Li *et al. Heritage Science* (2022) 10:151
https://doi.org/10.1186/s40494-022-00786-3

Heritage Science

RESEARCH

Open Access

Cultural exchange and integration: archaeometallurgical case study on underneath-blade bronze dagger-axes from Shuangyuan Village Site in the Eastern Zhou Dynasty

Yuexuan Li[1,2], Yingdong Yang[3], Tianyou Wang[3], Xiaoting Wang[1,2] and Wugan Luo[1,2*]

Abstract

As typical artifacts of the Ba-Shu culture, bronze dagger-axes have always been highly valued by academia. Underneath-blade bronze dagger-axes were utilized widely in both the Central Plains and southwest China. However, opinions differ on whether these underneath-blade bronze dagger-axes which excavated from Ba-Shu culture were produced locally. Combined with archaeological typology study, p-XRF and MC-ICP-MS were used to analyze 12 underneath-blade bronze dagger-axes unearthed from Shuangyuan Village Site, an Eastern Zhou cemetery in Chengdu city, Sichuan Province, Southwest China in order to investigate the cultural exchange and integration centered on the Shu culture. The composition results show that the majority of samples were made from copper, tin, and lead ternary alloy. The data on lead isotopes indicate that underneath-blade bronze dagger-axes have different mineral sources. The lead isotope ratio $^{206}Pb/^{204}Pb$ of 18.3 can draw the conclusion to be used as one of the bases for judging that underneath-blade bronze dagger-axes originated in the Chengdu Plain or the Central Plains which was consistent with the typology. The southern China lead materials of underneath-blade bronze dagger-axes in the Ba-Shu and Central Plains style probably came from southern Sichuan; while the rest of underneath-blade bronze dagger-axes in the Central Plains style might use lead materials in the western Hunan-western Hubei area. The Shu culture which was represented by Shuangyuan Village Site in Chengdu Plain during the Eastern Zhou Dynasty had close cultural communication with the Central Plains and Chu cultures. This study reveals that Ba-Shu had a direct exchange of minerals or metal products with the Central Plains and Chu, as well as an imitation based on the identification of the foreign culture and the belief in the local Shu cultural traditions.

Keywords: Underneath-blade bronze dagger-axes, Typology, Lead isotope ratio, The Shu culture, China, Eastern Zhou Dynasty

Introduction

During the Eastern Zhou Dynasty, there were two vassal states in the present-day Chongqing and Sichuan area, namely Ba and Shu. The two states are geographically adjacent and have similar cultures. Archaeologists often refer to them as "Ba-Shu Area" or "Ba-Shu Culture" [1].

As typical artifacts of the Ba-Shu culture, bronze dagger-axes have always been highly valued by academia.

*Correspondence: xiahua@ucas.ac.cn

[2] Department of Archaeology and Anthropology, University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China
Full list of author information is available at the end of the article

As an important demonstration of cultural communication and interaction between southwest China and surrounding areas in the Eastern Zhou Dynasty, Ba-Shu bronze dagger-axes are of great significance in archaeological research. During the Eastern Zhou Dynasty, two types of bronze dagger-axes were popularly used in the Ba-Shu area, namely non-underneath-blade (无胡戈) and underneath-blade bronze dagger-axes (有胡戈). Among them, non-underneath-blade bronze dagger-axes include the following four subtypes, such as triangular short-blade dagger-axes, straight long-blade dagger-axes, double-wing-blade dagger-axes, and spire-blade dagger-axes. It is widely accepted that the non-underneath-blade bronze dagger-axes were seldom used in the Central Plains during the Eastern Zhou Dynasty, but were prevalent and distinctive in southwest China [2]. Meanwhile, underneath-blade bronze dagger-axes (Fig. 1) can also be classified into three categories, one that combined the decorative features of Ba-Shu region on the basis of imitating the original shape of underneath-blade bronze dagger-axes in the Central Plains, and other that had the same shape as underneath-blade dagger-axes in the Central Plains. The third category was similar to the underneath-blade bronze dagger-axes which were common in the Chu culture during the Spring and Autumn Period.

Existing archaeological research on bronze dagger-axes of the Eastern Zhou Dynasty mainly focuses on typology, allowing for thematic discussions on the characteristics of era, function, origin, and flow direction of bronze dagger-axes in a specific area or a certain shape. Li Ji analyzed the evolution of bronze dagger-axes from the late Shang Dynasty to the Warring States period in northern Henan, including some underneath-blade dagger-axes in the Eastern Zhou Dynasty. He believed that hu (胡) was formed by the downward extension of the lower blade of yuan (援), which gradually lengthened [3]. Additionally, Zhu Fenghan made a systematic classification and periodization of bronze dagger-axes [4].

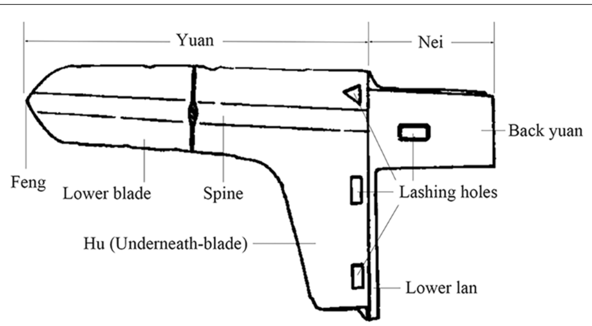

Fig. 1 The major components of the typical underneath-blade dagger-axe (The image modified from [2])

Bronze dagger-axes are geographically dispersed in archaeological discovery, so archaeologists primarily focus on the research of bronze dagger-axes unearthed in a specific region or a certain vassal state. The studies of underneath-blade dagger-axes in the Eastern Zhou Dynasty in northern China mainly concentrate on the Liaoning region, which conducted a preliminary discussion based on the inscriptions [5, 6]. Meanwhile, the Eastern Zhou dagger-axes in southern China were dominated by underneath-blade dagger-axes, and researches mainly focused on the Chu cultural area [7, 8], Wu-Yue cultural area [9], Ba-Shu and Southwest Yi cultural areas.

There is a lack of thematic discussions on the underneath-blade dagger-axes in Ba-Shu culture during the Eastern Zhou Dynasty currently. It is only mentioned briefly in the collective study of bronze dagger-axes, and the research is mainly about triangular short-blade dagger-axes. As a pioneer, Feng Hanji developed a concept of Shu style bronze dagger-axes and categorize them into five categories according to their shape, one of which is underneath-blade dagger-axes [10]. Afterwards, Tong Enzheng proposed that bronze dagger-axes in the Ba-Shu system could be classified into five types [11]. The typical one is underneath-blade dagger-axes, which was relatively common in Sichuan and still used from the Spring and Autumn Period to the unification of Qin Dynasty. Li Xueqin refined the subtypes on the basis of the traditional five-type division method, emphasizing the uniqueness of Shu style weapons [12]. According to previous research findings and existing archaeological discoveries, Jing Zhongwei divided the Eastern Zhou bronze dagger-axes in the Sichuan-Chongqing area into several types, and conducted a comprehensive discussion on staging, age, origin, evolution, distribution and clan [2].

The technological studies of bronze dagger-axes in the East Zhou Dynasty are relatively scattered, mainly found in the metallurgical analysis of bronze artifacts unearthed from a specific site, including Liulihe Cemetery of Yan State in Beijing [13]; Fenshuiling Cemetery of the Eastern Zhou Period in Changzhi, Shanxi [14]; Xinghe Road Locality of Jinsha Site of the Eastern Zhou Period in Chengdu [15]; and some bronze wares of Qin [16] and Chu [17]. Li Haichao pursued the research on the production and development of bronze wares in Chengdu Plain, which included samples of several bronze dagger-axes of the Eastern Zhou Dynasty [18]. Chen Dian [19, 20] and Wang Xiaoting [21, 22] conducted discussions on some bronze weapons unearthed in Shuangyuan Village based on archaeo-metallurgical analysis data. Non-destructive studies on the microstructure of the Eastern Zhou bronze dagger-axes were also conducted by some scholars [23]. As crucial indicators of material trade and cultural exchanges between regions in the Bronze Age, bronze weapons not only were practical tools but also had a symbolic significance of power and more cultural value. Therefore, many international scholars launched research on the sources of bronze weapon minerals in order to explore the metal resources and regional cultural exchanges [24, 25].

As a common weapon which was used in the war of annexation in the turbulent and changeable Warring States Period, the shape and decoration of the unearthed bronze dagger-axes always indicated the cultural differences and cultural communication between different states. In the Eastern Zhou Dynasty, underneath-blade bronze dagger-axes were widely used in various vassal states. Numerous underneath-blade bronze dagger-axes of various styles were found in the Chengdu plain. However, it is still under controversy as to their casting location. According to the differences in shape and decoration, archaeologists proposed different viewpoints, such as local production, import of the Central Plains, and influence from Ba and Chu [26]. It is difficult to determine their origin accurately from the standpoint of typology, but they can be further understood through archaeological science analysis. A large number of underneath-blade bronze dagger-axes excavated in the Shuangyuan Village Cemetery in Chengdu, which combined with the cultural factors from Ba-Shu, Central Plains, and Chu, provided new materials for the comprehensive study of archaeometallurgy. In view of traditional archaeological research, this paper conducts a primary scientific analysis on some underneath-blade bronze dagger-axes and discusses with the typology and detection data.

Archaeological context

The Shuangyuan Village Cemetery of the Eastern Zhou Dynasty is located in Shuangyuan Village, Dawan Town, Qingbaijiang District, about 27 km away from the center of Chengdu city (Fig. 2). In March 2016, Chengdu Municipal Institute of Cultural Relics and Archaeology and Cultural Relics Protection Center of Qingbaijiang

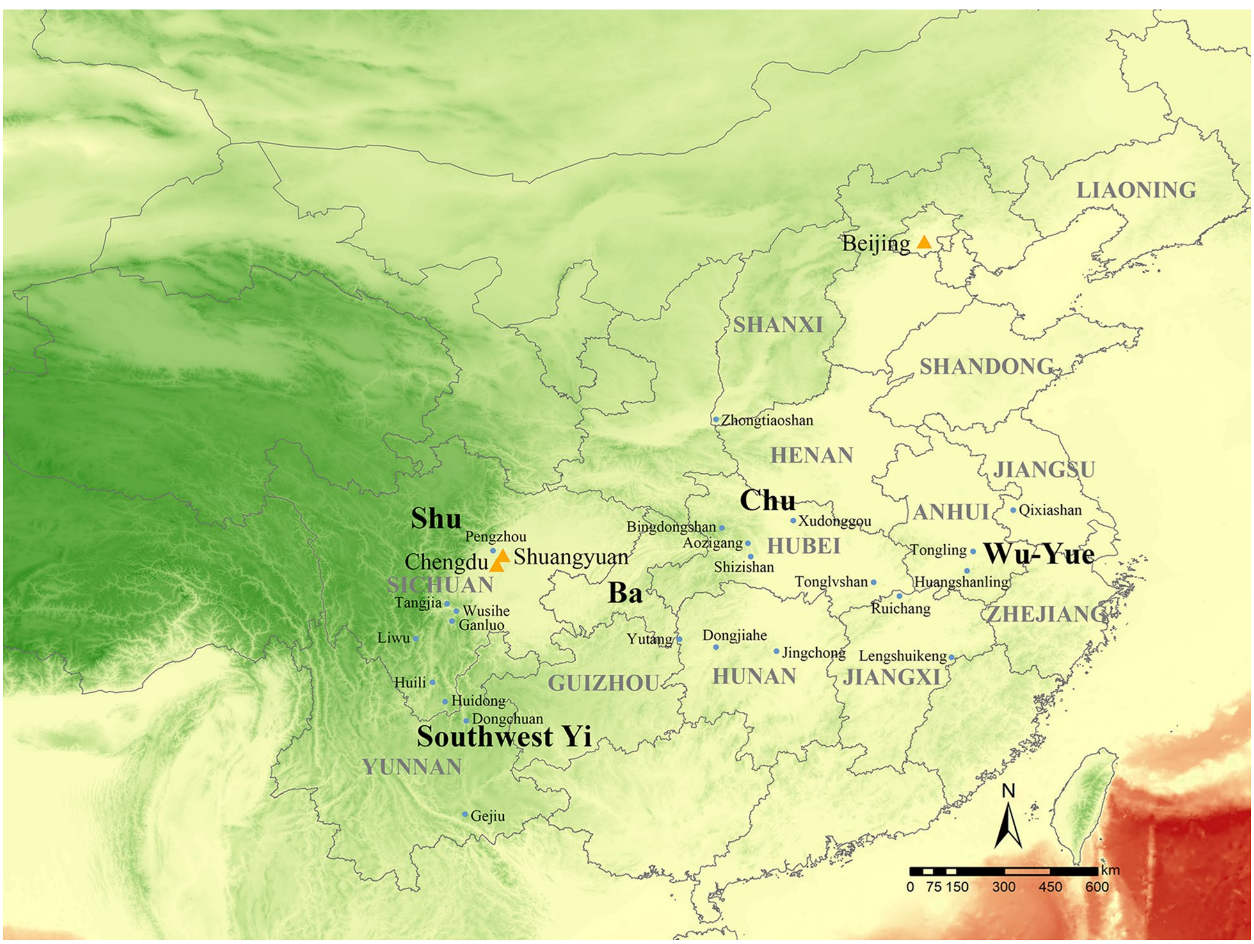

Fig. 2 The location of Shuangyuan Village, lead deposits and mentioned states in the Eastern Zhou Period

District excavated a great number of tombs of the Eastern Zhou Dynasty during the archaeological exploration of an infrastructure project in Shuangyuan Village. From May 2016 to July 2018, 270 tombs of the Eastern Zhou Dynasty were excavated and cleared. Among them, M154 is the highest-ranking tomb in the Eastern Zhou cemetery in Shuangyuan Village. Archaeologists believed that the owner of the tomb should be the Kaiming royal family or the highest ruling class of the ancient Shu society in the early and middle Warring States Period.

Shuangyuan Village Cemetery is currently one of the Eastern Zhou tombs with the largest uncovered area at one time and the most abundant burial objects unearthed in Sichuan province. The tombs in the two sections of the cemetery are regularly spaced and obviously arranged by grade. Accordingly, Shuangyuan Village Cemetery serves as an important comparative demonstration for discussions on the origin, spread, clan, social structure, and cultural relationship of late Shu culture [27].

There are abundant kinds of bronze artifacts unearthed in Shuangyuan Village Cemetery, including swords, spears, dagger-axes, knives, axes, chisels, mirrors, belt hooks, seals, building components, ding, zunfou, yan, basins and others. Among them, the underneath-blade dagger-axe is one of the most common weapon types, which can be found in many tombs. Its shape and decoration reflect a mix of indigenous Ba-Shu cultural factors and foreign -elements from the Central Plains and Chu state. Therefore, 19 underneath-blade dagger-axes were systematically discussed in this paper. While 12 of them were tested in this paper, the data of remaining 7 samples, including SYHG1-2, SYHG4, and SYHG15-18, were obtained from the Ref. [19].

Methods and results

Typological analysis

On the basis of the previous typological research on the Ba-Shu style bronze dagger-axes, these 19 underneath-blade dagger-axes were divided into three types according to morphological differences in the shape of hu (胡) and yuan (援) (Fig. 3).

Type A has long straight yuan and taper pointed feng (锋). Lower hu appears smooth transition without lower lan (阑), but has teeth that protrude backward for setting bi (柲). There is a lashing hole on top of yuan and two rectangular lashing holes on hu. Most rectangular nei (内) of Type A has a round lashing hole, a few without the hole. Yuan, hu or nei was sometimes decorated with tiger grain. And, there are 4 underneath-blade dagger-axes of Type A. According to the existence and layout of tiger patterns, Type A can be divided into three subtypes.

Type Aa has no ornamentation. The pattern of type Ab is decorated with the head of a tiger, with two ears beyond yuan without the body or tail. Tiger head decoration of Type Ac is located in yuan, body with cloud and thunder patterns and tail is decorated on hu, which is overall more abstract. The boundary between tiger head and body is not obvious.

Type B is well proportioned. The individual feng of Type B bulge slightly. There are two or three lashing holes on hu and a rectangular or circular lashing hole on the top of yuan. The lashing hole on nei is in the shape of a flat rectangle, a droplet, or a diamond. And, there are 13 underneath-blade dagger-axes of Type B.

The yuan of Type C has a middle waist and turns up. Feng obviously bulges. Hu with lower lan is of medium length. And, there are 2 underneath-blade dagger-axes of Type C.

Component analyses

Due to the preciousness of underneath-blade dagger-axes samples and the need for follow-up research, non-destructive analysis was conducted on the samples to ensure their integrity. Therefore, we used the Niton XL3t 950He handheld XRF analyzer (Thermo Fisher Scientific, Billerica, USA) to analyze the composition data of underneath-blade dagger-axes unearthed from Shuangyuan Village. The operating voltage of the main filter is 50 kV and the current is 100 μA. The X-ray spot on the sample is 3 mm in diameter. The portable X-ray fluorescence spectrometry (p-XRF) instrument is equipped with a silicon PIN (Si-pin) detector with a resolution of 190 eV. The metal analysis mode is selected and applied. The detection limits of p-XRF for tin and lead were 70 PPM and 35 PPM respectively.

The corroded parts of the sample were lightly polished until the exposed matrix is measured. For a small number of samples with serious corrosion, the analysis was carried out in areas with relatively little corrosion. We measured three different areas for each sample, and set the acquisition time to 60 s to obtain the average result (Table 1). The copper alloy standard sample ETM-EB375 (EU copper alloy standard sample) was selected to determine the alloy composition, and compared with the standard value to ensure the reliability of the test data [28]. According to the test data, the majority of samples contain tin and lead more than 2%, indicating that they are tin-lead bronze alloys. Meanwhile, SYHG3 of Type A, SYHG 17 of Type B and SYHG 18 of Type C are tin bronze alloys with lead less than 2%.

Lead isotope analyses

In this paper, the multicollector inductively coupled plasma mass spectrometry (MC-ICP-MS, VGAXIOM, Thermo-Elemental Inc., Winsford, England) of the School of Earth and Space Sciences, Peking University

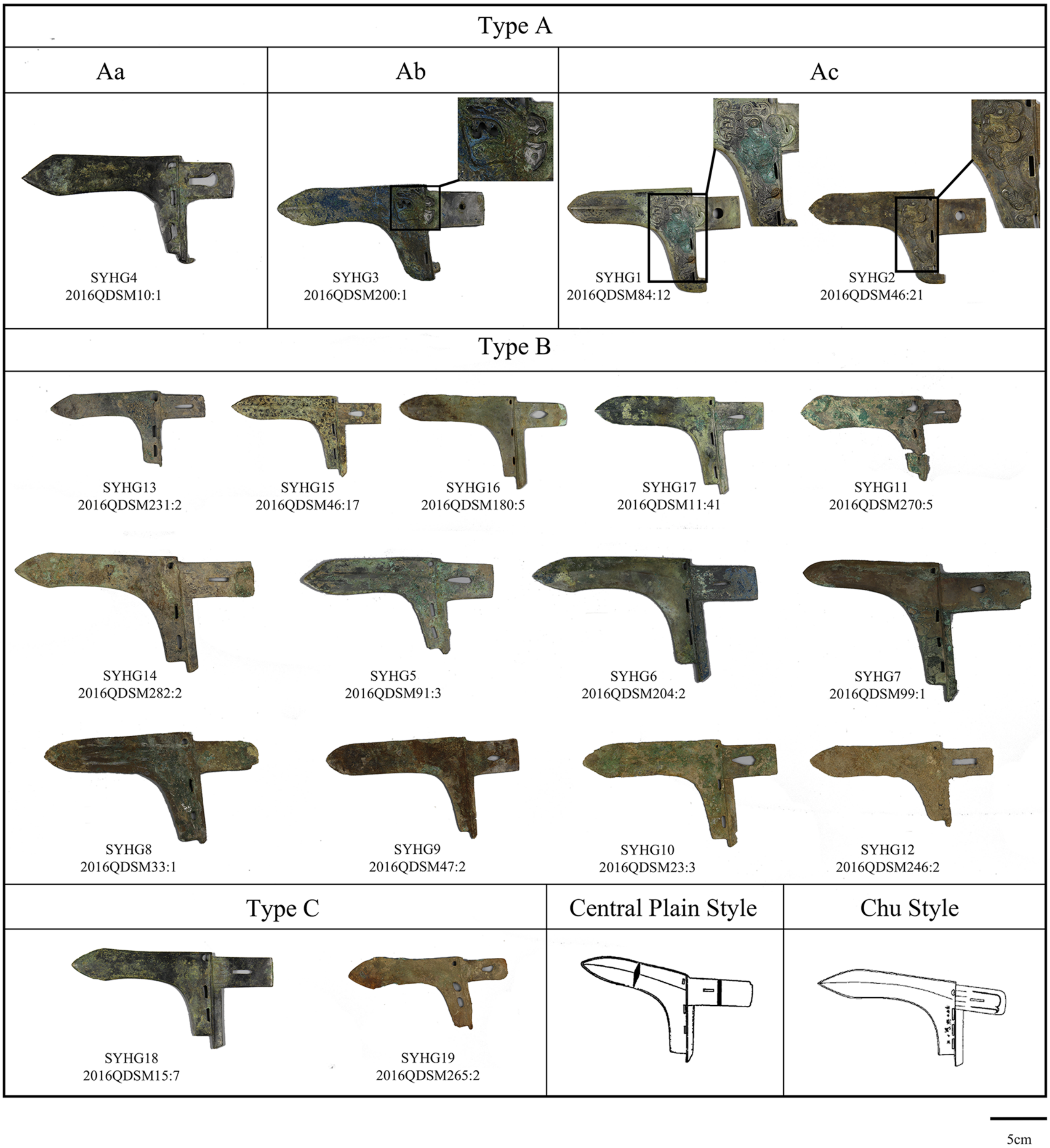

Fig. 3 The underneath-blade bronze dagger-axes from Shuangyuan Village Site and their groups (The image of the Central Plain Style and Chu Style modified from [2])

was used to analyze the lead isotope ratio of samples. Before analysis, put 2 mg sample powder into the beaker. Dissolve the sample by adding a certain volume of aqua regia. After the sample is completely dissolved, add high-purity deionized water to 100 ml and take a 20-30 mL clear solution for detection. Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) was used to determine the content of lead in the solution. According to the amount of lead in the solution, the lead content was diluted to about 500 ppb and then thallium (Tl) standard solution (SRM 997) was added, which had about 2/3 of lead content. Then the sample preparation

Table 1 Principal elements of underneath-blade bronze dagger-axes from Shuangyuan Village Site (Wt%)

Lab No.	Burial No.	Cu	Sn	Pb	Source
SYHG1	2016QDSM84:12	29.90	58.60	2.30	Chen et al. [19]
SYHG2	2016QDSM46:21	39.04	45.87	4.86	–
SYHG3	2016QDSM200:1	13.12	36.92	0.69	This paper
SYHG4	2016QDSM10:1	29.01	60.39	4.13	Chen et al. [19]
SYHG5	2016QDSM91:3	22.14	24.16	5.85	This paper
SYHG6	2016QDSM204:2	37.95	22.50	3.68	–
SYHG7	2016QDSM99:1	25.87	30.15	2.79	–
SYHG8	2016QDSM33:1	7.04	30.89	4.09	–
SYHG9	2016QDSM47:2	21.61	15.99	9.39	–
SYHG10	2016QDSM23:3	24.36	15.14	15.08	–
SYHG11	2016QDSM270:5	25.55	30.17	28.15	–
SYHG12	2016QDSM246:2	48.12	17.67	14.89	–
SYHG13	2016QDSM231:2	15.99	58.09	22.55	–
SYHG14	2016QDSM282:2	20.71	52.99	12.09	–
SYHG15	2016QDSM46:17	79.92	17.02	2.39	Chen et al. [19]
SYHG16	2016QDSM180:5	69.29	11.34	19.06	–
SYHG17	2016QDSM11:41	77.97	21.21	0.08	–
SYHG18	2016QDSM15:7	79.88	19.58	0.08	–
SYHG19	2016QDSM265:2	33.62	4.91	18.00	This paper

"–" means ditto. Additionally, due to the serious corrosion of some samples,data of principal elements have certain deviation. Elements related to the corrosion process take a large proportion [73]

is completed. Finally, lead isotope analysis was performed on MC-ICP-MS. The SRM981 international lead isotope standard was used as the standard reference. The test error of $^{206}Pb/^{204}Pb$ is between 0.000517 and 0.043, and it is between 0.000551 and 0.047 when it comes to $^{207}Pb/^{204}Pb$ and between 0.002160 and 0.095800 when it comes to $^{208}Pb/^{204}Pb$ (Table 2).

According to the difference in lead isotope ratios and the related research of China geochemistry province [29], underneath-blade dagger-axes of Shuangyuan Village can be divided into two groups: the Yangtze geochemical province lead with $^{206}Pb/^{204}Pb$ ratio of 18.020–18.300 and the southern China geochemical province lead with $^{206}Pb/^{204}Pb$ ratio of 18.300-18.664. As the source of lead in the alloy is complicated, it is artificially specified for ease to analyze [30, 31]. Combining data from Europe, Gale advocated that the lead isotope ratio reflects the source of copper ore for copper wares with the lead content of 50 ppm ~ 4% [32]. However, some European academics think the standard should be lowered to 1% [33]. Several Chinese scholars have proposed that 1% lead content is sufficient to prove the artificial addition of lead ore which dominates the isotope signature based on the geological and geochemical characteristics of copper mines in China with the lead isotope analysis of ancient bronze wares [34, 35]. Meanwhile, the lead content of copper ingots discovered in mining and smelting sites of the pre-Qin period in China is generally less than 0.1% [36]. Therefore, Chinese scholars generally take 2% as the

Table 2 Lead isotope ratios of underneath-blade bronze dagger-axes from Shuangyuan Village Site

Lab No.	Burial No.	$^{206}Pb/^{204}Pb$	Error	$^{207}Pb/^{204}Pb$	Error	$^{208}Pb/^{204}Pb$	Error
SYHG1	2016QDSM84:12	18.599	0.002250	15.674	0.002830	38.955	0.002350
SYHG2	2016QDSM46:21	18.343	0.005620	15.665	0.005670	38.612	0.071900
SYHG3	2016QDSM200:1	18.578	0.001220	15.717	0.000876	38.910	0.002690
SYHG4	2016QDSM10:1	18.336	0.003140	15.593	0.003160	38.526	0.010200
SYHG5	2016QDSM91:3	18.054	0.000701	15.598	0.000651	38.414	0.002540
SYHG6	2016QDSM204:2	18.582	0.001390	15.734	0.001450	38.963	0.004820
SYHG7	2016QDSM99:1	18.518	0.001000	15.733	0.000811	38.927	0.002160
SYHG8	2016QDSM33:1	17.842	0.000902	15.596	0.000886	38.432	0.003530
SYHG9	2016QDSM47:2	18.180	0.000978	15.643	0.000551	38.561	0.004570
SYHG10	2016QDSM23:3	18.020	0.000517	15.582	0.000566	38.369	0.002490
SYHG11	2016QDSM270:5	18.123	0.000848	15.650	0.000991	38.492	0.004120
SYHG12	2016QDSM246:2	18.664	0.000528	15.771	0.000622	39.117	0.005400
SYHG13	2016QDSM231:2	18.427	0.001220	15.702	0.001380	38.795	0.005590
SYHG14	2016QDSM282:2	18.463	0.00069	15.723	0.000673	38.915	0.003910
SYHG15	2016QDSM46:17	18.115	0.005790	15.572	0.004300	38.385	0.014600
SYHG16	2016QDSM180:5	18.093	0.043000	15.448	0.047000	38.158	0.095800
SYHG17	2016QDSM11:41	18.430	0.001210	15.612	0.001190	38.705	0.002790
SYHG18	2016QDSM15:7	18.492	0.012000	15.632	0.004140	38.815	0.017400
SYHG19	2016QDSM265:2	18.424	0.001530	15.690	0.001260	38.762	0.003580

standard. If the lead content of the bronze wares exceeds 2%, it can be assumed that the lead isotope ratio reflects the source of lead ore, and vice versa for copper ore [37]. At the moment, the international academia has accepted the lead content of 2% as the standard of lead isotope to indicate the source of lead ore in Chinese bronzes [38, 39].

Since most lead in underneath-blade dagger-axes is more than 2%, the lead isotope results primarily reflect the characteristics of lead ore. Meanwhile, the lead content of SYHG3 of Type A, SYHG 17 of Type B and SYHG 18 of Type C is less than 2%, which demonstrates the source of copper. Obviously, there are differences in the source of lead ore between the two groups.

Discussion

Typology and mineral

The typological studies indicated that the type A was prevalent in Chengdu Plain during the Eastern Zhou Dynasty. From the perspective of shape and structure, this type of underneath-blade dagger-axes was restructured by learning those from the Central Plains and combining them with local typical cultural factors such as teeth and tiger patterns. These Ba-Shu cultural factors and the lead isotope ratio of $^{206}Pb/^{204}Pb$ more than 18.3, which reflects the lead source from southern China, collectively formed the local style of underneath-blade dagger-axes produced in the Chengdu Plain.

Type B was roughly similar to the popular underneath-blade dagger-axes in the Central Plains after the Spring and Autumn Period, but it was relatively older. Archaeological researchers hypothesized that these typical Central Plains style dagger-axes came directly from the Central Plains, and were brought into the Chengdu Plain via wars or other cultural exchanges [2]. Among 12 Type B underneath-blade dagger-axes with the lead more than 2% made by ternary alloys in Shuangyuan Village, 7 pieces had a lead isotope ratio $^{206}Pb/^{204}Pb$ less than 18.3, and the other 5 pieces more than 18.3. The difference in the lead ore of underneath-blade dagger-axes with Central Plains style in Shuangyuan Village suggests that their origins might be different and cannot be distinguished solely by typology. Consequently, lead isotopes may help archaeologists determine whether underneath-blade dagger-axes in the Central Plain style were imported or imitation products.

As previously discussed, some underneath-blade dagger-axes with lead isotope ratio $^{206}Pb/^{204}Pb$ less than 18.3 probably originated in the Central Plains, which can be further confirmed by the fact that the lead isotope ratio $^{206}Pb/^{204}Pb$ of underneath-blade dagger-axes from the Jin [40] and Qin [41] which located in the Central Plains and surrounding areas are less than 18.3 (Fig. 4). Meanwhile,

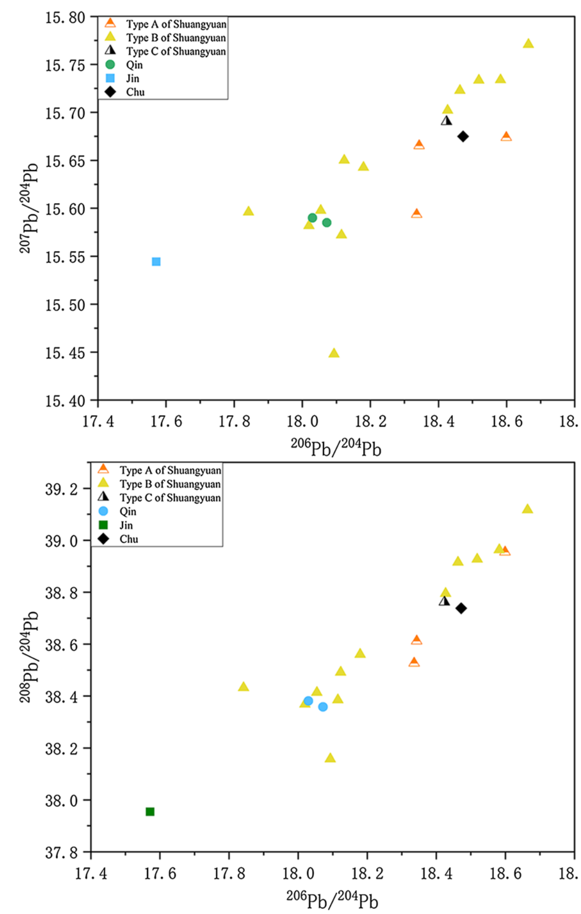

Fig. 4 The lead isotope ratios of Eastern Zhou underneath-blade bronze dagger-axes from different localities

those with a $^{206}Pb/^{204}Pb$ ratio more than 18.3 should be considered local products. According to the general situation of cultural exchange, it needs a gradual process for foreign cultural factors to be accepted by local people and adopted as their own [42]. Simultaneously, excavators (personal communication with Wang Tianyou) determine that the upper limit of age of underneath-blade dagger-axes in the Central Plain style unearthed in Shuangyuan Village is slightly older than those in Ba-Shu style. Therefore, it can be speculated that the earliest underneath-blade dagger-axes in Chengdu might came directly from the Central Plains. After ancestors in Shuangyuan Village accepted this kind of new bronze weapon, they began to produce underneath-blade dagger-axes locally. At first, they might completely imitate the shape of the underneath-blade dagger-axes in the Central Plains. With the development of the bronze metallurgy industry and aesthetic requirements, the local characteristics such as teeth and tiger patterns were gradually added, eventually forming a unique Ba-Shu style of underneath-blade dagger-axes. As the development process analyzed above, it reflected not only their belief in the Shu cultural tradition but also showed their strong psychological identification with the Central Plains culture [43].

Type C, with its middle waist and bulging feng, is reminiscent of the common underneath-blade dagger-axes used in Chu culture during the Spring and Autumn Period. From the perspective of archaeology, such artifacts mainly inherited the characteristics of underneath-blade dagger-axes in Chu culture of the Spring and Autumn period as imitations, indicating that the cultural factors carried by bronze weapons spread between the two regions for a long time. According to the materials that have been published so far, King Zhuang of Chu (楚庄王) reigned supreme, and his national power was at its peak in the middle and late Spring and Autumn period [44]. During the reign of the Kaiming clan (开明氏) by which period the Shuangyuan Village cemetery belonged, a relatively complete system was formed for the bronze wares in the Chu style, and cultural factors of Chu were popular in Shu [45]. It was also determined that several bronze and decorations engraved on lacquerware unearthed in M154 were mostly in the style of Chu culture. The Kaiming clan established the ritual and music system at this time, which was probably motivated by their admiration for the Chu culture. Chu is a major southern state relatively geographically close to Ba-Shu area, so the Kaiming clan strengthened their connection with Chu by importing or imitating artifacts of Chu culture. Some scholars also suggested the ruling class of Shu and Chu might have formed a political alliance at that period, and the ruling class of Shu obtained some bronze wares from the Chu state through trades or gift-giving [46]. Meanwhile, the lead isotope ratios $^{206}Pb/^{204}Pb$ of SYHG19 and an underneath-blade dagger-axe of Chu unearthed from Henan [17] are highly close (Fig. 4). However, studies on lead isotopes of bronze weapons in Chu state of the Eastern Zhou Dynasty are lacking, and only two sets of data are insufficient to determine the accurate model of ore circulation network [47] between Ba-Shu and Chu states. Thus, further research needs to be conduct with more subsequent data.

Ore material source

Due to the complexity of the cultural elements influencing underneath-blade dagger-axes unearthed in the Chengdu Plain and the rarity of those with Ba-Shu style in other areas in the same period, it is assumed that these artifacts are local creations. Considering geographical relationships, this paper selected the isotopic data of lead ore in the Chengdu Plain and surrounding areas, in order to determine whether the lead material used in Shuangyuan Village to make underneath-blade dagger-axes of the Ba-Shu style, which has a ratio $^{206}Pb/^{204}Pb$ more than 18.3, was mined locally.

The lead ores in Sichuan and nearby areas were mainly derived from large-scale lead-zinc deposits in the low-temperature metallogenic domain of Sichuan, Yunnan and Guizhou, represented by Daliangzi in Huidong [48] and Tianbaoshan in Huili [49], etc. In addition, there are some relatively small mines. Therefore, the parts of lead isotope data of galena and lead-zinc ores in some lead-zinc deposits in the Sichuan-Yunnan-Guizhou area were collected in this paper (Fig. 5) [50–54].

In general, the lead isotope data of underneath-blade dagger-axes in Ba-Shu type with the ratio $^{206}Pb/^{204}Pb$ of 18.300-18.664 generally concentrate in the region shown by the solid line ellipse in Fig. 5, which differ significantly from the data of Daliangzi in Huidong. Some data from other locations, such as Tangjia and Wusihe, are distributed in the range where the data of underneath-blade

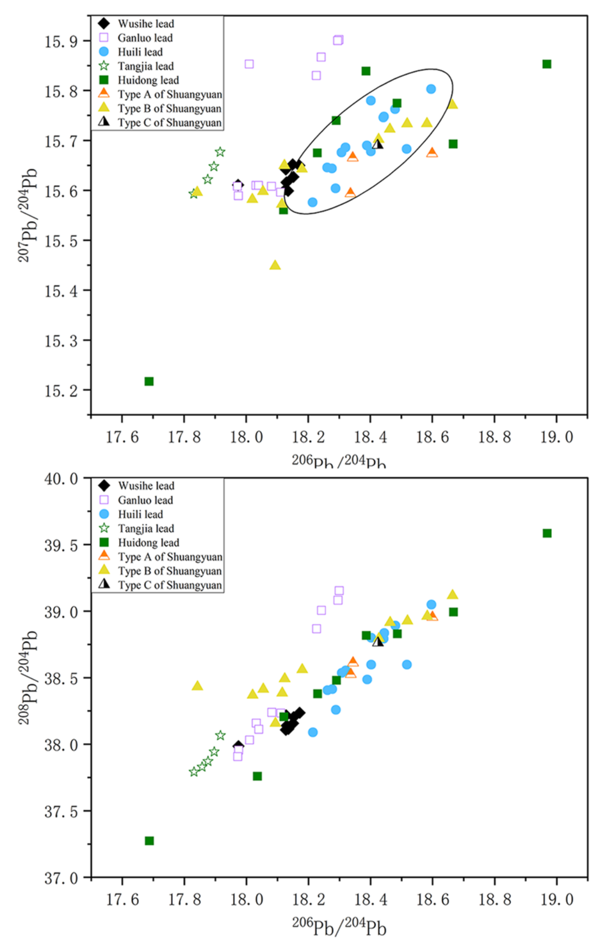

Fig. 5 The lead isotope ratios of underneath-blade bronze dagger-axes and lead ores from different localities in Sichuan Province

dagger-axes is available with partial overlap but lack of overall fit. Only a portion of Ganluo galena and lead-zinc ore fall within the data range of underneath-blade dagger-axes. Such data show a relatively independent regional distribution, but it does not completely match with the lead isotope characteristics of underneath-blade dagger-axes in Shuangyuan Village. Studies have shown that several underneath-blade dagger-axes from Shuangyuan Village and Huili copper have similar lead isotope data [19]. In addition, it is the only location in Sichuan that can simultaneously supply three main raw elements of bronze, namely copper, tin, and lead. The data demonstrate that the lead isotope of Huili lead and underneath-blade dagger-axes of Ba-Shu style in Shuangyuan Village are relatively consistent. Therefore, it can be further inferred that lead materials utilized in underneath-blade dagger-axes of Ba-Shu style with the ratio $^{206}Pb/^{204}Pb$ 18.300-18.664 might originate in Sichuan, and the precise mining site might be in the Huili area.

According to the notion of geochemical provinces, lead materials for underneath-blade dagger-axes in Central Plain style with ratio $^{206}Pb/^{204}Pb$ 18.020–18.300 should come from the Yangtze metallogenic province [29]. Meanwhile, the shape of the underneath-blade dagger-axes in the Central Plain style of Shuangyuan Village and those found in the Wu-Yue area in the Eastern Zhou Dynasty is obviously different, ruling out the possibility that they were originated in the Wu-Yue area. Therefore, the lead ore of such samples may come from the area with lead and zinc deposits in the Yangtze metallogenic province except the Wu-Yue area, where the largest lead-zinc deposits in the Yangtze metallogenic province are at the intersection of Hunan, Hubei, Guizhou and Chongqing, with a few mines in other areas.

The Eastern Zhou bronze artifacts in the Central Plains are dominated by lead-tin bronze, which required a large amount of lead mineral resources, while larger lead-zinc deposits are not found in northern China [55]. In order to maintain the output and quality of bronzes, the Central Plains were likely to engage in metal resource exchanges with the surrounding vassal states in various forms. For example, the majority of important copper mining and smelting sites in the Eastern Zhou Dynasty were distributed in the Yangtze River Basin, including Tonglu Mountain in Hubei; Jiangmuchong in Nanling, Anhui; Tongling in Ruichang, Jiangxi; and Jiuqu Bay in Mayang, Hunan. Therefore, rich bronze ore resources were mainly controlled by Chu and Wu. In the early and mid-Spring and Autumn Periods, Chu actively used foreign troops to expand towards the Central Plains. However, from the late Spring and Autumn Period to the early Warring States Period, Chu was constantly in the midst of wars with Jin and Wu and lost a large portion of its territory [56]. As a result of the long-term war and the replacement of territorial sovereignty, the material and cultural exchanges between the Central Plains, Chu and Wu-Yue regions accelerated. Under the social circumstance, bronze wares and mineral resources were both important objects of circulation.

The lead isotope ratio $^{206}Pb/^{204}Pb$ 18.020–18.300 of underneath-blade dagger-axes in Central Plain style is roughly concentrated in the area shown by the solid line ellipse in Fig. 6 [57–62], which is significantly different from majority of the data. Part of the data of Shizishan galena deposits in the western Hunan-western Hubei area fall within the range of underneath-blade dagger-axes in Shuangyuan Village. Although such data may not completely coincide with the lead isotopic characteristics of underneath-blade dagger-axes in Central Plains style, they raise the possibility that some underneath-blade dagger-axes in Central Plain style used lead materials in the western Hunan-western Hubei area.

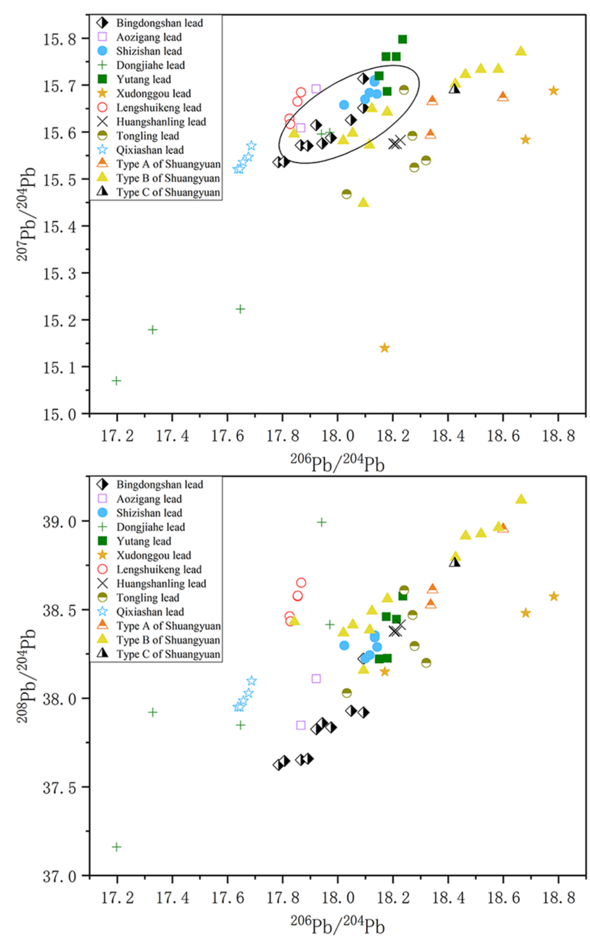

Fig. 6 The lead isotope ratios of underneath-blade bronze dagger-axes and lead ores from different localities in Yangtze Block

Among the 19 samples studied in this paper, 16 samples contained lead of more than 2%, while 3 samples contained lead of less than 2%. The latter belong to Type A, Type B, and Type C respectively. In Fig. 7 [63–72], the lead isotope ratio of the three underneath-blade dagger-axes fall into the partial range of Zhongtiaoshan, Ruichang, Gejiu, and Huili copper, implying that their copper raw materials may partly come from these mines. As there is only one sample of each type and the lead isotope data from different copper mines overlap, the data cannot adequately reflect the source of the copper mine, which is entirely coincidental. Relevant issues are being researched further.

The analysis above points out that the shape, decoration and source of mineral materials of underneath-blade dagger-axes can reflect local traditions as well as the infiltration of other cultural factors into the bronze ware making process. The lead isotope ratio $^{206}Pb/^{204}Pb$ of underneath-blade dagger-axes with typical Ba-Shu cultural factors such as teeth and tiger patterns are more than 18.3, indicating that they were produced locally in the Chengdu Plain. Some underneath-blade dagger-axes in the Central Plains style with the ratio $^{206}Pb/^{204}Pb$ less than 18.3 might come directly from the Central Plains area; whereas those with the ratio $^{206}Pb/^{204}Pb$ more than 18.3 should be produced locally and completely imitate the former. This feature reflects the close cultural exchanges that occurred between the Chengdu Plain and the Central Plains during the Eastern Zhou Dynasty, as well as the process of Ba-Shu's absorption and transformation of the cultural factors of the Central Plains. The form of the underneath-blade dagger-axes in Chu style reflects the long-term communication of cultural factors based on bronze weapons between the two cultural areas. At the same time, different types of underneath-blade dagger-axes in Shuangyuan Village have different characteristics of mineral resources. Underneath-blade dagger-axes in Ba-Shu style used minerals from southern China, which probably came from southern Sichuan according to lead isotope analysis. While the minerals of the Central Plains style underneath-blade dagger-axes are relatively diverse, in which some of them use minerals from southern China. Furthermore, the specific mines may also originate in southern Sichuan. Meanwhile, more than half of them used the same ore materials as underneath-blade dagger-axes in the Central Plains style, and the specific mines are probably to be located in the western Hunan-western Hubei region. It shows that the Shu culture in the Chengdu Plain during the Eastern Zhou Dynasty had a very close communication with the Central Plains and Chu. Accordingly, there are clear exchanges of minerals or metal products between the Chengdu Plain and the Central Plains, as well as imitations based on identification with the Central Plains culture and the belief in the cultural traditions of Ba-Shu culture. Ba-Shu rulers might have introduced or imitated Chu cultural artifacts because of their admiration for Chu culture or strengthening alliances.

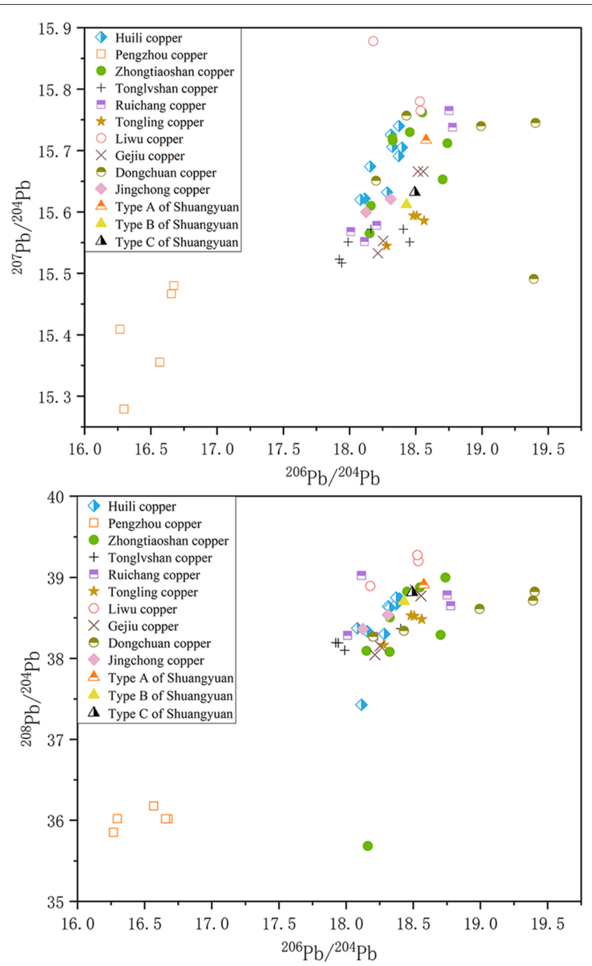

Fig. 7 The lead isotope ratios of underneath-blade bronze dagger-axes and copper ores from typical ancient copper ore regions

Conclusion

On the basis of archaeological typology research, this paper shows a series of scientific analyses on 19 underneath-blade dagger-axes found in the Shuangyuan Village Cemetery in Chengdu and discusses the three aspects of typology, alloy composition and lead isotope data. The results indicate that underneath-blade dagger-axes in Shuangyuan Village are primarily made of tin-lead bronze alloys derived from various ore deposits. The ratio $^{206}Pb/^{204}Pb$ of 18.3 can be used as one of the pieces of evidence to determine whether underneath-blade dagger-axes came from Chengdu Plain or the Central Plains, which was coincided with the typological characteristics. There is a significant difference between the lead isotope data of underneath-blade dagger-axes and the data of galena from the surrounding area of Shuangyuan Village site, which is relatively consistent with Huili lead. Thus, the raw materials of the Ba-Shu style underneath-blade dagger-axes are probably from southern Sichuan. Underneath-blade dagger-axes in Central Plains style made of lead from southern Sichuan were at a stage of development when the ancestors of Shuangyuan Village completely imitated those from the Central Plains. And the rest could be made of lead materials from the western Hunan-western Hubei region in the Yangtze River Basin. During the Eastern Zhou Dynasty, Ba-Shu culture in the Chengdu Plain, represented by Shuangyuan Village, maintained close contact with the Central Plains. On the basis of the direct exchange of minerals or metal products with the Central Plains, it had gradually developed into imitation based on cultural identity and confidence of their traditional culture. Meanwhile, Ba-Shu imported or imitated some Chu cultural artifacts out of the admiration for Chu culture or other profound political reasons.

Acknowledgements
The authors are grateful to anonymous reviewers whose comments greatly improved the quality of the manuscript.

Author contributions
Y.L. and W.L. performed the analyses and wrote the original draft. Y.Y. and T.W. provided underneath-blade Bronze Dagger-axe samples and background information. X.W. and W.L. conducted the experiment and provided data. W.L. supervised the entire process and reviewed the paper. All authors have read and agreed to the published version of the manuscript. All authors read and approved the final manuscript.

Funding
This research was funded by the National Social Science Foundation of China (No. 20VJXG018), the Beijing Social Science Found Project (No. 21DTR046) and the Fundamental Research Funds for the Central Universities.

Availability of data and materials
All data generated during this study are included in this published article or are available from the corresponding author upon reasonable request.

Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Author details
[1]Key Laboratory of Vertebrate Evolution and Human Origin of Chinese Academy of Sciences, Institute of Vertebrate Paleontology and Paleoanthropology, Beijing 100049, People's Republic of China. [2]Department of Archaeology and Anthropology, University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China. [3]Chengdu Archaeological Institute, 610000 Chengdu, People's Republic of China.

Received: 3 June 2022 Accepted: 17 September 2022
Published online: 28 September 2022

References

1. Xiang MW. Archaeological perspective on Ba's and Shu's ancient histories. Changchun: Jilin University; 2017. [in Chinese with English abstract].
2. Jing ZW. Study on Bronze Ge and Ji of China's early dynasties. Beijing: Science Press; 2011. [in Chinese].
3. Li J. Graphical classification of Bronze Weapons unearthed in north Heinan. Beijing: Cultural Relics Publishing House; 1990. p. 672–702. [in Chinese].
4. Zhu FH. Bronze wares of ancient China. Tianjin: Nankai University Press; 1995. [in Chinese].
5. Zhang ZZ. Textual Interpretations on the Ge Axes of the Marquis Zhi of the Yan. Archaeology. 1973;04:244–6. [in Chinese].
6. Han Y. Study on Bronze Ge of the warring states period in the liaoning area and the relative questions. J Liaoning Univ. 1993;02:107–8. [in Chinese].
7. Jin ZG. Periodzation of Bronze Ge of the Eastern Zhou Period in Hunan and the Relative Questions. Changsha: Yuelu Press; 1984. p. 158. [in Chinese].
8. Zhou SR. Study on weapons from shang to han dynasty in Hunan(I). Changsha: Yuelu Press; 1987. p. 87–93. [in Chinese].
9. Xiao ML. Preliminary discussion of bronze weapons of Wu and Yue State. Archaeol Cult Relics. 1996;06:16–28+15. [in Chinese].
10. Feng HJ. About the authenticity of "Chu Gong" Ge and a brief discussion on the weapons of Sichuan during the "Ba-Shu" period. Cult Relics. 1961;11:32 – 4+6. [in Chinese].
11. Tong EZ. Research on bronze Ge in southwest China. Acta Archaeologica Sinica. 1979;04:441–57. [in Chinese].
12. Li XQ. Discussion of Bronzes in Shu Style Unearthed at Xindu. Cult Relics. 1982;01:38–43. [in Chinese].
13. Zhang LJ, Zhao FS, Sun SY, Yin WZ. Research on the composition of and processing technology for copper objects unearthed at liulihe cemetery of Yan State in Beijing. Cult Relics. 2005;06:82–91 [in Chinese].
14. Han BH, Cui JF. A Scientific Analysis of the Bronzes from the Fenshuiling Cemetery of the Eastern Zhou Period in Changzhi, Shanxi. Archaeology. 2009;07:80–8. [in Chinese].
15. Li HC, Zhou ZQ, Liu Y, Wang Y, Wang ZK, Wang L, et al. Fighting and burial: the production of bronze weapons in the Shu state based on a case study of Xinghelu cemetery, Chengdu, China. Herit Sci. 2020;8:36.
16. Jia LJ, Zhao CC, Jin PJ, Yang XG, Ling X, Liu XM, et al. Preliminary analysis on a group of bronze weapons of Early Qin Period. J Northwest Univ (Natural Sci Edition). 2011;41(01):67–72. [in Chinese].
17. Luo WG, Song GD, Hu YQ, Chen D. Tentative determination of a special bronze material by multiple technological test on a xuan-liu dagger-axe from the Xujialing Site, the Eastern Zhou period, Henan Province, China. J Cult Herit. 2020;46:304–12.
18. Li HC, Zuo ZQ, Cui JF, Tian JB, Yang YD, Yi L, et al. Bronze production in the Ancient Chengdu Plains: a diachronic metallurgical perspective on a separate cultural region. J Cult Herit. 2020;43:26–36.
19. Chen D, Yang YD, Wang TY, Wang XT, Luo WG. Imitation or importation: Archaeometallurgical research on bronze dagger-axes from Shuangyuan Village Cemetery of the Shu State in the Eastern Zhou Dynasty. J Archaeol Sci Rep. 2021;40:103218.
20. Chen D, Yang YD, Wang TY, Wang XT, Luo WG. Improvement and integration: scientific analyses of willow-leaf shaped bronze swords excavated from the Shuangyuan Village Cemetery, Chengdu, China. Herit Sci. 2022;10:92.
21. Wang XT, Yang YD, Wang TY, Chen D, Luo WG. How can archaeological scientist integrate the typological and stylistic characteristics with scientific results: a case study on bronze spearheads unearthed from the Shuangyuan Village, Chengdu City, Southwest China. Curr Anal Chem. 2021;17(7):1044–53.
22. Wang XT, Yang YD, Wang TY, Luo WG. Subdivision of culture and resources: raw material transformation and cultural exchange reflected by bronze poleaxes from the Warring States sites in the Chengdu Plain. Archaeol Anthropol Sci. 2022;14:121.

23. Young ML, Casadio F, Schnepp S, Almer J, Haeffner DR, Dunand DC. Synchrotron X-ray diffraction and imaging of ancient Chinese bronzes. Appl Phys A. 2006;83:163–8.
24. Cattin F, Guénette-Beck B, Curdy P, Meisser N, Ansermet S, Hofmann B, et al. Provenance of Early Bronze Age metal artefacts in Western Switzerland using elemental and lead isotopic compositions and their possible relation with copper minerals of the nearby Valais. J Archaeol Sci. 2011;38(6):1221–33.
25. Ling J, Hjärthner-Holdar E, Grandin L, Stos-Gale Z, Kristiansen K, Melheim AL, et al. Moving metals IV: Swords, metal sources and trade networks in Bronze Age Europe. J Archaeol Sci Rep. 2019;26:101837.
26. Yang Y. Discussion of Types and Clan of Bronze ge with pattern of tiger in the Ba-Shu Culture. Sichuan Cult Relics. 2003;02:51–8. [in Chinese].
27. Wang TY, Chen HH, Yuan HB, Bai TY. The excavation of tomb M154 of the Eastern Zhou Dynasty cemetery at Shuangyuan Village in Chengdu City, Sichuan. Acta Archaeol Sin. 2020;03:399-403+-28+61-76 [in Chinese].
28. Shugar AN, Mass JL. Handheld XRF for art and archaeology. Leuven: Leuven University Press; 2012.
29. Zhu BQ. The mapping of geochemical provinces in China based on Pb isotopes. J Geochem Explor. 1995;55(1–3):171–81.
30. Gale NH, Stos-Gale ZA. Bronze Age copper sources in the Mediterranean: a new approach. Science. 1982;216(4541):11–9.
31. Albarède F, Desaulty AM, Blichert-Toft J. A geological perspective on the use of Pb isotopes in archaeometry. Archaeometry. 2012;54(5):853–67.
32. Gale NH, Stos-Gale Z. Lead isotope analyses applied to provenance studies. In: Ciliberto E, Spoto G, editors. Modern analytical methods in art and archaeology. Chicago: Wiley; 2000. p. 503–84.
33. Melheim L, Grandin L, Persson P-O, Billström K, Stos-Gale Z, Ling J, et al. Moving metals III: Possible origins for copper in Bronze Age Denmark based on lead isotopes and geochemistry. J Archaeol Sci. 2018;96:85–105.
34. Liu S, Chen KL, Rehren T, Mei JJ, Chen JL, Liu Y, et al. Did China import metals from Africa in the Bronze. Age? Archaeometry. 2018;60(1):105–17.
35. Chen KL, Mei JJ, Rehren T, Liu S, Yang W, Martinón-Torres M, et al. Hanzhong bronzes and highly radiogenic lead in Shang period China. J Archaeol Sci. 2019;101:131–9.
36. Wei G. The new developments of study on ores source and casting place of bronze vessel. China: University of Science and Technology of China; 2007. [in Chinese with English abstract].
37. Jin ZY. Lead Isotope Archaeology in China. Hefei: Press of University of Science and Technology of China; 2008. [in Chinese].
38. Wang YJ, Wei GF, Li Q, Zheng XP, Wang DC. Provenance of Zhou Dynasty bronze vessels unearthed from Zongyang County, Anhui Province, China: determined by lead isotopes and trace elements. Herit Sci. 2021;9:97.
39. Luo Z, Fan AC, Jin ZY, Liu L, Li Y, Fan ZY, et al. Scientific analysis and research on the Warring States bronze mirrors unearthed from Changsha Chu cemetery, Hunan province, China. Archaeometry. 2022;64(5):1187–201.
40. Nan PH. Research on bronze technology of Jin Kingdom in spring and autumn period. China: University of Science and Technology Beijing; 2017. [in Chinese with English abstract].
41. Jia LJ. Archaeological science research on bronzes of early Qin period. Washington: Northwest University; 2010. [in Chinese with English abstract].
42. Renfrew C, Bahn P. Archaeology: theories, methods and practice. London: Thames and Hudson; 2012.
43. Jiang ZH. Social transformation of ancient Shu of the Warring States Period: starting with cemetery analysis. Sichuan Cult Relics. 2008;02:53–9. [in Chinese].
44. Zhang ZM. The history of Chu. Beijing: Renmin University Press; 2010. [in Chinese].
45. Yuan YL. Circulation and distribution of bronzes of the Chu system. Beijing: Science Press; 2019. [in Chinese].
46. Zhou L, Jiang ZH. Preliminary discussion of the archaeological cultures of the spring-and-autumn period in the chengdu plain. Archaeology. 2020;02:102–11+2 [in Chinese].
47. Liu RL, Pollard AM. Asking different questions: highly radiogenic lead, mixing and recycling of metal and social status in the Chinese Bronze Age. Mineral Mag. 2022;86(4):677–87.
48. Zhang JH. The mineralography characteristics and its genetic significance of the Daliangzi Pb-Zn deposit in Huidong. Sichuan: Chengdu University of Technology; 2015. [in Chinese with English abstract].
49. Tu SY. The mineralography characteristics and its genetic significance of the tianbaoshan pb-zn deposit in Huili Sichuan. Sichuan: Chengdu University of Technology; 2014. [in Chinese with English abstract].
50. Li FY. Study on occurrence state and enrichment mechanism of dispersed elements in MVT deposits: a case study for the Tianbaoshan and Daliangzi Pb-Zn deposits in Sichuan Province. Sichuan: Chengdu University of Technology; 2003. [in Chinese with English abstract].
51. Zeng LG. Discussion on the genesis and prospecting direction of the Zebangou lead-zinc deposit in Ganluo. Sichuan: Chengdu University of Technology; 2006. [in Chinese with English abstract].
52. Zheng XZ. Geological features and genesis of WuSiHe Pb-Zn deposit. Sichuang: Chang'an University; 2012. [in Chinese with English abstract].
53. Lin XX. Study on dolomite and metallogenic regularity of lead-zinc deposits within the Sinian Dengying Formation in Hanyuan region. Sichuan: Chengdu University of Technology; 2014. [in Chinese with English abstract].
54. Sun HR, Zhou JX, Huang ZL, Fan HF, Ye L, Luo K, et al. The genetic relationship between Cu-and Zndominant mineralization in the Tianbaoshan deposit, Southwest China. Acta Petrologica Sinica. 2016;32(11):3407–17. [in Chinese].
55. Liu LL, Li FY, Cheng JH, Jiao HY. The distribution signatures of Pb-Zn deposit in China. The First National Mineral Exploration Conference 2021. p. 345 – 51. [in Chinese].
56. Liao H. Chu's forces change in the Western Jianghan Plain during the Eastern Zhou Dynasty. China: Wuhan University; 2017. [in Chinese with English abstract].
57. Huang XC, Chu GZ, Zhou J, Zhang CH, Wu CL, Huang HS, et al. Discussion on sources of the ore metals and ore-forming fluids. Geol Anhui. 1994;03:1–9. [in Chinese].
58. Wang CM, Xu YG, Wu GG, Zhang D, Yang L, Liu JG, et al. C, O, S and Pb isotopes characteristics and sources of the ore metals of the Lengshuikeng Ag-Pb-Zn ore field, Jiangxi. Earth Sci Front. 2011;18(01):179–93. [in Chinese].
59. Duan QF. The research of the metallogenic regularity of stratabound zinc-iead deposits from Sinian-Cambrian in the Western Hunan and Western Hubei. China: China University of Geosciences; 2014. [in Chinese with English abstract].
60. Huang B, Liu ZM, Duan BH, Li WD, Han PG. Essential features and prospecting direction of the Xudonggou lead-silver deposit in Zaoyang. Hubei Resour Environ Eng. 2015;29(S1):33–6. [in Chinese].
61. Li SM. Research on metallogenic regularities and prognosis of lead -zinc deposits in Northwestern Hunan. Beijing: China University of Geosciences (Beijing); 2016. [in Chinese with English abstract].
62. Zuo N. Study on Geological Characteristics and Genesis of the Huangshanling Pb-Zn-Mo Deposit in Chizhou. Anhui Province: China University of Mining and Technology; 2018. [in Chinese with English abstract].
63. Peng ZC, Sun WD, Huang YL, Zhang X, Liu SZ, Lu BS. A preliminary study on the destination of ancient mineral materials in Jiangxi, Hubei and Anhui. Archaeology. 1997;07:53–61. [in Chinese].
64. Liu GQ, Jin WQ, Zhang LX, Shen KF. Discussion on sources of metallogenetic materials of porphyry-type and hydrothermal copper deposits in northeastern Hunan Province. Geol Mineral Resour South China. 2001;1:40–7. [in Chinese].
65. Xu QL. Study on the Geological Characteristics and Ore Genesisof Tongkuangyu Copper Deposit in the Zhongtiaoshan Mountains. Shanxi Province: Jilin University; 2010. [in Chinese with English abstract].
66. Yang ZX, Mao JW, Chen MH, Cheng YB, Chang Y. Geology, geochemistry and genesis of Kafang copper deposit in Gejiu, Yunnan Province. Acta Petrol Sin. 2010;26:830–44.
67. Wang YB. Geochemical characteristics and genesis of the Tonglushan Cu-Fe deposit in Hubei Province. Beijing: China University of Geosciences (Beijing); 2012. [in Chinese with English abstract].
68. Xiang F, Meng FX, Jiang ZD, Wang XM, Zhang Q. Chemical characters of Dabao copper ore in Pengzhou and their relationship with Jinsha bronze wares of Chengdu, China. J Chengdu Univ Technol (Science Technol Edition). 2012;39(05):563–6. [in Chinese].

69. Wu XY. The Stable Isotope Geochemistry of the Liwu Copper Deposit in Jiulong. Sichuan: Chengdu University of Technology; 2016. [in Chinese with English abstract].
70. Liu WH, Liu JS, Luo JH, Pan JY, Niu YB, Yang WQ. Geological and Geochemical Features and Metallogenic mechanism of concealed copper deposit in Xueling mining area at the southern margin of Dongchuan, Yunnan, China. Contrib Geol Miner Resour Res. 2018;33(04):495–506. [in Chinese].
71. Wang CS, Wu CL, Zheng K, Wu D, Shan SF, Li X, et al. Ore-forming ages and sources of metallogenic materials of Fenghuangshan ore field in Tongling. Mineral Deposits. 2018;37(06):1195–216. [in Chinese].
72. Chen D, Yang YD, Du J, Tang X, Luo WG. Alloy ratio and raw material sourcing of Warring States Period bronze bracelets in Huili County, Southwest China by pXRF and MC-ICP-MS. Herit Sci. 2020;8:69.
73. Nørgaard HW, Portable. Portable, XRF on prehistoric bronze artefacts. Limitations and Use for the detection of bronze age metal workshops. Open Archaeol. 2017;3(1):101–22.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.