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STUDY OF THE ELEMENTAL COMPOSITION AND POSSIBLE SOURCES OF SASANIAN COINS, CASE STUDY: COINS OF PIRUZ I

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Abstract

Measurement of the elemental composition and isotopic analysis of silver coins can be used to determine the location of silver mines and identify metal sources. This study provides new information about a possible source of silver coins minted in the Piruz King period during the Sasanian Empire. The purpose of this research is to study the chemical composition of 15 Sasanian silver coins of the Piruz King using the Proton Induced X-ray Emission (PIXE) technique. Moreover, to study and identify the mines that might have provided raw materials for the coins, we used the reported results of lead isotopic analyses of some mines conducted by ICP-MAS. In addition, a few samples of different minerals from the Ahangaran mine were analyzed using SEM-EDS to investigate a connection between the silver mine and the minted silver coins. The results of these analyses provide valuable information on provenance, metal extraction technology, and the coins' purity and fineness. According to the PIXE results, the important elements in the elemental composition of silver coins are Ag, Cu, Pb, Au, and Fe, which were measured in all the coins. The Ag content varies between 84.97 and 97.33wt.%, and the amount of copper (Cu) ranges from 1.4 to 11.23 wt.%. Copper is naturally presented in silver coins in level of less than 2wt.%, Also, according to copmition the results show that the possible sources of silver mines in the Sasanian era are the Surme and Nakhlak mine, an active Pb-Ag mine in Iran

Keywords: *Silver Coins, Elemental composition, Isotopic analysis, PIXE, Sasanian Empire, Pb/Ag Minerals*

Introduction

Coins are one of the most valuable objects among ancient materials, which might give more accurate and significant information about the metallurgy, minting place, and politico-economic conditions[1]. Therefore, research on the chemical compositions and measuring the elemental composition of coins gives information about the technology and historical facts in the past [2.) that can reveal important technological and environmental features and manufacturing processes [3]. Today, archaeologists attempt to answer, questions about the history, provenance, production technique, or authenticity of ancient coins. Identifying trace elements and isotopic ratios can indicate the origin of the mint or raw materials [4,5,6,7]. One of these techniques is Physical chemistry techniques, which can be useful in historical coin research, and their application has increased significantly in recent decades [8,9,10]. Ancient silver contains trace elements such as Pb and Au that can display the type of ore or deposit mined or the technological process used in mining. Of course, it should be mentioned that alloying, reusing, and mixing of metals from different mines affect their concentrations and amount of trace elements, and determining the

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origin of metals based on their trace elements is problematic[11]. Among the rare elements that identify silver are Pb and Au, which only gold remains unaffected by technological steps and remains linked to silver mining [12]. Measurement of Lead sources and combinations of lead and silver isotopes in silver coins and ores can greatly help identify ancient metal sources [13].The first researcher, who investigated Sasanian silver coins and compared their results with Rome silver coins were Bacharach and Huges, and Hall [14,15]. Meyers and Gurdus worked on cupellation, a technique that was applied to galena to extract silver by oxidation of Pb and S. These researchers reported the presence of Au, as a trace element, in the ancient coins, could be used for determining the origin of silver sources in the case of Sassanian silver[16] They showed an empirical relationship that was independent of the thickness of the coin over a wide range of thicknesses. However, when re-melting and re-using are carried out in raw materials, the Au element might not be a criterion of provenance [17]. Kontos showed that Bi can be utilized as an index of a silver mine located in the case of silver coins from Athens [18]]. and Guerra showed that a few components might characterize Au mines and gold coins[19,20,21,22]. Sodaei shows that Au and Pb might use as criteria for silver mines in Iran [23]. Moreover, Sodaei shows the variation of the Fe/Cu ratio versus Ag can be helpful in the investigation of economic conditions of the different periods[24].In addition, trace elements have often been used to track ore origin and metallurgical processes. Volatile components are affected by high-temperature metallurgy, and elements such as Pb, Ir, Au, and Bi can be like a fingerprint indicating ore [25, 26,27,28,29]. On the other hand, trace element abundance in silver coins can be determined by non-invasive surface analyses, such as XRF or PIXE. A limitation of surface analyses is that the concentration of elements may vary from the surface to the core [30]. The aforementioned studies surveyed coins' mines based on PIXE and XRF techniques, which were surface analysed. Given that silver is mined from lead ore (galen), lead isotope analysis (LIA) can be used to identify the source of ancient silver. Isotope analysis, particularly of lead, can enhance provenance studies by linking mineralizations to geodynamic provinces and providing insights into their timing [31].The use of isotope analysis of lead in geology and archaeology is based on the physical and chemical properties of the element. Lead has four isotopes which included: the stable and least abundant 204Pb; and the radioactive and relatively abundant 206Pb, 207Pb, and 208Pb formed by the radioactive decay of 238U, 235U, and 232Th, respectively. isotope 204Pb is not the product of any radioactive decay for which reason its amount does not change during the geological history. Since radioactive decay is irreversible, the ratio of Pb isotopes in each system containing U and Th will change with time. Thus, the ratios of 206Pb/204Pb, 207Pb/204Pb and 208Pb/204Pb will increase steadily over time. This important feature of the Pb isotope system is a useful property in geosciences and has been widely used for studies of geological age and evolution through isotope analyses of rocks and minerals [32]. These features make the abundance of Pb isotopes in above-ground deposits highly variable. In sulfide ores, U is not usually included in the mineral structure. In this way, the Pb isotope composition was frozen at the time of the ore formation event, ensuring that it would maintain a constant Pb isotope composition and provide individual Pb isotope traces. In addition, the isotope composition of a heavy element such as lead does not change through natural processes or when handling lead-containing ores or metals. Whether affected by roasting or smelting, delamination, smelting, alloying, dissolution, or corrosion, the isotopic composition of the lead component remains constant. Therefore, the isotopic composition of the ore containing Pb and the archaeological metalwork made from it will show the same Pb isotope ratio. This will be a constant ratio related to the geological character of the lead source. This isotopic composition of Pb in minerals that do not contain U and or Th is known as common Pb. However, the common Pb composition and the age of the computational model are good indicators of the type of ore-forming eological event and can be an effective way to distinguish metal sources [33-34]. Research in this field is limited and includes: Meert et al.used micro-X-ray fluorescence and multi-collector inductively coupled plasma mass spectrometry were used to perform elemental and isotopic analysis on Sasanian lead coins from the Royal

Museums of Art and History and a private collection. Lead isotope analysis identified at least four distinct sources of lead used to mint Sasanian coins [35]. Merkel el al. used lead isotope and trace element analyses of more than 100 Islamic silver coins and shows multiple new sources, stretching from Morocco to the Tien Shan. So, indicate an Abbasid period mining [36]. Albarede et al. developed a Pb isotope algorithm to determine the provenance of bullion in ancient Greek coinage, accounting for natural and analytical fractionation to identify silver ore sources in Antiquity. Applying this algorithm to 368 lead isotope compositions of silver coins (late 6th to late 2nd centuries BC), Albarde et al, they identified local mint sources linked to the main silver ores of Athens, Thasos, and Thrace. The study revealed that recycled and mixed bullion significantly contributed to mint silver reserves. Precise lead isotopic studies of dated coins, facilitated by the new algorithm, are crucial for tracking evolving silver fluxes over time [37]. Kataska et al. aimed to identify the sources of lead ore used by the Romans to produce lead artifacts, and the results show that they mainly used Greek, Serbian, and Bulgarian deposits. This is a good match for deposits in North Macedonia, Italy, Romania, Turkey, and Tunisia [38]. Canti et al analyzed three coins attributed to Roman Empire to identify the geographic origin of raw materials utilized. The results show that the samples have residual lead isotopic ratios compatible with the Oxalid database for the Roman Empire region [39] De Ceuster et al., in an article entitled, Lead isotope analysis for provenance ancient material a comparison of approaches, 99 Roman Republican silver coins. They discussed the possibilities and pitfalls of three methods for assessing lead isotope data in archaeological provenance. The conventional evaluation of bimodal plots, a clustering method combined with model age calculations and relative likelihood calculations using core density estimates and different approaches are compared, and the strengths and weaknesses of each are highlighted and different approaches are compared, and the strengths and weaknesses of each are highlighted. The results show that while conventional biplots offer valid visual information, kernel density estimation provides a more transparent and statistically sound approach for large datasets, creating an overview of likely origin candidates for each artifact. They state that the clustering and age modeling method by Albarède et al. [37], broadens the analytical spectrum by incorporating geological parameters and enhanced visualization [40].The present study attempts to clarify the relationship between the silver used in coins minted at the Piruz (Sasanid king) mint and the probable source of the raw materials that might have been used to issue the silver coins. Therefore, in this research, first, 15 Piruz silver coins were analyzed by the PIXE method. Due to the fact that the coins belonged to the National Museum of Iran, there was a limitation in sampling to perform lead isotopic analysis, so the results of the isotopic analysis of Pirouz lead coins conducted by Meert et al. were used to identify the ore. Meert and colleagues analyzed 37 Sasanian lead coins, including six of King Piruz; four of these six coins were from the Ahvaz mint (AW) [35]. The results show that coins of Piruz have antimony-lead alloys with varying proportions, containing significant amounts of antimony (3–12% by weight). During the Sasanian Empire, the Caucasus was an important source of antimony [41]. The use of Caucasian raw materials could be a special case of Sasanian dominance over a new region[35]. Now, considering that the Iranian plateau is one of the oldest areas where silver has been mined and used. The research hypothesizes that the Pirus coins also have an internal origin, so we have compared them with three ancient mines, which are the Surmeh mine located near Ahvaz, the Nakhlak mine, which is one of the silver mines used in the Sassanid period, and the Ahangaran mine, which has a high antimony content [42,43,44]. For this purpose, the results of lead analysis of the Nakhlak, Ahangaran, and Surmeh mines were used, considering the geological location of the mine.

The Political History of Piruz I King (459-484 AD)

Political history shows Piruz is one of the kings of the Sassanid period who ruled between 459-484 AD. When Piruz ascended the Sassanid throne, the Sassanid position in the northeast of Iran was not good. Yazdegerd II, the father of Piruz, was not able to give a definite defeat to the Kidariate and after some time he died. Piruz after coming to power temporarily overthrew the Kidarath and succeeded in settling them in what is now a part of Afghanistan. Piruz fought the Heptalites twice, in the first battle he was taken hostage by them, and the Sassanians paid to free him. When he entered Heptilite territory for the second time, he was killed and the northern regions of the Sassanid realm were conquered by the Heptilites, including the cities of Balkh and Herat, possibly Marve. This situation continued until Khosro I, which was part of the problem of this period, also during this period, we witnessed seven years of drought and natural disasters [45]. This era issues gold coins occasionally, while silver and copper coins were common. The characteristics of the silver coins of this period are: the obverse of the coin represents the bust of the king, while the reverse of the coin represents the Fire Altar, and Pahlavi writes the mint name and date corresponding to the reign of the King (Fig. 1).

Fig. 1. Piruz silver coins of the Sassanid king, National Museum of Iran

Materials and Methods

Selection of coins and Methodology of Producing

Fifteen coins from the Piruz I period were selected for PIXE Analysis. These coins were recovered at archaeological excavations in Qouchan. The weight of coins' ranges from 3.50 to 4.10 g. These coins belong to various mints; Nahavand (NH), Darabgird (DA), Isfahan, (As), Vah Ardeshir (VH), Hamedan (AHM), Ardeshir Khoreh (ART), Istakhr (ST), and Azerbaijan (AT), that are kept in the National Museum of Iran (Fig. 2).

Fig. 2. A map of Iran showing the studied coin mints and the location of their discovery

The photos of the studied coins are shown in Fig. 3.

Fig. 3. The photo of studied coins by PIXE analysis

The most important lead-zinc-silver deposits in the vicinity of these cities are the Ahangaran, Nakhlak, and Surme mines, which in this study have been investigated.

Experimental

The PIXE method is of particular interest for archaeological specimens [46]. This technique is non-destructive, highly sensitive, and suitable for multi-elemental analysis as well as quantitative analysis [47-48-49]. This technique provides useful information about ancient coins based on the chemical composition of the coins [48,49,9,50]. PIXE measures elemental composition ranging from Na to U[51,52,53]. Herein PIXE is used to determine the major and minor elemental composition of the coins and to evaluate their fineness of them [54,55,56]. Therefore, the coins are bombarded with a 2 MeV proton beam with a current of 2–3 nA. , under a high vacuum (10-5 Torr) in a multi-purpose chamber. Characteristic X-rays emitted from the sample were detected by a Si(Li) detector with 170 eV resolution at 5.9 keV. Major elements are those that contribute to about 10wt.% in the composition of the samples, while minor elements are in the range from 0.1 to 10wt.%, and trace elements range from <0.1% to the limit of detection [57,58]. The overall uncertainty of the PIXE method was 5% for major elements, 5-10% for minor elements, and 15% for trace elements. Uncertainty in elemental analysis of the ancient coins is not only statistical in nature, but also due to the surface roughness of the coin, chemical corrosion, and/or wear of the object, which alters the accuracy of the results [59,60,61,23]. It is noticed that to remove surface contamination, studies coins before analysis were dipped in the 3–5.5% formic acid for several minutes, then scrubbed with a toothbrush, and finally cleaned with acetone and alcohol. To study and identify the mines, we used the reported results of lead isotopic analysis obtained by the ICP-MAS method. This analysis was performed at the Radiogenic Isotopes Laboratory, University of Alberta, Canada. Moreover, SEM analyses were performed on a few mineral samples from the Ahangaran mine to identify the raw materials that were used. This analysis was performed at the Razi Metallurgy Center using equipment from VEGA\TESCAN-XMU with qualitative and semi-quantitative analysis.

Results and discussions

Element Analysis PIXE

The elemental composition of the analyzed coins in weight percentage (wt.%) are shown in Table 1. To measure the elemental composition of the samples, at least three different points on the coins were analyzed and the mean value of the concentration was reported in Table 1. Elements Ag, Cu, Au, Pb, Fe, Ti, Ca, and S were identified on the examined coins.

Table 1. The Elemental composition of Sassanid silver coins obtained by PIXE analysis in weight percentage(wt.%), (nd= not detected)

Sample	Weight (g)	Mint	Ag	Cu	Au	Pb	Fe	Ti	Ca	S
1	4.00	NH	94.47	2.37	0.8	0.39	nd	0.08	1.89	Nd
2	4.00	DA	97.33	1.03	0.89	0.21	nd	nd	0.54	Nd
3	4.00	DA	92.56	3.53	0.61	018	1.4	0.25	1.1	0.37
4	4.00	As	93.31	4.18	0.89	0.42	0.1	nd	1.1	Nd
5	4.00	NH	96.91	1.23	0.82	nd	nd	nd	1.04	Nd
6	4.00	VH	90.02	7.03	0.67	0.26	0.7	0.13	1.19	Nd
7	4.00	VH	96.64	1.15	0.9	0.27	nd	nd	1.04	Nd
8	4.10	DA	95.34	2.08	0.8	0.31	0.17	nd	1.3	Nd
9	4.00	AHM	93.2	4.16	0.77	0.51	0.26	nd	1.1	Nd
10	4.00	ART	92.14	2.6	0.77	nd	2.84	0.55	1.1	Nd
11	4.00	VH	90.5	4.43	0.88	0.69	0.22	nd	2.7	0.58
12	4.00	VH	96.53	1.04	0.88	nd	0.07	nd	1.3	0.28
13	4.00	VH	92.78	3.93	0.99	nd	0.5	0.14	1.3	0.36
14	3.70	ST	88.98	6.28	0.11	0.45	1.35	0.33	2.5	Nd
15	3.50	AT	84.97	11.23	0.62	0.32	1.29	0.28	1.29	Nd

According to the PIXE results, the important elements in the elemental composition of silver coins are Ag, Cu, Pb, Au, and Fe, which were measured in all the coins. The Ag content varies between 84.97 and 97.33wt.%, and the amount of copper (Cu) ranges from 1.4 to 11.23 wt.%. Copper is naturally presented in silver coins in level of less than 2wt.%, but if the amount of this element is more than 2wt.%, it is not considered that origin from natural resources, while the optional alloys for conditioning coin panels used to provide the high value of copper [15]. Therefore, silver artifacts often contain copper as an alloying element [61] . This element greatly increases the mechanical properties and strength of silver [62-63]. The addition of 3-4wt.% copper to silver was common in ancient times. This process resulted in degraded silver artifacts and subsequently resulted in cost savings [64-61]. The copper content of the samples ranges from 1.04wt.% to 11.23wt.%. In addition to the hardness of the silver metal, the presence of copper made the Sassanids' monetary goals for issuing silver coins more or less daunting due to political circumstances or international economic standing to maintain the same standards in commercial transactions. Samples 14 (Istakhr mint) with 6.28 wt.% and sample 15 (Azarbayejan mint) with 11.23 wt.% have the highest amount of copper, probably added deliberately. With the rise of copper, we see silver in these coins' decrease which shows that there is a direct relationship between the amount of copper, and silver and a rise in copper leads to a decrease in silver (Fig. 4 -5). As shown in Fig. 5a, the amount of Cu in terms of Ag have a strong negative linear correlation between the two elements with a correlation coefficient of 0.91 (R2 = 0.91). Therefore, based on the correlation between these elements, we can conclude that in these coins the manufacturing process to issue the silver coins were most likely similar.

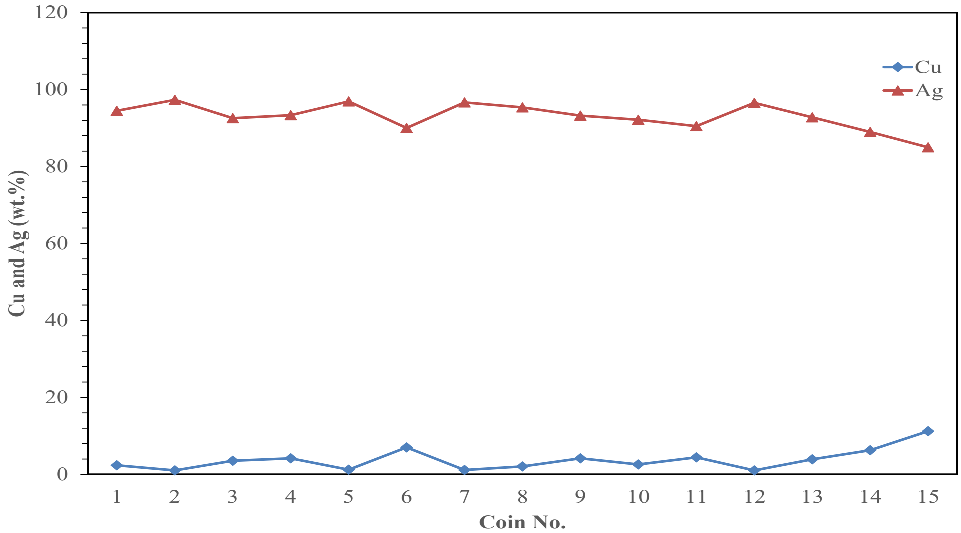


Fig. 4. The variation of the concentration of Ag and Cu in analyzed coins

The amount of gold (Au) ranges from 0.8 to 0.99wt.%, which is below 1wt.%. This amount of gold in alloys used in silver artifacts is considered a natural impurity and can be used as an indicator of primary ore resources as it is unaffected by smelting and Cupellation [65,66,67,68]. According to Craddock any gold contained in an ore flows from with silver during cupellation. In other words, relatively the same amount of gold in coin and ore alloys used to mine silver may have similar mineralogy and chemistry. On the other hand, the gold content in the samples confirms the use of ores other than galena for silver extraction [69-70]. This amount of gold in the alloys of the coins implies the use of argentiferous lead ore for silver mining [71,72]. The variation of the concentration of Ag versus Au in analyzed coins shows a relatively positive correlation with a correlation coefficient of R2 = 0.31 in the samples as shown in Fig. 5b Similar results were obtained from a study of Sasanian silver objects by Meyers and Sayre [63], and Mortazavi et al [73], which showed that most objects are made of metal alloys containing 92 to 96wt.% silver, 3 to 7wt.% copper and 0.5 to 1wt.% gold. Therefore, based on the correlation between Ag and Au elements, we can conclude that in these coins the minerals which used as recourse to extract Ag are most likely similar.

The amount of Pb in the samples is less than 1wt.%. However, in samples No.3, 11, 12, and 13, less than one percent of S is also detected. The technology of silver production from lead ore can rise in the beginning or in the middle of the third millennium BC [62]. Silver smelting was developed from lead smelting technology, and silver metal was extracted from argentiferous lead ore [16]. In other words, silver refining originated from lead smelting technology, extracted from cerussite (PbCO3) and galena (PbS), by the separation [72].The cupellation was largely used in ancient times to obtain silver fineness and cannot be considered very precise [50]. Recently, there has been a consensus that in the earliest stages, oxidized ores such as cerussite (PbCO3) may have been the primary source of silver [70]. It is also assumed that among the various lead ores, argentiferous galena (PbS) was the primary source in antiquity for the production of silver [16]. The presence of PbS in the alloys indicates the use of a galena mine, and lower Pb content in some of the coins can mean a good silver refining process [74]. In samples number 3 and 11, the amount of sulfur is 0.37wt.% to 0.58wt.%, and the amount of lead is 0.18wt.% and 0.69wt.%, and in two other samples (No. S 12 and13), they do not contain Pb, which shows that extraction has been done well in this period. Fig. 6a shows the changes in the weight percentage of Ag versus Pb. As shown in this Fig., based on the concentration of Ag and Pb in these coins, few distinct groups can be identified. In addition, Pb has a significant correlation with Ag in these groups. These results indicated that Pb impurities might come initially from Pb-bearing ore and minerals. It is also possible that different technologies to extract the Ag were used.

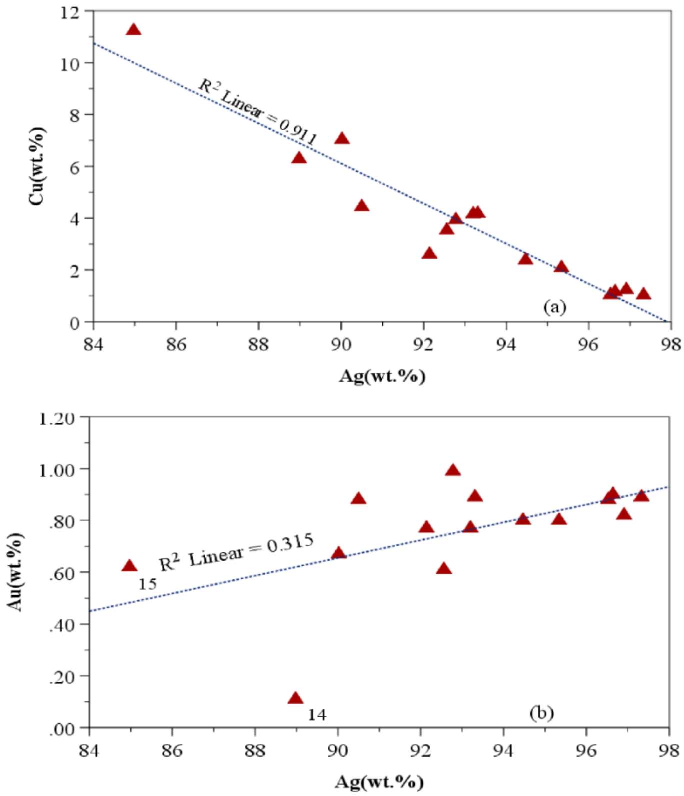


Fig. 4. (a) The variation of the concentration of Ag versus Cu, **(b)**. Ag versus Au in analyzed coins

The ratio of Au/Ag versus Au/Cu shows in the mint house in Sasanian that several sources of Ag have been used for exploration and issuing the coins. According to Meyers [16], if the silver were produced from cerussite, then the gold content would vary approximately from 0.25 %-1.0wt.% which is true for our case [53, 67]. The results show that cerussite and galena were used in this period. The ratio of Au/Ag versus Au/Cu is plotted in Fig. 6b as shown in this Fig., in the analyzed coins, based on the ratio of these elements, almost two distinct groups can be identified. These groups may originate from the difference in the extraction process used to provide Ag to issue the coins. The amount of Iron in the silver samples is between 0.5 and 2.84%, Usually, there is a small amount (less than 1%) of iron in their structure due to surface contamination of the coin burial environment [75], But if a certain amount of iron is added to the coins, it can be considered as a sign to adjust the coin tablet size or as the minor elements which these impurities have been in the coins are due to the geological differences in the lead-silver mines which have different chemical compositions, or may be due to the base copper during the smelting process which also is observable in Western Europe [76]. Iron in the Pirus coins is a minor element that can't originate from surface pollution. The presence of Ca in silver coins is because its elimination during the metallurgical process was impossible at that time.

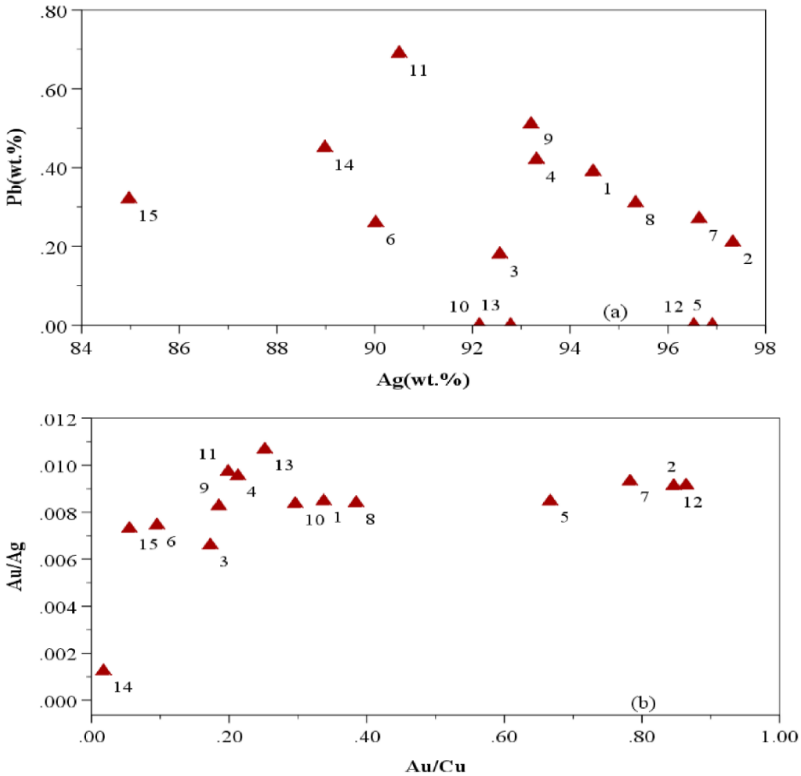


Fig. 6. (a) The variation of the concentration of Ag versus Pb. **(b)**. The ration of Au/Cu versus the ratio of Au/Ag in analyzed coins

Mineralogical Studies

The lead and lead-zinc deposits are widespread in Iran in terms of geological time and space. Most of these deposits(ores) contain a high percentage of silver. Geographically, most of Iran's lead-zinc (silver) deposits are located in four zones: Malayer-Isfahan, Alborz-Azerbaijan, Anarak-Yazd, and Tabas-Ferdows. Ahngaran mine is located in the west of Iran, in the southeast of Hamadan province, and 23 km east of Malair city, and its approximate area is 29 km2.

To investigate the galena minerals in the Ahangaran mine, 3 thin samples from the Ahangaran mineral were prepared and examined by the SEM and SEM-EDS techniques. The microscopic studies show that gallen is the most abundant lead mineral in the Ahangaran mine, and the results of the elemental analysis show that sulfur (S), antimony (Sb), and lead (Pb) are the major elements of the mineral network. The weight percentage of silver in the mineral is 1.07wt.%. Another trace element measured in this mineral is copper (Table 2). Moreover, the main elements in galena are sulfur and lead with 4.88wt.% and 74.95wt.%, respectively. However, the concentration of silver in this mineral is 1.33wt.%. Antimony with an average of 21.69% by weight, an important mineral at Ahangran has been identified as silver. Given the high antimony content in the four Piruz lead coin samples, we compared the results with the Ahangaran mine. Since lead isotope analysis is a more reliable method for determining the origin of silver. we have used its results for the Pirouz coins. The results of the lead isotopic composition of the Ahangaran mine galena sample show that its lead isotopic composition is radioactive and has characteristics of lead with an orogenic reservoir, where lead is largely derived from the upper and lower crust. The lead age model indicates that the origin of lead is Triassic rocks (249 million years old) [77].

Table 2. Microscopic results on the lead minerals of Ahangaran mine

Sample	S	Ag	Sb	Pb	Cu	Fe
1	19.00	1.07	17.76	60.89	1.28	Nd
2	4.88	1.33	18.84	74.95	Nd	Nd
3	18.14	18.36	28.47	Nd	27.39	7.64
Mean	14.01	6.92	21.69	67.92	14.34	7.64

Autonomous labs are a paradigm change in experimental polymer research. These platforms use To know the ore used in the silver coins of Piruz, we need to do an isotope analysis of lead on coins, but due to the limitations of lead analysis on Piruz silver coins from the National Museum of Iran, this study used the results of the analysis of lead coins conducted by Meert (Table 3).

Table 3. The lead isotopic analysis of lead coins of Piruz [35]

Isotopic ratio	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$*	$^{207}Pb/^{206}Pb$*
Sample1	18.107±0.003	15.692±0.002	38.255±0.006	2.113 ± 0.000	0.867 ±0.000
Sample2	18.278± 0.002	15.691± .002	38.429± 0.006	2.102 ± 0.000	0.858 ± 0.000
Sample3	18.280± 0.002	15.692± 0.002	38.437± 0.005	2.103 ± 0.000	0.858 ± 0.000
Sample4	18.141± 0.003	15.691± 0.003	38.284± 0.008	2.110 ± 0.000	0.865 ± 0.000

Chemical results analyzed show that lead coins of Piruz were alloyed with tin and antimony in various proportions, Ahvaz (AW) and BN (unknown mint) mints produced coins with higher tin proportions, and Darabgerd (DA) produced coins with more antimony [35]. Meert believes the presence of important quantities of antimony (ca. 3–12 wt%) coincides with a period where the Sasanian empire reached the Caucasus, which bears important antimony sources [35, 41]. It also states that the main ingredients of the six lead coins found in Kharasen (in modern-day Southern Iraq) are lead and antimony and are very similar to coins of Piruz produced in Darabgerd [35]. We assumed that they were used local mine, So, will compare the lead isotope results of the Piruz coin with the Ahangaran, Nakhlak, and Surme mines (Table 4).

Table 4. The lead isotopic analysis of lead coins of Piruz [35]

Isotopic ratio	Mine	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Modle age (Ma)	μ(^{238} U/ ^{204}Pb)	K(^{232}th/ ^{238}U)	$^{208}Pb/^{206}Pb$*	$^{207}Pb/^{206}Pb$*
deposit 1	Ahangaran	18.407± 0.003	15.641± 0.003	38.572±0.011	249	9.16	3.95	2.095	0.850
deposit 2	Surme	18.062	15.684	38.230	585	10.16	4.02	2.116	0.8663
deposit 3	Nakhlak1	18.511	15.637	38.642	163±3	9.89	-	2.087	0.8447
deposit 4	Nakhlak2	18.516	15.638	38.641	163±3	9.89	--	2.087	0.8446

Lead Isotopes Studies

The proportions of the four lead isotopes (204Pb,206Pb, 207Pb, and 208Pb) in a lead ore sample will depend on the geological age of the ore deposit. Therefore, lead isotope ratios determine the source of the sediment used to produce lead-containing archaeological objects [79]. Isotopic ratios used for geological studies include 206Pb/204Pb, whereas for archaeometallurgical studies, 207Pb/206Pb and 208Pb/206Pb should be measured, as indicated by asterisks in the tables [80,81]. whereas for archaeometallurgical studies, 207Pb/206Pb and 208Pb/206Pb should be measured, as indicated by asterisks in the tables Gale, and Tomczyk, plot different ratios of Pb-isotopes such as 208Pb/204Pb versus 206Pb/204Pb to investigate the origin of Piruz silver coins. Three isotope ratios have plotted in a bi-scatter plot, where the horizontal axis is always 207Pb/206Pb, and the vertical axis is 206Pb/204Pb and 208Pb/206Pb (Fig. 7) [80,81,82].

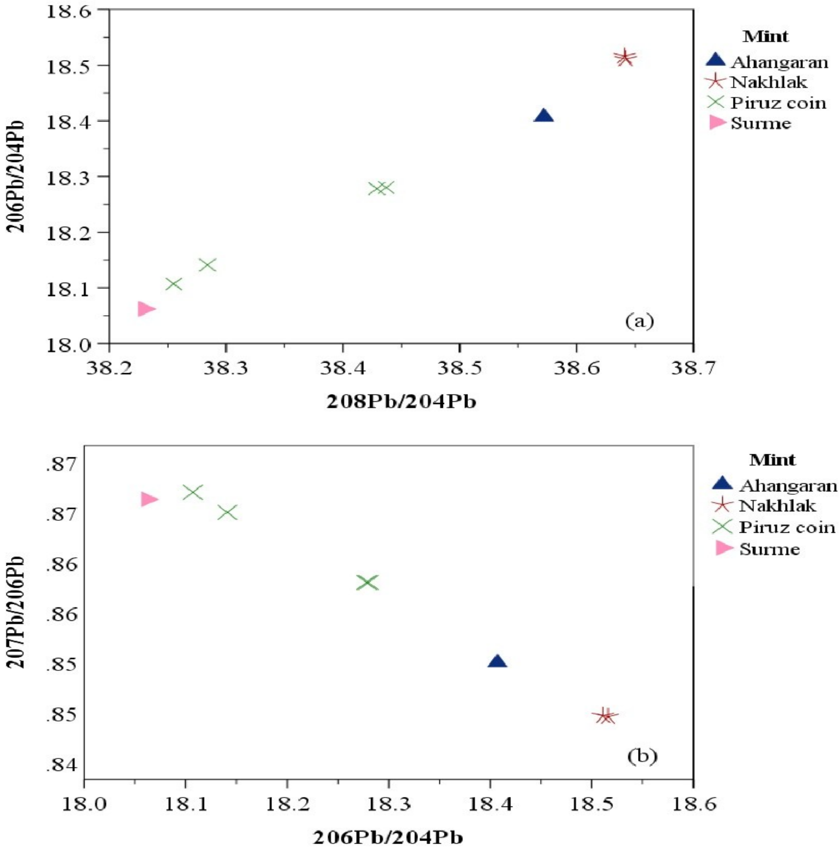
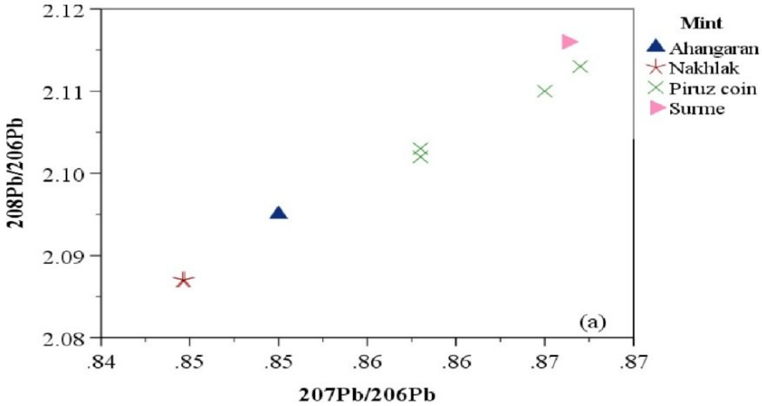


Fig. 7. (a) $^{207}Pb/^{206}Pb$ vs. $^{208}Pb/^{206}Pb$. **(b)**. 207Pb/204Pb vs. $^{206}Pb/^{204}Pb$ for four Sasanian silver coins of Piruz, two samples from the Nakhlak deposite, a sample from the Ahangaran deposite, and a sample from the Surme deposite. Therefore, a comparison was made with two other lead and zinc mines. The first is the Surmeh mine, which is located in the south of Iran in the Firouzabad region, and the other is the Nakhlak mine

The results of the lead isotope analysis of the Pirouz coins, with the lead isotope ratios of the Ahangaran mine, show that the samples are not compatible with each other. Therefore, a comparison was made with two other lead and zinc mines. The first is the Surmeh mine, which is located in the south of Iran in the Firouzabad region, and the other is the Nakhlak mine. Nazafti and Pernika, by conducting a lead isotope analysis in the Nakhlak mine and comparing it with some silver artifacts, have identified that the Nakhlak mine might be one of the mines used in the Sassanian and Islamic periods [45].

The results of the lead isotope analysis of the Piruz coins were compared with the lead isotope ratios of the old silver mines (Nakhlak, Surme and Ahangaran) to determine the origin .The results show that the lead isotope ratios of the two Piruz coins are compatible with the lead isotope ratios of the Surme mine and one of its samples is compatible with the Nakhlak mine (Fig. 8).



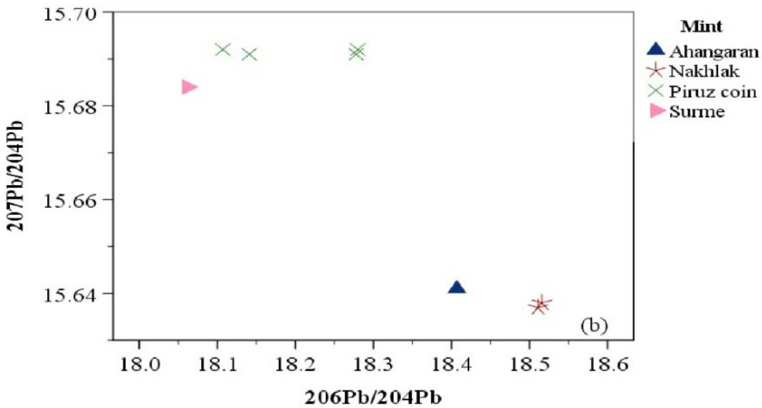


Fig. 8. (a) $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$, **(b)** $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ for four Sasanian silver coins of Piruz, two samples from Nakhlak deposite, a sample from Ahangaran deposite and a sample from Surme deposite.

The results of lead tests on the Piruz coins with mines inside Iran show that two coins' overlap with the Surme mine and one with the Nakhlak mine, which also. shows that they probably used local mines inside Iran.

Conclusions

This paper evaluates the surface features and elemental composition of Sasanian coins obtained from the archaeological excavations of Quchan in northeastern Iran. PIXE analysis of fifteen coins of Shah Pirouz revealed that the main components were silver, gold, lead, copper, iron, and sulfur. The concentration of silver, which is the main component of the coins, varies between 84.97% by weight and 97.33% by weight, indicating a high silver content and an increase in the purity of the coins over time as the coinage policy became more regular. Based on the trace elements of lead and gold, it can be suggested that at least two types of silver minerals were used: galena and cerussite. To identify possible mines, given the limitations of lead analysis for coins in the National Museum, we decided to use the results of the lead analysis of Pirouz coins conducted by Mirt et al. The lead results of Sasanian coins were compared with the lead results of mines inside Iran (Ahangaran, Surmeh, and Nakhlak), and the results show that the lead isotope of Pirouz coins overlaps with the lead isotope of the Surmeh and Nakhlak mines, and they probably used these two mines. Finally, it can be said in the Sassanid period in addition foreign sources, local mines have been used.

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Declaration of competitive interest

The authors declare that they agreed to participate in the present paper and there is no competing interests.

Credit authorship contribution statement

Bita Sidaei's contribution is 60% of this article and Davoud Agha- Aligol's contribution is 40 %.

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