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ORIGINAL ARTICLE

Investigation of the recycling of Han Chinese bronze mirrors into Japanese imitation mirrors

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Abstract
We revisit the chemical data on imitation Japanese bronze mirrors of the Kofun period (c. 300–538 CE), which Hisao Mabuchi (馬淵久夫) has used to suggest that these mirrors were made from broken imported Han-style mirrors diluted with additional copper. Using a different approach, we confirm that the composition of these mirrors is consistent with Mabuchi's suggestion. In addition, we can use data from our model to take this analysis further, by combining the elemental and lead isotope data, determining how much each source contributes to the lead in the mirrors, and calculating the possible isotope composition of the lead in the imported mirrors and in the added copper. This shows that both the mirrors and the added copper are unlikely to contain Japanese lead. As Mabuchi suggested, there appears to have been a trade in both Han-style mirrors and copper ingots from China to Japan in the Kofun period. Not only does this work support the previous conclusions, but it also sets out a new methodological approach that can be used to further such research.

KEYWORDS
bronze mirrors, Han, kofun, lead isotopes, modelling, recycling

INTRODUCTION

In an important paper published in 2018, Mabuchi demonstrated that a particular group of 18 Japanese bronze imitation mirrors from the Kofun period (c. 300–538 CE) Maruyama Tomb in Tsuruyama, Okayama Prefecture, Japan (鶴山丸山古墳) were made from recycled imported

Chinese Han-style mirrors diluted with copper. These data had originally been published by Hirao et al. (2006) in a paper that compared the composition of these imitation mirrors with those of 'imported' triangular-rimmed mirrors with deity and beast motifs (三角缘神兽镜) excavated from the Tsubai Otsukayama Tomb (椿井大塚山古墳) in Kyoto Prefecture, concluding that the major element compositions and lead isotope values were different but making no further observations. Figure 1a shows images of two of these imitation mirrors from Maruyama, and Figure 1b one of the imported mirrors from Otsukayama. This paper takes the same data on the 18 mirrors and, using a different approach, supports Mabuchi's conclusion as to how these imitation mirrors may have been made. The modelling used here, however, also allows this to work be extended by combining the lead isotope data with the major element data

FIGURE 1 a. Images of two of the 18 imitation Japanese bronze mirrors considered here (left J-33974, right J-33958: images posted by Saigen Jiro on Wikimedia commons, from Tokyo National Museum); b. Shinjūkyō from the Tsubai Ōtsukayama kofun in Yamashiro, Kyoto (Wikimedia commons).

in order to predict the lead isotope ratios in the recycled Han-style mirrors and the added copper. This in turn allows further inferences to be made about the nature of this process.

Mabuchi (2018) reached his conclusion from the observation that the lead and tin concentrations in these Maruyama mirrors (as determined by XRF) extended over a wide range (Sn = 7 to 27%; Pb = 2 to 7.8%) and were also highly correlated (see Table 1 and Figure 2). From this he deduced that this group of mirrors represented the re-use of Chinese Han-style bronze mirrors diluted with increasing quantities of copper. This idea was an extension of one he had previously published, deriving from his extensive work on lead isotopes in Japanese and Chinese bronzes. In Mabuchi (2007), he proposed that Yayoi period (弥生時代; c. 300 BCE – 250 CE) *Dōtaku* (銅鐸) (bells) could be made from imported Western Han Dynasty Chinese bronzes diluted with copper. Subsequently, he proposed (Mabuchi, 2010a) that the imitation triangular-rimmed mirrors with deity and beast motifs in Japan were made using the same 'scraps and copper addition' method. In particular, he proposed that 'fragments of imported triangular-rimmed mirrors with deity and beast motifs were used as the raw material', although the full meaning of this suggestion, in terms of how and why mirror fragments may have been imported, was not explored.

The conclusions in these two earlier papers, one comparing imported and locally made bells, and one focussing on imported and local imitations of a specific form of mirror, were based on comparing lead isotope data alone. In Mabuchi (2018), he extended his attention to the major element concentration (Cu, Pb, and Sn) in the mirrors. Table 1 reproduces these data as given in Mabuchi (2018), bringing together the data in his Tables 1 and 7–13 to present both elemental and lead isotope data. From the observation of high correlation, and assuming that the average composition of the Han dynasty mirrors was 66.9% Cu (±1.4%), 24% Sn, and 6.1% Pb (±1.4%) (total 97%) (derived originally from Umehara, 1937, and supported by many subsequent analyses Mabuchi, 2010b), we carried out the following set of calculations:

TABLE 1 Chemical and lead isotope composition of imitative mirrors excavated from the Tsuruyama Maruyama tumulus (from Mabuchi, 2018, after Hirao et al., 2006).

No.	Cu%	Sn%	Pb%	Total	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}Pb
J-33958	82	15	2.4	99.4	18.173	15.647	38.594
J-33959	76	18	5.2	99.2	18.22	15.656	38.683
J-33961	63	27	7.8	97.8	18.143	15.639	38.623
J-33960	71	22	5.9	98.9	18.411	15.67	38.858
J-33963	64	28	6.7	98.7	18.185	15.648	38.598
J-33962	87	10	2.2	99.2	18.009	15.621	38.451
J-33964	68	23	7.2	98.2	18.137	15.636	38.599
J-33970	85	11	2.9	98.9	18.186	15.638	38.605
J-33971	74	19	5.7	98.7	18.256	15.66	38.683
J-33973	77	17	5.2	99.2	18.19	15.651	38.605
J-33972	85	11	3.8	99.8	18.154	15.64	38.535
J-33967	85	12	2	99	17.963	15.599	38.561
J-33969	83	13	2.9	98.9	18.194	15.647	38.624
J-33968	86	11	3.1	100.1	18.556	15.672	39.062
J-33974	85	11	3.5	99.5	18.201	15.651	38.617
OM-1	86	11	2.1	99.1	18.127	15.636	38.589
OM-3	88	7	3.9	98.9	18.011	15.594	38.639
OM-4	84	14	2	100	18.193	15.651	38.618

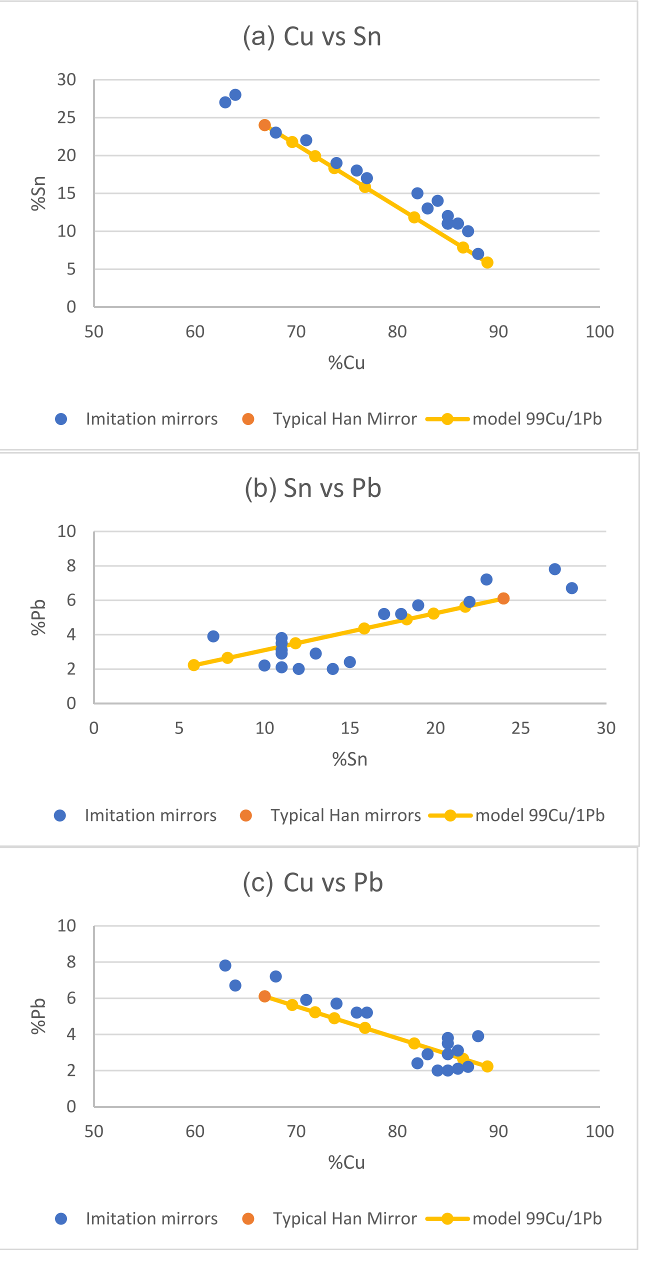

FIGURE 2 Comparisons of data on imitation mirrors with model described in Table 1. The 'typical Han mirror' is 66.9% cu, 24% Sn, and 6.1% pb, from Mabuchi (2018).

i. The major element compositions of the 18 mirrors were scaled so that the tin concentration was 24% (Mabuchi, 2018, Table 3);
ii. The amount of copper contributed to the overall composition (scaled) from the scrap mirrors (D), allowing for 3% minor elements in the scrap (Mabuchi, 2018, Table 3, Column D):

%age copper from scrap = 100 – (scaled Sn% + scaled Pb% + 3);

iii. The amount of added copper (assumed to be 100% pure) was then calculated by subtracting D from the scaled copper total (Mabuchi, 2018, Table 3, Column E).

This estimated added copper (E) ranged from −12.4% to 242%, relative to the original mass of scrap bronze. Within errors, this was assumed to show that the imitation bronzes ranged from pure undiluted scrap bronze (i.e., added copper = 0%) to highly diluted scrap bronze, in which 1 unit of scrap bronze was diluted with c. 2.5 units of pure copper.

The aim of this paper is to validate these results using a different approach and also to extend the conclusions by predicting the lead isotope values of the two starting materials (scrap Chinese Han bronze and 'pure' copper).

MAJOR ELEMENT MODELLING

In a previous set of papers, the current authors have proposed a graphical method of modelling the major element composition of Chinese bronzes, based on the mixing of two components, calculated as the dilution of a starting alloy with a second alloy in increasing quantities, to give a modelled dilution line (Pollard et al., 2024; Pollard & Liu, 2021; Pollard & Ruiliang, 2022, 2023). This differs from the method used by Mabuchi (2018) as described above, although the basic premise is the same.

Using the conclusion given by Mabuchi, the model constructed here consists of adding increasing quantities of copper to a starting alloy of 66.9% Cu, 24% Sn, and 6.1% Pb (representing the average composition of scrap Chinese Han-style mirrors). Mabuchi assumed that the added copper was impure and contained 1% Pb (from his knowledge of the purity of Kofun period copper but also because the lead isotope data showed a slightly wider distribution in the imitation mirrors than in the imported mirrors), so we have modelled the addition of a slightly impure copper of 99% Cu + 1% Pb (99Cu/1Pb) (Table 2). The addition runs in steps from 10% by weight to 300%, equivalent to the addition of 100 g copper to 1 kg scrap bronze (10%), to 3 kg of copper to 1 kg scrap bronze. The data are normalized to 97% (as done by Mabuchi, to reflect the presence of minor elements), and the results are plotted in Figure 2.

TABLE 2 Model based on Mabuchi's conclusion—typical Han dynasty Mirror diluted with 99Cu/1Pb.

	Start	Add 10% cu	Add 20% cu	Add 30% cu	Add 50% cu	Add 100% cu	Add 200% cu	Add 300% cu
Cu	66.9	76.8	86.7	96.6	116.4	165.9	264.9	363.9
Sn	24	24	24	24	24	24	24	24
Pb	6.1	6.2	6.3	6.4	6.6	7.1	8.1	9.1
Sum	97	107	117	127	147	197	297	397
Normalize to 97%:								
Cu	66.9	69.6	71.9	73.8	76.8	81.7	86.5	88.9
Sn	24	21.8	19.9	18.3	15.8	11.8	7.8	5.9
Pb	6.1	5.6	5.2	4.9	4.4	3.5	2.6	2.2
Sum	97	97	97	97	97	97	97	97
1/pb	0.164	0.178	0.191	0.204	0.230	0.286	0.378	0.450
%age pb from scrap	100	98.4	96.8	95.3	92.4	85.9	75.3	67.0
%age pb from 99/1	0	1.6	3.2	4.7	7.6	14.1	24.7	33.0

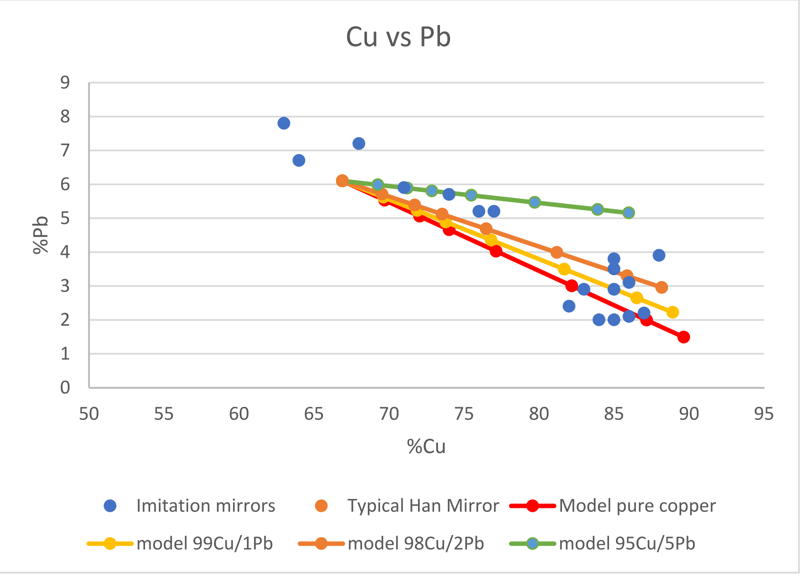

FIGURE 3 Comparison of data on imitation mirrors with four models: scrap + pure copper, scrap + 99Cu/1Pb, scrap + 98Cu/2Pb, scrap + 95Cu/5Pb.

Within the constraints of such models, the modelled data provide a very good visual fit to the correlations between the data on the imitation mirrors, bearing in mind that the main objective is to reflect the *correlation* between the variables, and that scatter around the modelled line is to be expected because of variation in the raw materials (note that in Mabuchi [2018] the 'typical composition of Han-style mirrors' is quoted with errors of ±1.4% (absolute) for both copper and lead [and presumably also similar for tin]).

So far, the modelling provides nothing more than an alternative means of demonstrating that the original proposal of Mabuchi is consistent with the analytical data. We can, however, extract more information from the modelling, which allows further predictions to be made about the associated lead isotopes. We can, for example, show that the added copper cannot contain more than a few percent lead, because the model begins to deviate significantly from the data at an addition of 95Cu/5Pb (Figure 3). It is possible to provide a numerical measure of the goodness of fit between the data points and the model lines by calculating the sum of the squares of the differences between each point and the equation of the model line (calculated as the difference between measured Pb in the object and predicted value of Pb from the model). In Figure 3 these sums are 15.84 for pure copper, 12.29 for 99Cu/1Pb, 14.93 for 98Cu/2Pb, and 73.0 for 95Cu/5Pb, showing that the 99Cu/1Pb gives the best fit to the data for these four models, thereby also supporting the original assumption that the imitation mirrors were diluted with copper containing about 1% Pb.

MODELLING LEAD ISOTOPE DATA

It is clear from the model shown in Table 2 that lead from two different sources is present in the resulting alloy once the additions commence—the majority (originally 6.1% lead by weight, contributing 100% to the combined lead at zero dilution) comes from the scrap bronze, but if we assume that a small percentage is associated with the added copper (modelled here as 1% of the weight of the added copper), then as increasing additions of diluent are made, the proportion of lead from this second source increases (despite the fact that the *total* amount of lead in the sample appears to decrease). For each addition point, we can calculate the contribution of lead from the added 99Cu/1Pb by subtracting the 6.1 from the total amount of lead in the unnormalized data and expressing this as a percentage of the total amount (i.e., for 10% addition, the percentage of lead from the 99Cu/1Pb component = [6.2–6.1]/6.2*100 = 1.6%). The remainder (98.4%) is obviously contributed from the scrap bronze at this dilution. The model data (bottom lines of Table 2) show how the ratio of lead associated with the scrap bronze to that provided by the lead in the copper changes as the amount of copper added increases. Figure 4 (based on Table 2) plots this relationship as the percentage of lead supplied by the added 99Cu/1Pb as a function of the total amount of lead in the sample, showing that at the maximum addition modelled here (300%, or the addition of three times as much 99Cu/1Pb to the original mass of scrap), the lead provided by the addition of 99Cu/1Pb contributes 33% of the total lead. A plot of this contribution becomes linear if the lead axis is plotted as 1/Pb.

The ratio between the contribution of each source to the total lead is clearly of significance in the measured lead isotope values in the samples, if the two sources of lead have different isotopic ratios. In order to apply this knowledge from the modelled data, we will follow a sequence of steps:

i. The overall aim is to predict how much added lead (from the 99Cu/1Pb) is added to each sample and to use this information to predict the lead isotope ratios in the original scrap and the 99Cu/1Pb

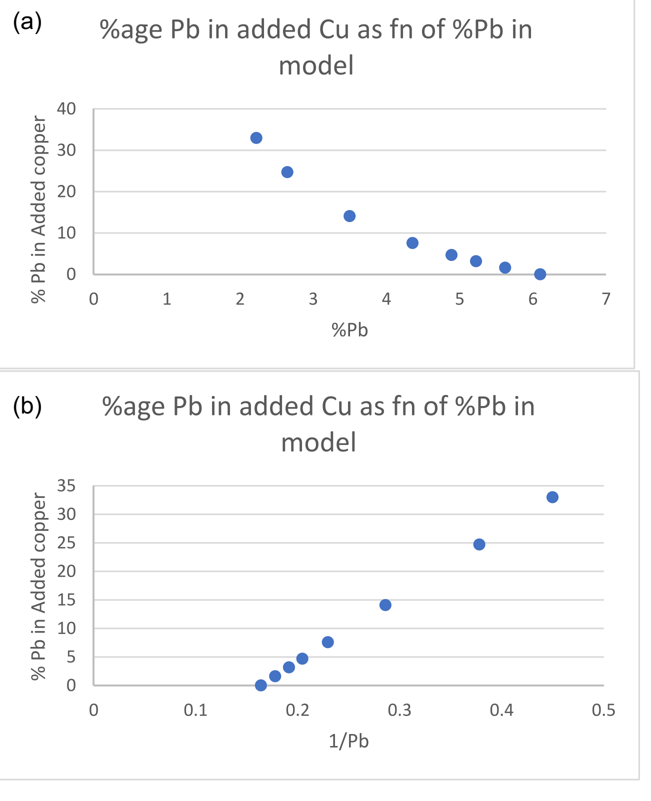

FIGURE 4 Plot of (a) percentage of lead contributed by the addition of 99Cu/1Pb, as a function of (a) percentage of lead in the modelled points, and (b) as 1/pb in the modelled points.

ii. Assuming that the model in Table 2 represents the behaviour of the 18 imitation mirror samples, we can use Table 2 and the regression line in Figure 4b to calculate how much of the lead in each of the samples is contributed by the lead added by the addition of 99Cu/1Pb.
iii. We can plot this proportional addition against the measured lead isotope values in each sample (Figure 5)
iv. By using the regression line through these data, we can calculate the lead isotope value for zero addition (i.e., the value in the scrap bronze) and also the value at 100% addition (i.e., the value in the added 99Cu/1Pb).
v. By doing the same for the other two isotope ratios, we can calculate all three isotope ratios in each these two components.

This of course assumes that these two end member values are point values, which they will not be, but providing they have a variation that is small compared to the predicted difference, the two values will provide a reasonable approximation to the end members of the binary mixture. In other words, to be realistic, the average lead isotope values in the scrap bronze and in the added 99Cu/1Pb need to be internally coherent, and the assumption of only two sources of lead needs to be valid. This translates into assuming that in the archaeological situation being modelled, the scrap bronze has to be reasonably isotopically and elementally consistent, as does the added copper.

The line of regression in Figure 4b has the form:

$$y = 115.34x + 18.908.$$

where y is the proportion of lead provided by the added 99Cu/1Pb, and x is (1/Pb) in the modelled points. We use this equation to estimate the proportion of lead from the 99Cu/1Pb in the total lead in each of the samples listed in Table 1, simply by inserting the measured lead value for each sample in the above equation. As shown in Table 3, these values range from −4.1% (taken to mean 0 % contribution from the added 99Cu/1Pb, within errors) up to 38.8%.

We may now plot the measured lead isotope value in each sample as a function of the calculated contribution from the lead in the added 99Cu/1Pb. Here we show only the plot of $^{206}Pb/^{204}Pb$ (Figure 5).

The regression equation here is:

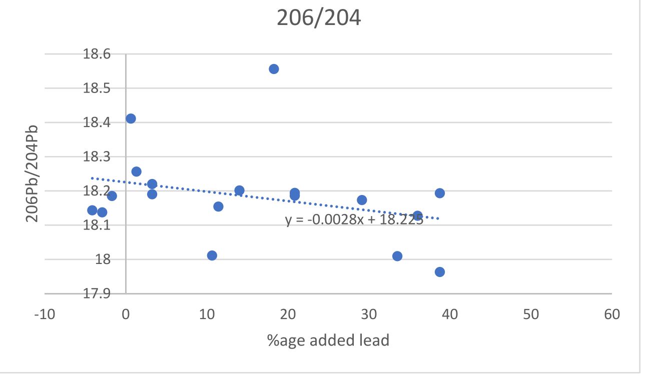

FIGURE 5 Plot of $^{206}Pb/^{204}Pb$ measured in the samples (Table 1) against the calculated percentage lead from the added 99Cu/1Pb.

TABLE 3 Calculation of percentage of lead contributed by added 99Cu/1Pb in the samples from Table 1.

Sample	Measured pb		Calculated %age added pb	Measured $^{206}Pb/^{204}Pb$
	Pb	1/pb		
J-33958	2.4	0.417	29.2	18.173
J-33959	5.2	0.192	3.27	18.22
J-33961	7.8	0.128	−4.1	18.143
J-33960	5.9	0.169	0.64	18.411
J-33963	6.7	0.149	−1.69	18.185
J-33962	2.2	0.455	33.5	18.009
J-33964	7.2	0.139	−2.89	18.137
J-33970	2.9	0.345	20.9	18.186
J-33971	5.7	0.175	1.33	18.256
J-33973	5.2	0.192	3.27	18.19
J-33972	3.8	0.263	11.4	18.154
J-33967	2	0.500	38.8	17.963
J-33969	2.9	0.345	20.9	18.194
J-33968	3.1	0.323	18.3	18.556
J-33974	3.5	0.286	14.0	18.201
OM-1	2.1	0.476	36.0	18.127
OM-3	3.9	0.256	10.7	18.011
OM-4	2	0.500	38.8	18.193

$$y = -0.0028x + 18.225.$$

where y is the lead isotope ratio and x the proportion of lead added by the second source of lead. By setting x to zero we obtain the value of 18.225 for the $^{206}Pb/^{204}Pb$ ratio in the scrap bronze, and by setting x to 100 we can estimate the $^{206}Pb/^{204}Pb$ ratio for the lead in the added 99Cu/1Pb. This value is 17.945. From the equivalent diagrams for $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ (not shown) we can predict the following isotopic values for the two end members:

$$\text{scrap bronze}: {}^{206}Pb/{}^{204}Pb = 18.225;\ {}^{207}Pb/{}^{204}Pb = 15.649;\ {}^{208}Pb/{}^{204}Pb = 38.673.$$

$$\text{added 99Cu/1Pb}: {}^{206}Pb/{}^{204}Pb = 17.945;\ {}^{207}Pb/{}^{204}Pb = 15.599;\ {}^{208}Pb/{}^{204}Pb = 38.463.$$

These values can be plotted on a pair of lead isotope diagrams (Figure 6), including data from Japanese lead ores (Mabuchi, 2012). The Japanese ore data show a bimodal distribution, with the majority clustering between $^{206}Pb/^{204}Pb = 18.4$ and 18.6, but with a smaller group between 18.0 and 18.2. This smaller group of samples come from three mines: Kamioka Tochido (神岡栃洞), Kamioka Maruyama (神岡円山), and Kamioka Mozumi (神岡茂住), all in Gifu prefecture (Mabuchi, 2012, Table 10 nos. 44–58). According to the mine website (https://gakuen.gifu-net.ed.jp/~contents/virtualmuseum/sanpo/11/p2.htm, accessed 21/7/2024), the Kamioka mine produced gold in the Yoro period (養老: 717–724 CE), but there is no information about earlier mining. This mine is an unlikely source for copper because it is primarily a zinc, lead, and silver mine, and current opinion is that mining in the Japanese archipelago did not begin until after the Kofun period, probably in the second half of the sixth century, that is,

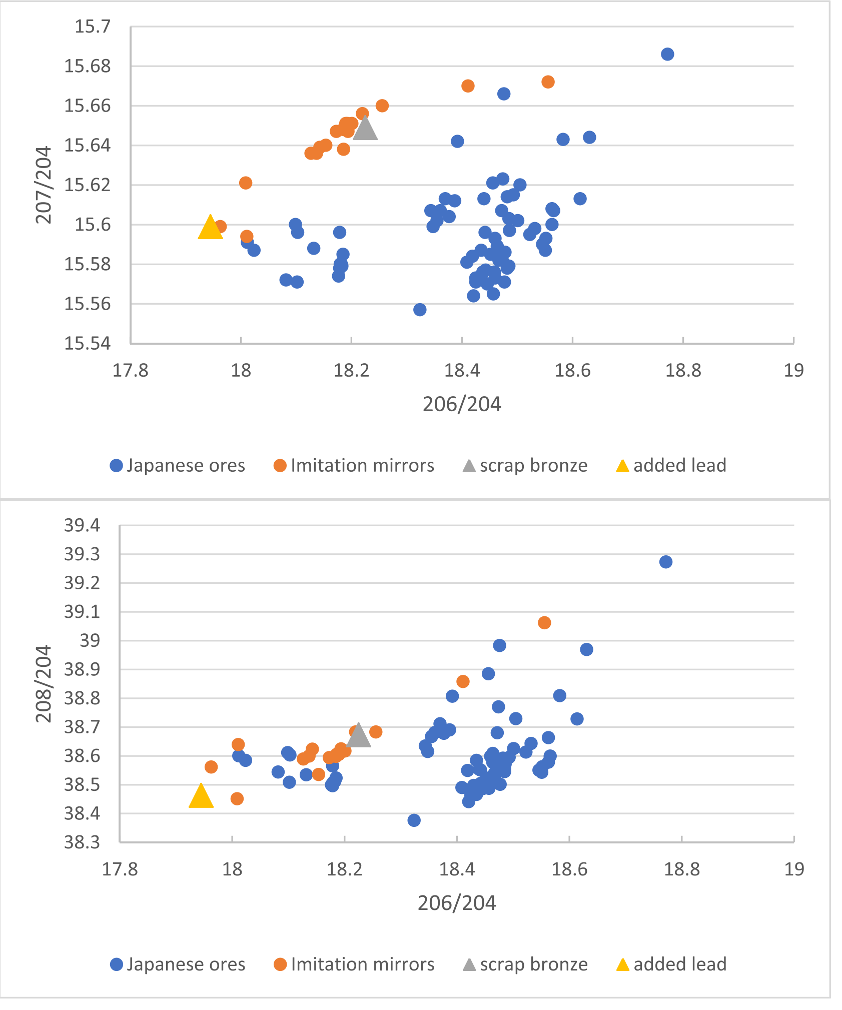

FIGURE 6 Plot of (a) $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ and (b) $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ showing the predicted values in the scrap bronze and added copper, and the distribution of the imitation mirrors, superimposed on Mabuchi's (2012) data for the lead isotope values of Japanese ore sources.

the Asuka period (飛鳥時代: 538–645), for both lead and copper (Mabuchi, pers. comm.). The predicted value of the lead in the added 99Cu/1Pb and a few of the imitation mirrors lie close to (but are not enclosed by) the values in these Kamioka ores, but the predicted value in the scrap bronze and the majority of the imitation mirrors are not associated with any Japanese ores (seen most clearly in $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$). This suggests that the lead in the scrap bronze is unlikely to be of Japanese origin, whereas the lead in the added copper *could possibly* be Japanese. However, consideration of the distribution of lead isotope values from Chinese lead ores (e.g., Hsu & Sabatini, 2019) shows that all of these values could be matched with Chinese sources (Figure 7). Hence, most likely assumption is that these imitation mirrors were made by diluting imported Chinese Han-style mirrors with imported (Chinese) copper, as originally suggested by Mabuchi (2018).

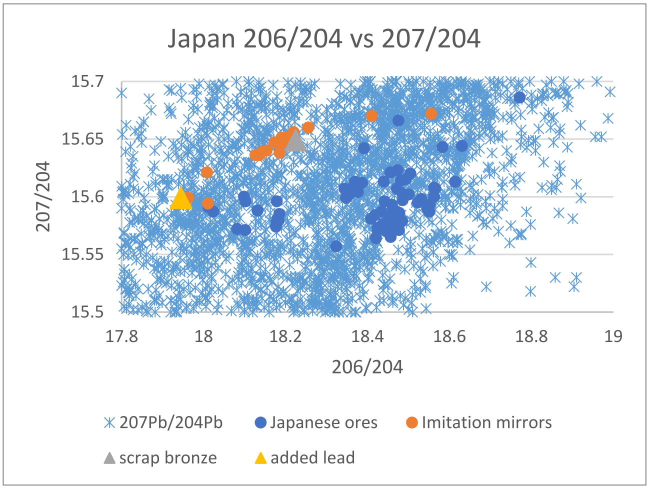

FIGURE 7 Plot of $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ showing the predicted values in the scrap bronze and added copper and the distribution of the imitation mirrors, superimposed on a section of Hsu and Sabatini's (2019) data for the lead isotope values of Chinese ore sources (blue crosses).

CONCLUSIONS

This paper has confirmed (using a different methodology) the suggestion made by Hisao Mabuchi that a particular group of 18 Kofun period (c. 300–538 CE) bronze imitation mirrors from the Maruyama Tomb in Tsuruyama, Okayama Prefecture, Japan, were probably made using the 'scraps and copper addition' method. This of itself is an important conclusion in terms of understanding the development of copper technology in Japan, and the potential prevalence of recycling practices in the past.

However, the modelling proposed here also allows other features of the data to be explored, including placing an upper limit on the amount of lead that was present in the added copper (probably around 1%). Again, using data provided by the model we can calculate the ratio of lead in the scrap bronze to that added by the use of this slightly impure copper for any point within the model. This in turn allows us to construct predictive models for the lead isotope ratios in the scrap bronze and in the added lead. In this case, it suggests that both the scrap bronze mirrors and the lead added in the copper were unlikely to be of Japanese origin.

Using this case study as an example, we suggest that this combination of modelling applied to both major element *and* lead isotope compositions offers a powerful predictive tool, provided that the necessary simplifications can plausibly be applied, particularly that a binary mixing model is a reasonable approximation, and that the end members have relatively coherent isotope values. The validity of these assumptions is critically dependent on the precise nature of the archaeological situation being modelled.

Although the model derived here demonstrably does not apply to the production of Chinese Han-style mirrors themselves, it does seem to have a wide application to the study of the production of imitation mirrors in Japan, as well as other situations where bronze objects are made using recycled metal. If we accept Mabuchi's model, and the extension to it provided here, then there are a number of very important archaeological questions to be answered about these imitation mirrors. Did the 'scrap' consist of broken or substandard mirrors specifically imported as such, with the intention of using them to manufacture imitation mirrors? Or were they made from precious imported mirrors but diluted to produce a greater number of mirrors? Many fragments of Korean and Chinese mirrors have been excavated from sites dating from the Yayoi period to the Kofun period, which are distributed from Kyushu to the Kansai region (centered around Kyoto, Osaka, and Nara). One example is the Sakurai-Chausuyama Tomb in Nara Prefecture (奈良県桜井茶臼山古墳), where archaeologists report that 385 fragments were found that could be reconstructed into 103 mirrors (56 imported Chinese, 26 triangular-rimmed, and 21 imitation; Okabayashi, 2024). It also appears that the diluting copper was specifically imported in the form of ingots, presumably because at this stage Japanese copper was not available. Clearly, this represents a major activity in the history of Chinese and Japanese bronze mirrors. This paper, deeply indebted as it is to the immense volume of work produced by Mabuchi and his colleagues on mirrors and *dotaku*, can only but provide the impetus for further work on these issues.

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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are all included in the text.

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