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Circulation of bronze mirrors between China and Japan during the Western Han dynasty: A scientific analysis on bronze mirrors excavated in Linzi city

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ABSTRACT

Bronze mirrors of the Western Han dynasty (202 BCE-8 CE) present in Eurasia are strong evidence for far-reaching trade and exchange networks. However, more evidence is still needed on the provenance and circulation form of the mirrors. In this study, a scientific analysis including metallography, chemical composition, and lead isotope ratios was carried out on 35 mirrors excavated from the Xiangjianan cemetery near the capital of state Qi in Linzi city, China, which is the only archaeologically confirmed centre for mirror production found so far. By incorporating previous research, this study uses the lead isotope ratios to establish the characteristics of Linzi mirrors from different periods, and provides a preliminary discussion on the provenance of those mirrors with the highly radiogenic lead found in Shandong province. The study suggests that most of the imported mirrors of the Western Han dynasty unearthed in Japan may have been produced in Linzi city, and the highly radiogenic lead in mirrors found in Linzi city during the Warring States period (475–221 BCE) and the Western Han dynasty may have been sourced from the local Luxi metallogenic province. This study provides new solid evidence for the cross-regional circulation of bronze mirrors during the Western Han dynasty.

1. Introduction

The widespread bronze mirrors discovered in recent years in North Central Asia, the Korean peninsula, the Japanese archipelago, and the Indo-China Peninsula have served as evidence of far-reaching trade and exchange networks in early Eurasia (O'Sullivan & Shao, 2023; Treister & Ravich, 2023; Gao et al., 2024). The cross-regional circulation of bronze mirrors provides evidence for trade, technology transfer and population interaction along the Overland and Maritime Silk Roads during the Western Han dynasty (WHD, 202 BCE-8 CE; Guo, 2022; Franklin, 2024). It attracted scholars' attention at home and abroad (Chase, 1994; Chen et al., 2020a). However, bronze mirrors are typologically easy to imitate. A question can be raised: did the mirrors with similar form and decoration to the Han mirrors found outside China result from product circulation or technology transfer? This remains a hot ongoing debate (SPIAAC & AIKNPJ, 2007; Wang et al., 2024).

Research on the product features originating from different mirror production centres will provide more direct evidence to explore the routes and forms of circulation for mirror (Cui et al., 2009; Chen et al., 2020b). In the present, scholars have summed up the stylistic characteristics and spatial distribution of Chinese mirrors from different regions and proposed terms such as the *Linzi style* and the *Guangling style* (IACASS et al., 2024). Beyond typological study, the lead isotope ratios was employed by Japanese scholars on imported mirrors found in Japan which was termed *舶載鏡* (Mabuchi, 2007). The *Japanese model* that claimed the lead used in mirrors of WHD and Eastern Han dynasty (25–220 CE) were respectively from North China and South China, has been widely accepted in the past decades (Mabuchi & Hirao, 1982; 1983; Mabuchi et al., 1985; Mabuchi, 2011). However, recent scientific analysis of mirrors found in China has revealed a mixed lead provenance model of North China and South China since the beginning of WHD (Gao et al., 2024; Wang et al., 2024).

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Among the tens of thousands of mirrors of WHD found at home and abroad, those found in Linzi city are undoubtedly one of the most important. The Linzi city was where Qigucheng, the capital of the state Qi, was located during the Warring States period (475–221 BCE), Qin and Han dynasties (Fig. 1; IACASS et al., 2024). It is the exclusive mirror production centre confirmed by archaeological excavations and may have been responsible for the production of exported mirrors. The mirrors produced in Linzi city have been typologically defined as *Linzi style*, which had a profound impact on the surrounding areas centred on Shandong province, as well as Chang'an, the imperial capital of WHD, and Northeast Asia (Bai & Zhang, 2005; Zhangsun et al., 2017). Scientific analysis of bronze mirrors dated to different periods of WHD from Linzi city has been reported (Cui et al., 2009; Chen et al., 2019; Gao et al., 2024). However, the dates of those reported mirrors may need a more extensive database to verify due to the lack of early WHD mirrors and the limited type of the analysed mirrors. The discoveries of mirrors of WHD with different dates and types from the Xiangjianan cemetery near Linzi city provides us a great opportunity to study the diachronic characteristics of the Linzi-style mirrors in detail and provide evidence for their circulation. Metallographic, chemical compositional and lead isotope analyses were carried out to search for more product features beyond typology.

2. Materials and analytical methods

Xiangjianan cemetery (36°49′21″N, 118°18′21″E) is located about 5 km southwest of the Qigucheng in Linzi city. It was a large-scale civilian burial complex during the Warring States period and WHD, with more than 700 burials having been excavated. This cemetery is vital for the study of the social and economic history of the Qi state.

The Xiangjianan cemetery has been divided into three periods according to the archaeological remains including bronze mirrors, coins, and pottery. The representative mirrors of different types and periods of WHD from Xiangjianan cemetery are shown in Fig. 2. Among them, the bronze mirrors of the early WHD (202–118 BCE) are mainly either plain or decorated with *Panchi* (蟠螭, simplified design of loong) with a few decorated with designs of *Caoye* (草叶, grass leaves) and *Huaye* (花叶, flower leaves). The mirror with loong design unearthed from Tomb 625 (M625) is eye-catching. Compared to other mirrors with loong design, the loong design in this mirror are more vivid and realistic, with a wide-open mouth which swallows clouds and spits mist. Bronze mirrors of the middle WHD (118BC-48BC) are mainly decorated with designs of *Caoye* and *Xingyun* (星云, stars and clouds). In addition, many mirrors with inscriptions, including *Riguang* (日光, sunlight), *Zhaoming* (昭明, illumination), and as well as mirrors with *Caoye* design appeared. Also noteworthy is a mirror with twin-loong design unearthed from M275; it is so peculiar that its head is in a snake shape and connected to the tail and has four claws. Different types of bronze mirrors were found in the late WHD (48BC-AD8), with those with designs of *Xingyun*, *Qinshou* (禽兽, birds and beasts) and inscription of *Riguang* being predominated. At the same time, mirrors with inscription of *Jiachangfugui* (家常富贵, eternal wealthy noble family) and design of *Boju* (博局, chessboard) also began to appear (detailed descriptions of mirror typology see Supplementary Material S1).

In this study, 35 bronze mirrors from the Warring States period and WHD from the Xiangjianan cemetery, almost covering all types of mirrors excavated from the cemetery, including the two mirrors with loong designs mentioned above, were analysed. Since many middle and late WHD mirrors have been analysed previously, this research focuses on the mirrors of early WHD. The mirror designs of the Warring States period are mainly plain and include one mirror with *Yunlei* (云雷, clouds and thunders) design and one with *Panchi* design. The plain square mirrors have rarely been unearthed in the Linzi area. At this time, the square mirrors are usually painted, primarily found in the aristocratic tombs of state Chu, state Qi and the capital Luoyang in the Eastern Zhou dynasty (770–256 BCE; Li, 2022). The plain square mirrors unearthed from Xiangjianan cemetery appeared quite rough, which may be an imitation of the painted square mirrors.

Only two broken mirrors were allowed to be sampled for metallography, each sample was about a lump of two cubic millimetres. The metallographic samples were made and observed in the Archaeometallurgy Laboratory of the Institute of Cultural Heritage, Shandong University. The samples were mounted with epoxy resin and ground with sandpaper of different grit sizes (of 600–1200), and then polished with diamond pastes (of 9, 6, 3, 1 μm) to a finish of 0.25 μm. The samples have been naturally corroded, and the metallographic microstructure was observed without etching using a Leica DMi8 inverted microscope.

For the preservation of bronze mirrors and in compliance with the

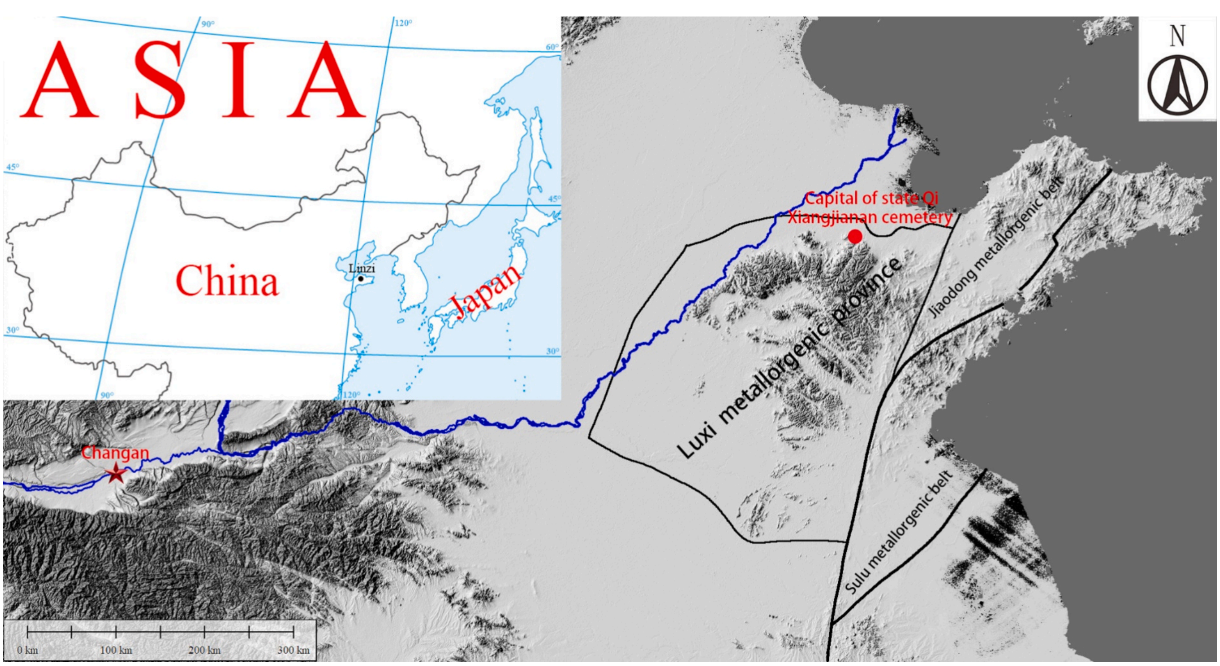

Fig. 1. Location of Xiangjianan cemetery and the metallogenic province division of Shandong province.

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

principle of minimal damage to archaeological remains, in-situ chemical composition analysis was carried out using a portable X-ray fluorescence instrument (p-XRF, Bruker Tracer 5g). Prior to analysis, 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 was applied in this case. For heavy elements, the voltage was set at 45 kV and the current set at 15 μA. The spectra were acquired for 60 s using a Ti 25 μm-Al 300 μm filter. The detection limit varies depending on the element but generally falls within the range of 0.001–0.03 wt%. The analytical accuracy varies depending on the element content, with relative errors of around 2 % for major elements. Details can be seen in the Supplementary Material S2.

For lead isotope analysis, corrosion powder of about 100 mg was taken from the plain surface and dissolved in weak superior pure nitric acid. Lead was separated electrochemically by deposition on a platinum electrode and then dissolved by a few drops of 2 % nitric acid in a polyethylene bottle (Gao et al., 2021). Inductively coupled plasma mass spectrometry (ICP-MS) was used to determine the lead concentration of the solution. The solution was diluted to a standard concentration of 250 ppb with ultrapure water according to the test concentration and subsequently determined by a multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS). The maximum errors (2σ) of $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{206}Pb$ for the samples were 0.001, 0.0009 and 0.002, respectively (see Supplementary Material S2). The differences in lead isotope ratios between corrosion products and the corresponding artefacts are within experimental error (Snoek et al., 1999).

3. Results

The dendritic structure of a cast bronzes generally has a matrix of α-solid solution with (α + δ) eutectoids. When the tin content exceeds 23 wt%, the (α + δ) eutectoid becomes the matrix of tin bronze instead of the α-phase, with the α-phase becoming a strip and needle-like structure distributed among (α + δ) eutectoid (Scott, 1992). The α-solid solution will become thinner and tinier with increasing tin contents. As shown in Figs. 3a and 3b, the mirror with *Panchi* design in the early WHD and the plain square mirror of the Warring States period show a metallographic structure of high tin bronze, similar to that described above. Small lead particles are present on the grain boundaries.

The lead isotope analysis shows the lead used in 34 out of 35 bronze mirrors falls into the traditionally known category of common lead, ranging from 17.503 to 18.476 for $^{206}Pb/^{204}Pb$, 15.445–15.683 for $^{207}Pb/^{204}Pb$, and 37.953–38.969 for $^{208}Pb/^{204}Pb$ (Table 1). The lead isotope ratios change rate exceeding 0.6 % suggests diverse sources of lead or a source of anomalous Pb deposits (IIGYIGMRMLRC, 1979). Notably, the plain square mirror from M462 of the Warring States period has a value of 23.553 for $^{206}Pb/^{204}Pb$, usually termed as highly radiogenic lead (HRL). It is the first HRL mirror of the Warring States period discovered up to date. To reduce the overlap effect in lead isotope analysis, the value of kappa (κ = initial $^{232}Th/^{238}U$) back-calculated from lead isotope ratios are also listed in Table 1. They will help enhance the comparison dimension (Albarede et al., 2012).

The chemical compositions of 33 mirrors show that, all the mirrors are ternary bronzes with > 18 wt% Sn and > 2 wt% Pb. At that time, the addition of lead as an alloy element had become very popular in Chinese bronze production (Jin et al., 2017). Therefore, the lead isotope ratios data mainly reflect the source of lead.

4. Discussion

(1) Mirrors identified as with common lead by lead isotope

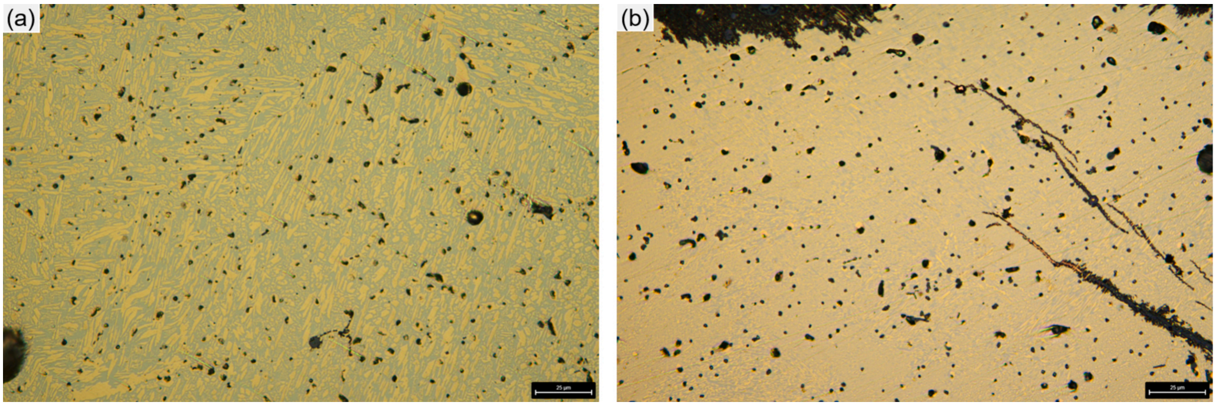

Fig. 3. Metallographic structure of mirrors from Xiangjianan cemetery, showing the representative microstructure of high tin content bronze. (a) M155:1 of early WHD, the average tin content is 27.2 wt%; (b) M462:4 of the Warring States period, the average tin content is 26.2 wt%.

Table 1
Results of chemical compositional and isotopic analyses on bronze mirrors from the Xiangjianan cemetery.

Context	Mirror type	Period	Cu%	Sn%	Pb%	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	κ ($^{232}Th/^{238}U$)
M227:2	Plain square	Warring States period	73.2	21.2	4.9	18.384	15.649	38.908	4.1941
M462:2	Plain round	Warring States period	66.6	30.2	2.8	18.332	15.660	38.770	4.1610
M462:4	Plain square	Warring States period	71.1	26.2	2.3	23.553	16.443	42.955	3.4156
M656:1	*Yunlei*	Warring States period	60.9	31.8	6.0	17.577	15.489	38.172	4.3305
M37:1	*Huaye*	Early WHD	74.0	18.7	6.2	17.567	15.499	38.148	4.3269
M59:2	Plain	Early WHD	70.7	24.1	4.5	17.723	15.539	38.193	4.2451
M101:1	*Caoye*	Early WHD	67.8	24.5	5.9	17.734	15.544	38.382	4.3497
M123:1	*Panchi*	Early WHD	67.1	24.7	7.2	17.549	15.483	38.134	4.3272
M125:1	*Panchi*	Early WHD	70.6	23.6	5.0	17.756	15.529	38.272	4.2624
M155:1	*Panchi*	Early WHD	68.3	27.2	3.8	17.750	15.532	38.297	4.2830
M168:2	*Caoye*	Early WHD	67.1	24.0	6.8	17.670	15.529	38.356	4.3803
M203:1	*Caoye*	Early WHD	56.1	31.2	10.2	17.682	15.522	38.342	4.3597
M206:2	Plain	Early WHD	67.2	28.6	3.3	17.618	15.501	38.141	4.2828
M253:2	*Panhui*	Early WHD	69.0	18.8	9.6	17.629	15.513	38.227	4.3300
M257:1	*Panchi*	Early WHD	57.5	27.4	13.0	17.619	15.506	38.219	4.3306
M277:2	Plain	Early WHD	73.0	22.7	3.8	18.007	15.577	38.502	4.2202
M389:1	*Huaye*	Early WHD	66.2	28.2	4.8	17.753	15.532	38.317	4.2921
M460:1	Unknown	Early WHD	\	\	\	17.697	15.523	38.326	4.3387
M505:1	Plain	Early WHD	65.1	26.4	7.3	17.503	15.476	38.094	4.3377
M514:1	Plain	Early WHD	68.5	23.2	7.4	17.564	15.475	38.031	4.2503
M650:1	*Panchi*	Early WHD	\	\	\	17.565	15.488	38.156	4.3302
M625:2	*Loong*	Early WHD	57.7	33.9	6.9	18.291	15.620	38.910	4.2514
M685:4	*Panchi*	Early WHD	57.7	33.0	7.5	17.568	15.490	38.134	4.3154
M24:2	*Xingyun*	Midlle WHD	63.9	26.4	7.6	17.682	15.526	38.323	4.3498
M211:1–1	*Zhaoming*	Midlle WHD	68.7	22.9	6.8	17.854	15.556	38.495	4.3258
M243:4	*Xingyun*	Midlle WHD	68.2	23.7	6.5	17.730	15.538	38.371	4.3444
M275:3	*Loong*	Midlle WHD	65.7	26.8	6.3	17.513	15.475	38.049	4.3026
M316:2	*Xingyun*	Midlle WHD	66.8	25.6	6.0	17.717	15.539	38.363	4.3502
M530:1	*Xingyun*	Midlle WHD	66.5	26.8	4.7	17.768	15.551	38.417	4.3460
M597:2	*Caoye*	Midlle WHD	65.5	29.7	3.1	17.632	15.508	38.230	4.3274
M89:2	*Qinshou*	Late WHD	69.2	22.1	8.0	17.524	15.502	37.953	4.2436
M152:1	*Jiachangfugui*	Late WHD	68.9	24.8	4.7	17.682	15.526	38.324	4.3504
M219:1	*Qinshou*	Late WHD	63.5	25.8	8.7	17.612	15.538	38.299	4.3970
M334:2	*Boju*	Late WHD	66.1	25.1	7.3	17.628	15.509	38.213	4.3210
M416:4	*Qinshou*	Late WHD	67.8	25.3	5.2	17.666	15.532	38.198	4.2899

ratios. Because of the advancement of the instrument, a large amount of lead isotope data has been published, and the application of the lead isotope a has been diversified beyond the initial function of tracing mineral provenance. The lead isotope ratios are fingerprints embedded in lead-containing artefacts, and their changes are assumed to be caused by changes in resource supply. The regime change, economic policy adjustment, administrative boundary movement, and changes in diplomatic relations over time may have mainly been responsible for the shift of the resource supply (Yang et al., 2023). Therefore, the changes in lead isotope ratios can potentially indicate diachronic change. In recent years, researchers have paid more attention to the diachronic change of lead isotope ratios in lead-contained objects, which has become a new perspective of lead isotope analysis for archaeological research (Zhang & Chen, 2017; Sun et al., 2023).

Linzi city was the production centre of mirrors during the Warring States period and WHD, and the 'Linzi style' mirrors had a broad and far-reaching influence on the Korean peninsula and the Japanese archipelago (Bai, 2018). This influence is reflected in the decoration, which results from either the direct circulation of goods (imported mirrors, termed *舶载镜*) or indirect imitation (imitative mirrors, termed *仿制镜*). It is reasonable to assume that the influence can also be reflected in provenance of the mirrors, i.e., the lead isotope ratios of mirrors found abroad could be consistent with that produced in Linzi city and synchronously change with time. Although scholars have speculated that the mirrors found in Northeast Asia may have been directly imported from Linzi city (Cui et al., 2009; Chen et al., 2019), the lack of lead isotope data has limited in-depth discussion.

A recent scientific analysis of mirrors from Zonglvcheng cemetery has preliminarily summarised the change of lead isotope ratios with time in mirrors from Linzi city (Gao et al., 2024). Due to the overlap effect, the lead isotope analysis failed to further distinguish mirrors of different periods of WHD. Bronze mirrors from different periods of WHD were divided into three groups according to the differences in κ values ($^{232}Th/^{238}U$), with the κ values of Group I > 4.33, Group II between 4.29–4.33, and Group III lower than 4.29. However, due to the lack of analysed mirrors belonging to the Warring States period and the early WHD, the limited type of mirrors, and the lack of representative archaeological sites, it is impossible to draw more reliable conclusions. This study focuses on the bronze mirrors of early WHD. In addition, new types of mirrors, such as square mirrors and mirrors with loong, *Boju* and *Qinshou* designs, were considered to establish a preliminary temporal framework via isotopic differences present in the mirrors produced in Linzi city.

As illustrated in Fig. 4, the early WHD samples show a broader distribution of lead isotope ratios, which tends to differ from later samples. It is particularly notable that for the early WHD period, plain mirrors are generally characterised by lower kappa values compared to other mirrors (Table 1). It is noteworthy that the kappa values of plain mirrors from the Warring States period ($3.4156 < \kappa < 4.1941$) are significantly lower than those of WHD mirrors ($4.2060 < \kappa < 4.3970$) found in the Linzi region. Previous research suggests that plain mirrors may have been the type used by the indigenous inhabitants of Linzi region during the Warring States period (Gao et al., 2024). During the early years of the Han dynasty, due to minimal state intervention in handicraft production, certain mirrors likely continued to use lead resources from the Warring States period, or may have been produced through mixed smelting. Therefore, lead from the Warring States period could have contributed to the low kappa values of plain mirrors, possibly indicating an earlier production date compared to the patterned mirrors. The lead isotope ratios of mirrors from middle and late WHD are more consistent and are mainly narrow-range distributed. This feature may have resulted from implementation of state-intervention economic policies, such as the *Junshu-pingzhun and salt and iron monopoly policies*.

To sum up, the lead isotope analysis of a total of 76 bronze mirrors from Zonglvcheng (Gao et al., 2024) and Xiangjianan cemeteries has demonstrated the diachronic change of bronze mirrors produced in Linzi city from the Warring States period to WHD. As a fundamental database, it will help to pinpoint the provenance of other bronze mirrors found in China and abroad, especially for the exported mirrors believed to be produced in a single production centre.

(2) Tracing the mirrors with highly radiogenic lead (HRL). The prevalence of HRL in bronzes of the Shang dynasty (1600–1046 BCE) has attracted lots of discussion and attention from researchers, and various opinions have emerged (Jin, 2008; Zhangsun et al., 2024). Of note is the use of lead-bearing artefacts with HRL found after the Shang dynasty to discuss the source of such lead (Liu et al., 2018).

As mentioned above, two mirrors with HRL were identified among those found in Linzi city. One was from the Warring States period in the Xiangjianan cemetery, and the other was from the early WHD in the Zonglvcheng cemetery (Gao et al., 2024). These two HRL mirrors are both plain, showing the characteristics of an earlier stage. During the Warring States period and WHD, the discovery of HRL artefacts was more dispersed and scarcer, with finds from as far west as Xinjiang and the Tibetan plateau, as far south as Hubei, as far north as Hebei, and as far east as Japan. Among them, the most notable discoveries of HRL artefacts and deposits are from Shandong province (Wu et al., 2024).

The metallogenic provinces/belts in Shandong province are mainly divided into the Luxi metallogenic province, the Jiaodong metallogenic belt and the Sulu metallogenic belt. Compared with the other two metallogenic zones, a high proportion of the HRL ores in the Luxi mineralisation zone was identified. In addition, smelting slags as early as the Shang dynasty were found at the Yingcheng site (located in Luxi metallogenic province), proving the long history of mining and metallurgy in the Luxi metallogenic province (Wang et al., 2023). The lead isotope analysis on remains from the Yingcheng site shows that the smelting slag and ores found at this site fall into the range of HRL. Looking into the lead isotope data on ores from the Luxi metallogenic zone (including the archaeometallurgical remains from the Yingcheng site and the Zhu state; Yan et al., 2024), it can be seen that part of the HRL of the Luxi metallogenic province with a higher $^{208}Pb/^{204}Pb$ value (Fig. 5b Line a) differs from that of bronze objects of the Shang dynasty (Fig. 5a). In contrast, the lead isotope ratios of the Luxi metallogenic province are closer to those of the artefacts of the later period from Shandong province. Both fall alone the 2.29 Ga isochron line in the $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ diagram (Fig. 5a; Wu et al., 2024), suggesting a similar provenance. As shown in Fig. 5b, the HRL in archaeological remains and ores found in Shandong province can be subdivided into three groups based on the difference in $^{208}Pb/^{204}Pb$. It is worth noting that the HRL mirrors and other lead-bearing objects found in Linzi city, from the Warring States period to WHD, correspond to these three groups, respectively, and so do the ores and slags found in the Yingcheng site and the Zhu state. Therefore, the local Luxi metallogenic province is very likely the source of the HRL objects discovered in Shandong province from the Warring States period to WHD.

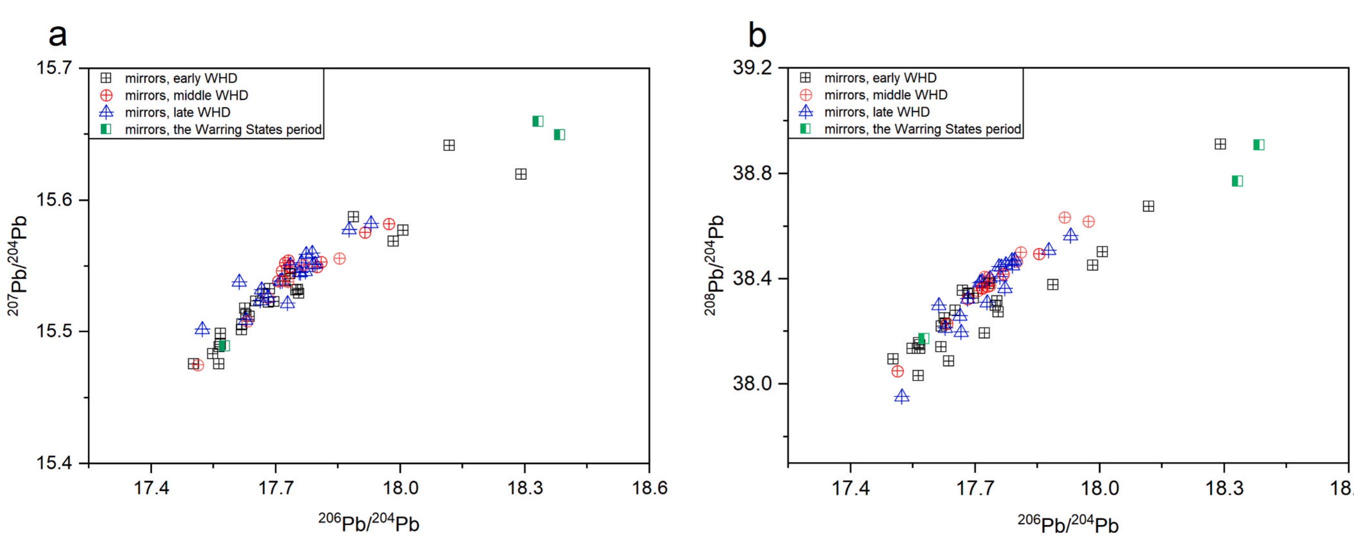

Fig. 4. Lead isotopic difference of Linzi mirrors in different periods of WHD and the Warring States period.

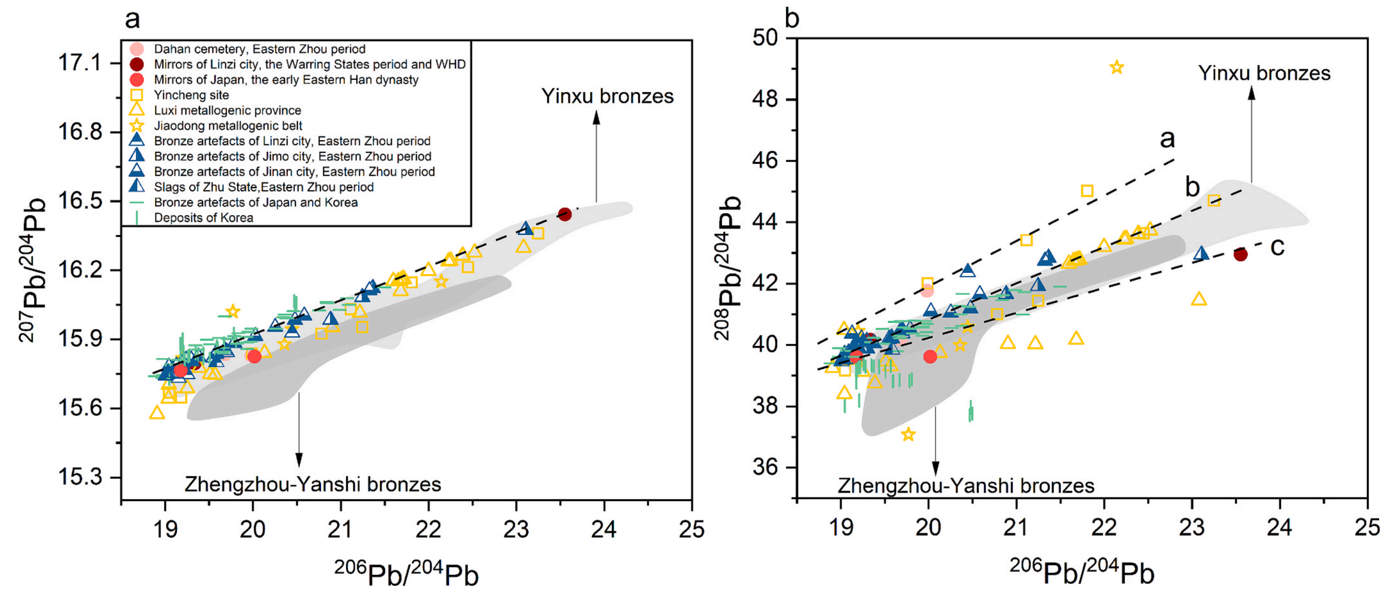

Fig. 5. Comparison of HRL artefacts and deposits from China and Japan, showing that the provenance of HRL artefacts from Shandong province after the Shang dynasty is very likely the local Luxi metallogenic province. The Zhengzhou-Yanshi and Yinxu bronzes represent the HRL bronzes of the Shang dynasty.

It needs to address (as mentioned above) that the sources of HRL bronze artefacts from the later periods differs from that of the Shang dynasty. However, whether the HRL of the Shang dynasty came from the Shandong metallogenic provinces/belts still requires more solid evidence to explore. In comparison, the HRL artefacts found so far in Japan and South Korea also differ from ore samples from South Korea and Shandong province, with most of the samples having a lower $^{206}Pb/^{204}Pb$ values (<21.5, Fig. 5b; Saito, 2019). This may be due to the limited amount of data, the mixing of the HRL bronzes with common lead or those with unknown provenance. Identifying more HRL objects found in Japan and Korea in the future may address this issue.

(3) Mirror export from Linzi city to Japan. Previously, researchers have preliminarily argued for the export of bronze mirrors from Linzi city to Japan from the perspectives of typology, alloy composition and lead isotope ratios. However, identical mirrors cast from the same mould have not been found up to date (Zhao & Lang, 2021), hence, the typological analysis of mirrors lacks conclusive evidence to prove the export from Linzi city to Japan during the WHD. Therefore, researchers tend to use 'style' rather than 'type' to argue for the wide spread of mirrors of *Linzi style*. In addition, the copper-tin–lead ratio of bronze mirrors in WHD has been highly standardised (Cu 70 %, Sn 25 % and Pb 5 %) to meet daily use (Gao et al., 2024). As a result, distinguishing bronze mirrors from different production centres in terms of alloy composition is tricky (Wang et al., 2024).

In this case, the similarity in lead isotope ratios between mirrors found in China and Japan is relatively reliable evidence for the export of mirrors from Linzi city to Japan (Zhangsun et al., 2017). However, Wang et al. (2024) have identified subtle differences in lead isotope ratios between mirrors found in China and those found in Japan from different periods of WHD. The lead in mirrors found in Japan has been divided into 'Northern Chinese lead' and 'Southern Chinese lead' to characterise the change from WHD to the Eastern Han dynasty (25–220 CE, Mabuchi, 2011). Furthermore, the finding of 'Southern Chinese lead' in mirrors of WHD revealed the complexity of the export model between China and Japan during the Han dynasty (202 BCE- 220 CE; Wang et al., 2024).

What causes the subtle differences in lead isotope ratios between mirrors found in China and those found in Japan? Answering this question is vital to reconstruct the export of mirrors from China to Japan, as the lead isotope ratios of mirrors produced in the same production centre during the same period is supposed to be identical. The κ values of the plain mirrors of WHD from Linzi city analysed here are lower than 4.29 apart from one whose κ value is 4.34 (Table 1), while that of most other types was found to be higher than 4.29 (Gao et al., 2024). This suggests that, for some reasons, different types of mirrors produced in the same production centre may have different lead isotope ratios. Therefore, the difference in the types of analysed mirrors found in China and those found in Japan should have been taken into consideration.

The same types of analysed mirrors found in Linzi city and Japan include the mirrors with *Panchi*, *Panhui*, *Caoye* and *Xingyun* designs, and inscription of *Riguang* and *Zhaoming*. Comparison of lead isotope ratios of the above types between those found in China and Japan reveals that the lead in mirrors produced in Linzi city from the early to late period of WHD all belongs to the 'Western Han lead' as defined by lead isotope ratios of mirrors found in Japan, except for one mirror with *Panchi* design (Fig. 6a). Therefore, the difference in lead isotope ratios between mirrors of WHD found in China and those found in Japan may be due to the differences in the types of mirrors analysed and exported/imported, rather than indicating different provenance.

Numerous studies have shown that the lead isotope ratios of mirrors is more consistent than other types of bronze artefacts during the WHD due to a controlled exchange network of metal resources (Li et al., 2023, Wang et al., 2024). However, it is worth noting that there may still be measurable differences in the lead isotope ratios of metal resources used by different production centres in different periods. Such differences may be due to the internal variation of the same or adjacent deposits themselves or, by factors such as the choice of fuels and fluxes for the smelting process, as demonstrated by the Egyptian copper smelting experiments (Rademakers et al., 2020). Focusing on the diachronic characteristics of specific production centres makes the lead isotope ratios, as a fingerprint feature, play a better role in provenance study of the mirrors.

If the mirrors found in Japan had been imported from Linzi city or other potential production centres, the lead isotope ratios of those found in China and Japan would have synchronously changed in different periods of WHD. This study compared the differences in lead isotope ratios of mirrors found in China and imported mirrors (舶载镜) found in Japan. As shown in Fig. 6c-h, almost all the lead isotope data on mirrors found in Japan fall into the range of those found in Linzi city throughout the different periods of WHD. Providing that the mirrors found in different parts of China are produced locally, the lead isotope data on mirrors found in Linzi city fall into a broader range than any other

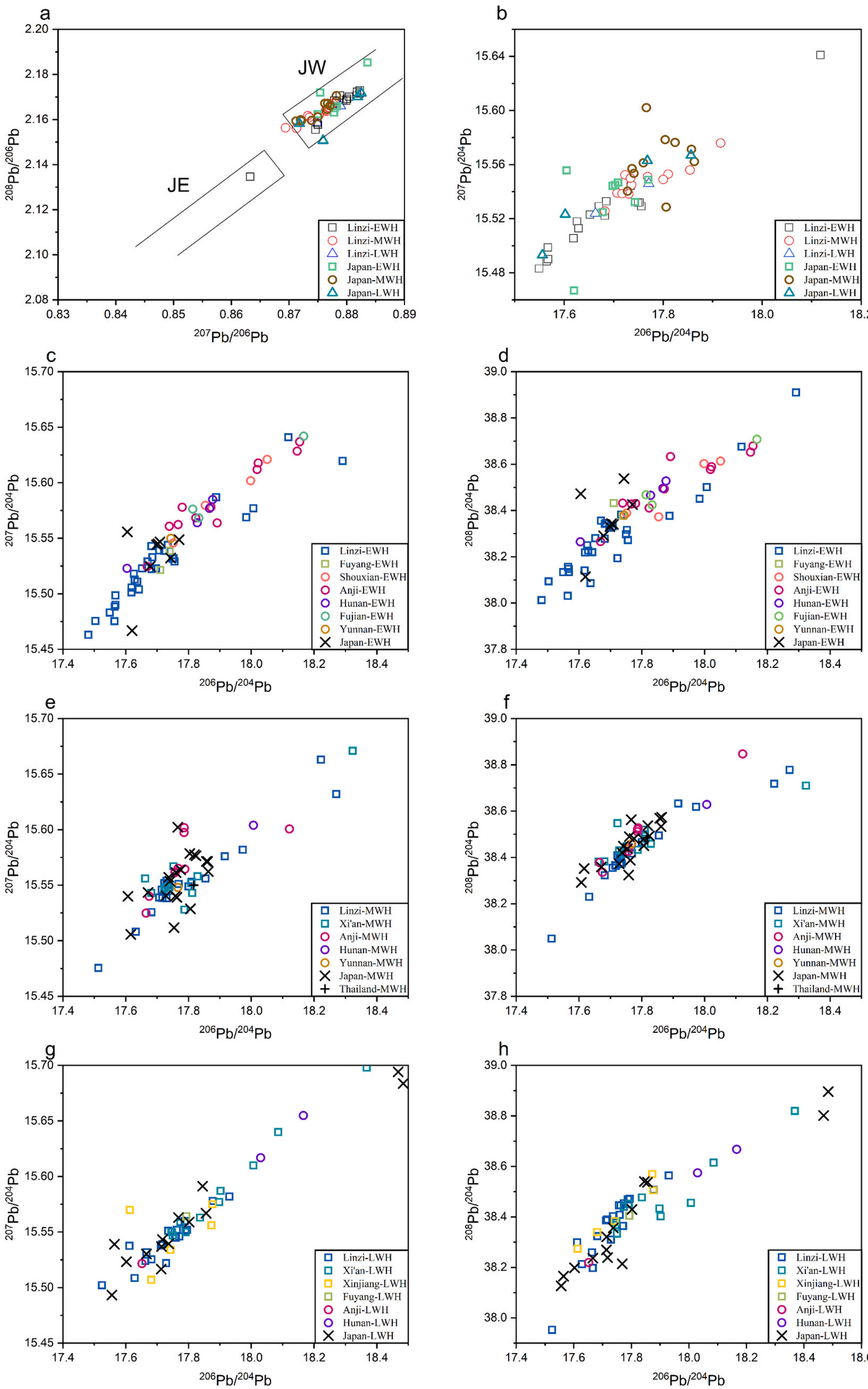

Fig. 6. Comparison of bronze mirrors between those found in China and in Japan, showing similar provenance. (a-b) comparison of the same analysed types of mirrors found in Linzi city and Japan in different periods of WHD; (c-h) comparison of bronze mirrors of different periods between those found in different parts of China and in Japan. JE refers to lead of southern China, JW refers to lead of northern China, boxes refer to mirrors from North China, and dots refer to mirrors from South China. EWH, MWH and LWH refer to the early, middle and late WHD.

production centres during the early and middle WHD (Fig. 6c-f). During the late WHD, the mirrors found in Hunan (n = 2) and 3 mirrors found in Xi'an (accounting for 27.27 %) contain higher values of $^{206}Pb/^{204}Pb$ (>18.0), which is beyond the range of those found in Linzi city (Fig. 6 g-h). It suggests a new supply chain of lead which could have been derived from Hunan province, although it was not adopted by Linzi city when the mirror production centre there declined during the late WHD. What makes it more interesting is that, nevertheless, almost all the mirrors found in Japan isotopically fall into the range of those found in Linzi city but show clear differences from those found in other sites of China. It is worth noting that two mirrors of the late WHD found in Japan contained lead whose values of $^{206}Pb/^{204}Pb$ are higher than 18.4. This value is higher than those of other mirrors with common lead found in China. Whether these two mirrors were produced with the new supply of lead from South China as mentioned before or produced locally, requires more evidence.

Limited by the scarcity of lead isotope data on mirrors at that time, previous studies have cautiously proposed Chang'an (Xi'an) as a potential mirror production centre with possible exports to Japan (Zhangsun et al., 2017). However, there seems no direct evidence reported to verify this hypothesis. The *History of the Han dynasty* mentions that "there were Japanese in the Sea of Lelang, divided into more than a hundred countries, who came to offer their tribute every year (乐浪海中有倭人, 分为百余国, 以岁时来献见云)". However, this historical record was written by a historiographer of the Eastern Han dynasty. It seems unreasonable to believe that the Japanese have been to Chang'an to import mirrors during the WHD. In contrast, the interaction among people in Northeast Asia including the Shandong peninsula, the Korean peninsula and the Japanese archipelago since the Warring States period has been well recorded by archaeological materials and related scientific analyses (Bai, 2018; Wu et al., 2024). Therefore, taking Chang'an as a place for mirror export to Japan requires more evidence, especially when workshops of mirror production have not been found there.

In summary, the subtle difference in lead isotope ratios of mirrors from China and Japan appeared to mainly due to the intentional or accidental selection of the type of mirrors imported/exported. The general synchronous changes in the lead isotope ratios between mirrors of different periods of WHD from different production centres in China and these found in Japan provide direct evidence for the latter to have mainly been imported from Linzi city. Judging from the similar and even identical typology, alloy composition and lead isotope ratios of the bronze mirrors between those found from Linzi city and in Japan, the circulation of mirrors from Linzi city to Japan during WHD was highly likely the result of a direct circulation of the artefacts rather. Craftsmen migration and metal raw material exchange cannot be ruled out (Pollard et al., 2025). However, the absence of contemporaneous mirror-casting foundry and moulds in Japan has made the latter speculation less possible.

5. Conclusions

In this paper, 35 excavated bronze mirrors from the Xiangjianan cemetery, produced in Linzi city during the Warring States period and WHD were scientifically analysed. The results show a diachronic change in the lead isotope ratios of mirrors of different periods of WHD produced in Linzi city, providing a fingerprint for the identification of 'Linzi style' mirrors found inside and outside China. This study suggests that the differences in the lead isotope ratios of mirrors of different periods of WHD found in China and Japan, as claimed by other researchers in a recent study, may have been caused by the limitations of the types exported to Japan from China. The changes in the isotopic ratios of mirrors found in the Linzi city and imported mirrors found in Japan are highly synchronised compared to other potential production centres in China, providing direct evidence for mirrors found in Japan being imported from the Linzi city. However, the possibility that Japan imported mirrors from other production centres of China cannot be ruled out before more data on mirrors found in other regions of China are reported.

This study also identified one mirror of the Warring States period as with HRL lead. Other HRL of metal objects found in Shandong province, the Korean peninsula, and the Japanese archipelago, as well as the deposits' data on different metallogenic provinces in Shandong province and the Korean peninsula, were collected for comparison. The source of HRL for metal objects found in Shandong province, which was found different from that of Korea and Japan, is most likely to be the local Luxi metallogenic provinces. However, differences are present between the HRL data on the bronze objects of the Eastern Zhou period and of the Shang dynasty. It needs to explore further whether the source of HRL used during the Shang dynasty came from the local Shandong province.

CRediT authorship contribution statement

Jun Gao: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Xiang Wang:** Visualization, Resources, Formal analysis, Data curation. **Jinxuan Li:** Visualization, Software, Methodology, Investigation. **Chenghao Li:** Visualization, Resources, Funding acquisition, Conceptualization. **Xintian Zhang:** Visualization, Resources, Investigation. **Wenbin Dong:** Resources, Investigation, Data curation. **Quanyu Wang:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105393.

Data availability

Data will be made available on request.

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