In our study, we analyzed samples from these weapons for alloy compositions, trace elemental compositions, lead isotope ratios, and metallographic observations in order to compare the different kinds of weapons and form our understanding of weapons production in the Shu state. For the first time, this paper will provide a baseline for future studies on the Shu state weapons and, even more broadly, Chinese bronze weapons.

Archaeological context

The Xinghelu cemetery is located inside the famous Jinsha site in Chengdu (Fig. 1), which was uncovered in 2001 and includes many small sites. Large quantities of bronze and gold artifacts of the Western Zhou period (1046–776 BCE), the primary time period of this site, were located here [7]. The Xinghelu cemetery was discovered during road construction in northwest Chengdu. In 2008, the Chengdu Municipal Institute of Cultural Relics and Archaeology excavated 800 m^2 and uncovered the entire cemetery. Forty-eight tombs were excavated; of these, Tombs M2725 and M2722 were the largest, and each contained two canoe-shaped coffins. The remaining tombs were smaller, common, rectangular-shaped pits. The excavators assumed this was a family cemetery due to the clustering of the tombs [8]. Objects in this cemetery date from the late phase of the Spring and Autumn period (6th century–5th century BCE) to the early phase of the Warring States period (5th century–4th century BCE) [8].

For our research, the two high-status tombs (M2725, M2722) and three low-status tombs (M2720, M2727, M2712) were selected. The definition of high- and low-status tombs was mainly based on the number of bronze objects found in each tomb and their overall size. Of the Shu state cemeteries and tombs in the Chengdu Plains that have been excavated so far, most show similar features in terms of status and scale with the Xinghelu cemetery. The few exceptions, such as the Shangyejie tomb and Majia tomb, show much higher status features and were found with hundreds of bronze objects; these tombs may related to the King of Shu state [4]. The Xinghelu

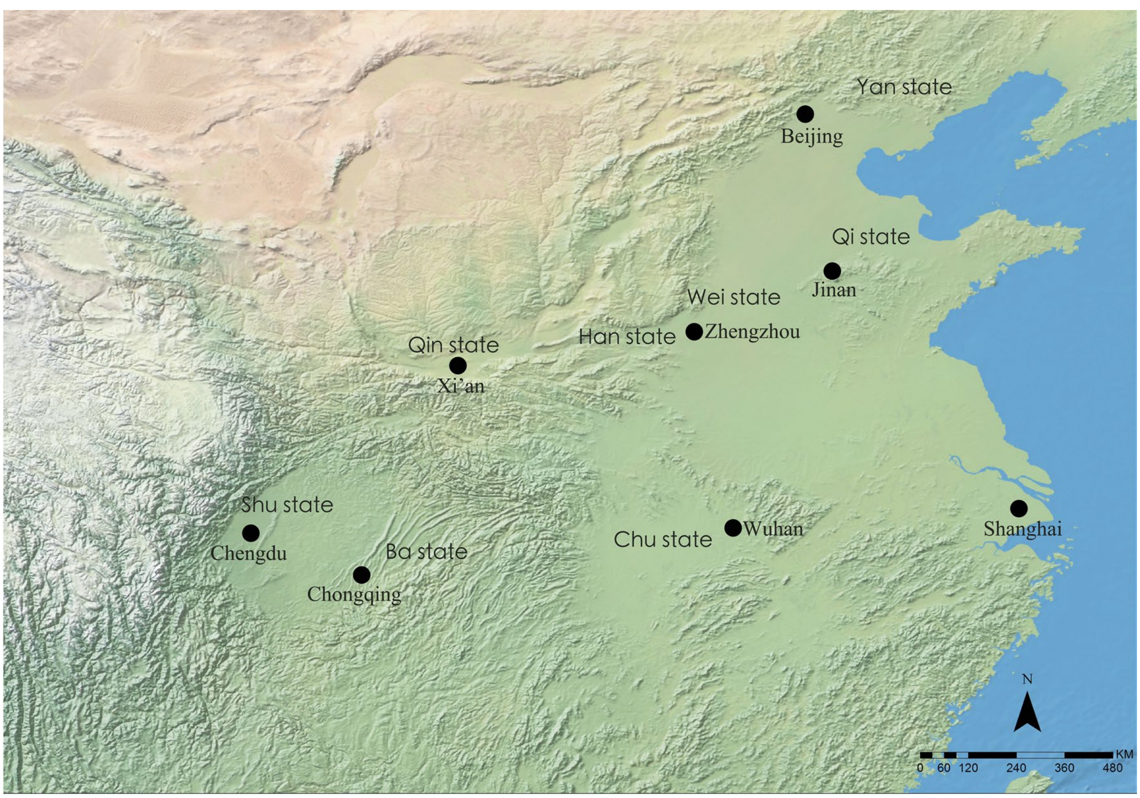

Fig. 1 Map of modern cities and important states in the Eastern Zhou period (770-256BCE)

cemetery is a more typical Shu state cemetery and contains three status levels of tombs [8]. The first level includes only two tombs (M2725, M2722); these are over 3.5 m long and contain over 10 bronze objects. The second level of tombs were buried with less than 10 bronze objects and had a length between 2.6 m and 3.5 m. Five tombs were found that fit this level. All the other tombs belong to the third level; these were were found with no bronze objects and were between 1.3 m and 2.6 m. Since only the tombs found with bronzes objects were studied in this paper, the first level tombs were called high-status tombs and the second level tombs were called low-status tombs. The details of these tombs are shown in Table 1. As an example of a high-status tomb, Tomb M2725 includes two chambers (Fig. 2a, b). Each chamber contained a decayed canoe-shaped coffin and one human skeleton. In the west chamber, the skeleton was identified as a woman between the ages of 18 and 22 [8]. The body was covered with cinnabar. Burial objects included ceramic jars, bronze dagger-axes, swords, spearheads, and abraders. In the east chamber, the skeleton was a male between the ages of 25 and 30 [8]. It was also covered with cinnabar and buried with the same kind of bronze weapons and abraders, as well as a scabbard. A human sacrifice covered with cinnabar was also buried in this chamber [8]. Tomb M2722 is similar to M2725 in its size and structure.

During the excavation of Xinghelu cemetery, typical Shu state weapons were recovered, including spearheads, dagger-axes, swords, and scabbards [8]. The authors rechecked the excavators' findings and agreed that 54 of the weapons found were identifiable as small-sized weapons. This definition is based on a universal standard regarding small weapons in the Shu state [3]. Based on previous studies, as well as the authors' examination of the most discovered weapons from the Shu state, small weapons are considered to be spearheads shorter than 180 mm, dagger-axes shorter than 60 mm, and swords shorter than 165 mm. Small weapons that meet this standard share other common features, such as being much thinner and having lighter bodies compared to normal size weapons. More importantly, small weapons were extremely poorly cast and often had serious deformations. In some of the small spears, ceramic cores were still left inside the sockets, indicating that wooden poles were never fixed to spearheads and the weapons were never used (Fig. 3, XH-43). This demonstrates that the spearheads were probably not designed for practical use.

Normal size weapons were usually 1/3 to 1/2 bigger than small ones (Fig. 3). They were well cast and showed no sign of deformation, meaning they remained in excellent condition when excavated. For both normal and small size weapons, most weapons of the same type were quite uniform in shape and size. Therefore, the differences between small and normal size weapons were rather obvious.

Since the small weapons are not suitable for practical fighting, what role did they serve? Interestingly, these small weapons were only recovered from the two highest-status tombs (M2725 and M2722). The three low status tombs (M2720, M2727, M2712) examined in Xinghelu cemetery contained only normal size weapons.

Preliminary research suggests that the small weapons included 21 spearheads, 13 swords, and 20 dagger-axes [9]. The normal size weapons in the two high-status tombs included only seven swords, two scabbards, and one sword accessory. The combination of 10 normal size weapons and 54 small weapons creates an interesting contrast in the high-status tombs. Chinese researchers previously collected small weapons found in five other tombs from the Chengdu Plains [10] (Table 1). Based on the size and number of burial objects, each of these tombs, including those in Xinghelu cemetery, are high-status (Table 1). Therefore, these small weapons must have been considered specialized burial objects only for use in high status tombs.

Materials and methods

For our research, 56 samples were taken from 55 bronze weapons in five different tombs. Analyzed objects include 16 dagger-axes, two scabbards (two samples were taken from two parts of the same scabbard (XH-16, XH-17)), 19 spearheads, 17 swords, and one sword accessory (Fig. 4). Details of these samples are shown in Table 2. For the 45 small weapons, samples were taken from the edge/blade; for the 11 samples of normal size weapons, three scabbard samples, and one sword accessory, samples were taken at the edge; the others were taken from different parts of the weapon due the value of the items (Table 2). One sample (XH-15) was heavily corroded and the elemental result is only provided for reference. Elemental compositions were measured in all 56 samples. Lead isotope ratios were measured in only 39 representative samples because of our limited budget. The metallographic observation was conducted on all types of small weapons (spears, swords, and dagger-axes), but it was only conducted on one normal size scabbard due to the destructive nature of the testing and rarity of the samples.

Elemental compositions were measured by the ICP-AES method. Lead isotope ratios were tested with the MC-ICP-MS system. The mounted samples used cold mounting in epoxy resin. A Struers Tegramin-20 polish-grinding machine was used to grind and polish samples. A Nikon LV-100 polarizing/metallographic microscope was used to observe the samples before and after etching with alcoholic ferric chloride solution ($FeCl_3$).

Table 1 Comparison of the context between the normal size weapons and small weapons in Shu state

Tombs	Burial type	Chamber size (length × width, cm)	Spearhead		Sword		Dagger axe		Scabbard	Sword accessory	Other burial objects	Complete
			Normal size	Small	Normal size	Small	Normal size	Small				
M2725	Two canoe coffins	West: 375 × (50–60), East: 375 × (42-56)		16	2	13		15	1	1	9 abraders, dear horn and bones	Incomplete
M2722	Two canoe coffins	West chamber: 360 × (170-220), East chamber: 360 × (170–220)		5	5			5	1		2 abraders, dear horn and bones	Complete
M2720	Unclear	340 × (70–90)	1		3						6 potteries	Incomplete
M2727	Unclear	340 × (35–90)			1		1				6 potteries	Complete
M2712	Unclear	293 × (125–136)			2				1		2 potteries	Complete
Shangyejie tomb	9 canoe coffins, 8 wooden coffins	3005 × 2003	?	1	?	?	2				186 potteries, lacquers,wooden artifacts	Robbed
Zaozixiang tomb	Unclear	Unclear	9	4	2	9	1	10				Heavily destroyed
Renfang tomb M280	Unclear	(92–101) × 50			1	2						Heavily destroyed
Guojihu-ayuan M943	Canoe coffin	401 × 202		?	1	?	1	?			2 abraders, 1 stone adze, 1 jade artifact	Complete
Guojihu-ayuan M850	Canoe coffin	390 × 76		?	?	?					1 abrader	Complete

Fig. 2 **a** Part of Xinghelu cemetery. **b** Picture of one chamber of Tomb M2725. **c** Original position of scabbard and sword accessory in Tomb M2725 when discovered

Before the samples could be dissolved, corrosion and contamination of the samples were removed; then, the sample was completely dissolved in aqua regia and diluted to 100 ml with deionized water. The elements were tested with a Prodigy inductively coupled plasma-atomic emission spectrometer produced by Leeman Labs. The working conditions were as follows: RF power of 1.1 kW, argon gas flow rate of 20 L/min plasma gas, and nebulizer gas at 20 MPa. Eight elements were measured in this experiment: Sn, Pb, Fe, Ni, As, Sb, Ag, and Au.

Lead isotope ratios were measured using a VG Elemental multi-collector inductively coupled plasma mass spectrometer (VG Elemental Axiom, Thermo Fisher Scientific Inc., USA). The relative errors of the $^{207}Pb/^{206}Pb$, $^{208}Pb/^{206}Pb$, and $^{206}Pb/^{204}Pb$ ratios were < 0.01%, 0.01%, and 0.1%, respectively. The SRM981 international lead isotope standard was used as the standard reference to calibrate the spectrometer. The calibration was checked after every set of 6–8 measurements.

Lead isotope ratios and trace elemental data were used to discuss the ore sources. Among the elements evaluated, arsenic, antimony, silver, and nickel were the most published and suitable to build the classification of metal material [11]. To compare the data in a uniform method, this paper applied the "copper groups" (CG) method to classify the material. This method is part of the "Oxford system" proposed by the research team at the Research Laboratory for Archaeology and the History of Art at the University of Oxford, led by Professor Mark Pollard. The method was designed to pursue the circulation of copper and copper alloys [12, 13]. To be more specific, 16 copper groups were defined based on the presence/absence of arsenic, antimony, silver, and nickel using 0.1% as the cut-off. The different groups only provide a classification of the material. Sufficient archaeological context and comparable data are necessary for the interpretation to be meaningful.

Fig. 3 Comparison between normal size weapons and small weapons

Results and discussion

Relationships between small weapons and normal size weapons

As mentioned above, it is important to understand whether the small and normal size weapons were made

Fig. 4 Typical bronze weapons analysed in this paper

using the same techniques and from the same raw materials. The results of the ICP-AES analysis are shown in Table 3. From the different standards for defining alloy types, most Chinese scholars chose a 2% threshold for detected elements to describe the alloys [14, 15]. This study uses the same standard. Results indicate that seven samples are copper-lead alloys; the other 49 objects are copper–tin–lead alloys. Compositions of both tin and lead varied in most samples (Fig. 5). The tin content varied from 0.11 wt% to 17.42 wt%, while the lead content varied from 2.18 wt% to 27.33 wt%.

Based on the ICP-AES results, we first considered the alloy compositions shown in Fig. 5. The comparison between normal and small weapons of the same type shows that the normal size weapons usually contained more lead or tin. The only normal size spear contained the highest tin (16.68%) content, which is almost the same amount as the normal size sword accessory. The normal size dagger-axe, on the other hand, contained the most lead (27.33%). Among the swords, normal size swords generally contained more lead; one sample, however, contained the lowest lead content of both normal and small size swords (Fig. 5). Since the number of normal size weapons is limited, we are not sure whether this represents a pattern. Most small weapons clustered together; it is difficult to see any clear alloy pattern related to weapon type. The alloy composition of normal size weapons also showed no clear pattern, which might be caused by their limited number. In China, one famous historical work, *The Ritual Works of Zhou·Artificers Record (zhouli·kaoguji)*, recorded that bronze types and alloy compositions are strongly connected. However, many modern researchers have found that this does not correspond with the current bronze analysis throughout China [16–18]. Previous studies do suggest that ancient metalworkers understood the difference between tin, lead and copper since at least the Shang Dynasty (17th century BCE–1046 BCE) [19].

Figure 6 presents the metallographic pictures of different weapons. All analyzed samples present typical casting microstructure, which shows a dendritic microstructure. Lead inclusions and ($\alpha+\delta$) eutectoid were seen in some of the samples [15, 20] (Fig. 6). There is no sign of secondary processing. Therefore, all analyzed samples were cast with no further processing.

Logically speaking, a weapon's blade might be hammered to increase hardness, polished to sharpen it, or deformed when fighting [15]. All samples of small weapons were taken from the edge/blade; however, no sign of secondary processing or use could be observed. This supports our belief that these small weapons were never used or intended for fighting.

The microstructure of the only normal size weapon (XH-16) contains ($\alpha+\delta$) eutectoid. This phase is visible in objects with significant amounts of tin [15]. The microstructures of several small weapons also contain

Table 2 Context and archaeological information of analysed samples

Lab number	Type	Context number	Length	Width	Thickness	Status	Size	Sampling position
XH-01	Dagger-axe	M2725:2	46.5	38.7	3.3	Complete	Small	Edge
XH-02	Dagger-axe	M2725:5	39.6	39.4	3.2	Nearly complete	Small	Edge
XH-03	Dagger-axe	M2725:15	47.0	39.4	3.1	Complete	Small	Edge
XH-04	Dagger-axe	M2725:25	45.3	39.1	3.1	Complete	Small	Edge
XH-05	Dagger-axe	M2725:4	50.8	39.2	3.0	Incomplete	Small	Edge
XH-06	Sword	M2725:10	156.0	28.9	2.7	Complete	Small	Edge
XH-07	Sword	M2725:20	156.5	24.8	3.0	Complete	Small	Edge
XH-08	Sword	M2725:36	156.0	28.8	2.9	Nearly complete	Small	Edge
XH-09	Sword	M2725:41	156.0	28.0	2.7	Complete	Small	Edge
XH-10	Sword	M2725:46	160.0	29.0	2.6	Complete	Small	Edge
XH-11	Spearhead	M2725:1	173.1	42.5	–	Complete	Small	Edge
XH-12	Spearhead	M2725:32	170.3	24.2	–	Nearly complete	Small	Edge
XH-13	Spearhead	M2725:33	176.6	24.2	–	Complete	Small	Edge
XH-14	Spearhead	M2725:37	176.5	26.8	–	Complete	Small	Edge
XH-15	Spearhead	M2725:39	172.7	25.8	–	Complete	Small	Edge
XH-16	Scabbard	M2725:13-1	–	159.0	–	Complete	Normal	Edge
XH-17	Scabbard	M2725:13-2	–	–	–	Complete	Normal	Edge
XH-18	Sword accessory	M2725:14	50.0	49.1	–	Complete	Normal	Edge
XH-19	Dagger-axe	M2725:1	44.5	39.3	3.2	Incomplete	Small	Edge
XH-20	Dagger-axe	M2725:26	–	40.0	3.0	Incomplete	Small	Edge
XH-21	Dagger-axe	M2725:28	44.8	40.3	3.0	Nearly complete	Small	Edge
XH-22	Dagger-axe	M2725:3	–	40.3	3.1	Incomplete	Small	Edge
XH-23	Dagger-axe	M2725:6	–	40.1	3.2	Incomplete	Small	Edge
XH-24	Sword	M2725:40	160.0	29.0	2.6	Incomplete	Small	Edge
XH-25	Sword	M2725:47	–	28.2	2.5	Incomplete	Small	Edge
XH-26	Sword	M2725:44	157.0	28.3	3.0	Incomplete	Small	Edge
XH-27	Sword	M2725:5	155.0	–	2.9	Incomplete	Small	Edge
XH-28	Spearhead	M2725:24	168.7	25.0	–	Complete	Small	Edge
XH-29	Dagger-axe	M2725:8	45.5	39.6	3.3	Complete	Small	Edge
XH-30	Dagger-axe	M2725:㉗	45.9	39.0	2.9	Complete	Small	Edge
XH-31	Sword	M2725:⑲	160.0	29.1	2.9	Complete	Small	Edge
XH-32	Sword	M2725:11	157.0	28.8	2.4	Complete	Small	Edge
XH-33	Sword	M2725:㊺	160.0	28.5	2.6	Complete	Small	Edge
XH-34	Spearhead	M2725:30	170.7	25.2	–	Complete	Small	Edge
XH-35	Spearhead	M2725:42	175.4	24.8	–	Nearly complete	Small	Edge
XH-36	Spearhead	M2725:70	171.5	24.57	–	Nearly complete	Small	Edge
XH-37	Spearhead	M2725:⑦	174.8	26.22	–	Complete	Small	Edge
XH-38	Spearhead	M2725:⑧	175.6	24.83	–	Nearly complete	Small	Edge
XH-39	Spearhead	M2725:⑨	172.6	24.37	–	Nearly complete	Small	Edge
XH-40	Spearhead	M2725:71	130.9	26.13	–	Incomplete	Small	Edge
XH-41	Spearhead	M2722:13	141.0	21.42		Complete	Small	Edge
XH-42	Spearhead	M2722:14	144.1	22.21		Complete	Small	Edge
XH-43	Spearhead	M2722:15	98.7	22.5		Incomplete	Small	Edge
XH-44	Spearhead	M2722:6	143.8	22.22		Complete	Small	Edge
XH-45	Spearhead	M2722:5	143.7	22.48		Complete	Small	Edge
XH-46	Dagger-axe	M2722:11	40.39	30.42	3.13	Complete	Small	Edge
XH-47	Sword	M2722:12	180.5	28.7	4.2	Complete	Normal	Hilt
XH-48	Sword	M2722:2	180.6	29.2	4.1	Nearly complete	Normal	Hilt
XH-49	Sword	M2722:3	180.7	29.0	4.2	Complete	Normal	Hilt

Table 2 (continued)

Lab number	Type	Context number	Length	Width	Thickness	Status	Size	Sampling position
XH-50	Dagger-axe	M2722:7	36.4	29.9	3.2	Complete	Small	Edge
XH-51	Dagger-axe	M2722:9	36.9	30.5	3.1	Complete	Small	Edge
XH-52	Sword	M2720:1	354.5	33.7	8.4	Complete	Normal	Hilt
XH-53	Spearhead	M2720:4	221.0	23.0		Complete	Normal	Socket
XH-54	Scabbard	M2712	101.0			Complete	Normal	Edge
XH-55	Sword	M2712	183.5	28.6	4.6	Complete	Normal	Hilt
XH-56	Dagger-axe	M2727:4	141.1	–	3.9	Complete	Normal	Bottom part

($\alpha + \delta$) eutectoid. This is typical of casting microstructures, and no further assumptions can be made due to lack of normal size weapons analyzed.

Lead isotope ratios and trace elemental data were used to discuss the ore sources in this study. The results of MC-ICP-MS are listed in Table 4 and presented in Figs. 7 and 8. According to Fig. 7, most of the lead isotope data were distributed in the same area; only four data were clearly out of this range. Discussing which material is indicated by the lead isotope data is necessary. Generally, in samples with lead content from 50 ppm to 4%, the lead is introduced by copper ores [21–23]. Among the 56 samples, 13 contain less than 4% lead, ranging from 2.18 to 3.99%. For the other 43 samples, the lead composition is between 4.15 and 33.08% (the corroded sample is 33.08%). Figure 7a presents the comparison between two categories; it shows that most data overlapped in the same area and the samples with $Pb \geq 4\%$ covered a larger area. The only two samples with $Pb < 4\%$ that were not covered by samples with $Pb \geq 4\%$ are two scabbards. Therefore, most of the lead isotope data indicate lead ore sources.

Figure 7b shows the lead isotope comparison between normal and small weapons. Among the 11 samples of normal size weapons, seven samples overlap with small ones; the other four samples are distributed elsewhere. The four samples include two scabbard samples from Tomb M2725, one scabbard sample from Tomb M2712 and one dagger-axe from Tomb M2727. The scabbards from Tombs M2725 and M2712 were rare in the Shu state. Archaeological evidence suggests that similar scabbards were found in Zhuyuangou cemetery, Baoji, Shaanxi province, which might be the origin of this type of scabbard [24]. The dagger-axe from M2727 was not the type popular in the Shu state at the time, however, a similar type was far more popular in the Central Plains and the Yangtze River [2]. Therefore, all four samples could have originated from outside the region. Excluding these samples, however, the normal and small weapons were made from similar lead sources.

We also tried to look for the geographic origin of the lead sources. All published lead isotope data of modern lead ore in Sichuan Basin were collected and compared with Xinghelu data [25]. Figure 8 shows that there is no clear overlap with any current lead ore sources, meaning that the source of the lead ore remains unclear. We must also consider that damaged weapons or other bronze materials may have been recycled, leading to difficulties in interpreting lead isotope data. Data on ancient mining and smelting sites will help address this problem. We plan to carry out this work in the near future.

The results of ICP-AES show that 13 samples contain more than 1% iron; one of them also contains 1.66% silver. The composition of the rest of elements are all below 1% (Table 3). The copper groups method was used to study the trace element data in this paper. Results show that the 56 samples were distributed in six different groups including CG1(clean metal), CG2(As), CG4(Ag), CG7(Sb + Ag), CG12(As + Sb + Ag), and CG13(Sb + Ag + Ni). CG2, CG4, and CG7 are the three primary groups (Fig. 9). Figure 10 shows the degree of difference among CG2, CG4, and CG7. In the As/Sb scatter diagram, three CGs were distributed in totally different regions and there is no overlap (Fig. 10b). In the Ag/Ni scatter diagram, most of the CG data were distributed in their own region. However, there are some overlaps between CG4 and CG7. Nevertheless, each CG is different from the others when combining two scatter diagrams.

Then, the relationship between copper groups and lead composition were studied; however, no clear differences were observed (Fig. 9). It is unclear which material is indicated by the copper groups. Comparing the normal size weapons with the small ones shows that most small weapons were made from CG2, CG4, and CG7 material, and most normal size weapons used CG4 and CG7 material. Therefore, the copper groups analysis indicates that most of the normal size weapons used the same material as the small ones; CG2 material,

Table 3 Results of ICP-AES analysis of analysed samples (wt%)

Lab number	Type	Copper groups	Sn	Pb	Fe	Ni	As	Sb	Ag	Au
XH-01	Dagger-axe	7	2.35	7.52	1.1	–	0.01	0.1	0.24	0.01
XH-02	Dagger-axe	7	6.77	7.39	1	–	0.01	0.15	0.38	0.01
XH-03	Dagger-axe	4	2.98	5.35	0.58	–	0.01	0.06	0.2	0.01
XH-04	Dagger-axe	7	4.37	4.15	1.63	–	0.01	0.13	0.36	0.01
XH-05	Dagger-axe	7	10.53	10.19	0.82	–	–	0.11	0.27	0.01
XH-06	Sword	4	0.11	6.43	0.55	–	–	–	0.14	0.01
XH-07	Sword	7	4.15	3.99	0.79	–	0.01	0.12	0.4	0.01
XH-08	Sword	7	16.69	7.03	2.44	0.01	0.01	0.32	1.66	0.03
XH-09	Sword	4	2.57	5.88	0.62	–	0.01	0.07	0.21	0.01
XH-10	Sword	4	2.65	6.91	0.64	–	0.01	0.09	0.23	0.01
XH-11	Spearhead	4	3.27	8.19	0.39	–	0.01	0.08	0.21	0.01
XH-12	Spearhead	7	6.81	7.75	0.77	0.01	0.01	0.13	0.42	0.01
XH-13	Spearhead	4	0.94	3.78	0.62	–	–	0.05	0.23	0.01
XH-14	Spearhead	7	5.62	16.03	0.38	–	0.01	0.12	0.43	0.01
XH-15	Spearhead	4	0.63	33.08	1.16	0.01	0.01	0.01	0.11	0.02
XH-16	Scabbard	7	11.88	2.4	1.24	–	0.01	0.17	0.21	0.01
XH-17	Scabbard	7	14.69	3.36	1.5	–	0.01	0.25	0.32	0.02
XH-18	Sword accessory	7	17.42	15.08	0.56	–	–	0.22	0.58	0.02
XH-19	Dagger-axe	4	3.25	4.31	0.68	–	0.01	0.09	0.29	0.01
XH-20	Dagger-axe	7	8.66	6.41	1.42	–	–	0.23	0.68	0.03
XH-21	Dagger-axe	7	5.12	3.64	0.9	–	0.01	0.17	0.39	0.01
XH-22	Dagger-axe	7	7.36	8.85	2.01	0.01	0.01	0.2	0.52	0.02
XH-23	Dagger-axe	7	3.95	3.77	0.33	–	–	0.15	0.23	0.01
XH-24	Sword	7	6.45	5.38	0.59	–	0.01	0.14	0.53	0.01
XH-25	Sword	7	3.54	6.36	1.09	0.01	0.01	0.11	0.25	0.01
XH-26	Sword	7	5.65	6.82	1.05	–	0.01	0.14	0.46	0.01
XH-27	Sword	7	4.71	3.83	1.41	–	0.01	0.14	0.36	0.01
XH-28	Spearhead	13	12.74	10.57	2.37	0.09	0.01	0.24	0.41	0.02
XH-29	Dagger-axe	2	7.07	5.78	0.52	0.02	0.12	0.00	0.04	0.41
XH-30	Dagger-axe	1	2.64	2.33	0.25	0.01	0.06	0.00	0.02	0.20
XH-31	Sword	2	5.46	6.33	0.45	0.02	0.12	0.01	0.04	0.36
XH-32	Sword	2	12.74	5.66	0.16	0.02	0.25	–	0.06	0.12
XH-33	Sword	2	5.53	6.63	0.65	0.03	0.13	0.00	0.04	0.52
XH-34	Spearhead	2	4.81	7.17	0.15	0.02	0.12	0.01	0.04	0.12
XH-35	Spearhead	2	7.31	5.98	0.09	0.02	0.11	0.00	0.04	0.07
XH-36	Spearhead	2	4.20	6.78	0.16	0.02	0.12	0.01	0.04	0.12
XH-37	Spearhead	2	9.74	6.30	0.08	0.02	0.12	–	0.04	0.07
XH-38	Spearhead	2	4.05	2.18	0.01	0.02	0.11	0.01	0.05	0.01
XH-39	Spearhead	2	3.51	4.47	0.01	0.02	0.11	0.01	0.04	0.01
XH-40	Spearhead	2	3.40	6.66	0.37	0.02	0.11	0.01	0.04	0.29
XH-41	Spearhead	4	0.47	5.84	0.12	0	0	0	0.29	0.01
XH-42	Spearhead	4	0.29	3.69	0.04	0	0	0.01	0.14	0
XH-43	Spearhead	4	0.51	15.3	0.37	0	0	0.01	0.35	0.01
XH-44	Spearhead	4	13.87	10.21	0.44	0.01	0.02	0	0.22	0
XH-45	Spearhead	7	6.9	7.5	0.29	0	0.01	0.11	0.61	0.01
XH-46	Dagger-axe	4	4.3	2.47	0.12	0	0.01	0.08	0.22	0
XH-47	Sword	7	9.81	11.94	0.94	0.01	0.01	0.11	0.29	0.03
XH-48	Sword	7	6.44	7.14	0.07	0	0.01	0.1	0.34	0.01
XH-49	Sword	4	14.11	10.05	0.13	0	0.01	0.07	0.18	0

Table 3 (continued)

Lab number	Type	Copper groups	Sn	Pb	Fe	Ni	As	Sb	Ag	Au
XH-50	Dagger-axe	7	8.86	14.48	0.19	0	0.01	0.13	0.35	0.01
XH-51	Dagger-axe	7	13.27	9.84	0.28	0	0	0.14	0.43	0.01
XH-52	Sword	7	11.79	2.6	0.25	0	0.01	0.14	0.13	0.01
XH-53	Spearhead	7	16.68	2.95	0.48	0	0.02	0.23	0.27	0
XH-54	Scabbard	4	0.29	19.81	0.67	0.02	0	0	0.53	0.01
XH-55	Sword	4	2.02	8.72	0.46	0.01	0	0.03	0.3	0.01
XH-56	Dagger-axe	12	8.17	27.33	0.92	0.04	0.09	0.61	0.67	0.01

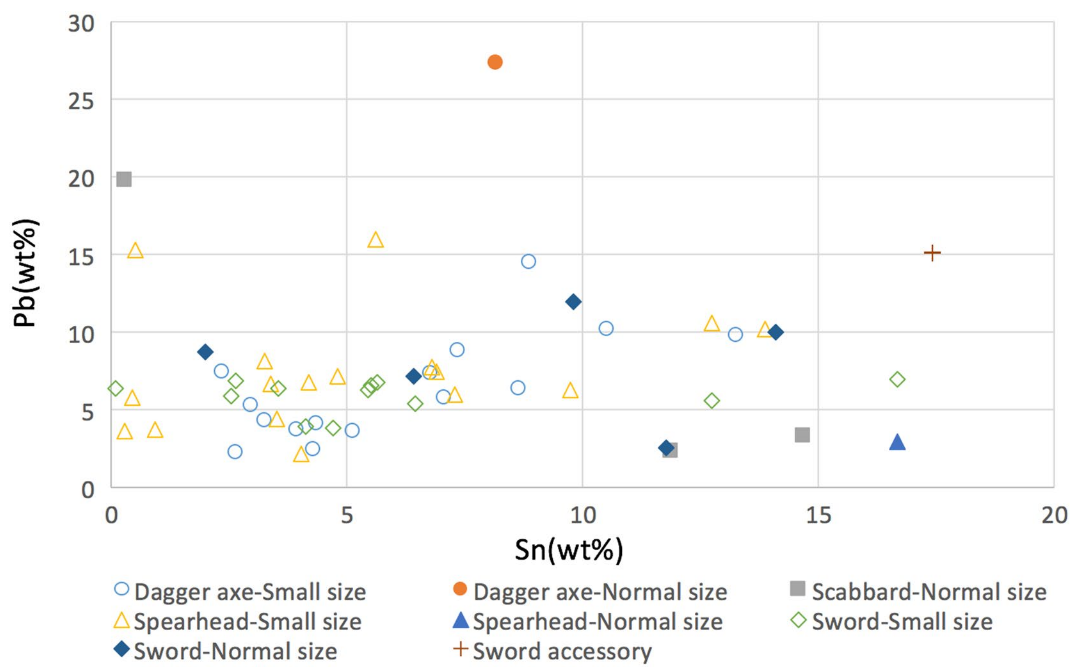

Fig. 5 Scatter plot showing Pb versus Sn of different types and qualities bronze weapons

however, was only used in small weapons. The normal size dagger-axe (CG12) is the only exception (Fig. 9). Considering the lead isotope ratio of this dagger-axe was also plotted separately, we are fairly certain that this dagger-axe came from a different area.

Based on the lead isotope ratios and copper groups analysis, we can state that at least some of the normal size weapons were made from similar lead sources and some normal size weapons might be imported products. More data on normal size weapons will improve the study in the future.

Production methods for bronze weapons

Since no bronze casting workshop has been found in the Shu state, we can only discuss the production methods based on the analytical results. Two things are theoretically true about bronze production here. First, the objects made of melted metal from the same crucible presumably present the same elemental and lead isotopic features. Second, objects made from the same casting mold should show the same size and detail. These two points will be our primary basis for discussing production modes. In this paper, we consider that the object or objects made of metal melted in the same crucible at the same time belong to the same casting process.

We first investigated the production of small weapons. That all small weapons show uniform style and size is noteworthy (Fig. 4). Considering that these weapons were specialized burial objects in an assemblage, it is easy to imagine that the weapons were created from the

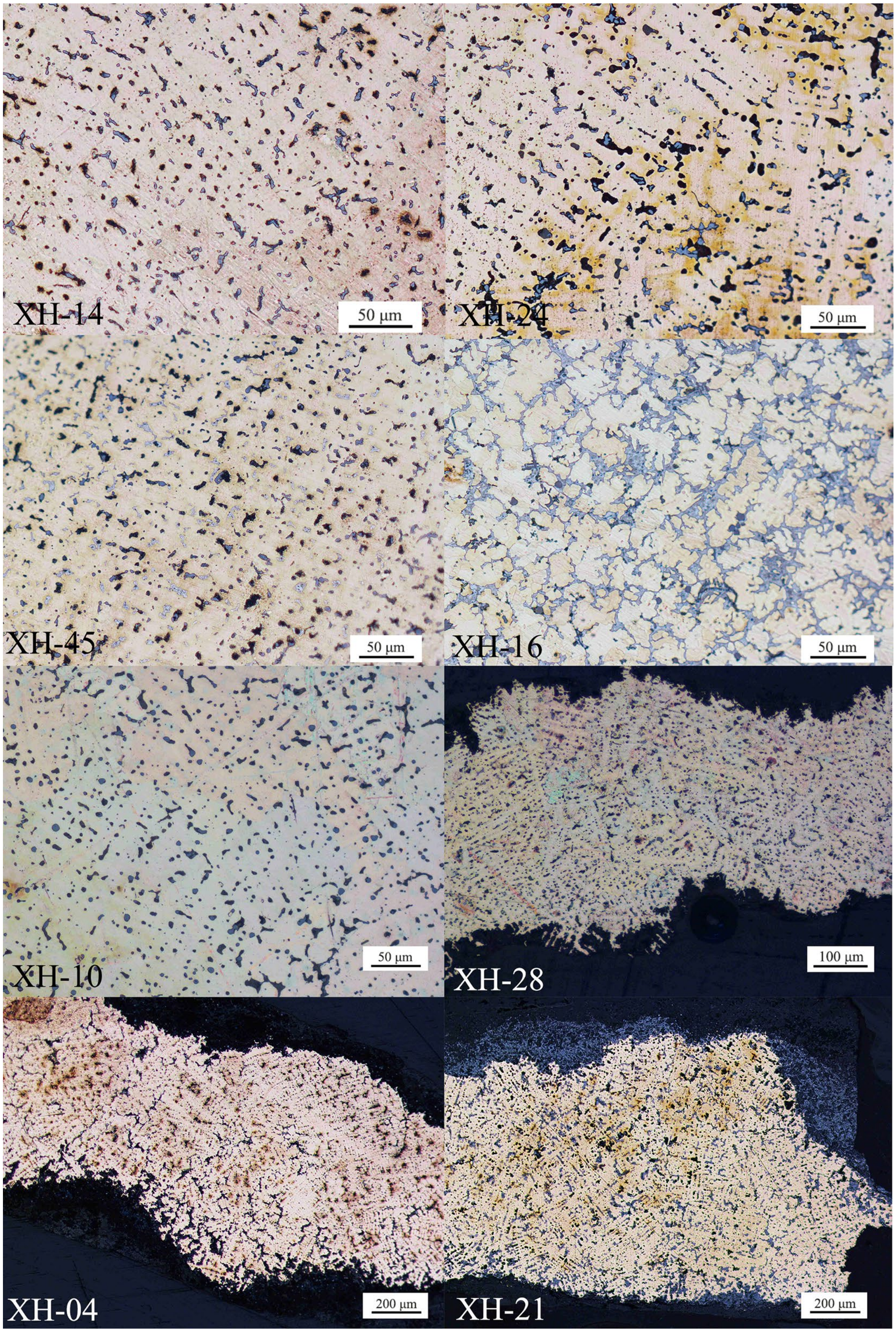

Fig. 6 Photomicrograph of the analysed samples

Table 4 Results of MC-ICP-MS analysis of analysed samples

Lab number	Type	$^{208}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$
XH-02	Dagger-axe	38.288	15.526	18.090	2.117	0.858
XH-03	Dagger-axe	38.157	15.469	18.026	2.117	0.858
XH-05	Dagger-axe	38.584	15.538	18.380	2.099	0.845
XH-08	Sword	38.412	15.564	18.131	2.119	0.858
XH-09	Sword	38.247	15.520	18.066	2.117	0.859
XH-10	Sword	38.302	15.528	18.093	2.117	0.858
XH-12	Spearhead	38.603	15.645	18.287	2.111	0.856
XH-13	Spearhead	38.491	15.606	18.218	2.113	0.857
XH-14	Spearhead	38.489	15.566	18.266	2.107	0.852
XH-15	Spearhead	38.310	15.504	18.154	2.110	0.854
XH-16	Scabbard	38.017	15.455	17.819	2.134	0.867
XH-17	Scabbard	38.191	15.538	17.916	2.132	0.867
XH-18	Sword accessory	38.333	15.522	18.152	2.112	0.855
XH-19	Dagger-axe	38.315	15.530	18.112	2.116	0.857
XH-20	Dagger-axe	38.225	15.484	18.059	2.117	0.857
XH-21	Dagger-axe	38.286	15.511	18.090	2.116	0.857
XH-22	Dagger-axe	38.398	15.601	18.122	2.119	0.861
XH-23	Dagger-axe	38.437	15.606	18.143	2.119	0.860
XH-24	Sword	38.237	15.498	18.075	2.115	0.857
XH-25	Sword	38.153	15.463	18.029	2.116	0.858
XH-26	Sword	38.260	15.517	18.068	2.118	0.859
XH-27	Sword	38.227	15.488	18.053	2.117	0.858
XH-28	Spearhead	38.284	15.513	18.106	2.115	0.857
XH-41	Spearhead	38.449	15.526	18.271	2.1044	0.8498
XH-42	Spearhead	38.668	15.606	18.41	2.1004	0.8477
XH-43	Spearhead	38.747	15.655	18.436	2.1017	0.8492
XH-44	Spearhead	38.73	15.653	18.397	2.1052	0.8508
XH-45	Spearhead	38.685	15.618	18.391	2.1034	0.8492
XH-46	Dagger-axe	38.689	15.655	18.401	2.1026	0.8508
XH-47	Sword	38.529	15.535	18.352	2.0994	0.8465
XH-48	Sword	38.731	15.656	18.414	2.1034	0.8502
XH-49	Sword	38.836	15.684	18.513	2.0977	0.8472
XH-50	Dagger-axe	38.528	15.542	18.343	2.1005	0.8473
XH-51	Dagger-axe	38.504	15.535	18.311	2.1027	0.8484
XH-52	Sword	38.585	15.679	18.24	2.1154	0.8596
XH-53	Spearhead	38.339	15.527	18.107	2.1173	0.8575
XH-54	Scabbard	38.88	15.672	18.583	2.0922	0.8433
XH-55	Sword	38.701	15.658	18.388	2.1047	0.8516
XH-56	Dagger-axe	37.725	15.439	17.469	2.1595	0.8838

same casting process or used the same casting mold and then were buried together. Whether the assumption is true is vital to our understanding of the production of small weapons and burial practice. The metallographic observations show that these small weapons have similar microstructure, suggesting the similarity of casting technique (Fig. 6). The scatter of alloying compositions shows that the tin and lead compositions are highly variable (Fig. 5). No two objects were found with identical composition (Table 3). The copper groups analysis indicates that these small weapons were distributed in multiple groups, including CG2, CG4, and CG7 (Fig. 9). The lead isotope ratios of small weapons rarely show complete overlap (Fig. 7). These variable data indicate that one small weapon does not overlap with another with regards to alloy composition and ore sources,

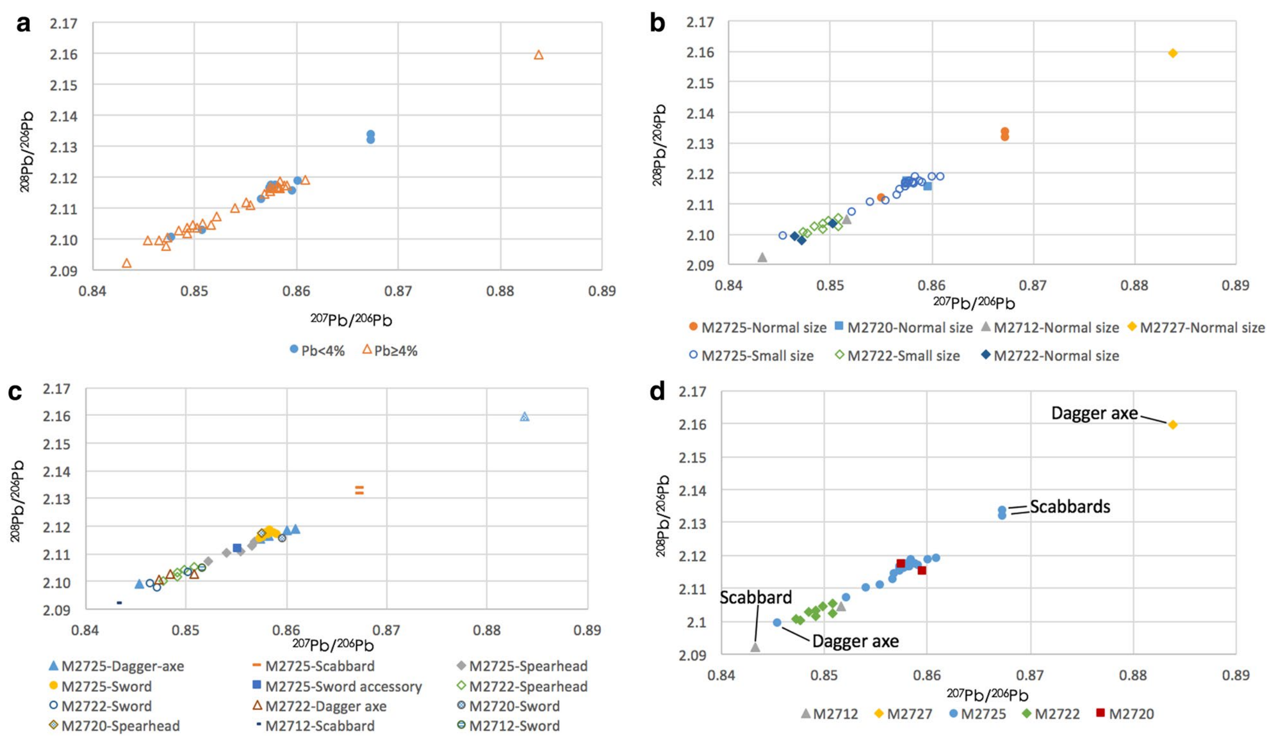

Fig. 7 **a** Lead isotope data comparison of objects with different lead compositions. **b** Comparison of weapons of different quality. **c** Comparison of different types of weapons. **d** Comparison of weapons from different tombs

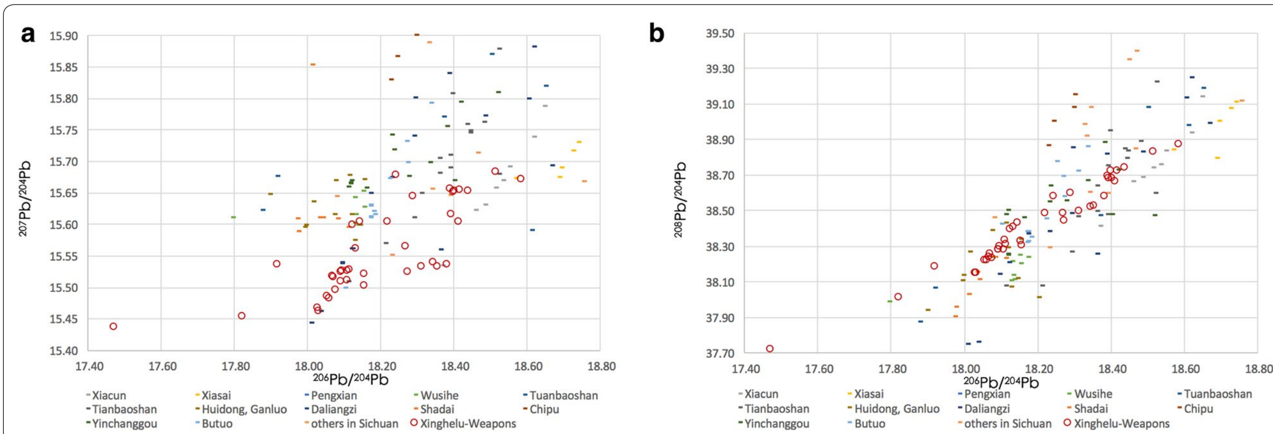

Fig. 8 Comparison of the lead isotope data between modern lead ore sources in Sichuan Basin and bronze weapons in Xinghelu cemetery. **a** $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$. **b** $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$

which probably indicates that they came from different casting processes.

Furthermore, we need to examine the casting procedure. First, based on the ceramic core left inside the spearhead, they were probably cast with ceramic molds, which is characteristic of the Chinese Bronze Age [2]. The ceramic mold might be single-use or reusable. However, the possibility of using stone molds cannot be completely excluded. Thus, it remains unclear whether weapons were made from single-use or reusable molds. As mentioned above, objects from the same casting mold should share the same details and size. All the weapons in this study were carefully measured, and the results show that most weapons of the same type have variable size and many differences in details, such as the shape of holes on the objects (Table 2, Fig. 4).

Data type	CG1 (NNNN)	CG2 (YNNN)	CG3 (NYNN)	CG4 (NNYN)	CG5 (NNNY)	CG6 (YYNN)	CG7 (NYYN)	CG8 (NNYY)	CG9 (YNYN)	CG10 (NYNY)	CG11 (YNNY)	CG12 (YYYN)	CG13 (NYYY)	CG14 (YYNY)	CG15 (YNYY)	CG16 (YYYY)	Total
Pb<4%	7.69	7.69	0	23.08	0	0	61.54	0	0	0	0	0.00	0.00	0	0	0	13
Pb≥4%	0.00	23.26	0	30.23	0	0	61.54	0	0	0	0	2.33	2.33	0	0	0	43
M2725	2.50	27.50	0	20.00	0	0	47.50	0	0	0	0	0	2.50	0	0	0	40
M2722	0	0	0	54.55	0	0	45.45	0	0	0	0	0	0	0	0	0	11
M2720	0	0	0	0	0	0	100.00	0	0	0	0	0	0	0	0	0	2
M2712	0	0	0	100.00	0	0	0.00	0	0	0	0	0	0	0	0	0	2
M2727	0	0	0	0	0	0	0.00	0	0	0	0	100.00	0	0	0	0	1
Spear-Small size	0	38.89	0	38.89	0	0	16.67	0	0	0	0	0	5.56	0	0	0	18
Spear-Normal size	0	0	0	0	0	0	100.00	0	0	0	0	0	0	0	0	0	1
Dagger axe-Small size	6.67	6.67	0	20.00	0	0	66.67	0	0	0	0	0	0	0	0	0	15
Dagger axe-Normal size	0	0	0	0	0	0	0.00	0	0	0	0	100.00	0	0	0	0	1
Sword-Small size	0	25.00	0	25.00	0	0	50.00	0	0	0	0	0.00	0	0	0	0	12
Sword-Normal size	0	0	0	40.00	0	0	60.00	0	0	0	0	0.00	0	0	0	0	5
Scabbard	0	0	0	33.33	0	0	66.67	0	0	0	0	0.00	0	0	0	0	3
Sword accessory	0	0	0	0	0	0	100.00	0	0	0	0	0.00	0	0	0	0	1
In total	1.79	19.64	0	28.57	0	0	46.43	0	0	0	0	1.79	1.79	0	0	0	56

Fig. 9 Percentage results of 'Copper groups' analysis. The grey areas represent the proportionally largest groups. N: No, Y: Yes, sequence of elements: As, Sb, Ag, Ni

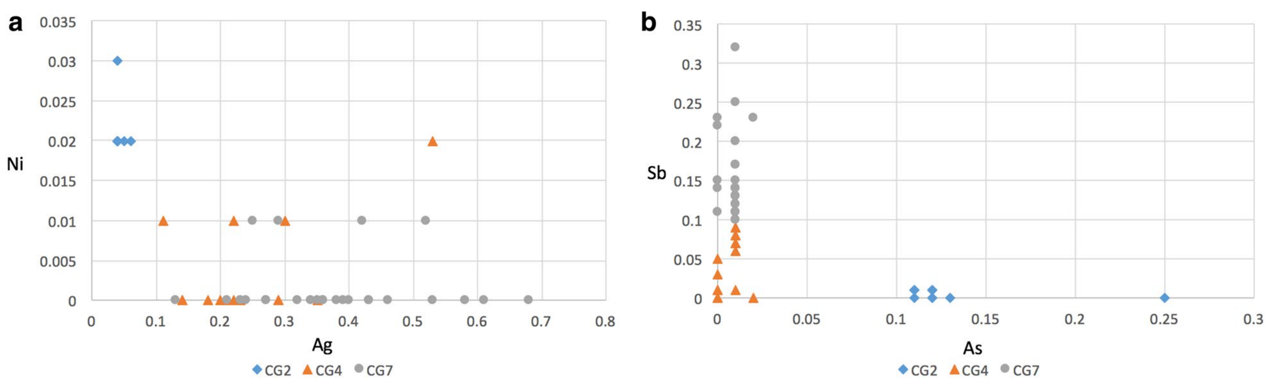

Fig. 10 Scatter plot showing the difference of copper groups. **a** Ni versus Ag. **b** Sb versus As

Therefore, we assume that most weapons were cast with single-use ceramic molds. On the other hand, several groups of weapons show extremely similar sizes; however, the elemental compositions are clearly different (Table 3, XH-50,51; XH-47,48,49). Perhaps they were made from different but extremely similarly sized molds, or they might have been made from reusable molds with raw material melted from different melting processes. We cannot determine this yet.

Thus, we assume that most small weapons came from multiple casting processes and were possibly made with multiple single-use molds. The issue of production method is more complicated than it appears. The lead isotope analysis suggests that one small dagger-axe in tomb M2725 was made of clearly different lead sources from the other small weapons (Fig. 7b–d). Interestingly, this dagger-axe is the only one of its type without a motif, though it is extremely similar to other dagger-axes in shape (Fig. 4, XH-05). This unique dagger-axe with a different production background was chosen to complete the assemblage.

Figure 7c shows the comparison of lead isotope ratios between different types of weapons. It suggests that most of the small weapons of the same type and from the same tomb clustered together, such as the small swords, dagger-axes, and spears in tomb M2725, and the small spears in tomb M2722. This means that most of the small weapons of the same type were produced with similar lead ore sources. This leads us to believe that they were produced by type.

Figure 7d presents the comparison of different tombs. It clearly shows that weapons of the same tomb cluster together, except for the normal size scabbards and spear, which were potentially of foreign origin, and the one small dagger-axe mentioned above (XH-05) (Fig. 7d). Therefore, most of the small weapons from the same tomb were made from similar lead ore sources. This provides us with important clues to understand the production of small weapons. This question needs to be studied with further evidence in the future.

To consider the production methods of the normal size weapons, the variable alloy compositions are shown in Fig. 5. Even within the same weapon type, the five normal size swords differ from each other in alloy composition. This suggests that they were created from different casting processes. Figure 7b–d show that two scabbard parts from tomb M2725 cluster together, and one normal size sword and spear in tomb M2720 cluster together. They are made of the same lead sources. The normal size weapons of the same tomb generally shared more similar lead ore sources (Fig. 7b).

Another interesting point worth discussing for the normal size weapons is the production of scabbards and swords belonging to the same set. The two normal size weapons of tomb M2712 include a sword and a scabbard, which are an original set (Fig. 4, XH-54, XH-55); the three normal size weapons of tomb M2725 include two parts of a scabbard and a sword accessory which also belonged to an original set. The scabbard and sword accessory were in situ when discovered (Fig. 2c). The sword accessory was the bottom section previously affixed to the hilt. The sword, used together with the accessory, was not the type of sword common in the Shu state; that sword has a thin hilt and cannot be affixed to the round accessory. However, the corresponding sword was not found in the tomb (Fig. 2c).

We have collected data on known bronze scabbards found in the Shu state. There are two types of scabbards: those which contain a single sword and those which contain two matching swords. Only four single sword scabbards and eight double sword scabbards have been recovered in the Shu state to date [26–28]. The scabbard found in tomb M2725 was a double sword scabbard (Fig. 4, XH-16, XH-17), and that from tomb M2712 is a single sword scabbard (Fig. 4, XH-54, XH-55).

Figure 7b–d suggest that the sword and scabbard of tomb M2712 do not cluster closely; the two parts of the same scabbard in tomb M2725 overlap with each other while the sword accessory was plotted in a different area. Therefore, we assume that the sword and scabbard of the same set might have been formed by different casting processes. Moreover, unlike the sword and sword accessory, all three scabbard samples plotted in different areas than the small bronzes, making it more convincing that the scabbards may not have been made locally, but the sword and sword accessory were. Therefore, the scabbard and swords might not have been originally designed as a set and were only combined later. How did the swords and scabbard match so well if they were not produced as a set? Could the swords have been cast according to the size of scabbard, or did the owner search for a sword that would match the scabbard? This remains a difficult question to answer.

Conclusions

This paper presents analytical data on 56 bronze weapons, including those of both small and normal size. The metallographic observations indicate that the small weapons were all cast without further processing. Considering the casting flaws and impractical size, we believe these small weapons have no practical function and were specially made for burial. Comparison between normal and small weapons shows that the normal size weapons were usually alloyed with more tin or lead. The lead isotope ratios and copper groups results both show that some of the normal size weapons used the same ore sources, especially lead sources, as the small ones; on the other hand, the two scabbards and one normal size spear were made from different lead sources and may not have been locally made. This study only discloses preliminary clues about the relationships between the differently sized weapons due to the small number of normal size weapons analyzed.

For the production mode of these weapons, we first investigated the small weapons. Most of the small weapons in the same tomb were made from similar lead ore sources, and the weapons of the same type in the same tomb clustered closely. However, among the same type of weapons in the same tomb, each weapon showed different alloying compositions. The sizes also varied. The copper groups of these weapons were concentrated in three different areas. These variables indicate that the small weapons of the same type in the same tomb were not from the same casting process. They were produced from multiple casting processes, possibly with multiple single-use ceramic molds. This provides important clues to understand the production of specialized burial weapons. The production of normal size weapons is more complex since the possibly imported products, including the scabbards and one normal size dagger-axe, must be considered. To match the possibly imported scabbards, the locally made swords might have been specially made or chosen later. The lead sources used for these weapons remains unknown.

Normal and small weapons played different roles in burial practice. The high-status people in the Shu state selected small weapons for their privileged burial practice while the tombs of lower-status people contained only normal size weapons. The production methods for weapons provide more information for us to understand the burial practice and bronze production of the time. This paper only presents a preliminary observation on this topic; we still cannot answer many questions, such as the lead sources of these weapons and the situation of casting workshops. However, we believe that further studies in this field will provide new insight into the study of Chinese bronze.

Abbreviations
ICP-AES: Inductively coupled plasma atomic emission spectroscopy; MC-ICP-MS: Multi-collector inductively coupled plasma mass spectrometry; CG: Copper groups.

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Authors' contributions
HL performed the data analysis and was a major contributor in writing the manuscript. JC analyzed and interpreted the lead isotope data. ZZ, YL, YW, ZW, LW, and JT provided the archaeological context. All authors read and approved the final manuscript.

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Availability of data and materials
All data generated or analyzed during this study are included in this published article. The dataset supporting the conclusions of this article is included within the article.

Competing interests
The authors declare that they have no competing interests.

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