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Archaeometallurgical Study of a Han Dynasty Thin-Walled Bronze Basin Excavated from the Fengzhou Cemetery, Baoji, Shaanxi, China

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Abstract

Archaeometallurgy of Han Dynasty thin-walled bronzes is a hot topic of current research and has made some achievements. But several issues remain insufficiently understood. These include alloying and production strategies, technological variation among social groups, and metal-resource circulation. This study analyze a thin-walled bronze basin excavated in Feng County, Baoji, using SEM-EDS, metallography, and MC-ICP-MS to investigate alloy composition, production techniques, and lead provenance. The basin was made from a ternary Cu-Sn-Pb alloy through casting, repeated hot forging and hammering, followed by trimming. Its thin walls were formed through combined hot forging and cold working. Lead isotope ratios suggest that the lead was derived from the Xiaoqinling region of western Henan and may have circulated through established transportation networks. Comparative analysis shows regional and social variation in alloy composition and production practices. The results indicate that Han Dynasty thin-walled bronze vessels shifted from ritual functions toward everyday use and commodity circulation, reflecting changes in production organization, social demand, and metal-resource circulation.

Thin-walled bronze vessels are generally defined as artifacts with an average wall thickness not greater than 1.5 mm^[1]. They represent one aspect of the technological diversity of bronze production in ancient China, while changes in their use reflect shifts in social demand over time. From the Western Zhou to the Spring and Autumn periods, thin-walled bronze artifacts were mainly recovered from high-status burial contexts, including those associated with the Zeng State^[2], the Rui State^[3], the Ying State^[4], and other regional polities. These artifacts mainly include horse armor, shield bosses, and ceremonial fans, which are generally interpreted as having decorative or funerary functions. Protective equipment and weapons also served ritual purposes. From the Eastern Zhou through the Qin and Han periods, the archaeological

contexts of thin-walled bronze artifacts became more diverse. Their distribution was no longer confined to high-status burials—such as those of the Qin State^[5], the Shangma Cemetery^[6], and the Chutai Cemetery^[7]—but extended to a wider range of social contexts, including the Dingxiang Zhonghuo Cemetery^[8], the Qin tombs in the suburbs of Xi'an^[9], and the Pengling Warring States–Western Han cemeteries^[10]. Artifacts from these later periods also show greater diversity in form than those of the Western Zhou period. In addition to ornaments, protective equipment, horse tack, and funerary objects, the number of utilitarian containers—such as basins, ewers, washbasins, trays, and cauldrons—increased markedly. By the Qin and Han periods, such containers had become the dominant category. During the Western Zhou period, thin-walled bronze objects formed part of the military equipment and ritual assemblages of the elite. From the Eastern Zhou through the Qin and Han periods, they were increasingly used in everyday life. This change may reflect a broader shift in social values, from an emphasis on elaborate ritual practices toward greater attention to practical function.

Due to their thin walls, such bronze artifacts are rarely preserved intact. The limited number of scientific analyses carried out to date has also restricted the number of securely dated examples available for study. The earliest hot-forged thin-walled bronze artifacts are the bronze bubbles excavated from the Gamatai Cemetery in Guinan, Qinghai, dating approximately to the transition between the Xia and Shang dynasties. Xu Jianwei^[11] analyzed these artifacts and identified them as hot-forged tin bronzes. Chen Kunlong^[12] examined the compositional and production techniques of thin-walled armor excavated from Western Zhou tombs at Shigushan in Baoji. The study found that techniques such as hot forging, stamping, and engraving show affinities with bronze-working traditions beyond China. It further suggested that the armor may represent a technological synthesis between Western bronze-working traditions and indigenous Central Plains practices. Huang Ruoxi^[13] studied thin bronze sheets (shu) from the early Spring and Autumn period at the Weijiaya site. Analysis of production processes including hot forging, hammering, die pressing, and engraving revealed the technical characteristics of early Qin hot-forged thin-walled bronze artifacts. Li Yang^[14] examined thin-walled bronze fragments excavated from Anlu City, Hubei Province, focusing on forging temperatures and production processes, including tin plating. The study showed the diversity of techniques used in thin-walled bronze production. Cai Youzhen^[1] analyzed thin-walled bronze artifacts from the Shang Dynasty Liujiazhuang site in Jinan and found that most had been produced by casting, in contrast to the processes commonly identified in forged thin-walled bronze artifacts. Li Yang^[15] carried out a systematic study of hot-forged thin-walled bronze artifacts from the Pre-Qin and Han periods. The study identified

a technological shift from a “unary” (low-tin) alloy system to a “binary” system characterized by both low-tin and high-tin compositions. It also summarized changes in alloy composition and the related technical characteristics of these artifacts. The “heating–forging–annealing/quenching” techniques developed by ancient craftsmen during bronze production provided important technical basis for the production of iron objects, reflecting both continuity and change in metalworking traditions from the Bronze Age to the Iron Age.

From October to December 2019, the Baoji City Archaeological Research Institute conducted an archaeological excavation at the Fengzhou Cemetery, located on a terrace on the west bank of the An River, south of Fengzhou Village. (Fig. 1). The excavation uncovered nine Han Dynasty tombs and several bronze artifacts. During the Western Han Dynasty, Emperor Wu’s state monopolies over salt and iron strengthened central government control over local regions and promoted the development of major transportation networks. One of these routes, the Gudao also known as the Chencang Road or Jialing Road, served as an important transportation corridor between the Guanzhong and Hanzhong regions. From the Guanzhong Plain, the route extended westward to Chencang, present-day Baoji, before turning south and passing through the southwestern part of Feng County along the Shuidao River valley. It then continued through Liangdang and Hui County before reaching Luoyang, where it connected with the Juzhou Waterway and ultimately provided access to Hanzhong^[16]. Feng County in Baoji lies along this important transportation corridor and therefore has particular historical significance. Scientific studies of bronze artifacts from the Baoji area have so far focused mainly on the Pre-Qin period, while Han Dynasty bronzes have received relatively little attention. Studies of thin-walled bronze artifacts from Baoji have likewise concentrated on protective equipment, armor, weapons, and funerary objects, with much less work on vessels used in everyday life. The results were then compared with data from related artifacts to investigate the alloy compositions, production technologies, and provenance and circulation of raw materials used in Han Dynasty thin-walled bronze vessels. This comparison also provides a basis for discussing the organization of bronze production and exchange networks during the Han Dynasty.

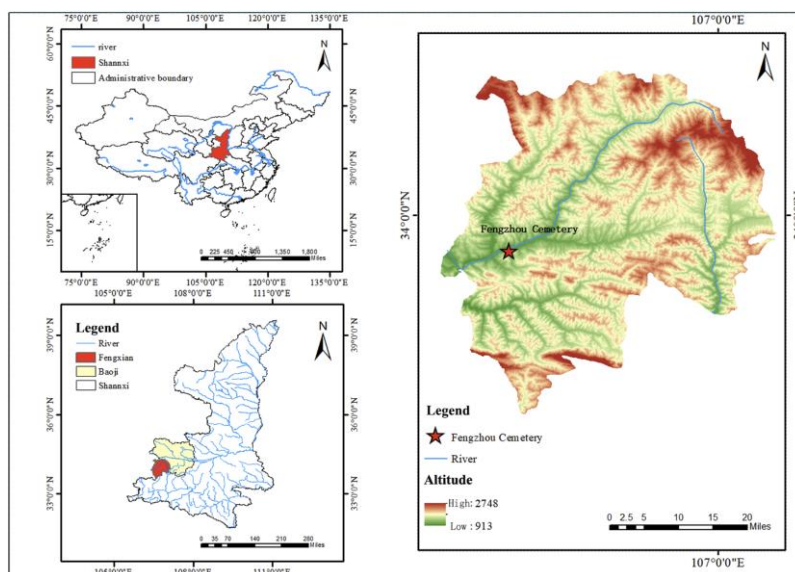


Fig. 1 Geographical location of the Fengzhou Cemetery in Baoji, Shaanxi Province, China

Methods

Materials

The samples were taken from a bronze basin excavated from an early Western Han Dynasty tomb. Sampling followed the principle of minimal intervention, with only limited, targeted samples collected from the basin base and from fragile or damaged areas of the vessel wall. The samples were designated M7:21-1 and M7:21-2, corresponding to fragments from the vessel wall and basin base, respectively (Fig. 2). M7:21-1 has a maximum length of 12 mm and a maximum width of 11 mm. M7:21-2 measures 17 mm in both maximum length and width and has an average thickness of 0.33 mm. As shown in Fig. 2, the fragment surfaces are grayish black, with greenish blue and reddish brown corrosion products. After mechanical polishing and removal of the corrosion layer, the exposed substrate appears pale yellow. Machining marks are visible on both the inner and outer surfaces of the fragments and are relatively uniform distribution.

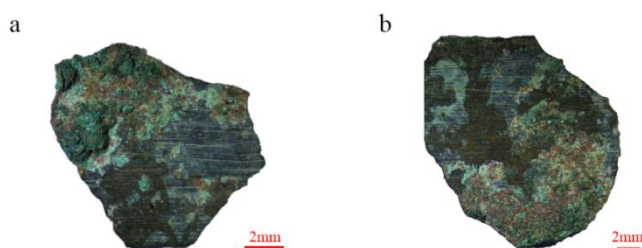


Fig. 2 Photo of the fragment sample of the bronze basin M7:21

Analytical methods

metallographic analysis

Metallographic specimens were prepared using a fully automatic embedding machine (LHM-3000, Naibo Testing Technology Co., Ltd., Shanghai, China) and an automatic metallographic grinding and polishing machine (DS-LAP-2000, Naibo Testing Technology Co., Ltd., Shanghai, China). The samples were embedded in epoxy resin by hot pressing at 150 °C and then ground and polished. The microstructures were first examined before etching. The polished surfaces were then etched with a 3% ferric chloride solution prepared in hydrochloric acid and ethanol. The microstructures were examined using a polarizing microscope (Axioscope 5, Carl Zeiss AG, Germany), and metallographic images were taken from representative areas.

Alloy composition analysis

The samples were examined using a Tbenchtop scanning electron microscope (M-4000Plus, Hitachi, Tokyo, Japan) equipped with an energy dispersive spectrometer (AZtecOne, Oxford, Abingdon, UK). Elemental compositions were analyzed by EDS using both area and point analyses. Because corrosion, elemental segregation, and other factors may affect the analytical results, corroded and heterogeneous areas were avoided as far as possible. To determine the average composition, three representative areas were selected for EDS area scans, and the mean value was used as the final compositional result. The analyses were carried out in backscattered electron mode at an accelerating voltage of 15 kV, and an acquisition time of 50 s.

Lead isotope analysis

Sample pretreatment for lead isotope analysis was carried out at the Archaeology Laboratory of the University of Science and Technology of China. The Pb content of the samples exceeded 1%. Approximately 5 to 10 mg of corrosion products were collected from the bronze artifacts, rinsed with acetone and deionized water, and dried. Lead was then extracted by electrolytic deposition. The Pb concentration of the resulting solution was measured using inductively coupled plasma mass spectrometry (ICP-MS, Agilent Technologies, Tokyo, Japan,). All lead solutions were diluted to a uniform Pb concentration of 200 ppb. Lead isotope ratios were measured at the Metal Stable Isotope Laboratory of the University of Science and Technology of China (USTC) using a Thermo Fisher Scientific Neptune Plus™ multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS, Thermo Fisher Scientific, Bremen,

Germany). NIST SRM 981 was used as an external standard, while a thallium (Tl) standard solution was used as an internal standard for instrumental mass bias correction. The maximum analytical uncertainties for the $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios were ± 0.0005 , ± 0.0005 , and ± 0.001 , respectively.

Results

Metallographic results

The microstructure, lead distribution, and inclusions of the bronze vessel were examined using a polarizing microscope, and representative metallographic images are shown in Fig. 3. The microstructure of the bronze basin is characterized by α -phase recrystallized grains and annealing twins, indicating that the vessel underwent hot forging during production. Grain size varies considerably between different areas. In Fig. 3a, relatively coarse grains are observed, with slip bands near both the upper and lower edges of the microstructure. In contrast, Fig. 3b shows finer and fragmented grains, together with pronounced slip bands within the grains. These features suggest that different regions of the bronze vessel experienced different degrees of cold deformation. Taken together, the microstructural evidence supports the conclusion that the basin was produced through a combination of hot forging and cold working. The ($\alpha+\delta$) eutectoid phase was preferentially corroded and occurs along the grain boundaries, whereas Cu_2S inclusions, Ag-rich inclusions, and other impurity phases are distributed along the grain boundaries or within corroded intergranular regions.

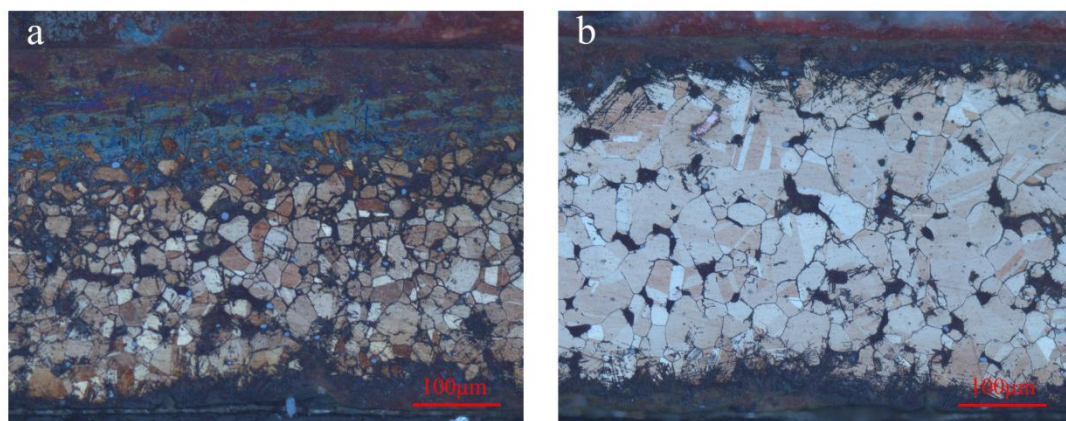


Fig. 3 Metallographic image of bronze basin M7:21

a M7:21-1; b M7:21-2

Alloy composition results

The SEM-EDS results are presented in Table 1. Based on the area-scan data, the bronze basin samples had average contents of 83.37 wt.% Cu, 11.56wt.% Sn, and 2.22wt.% Pb. According to the conventional 2wt.% criterion for alloying elements^[17], the analyzed material can be classified as a ternary Cu–Sn–Pb alloy. Area scans and point analyses indicate that the main trace impurity elements in the bronze basin fragments are S, Ag, Si, and Co. Trace Ag may originate from the copper ore sources and could provide information on the the provenance of raw materials used in ancient bronze production. Sulfur occurs mainly as Cu₂S inclusions, which are mostly distributed adjacent to Pb-rich particles. Ag inclusions have a granular morphology and occur in small quantities within corroded regions along the grain boundaries (Fig. 4).The EDS area scans also show differences in Pb distribution across the matrix. The matrix on the left contains relatively little Pb, occurring as fine particles, whereas the matrix on the right contains abundant irregularly shaped Pb-rich particles. Pb content decreases gradually from left to right, while Pb enrichment increases in the corroded regions along the upper and lower sides (Fig. 5). This distribution suggests that corrosion may have promoted the migration of Pb from the metallic matrix toward the surface corrosion layers.

Table 1 EDS analysis results of the samples (wt%)

Sample	Scanning Area	Major Element Content			Other Element Content	Thickness	Remarks
		(Wt%)			(Wt%)	(mm)	
		Cu	Sn	Pb			
M7:21-1	Surface Sweep 1	75.6	12.20	3.18	Si: 0.54, Sb: 0.6	0.24	Silver inclusions
	Surface Scan 2	87.35	12.41		Co: 0.24		
	Surface Scan 3	83.63	10.83	1.18	Si: 0.45		
	Spot Scan 1	56.62	3.02		O: 9.25, Ag: 13.85, Co: 0.12		
	Surface scan 1	79.43	11.85	2.34	Si: 0.36		
M7:21-2	Surface Scan 2	79.30	11.97	2.17	S: 0.39	0.43	
	Surface Sweep 3	89.00	11.00				

Surface Sweep 4	89.31	10.69		
Spot Scan 1	82.81	5.86	S: 10.79, Fe: 0.54	Cu ₂ S inclusions

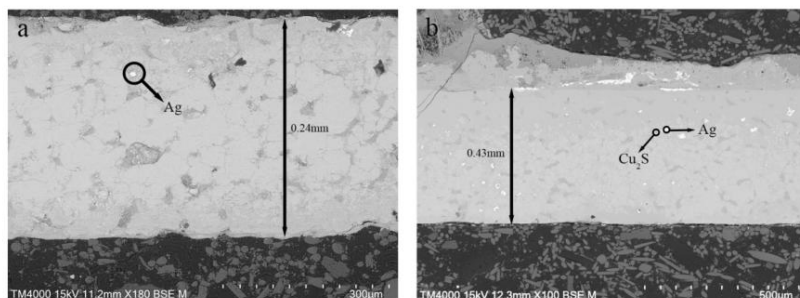


Fig. 4 BSE image of bronze basin M7:21

a M7:21-1; b M7:21-2

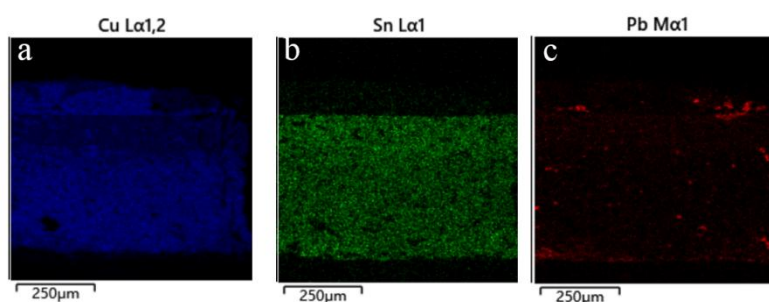


Fig.5 Energy spectrum maps of copper (Cu), tin (Sn) and lead (Pb) elements in bronze basin M7:21.

a Cu; b Sn; c Pb

Lead isotope results

Lead isotope ratio analysis revealed that the sample exhibited a $^{206}\text{Pb}/^{204}\text{Pb}$ ratio of 17.676, a $^{207}\text{Pb}/^{204}\text{Pb}$ ratio of 15.579, and a $^{208}\text{Pb}/^{204}\text{Pb}$ ratio of 38.555. The calculated $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{208}\text{Pb}/^{206}\text{Pb}$ ratios were 0.881 and 2.181, respectively (Table 2). According to the classification criteria for lead isotope compositions, lead with a $^{207}\text{Pb}/^{206}\text{Pb}$ ratio lower than 0.8 and a $^{206}\text{Pb}/^{204}\text{Pb}$ ratio higher than 20 is generally considered highly radiogenic lead. Therefore, the analyzed sample is classified as common lead rather than highly radiogenic lead.

Table 2 Lead isotope ratios of bronze basin M7:21

	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{208}\text{Pb}/^{206}\text{Pb}$
M7:21	17.676	15.579	38.555	0.881	2.181

Discussion

The optimization of alloy composition, together with the combined use of hot forging and cold working, appears to have allowed the bronze basin to balance mechanical performance, material efficiency, and the requirements of wall thinning.. Metallography revealed α -phase recrystallized grains and annealing twins, features characteristic of a hot-forged microstructure and consistent with the basin having undergone forging. Similar microstructural characteristics have been reported for other ancient forged bronzes. Thin-walled forged objects were generally produced by repeated hammering and annealing of cast blanks to progressively reduce wall thickness. The presence of slip bands on both sides provides evidence for subsequent cold working^[18]. Hot forging contributes to structural densification by eliminating or reducing casting defects such as porosity, whereas cold working introduces work hardening that improves the strength, hardness, toughness, and ductility of the alloy. The combined use of hot forging and cold working not only enhanced the mechanical performance of the bronze basin but also enabled further wall thinning, thereby reducing raw material consumption during production. The production sequence of the basin comprised four stages: casting, hot forging, cold working, and machining. Microscopic examination revealed uniform and regularly distributed machining marks on both the inner and outer surfaces of the fragments. Because the basin was formed mainly by hot forging rather than direct casting, these surface features are interpreted as machining traces produced during the finishing process rather than impressions left by casting molds. Machining removed surface defects generated during the hot forging and improved the surface quality and aesthetic appearance of the vessel. Similar machining traces have been identified on numerous Han Dynasty bronze artifacts, including a bronze boat excavated in Nanyang and a bronze steamer in the Henan Museum. These examples suggest that Han Dynasty craftsmen had developed sophisticated metal-finishing techniques. The basin was therefore likely produced from a cast blank, either cast directly in a mold or prepared as a cast copper plate. The blank was then heated to an appropriate forging temperature and repeatedly hammered until the required wall thickness was reached. Machining was carried out at the final stage to obtain the finished shape.

Lead isotope analysis is an important method for investigating the provenance of ancient copper and lead resources and tracing the circulation of related metal products^[19]. Lead isotope ratios are relatively stable during metallurgical processing and can therefore retain information on ore sources, providing useful evidence for provenance studies. As shown by the compositional data in Table 1, the Pb content of the Baoji bronze basin exceeds 2 wt.%. The

lead isotope ratios can therefore provide information on the provenance of the added lead and help investigate the origin and circulation of lead-bearing raw materials^[20]. Previous studies have rarely addressed the provenance of raw materials used in thin-walled bronze artifacts, and systematic investigations remain limited. To investigate the provenance of the raw materials used in the bronze basin, lead isotope data from Western Han bronze artifacts excavated at Gejiagou, Nanyang, Henan Province^[21]; Wuchuan, Guizhou Province^[22]; Xi'an, Shaanxi Province^[23]; Xiajiang, Chongqing Municipality^[24]; and Jinning, Yunnan Province^[25] were compared with the isotope data obtained from the bronze basin (Fig. 6). Figure 6 shows two distinct lead isotope distribution fields. Bronze artifacts from Gejiagou in Nanyang, Henan Province; Wuchuan in Guizhou Province; Xi'an in Shaanxi Province; and the Fengzhou Cemetery in Baoji form one cluster. Those from Xiajiang in Chongqing Municipality and Jinning in Yunnan Province form another. The Pb isotope compositions of the Baoji bronze basin show closer affinities with those of bronze artifacts from Xi'an and Wuchuan. This similarity suggests that the lead used in its production may have derived from ore sources with isotopic signatures similar to those represented by these assemblages.

The ore sources used for early Western Han bronze artifacts were relatively diverse, suggesting a decentralized pattern of raw material procurement. By the middle and late Western Han periods, however, Emperor Wu of Han's state monopolies on salt and iron contributed to greater centralization in the management and distribution of mineral resources. Ore supply also appears to have become more centralized^[26]. The Xi'an bronze mirrors included in this study date to the middle and late Western Han period, and previous research has suggested that their lead sources were associated with the Xiaoqinling region of western Henan Province^[26]. Early Western Han bronze artifacts excavated at Wuchuan, Guizhou Province, have likewise been shown to contain lead derived from ore sources in the Xiaoqinling region of western Henan and the eastern Qinling area of Shaanxi Province within the Central Plains region^[22]. The lead isotope ratios of the Baoji bronze basin samples also fall within the range reported for lead deposits in the Xiaoqinling region of western Henan Province. These isotopic similarities suggest that the lead used in the production of the basin was likely derived from ore sources in this region.

As a strategically important region close to the capital Chang'an, Baoji likely shared similar metal resource procurement and supply networks with the capital area during the Western Han Dynasty. The results of this study provide new material evidence for understanding the circulation of metal resources and the organization of bronze production during this period. Chang'an, present-day Xi'an, was the political and economic center of the

empire and an important administrative hub for the allocation and circulation of resources. Baoji lay at the western margin of the Guanzhong Plain, close to Chang'an. It served as an important strategic gateway connecting the capital region with the southwestern territories and was also the northern terminus of the Gudao Road. Feng County was the first major river valley and plain area reached after the Gudao Road crossed the Qinling Mountains. During the Western Han Dynasty, the administrative system inherited from the Qin Dynasty continued with the establishment of "Gudao County" in this region^[27], accompanied by formal administrative governance. According to the Table of Officials and Ministers in the Book of Han, a postal relay system of "one station every ten li" was established during this period^[28]. This evidence suggests that Feng County had already been incorporated into the national postal relay system during the Western Han Dynasty. A relatively complete transportation network connecting Chang'an and Feng County was therefore established, facilitating both administrative communication and commercial exchange. Within this network, Chang'an functioned as the center of political authority and resource allocation. Baoji served as a strategic gateway and an important transit hub for circulation of materials, while Feng County formed a key node along the Gudao Road, linking the capital region with the southwestern territories. The Gudao Road was not only a transportation route but also as an important channel for the circulation of materials and resources. As shown in Fig.6, the lead isotope ratios of bronze artifacts from Wuchuan are similarities to those of bronze artifacts excavated in Xi'an and Baoji. This similarity may reflect connections related to population movement and cultural exchange during the Qin and Han periods^[22]. During this period, indigenous communities in the southwestern region engaged in mercury mining and transported mercury resources to the Central Plains. The economic benefits associated with mercury exploitation may have attracted migrants from northern China. These migrants may, in turn, have facilitated the movement of bronze artifacts and metallurgical resources from the Guanzhong region to Wuchuan.

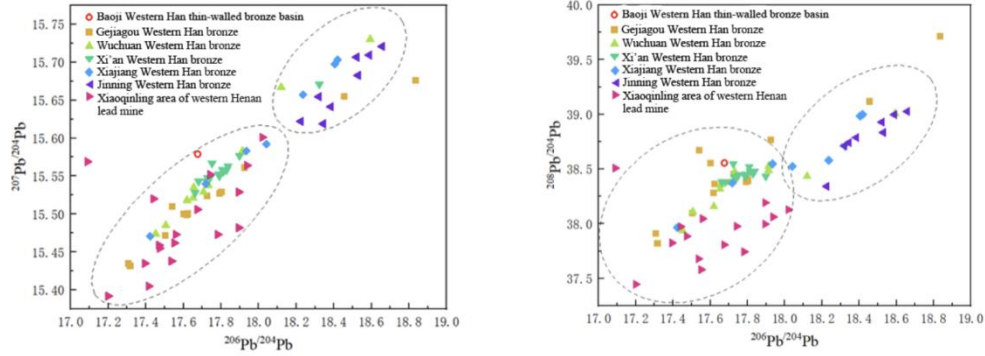


Fig. 6 Scatter plot of lead isotopes of bronze basin M7:21 with Other Han Dynasty Bronze Artifacts

Few Han Dynasty thin-walled bronze artifacts from the Baoji region have been systematically analyzed. The alloy composition of the bronze basin examined in this study was therefore compared with that of thin-walled bronze vessels excavated from the Zhouyuan cemetery in Baoji (Table 3). The average Sn and Pb contents of thin-walled bronze artifacts from the Baoji region are 13.59wt% and 3.74wt%, respectively. According to the Cu–Sn–Pb ternary phase diagram established by W. T. Chas^[30], increasing the Sn content while decreasing the Pb content can increase alloy hardness, whereas reducing both Sn and Pb contents improves elongation. When Sn content range from 5wt% to 20wt% and the Pb remains below 10wt%, bronze alloys exhibit relatively favorable tensile strength. Considering hardness, tensile strength, and elongation together, bronze alloys containing 5wt%–15wt% Sn and less than 10 wt.% Pb show a relatively balanced combination of mechanical properties. The bronze basin analyzed in this study contains 11.56 wt.% Sn and therefore falls within this optimal compositional range. This composition provided sufficient strength and overall mechanical performance while maintaining relatively reasonable levels of raw material consumption and production costs.

Table 3 Alloy compositions and production techniques of Han Dynasty thin-walled bronze vessels from

Baoji									
Site of Discovery	Date	Object	Status of the Interred Individual	Number	Elemental Content (Wt%)			Material	Crafting Characteristic s
					Cu	Sn	Pb		
Feng County, Baoji,	Western Han Dynasty	Bronze basin		M7:21	83.3	11.5	2.2	Cu-Sn-P	Hot Forging Cold Working
					7	6	2	b	

Shaanxi													
Han													
Dynasty	Early to												
Tombs in	mid-Weste	Bronze	Officials	05FZM1	79.7	15.6	4.7	Cu-Sn-P	Hot Forging				
Zhouyuan,	rn Han	vessel		9:9				b	Cold Working				
n,	Dynasty												
Shaanxi													
Han													
Dynasty	Early to												
Tombs at	mid-Weste	Bronze	Officials	05FZM1	82	13.6	4.3	Cu-Sn-P	Hot Forging				
Zhouyuan,	rn Han	bowl		9:3				b	Cold Working				
n,	Dynasty												
Shaanxi													

Compositional data of Han Dynasty thin-walled bronze vessels from Xi'an^[30], Yulin^[31], Beijing^[32], Henan^[33], Jiangxi^[34], Anhui^[35,36], and other regions were compiled for comparison. The vessels were grouped according to the social status of the tomb occupants to examine variation in alloy composition among different regions and social groups (Table 4).

Table 4 Alloy compositions and production characteristics of Han Dynasty thin-walled bronze vessels

Site of Discovery	Date	Object	Status of the		Elemental Content			Crafting	
			Interred	Num	(Wt%)			Material	Characterist
			Individual	ber	Cu	Sn	Pb		ics
Longshouyuan, Xi'an, Shaanxi	Early Western Han Dynasty	Bronze basin	Commoners	M14: 8	86.66	5.32	7.74	Cu-Sn-Pb	
Zoumalang, Yulin, Shaanxi	Late Western Han Dynasty	Bronze basin	Officials	YL-1	81.11	16.72	1.55	Cu-Sn	Hot forging, cold working
Zoumalang, Yulin,	Late Western Han	Bronze Zeng	Officials	YL-2	78.95	18.17	1.86	Cu-Sn	Hot forging, cold

Shaanxi	Dynasty								working
Nanyang,	Han								Quenched
Henan	Dynasty	Bronze boat	Officials	YN1 1	79 3	18.7 3		Cu-Sn	after hot forging
Nanyang,	Western								Hot
Henan	Han	Bronze	Commoners	M26: 1	90.6	4.38	3.18	Cu-Sn-Pb	forging
Nanyang,	Western								Hot
Henan	Han	Bronze	Commoners	M30: 6	87.3	6.85	3.75	Cu-Sn-Pb	forging
Nanyang,	Western								Hot
Henan	Han	Bronze	Commoners	M35: 12	88.19	6.29	2.14	Cu-Sn-Pb	forging
Nanyang,	Western								Hot
Henan	Han	Bronze	Commoners	M38: 1	89.61	4.8	3.2	Cu-Sn-Pb	forging
Xitun,	Han								Hot
Yanqing,	Dynasty	Bronze basin	Commoners	M15 1:1	83.13	10.9 4	5.94	Cu-Sn-Pb	forging
Beijing									
Han	Middle								
Dynasty	to Late								Hot
Tomb in	Western	Bronze	Officials	M62: 20	82.2	10.4	2.9	Cu-Sn-Pb	forging
Dongyang,	Han	basin							
Jiangsu	Dynasty								
Han	Late								
Dynasty	Western								Hot
Tomb in	Han	Bronze	Officials	M11 4:21	74.6	11.7	2.9	Cu-Sn-Pb	forging
Dongyang,	Dynasty	basin							
Jiangsu									
Han	Late								
Dynasty	Western								Hot
Tomb in	Han	Bronze	Commoners	M12 4:4	75.7	13.2	4.5	Cu-Sn-Pb	forging
Dongyang,	Dynasty	basin							

Jiangsu										
Han	Late									
Dynasty	Western									Hot
Tomb in	Han	Bronze	Commoners	M13	77.2	8.5	6.4			
Dongyang,	Dynasty	basin		8:11				Cu-Sn-Pb		forging
Jiangsu										
Han	Late									
Dynasty	Western									Post-castin
Tomb in	Han	Bronze	Commoners	M21:	85.5	6.4	3			
Dongyang,	Dynasty	basin		9				Cu-Sn-Pb		g heat treatment
Jiangsu										
Han	Late									
Dynasty	Western									Post-castin
Tomb in	Han	Bronze	Officials	M14	81.1	8.5	1.5			
Dongyang,	Dynasty	basin		6:24				Cu-Sn		g heat treatment
Jiangsu										
Feidong,	Western									Hot
Anhui	Han	Bronze		M7:1		18.1				Forging
	Dynasty	basin		3-3	79.94	7	5.26	Cu-Sn-Pb		Cold Working
	Late									
Tianchang,	Western									Hot
Anhui,	Han	Bronze	Officials	M10:	87.9					
Jiaotangwei	Dynasty	Xi		59		6.21	5.09	Cu-Sn-Pb		forging
Tomb of	Mid-to-L									
the Marquis	ate									
of Haihun,	Western	Bronze	Feudal lord	M1:	84.9	11.3	2.3			Post-castin
Jiangxi	Han	Ding		1756				Cu-Sn-Pb		g heating
	Dynasty									
Tomb of the	Mid-to-lat									Post-castin
Marquis of	e Western	Bronze								
Haihun,	Han	Ding	Feudal lord	M1:	84.4	10.8	2.5			g heat treatment
Jiangxi	Dynasty			1760				Cu-Sn-Pb		

Tomb of the Marquis of Haihun, Jiangxi	Mid-to-late Western Han Dynasty	dragon- headed yi vessel	Feudal Lord	M1:1 80 74	13.1	4.5	Cu-Sn-Pb	Hot forging
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As shown in Tables 3 and 4, the analyzed thin-walled bronze vessels are predominantly Cu–Sn–Pb alloys, accounting for 83% of the samples, whereas Cu–Sn binary alloys account for only 17%. By the Han Dynasty, the alloy compositions of thin-walled bronze vessels had developed into a relatively mature and standardized system, generally characterized by approximately 10 wt.% Sn and less than 5 wt.% Pb. Considerable regional variation nevertheless remained. The Sn contents shown in Tables 3 and 4 range widely from 4.38 wt.% to 18.73 wt.%, with an average of 11.2 wt.%. Pb contents vary over a narrower range, from 1.5 wt.% to 9.9 wt.%, except for the bronze boat YN11 excavated from Nanyang, Henan, in which no Pb was detected. The average Pb content is 4.3 wt.%. Compared with bronze artifacts from the Warring States period, Han Dynasty thin-walled bronze vessels show notable changes in alloy composition, including lower Sn contents and greater variation in Pb addition. Experimental simulations have shown that bronze alloys containing 9 wt.% to 15 wt.% Sn and less than 5 wt.% Pb have greater resistance to bending deformation under external loading ^[37]. Lead also has a much lower thermal conductivity than copper and Cu–Sn alloys. During hot forging, the presence of lead may therefore help retain heat, prolong the effective forging time, and facilitate the production of thinner vessel walls ^[33]. These results suggest that a relatively mature and standardized alloying strategy for thin-walled bronze vessels had been established by the Han Dynasty. Clear differences are also evident in the alloy compositions of Han Dynasty thin-walled bronze vessels associated with different burial ranks. To examine the relationship between alloy composition and burial hierarchy, scatter plots and box-and-whisker plots of Sn and Pb contents were prepared for thin-walled bronze vessels excavated from tombs of different social statuses (Fig. 7). The bronze basin from tomb M7:21 in Feng County, Baoji, and the bronze vessel from tomb M7:13-3 in Feidong, Anhui, were excluded from this analysis because the social identities and ranks of the tomb occupants remain undetermined.

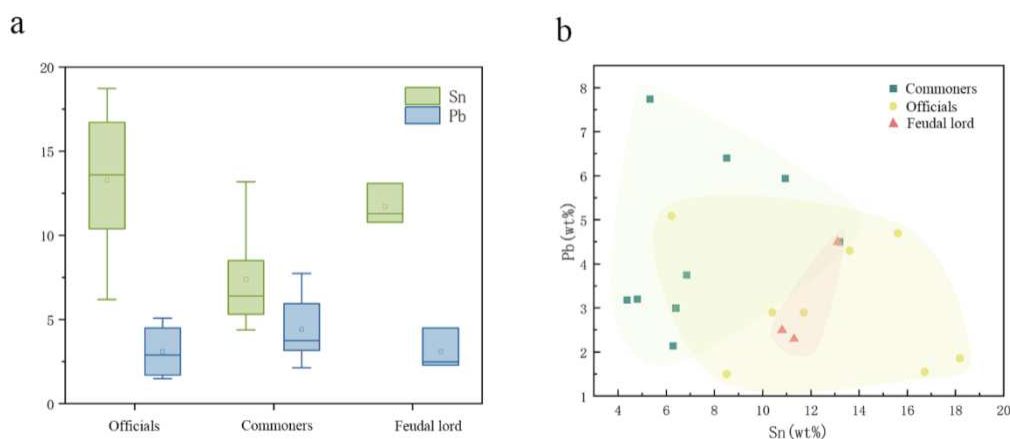


Fig. 7 Box-and-whisker plots of Sn and Pb contents and scatter plot of alloy composition ratios for Han Dynasty thin-walled bronze artifacts from tombs of different ranks in various regions of China

a Box plots of alloy compositions; **b** scatter plots showing the distribution of alloy compositions.

As shown in Fig. 7a, thin-walled bronze vessels from tombs of different social ranks show clear differences in alloy composition. In terms of Sn content, vessels from officials' and feudal lords' tombs generally contain more Sn. Among high-status tombs, Sn contents range from approximately 6% to 18%, with a median of 13 wt.%. Most samples fall within the range of 10 wt.% to 13 wt.%, with relatively limited variation and a certain degree of compositional stability. In contrast, vessels from commoner tombs generally have lower Sn contents, mainly between 5% and 8%, together with a broader distribution and greater compositional variability. Pb content partly overlaps among the different groups, but the overall differences remain clear. Thin-walled bronze vessels from officials' tombs generally have relatively low Pb contents, mainly between 2 wt.% and 5 wt.%, with a narrow distribution. Vessels from feudal lords' tombs likewise show relatively stable Pb contents with limited variation. In contrast, samples from commoner tombs are more dispersed, and some contain considerably more Pb, reaching 6 wt.% to 8 wt.%. This wider distribution suggests less consistent control over alloy composition. The scatter plot in Fig. 7b further shows differences in the relationship between Sn and Pb contents among the groups. Thin-walled bronze vessels from officials' and feudal lords' tombs form relatively concentrated distributions, mainly within a range of higher Sn contents, approximately 10 wt.% to 15 wt.%, and moderate Pb contents. This clustering indicates a relatively consistent alloying strategy and suggests a higher degree of standardization in alloy composition among high-status bronze vessels. In contrast, vessels from commoner tombs show a more dispersed distribution, with lower Sn contents of approximately 4 wt.% to 8 wt.% and greater variation in Pb contents. The absence of a clear cluster suggests less consistency in alloy selection and production control. Some overlap is

present between vessels from officials' and feudal lords' tombs, suggesting that these two groups may have shared similar alloying practices or raw material sources. Limited overlap also occurs between vessels from officials' and commoner tombs in some parts of the distribution. Overall, however, the distributions remain clearly separated, reflecting differences in alloying strategies and production systems.

In summary, thin-walled bronze vessels of the Spring and Autumn and Warring States periods were primarily associated with ritual functions and were recovered mainly from high-status burials. By the Han Dynasty, they had gradually shifted from elite ritual contexts toward everyday use and wider social circulation, with increasing numbers appearing in commoner tombs. This transition reflects the gradual secularization and broader social dissemination of thin-walled bronze vessels. During the Xia and Shang dynasties, bronze vessels mainly functioned as ritual implements and were closely associated with elite ceremonial practices. As Zhou ritual institutions declined during the Eastern Zhou period, their exclusive ritual status gradually weakened, and bronze vessels became increasingly integrated into broader social contexts. By the Han Dynasty, their transformation from ritual objects to everyday utensils had been largely completed^[38]. At the same time, differences in production organization appear to have contributed to variation in alloy composition. Thin-walled bronze vessels produced in private workshops, such as those excavated from commoner cemeteries in Nanyang and Xi'an, generally have lower Sn contents of approximately 5%–6%, greater variation in alloy ratios, and less consistent compositional control. In contrast, vessels associated with state-run workshops, including those from Baoji and the Tomb of the Marquis of Haihun, show relatively stable Sn contents above 10%. This pattern reflects a more mature and standardized production system with stricter control over alloy preparation. Variation in alloy composition among Han Dynasty thin-walled bronze vessels provides material evidence for social stratification and differentiation between production systems. Increasing demand for bronze commodities encouraged the involvement of private production sectors and facilitated the wider distribution of these vessels. State-controlled production, in contrast, maintained relatively consistent product quality through standardized production practices and the regulation of resources. The interaction between these two modes reflects a distinctive feature of Han Dynasty bronze production, namely a shift from a ritual-centered system toward a more diversified and market-oriented production system.

As shown in Table 3, all thin-walled bronze vessels from the Baoji region were produced through a combination of hot forging and cold working. These processes altered the bronze

microstructure, producing recrystallized equiaxed grains accompanied by annealing twins, strain lines, and deformed sulfide inclusions. The increased ductility of the alloy during thermal processing facilitated wall thinning and contributed to the formation of the thin-walled structure^[39]. Bronze alloys containing more than 10 wt.% Sn have limited cold workability, so hot working is more effective approach to wall thinning^[40]. At high temperatures, increased atomic diffusion promotes recrystallization and formation of equiaxed recrystallized grains with annealing twins^[41]. Both forging temperature and applied force require careful control. Temperature is particularly important during hot forging. Excessively high temperatures may cause oxidation, overheating, or material loss, whereas temperatures that are too low may hinder plastic deformation and prevent effective wall thinning. Appropriate forging force is also needed to achieve a uniform reduction in wall thickness while minimizing the risk of cracking. This processing sequence may produce a work-hardened microstructure resembling that generated by cold working. Such features may result from insufficient cooling control during hot forging, with deformation occurring while the metal is still undergoing recrystallization. Some cold-working characteristics observed in the microstructure may therefore not necessarily represent intentional cold working. They could instead reflect deformation during the hot-forging process. This combined production approach enabled the thin-walled bronze vessels from Baoji to achieve a balance between favorable mechanical properties and a lightweight, slender form.

Thin-walled bronze vessels of the Han Dynasty show distinctive technological characteristics in their production, most notably the widespread use of hot forging and a marked decrease in Pb content among cast thin-walled bronze artifacts. The main production techniques were forging, casting, and heat treatment. As summarized in Tables 3 and 4, hot-forged vessels form the largest group, comprising 11 specimens (48%). Six specimens (26%) underwent cold working after hot forging, while four cast vessels (16%) received post-casting heat treatment. One additional specimen was identified as having been quenching after hot forging. Hot forging was the principal technique used to produce thin-walled bronze vessels, with wall thickness reduced repeated hammering. Thin-walled could also be achieved by casting. By minimizing the gap between the outer mold and inner core, the space available for molten metal was restricted, allowing the final wall thickness to be controlled^[34]. Compared with the Pre-Qin period, cast thin-walled bronze vessels became more common during the Han Dynasty. The Han Dynasty thin-walled bronze vessels examined in this study have an average Pb content of 2.33% despite having undergone post-casting heat treatment. This value is significantly lower than that reported for Eastern Zhou thin-walled bronze vessels

excavated from the Zhoujiazhuang cemetery in Xintai, Shandong Province. During the Eastern Zhou period, higher Pb contents were used to improve the fluidity of molten bronze when casting thin-walled vessels. Han Dynasty vessels, by contrast, show a tendency toward lower Pb contents. This suggesting that their production relied less on high Pb additions and more on optimized alloy compositions and improved casting techniques. A bronze boat excavated from Nanyang, Henan Province, exhibited a quenched microstructure. Bronze objects containing more than 20% Sn commonly underwent post-forging heat treatments such as quenching or annealing. Quenching was intended to retain the high-temperature β phase at room temperature, thereby improving the strength and ductility of the alloy and enhancing its workability ^[42].

The complexity of production processes for Han Dynasty thin-walled bronze vessels varied among social groups, particularly in the completeness of their processing sequences. Artifacts from feudal lords' tombs generally involved composite production sequences combining hot forging, cold working, and heat treatment. These relatively complete technological sequences reflect substantial technical investment and stringent quality control. Artifacts from officials' tombs were mainly produced by hot forging, sometimes followed by simple finishing processes, indicating a moderate degree of standardization. Artifacts from commoner tombs were generally produced through relatively simple hot forging, with limited evidence of more complex subsequent processing. This suggests a simplification of production practices. These differences indicate that, although techniques for producing thin-walled bronze vessels had become widespread among different social groups during the Han Dynasty, their application varied considerably according to social status. High-status groups, supported by state-controlled craft industries or advanced workshop systems, had significant advantages in raw material procurement, artisan expertise, and production management. This allowed the use of more complex and standardized production procedures. Production for commoners, in contrast, was more constrained by economic costs and resource availability, resulting in a preference for simpler techniques that met basic functional requirements.

Conclusion

Scientific analysis and contextual investigation of the Western Han thin-walled bronze basin M7:21 excavated from the Fengzhou Cemetery lead to the following conclusions. (1) The bronze basin was produced from a ternary Cu–Sn–Pb alloy containing 11.56 wt.% Sn and 2.22

wt.% Pb. The vessel was initially subjected to hot forging, followed by cold working and final mechanical finishing to remove surface defects generated during forging. This production process is consistent with the mature technological standards of Han Dynasty thin-walled bronze production and achieved a balance between structural strength and workability. (2) Lead isotope analysis indicates that the lead ore used in the bronze basin was likely derived from the Xiao qinling region of western Henan, providing evidence for centralized state control over metal resources during the middle to late Western Han Dynasty. Combined with geographical analysis and transportation route reconstruction, the results suggest that the ore was distributed through state-controlled channels and transported along the Gudao Road. These findings contribute to a better understanding of Han Dynasty metallurgical resource management in the Feng County area of Baoji and provide new insights into cultural interactions along ancient transportation networks. (3) Han Dynasty thin-walled bronze vessels were primarily produced from ternary Cu–Sn–Pb alloys, generally containing approximately 10 wt.% Sn and less than 5 wt.% Pb. Through precise control of alloy composition, Han Dynasty craftsmen achieved a balance among lightweight construction, mechanical durability, and production efficiency in the production of thin-walled bronze vessels. At the same time, thin-walled bronze objects gradually shifted toward everyday use and became increasingly commodified during the Han Dynasty, extending beyond elite contexts. Such objects have been frequently recovered in substantial numbers from commoner tombs.. (4) Hot forging was widely used in the production of Han Dynasty thin-walled bronze vessels, and some artifacts involved integrated production sequences combining hot forging, cold working, and quenching. The compositional stability of high-status artifacts was closely associated with their complex production procedures, whereas greater variability in alloy composition and simpler processing sequences were observed in commoner artifacts. These differences indicate disparities in technological control and craftsmanship among social groups, reflecting the hierarchical organization of Han Dynasty bronze production.

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L.Z.: methodology, formal analysis, project administration, supervision, writing—review and editing. H.W. and

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Competing interests

The authors declare no competing interest.

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