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Improvement and integration: scientific analyses of willow-leaf shaped bronze swords excavated from the Shuangyuan Village Cemetery, Chengdu, China

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Abstract

Willow-leaf shaped sword is a kind of exclusive bronze weapon popular only in the states of Ba and Shu during the Eastern Zhou Dynasty (770-256 BC). Its prototype may originate from Central Asia and India and is a typical example of a trans-regional and cross-cultural artifact. Here, we present a scientific study of willow-leaf shaped swords of Shu State from the Shuangyuan Village Cemetery, Chengdu, by pXRF and MC-ICP-MS, and attempted to argue for the improvement and integration of weapon production in Shu by characterizing its elemental composition and lead isotopic signature. The results show that there is a significant difference in the tin content and lead material source between the Ba and Shu bronze swords. This feature can be applied as an important indicator to distinguish willow-leaf shaped swords from Ba and Shu, especially when the appearances are almost confused. The alloy formula of the Shu bronze sword was influenced by the bronze-making technology of Chu and other states. Combining the published lead isotope data of the willow-shaped bronze swords, it can be inferred that Shu State has produced bronze weapons with considerable frequency and in many batches, which was a major motivation for triggering faster progress in its craft.

Keywords: Bronze sword, Chemical composition, Lead isotope ratio, Eastern Zhou, Chengdu

Introduction

In human civilization, for thousands of years, the bloodshed of war has been shrouded almost all the time. As a byproduct of the evolution of civilization, weapons are a political, economic, military and cultural combination of successive generations, bearing the mark of a nation and an era [1]. During the Bronze Age of southwest China, the bronze sword with a willow-leaf shaped blade was the most commonly used weapon, and the archaeological finds are not only numerous but also concentrated [2]. The willow-leaf shaped swords are a distinctive bronze weapon type dating from the late second millennium to the tenth century BCE or during the late Shang and Western Zhou periods in ancient China [3].

At first, there was a theory that willow-leaf shaped swords were first used in an area adjacent to present-day Shaanxi and Gansu provinces [4]. Later, newer data enabled archaeologists to conduct more refined typological analyses and construct a temporal diagram based on morphological variations and excavated sites, before realizing that the previous view had reversed the chronological order and that Shaanxi and Gansu were instead the areas where willow-leaf shaped swords were introduced. [5–9]. The prevailing consensus is that the earliest willow-leaf shaped bronze swords discovered thus far were from the Sanxingdui, Shi'erqiao, and Xinyi Village sites on the Chengdu Plain, i.e., in the ancient Shu Kingdom.

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Moreover, a jade sword was also unearthed from the No. 1 sacrificial pit at Sanxingdui, closely resembling the style of the bronze willow-leaf shaped sword, which is also important evidence of chronology [10, 11]. A number of bronze swords with very similar appearances are found in some more ancient sites in Western and Southern Asia [12]. This has led some scholars to speculate that the willow-leaf bronze swords originated in Anatolia in the third millennium BC and then spread via India and Central Asia (between mid-3000 and 1500 BC) and to southwest China approximately 1300 BCE [13, 14].

During the period of the Western Zhou Dynasty (1100-771 BC), willow-leaf bronze-shaped swords spread northward from the Chengdu Plain to the Guanzhong region. From the Spring and Autumn Period (770-476 BC) and Warring States Period (475-221 BC) to the early Western Han Dynasty (202 BC-8 AD), this type of sword radiated successively to the eastern area of the Sichuan Basin, as well as the barbarian areas in southwestern Sichuan, Yunnan and Guizhou [6, 15]. However, they are rarely found in the Central Plains. In the late Shang and Western Zhou dynasties, as wars were dominated by chariot warfare in the Central Plains, swords were mostly used as a last defense when all other weapons had failed, while they were a sign of aristocratic status. By the Spring and Autumn Period and the Warring States Period, swords gradually became combat weapons in the Central Plains due to greater flexibility and portability than other long weapons [16]. Throughout the process, the Central Plains bronze sword differs significantly from the willow-leaf shaped bronze sword. The biggest difference is that the willow-leaf shaped sword lacks a cross guard between the flat grip and the blade, and it also has no pommel. To use this type of sword, a wooden hilt would have been secured onto the short grip by an encircling cord that crosses one or two perforations on the grip [3]. Another discrepancy is that the willow-leaf shaped swords were usually cast integrally with the slender blade, while some Central Plains bronze swords used a complex process of segmented casting [17]. The willow-leaf shaped swords without the wooden hilt typically range from 20 to 30 cm in length, generally shorter than the Central Plains swords. In addition to being used as a close-quarters weapon, willow-leaf shaped swords are used in a variety of other ways. Due to the unique rugged terrain and tree-laden environment of southwest China, they are sometimes less conductive to chopping and may instead be used for throwing in battle as missile weapons. The increasing strife with outsiders has also stimulated experimentation in weapons and tactics, some modifications to meet new military situations in which willow-leaf shaped swords could even be attached to long shafts and employed as pikes [18].

Since the willow-leaf shaped bronze swords may have been influenced by external factors in their practical function, would they have incorporated some of the features of the Central Plains bronze swords into their manufacturing techniques? The production of bronze artifacts is not only related to the social and economic organization of the time but is also important for the study of the source and composition of the burial objects. As a kind of funerary object, what would be the production pattern of the willow-leaf shaped bronze sword? Is their quality uniform, are the bronze swords of the same burial complex cast in the same batch, and are the raw materials used for casting the same? The analysis of an array of willow-leaf shaped bronze swords from the Shuangyuan Village Cemetery site in Chengdu can help us to better understand these issues. By revealing the characteristics of the alloy and the source of raw materials and combining relevant scientific data, we can also gain more insight into this particular type of bronze sword from beyond the typology.

The archaeological context

While other types of bronze swords have been improved in shape, such as in length and spine, the willow leaf-shaped bronze sword continues an ancient form that has remained the same for centuries [3, 6]. They were in continuous use and became widely popular during the Eastern Zhou Dynasty in Ba and Shu, two important states that existed mainly in present-day Chongqing city and Sichuan Province (Fig. 1) [6]. In the later Warring States Ba-Shu tombs, swords of this type were even more commonplace and became a highly distinctive regional trait [19]. Ba and Shu, names are often coupled in Chinese texts, as they were neighboring, intertwined, and had similar cultural practices, especially characteristic of boat-coffin burials set on river terraces and various bronze weapons that often bear a sort of pictogram that combines a hand, the head of a snake, and sometimes a tiger.

The Shuangyuan Village Cemetery is currently the largest uncovered Eastern Zhou Dynasty cemetery in Sichuan, with the largest number of excavations and the richest collection of burial artifacts. It is located in Dawan town, Qingbaijiang District, Chengdu city, approximately 27 km northeast of downtown Chengdu. The cemetery was excavated from May 2016 to July 2018 by the Chengdu Archaeological Institute and the Qingbaijiang District Cultural Relics Protection Center, and a total of 270 tombs of the Eastern Zhou Dynasty were excavated and cleared, most of which were boat-shaped coffin tombs. More than 120 willow-leaf shaped bronze swords were unearthed. This extremely high percentage of burials with swords shows the warlike

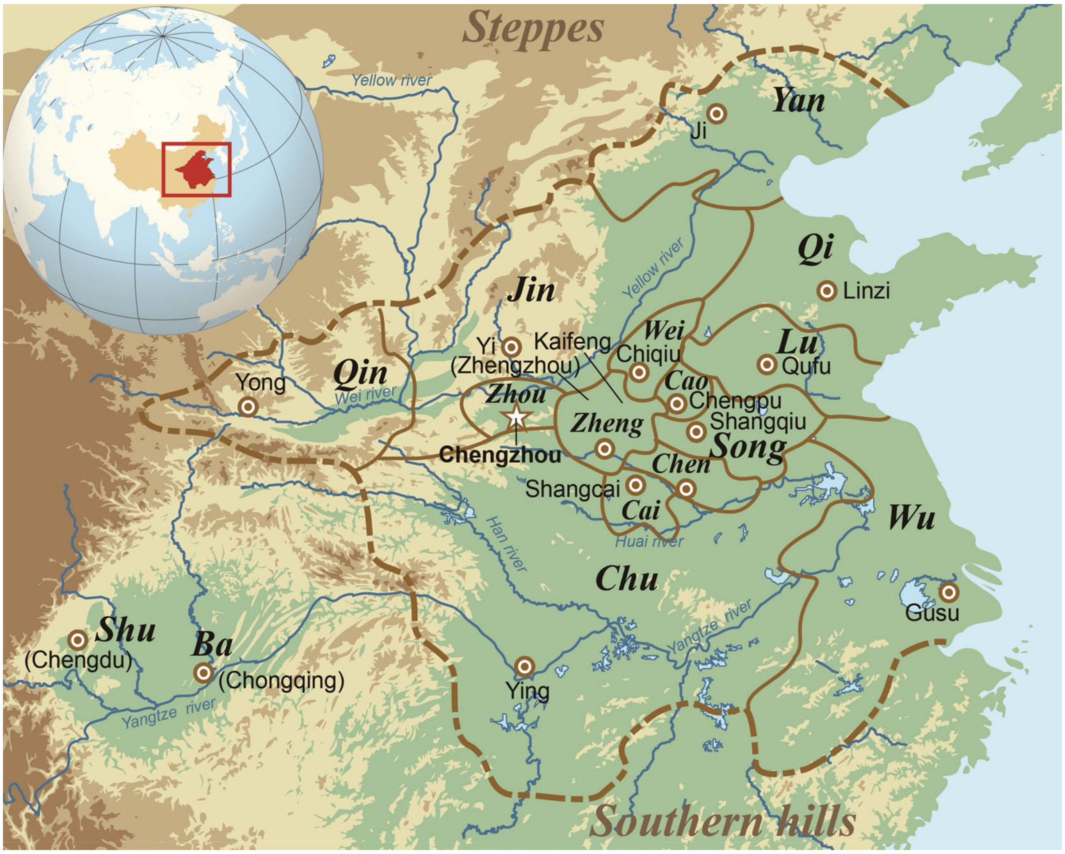

Fig. 1 The distribution of various states and their capitals in the late Spring and Autumn period (fifth century BC)

nature of the Shu people. Beyond that, there are some well crafted bronze weapons that belong to female tomb owners [20].

With the generous permission of the Chengdu Archaeological Institute, we are allowed to carry out a series of tests on 18 precious willow-leaf shaped bronze swords (Fig. 2). Their preservation conditions are generally good, and gouges or nicks are still clearly visible on some of the swords, which should be signs of use. They are similar in shape, although slightly different in length (20–30 cm), and all have two perforations in the grip at the bottom. Some of the bronze swords appear to have been treated with a special process, presumably tin plating, that left regular spots on the surfaces enhance their beauty [21]. There are also some bronze swords decorated with distinctive local cultural patterns. Compared with before, these willow-leaf shaped swords show stronger lethality, the blade becoming narrow and long, with a ridge arching up the center, and deep blood grooves carved out of the sword body. They are heavy, well-made, and sharp-edged, clearly the weapons used in combat rather than improvised items specifically for funeral purposes.

Analytical methods

Component analyses

Due to the preciousness of these bronze swords, we cannot take samples but perform composition testing in situ. The sword points and edges were bevelled and too thin to handle, so they were not chosen for detection. We selected as few rusted or corroded surfaces as possible near the sword blade, which avoid areas that appear to have been surface-treated. Then sandpaper was used to polish them until the metal substrate was exposed to roughly 0.5×0.5 cm^2 (whichever appeared metallic luster).

The analysis was conducted by using a hand-held XRF (Niton XL3t 950He by Thermo Fisher Scientific, Billerica, USA). The X-ray beam spot on the samples was 3 mm in diameter, which is smaller than the exposed metallic area, to the extent that avoids accidental misdetect of the rust. The main filter operates at a voltage of 50 kV and current of 100 μA. The pXRF instrument is equipped with a silicon PIN (Si-PIN) detector with a resolution of 190 eV. The limits of detection of the pXRF were 70 ppm for Sn and 35 ppm for Pb. The alloy mode was selected for bronzes, and the elemental data were collected with

Fig. 2 The willow-leaf shaped bronze swords from Shuangyuan Village Cemetery analyzed in this paper

an acquisition time set to 40–70 s. The final results were obtained by averaging three tests on the same spot.

Lead isotope analyses

No contact with the metal matrix is required, and some corrosion powders on the surface are representative of the lead isotopic signature of the metal relics, so only a very small number of samples were collected for this lead isotopic analysis. First, approximately 2 mg of bronze powder needed to be completely dissolved in a mixture of 3 ml of HCl and 1 ml of HNO_3. Subsequently, the clear solution was leached and diluted to 10 ml with deionized water. These solutions were then measured by ICP–AES (PHD, Leeman Labs Inc., California, USA) to detect the lead content. The solutions were diluted to 1000 ppb based on the results representing the lead content. Thallium (T1) standard SRM997 was added to the solutions. The isotopic analysis of lead was carried out by MC-ICP-MS (VG AXIOM, Thermo-Elemental Inc., Winsford, England). The spectrometer is a dual-focus magnetic sector instrument equipped with an array of 10 variable Faraday collectors. In addition, it has a fixed Faraday and an electron multiplier detector. The overall analytical 2σ error for all lead isotope ratios was less than 0.086% based on replicate analyses of SRM981 (Table 1). This result is in good agreement with the published values.

Table 1 SRM981 solution was used as the standard reference material in the MC-ICP-MS analysis

ICP–MS	SRM981		
Number	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
1	16.9436	15.4965	36.7190
2	16.9438	15.4942	36.7182
3	16.9425	15.4948	36.7287
[22]	16.9420	15.4960	36.7200
Analytical error (%)	0.086	0.085	0.039

The results of three runs for SRM981 determination, analytical error and published values from [22] are shown

Results and discussion

Chemical compositions

The pXRF analysis indicates that the chemical composition of these willow-leaf shaped bronze swords is relatively concentrated except for the rusty samples, with a copper content ranging from 72 to 82% and a tin content from 16 to 21%. Five of the corroded samples had grossly inaccurate data and were not taken into account for reference (Table 2). Based on lead content, usually 2% as the boundary, they can be classified into two different alloy systems: one is the Cu-Sn–Pb ternary formula, and the other is the Cu-Sn binary metal. Lead should be considered an intentional alloy component if the lead content is more than 2% [23]. Conversely, low amounts of lead imply that it comes from lead impurities in copper ore or tin ore residues.

Tin plays a role in improving the fluidity of the copper liquid and lowering the melting point. The amount of tin content in tin bronze directly affects the hardness, tensile strength, elongation and other properties of the alloy [24]. With increasing tin content, the hardness of bronze is improved; the tensile strength first increases and then gradually decreases, but its elongation gradually decreases until it becomes zero when the tin content exceeds 30% [17]. The blade edges of bronze sword may sometimes forged during the shaping process. Previous simulation experiments have revealed that copper-tin binary alloys have two ductile forging zones, with bronze containing less than 18% tin at 200 ~ 300℃ and 20% ~ 30% tin at 500 ~ 700℃. The former condition is more applicable for some degree of thermal processing, which is not only easier to implement and control but also allows sufficient time for the forging process [25]. Moreover, when the tin content exceeds 25%, the brittleness of the alloy will rise rapidly, making subsequent processes more difficult [26]. To avoid breaking during actual combat, a certain degree of tensile strength and elongation must be provided to prevent brittleness. Taking into account performance requirements and process costs, the tin content of the bronze sword is supposed to be controlled in the range of 10–20%.

Lead is generally insoluble in high-tin bronze alloys but exists in the form of soft inclusions. Thus, the addition of lead to bronze can weaken the thermal conductivity of the copper matrix, improve the mold-filling capacity, slow down the intergranular shrinkage, and reduce mechanical impact and cracking. However, too much lead is counterproductive, abating the strength and hardness of the alloy, as well as its corrosion resistance [26]. In general, the relatively stable copper-tin ratio and the tin content of these willow-leaf shaped bronze swords are in line with scientific cognition, indicating that the ancestors of Shu State have been fully aware of the experience of making bronze swords. The dramatic fluctuations in lead content, on the other hand, reflect the fact that it was still the experimental phase of adding lead materials into the bronze weapon.

Table 2 Major elements (wt%) of the bronze swords from Shuangyuan Village Cemetery, Chengdu (blank means data under limitation)

Lab No	Archaeological No	Cu	Sn	Pb	Fe	Sb	As	Ti	Condition
QBS01	2016QDSM11:30	79.98	18.66	0.76	0.05	0.03	0.21		Metallic
QBS02	2016QDSM11:32	78.42	19.82	0.88		0.16	0.41		Metallic
QBS03	2016QDSM15:13	81.99	17.41	0.11	0.03		0.15		Metallic
QBS04	2016QDSM19:2	75.77	19.79	3.70	0.37	0.05			Metallic
QBS05	2016QDSM19:3	82.79	16.36	0.07	0.05	0.07	0.43		Metallic
QBS06	2016QDSM19:4	80.60	17.91	0.99	0.06	0.04	0.11		Metallic
QBS07	2016QDSM21:6	80.12	18.59	0.35	0.10		0.22		Metallic
QBS08	2016QDSM23:5	46.54	49.93	0.43	1.36		0.61	0.75	Corroded
QBS09	2016QDSM25:3	74.25	16.26	8.99	0.08	0.05			Metallic
QBS10	2016QDSM29:1	77.35	20.85	1.05	0.09	0.04	0.24		Metallic
QBS11	2016QDSM30:2	76.10	20.50	2.69		0.07	0.29		Metallic
QBS12	2016QDSM46:15	79.61	19.03	0.64		0.06	0.40		Metallic
QBS13	2016QDSM74:8	72.01	17.63	9.95	0.04				Metallic
QBS14	2016QDSM87:2	21.57	39.75	0.58	3.36		0.08	0.07	Corroded
QBS15	2016QDSM104:9	44.57	45.02	1.76	7.59	0.05	0.53	0.27	Corroded
QBS16	2016QDSM152:1	80.84	18.48	0.36	0.03				Metallic
QBS17	2016QDSM161:4	23.54	63.33	3.82	8.37				Corroded
QBS18	2016QDSM171:5	54.00	37.52	3.06	3.96		0.51	0.51	Corroded

The development and exchange of alloy technology latent in metal weapons has always been a key concern, and as a very typical localized artifact, the craft of the willow-leaf shaped bronze sword can be explored here with the help of data as to whether it is native or externally influenced. To determine the relationship between willow-leaf shaped bronze swords and other bronze swords of the same period in terms of alloy ratios, we also collected the composition data of bronze swords from different states in the Eastern Zhou Dynasty for comparison (Fig. 3). They include the willow-leaf shaped bronze swords from other sites of Shu State and Ba State, bronze swords from Chu and Qi, and some of the Central Plains system from Shanghai Museum (Additional file 1: Table S1) [27–30].

The willow-leaf shaped bronze swords, exclusive to the Shu and Ba states, despite being of the same typology and even often confusing to archaeologists [6], differ greatly in their tin content. The swords of Shu almost always a tin content above 13%, while the swords of Ba are below 13%. This incongruity is an interesting phenomenon, especially since the bronze swords of Ba dated to the late Eastern Zhou Dynasty, a little later than those of Shu. As mentioned before, the earliest willow-leaf shaped bronze swords of Ba were also introduced from Shu [5, 14], and the technical characteristics of the bronze alloy were probably affected at the same time. Indeed, bronze weapons from an earlier period in Shu, such as those from Sanxingdui or Jinsha, are generally lower in tin content, certainly less than 13% [30]. The bronze weapons of Ba appear to be closer to the alloy ratios of these much older artifacts. For both Ba and Shu, there is a clear elevation in tin content for later bronzes. The bronze-making technique, represented by the moderate addition of tin, was probably influenced by foreign cultures, especially the Central Plains [28]. The performance enhancement of high tin bronze was originally a driver of technological evolution, and the intermittent contact between Ba and Shu and the Central Plains substantially accelerated such a process, which can be reflected in the emergence of foreign factors in a number of archaeological cultures that accompanied high tin bronze [31]. However, the Ba State's own development is not in sync with that of its neighbors, so it is shown in the same kind of artifact, whose alloy technology is behind Shu, and the willow-leaf shaped bronze sword is an excellent example [28].

Another fact is that the willow-leaf shaped bronze swords of Ba and Shu are generally lower in lead content. There are also a number of bronze swords from Chu that contain less than 2% lead, which may be their common regional technical feature and can be distinguished from other states in Central Plains. Not by accident, some artifacts with distinctive Chu characteristics were found in some tombs in Shuangyuan Village [20]. Moreover, Ba and Chu are in contact with each other more frequently because of their bordering relationship

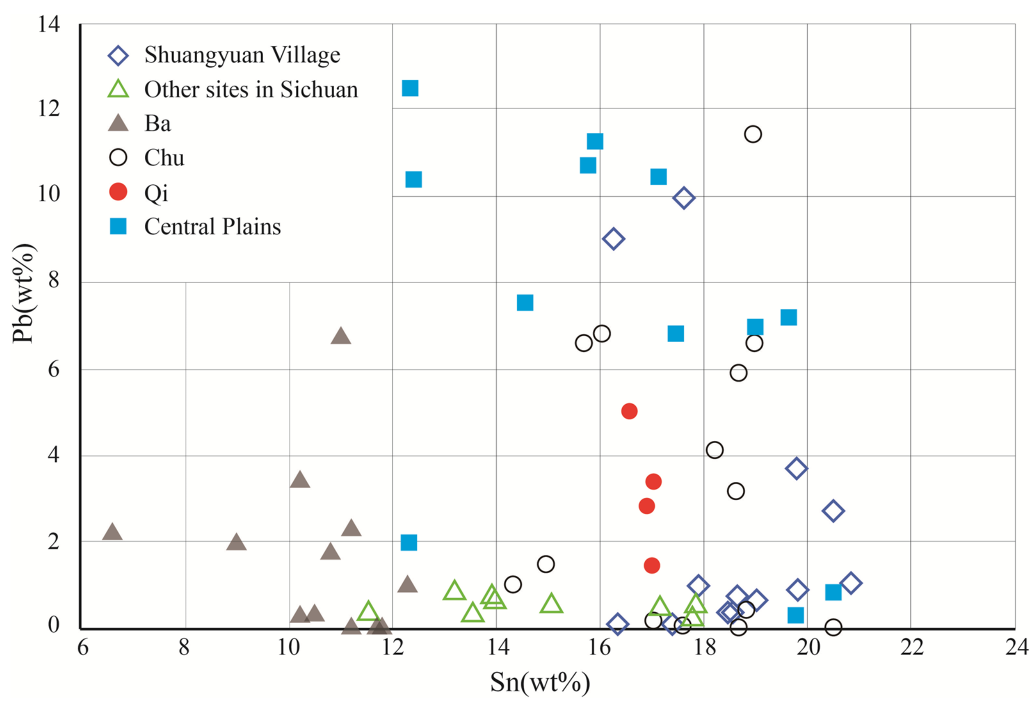

Fig. 3 Sn–Pb contents of bronze swords from different states in Eastern Zhou

[31]. In that eras of war and strife, there was a ploy of befriending distant states while attacking those nearby between states that was often implemented. As a result, there was a lot of friendly contact between Shu and Chu, and perhaps the secret of the alloy formula for making bronze swords was introduced to Shu in this way [32]. Other willow-leaf shaped swords from other sites of Shu presumably display a gradual process of imitation of this high-tin technique, as indicated by the variations in their tin content. Although Shu is further away from the Central Plains than Ba, it has a more flexible ability to learn and accept foreign crafts from the East, and thus the rate of improvement in alloy technology was faster, with the process becoming increasingly localized in this otherwise exotic weapon type. On this basis, it may provide important clues for the identification of bronzes that were previously indistinguishable between the Ba and Shu states.

Lead isotopic results

The results of lead isotope analysis of the bronze swords from Shuangyuan Village are given in Table 3, ranging from 17.63 to 18.77 for $^{206}Pb/^{204}Pb$, 0.83 to 0.88 for $^{207}Pb/^{206}Pb$ and 2.08 to 2.17 for $^{208}Pb/^{206}Pb$. These lead isotope data should be treated in two groups. One group reflects the characteristics of the lead ore, while the other group reveals the characteristics of the copper ore. The data of the two groups are mixed, but the span of the latter group is larger than that of the former group, which may reflect a more extensive source of copper material than lead material in Shu at that time. According to the geochemical province theory in China, most of the data in this batch belong to the lead isotope zone of the geochemical provinces of Yangtze, or South China, and a small part may come from the geochemical province of North China [33, 34]. Such a situation suggests that the source of the metal minerals is relatively wide, and at least part of them is likely to come from outside the territory of Shu. It is clear from the communication with Chu State that the ties between Shu and other powers were not restricted by its relatively isolated geographical location.

Tracing the mineral material is not the focus of this section, and we hope to explore the issue of production batches from the distribution pattern of lead isotope data. Therefore, we collected data on willow-leaf shaped swords unearthed from other sites on the Chengdu Plain (Additional file 1: Table S2) (Fig. 4). The Baishoulu and Xinghelu sites are dated at almost the same stage as the Shuangyuan Village cemetery, and they are all located less than 30 km away from each other [35–37]. The bronze swords from both Baishoulu and Xinghelu contain more than 2% lead and are typical of lead–tin bronze. In addition, the weapon data of Ba is directly characterized as a distribution area for comparison [38].

It is obvious that the metallic materials of Shu and Ba do not intersect in source, which is in line with some previous understanding [38]. Our previous analysis of other artifacts excavated from the Chengdu Plain suggests that a large part of the resources of the of the Shu state during Eastern Zhou period most likely came from southern

Table 3 Lead isotope ratios of the bronze swords from Shuangyuan Village Cemetery, Chengdu

Lab No	Archaeological No	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Alloy Type
QBS01	2016QDSM11:30	18.770	0.8357	2.0801	15.686	39.045	Cu–Sn
QBS02	2016QDSM11:32	18.442	0.8487	2.1041	15.652	38.802	Cu–Sn
QBS03	2016QDSM15:13	18.510	0.8472	2.0966	15.679	38.808	Cu–Sn
QBS04	2016QDSM19:2	18.417	0.8507	2.1051	15.667	38.770	Cu–Sn–Pb
QBS05	2016QDSM19:3	18.346	0.8506	2.1049	15.605	38.616	Cu–Sn
QBS06	2016QDSM19:4	18.472	0.8477	2.0986	15.659	38.766	Cu–Sn
QBS07	2016QDSM21:6	18.045	0.8636	2.1295	15.583	38.427	Cu–Sn
QBS08	2016QDSM23:5	18.182	0.8584	2.1164	15.607	38.486	Cu–Sn
QBS09	2016QDSM25:3	17.852	0.8703	2.1477	15.537	38.340	Cu–Sn–Pb
QBS10	2016QDSM29:1	17.637	0.8797	2.1677	15.514	38.233	Cu–Sn
QBS11	2016QDSM30:2	18.286	0.8544	2.1151	15.621	38.676	Cu–Sn–Pb
QBS12	2016QDSM46:15	18.186	0.8581	2.1156	15.606	38.475	Cu–Sn
QBS13	2016QDSM74:8	18.579	0.8445	2.0939	15.690	38.904	Cu–Sn–Pb
QBS14	2016QDSM87:2	18.407	0.8514	2.1049	15.673	38.755	Cu–Sn
QBS15	2016QDSM104:9	18.325	0.8535	2.11	15.640	38.666	Cu–Sn
QBS16	2016QDSM152:1	18.449	0.8483	2.099	15.650	38.724	Cu–Sn
QBS17	2016QDSM161:4	18.263	0.8553	2.1098	15.621	38.531	Cu–Sn–Pb
QBS18	2016QDSM171:5	18.288	0.8574	2.1112	15.686	38.630	Cu–Sn–Pb

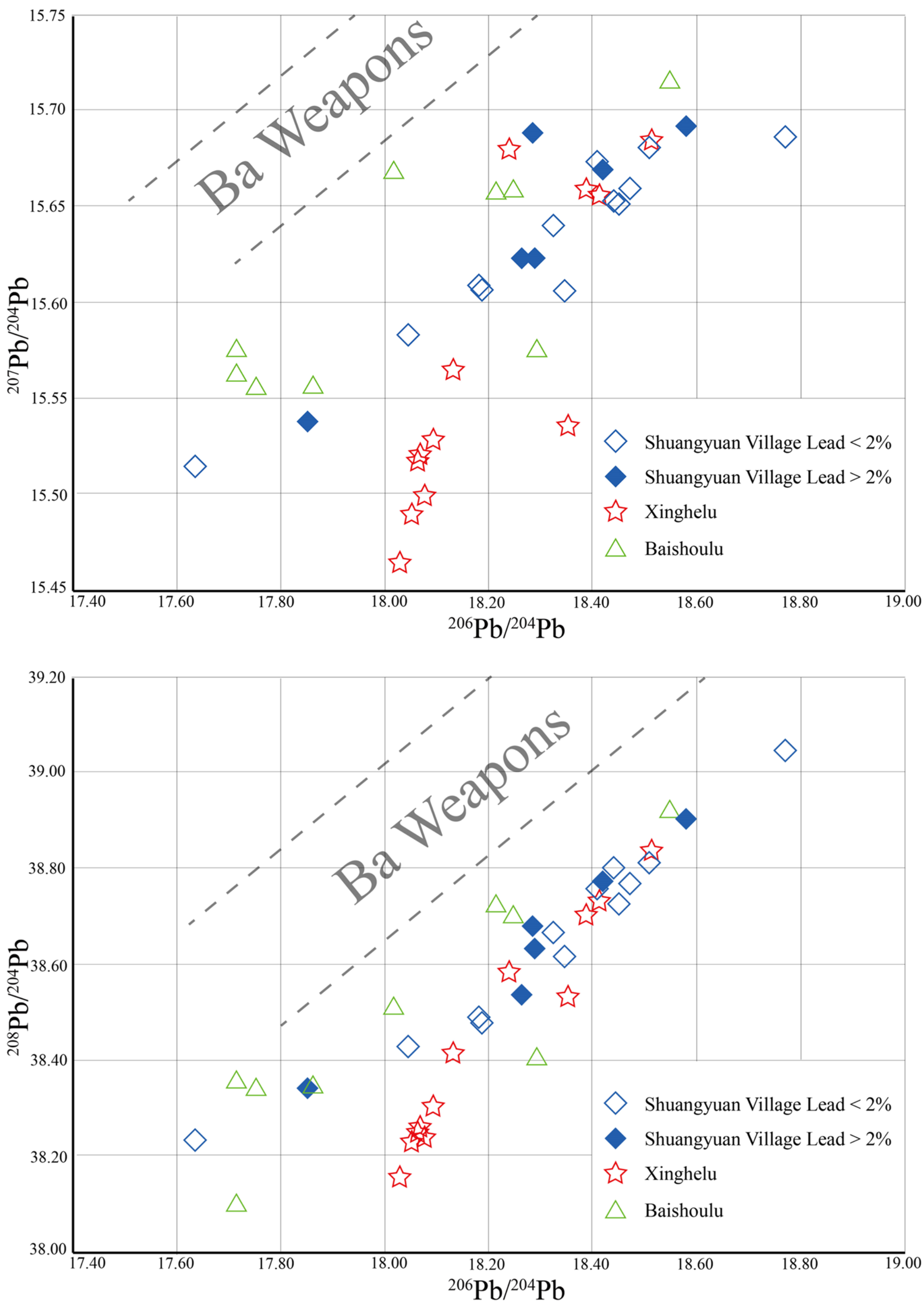

Fig. 4 The lead isotope ratios of willow-leaf shaped bronze swords from different localities of Shu State

Sichuan, which was certainly an area beyond the reach of Ba [39]. Therefore, although it is the same type of bronze sword, the source of material and the alloy technology are very different between the two states, which can bring a hard basis for distinguishing the cultural affiliation of the willow-leaf shaped swords. For the same local culture, the willow-leaf shaped bronze swords excavated from three sites in the Chengdu Plain provide an excellent example for a more detailed discussion of the production patterns of the same type of artifacts. In Fig. 4, these data points of Shu bronze swords are all approximately on a line with the same slope, but the three sites occupy different dominant intervals. In particular, the isotope ratios of Xinghelu bronze swords are significantly lower and more concentrated, and this region of values reflects a source of lead materials that appears to have been the more predominant one used at that time. This discrepancy undoubtedly indicates that these willow-leaf shaped bronze swords were produced in multiple batches. Due to the very local style, these bronze swords were certainly made locally [36]. The scattered data also suggest that the swords from the various sites could have come from different production workshops, or the same workshop could have produced them at different times. Since it is impossible to determine the exact date of each bronze sword, high-precision speculation has lost its foundation.

A reasonable assumption is that bronze weapons produced in the same batch would have very similar lead isotope signatures and elemental characteristics. However, these willow-leaf shaped bronze swords can be distinguished into many groups by both isotope data and composition data. This sign implies the high frequency of weapons production in Shu State during the Eastern Zhou Dynasty. Compared to other cultures of the same period, Shu had a much higher percentage of bronze swords accompanied in each tomb [2, 27]. Moreover, the span of lead isotopes in Shu weapons is also larger than that of several Central Plains states, implying that its mineral sources were more abundant, occupying not only indigenous resources but also exchanging some of them with other powers [39]. Shu people did not choose to keep these weapons to prepare for warfare. This practice of using bronze swords as funerary objects undoubtedly depleted war reserves. Therefore, the demand for bronze weapons in turn spawned a steady stream of weapons manufacturing in Shu to fill the shortfall. Thus, the high-frequency, multiple-batch production mode became the best choice. This is indeed consistent with the warlike proclivities of Shu people in historical records. With this kind of mass production, the technological improvement of metal artifacts was certainly more likely to occur. And coupled with the relatively benign interaction with the Central Plains culture at that time, it was possible to introduce foreign knowledge to trigger the integration of craft.

Conclusions

This paper analyzes eighteen pieces of Eastern Zhou willow-leaf shaped bronze swords of Shu excavated from Shuangyuan Village, Chengdu. They are almost identical in shape, varying slightly in length and thickness. In terms of elemental composition, they have relatively stable copper and tin contents; however, the lead content fluctuates widely, with some samples containing almost no lead and others having deliberately added lead. Although Ba, which was close to Shu, also used willow-leaf shaped bronze swords, the tin content of bronze swords in Shu is remarkably higher than those in Ba. In addition, the alloy ratio of the bronze swords of Shu appears close to that of Chu, which should be an integration of this technique to improve the performance of the weapon.

The metal materials used in Shu are also very different from those of Ba, and some of them are also related to Chu. Compared with other willow-leaf shaped bronze swords from other localities in the Chengdu Plain, they used multiple sources of lead materials. Unconcentrated lead isotope data and fluctuating lead content suggest that bronze weapons production at Shu was in multiple batches, according to the high proportion of bronze swords used for burial purposes. This high-frequency production mode of bronze weapons fits the warlike character of the Shu people. Probably due to the influence of the foreign policy of the time making Shu's interaction with other foreign states more frequent, the technological exchange and Shu's own large-scale manufacturing also stimulated the technical improvement and integration of Shu's unique artifacts.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-022-00725-2.

Additional file 1: Table S1. The composition data of bronze swords from different states in Eastern Zhou Dynasty (Blank means not reported). **Table S2**. The lead isotope ratios of willow-leaf shaped bronze swords from different localities of the Shu State.

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Author contributions
DC and WL performed the data analysis and were major contributors in writing the manuscript. XW helped the data collecting. YY and TW provided the archaeological context. All authors read and approved the final manuscript.

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Availability of data and materials
The authors confirm that the data supporting the findings of this study are available within the article its supplementary materials.

Declarations

Competing interests
We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is

no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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