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RESEARCH

Scientific analysis of bronze objects of the first millennium to the second century BCE excavated from the Jiangkou Site, Pengshan, Sichuan

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Abstract
The Jiangkou site is located in the Min River channel in Pengshan County, Sichuan Province, China. One hundred and four bronze weapons and tools of the First millennium to the second century BCE were found throughout five excavations from 2016 to 2022. Typology and radiocarbon dating suggest that the bronze objects could be dated as early as the early Western Zhou dynasty. There is a great variety of object types, and some types have not been discovered before. In order to study the technical characteristics and the sources of raw materials of these bronze objects, through analysis of observation of the wood handles in the socket of the axes and alloy composition, we found that the wood handles were most likely sourced locally, and the people at that time consciously chose tree species suitable for tool and agricultural implement handles. Compositional analysis shows that Jiangkou bronzes have diachronic differences in alloy compositions, Western Zhou bronzes exhibited the highest copper content, with lower lead and tin content, but the copper content in the bronzes of the Eastern Zhou dynasty declined significantly, while lead and tin content increased to varying degrees. Furthermore, the alloy compositions of the Jiangkou bronzes were directly related to their forms and functions. The lead isotope study indicates that the copper materials used in the Western Zhou bronzes from Jiangkou were found to be diverse, including both Central Plains-type materials and local materials. Moreover, six bronzes displayed highly radiogenic lead. Compared with the Western Zhou bronzes, the lead isotope ratios of Eastern Zhou bronzes from Jiangkou site are more concentrated, some of the copper used in Eastern Zhou bronzes may have originated from local sources in Sichuan. Through scientific analysis, this research provides new understandings and a new perspective for the study of early bronzes in the Chengdu Plain.

Keywords Chinese bronzes · Zhou dynasty · Chengdu Plain · Lead isotope · Alloy composition · Wood science

Introduction

The Chengdu Plain is located in Southwest China, and it was the political and economic center during the pre-Qin period. It has developed unique cultures, represented by distinctive local features with regard to the style and decoration of bronzes. In the late Shang dynasty, fewer bronzes were excavated in the Chengdu Plain, but a large number of fine bronzes were concentrated in the sacrificial pits of the Sanxingdui site, where not only bronze ritual objects with the style of the Central Plains but also bronze figures, sacred trees and other sacrificial objects with local styles can be seen (Li et al. 2023). Combined with the relevant archaeological materials, it can be seen that theocracy was more prominent in this period, and social management tended to be centralized, but the social management hierarchy was not complex (Jiang 2015). From the Zhou dynasty onwards, the Chengdu Plain gradually transitioned from a theocratic state to a monarchy or military state, with obvious social stratification (Xiang 2017, 251). The number of bronze objects gradually increased during this period, forming a unique tradition of bronze use and ceremonial systems in the region

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(Yuan 2013). Meanwhile, bronze weapons with local styles, such as willow-leaf-shaped swords and pocket-shaped axes, began to be commonly buried in tombs, reflecting the intensification of wars and social conflicts during this period (Shi 2019). We suggest that the production and use of bronzes are reflections not only of the utilization of bronze resources and the development of the craft industry but also of the political system and cultural exchange. Thus, the study of bronzes excavated from the Chengdu Plain is of great importance in addressing these issues.

Recently, some scholars have carried out analyses of the alloy composition, lead isotopes, and trace elements of bronzes from the late Shang dynasty to the Warring States period (c.1000–221BC) in the Chengdu Plain. There have been plenty of discussions on the alloy composition and the provenance of copper and lead of the bronzes (Li et al. 2020b, 2022, 2020c, 2020a; Chen et al. 2021, 2022; Wang 2021, 2022). However, there is relatively little discussion about the mechanical performance of bronzes, and very few studies have focused on the relationship between alloy composition and the purposes of bronzes. In addition, no previous research has been done on the mechanical performance of bronze weapons and tools using methods of wood science due to the extremely poor preservation conditions of the wooden handle remains in the socket of axes. Meanwhile, the bronzes excavated in the Chengdu Plain mainly belong to the Eastern Zhou dynasty (770–256 BC) (Zhou, 2021). There are very few confirmed samples of Western Zhou dynasty (1046–771 BC) bronzes (Wang 1961; Fan and Hu 1981; Li et al. 2019b), and the associated archaeological sites are also extremely limited. Furthermore, most of the analyzed Western Zhou bronzes are fragmented, making it impossible to use archaeological typology to compare their stylistic features. This poses certain difficulties in the investigation of the production and circulation of Western Zhou bronzes in the Chengdu Plain and the discussion about the material changes of pre-Qin bronzes in the Chengdu Plain from a diachronic perspective. From 2019 to 2022, the Sichuan Provincial Institute of Archaeology and Cultural Relics carried out 3 excavations at the Jiangkou site and excavated 104 bronzes of the Western and Eastern Zhou dynasties that are well-preserved, including 63 axes, 19 swords, 9 dagger-axes, 7 spearheads, 4 knives, and 2 chisels. These bronzes exhibit notable characteristics in terms of abundance, variety of forms, and remarkable conditions of preservation. Furthermore, they encompass a significant temporal scope, encompassing a comprehensive array of bronze weaponry and tools that were prevalent during the Western and Eastern Zhou dynasties. Notably, the identification of a substantial quantity of Western Zhou bronzes represents a particularly exceptional occurrence, signifying a significant archaeological discovery of Western Zhou dynasty bronzes in the Chengdu Plain, following the notable findings at the Jinsha site and Zhuwajie site. It is an important addition to previous archaeological discoveries, both chronologically and geographically. This study will focus on the mechanical performance of bronze weapons and tools and the provenance of their raw materials.

Archaeological context

The Jiangkou site is located in the Min River channel in Pengshan County, Sichuan Province, China. The Nan River crosses the Chengdu Plain and then joins the tributary of the Min River at this location (Fig. 1). This site is approximately 60 km south of Chengdu and 20 km north of Meishan. Due to its unique geographical location, the area has been a water transport hub to and from Chengdu for generations. In addition to the gold and silver objects associated with the Zhang Xianzhong Jiangkou silver sinking incident (Liu et al. 2023), a large number of precious artifacts from different eras have been excavated at this site, the earliest of which are bronzes of the Western and Eastern Zhou Dynasties. Because of the unique environment in which the artifacts were deposited, East China Normal University has carried out an experimental archaeology of the deposition-forming process. The results of the experiment show that the deposition of the artifacts onto the riverbed is subjected to limited scouring by the current and will not be transported over long distances and that these artifacts should be dropped not far from their emerging positions. After restoring the objects to their emerging positions based on the coordinates of their emergence (Fig. 2b and c), it can be observed that there is a tendency for the number of bronzes to increase as they approach the upper reaches of the river. Most of the emerging locations of bronzes on the profile are directly related to the bedrock morphology, primarily concentrated within a northeast-southwest-oriented U-shaped chute. The U-shaped chute is close to the foothills where the river is deep and easy to navigate, and could have been a main transportation route throughout history. Thus, objects from different eras are distributed to a certain degree within the U-shaped chute (Fig. 2a), but their distribution locations are not the same. Bronzes of the western and Eastern Zhou dynasties from the Jiangkou site were predominantly excavated mainly at the base of the U-shaped chute, alongside artifacts of clearly earlier periods, which indicates that the deposit time of these bronzes is relatively early. Some of the bronzes still have wood handles remaining in the socket of the axes. Three wood handle samples have been sent to the BETA Laboratory for radiocarbon dating test, providing an absolute date for the bronzes possibly no later than the transition period between the Shang and Zhou dynasties (Table 1). Due to the large number of the excavated

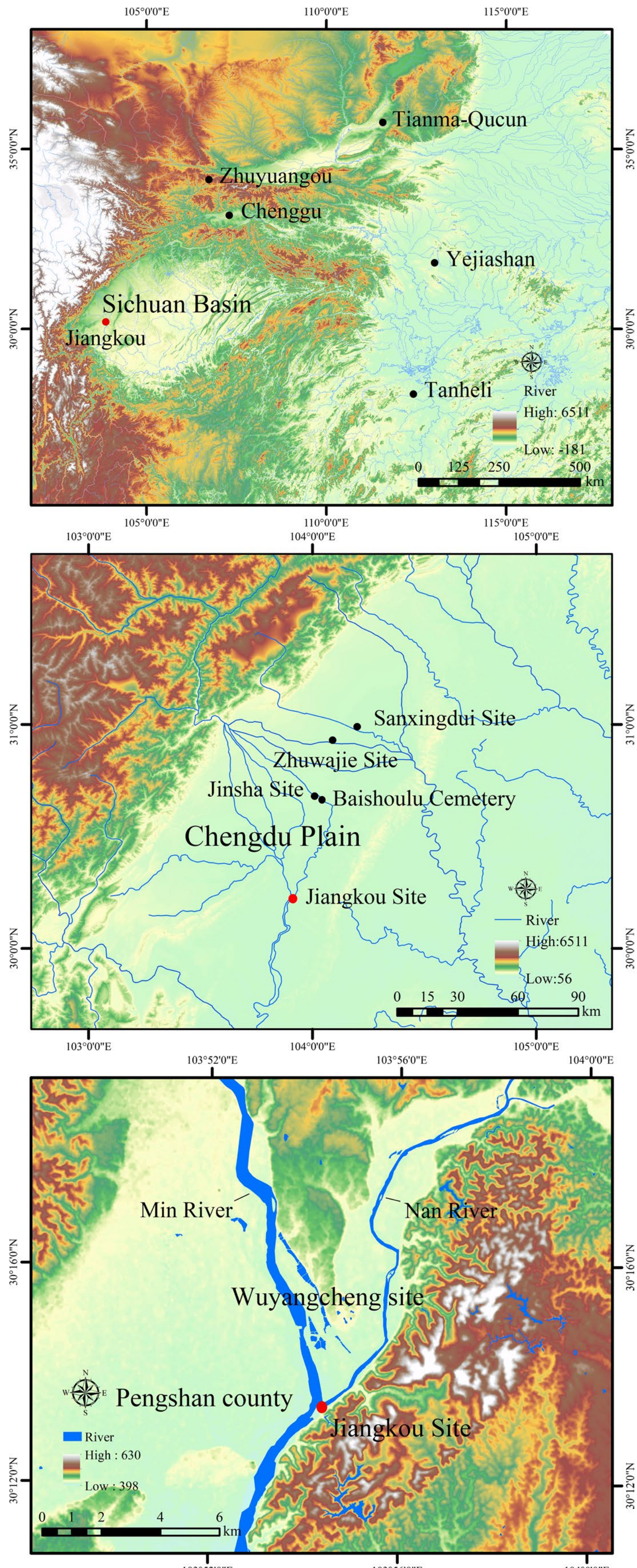

Fig. 1 Location of the Jiangkou site (map: Qiu Tian)

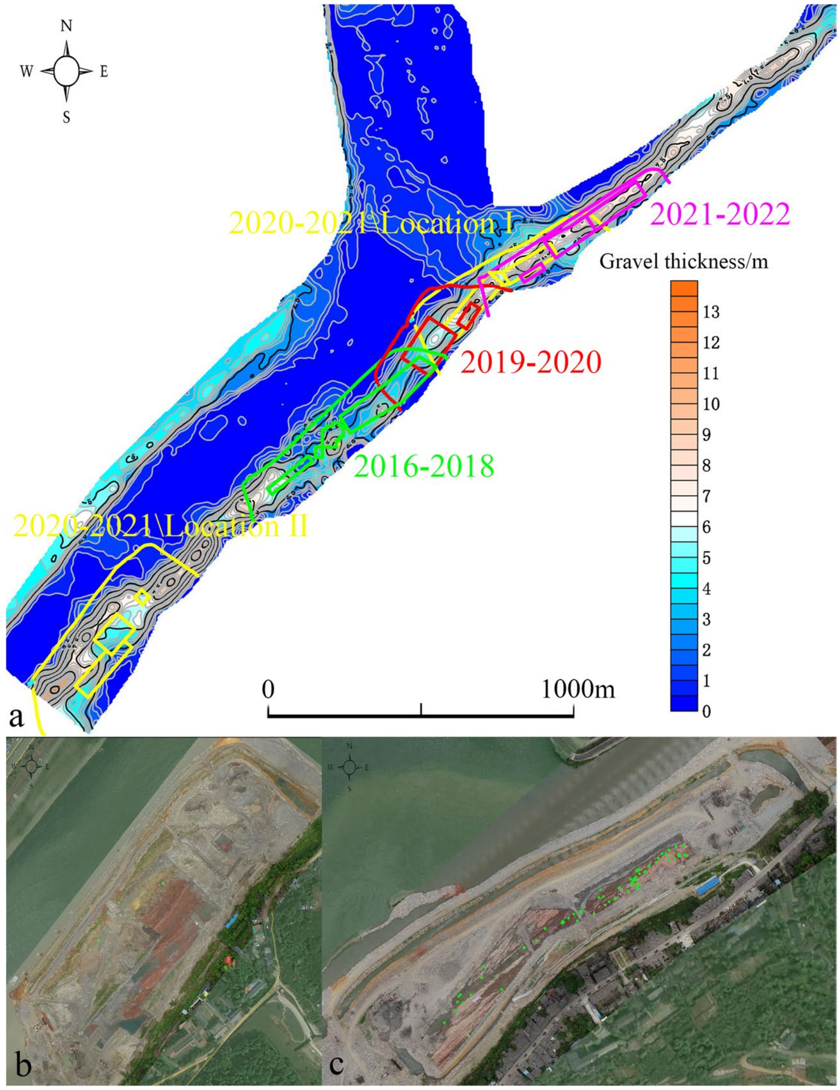

Fig. 2 **a** Location of the Jiangkou site excavation area over the years. **b** Location of the bronzes excavated from location II from 2020 to 2021. **c** Location of the bronzes excavated from location I from 2020 to 2021 (photos: Liu Zhiyan)

Table 1 Radiocarbon dating results for wood handles remaining in the socket of the axes

Beta Lab No	Lab No	Excavated No	Sample name	C14 (BP)	Calibrated
Beta—595,306	PJ22	2020PJIVT5754:29	axe	2830 ± 30	1056–904 BC (92.2%)
					1082–1068 BC (1.8%)
					1107–1096 BC (1.4%)
Beta—595,307	PJ23	2020PJIT4035:48	axe	2730 ± 30	928–810 BC (95.4%)
Beta—595,308	PJ05	2020PJIVT2336:9	axe	2810 ± 30	1050–897 BC (93.2%)
					871–849 BC (2.2%)

(Calibration: BetaCal4.20)

bronzes, their wide distribution across the site, and the dating spanning some eight hundred years, we believe that these bronzes were deposited at different times. On the other hand, approximately 2 km northwest of the Jiangkou site is the Wuyangcheng site, which is an ancient city site dated from the Warring States period (475–221 BC) to the Jin dynasty (266–420 AD) (Yi et al. 2014).

Materials and methods

As the deposit environment at the Jiangkou site is unique, it is not possible to determine the age of the excavated objects based on the deposit units and coexistence, therefore this research compares the bronze weapons and tools excavated from the Jiangkou site with previously published archaeological reports of bronze objects that have clear chronological information. At present, there are abundant relics excavated from Western and Eastern Zhou sites in the Chengdu Plain. Typological studies have basically sorted out the chronological system and developmental sequence of the bronzes of the Western and Eastern Zhou dynasties in this area (Xiang 2017, Zhou, 2021), providing a theoretical basis for determining the age of the Jiangkou bronzes through comparative analysis of their types. However, given the limitations of this method in providing absolute dating, the findings of this study were further validated using radiocarbon dating of wood handles found in the socket of the bronze axes. Taking PJ22 and PJ23 as examples, bronze axes of the same type were also excavated at the Zhuwajie site, which is a bronze hoard of the Western Zhou dynasty (Fan and Hu 1981). This type of bronze axe is normally associated with the Western Zhou dynasty (Li 2002), which aligns with the radiocarbon dating results. Thus, employing the typological method based on extensive reference to published archaeological reports and research appears feasible for dating the bronzes. Utilizing this approach, the 104 complete bronzes are divided into two phases: the Western Zhou dynasty and the Eastern Zhou dynasty (Fig. 3). Among them, 27 bronzes are attributed to the Western Zhou dynasty, 63 to the Eastern Zhou dynasty, and the remaining 14 bronzes could not be precisely dated due to the absence of comparative materials.

The mechanical performance of the bronze weapons and tools are directly related to the wood handles that remained in the socket of the bronze axes and the alloy composition of the bronzes. The bronzes excavated from the Jiangkou site contained remnants of wood handles, which provides an opportunity for further research into the material selection characteristics of the wood handles for bronze weapons and tools. We selected 12 weapons or tools from different time periods, each with distinctive identifying features, and took samples of the wood handles inside the bronzes. Using a manual slicing method, we cut out transverse, radial, and tangential sections The sections were then dehydrated, mounted on slides, and transformed into permanent optical sections. We observed and identified the tree species and inferred the material sourcing methods using a LEICA DM4P polarizing microscope.

In terms of alloy composition, as the bronzes excavated from the Jiangkou site are well preserved, most of them have a surface free from rust. Combined with previous research on bronzes in southwest China (Ma et al. 2018; Wang et al. 2022), we used a handheld X-ray fluorescence spectrometer (XRF-NitonXL3t) in the common metal mode to analyze the chemical composition of 104 unearthed bronzes of the Western and Eastern Zhou dynasties. For each artifact, non-corroded areas on the body were selected for analysis, with 3–7 measurement points selected for each sample, and the signal collection time was 30 s. The final results were averaged, and all data have been uploaded as supplementary file. Considering that handheld XRF is not good at detecting trace elements, we only selected four elements, Cu, Sn, Pb, and Fe, for publication in the paper, iron is often present as an impurity and is therefore generally low in content, and some of the higher iron content data in the manuscript probably reflect environmental contamination of the corrosion products during deposition (Orfanou and Rehren 2015). In order to analyze the data quantitatively with more care, after referring to the results of the alloy compositional analysis of previous bronzes from the Chengdu Plain, the data with higher iron content (> 10%) were excluded from the quantitative analysis. Based on understanding the types of alloys, the relationship between types, shapes, and chemical composition, was examined to analyze the variations in alloy composition across different periods.

In order to further understand the provenance of raw materials and circulation of bronzes from the Jiangkou site, this study conducted lead isotope analysis on 47 different types of bronze weapons and tools from various periods. Samples were taken after removing rust and other impurities. The lead isotope composition testing was performed using the Neptune Plus multicollector inductively coupled plasma mass spectrometer (MC-ICP-MS) from Thermo Fisher Scientific. Prior to the sample analysis, the instrument parameters of the Neptune Plus were optimized using a standard solution of NIST 981 at a concentration of 200 μg/L. This optimization included parameters related to the plasma source (such as skimmer cone position and carrier gas flow rate) and ion lens settings to achieve maximum sensitivity. The chemically separated samples were introduced into the mass spectrometer using a 2% HNO3 solution, ensuring that the signal intensity of 208Pb + was around 8 V (corresponding to a Pb concentration of approximately 200 μg/L), utilizing a free nebulizer for sample introduction. All the samples underwent column separation. After the completion of each sample measurement, the sample introduction system was cleaned with a 2% HNO3 solution before proceeding to the next sample. The lead isotope ratios were normalized using the exponential law with a 203Tl/205Tl ratio of 0.418922 for calibration purposes. NBS-981 standard was run with the samples yielding the following values (2SD, $n = 33$): $^{206}Pb/^{204}Pb = 16.9274 \pm 0.0011$, $^{207}Pb/^{204}Pb = 15.4810 \pm 0.0009$, $^{208}Pb/^{204}Pb = 36.6666 \pm 0.0028$.

Results and discussion

Wood handle analysis

For bronze weapons and tools with sockets to attach handles, the wood handle is an important component, for the technique and material of the handle directly affect the quality

Fig. 3 Western and Eastern Zhou bronzes from the Jiangkou site (photos: Zhang Ruojing)

and effectiveness of the weapons and tools. Out of the 14 wood handles, 2 pieces could not be identified, 5 pieces had incomplete preservation of identifying features and were only identified as diffuse-porous wood. Seven pieces with clear identifying features belonging to the genera *Osmanthus* sp. / *Olea* sp. (Osmanthus/Olive), *Adina* spp. (Waterberry) and *Quercus* sp. (Oak) (Cheng et al. 1992, 290–299, 483–485, 548–549) (Table 2), the identifying features are as follows:

Osmanthus sp. / *Olea* sp. (Osmanthus/Olive)—Growth ring indistinct. Diffuse porous. Pores solitary and in short radial multiples of 2 or more forming into clusters, arranged in diagonal columns or an oblique to dendritic pattern, not limited by growth rings. Helical thickenings are distinct. Perforations simple. Terminal and Vasicentric parenchyma cells are numerous. Rays heterogeneous, uni- to 3 seriate (Figs. 4 and 1a–c).

Adina sp. (Waterberry)—Growth rings distinct. Diffuse porous. Pores solitary and in short radial multiples of 2 or more. Perforations simple. Rays mostly uni- to 2 seriate, heterogeneous, with numerous rows of upright marginal cells and few rows of procumbent central cells (Figs. 4 and 2a–c).

Quercus sp. (Oak)—Growth rings distinct. Ring porous. Earlywood pores are large, and almost exclusively solitary. Latewood pores are small and solitary, following a radial arrangement. Perforations simple. Apotracheal banded parenchyma cells are numerous. Rays are homogeneous, of two distinct types, uni- and multiseriate. Multiseriate rays wide to many cells, separated by narrow rays (Figs. 4 and 3a–c).

The Osmanthus genus and Olea genus exhibit high strength and moderate impact toughness. They are easy to work with using sawing and planning techniques, resulting in a smooth surface. They are resistant to decay but not to termite infestation. The Oak genus has high strength, high impact toughness, and strong resistance to both ants and decay. The Adina genus demonstrates high strength, moderate impact toughness, and strong resistance to both ants and decay (Cheng 1985, 1072, 1103, 1104). In terms of wood science, all three types of wood are suitable materials for agricultural and tool handles. According to the distribution of forestry resources in China, these tree species are found in the Sichuan Province (Sichaun 1992, 71, 69), and there are also discoveries of the Adina genus and the Oak genus at the Baodun site, which dates back approximately 4500–4000 years (Yan et al. 2016). Considering that wood handles are typically made from locally available materials, we can infer that the wood handles of these 7 bronzes are more likely to have been sourced locally.

The results of the wood identification suggest that that the axes and chisels from the Jiangkou site have all chosen tree species suitable for the handles of agricultural and tool implements, which meets the need for mechanical performance and corrosion resistance. It reflects the fact that the people of this period already had some knowledge of the local forest resources and wood materials, and possessed the ability to adapt to local conditions and utilize appropriate materials. The similarity in the species of the wood handles remained in the socket of the bronzes from different time periods demonstrates the stability and continuity in material selection.

Alloying techniques

There are variations in how to determine whether humans intentionally added lead and tin to bronzes in different regions. This research follows the standard commonly used in the study of ancient Chinese bronzes, using 2% as the threshold for determining whether lead and tin are deliberately added (Cui and Wu 2008, 48) and for identifying their alloy type. Among the 104 bronzes excavated from the Jiangkou site, there are 10 copper objects, accounting for 9.62% of the total; 64 tin bronzes, accounting for 61.54%; and 30 lead–tin bronzes, accounting for 28.55%. The scatter plot shows that the data is characterized by high levels

Table 2 Results of the wood species identification of the wood handles

Excavated No	Date	Identification results	Latin name
2020PJIT5754:88	Western Zhou	Diffuse-porus wood(B)	
2020PJIT5955:60	Western Zhou	Diffuse-porus wood(A)	
2020PJIT6159:31	Western Zhou	Diffuse-porus wood(B)	
2020PJIT4035:48	Western Zhou	Osmanthus./Olea	*Osmanthus/Olea*
2020PJIVT2336:9	Western Zhou	Diffuse-porus wood(B)	
2020PJIT5042:23	Eastern Zhou	Diffuse-porus wood(C)	
2020PJIT5751:5	Eastern Zhou	Oak	*Quercus*
2020PJIT4539:178	Eastern Zhou	Oak	*Quercus*
2020PJIT5346:45	Eastern Zhou	Osmanthus./Olea	*Osmanthus/Olea*
2020PJIT4737:12	Eastern Zhou	Adina	*Adina*
2020PJIT4334:13	Eastern Zhou	Adina	*Adina*
2020PJIT6160:31	Unknown	Osmanthus./Olea	*Osmanthus/Olea*

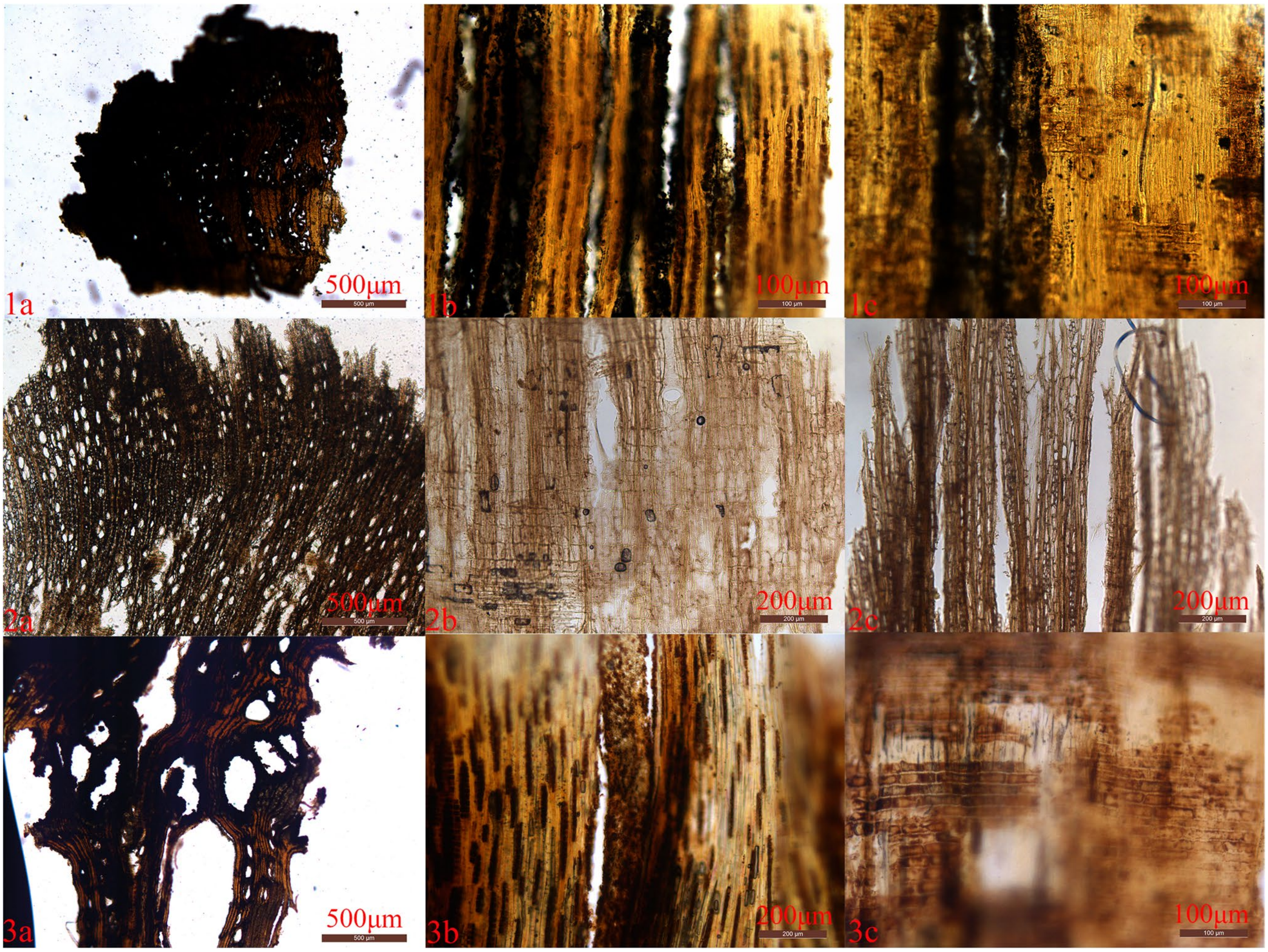

Fig. 4 Photomicrographs of the wood handles of some of the bronzes from the Jiangkou site. 1. *Osmanthus* sp./*Olea* sp. (2020PJIT4035:48) 2. *Adina* sp. (2020PJIT4334:13) 3. *Quercus* sp. (2020PJIT4539:178) (**a**, **b**, and **c** represent transverse, radial, and chordal sections respectively) (photos: Yan Xue)

of copper and tin (Table 3) (Fig. 5). Furthermore, the lead content of the bronzes is generally low. This distribution pattern is likely directly related to the function of bronze weapons and tools, as the addition of lead significantly reduces the strength and extensibility of the bronze (Li et al. 1989), thereby affecting the mechanical performance of the weapons and tools. However, the appropriate addition of tin not only lowers the melting point of the bronze, but also increases its hardness and tensile strength (Scott 1992, 82–83; Hauptmann 2020, 399–400).

There are also chronological differences in the alloying techniques of the bronzes (Fig. 5). In the Western Zhou dynasty bronzes, there are a total of 9 copper objects, accounting for 33.33% of the total; 14 tin bronzes, accounting for 51.85%; and 4 lead–tin bronzes, accounting for 14.81%. The scatter plot also indicates that the bronzes of this period have the highest copper content, with relatively low levels of lead and tin. Nevertheless, there are a small number of bronzes with outstanding tin content, including the dagger axes without *hu* (胡) (PJ27, PJ12), tongue-shaped axes (PJ03, PJ23, PJ22), and willow-leaf-shaped swords (PJ49), with tin contents ranging from 10 to 20%, all of which are well-cast and exquisitely decorated. Some of them, such as the dagger axes without *hu* and tongue-shaped axes are also found at the Zhuwajie site, Peng County (Wang 1961; Fan and Hu 1981), indicating a higher status and potential ceremonial nature rather than being ordinary bronze weapons or tools (Dai 2011). In addition, it is worth noting that all 6 red bronzes are from the Western Zhou dynasty, indicating a certain proportion of copper objects during this period. A similar phenomenon occurs at the Jinsha site of the same period (Li et al. 2019b; Jin 2008), which suggests that this is not an isolated case. In the Eastern Zhou dynasty bronzes excavated from the Jiangkou site, there are 38 tin bronzes, accounting for 59.38%, and 25 lead–tin bronzes, accounting for 40.63%. The scatter plot demonstrates a significant

Table 3 Alloy composition and lead isotope ratios of the Jiangkou bronzes

Lab No	Excavated No	Type	Alloy types	Cu	Sn	Pb	Fe	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Date
PJ01	2020PJIT5450:8	Axe	Cu–Sn	93.07	6.20	0.06	0.53	18.5514	15.7123	38.7568	Unknown
PJ02	2020PJIT5956:24	Axe	Cu–Sn	84.38	14.60	0.14	0.57	18.5947	15.6428	38.8536	Unknown
PJ03	2020PJIT6159:31	Axe	Cu–Sn	92.93	6.04	0.60	0.09	18.5888	15.6775	38.9338	Western Zhou Dynasty
PJ04	2020PJIT5552:32	Axe	Cu–Sn	92.27	6.44	0.27	0.88	18.4908	15.6273	38.6166	Unknown
PJ05	2020PJIVT2336:9	Axe	Cu–Sn	96.80	2.65	0.30	0.17	18.0947	15.6532	38.1568	Western Zhou Dynasty
PJ06	2020PJIT6260:13	Axe	Cu–Sn	93.80	0.82	0.67	4.62	18.7387	15.7053	39.1003	Unknown
PJ07	2020PJIVT3748:1	Axe	Cu–Sn	88.80	8.98	1.49	0.53	18.2387	15.6842	38.6171	Unknown
PJ08	2020PJIT6160:14	Axe	Cu–Sn	89.48	8.07	0.18	1.98	19.3737	15.8023	39.5436	Western Zhou Dynasty
PJ09	2020PJIT5855:130	Axe	Cu–Sn–Pb	80.36	13.62	3.22	2.35	18.2384	15.6347	38.5757	Western Zhou Dynasty
PJ10	2020PJIT5755:146	Axe	Cu–Sn	87.54	10.34	0.62	1.18	18.2838	15.6478	38.6297	Eastern Zhou Dynasty
PJ11	2020PJIT6160:12	Axe	Cu–Sn	93.71	4.58	0.05	1.56	18.8143	15.6824	39.1075	Eastern Zhou Dynasty
PJ12	2020PJIT5955:60	Axe	Cu–Sn	86.20	11.24	1.41	0.80	17.7900	15.5715	38.1203	Western Zhou Dynasty
PJ13	2020PJIT5346:89	Axe	Cu	93.59	0.15	0.35	0.06	16.7564	15.2924	36.8574	Western Zhou Dynasty
PJ14	2020PJIT4737:12	Axe	Cu–Sn	85.09	12.34	1.61	0.63	18.5630	15.6785	38.9499	Eastern Zhou Dynasty
PJ15	2020PJIT5652:15	Axe	Cu–Sn	90.94	7.88	0.81	0.17	18.5700	15.7127	38.9434	Unknown
PJ16	2020PJIT5754:88	Axe	Cu–Sn	93.23	5.09	1.19	0.29	22.2378	16.1982	42.8246	Western Zhou Dynasty
PJ17	2020PJIT5551:74	Axe	Cu–Sn–Pb	83.96	3.92	10.96	0.62	17.9741	15.5659	38.2280	Unknown
PJ18	2020PJIT5042:23	Axe	Cu–Sn	93.99	4.17	1.58	0.10	18.0135	15.5754	38.2821	Eastern Zhou Dynasty
PJ19	2020PJIT5650:14	Axe	Cu–Sn	83.83	14.05	0.34	1.43	18.4075	15.6525	38.7098	Eastern Zhou Dynasty
PJ20	2020PJIT5244:21	Axe	Cu–Sn	68.90	18.43	0.84	11.27	18.3939	15.6500	38.6978	Eastern Zhou Dynasty
PJ21	2020PJIT6059:63	Axe	Cu–Sn	90.97	7.85	0.21	0.85	18.0683	15.6544	38.0900	Eastern Zhou Dynasty
PJ22	2020PJIT5754:29	Axe	Cu–Sn	85.05	12.94	0.91	0.85	18.6339	15.7156	38.9752	Western Zhou Dynasty
PJ23	2020PJIT4035:48	Axe	Cu–Sn–Pb	79.43	15.23	3.65	1.27	18.6311	15.7151	38.9736	Western Zhou Dynasty
PJ24	2020PJIT5855:63	Axe	Cu–Sn	94.99	3.69	0.56	0.26	22.0862	16.1487	42.5699	Western Zhou Dynasty
PJ25	2020PJIT6061:10	Axe	Cu–Sn	93.05	5.88	0.76	0.16	18.6737	15.7026	39.0708	Unknown
PJ27	2020PJIT4435:13	Dagger-axe	Cu–Sn	78.11	16.66	0.11	4.79	18.1014	15.5975	38.4445	Western Zhou Dynasty
PJ28	2020PJIT5448:148	Spearhead	Cu–Sn–Pb	79.76	13.42	4.65	1.50	18.1167	15.6160	38.6928	Eastern Zhou Dynasty
PJ29	2020PJIT5855:129	Sword	Cu–Sn	83.65	15.20	0.33	0.57	18.4711	15.7014	38.8456	Eastern Zhou Dynasty
PJ30	2020PJIT5956:75	Dagger-axe	Cu	94.30	0.01	0.03	0.28	18.9283	15.6947	39.2259	Western Zhou Dynasty
PJ31	2020PJIT5956:76	Sword	Cu–Sn	75.77	16.23	0.35	7.27	18.0361	15.5948	38.4530	Eastern Zhou Dynasty
PJ32	2020PJIT4534:11	Sword	Cu–Sn–Pb	81.14	14.11	3.01	1.31	18.5706	15.7085	38.9217	Eastern Zhou Dynasty
PJ33	2020PJIT4434:3	Sword	Cu–Sn–Pb	57.94	16.66	4.41	3.64	18.4909	15.6782	38.7965	Eastern Zhou Dynasty
PJ34	2020PJIT5755:73	Dagger-axe	Cu–Sn	75.00	14.72	1.69	7.06	18.0967	15.5847	38.4465	Western Zhou Dynasty
PJ35	2020PJIT5346:54	Dagger-axe	Cu–Sn	87.69	10.25	0.91	0.80	21.6139	16.0311	41.9248	Western Zhou Dynasty
PJ36	2020PJIT5448:108	Dagger-axe	Cu–Sn	80.31	16.98	0.78	1.70	18.6243	15.7017	38.9400	Eastern Zhou Dynasty
PJ37	2020PJIT5955:55	Spearhead	Cu–Sn	86.88	11.51	0.78	0.59	18.2282	15.6000	38.4885	Eastern Zhou Dynasty

Table 3 (continued)

Lab No	Excavated No	Type	Alloy types	Cu	Sn	Pb	Fe	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Date
PJ38	2020PJIT5855:113	Spearhead	Cu–Sn	91.66	7.52	0.39	0.34	22.5473	16.2165	43.3032	Western Zhou Dynasty
PJ39	2020PJIT5652:61	Spearhead	Cu–Sn–Pb	72.89	17.69	6.65	2.24	17.5684	15.5290	37.8910	Eastern Zhou Dynasty
PJ40	2020PJIT5448:166	Knife	Cu–Sn–Pb	66.42	21.82	7.47	3.76	18.3334	15.6353	38.6008	Eastern Zhou Dynasty
PJ41	2020PJIT6158:24	Knife	Cu–Sn	59.16	26.27	0.64	13.48	18.5757	15.6834	38.9339	Eastern Zhou Dynasty
PJ42	2020PJIT6058:86	Sword	Cu–Sn	59.38	19.79	0.29	19.99	18.4014	15.6725	38.6993	Eastern Zhou Dynasty
PJ43	2020PJIT5347:61	Axe	Cu–Sn	75.26	17.25	1.98	4.76	17.8749	15.5701	38.4072	Eastern Zhou Dynasty
PJ44	2020PJIT5348:166	Sword	Cu–Sn	83.23	12.98	0.84	2.49	18.2360	15.6692	38.4273	Unknown
PJ47	2021PJIT7076:56	Axe	Cu–Sn–Pb	85.34	7.52	4.89	0.62	22.7106	16.2539	43.6569	Western Zhou Dynasty
PJ48	2021PJIT7076:46	Dagger-axe	Cu–Sn	84.91	12.05	1.56	0.30	17.9912	15.5815	38.2698	Western Zhou Dynasty
PJ49	2021PJIT7076:47	Sword	Cu–Sn	64.61	20.49	0.28	10.52	21.8736	16.0935	42.1704	Western Zhou Dynasty

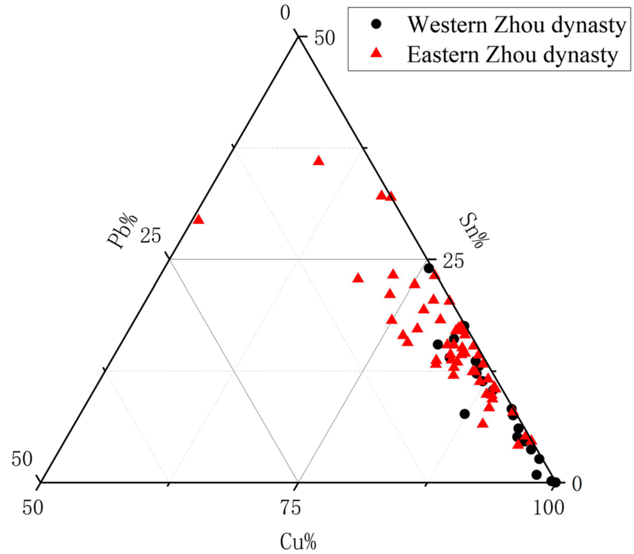

Fig. 5 Alloy composition of bronzes from different dates at the Jiangkou site (diagrams: Qiu Tian)

upward shift in the range of the alloy composition, a significant decrease in copper content, and varying degrees of increase in lead and tin content, particularly a noticeable increase in tin content. Notable tin content is found in such objects as the ring-headed knives (PJ41) and the willow-leaf-shaped swords (PJ29, PJ31, PJ32, PJ33, PJ42).

The characteristics of the alloy composition of the excavated bronzes are not only influenced by the chronology but also closely related to the artifact types. Taking axes, and swords as examples, which are the most frequently excavated artifacts from the Jiangkou site, we compared the main elemental compositions of swords, single-sided and double-sided blade axes. We found that the differences in lead content between the three were minimal and lead was concentrated in the same area. However, there are significant differences in copper and tin content (Fig. 6), which are directly related to the functional differences of these three types of objects. Some scholars have discussed the naming and functions of double-sided and single-sided blades based on archaeological and documentary materials, suggesting that double-sided blades are mainly used for splitting and chopping, while single-sided blades are primarily used for flattening wood (Zhu 1995, 299–300; Guo 1963, 19). These functional differences are also reflected in historical documents (Liu 2016, 94, 96). From a materials science perspective, the Brinell hardness of pure copper is about 50HB. However, when the tin content exceeds 15%, its hardness increases sharply with increasing tin content, and when the tin content reaches 25%, the Brinell hardness can reach 300HB (Zhu 1995, 520–521). The single-sided blade axes excavated from the Jiangkou site exhibit higher copper content and lower tin content, which may reflect that

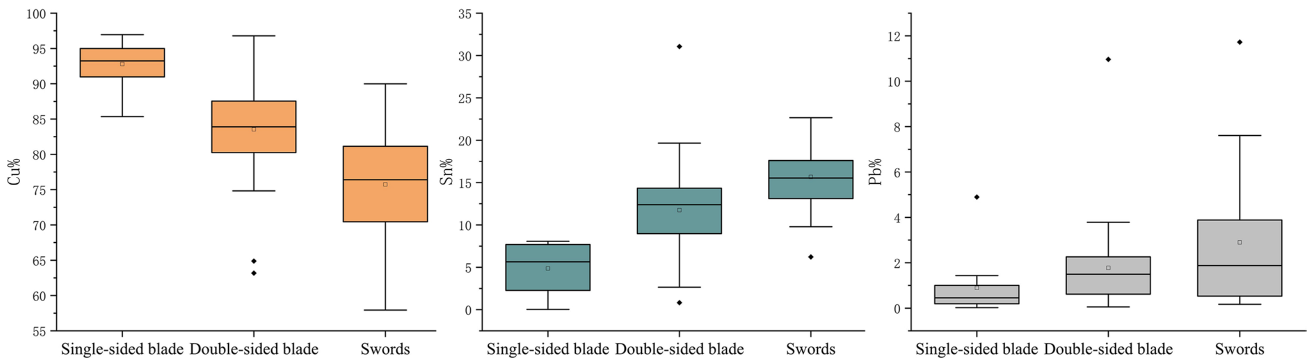

Fig. 6 Comparison of the alloy composition of different types of bronzes from the Jiangkou site (diagrams: Qiu Tian)

these types of artifacts do not require high strength and hardness. However, the double-sided blade axes, as they were mostly used for splitting and chopping, required a certain degree of hardness and strength of the bronzes and therefore had a significantly higher tin content compared to the single-sided counterparts. In contrast, the bronze swords and knives excavated from the Jiangkou site have the highest tin content, with some reaching over 20%. They belong to the typical high-tin bronze category, which also exhibits similar phenomena in bronze swords excavated from the Sichuan Basin and other areas (Chen et al. 2017, 953–960). These copper-tin alloys are quite close to the β-phase equilibrium values in the bronze system (Scott 1992, 25–27). They not only have a golden color but also possess higher hardness, providing the ability to resist deformation without breaking. This reflects the requirements of knives and swords as weapons for hardness, strength, and toughness.

Lead isotope analysis

There has been some controversy among scholars over the types of elements reflected in lead isotope data from archaeological copper alloys (Cui and Wu 2008, 48). Most scholars believe that the copper content in ancient Chinese tin bronze is much higher than the tin content, and the addition of tin does not affect the lead isotope ratio of the copper in the bronze. Therefore, when the lead content is relatively low, the lead isotope ratio in tin bronze is determined by the copper material (Ling et al. 2013), while in lead–tin bronze, the lead isotope ratio is determined by the lead material (Ying et al. 2020). Among the 47 lead isotope samples analyzed in this research, 2 were red copper bronzes, 35 tin bronzes, and 10 lead–tin bronzes, of which the lead content in tin bronzes was mostly below 1%. By comparing the lead isotope data from different alloy types (Fig. 7a and b), we found that the lead isotope ratio distribution range of tin bronze basically covers that of lead–tin bronze, indicating that the addition of lead material has a minimal influence on the lead isotope ratios. Therefore, based on the alloy characteristics of the bronzes excavated from the Jiangkou site, this research focuses on the source of the copper material through the analysis of lead isotopes. Meanwhile, considering the remelting of bronzes in this period and the possible existence of Cu–Pb symbiotic ores in the source of ore (Zhang and Chen 2017; Sun et al. 2023), lead–tin bronzes are compared with tin-bronze and copper objects together.

The distribution characteristics of lead isotope in bronzes during different stages of the Western and Eastern Zhou dynasties are not identical (Fig. 7c and d). Among them, Western Zhou bronzes have the widest distribution, overlapping to a certain degree with all bronzes from other periods. Based on their data distribution characteristics, they can be roughly divided into three groups (Fig. 8a and b).

Group I of Western Zhou bronzes contains a total of 6 samples, characterized by lead isotope ratios of $^{206}Pb/^{204}Pb > 21.0$, $^{207}Pb/^{204}Pb > 16.0$, and $^{208}Pb/^{204}Pb > 41.0$. Previous studies have suggested that data with the same characteristics have been identified as having a highly radiogenic lead component (Cui and Wu 2008, 15). Among the 6 bronzes with highly radiogenic lead, only 1 is a lead–tin bronze, while the others are tin bronzes. By comparing the bronzes with copper ore data, scholars concluded that the highly radiogenic lead in these low-lead bronzes may come from copper ore with varying lead content (Liu et al. 2018). However, there has been a significant debate among scholars regarding the provenance of the raw materials for such highly radiogenic lead. Various theories have been proposed, including the Yunnan theory (Jin et al. 2017), the Middle Yangtze River theory (Peng et al. 1999), the Qinling theory (Chen et al. 2019), the Central Plains theory (Jin et al. 2020), and the multi-location source theory (Zhu and Chang 2002). In terms of chronology, highly radiogenic lead was prevalent from the Upper Erligang Culture up to the Yinxu Phase II (c.1500–1200 BC), and was widely found at various sites outside the Central Plains. However, the use of this particular material declined significantly in the Western Zhou dynasty (Liu and Pollard 2022). Therefore, the available lead isotope data for Western Zhou

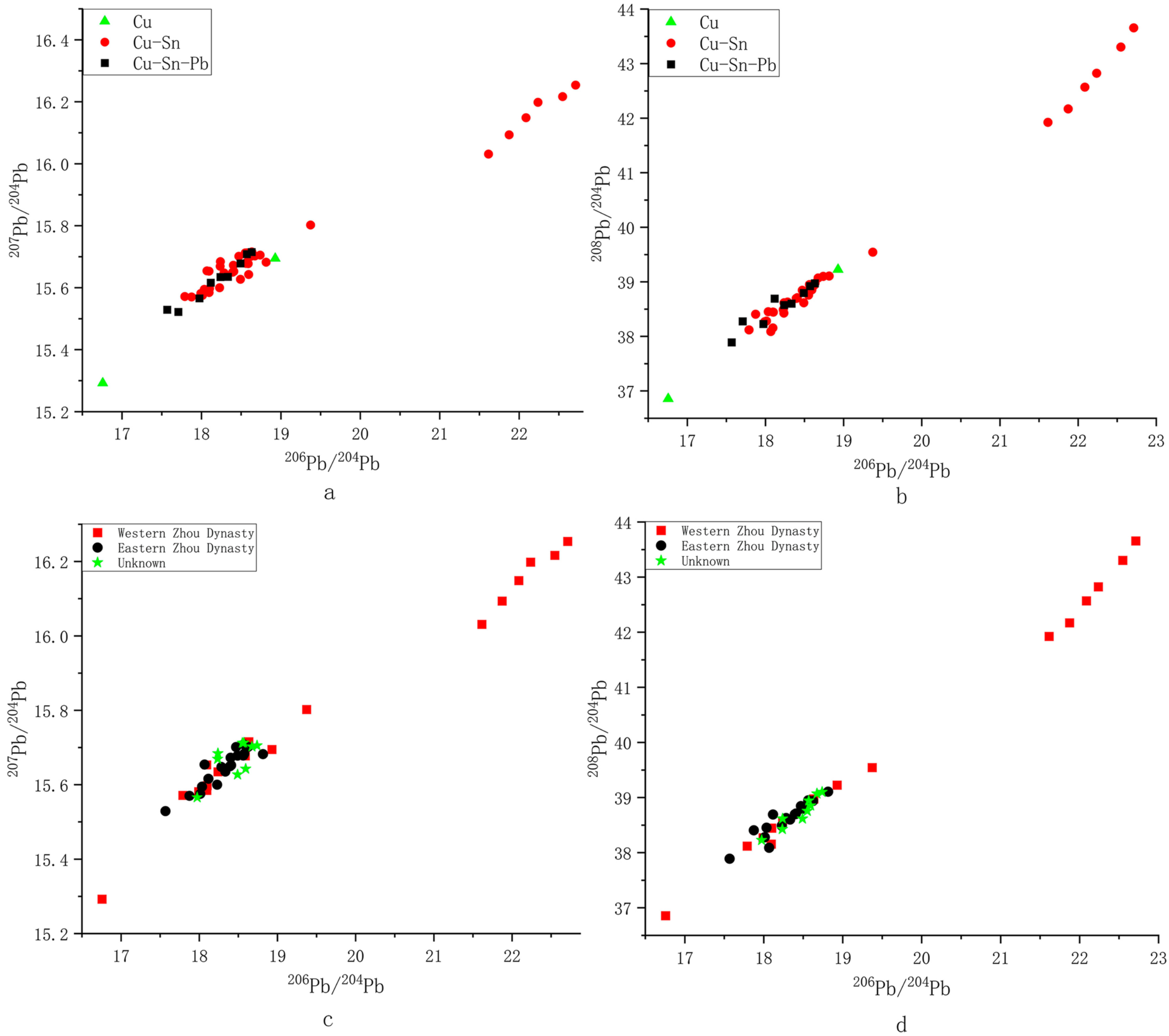

Fig. 7 **a b**: Plots of lead isotope ratios of different alloy types of bronzes from the Jiangkou site. **c**, **d**: Plots of lead isotope ratios of bronzes from different eras at the Jiangkou site (diagrams: Qiu Tian)

bronzes are relatively limited. By comparing the lead isotope data of the Jiangkou bronzes with those from other Western Zhou regions, such as Tanheli, Tianma-Qucun, and Yejiashan (Ma et al. 2016; Li et al. 2019a; Jin et al. 2003; Yu et al. 2022), discrepancies were found (Fig. 8c and d). Additionally, the copper ores with highly radiogenic lead characteristics found in Huili, Sichuan showed significant differences in their data compared to the highly radiogenic lead bronzes from the Jiangkou site (Wang et al. 2020). In contrast, the data characteristics of highly radiogenic lead from the Jiangkou site align more closely with those of the Sanxingdui and Jinsha sites bronzes (Jin 2008). Jin Zhengyao's analysis of the bronzes from the Jinsha site suggests that the widespread occurrence of highly radiogenic lead in the Chengdu Plain during the early Western Zhou dynasty is likely related to its provenance (Jin 2008). However, as research has advanced in recent years, it has become increasingly unlikely that highly radiogenic lead originated from Yunnan, challenging this view (Liu et al. 2021). Another possibility is that late-period bronze production involved re-melting early bronzes with highly radiogenic lead characteristics as raw materials. Such bronzes with early highly radiogenic lead material characteristics have also been found in tombs from the Eastern Zhou dynasty in the Chengdu Plain (Wang et al. 2021).

Group II of Western Zhou bronzes contains 7 samples, with lead isotope ratios characterized by ^{207}Pb/^{206}Pb ratios ranging from 0.85 to 0.9, ^{206}Pb/^{204}Pb ratios ranging from 17.9 to 18.3, ^{207}Pb/^{204}Pb ratios ranging from 15.56 to 15.65,

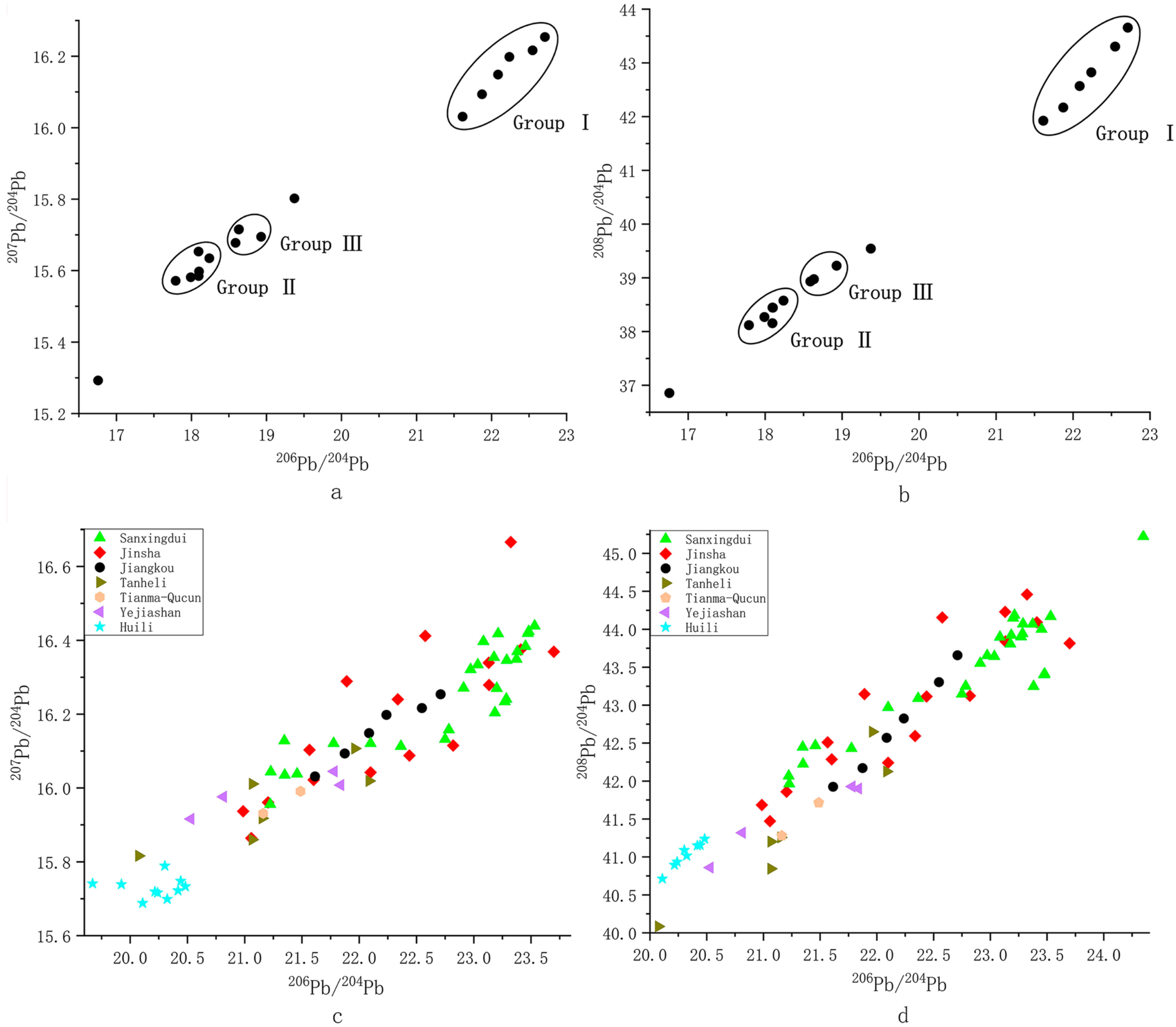

Fig. 8 **a**, **b** Plots of lead isotope ratios of Western Zhou bronzes excavated from the Jiangkou site. **c**, **d** Plots of highly radiogenic lead isotope ratios from the Jiangkou site and other sites (diagrams: Qiu Tian)

and ^{208}Pb/^{204}Pb ratios ranging from 38.1 to 38.6. An extensive comparison of lead isotope data of bronzes from Western Zhou vassal states and Yinxu Phase IV bronzes reveals that bronzes with ^{207}Pb/^{206}Pb ratios between 0.85 and 0.9 exhibit characteristics of early Western Zhou raw materials from the Central Plains, and bronzes from different regional states are characterized by similar lead isotope ratios, possibly reflecting the centralized control and distribution pattern of raw materials during the Western Zhou dynasty (Li et al. 2019a). There are a total of 7 bronzes from the Jiangkou site that are characterized by Central Plains raw materials, reflecting the fact that Western Zhou bronzes from the Chengdu Plain were not independent of the Central Plains system, and some of the bronzes in the group II are also differ significantly in type from local bronzes in the Chengdu Plain. For example, PJ12 is featured with a human-face motif on the socket of the axe, a decorative style not found in the bronze axes of the Sichuan Basin but discovered in bronzes at such sites as Wulangmiao in Chenggu, Shaanxi (Zhao 2006, 50–51). Furthermore, the barrel-shaped body with a tongue-shaped double-sided blade is similar to the bronze axes excavated from M21 in Zhuyuangou Cemetery, Shaanxi (Lu and Hu 1988, 230). The shape of PJ27 is similar to that of the dagger axes excavated from the early Western Zhou tomb at Zhuyuangou Cemetery in Baoji, Shaanxi (Lu and Hu 1988, 223). Additionally, its decorative motif of small bird patterns was popular during the Middle and Late Shang dynasties in the Central Plains (Zhu 1995, 392). PJ48 has backward-sloping wings on each side of the *lan* (阑) (The boundary between the blade and the hilt), with decoration on the *yuan* (援) (hilt of dagger-axes) and *na* (内) (blade of dagger-axes). Such craftsmanship and decorative style are extremely rare, but similar examples have been excavated in Hengyang and Ningxiang, Hunan in the middle reaches of the Yangtze River (Xiong 2018, 107–108). As these bronzes differ from local ones both in typology and raw materials, it is suggested that they were imported from other regions.

Group III of Western Zhou bronzes contains 8 samples with lead isotope ratios characterized by $^{206}Pb/^{204}Pb$ ratios ranging from 18.49 to 18.74, $^{207}Pb/^{204}Pb$ ratios ranging from 15.62 to 15.71, and $^{208}Pb/^{204}Pb$ ratios ranging from 38.61 to 39.10. The lead isotope ratios of these 8 samples are concentrated in the distribution shown in the figure and are very close to the lead isotope ratios of typical Eastern Zhou bronzes style of the Sichuan Basin, such as the pocket-shaped axe (PJ14) and the willow-leaf-shaped sword (PJ42) excavated from the Jiangkou site. By comparing the lead isotope data of Eastern Zhou Ba (Eastern Sichuan Basin) and Shu (Western Sichuan Basin) bronzes collected by Li Haichao and other scholars and lead isotope data from modern lead mines in Sichuan (Li et al. 2021), it is found that the lead isotope data of Group III bronzes from Jiangkou site fall within the range of Shu bronzes and overlap to some extent with the lead isotope ratios of modern Sichuan mining ores. In terms of typology, PJ03, PJ22, and PJ23 share similar types, which have been found not only in the Zhuwajie site (Fan and Hu 1981) but also bear a striking resemblance to the stone axe excavated from the Meiyuan point at the Jinsha site (Zhu et al. 2004). Similar bronzes are not found in other regions, which suggests that this type has a local style in terms of form. Combining the characteristics of the lead isotopes reflecting the raw materials used, it is inferred that local raw materials were utilized for local casting. This also suggests that local mineral resources may have been utilized to cast bronzes during the Western Zhou period in the Chengdu Plain.

A total of 19 Eastern Zhou bronzes excavated from the Jiangkou site have undergone lead isotope analysis. In order to investigate the similarities and differences in raw materials between these bronzes and others from the Chengdu Plain, we collected lead isotope data from bronzes excavated from Xinghelu cemetery (located within the Jinsha site) and Baishoulu cemetery. These two sites have relatively clear chronological periods, with Xinghelu Cemetery dating to the mid-to-late Spring and Autumn period (Li et al. 2020a) and Baishoulu Cemetery dating to the Warring States period (Li et al. 2020c). The plots indicate that the Jiangkou Eastern Zhou bronzes overlap to some extent with those from Xinghelu cemetery and Baishoulu cemetery (Fig. 9a and b). While some researchers suggest that these data consistently align with the Chu and Zeng states (Li et al. 2021), others believe that the provenance of raw materials for Chengdu Plain bronzes changed during the Warring States period. Data from the early to middle Warring States mostly show $^{206}Pb/^{204}Pb$ ratios greater than 18.3, possibly indicating the use of local minerals. From the late Warring States period onwards, $^{206}Pb/^{204}Pb$ ratios mostly range from 17.5 to 18.2, suggesting a possible shift in the provenance of raw materials for bronzes production toward the Chu culture region (Wang et al. 2022). The geochemical analysis shows some similarities in lead isotope ratios between the upper and middle reaches of the Yangtze River (Hsu and Sabatini 2019). However, more data from field archaeology are needed to provide further support for a more comprehensive discussion on this issue. In the case of the Jiangkou bronzes, there is still some overlap between the lead isotope data from modern mines within Sichuan and that of the Eastern Zhou bronzes (Fig. 9c and d). Therefore, it is possible that the raw materials used for these bronzes were locally sourced. These typical Ba and Shu bronzes in terms of their form mainly include the pocket-shaped axes (PJ14, PJ20), the willow-leaf-shaped swords (PJ29, PJ33, PJ42, PJ32), the carving knife (PJ40), and the ring-headed knife (PJ41).

Conclusions

The excavation of the first millennium to the second century BCE bronze weapons and tools from the Jiangkou site represents the largest, most complete, and best-preserved group of bronzes discovered in recent years on the Chengdu Plain. Although there is less traditional stratigraphic evidence available for the archaeological context, extensive comparisons with previously excavated bronzes from the Western and Eastern Zhou dynasties, combined with C14 dating results, have provided a basic understanding of their chronological period. There have been very few Western Zhou bronzes found in previous archaeological discoveries in the Chengdu Plain. The discovery of the Jiangkou bronzes provides a new opportunity for in-depth research into Western Zhou bronzes in the Chengdu Plain and provides a basis for studying pre-Qin bronzes from a diachronic perspective. Furthermore, the study of the mechanical performance, raw material provenance, and material circulation of Jiangkou bronzes through a combination of typology, archaeometallurgy, and wood science offers a new research case for multidisciplinary studies on bronzes in southwestern China from a comparative perspective. In this study, a significant amount of comparative analysis was conducted on published bronze materials from the Chengdu Plain and its surrounding areas. Combined with radiocarbon dating data, the excavated bronzes were classified into two periods: the Western Zhou Dynasty and the Eastern Zhou Dynasty, and further analysis was conducted on the wood handles within

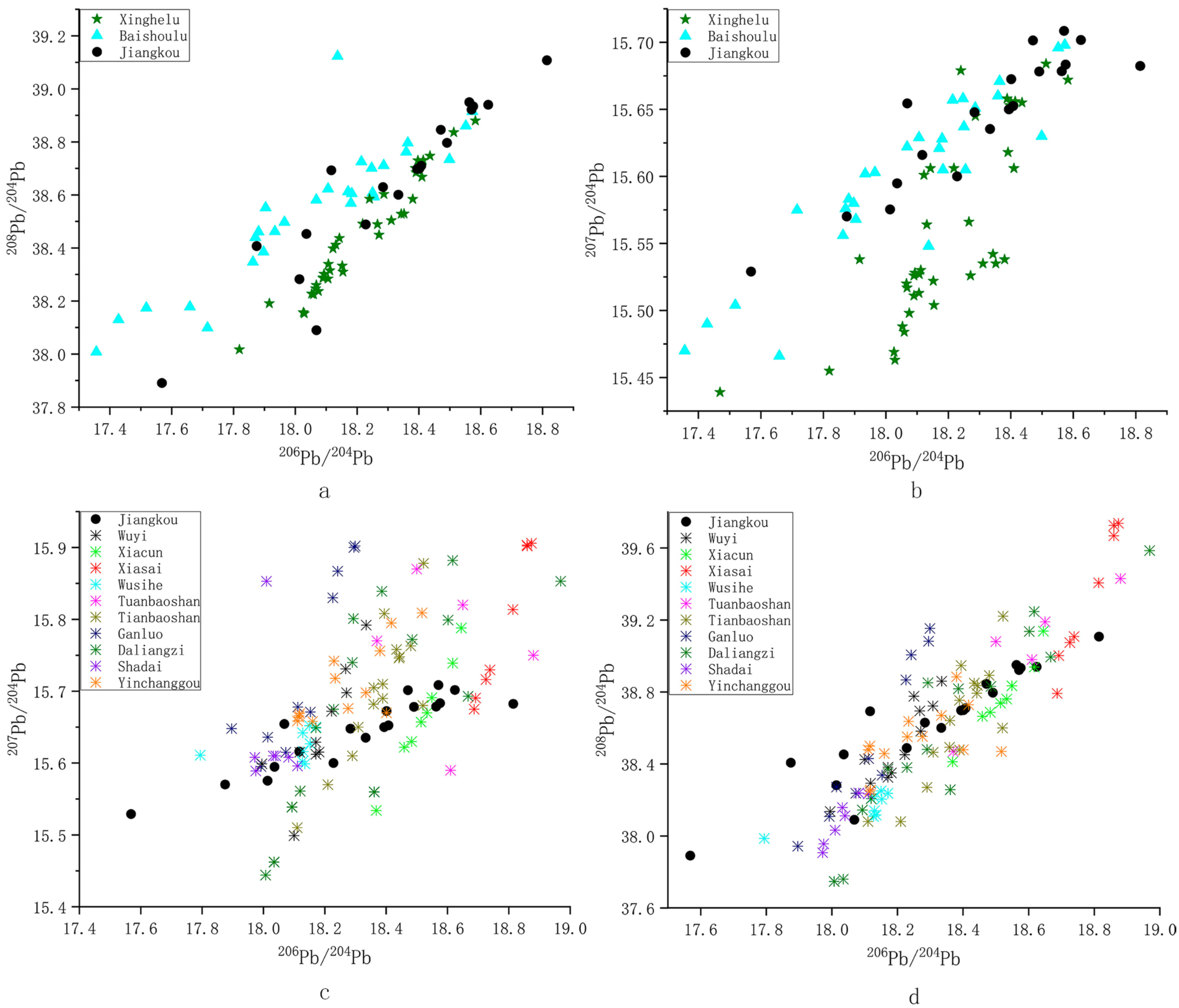

Fig. 9 **a**, **b** Comparison of Eastern Zhou bronzes from the Jiangkou site with other Eastern Zhou bronzes from the Chengdu Plain. **c**, **d**: Comparison of Eastern Zhou bronzes from the Jiangkou site with lead isotope data from a modern mine in Sichuan (diagrams: Qiu Tian)

the bronzes, bronze alloy compositions, and provenance of raw material. On this basis, the wood handles remained in the bronze axes, and the composition of the bronzes, and the lead isotope ratios were analysed. The wood analysis of the 7 samples revealed that the wood handles were most likely sourced locally, and the people at that time may had certain knowledge regarding the mechanical performance of wood, as they consciously chose tree species suitable for tool and agricultural implement handles. In terms of alloy compositions, Western Zhou bronzes exhibited the highest copper content, with lower lead and tin content, and the presence of a small number of copper objects. However, as the Eastern Zhou dynasty progressed, the copper content in the bronzes declined significantly, while lead and tin content increased to varying degrees, especially during the Warring States period when the tin content of such objects as ring-headed swords and willow-leaf-shaped swords were significant. Furthermore, the alloy compositions of the Jiangkou bronzes were directly related to their forms and functions, suggesting that the bronze casters may have consciously adjusted the alloy ratios of the bronzes according to the specific usage characteristics of the objects. In terms of raw material sources, the copper materials used in the Western Zhou bronzes from Jiangkou were found to be diverse, including both Central Plains-type materials and local materials. Moreover, 6 bronzes displayed highly radiogenic lead. The lead isotope ratio characteristics of these 6 bronzes were similar to those found in bronzes at the Sanxingdui and Jinsha sites, suggesting a potential similarity in raw material sources. Compared with the Western Zhou bronzes, the lead isotope ratios of Eastern Zhou bronzes from the Jiangkou site are more concentrated, possibly suggesting a more stable provenance of raw materials during the Eastern Zhou dynasty. Furthermore, a comparison with lead isotope data from modern mines in Sichuan indicates that some of the copper used in Eastern Zhou bronzes may have originated from local sources in Sichuan.

The discovery and research of the Jiangkou bronzes not only provide valuable materials for studying the pre-Qin bronzes in the Chengdu Plain but also offer new insights into the social dynamics of the region during the pre-Qin period. Previous archaeological findings indicate that bronzes from the Late Shang to the Western Zhou dynasty excavated in the Chengdu Plain are primarily concentrated in the Sanxingdui, Jinsha, and Zhuwajie sites, which are unique in nature and are located in the central and northern parts of the Chengdu Plain. The discovery of the Jiangkou bronzes challenges our understanding of the early distribution pattern of bronzes in the Chengdu Plain, providing important data for studying the production and circulation of early bronzes in the region. Additionally, historical documents suggest that Wuyang, located across the river from the Jiangkou site, was the stronghold where the King of Shu relocated after the Qin conquest and was later killed by the Qin army (Chang 1984, 192). Thus, both archaeological and documentary evidence shows that the area was rich in human activities and was of great political and military importance during the pre-Qin dynasty. This understanding not only inspires future archaeological work on the pre-Qin dynasty in the Chengdu Plain but also prompts a reevaluation of the settlement layout and social networks of the Chengdu Plain during that period.

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Author contributions TQ performed the experiments, did data analyses and paper writing, XY performed the experiments, YL, YL, ZL, and XY reviewed and edited the paper. All authors have read and approved the final manuscript.

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Data Availability The datasets generated or analysed during this study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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