

Article

Major and Trace Element Characteristics of Bronze Mirrors Excavated in Linzi and Their Implications for the Study of ‘*Jin liuji*’

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Abstract

Linzi was a pivotal bronze mirror production centre during the Western Han dynasty (202 BCE–8 CE). This study analyses 71 excavated bronze mirrors from Linzi via pXRF, PCA, and geometric median statistics to investigate elemental characteristics, ore provenance, and the ‘*Jin liuji*’ (Six Recipes of Bronze). Their alloy compositions exhibit continuity throughout the Warring States (475 BCE–221 BCE) and Western Han periods and are distinct from those in other regions of China during the same period, suggesting that the ‘*Jin liuji*’ possesses strong regional characteristics specific to the Qi state. Trace element analysis reveals that the copper ore supply experienced three stages, namely diverse and scattered sources (or recycling) during the Warring States period, a transition during the early Western Han, and a concentrated supply during the middle and late Western Han. This study demonstrates the strong intervention of the Han dynasty’s state economic policies in the allocation of local metal resources, providing empirical evidence for reconstructing the economic control network of the unified empire.

Keywords: bronze mirrors; trace elements; copper provenance; *Jin liuji*; state economic policy; pXRF; PCA

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1. Introduction

The Western Han dynasty marked the peak of ancient China’s exchanges with neighbouring regions, and it was the first golden age for the bronze mirror production [1]. Political stability and economic prosperity helped mirror casting industry grow rapidly. This led to a unique and standardised Han mirror production system [2]. These bronze mirrors became iconic objects representing the Han culture. Through the empire’s cultural influence and trade networks, Han mirrors spread even far beyond China’s borders. Han mirrors and their replicas have been excavated in Central Asia, the southern European steppes, the Mongolian Plateau, Siberia, the Korean Peninsula, the Japanese Archipelago, and parts of Southeast Asia such as Vietnam and Thailand [3–5]. Therefore, Han mirrors are key materials for studying foreign exchanges during the Western Han.

The extensive excavation of Han mirrors both within and outside China has prompted widespread scholarly discussion regarding their provenance. Based on historical records, inscriptions on mirrors, and excavated mirror moulds, scholars generally consider Chang'an and Linzi to be the primary bronze mirror production centres during the Western Han. In addition, independent workshops may have existed in Guangling (Yangzhou, Jiangsu) and the Huainan Kingdom (Lu'an, Anhui) [6]. Among these, the ancient capital of the Qi state in Linzi is currently the unique production centre confirmed by archaeological excavations, evidenced by the discovery of mirror moulds and casting workshop sites (Figure 1) [7]. Han mirrors produced in Linzi were widely circulated both domestically and internationally. Therefore, identifying the distinct features of these mirrors is academically significant, as it provides a crucial basis for tracing their distribution and evaluating their overall influence.

In studying Linzi Han mirrors, scholars combined archaeological typology with spatial distribution patterns [8]. By comparing mirror moulds excavated in Linzi with Han mirrors nationwide, the core types of Han mirrors cast in Linzi were identified. Based on the distribution of stylistically similar mirrors, it can be inferred that Linzi-produced Han mirrors circulated throughout the entire Western Han empire and possibly reached as far as the Korean Peninsula and Kyushu, Japan. Recently, several studies have established an initial profile for Han mirrors via scientific analyses. These studies examined manufacturing techniques, alloy composition, and raw material sources, revealing that a roughly stable alloy composition was already in use [9,10]. However, an important research gap remains. While scholars have extensively discussed the sources of lead for these mirrors [11–13], an analysis of the copper sources is still lacking. Trace elements are believed to be reliable indicators for sourcing copper [14–16]. Building on previous research [17], this study uses trace element analysis as its primary method to provide a more detailed profile of Han mirrors produced in Linzi. This approach facilitates a deeper understanding of their production systems and circulation networks. Furthermore, the roughly stable alloy composition of these mirrors is highly relevant for interpreting the *Kaogong ji* (The Artificers' Record) [18], compiled during the Warring States and Han periods. Using a new dataset and the 'geometric median' statistical method, this study aims to reinterpret *Jin liuji* (The Six Recipes of Bronze).

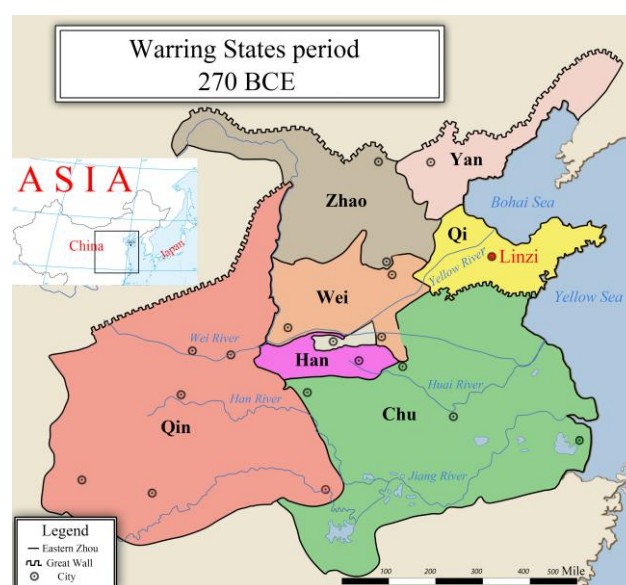


Figure 1. Location map of Linzi, the ancient capital of the Qi state, during the Warring States period (270 BCE). The red dot for 'Linzi' represents all three cemetery sites (Zonglvcheng, Xiangjianan, and Yafubei).

2. Materials and Methods

2.1. Materials

As the capital of the Qi state during the Warring States period and the administrative centre of the Qi kingdom in the Western Han, Linzi was the largest city in the east. During the Western Han, it was a prosperous metropolis described as being “larger and richer than Chang’an” and served as a major national centre for mirror casting. In recent years, many cemeteries have been excavated near Linzi. These primarily include the Zonglvcheng, Xiangjianan, and Yafubei cemeteries. Notably, the majority of these tombs belonged to commoners. In the socio-economic structure of the Han dynasty, commoners had limited purchasing power. Due to transport costs and limited circulation ranges, the bronze mirrors in their tombs were unlikely to come from long-distance trade or high-level official gifts [19]. Therefore, these mirrors were most likely bought from local workshops. This means the materials are mostly free from the influence of imported goods. They are capable of reflecting the production standard, raw material sources, and technical features of the local mirror industry in Linzi. This provides the necessary foundation for the analysis of product features.

Given that the bronze mirrors from the Zonglvcheng cemetery have already been analysed [10], this study focuses on 71 mirrors from the Xiangjianan (30) and Yafubei (41) cemeteries (Figure 1). In addition, to understand the technical origins and chronological changes in raw material supply for the mirror casting industry, we included the Warring States period bronze mirrors from the Yafubei cemetery for comparative analysis. This inclusion not only completes the chronological sequence of research in this area but also provides evidence for observing how mirror-making techniques of Qi state—such as standardisation of alloy composition and stable raw material selection—evolved from the Warring States period to the Western Han dynasty.

2.2. Methods

The excavated bronze mirrors in this study are relatively well-preserved. To achieve minimally destructive analysis, a portable X-ray fluorescence spectrometer (pXRF, Bruker Tracer 5 g, Kennewick, WA, USA) was used for in situ analysis on the sample surfaces. Corrosion products were mechanically removed from the plain surfaces using a handheld grinder equipped with carbide abrasive wheels (grit size 800) to have an area of metallic core of approximately 5 mm in diameter exposed. Three measurements were performed on each area, and the average was taken as the result. The instrument is equipped with a Rh thin window X-ray tube, the maximum voltage of 50 kV, and a graphene detector window of 1 µm. The emitted X-ray beam was collimated to 3 mm, and the calibration curve of ‘ancient copper’ supplied by the manufacturer was applied in this case. The spectra were acquired for 60 s using a Ti 25 µm Al 300 µm filter. The limit of detection (LOD) varies depending on the element but generally falls within the range of 0.001–0.03 wt%.

To ensure the precision and accuracy of the data, this study conducted an analysis on American Brammer Standard reference materials using testing conditions identical to those applied to the bronze mirror. The results are detailed in Supplementary S1. The measurement errors vary depending on the element content. The specific relative errors are presented in Supplementary S1. For major elements such as copper, tin, and lead with concentrations greater than 1 wt%, the error margin is approximately between 0.06% and 11%, with higher concentrations showing smaller relative errors. For trace elements (ranging between 0.001 wt% and 1 wt%) near their respective limits of detection, the relative error can mathematically inflate up to higher percentages (spans from 0.03% to 203%) due to the extremely low absolute concentrations. However, because the contents

of these trace elements are extremely low, errors of this level have a negligible impact. Therefore, the errors associated with major and trace elements do not significantly impact the discussions in this study.

It should be specifically noted that the characteristic X-ray $K\alpha$ line of arsenic highly overlaps with the $L\alpha$ line of lead, rendering the instrument unable to distinguish them accurately. Consequently, the arsenic content is subject to interference from the lead content within the sample, resulting in a positive error of the arsenic concentration. In this study, when the lead content exceeds 5 wt%, the relative error for arsenic can reach 166%; therefore, arsenic data for high-lead bronze mirrors must be interpreted with caution. However, the majority of the bronze mirrors in this study contain less than 7 wt% lead, while their arsenic contents generally exceed 0.2 wt%. Thus, the error has a limited impact on the results of the trace element grouping and does not constitute a substantive interference with the core discussions of this paper.

Statistical analysis was performed using OriginPro 2025 SR1. For the trace elements, Principal Component Analysis (PCA) was carried out after applying a log-transformation to the concentration data to handle the wide variance. For the alloy compositions (Cu-Sn-Pb), geometric median statistics were calculated using the Weiszfeld algorithm to minimize the sum of spatial Euclidean distances. This robust approach effectively reduces the weight of extreme compositional outliers caused by corrosion or anomalous recycling.

3. Results

The chemical composition of 71 bronze mirrors from the Yafubei and Xiangjianshan cemeteries in Linzi, dating from the Warring States to the Western Han periods, is presented in Table 1. Of these, one painted mirror (Tomb 1332:2 = M1332:2; Figure 2) underwent qualitative analysis on its decorative components. For the remaining 70 samples, complete and valid results for both major and trace elements were obtained.

Combining the previously published data from the Zonglvcheng cemetery [10], all 75 bronze mirrors from the three cemeteries in Linzi are Cu-Sn-Pb ternary alloys. Copper (Cu) content ranges from 59.2% to 87.7%. Tin (Sn) content ranges from 7.4% to 31.8%. Except for one Warring States sample (M1260:5, Sn 7.4%) with low tin, the majority of samples have tin levels concentrated between 20% and 30%. Lead (Pb) levels are relatively low, fluctuating between 2.0% and 11.0%, with most samples clustered in the 3–8% range.

Of the 70 bronze mirror samples with trace element data, the trace element concentrations are generally low, with the majority falling below 1%. Among the trace elements, arsenic (As) has the highest concentration and the greatest variation, ranging from 0.11% to 2.38%, with most samples clustering between 0.2% and 1.0%. Antimony (Sb) contents range from undetected to 0.81%, mostly falling within the 0.1% to 0.5% range. Silver (Ag) levels are relatively stable, ranging from undetected to 0.28%, with the majority concentrated in a narrow range of 0.1% to 0.2%. Nickel (Ni) levels are relatively low with minor fluctuations, ranging from 0.03% to 0.16%, and mostly fluctuate around the 0.1% classification threshold. For the other elements, the detected concentrations of bismuth (Bi), iron (Fe), and cobalt (Co) are extremely low, typically between 0.01% and 0.2%, with only occasional samples showing a relatively high iron content of 0.34%. Furthermore, gold (Au) is scarcely present in most mirrors, generally ranging between 0.01% and 0.07%. Overall, these samples show a typical chemical fingerprint characterised by high arsenic, high antimony, and high silver. In terms of trace element grouping using the Oxford system of copper groups and semi-quantitative analysis [20,21], this characteristic directly results in Groups 12 and 16 forming the majority of the entire sample set. There is much debate about using a 0.1% cutoff for this method [22]. However, for a stable data set, any cutoff or grouping method is a way to describe the data. Just as

newer methods later confirmed the Stuttgart data [23,24], many studies have also confirmed this method [25].

A painted mirror was also excavated from M1332 at Yafubei cemetery (Figure 2). This study conducted a preliminary analysis of its gold-coloured applique and pigments. It should be noted that the effective detection depth of a pXRF spectrometer varies depending on the element. Analysing thin-layer samples often leads to errors due to X-ray penetration. Therefore, specific quantitative values are not provided here; instead, the analysis is limited to qualitative spectral interpretation. The surface of the gold-coloured applique shows a golden lustre with no visible signs of corrosion. The results indicate a minimum Au content of 4% (Table 1), with the remaining composition being predominantly copper. Given the thinness of this applique, the detected copper signal highly likely includes components from the underlying bronze mirror matrix. A detailed spectral interpretation of this applique reveals a prominent Au $L\alpha$ characteristic peak at 9.71 keV (maximum count 13,224), accompanied by a minor Hg $L\alpha$ peak at 9.98 keV (maximum count 2170; Figure 3a). The coexistence of these Au and Hg peaks suggests that the applique on the mirror surface was most likely produced using the gold-amalgam gilding technique. Similarly, spectral analysis of the red pigment reveals a characteristic ‘double peak’ for Hg, with a primary Hg $L\alpha$ peak at 9.98 keV (maximum count 31,098) and a secondary Hg $L\beta$ peak at 11.82 keV (maximum count 20,014; Figure 3b). This means that the red pigment is probably cinnabar. Analysis of the white pigment shows a Pb content as high as 50%. Considering that lead white has been one of the most widely used white pigments since the Spring and Autumn period [26], it is highly probable that the white pigment on this mirror is lead white.

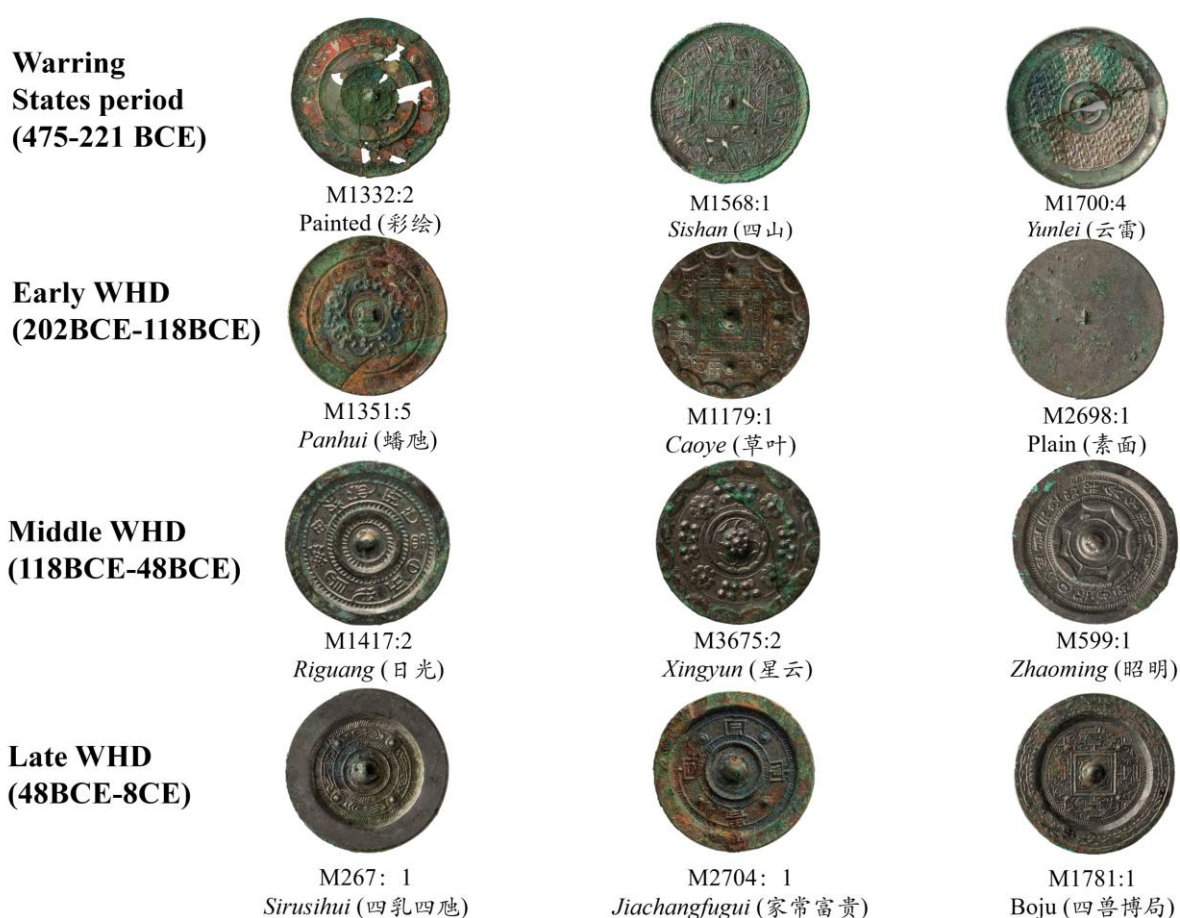


Figure 2. Representative bronze mirror samples of different periods used in this study.



Figure 3. XRF spectra of the attachments on the painted mirror excavated from M1332 at the Yafubei cemetery, Linzi. (a) detailed pXRF spectrum of the gold-coloured applique highlighting Au and Hg peaks; (b) spectrum of the red pigment showing characteristic Hg peaks.

Table 1. Normalised pXRF results (wt%) of bronze mirrors excavated from the Yafubei, Xiangjiana, and Zonglvcheng cemeteries in Linzi.

Context No.	Periods	Typology	Site	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Fe	Co	Au	Oxford Group
M1260:5	WS	Plain rectangular	Yafubei	87.7	7.4	4.1	0.22	0.07	0.28	0.13	0.02	0.01	0.05	0.01	G15
M1332:2	WS	Painted	Yafubei	/	/	/	/	/	/	/	/	/	/	>4	/
M1690:1	WS	<i>Sishan</i>	Yafubei	72.1	16.8	10.2	0.45	0.10	0.11	0.10	0.06	0.02	0.05	0.02	G16
M1568:1	WS	<i>Sishan</i>	Yafubei	73.1	23.9	2.5	0.16	0.00	0.07	0.11	0.03	0.03	0.05	0.01	G11
M161:1	WS	<i>Yunlei</i>	Yafubei	64.2	23.2	9.3	2.38	0.29	0.19	0.11	0.06	0.08	0.09	0.07	G16
M1700:4	WS	<i>Yunlei</i>	Yafubei	67.5	27.8	3.9	0.29	0.14	0.14	0.09	0.05	0.08	0.04	0.02	G12
M2659:6	WS	<i>Yunlei</i>	Yafubei	64.6	26.9	7.0	0.51	0.17	0.15	0.08	0.05	0.32	0.08	0.03	G12
M996:2	WS	<i>Yunlei</i>	Yafubei	59.2	29.0	9.5	1.24	0.24	0.21	0.12	0.07	0.09	0.24	0.05	G16
M2580:1	WS	<i>Caoye</i> with <i>Yunlei</i> grounded	Yafubei	68.4	24.0	6.6	0.28	0.15	0.15	0.08	0.04	0.24	0.04	0.02	G12
M3880:1	WS	<i>Panchi</i> with gold wire inlay	Yafubei	71.7	25.7	2.0	0.19	0.12	0.12	0.06	0.02	0.04	0.02	0.01	G12
M227:2	WS	Plain rectangular	Xiangjiana	73.2	21.2	4.9	0.22	0.06	0.06	0.07	0.02	0.01	0.02	0.01	G2
M462:4	WS	Plain rectangular	Xiangjiana	71.1	26.2	2.3	0.11	0.00	0.00	0.13	0.04	0.02	0.03	0.01	G11

M462:2	WS	Plain	Xiangjiana n	66.6	30.2	2.8	0.16	0.00	0.05	0.05	0.07	0.02	0.03	0.01	G2
M656:1	WS	Yunlei	Xiangjiana n	60.9	31.8	6.0	0.63	0.19	0.19	0.06	0.06	0.11	0.03	0.03	G12
M265:1	WS	Panhui	Zonglvche ng	64.0	24.0	11.0	/	/	/	/	/	/	/	/	/
M1210:1	EWB	Plain	Yafubei	66.3	24.2	8.2	0.73	0.19	0.15	0.09	0.05	0.02	0.03	0.03	G12
M1218:1	EWB	Plain	Yafubei	68.1	23.7	7.0	0.42	0.14	0.14	0.10	0.10	0.19	0.06	0.02	G16
M1227:4	EWB	Plain	Yafubei	66.2	29.4	3.7	0.30	0.06	0.11	0.04	0.04	0.11	0.05	0.02	G9
M1770:1	EWB	Plain	Yafubei	66.0	26.6	6.4	0.41	0.13	0.15	0.08	0.05	0.09	0.06	0.02	G12
M2064:1	EWB	Plain	Yafubei	75.9	19.5	4.0	0.24	0.06	0.07	0.16	0.02	0.02	0.06	0.01	G11
M2514:3	EWB	Plain	Yafubei	67.9	26.0	5.3	0.24	0.11	0.11	0.09	0.05	0.13	0.03	0.01	G12
M2698:1	EWB	Plain	Yafubei	71.3	21.3	6.7	0.23	0.09	0.09	0.10	0.04	0.04	0.09	0.01	G11
M206:2	EWB	Plain	Xiangjiana n	67.2	28.6	3.3	0.21	0.15	0.11	0.10	0.08	0.09	0.04	0.02	G16
M277:2	EWB	Plain	Xiangjiana n	73.0	22.7	3.8	0.20	0.00	0.09	0.10	0.03	0.04	0.05	0.01	G11
M460:2	EWB	Plain	Xiangjiana n	65.1	27.7	6.2	0.29	0.20	0.10	0.09	0.06	0.14	0.04	0.03	G12
M505:1	EWB	Plain	Xiangjiana n	65.1	26.4	7.3	0.54	0.19	0.15	0.08	0.04	0.09	0.03	0.02	G12
M514:1	EWB	Plain	Xiangjiana n	68.5	23.2	7.4	0.25	0.14	0.14	0.08	0.05	0.13	0.03	0.02	G12
M59:2	EWB	Plain	Xiangjiana n	70.7	24.1	4.5	0.28	0.12	0.12	0.08	0.06	0.04	0.03	0.02	G12
M1351:5	EWB	Panhui	Yafubei	63.8	26.6	8.3	0.65	0.27	0.13	0.03	0.08	0.09	0.03	0.02	G12
M253:2	EWB	Panhui	Xiangjiana n	69.0	18.8	9.6	1.34	0.73	0.13	0.11	0.06	0.08	0.05	0.04	G16
M1179:1	EWB	Caoye	Yafubei	66.6	25.3	6.4	0.71	0.39	0.11	0.10	0.12	0.05	0.13	0.03	G16
M1625:1	EWB	Caoye	Yafubei	68.1	23.0	7.1	0.53	0.58	0.13	0.12	0.06	0.16	0.06	0.03	G16
M46:2	EWB	Caoye	Yafubei	67.1	25.5	5.7	0.56	0.44	0.23	0.11	0.15	0.10	0.06	0.03	G16
M101:1	EWB	Caoye	Xiangjiana n	67.8	24.5	5.9	0.82	0.39	0.09	0.09	0.08	0.14	0.11	0.04	G6
M168:2	EWB	Caoye	Xiangjiana n	67.1	24.0	6.8	0.79	0.55	0.14	0.12	0.12	0.11	0.13	0.04	G16
M123:1	EWB	Panchi	Xiangjiana n	67.1	24.7	7.2	0.38	0.15	0.15	0.09	0.05	0.14	0.04	0.02	G12
M125:1	EWB	Panchi	Xiangjiana n	70.6	23.6	5.0	0.32	0.13	0.12	0.08	0.05	0.11	0.04	0.01	G12
M155:1	EWB	Panchi	Xiangjiana n	68.3	27.2	3.8	0.28	0.08	0.11	0.08	0.07	0.08	0.04	0.02	G9
M37:1	EWB	Huaye	Xiangjiana n	74.0	18.7	6.2	0.48	0.25	0.16	0.03	0.04	0.13	0.02	0.01	G12
M389:1	EWB	Huaye	Xiangjiana n	66.2	28.2	4.8	0.26	0.14	0.14	0.09	0.06	0.08	0.04	0.02	G12
M1108:1	MWB	Zhaoming	Yafubei	70.2	23.5	4.9	0.49	0.41	0.10	0.11	0.09	0.06	0.14	0.02	G16
M599:1	MWB	Zhaoming	Yafubei	68.5	24.5	5.6	0.56	0.40	0.14	0.10	0.13	0.03	0.11	0.03	G16
M211:1-1	MWB	Zhaoming	Xiangjiana n	68.7	22.9	6.8	0.54	0.40	0.10	0.10	0.07	0.15	0.12	0.03	G16
M1121:1	MWB	Inscribed with multiple concentric rings	Yafubei	67.6	24.5	6.5	0.47	0.37	0.09	0.16	0.16	0.05	0.10	0.02	G14
M1283:3	MWB	Riguang with linked-arc	Yafubei	64.5	26.8	7.2	0.58	0.35	0.13	0.09	0.07	0.18	0.11	0.03	G12
M1417:2	MWB	Riguang	Yafubei	63.9	27.7	6.5	0.80	0.50	0.14	0.12	0.14	0.09	0.12	0.03	G16
M2216:2	MWB	Riguang with linked-arc	Yafubei	68.6	24.1	6.1	0.38	0.28	0.14	0.09	0.08	0.07	0.07	0.02	G12

M322:1	MWH	Riguang with linked-arc	Yafubei	69.6	24.1	4.8	0.63	0.45	0.10	0.11	0.07	0.04	0.13	0.03	G16
M3533:1	MWH	Riguang with Concentric-band	Yafubei	67.5	24.2	6.7	0.60	0.40	0.12	0.11	0.10	0.14	0.11	0.03	G16
M193:2	MWH	Riguang with Concentric-band	Zonglvcheng	73.0	22.0	5.0	/	/	/	/	/	/	/	/	/
M261:2	MWH	Riguang with Concentric-band	Zonglvcheng	68.0	27.0	5.0	/	/	/	/	/	/	/	/	/
M1338:2	MWH	Xingyun	Yafubei	65.1	28.4	4.6	0.80	0.47	0.13	0.11	0.10	0.06	0.10	0.04	G16
M2509:2	MWH	Xingyun	Yafubei	63.4	26.8	7.9	0.96	0.48	0.11	0.10	0.13	0.05	0.09	0.04	G16
M3675:2	MWH	Xingyun	Yafubei	66.0	25.2	7.0	0.80	0.44	0.10	0.11	0.09	0.14	0.14	0.03	G16
M24:2	MWH	Xingyun	Xiangjiana	63.9	26.4	7.6	0.94	0.50	0.17	0.10	0.14	0.11	0.09	0.03	G16
M243:4	MWH	Xingyun	Xiangjiana	68.2	23.7	6.5	0.60	0.42	0.10	0.10	0.10	0.09	0.10	0.03	G16
M316:2	MWH	Xingyun	Xiangjiana	66.8	25.6	6.0	0.62	0.42	0.11	0.09	0.10	0.12	0.09	0.03	G12
M530:1	MWH	Xingyun	Xiangjiana	66.5	26.8	4.7	0.66	0.44	0.09	0.11	0.16	0.34	0.19	0.03	G14
M275:3	MWH	Loong	Xiangjiana	65.7	26.8	6.3	0.46	0.24	0.12	0.09	0.04	0.07	0.05	0.03	G12
M597:2	MWH	Caoye	Xiangjiana	65.5	29.7	3.1	0.53	0.47	0.17	0.12	0.07	0.16	0.06	0.03	G16
M1781:1	LWH	Boju	Yafubei	68.2	27.7	2.8	0.44	0.43	0.16	0.07	0.04	0.05	0.03	0.02	G12
M334:2	LWH	Boju	Xiangjiana	66.1	25.1	7.3	0.57	0.33	0.15	0.11	0.05	0.19	0.06	0.03	G16
M267:1	LWH	Siru Panhui	Yafubei	70.5	23.0	5.1	0.51	0.33	0.16	0.08	0.05	0.05	0.07	0.02	G12
M126:2	LWH	Siru Panhui	Yafubei	68.4	25.1	5.2	0.47	0.24	0.12	0.08	0.05	0.32	0.05	0.02	G12
M1786:1	LWH	Siru Panhui	Yafubei	67.3	24.1	7.2	0.59	0.36	0.15	0.08	0.06	0.05	0.07	0.03	G12
M3643:1	LWH	Siru Panhui	Yafubei	68.6	25.0	5.2	0.38	0.41	0.12	0.06	0.05	0.07	0.06	0.02	G12
M1373:1	LWH	Jiachangfugui	Yafubei	69.3	22.2	7.1	0.62	0.36	0.10	0.09	0.04	0.04	0.11	0.02	G12
M2103:2	LWH	Jiachangfugui	Yafubei	63.7	23.4	10.7	0.92	0.46	0.28	0.10	0.10	0.12	0.13	0.04	G16
M2704:1	LWH	Jiachangfugui	Yafubei	68.3	21.4	8.3	1.06	0.37	0.13	0.09	0.04	0.15	0.08	0.04	G12
M3680:1	LWH	Jiachangfugui	Yafubei	66.4	25.0	6.1	1.33	0.55	0.13	0.10	0.07	0.12	0.12	0.04	G16
M152:1	LWH	Jiachangfugui	Xiangjiana	68.9	24.8	4.7	0.59	0.50	0.11	0.08	0.06	0.09	0.09	0.03	G12
M219:1	LWH	Qinshou	Xiangjiana	63.5	25.8	8.7	1.11	0.17	0.15	0.10	0.06	0.28	0.09	0.04	G16
M416:4	LWH	Qinshou	Xiangjiana	67.8	25.3	5.2	0.65	0.58	0.20	0.04	0.05	0.06	0.03	0.03	G12
M89:2	LWH	Qinshou	Xiangjiana	69.2	22.1	8.0	0.33	0.07	0.08	0.06	0.04	0.05	0.03	0.02	G2
M25:1	LWH	Riguang with linked-arc	Zonglvcheng	72.0	25.0	3.0	/	/	/	/	/	/	/	/	/
M276:1	LWH	Zhaoming with linked-arc	Zonglvcheng	68.0	28.0	3.0	/	/	/	/	/	/	/	/	/

Note: Major element data for bronze mirrors from the Zonglvcheng cemetery are sourced from [10]; data for some mirrors from the Xiangjiana cemetery are sourced from [27]; WS, EWH, MWH and LWH refer to the Warring States, the early, middle and late Western Han. The general limit of detection (LOD) ranges from 0.001 to 0.03 wt%, with relative analytical errors around 2% for major elements and varying for trace elements near the LOD; detailed values for each tracked element are provided in Supplementary Material S1.

4. Discussion

4.1. The Six Recipes of Bronze

The *ZhouLi* (Rituals of Zhou), or more accurately the *ZhouGuan* (Institutions of the Zhou), is one of the earliest ancient Chinese materials to be translated into Western languages. Within the *ZhouLi*, the *Kaogong ji* (The Artificers' Record) holds a unique position. It is generally believed to have been inserted into the *ZhouLi* during the mid-Western Han dynasty to replace a missing section concerning artisan officials [28]. Modern research on the *Kaogong ji*, both within China and internationally, frequently centres on the *Jin liuji* (The Six Recipes of Bronze), which details the specific copper-to-tin ratios for various bronze objects (Table 2) [29]. Over the past century, scholars have interpreted these recipes from two primary perspectives, namely evaluating the metallurgical rationale of the copper-to-tin ratios, and back-calculating these ratios from the compositional analysis of excavated bronzes. Consequently, four mainstream interpretations of the *Jin liuji* have emerged.

We can illustrate these using the recipes for *Zhongding* (bells and cauldrons) and *Jiansui* (mirrors and burning mirrors) as examples. The first interpretation proposes that the recipe for *Zhongding*—‘divide the metal into six parts, with tin occupying one’ (六分其金而锡居其一)—indicates a copper-to-tin ratio of 5:1 (meaning six parts in total). The second interpretation argues that this phrase signifies a ratio of 6:1. The third interpretation, focusing on the recipe for *Jiansui*—‘metal and tin are halved’ (金锡半, i.e., tin is half of the metal)—suggests a copper-to-tin ratio of 2:1. The fourth interpretation offers a middle ground, suggesting that the true ratios likely fall somewhere between the first and second interpretations.

Table 2. The four interpretations of the *Jin liuji*.

Typology	First Interpretation	Second Interpretation	Third Interpretation	Fourth Interpretation
Recipe for bells and cauldrons (钟鼎之齐)	Sn = 16.67%	Sn = 14.29%	Sn = 14.29%	Sn = 16.7~14.3%
Recipe for axes and hatchets (斧斤之齐)	Sn = 20%	Sn = 16.67%	Sn = 16.67%	Sn = 20.0~16.7%
Recipe for dagger-axes and halberds (戈戟之齐)	Sn = 25%	Sn = 20%	Sn = 20%	Sn = 25.0~20.0%
Recipe for large blades (大刀之齐)	Sn = 33.33%	Sn = 25%	Sn = 25%	Sn = 33.3~25.0%
Recipe for knives and arrows (削杀矢之齐)	Sn = 40%	Sn = 28.57%	Sn = 28.57%	Sn = 40.0~28.6%
Recipe for mirrors and burning mirrors (鉴燧之齐)	Sn = 50%	Sn = 50%	Sn = 33.33%	Sn = 50%

Furthermore, differing interpretations of *Jin* (金, Gold, actually refers to copper) and *Xi* (锡, Tin) further complicate these recipes. For instance, some researchers have recently proposed that both *Jin* and *Xi* refer to pre-prepared copper-rich ingots rather than high-purity copper or tin [30]. A more precise definition of *Jin* and *Xi* can perhaps be drawn directly from the scientific analysis on excavated ingots.

Ancient copper ingots, primarily found in ore-rich regions such as Anhui, Hubei, Ningxia, and Guizhou, consist almost exclusively of pure copper or copper containing some iron, with no tin or lead (Supplementary S1) [31–38]. In addition, excavated tin ingots typically contain no copper but almost always include a certain amount of lead; high-purity tin ingots are rare [31,32]. Most tin ingots found across Hubei and Shandong contain over 90% tin and at least 6% lead, and tin objects similarly contain varying amounts of lead. Additionally, solders of the Eastern Zhou dynasty (770 BCE–221 BCE)

are primarily composed of tin and lead, with copper rarely detected [39]. In summary, archaeological evidence suggests that *Jin* is best understood as pure copper containing minor impurities, while *Xi* refers to the combined content of tin and lead rather than pure tin.

Extensive research indicates that the *Kaogong ji* was an official document of the Qi state during the Eastern Zhou or Han dynasties. This implies that the empirical knowledge compiled for various artisanal sectors is primarily based on the contemporary practices of the Qi state and may not necessarily be applicable to other regions and eras. Some scholars even suggest that the *Jin liuji* merely reflects the alloy proportions for vessels used exclusively by the elite [40]. Consequently, attempting to validate the authenticity of the *Jin liuji* using scientific data from bronzes excavated in other periods and regions is highly debatable.

From this perspective, the bronze mirrors excavated from Linzi, the capital of the Qi state during the Eastern Zhou and Han dynasties, are of significant value for interpreting *Jin liuji*. As shown by the box plots in Figure 4, across different periods from the Warring States to the Western Han, the median copper content of Linzi mirrors is approximately 67%, the median tin content is about 24%, and the median lead content is around 5–6%, resulting in a Cu:Sn:Pb ratio of roughly 14:5:1.

Given that ancient bronze composition data often contain extreme outliers caused by burial conditions or specific surface treatments, this study utilises the geometric median rather than the conventional arithmetic mean to characterise the central tendency of alloy compositions. By minimising the sum of spatial Euclidean distances, the geometric median effectively filters out the weighted interference of anomalous samples (such as rare high-copper, low-tin mirrors) [41], thereby providing a more objective reflection of the core technical recipes used by Han dynasty craftsmen. The geometric median derived from a large sample set likely represents the expected alloy ratio intended by the artisans. However, the actual casting process was susceptible to factors such as impure metal ingots, melt segregation during solidification, loss through oxidation, and operational errors, leading to minor deviations in the end products.

In this study, the geometric median was calculated following data normalisation. The geometric median for the Linzi bronze mirrors from the Warring States to Han periods is 68.61% copper, 25.23% tin, and 6.15% lead. This ratio essentially aligns with the third interpretation of the *Jiansui* recipe in the *Kaogong ji*—‘metal and tin are halved’—provided that *Xi* is understood as the sum of tin and lead. This also provides a rational explanation for why lead, an extensively used alloying element of the Chinese Bronze Age, was not mentioned separately in the *Jin liuji* [42]. Furthermore, this specific alloy composition ensures the superior mechanical properties required for long-term daily use and cross-regional circulation [10].

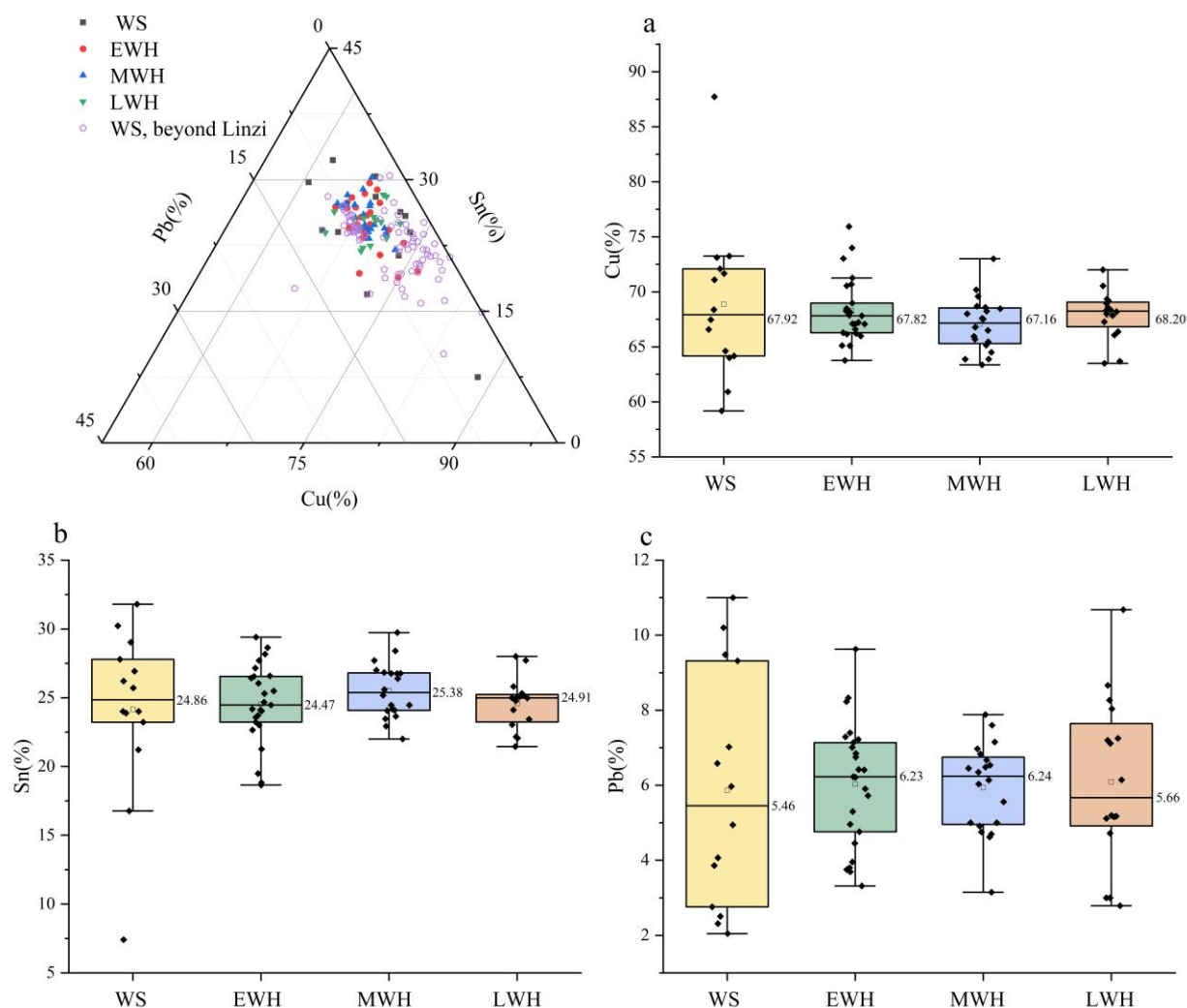


Figure 4. Major element characteristics of bronze mirrors from the Warring States to Western Han periods excavated in Linzi. Ternary plot showing Cu–Sn–Pb alloy compositions (top-left); (a) boxplot showing variations in copper (Cu) content; (b) boxplot showing variations in tin (Sn) content; (c) boxplot showing variations in lead (Pb) content. Inside the boxes, horizontal lines and open squares represent median and mean values, respectively. WS, EWH, MWH and LWH refer to the Warring States, the early, middle and late Western Han, respectively.

The preceding discussion indicates that validating the *Jin liuji* requires substantial support from high-quality data from the Qi state, or at least the Qi region, during the Eastern Zhou period. Given that the currently available data on Qi bronzes are limited and predominantly focus on *Zhongding* (bells and cauldrons), this study compiled chemical composition data for 77 *Zhongding* artefacts of tombs of the nobles from the Qi region (Supplementary S1) [31–38]. After normalising these data and calculating the geometric median, the composition stands at 82.75% copper, 13.31% tin, and 3.94% lead, yielding a combined tin and lead (*Xi*) content of 17.27%. When compared to the first interpretation—where the combined tin and lead content is 16.67%—the measured value differs by a mere 0.6%, indicating a close match. Conversely, under the second interpretation, the combined tin and lead content would be 14.29%, which shows a significant discrepancy from the measured data.

The data from this study demonstrate that one should not attempt to forcefully reconcile the *Jin liuji* in the *Kaogong ji* through a single mathematical model. Different

bronze artefacts possess distinct physical requirements; for instance, mirrors prioritise reflectivity and hardness, whereas *Zhongding* necessitate specific acoustic properties and toughness. Coupled with potential semantic variations among ancient craftsmen regarding the terms *Jin* and *Xi* (whether denoting pure metals or specific alloys), these factors result in the textual records being open to multiple mathematical interpretations.

The measured data presented here clearly reveal that *Zhongding* artefacts (with a combined tin and lead content of approximately 16–17%) align with the first interpretation, whereas bronze mirrors (with a combined content of approximately 31–33%) correspond closely with the third interpretation. This demonstrates that excavated materials serve as an optimal benchmark for calibrating ancient textual records. The true nature of the *Jin liuji* is not a rigid mathematical formula, but rather a flexible technological standard grounded in practical metallurgy and tailored to the specific function of each artefact.

4.2. Diachronic Variations in Major and Trace Element Characteristics and Copper Provenance

The chemical composition analysis results for the bronze mirrors excavated from the Yafubei and Xiangjiaan cemeteries in Linzi are presented in Table 1. To conduct a comparative analysis, this study also compiled previously published chemical composition data for bronze mirrors from the Zonglvcheng cemetery [10].

As illustrated by the ternary diagram in Figure 4, the copper, tin, and lead data for the Warring States bronze mirrors excavated in Linzi have a higher degree of dispersion compared to those from the Western Han dynasty. This pattern is not unique to the Linzi region; Warring States bronze mirrors excavated from other regions in China show similar characteristics [1,12,43–55]. The box plots in Figure 4 support this point. The boxes representing the copper, tin, and lead contents of Warring States mirrors are noticeably wider, further substantiating the greater data dispersion. This high degree of data dispersion suggests that mirror-casting artisans of the Warring States period had not yet established unified alloy recipes, or were still in an exploratory phase regarding the optimal alloy recipe for bronze mirrors.

A comparative data analysis reveals that the geometric medians for 80 Warring States bronze mirrors found in other regions of China are approximately 72.18% copper, 23.01% tin, and 4.82% lead. This recipe differs from that of the Warring States mirrors excavated in Linzi, which yield geometric medians of 68.87% copper, 25.35% tin, and 5.81% lead — values that are similar to those of Western Han mirrors from Linzi (Cu 68.59%; Sn 25.23%; Pb 6.15%). On the one hand, this further validates that the *Jin liuji* represents a summation of bronze manufacturing experience specific to the Qi state and may only be applicable within its borders. On the other hand, it indicates that by the Warring States period at the latest, mirror-casting workshops in Linzi had largely deduced an appropriate alloy recipe for mirror production. However, because they were still in an exploratory phase, their control over the copper, tin, and lead ratios remained somewhat inconsistent. By the Western Han period, artisans inherited and refined this traditional alloy recipe, achieving far more stable control over the alloy proportions.

For trace elements in the bronzes, this study employs a 0.1% threshold to determine the presence or absence of arsenic, antimony, silver, and nickel, classifying the samples accordingly (Figure 5) [56]. Given that copper is the primary raw material in bronze casting, whilst tin is often relatively pure and lead is used in smaller quantities in mirrors, trace elements are typically regarded as tracers for copper provenance [38]. While the Oxford system of copper groups provides a useful heuristic framework for identifying diachronic shifts in metal circulation, it is important to acknowledge the ongoing academic debate regarding its geochemical assumptions and the use of a fixed 0.1% threshold [57]. In this study, we employ this classification not as a definitive tool for ore provenance, but rather as a complementary exploratory data analysis method. To ensure

the robustness of our conclusions, the grouping results are cross-validated with PCA and geometric median statistics.

As shown in Figure 5, although the trace element groupings of bronze mirrors from the Warring States and Western Han periods differ slightly, G12 and G16 consistently remain the ‘core groups’. Specifically, during the Warring States period, minor amounts of G2, G11, and G15 were present alongside the core groups, with G15 being exclusive to this period. In the early Western Han, minor amounts of G6, G9, and G11 were also present, with G6 and G9 being unique to this phase. Furthermore, small quantities of G14 appeared in the middle Western Han, and G2 in the late Western Han. The overall dominance of G12 and G16 across all periods reflects a generally stable copper supply system for the mirror-casting workshops in Linzi.

Conversely, the relatively complex trace element groupings in the Warring States and early Western Han periods imply that copper sources during these stages may have been more diverse, or could be linked to the recycling and remelting of scrap bronze. Notably, the G11 samples from the early Western Han period are all plain mirrors. The use of these raw materials was prevalent during the Warring States period, suggesting that these plain mirrors were either cast earlier or produced using old copper stock from the Warring States period. This conclusion corroborates previous findings from lead isotope analyses of Linzi bronze mirrors [10,27]. By comparison, the trace element groups in the middle and late Western Han periods are relatively stable, with G12 and G16 collectively accounting for over 88% of the samples. This indicates that copper sources for Linzi mirror-casting workshops likely became more concentrated and the supply more stable during the mid-to-late Western Han period.

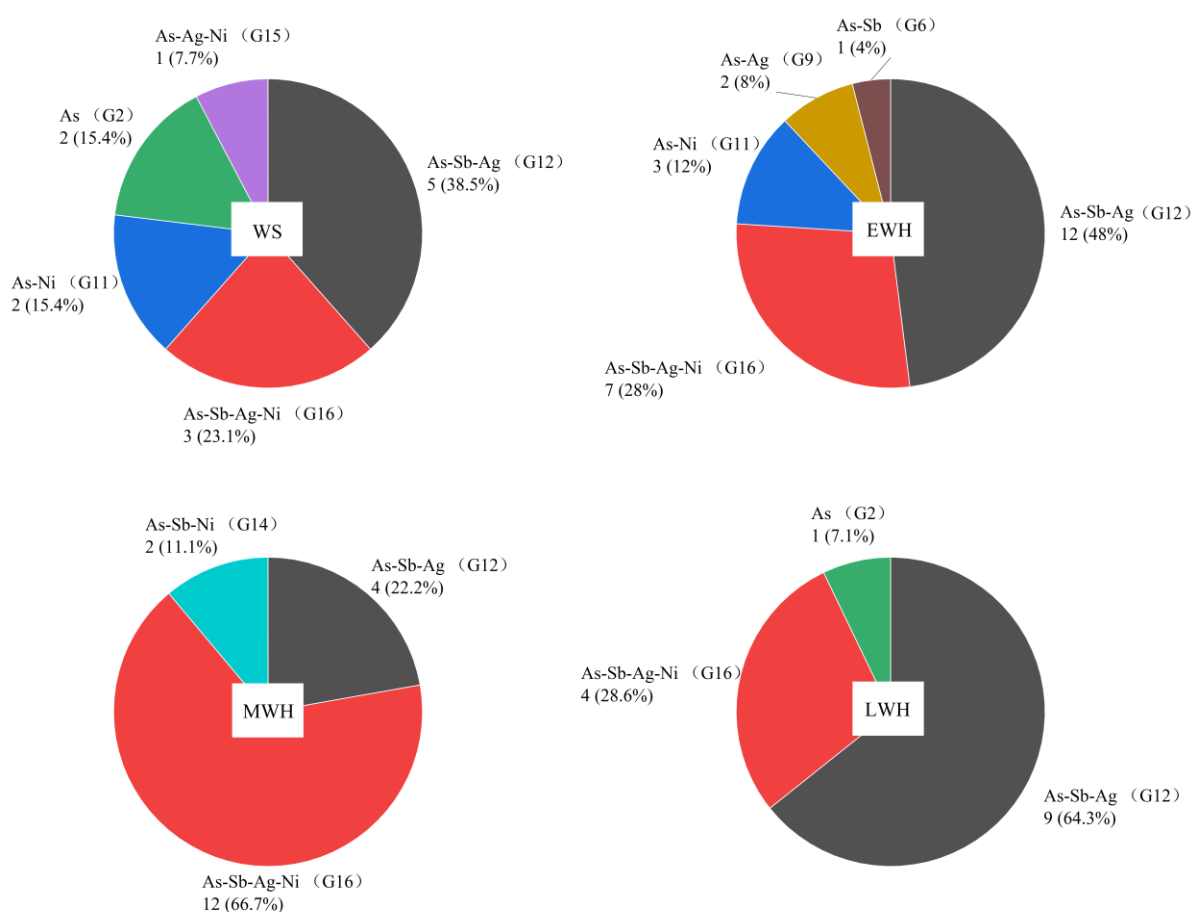


Figure 5. Trace element groupings of bronze mirrors excavated in Linzi. WS, EWH, MWH and LWH refer to the Warring States, the early, middle and late Western Han, respectively.

The diachronic change of the trace element levels in bronze mirrors from the Warring States to the Western Han periods is further illustrated in Figure 6a. In conjunction with Table 1, it is evident that the trace element contents in Warring States bronze mirrors show a wide range of fluctuation. Arsenic content varies from 0.11% to 2.38%; antimony in nearly half of samples is below 0.1%, with some samples slightly exceeding this threshold; and nickel fluctuates around 0.1%. The overall distribution range is broader than that of mirrors from any phase of the Western Han. These characteristics further corroborate that the provenance of copper in the Qi state during the Warring States period was diverse and unstable. On the one hand, multiple small-scale copper mines with distinct geological features around the Qi state may have been exploited simultaneously; on the other hand, frequent warfare might have led to the widespread recycling and remelting of scrap bronze, thereby manifesting diversity in the trace element compositions.

During the early Western Han, the trace element characteristics underwent a distinct shift. Arsenic and silver became the dominant trace elements, with the majority of samples containing over 0.2% As and over 0.1% Ag. Simultaneously, a batch of high-antimony samples emerged (e.g., 0.73% for M253:2 and 0.58% for M1625:1), although a small number of samples still have antimony contents below 0.1%. This implies that during the early Western Han, some local copper mines from the former Qi state might still have been in use, whilst a new type of copper ore rich in arsenic, antimony, and silver was being introduced, indicating a transitional phase in ore supply.

By the middle and late Western Han, trace element contents became highly stable. Arsenic stabilised at a high range of 0.4–1.3%; antimony was almost entirely above 0.1%, concentrating between 0.3% and 0.5%; silver stabilised at 0.10–0.17%; and nickel dropped and stabilised below 0.1% in the majority of cases. This suggests that the copper provenance for Linzi bronze mirrors became highly concentrated and the supply stable during the mid-to-late Western Han period. Although elements such as bismuth, iron, cobalt, and gold show certain fluctuations across different periods, their overall variation trends are similar to those of the core tracer elements (As, Sb, and Ag) and thus will not be elaborated upon further.

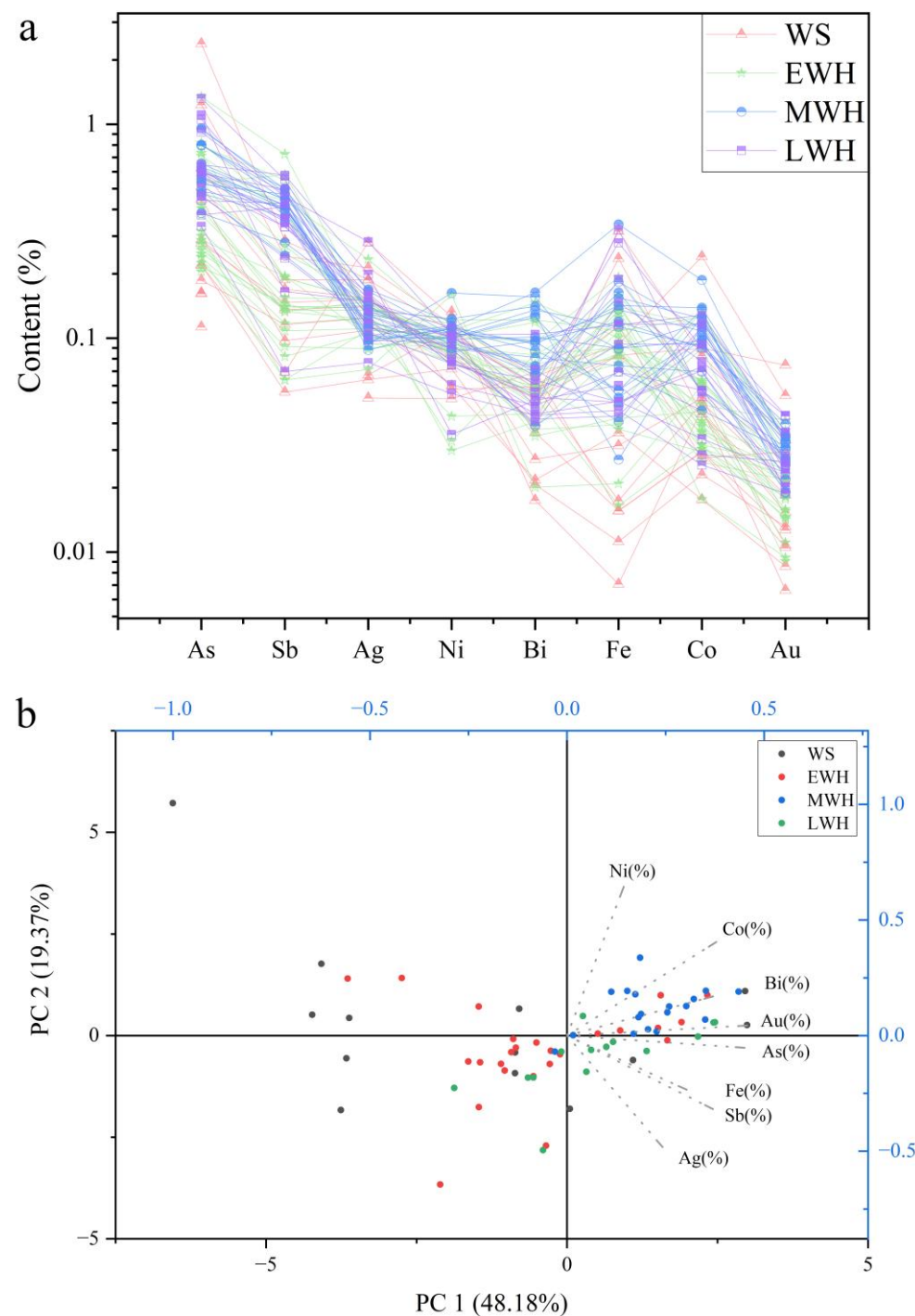


Figure 6. Trace element composition diagram of bronze mirrors excavated in Linzi. (a) Diachronic trace element patterns of mirrors from Warring States to late Western Han; (b) PCA biplot demonstrating sample clusters and element loading vectors based on trace element concentrations. WS, EWH, MWH and LWH refer to the Warring States, the early, middle and late Western Han.

The results of the Principal Component Analysis (PCA) for trace elements display similar characteristics. The data points representing mirrors of the Warring States period demonstrate a high degree of dispersion, with only a subset of data showing a clustering trend along the negative PC1 axis (Figure 6b). Both the mixing of ores from various small-scale mines and the remelting of metal stocks contribute to this high variance and data dispersion. Driven by the increased contents of As, Sb, and Ag, the data distribution in the early Western Han shifts away from the scattered pattern observed in the Warring States samples; while partial overlap with Warring States data remains along the negative

PC1 axis, an overall shift towards the right (positive PC1) is evident. Furthermore, as this was a transitional phase between old and new copper supplies (retaining some samples from inventory or low-antimony sources), the early Western Han data points begin to concentrate, yet their distribution remains slightly broader than that of the middle and late phases, representing a tightening trend. By the middle and late Western Han, the data points become increasingly clustered, highlighting the growing consistency in the trace element compositions of bronze mirrors. Notably, during the middle Western Han, almost all data points converge within the first quadrant of the PCA plot.

In summary, the trace element analysis demonstrates that the copper provenance for the bronze mirrors excavated in Linzi underwent three distinct phases, namely a diverse and dispersed phase during the Warring States period, which even relied on the remelting of metal stocks; a transitional phase in the early Western Han; and finally, a rapid shift towards a uniform, stable, and concentrated supply beginning in the middle Western Han. Previous studies have indicated that, driven by state economic intervention policy during the Western Han dynasty, the lead provenance for bronze mirrors similarly achieved greater stability by the middle Western Han [10,58]. This indicates that the impact of such state economic interventions was far-reaching, encompassing not only lead but also copper resources.

5. Conclusions

Through scientific analyses of the bronze mirrors excavated in Linzi, this study reveals the technological traditions and raw material transitions of the mirror-casting industry from the Warring States period to the Western Han dynasty. The results demonstrate that the casting process of Linzi bronze mirrors maintained a stable copper–tin–lead ratio, with clear continuity across different periods. This differs from the alloy recipes of bronze mirrors from other regions at least since the Warring States period, further evidencing the close connection between the *Jin liuji* specifications in the *Kaogong ji* and the metallurgical traditions of the Qi region.

The trace element analyses clearly reveal the changing dynamics of the copper supply network. It underwent a diverse and dispersed phase during the Warring States period, followed by a transitional phase in the early Western Han period, and ultimately shifted towards a uniform and stable supply model during the middle and late Western Han periods. This transition serves as a material manifestation of the unified political and economic framework of the Western Han dynasty within the artisanal sector.

Constrained by the requirements for minimally destructive analysis, this study primarily utilised pXRF to extract elemental characteristics. Notably, the trace element data in this study are only comparable under the exact same analytical conditions. Constrained by this, we did not conduct broader comparative research here. Future research could further incorporate high-precision quantitative analyses of trace elements alongside lead and copper isotopic analyses, broadening the scope to include excavated materials from other major mirror-casting centres of the Han dynasty (such as Chang'an, Guangling, and the Huainan Kingdom). This will facilitate the construction of a high-resolution database of Han dynasty bronze products, enabling a comprehensive reconstruction of both the cross-regional circulation networks of Han bronze mirrors and the macro-level distribution patterns of metal resources across the unified empire.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/heritage9070289/s1>. Table S1: Analytical dataset containing: (Sheet 1) accuracy, detection limits, and relative errors of pXRF measurements using certified reference materials; (Sheet 2) chemical compositions and lead isotope ratios of comparative ingots

and Zhongding bronze vessels; (Sheet 3) elemental compositions and archaeological metadata of comparative bronze mirrors compiled from published literature.

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Data Availability Statement: The datasets used and analysed during the current study are available from the corresponding author upon reasonable request.

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Reference

- Chen, D.; Zeng, Q.S.; Cui, B.X.; Luo, W. Source change of lead materials for mirror-making industry in Western Han, China: Evidence from Nanyang bronze mirrors. *Curr. Sci.* **2020**, *118*, 1442–1448.
- Takakura, H.; Teng, M.Y. Han dynasty bronze mirrors and the East Asian world. *Res. China's Front. Archaeol.* **2004**, *00*, 115–125.
- Bai, Y.X. Discovery and understanding of Han-style bronze mirrors in Central Asia. *Cult. Relics* **2010**, *1*, 78–86.
- Yang, Y. Han dynasty cultural relics unearthed in Southeast Asia and the Maritime Silk Road in the Han dynasty. *Sichuan Cult. Relics* **2023**, *4*, 75–87.
- O'Sullivan, R.; Shao, H. Exploring Complexity in Bronze Age Exchange Networks by Revisiting the Bronze Mirrors of Central Asia and China. *Camb. Archaeol. J.* **2024**, *34*, 385–402.
- Kong, X.X.; Liu, Y.S. *Ancient Chinese Bronze Mirrors*; Cultural Relics Press: Beijing, China, 1984.
- Institute of Archaeology CASS; Shandong Provincial Institute of Cultural Relics and Archaeology; Qi Culture Development Research Center of Linzi District. *Archaeology of Metallurgy and Casting Industry in Qi City of Linzi*; Science Press: Beijing, China, 2020.
- Bai, Y.X. On the method of inferring the provenance of archaeological remains based on style and distribution. *Archaeology* **2016**, *9*, 77–90.
- Zhangsun, Y.Z.; Liu, R.L.; Jin, Z.Y.; Pollard, A.M.; Lu, X.; Bray, P.; Fan, A.C.; Huang, F. Lead isotope analyses revealed the key role of Chang'an in the mirror production and distribution network during the Han Dynasty. *Archaeometry* **2017**, *59*, 685–713.
- Gao, J.; Dong, W.; Wu, X.; Wang, X.; Huang, F.; Wang, Q. Technical and economic history of western Han dynasty revealed by bronze mirrors from Zonglvcheng cemetery, Linzi, China. *Archaeol. Anthropol. Sci.* **2024**, *16*, 73.
- Cui, J.F.; Wu, X.H.; Bai, Y.X.; Huang, B.; Guli, B. Lead isotope ratio analysis of Western Han bronze mirrors excavated from the ancient Qi city site in Linzi, Shandong. *Archaeology* **2009**, *4*, 85–89.
- Wang, X.; Liu, R.; Gao, J.; Pollard, A.M.; Fan, A.; Huang, F.; Li, R.; Zhang, S.; Hua, F. Reconstructing the trade history: Provenance study of Han bronze mirrors in and out of Han China. *Archaeol. Anthropol. Sci.* **2024**, *16*, 110.
- Luo, Z.; Liu, R.; Pollard, A.M.; Jin, Z.; Liu, L.; Gu, Y.; Xu, Y.; Guo, R.; Huang, F.; Fan, A. High-precision chronology and scientific analysis of Panchi mirrors reveal the state policy impact in early Imperial China. *J. Archaeol. Sci.* **2025**, *180*, 106310.
- Tylecote, R.F.; Ghaznavi, H.A.; Boydell, P.J. Partitioning of trace elements between the ores, fluxes, slags and metal during the smelting of copper. *J. Archaeol. Sci.* **1977**, *4*, 305–333.

15. Pernicka, E. Trace element fingerprinting of ancient copper: A guide to technology or provenance? In *Metals in Antiquity*; Archaeopress: Oxford, UK, 1999; pp. 163–171.
16. Pollard, A.M.; Bray, P.; Homer, P.; Xu, Y.; Liu, R.; Rawson, J. Application of the Oxford Research System to the Study of Ancient Chinese Bronzes. *Archaeology*. **2017**, *1*, 95–106.
17. He, T.K. Several problems concerning the casting technology of ancient bronze mirrors in China. *Stud. Hist. Nat. Sci.* **1983**, *2*, 360–369.
18. Wenren, J. *Ancient Chinese Encyclopedia of Technology: Translation and Annotation of Kaogong ji, the Artificers' Record*; Routledge: Oxfordshire, UK, 2014.
19. Barbieri-Low, A.J. *Artisans in Early Imperial China*; University of Washington Press: Seattle, WA, USA, 2024.
20. Bray, P.; Cuénod, A.; Gosden, C.; Hommel, P.; Liu, R.; Pollard, A.M. Form and flow: The 'karmic cycle' of copper. *J. Archaeol. Sci.* **2015**, *56*, 202–209.
21. Liu, R.; Pollard, A.M.; Rawson, J.; Tang, X.; Bray, P.; Zhang, C. Panlongcheng, Zhengzhou and the movement of metal in early bronze age China. *J. World Prehistory* **2019**, *32*, 393–428.
22. Radivojević, M.; Roberts, B.W.; Pernicka, E.; Stos-Gale, Z.; Martínón-Torres, M.; Rehren, T.; Bray, P.; Brandherm, D.; Ling, J.; Mei, J.; et al. The provenance, use, and circulation of metals in the European Bronze Age: The state of debate. *J. Archaeol. Res.* **2019**, *27*, 131–185.
23. Pernicka, E. Entstehung und Ausbreitung der Metallurgie in prähistorischer Zeit. *Jahrb. Röm.-Ger. Zentralmuseum* **1990**, *34*, 607–714.
24. Krause, R. *Studien zur Kupfer-und Frühbronzezeitlichen Metallurgie Zwischen Karpatenbecken und Ostsee*; Verlag Marie Leidorf: Rahden, Germany, 2003.
25. Li, H.; Cui, J.; Chen, J.; Xu, T. Validation and Application of the 'Trace Element Grouping Method'. *Jiangnan Archaeol.* **2020**, *2*, 103–109.
26. Wu, M.; Tang, Z.; Bi, N.; Yang, Q.; Fang, H.; Wang, Q. Cosmetics for the non-elite 2000 years ago: Affordable raw materials and a complex production process. *Archaeol. Anthropol. Sci.* **2023**, *15*, 117.
27. Gao, J.; Wang, X.; Li, J.; Li, C.; Zhang, X.; Dong, W.; Wang, Q. Circulation of bronze mirrors between China and Japan during the Western Han dynasty: A scientific analysis on bronze mirrors excavated in Linzi city. *J. Archaeol. Sci. Rep.* **2025**, *67*, 105393.
28. Falkenhausen, L.; Jun, W. Review of ancient Chinese encyclopedia of technology: Translation and annotation of Kaogong Ji (the artificers' record). *East Asian Sci. Technol. Med.* **2014**, *40*, 100–103.
29. Lu, D.M. A new exploration of the "Liu Qi". *Relics Museol.* **1999**, *2*, 70–74.
30. Pollard, A.M.; Liu, R. The six recipes of Zhou: A new perspective on Jin (金) and Xi (锡). *Antiquity* **2022**, *96*, 1200–1213.
31. Zhang, J.; Hao, D.H.; Hu, G.; Yin, J.L.; Chen, J.L. Scientific analysis and study of metal artifacts excavated from the Spring and Autumn period tomb (M1) at Jiawanggu, Yishui, Shandong. *Cult. Relics* **2025**, *10*, 74–85.
32. Zhang, J.; Liu, J.Y.; Wu, H.; Yao, L.; Wen, L.; Chen, J.L. Research on Warring States tin and lead ingots and metal provenance in and around Jinan city of Jingzhou. *Jiangnan Archaeol.* **2025**, *6*, 135–143.
33. Hao, D.H.; Cui, J.F.; Lu, S.C. Analytical study of Eastern Zhou bronzes unearthed from Dubei cemetery in Changle, Shandong. *Orient. Archaeol.* **2020**, *17*, 335–347.
34. Hao, D.H.; Cui, J.F.; Liang, Z.H.; Fang, H. Scientific analysis of bronze artifacts unearthed from the first excavation of the Eastern Zhou cemetery at Dahan in Tengzhou, Shandong. *Orient. Archaeol.* **2021**, *18*, 281–298.
35. Zhao, F.Y.; Cui, J.F.; Ren, X.H.; Cui, D.Y. Preliminary analysis of lead isotope ratios of bronze objects unearthed from Xianrentai cemetery in Changqing. *Kaogu* **2005**, *10*, 75–80.
36. Luo, W.G.; Huang, F.C.; Cui, J.F. Study on copper ingots unearthed from tomb M28 of the Western Zhou cemetery at Yejiashan in Suizhou, Hubei. *Jiangnan Archaeol.* **2016**, *4*, 101–107.
37. Luo, W.G.; Li, D.S.; Cui, J.F. Preliminary study on bronze objects unearthed from ancient Jun territory. *Jiangnan Archaeol.* **2018**, *1*, 114–122.
38. Qian, W.; Sun, S.Y.; Kuai, S. Analysis and research on Eastern Zhou copper ingots from Guichi: A clue to the earliest use of sulfide ores for copper smelting in China. *Kaogu* **2000**, *3*, 85–90.
39. Chen, L.L.; Zhang, B.X.; Li, Q.; Wu, Y.H.; Ma, Z.S.; Wei, G.F. Detection and analysis of solders of bronzes unearthed from Xuyang cemetery. *Nonferrous Met. (Extr. Metall.)* **2023**, *2*, 117–122.
40. Zhang, S.X. *Seeing the Big Picture Through Small Details: The Application of Chemical Analysis of Ceramics and Bronzes in Some Historical Research*; Liberal Arts Press: Taipei, China, 1991; pp. 70–71.
41. Vardi, Y.; Zhang, C.H. The multivariate L 1-median and associated data depth. *Proc. Natl. Acad. Sci. USA* **2000**, *97*, 1423–1426.

42. Zhu, F.H. *A Comprehensive Study of Chinese Bronzes*; Shanghai Classics Publishing House: Shanghai, China, 2009.
43. Luo, Z.; Fan, A.C.; Jin, Z.Y.; Huang, F. Scientific analysis and research on the Warring States bronze mirrors unearthed from Changsha Chu cemetery, Hunan province, China. *Archaeometry* **2022**, *64*, 1187–1201.
44. Tian, C.H. Brilliant scientific achievement of Chinese ancient bronze casting by using modern analysis. *J. Chengdu Univ. Sci. Technol.* **1980**, *Z1*, 109–124.
45. Hunan Provincial Museum. Catalogue of Bronze Mirrors Unearthed in Hunan; Cultural Relics Press: Beijing, China, 1960.
46. Sun, S.Y.; Kennon, N.F. A study of microstructure of ancient Chinese mirrors. *Stud. Hist. Nat. Sci.* **1992**, *11*, 54–67.
47. He, T.K. Technical Study of Ancient Chinese Bronze Mirrors; China Science and Technology Press: Beijing, China, 1992.
48. Liang, L. Studies on alloying compositions in Zhou Dynasty. *Kexue* **1925**, *9*, 1261–1278.
49. Liang, S.Q.; Zhang, G.N. The chemical composition of Chinese ancient copper. *J. Chin. Chem. Soc.* **1950**, *17*, 9–18.
50. Sun, S.Y.; Han, R.B.; Li, X.H. Microstructure of ancient Chinese metal materials. In Volume of Nonferrous Metals; Science Press: Beijing, China, 2011; pp. 33–36.
51. Riederer, J. Metallanalysen chinesischer Spiegel. *Berl. Beitr. Archäom.* **1976**, *1*, 6–16.
52. Scott, D.A. Ancient Metals: Microstructure and Metallurgy; Conservation Science Press / Lulu.com: Los Angeles, CA, USA, 2011; Vol. 1.
53. Swallow, R.W. Ancient Chinese Bronze Mirrors; Henri Vetch: Peiping, China, 1937.
54. Liu, Y.X.; Chen, K.L.; Mei, J.J.; Sun, Z.W.; Zhao, H.C.; Qian, Y.P. Scientific analysis of bronze mirrors excavated from the Qin tombs at Xinfeng, Lintong, Shaanxi. *Cult. Relics Cent. China* **2015**, *4*, 111–115.
55. Chen, D.; Luo, W.; Bai, Y. The social interaction between China and Japanese archipelago during Western Han dynasty: Comparative study of bronze mirrors from Linzi and Yayoi sites. *Archaeol. Anthropol. Sci.* **2019**, *11*, 3449–3457.
56. Bray, P.J.; Pollard, A.M. A new interpretative approach to the chemistry of copper-alloy objects: Source, recycling and technology. *Antiquity* **2012**, *86*, 853–867.
57. Pernicka, E. Provenance determination of archaeological metal objects. In *Archaeometallurgy in Global Perspective: Methods and Syntheses*; Springer: New York, NY, USA, 2014; pp. 239–268.
58. Yang, D.; Wu, X.; Liu, R.; Wang, Q.; Shi, B.; Qu, T.; Tian, J.; Hua, F.; Zhang, X. From diversity to monopoly: Major economic policy change in the Western Han Dynasty revealed by lead isotopic analysis. *Archaeol. Anthropol. Sci.* **2023**, *15*, 37.

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