در جستجوی رنگ آبی: بررسی منشأ کبالت در سرامیک‌های لعاب‌دار ایران و چین (سده‌های ۱۲ تا ۱۷ میلادی)

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چکیده

نخستین بهره‌برداری از معادن کبالت برای استفاده از رنگ‌آمیزی آبی در مواد زجاجیه به هزاره دوم پیش‌ازمیلاد در ایران، مصر و بین‌النهرین بازمی‌گردد. به همین دلیل، معادن کبالت ایران برای مطالعه رنگ آبی در سرامیک‌های لعاب‌دار اهمیت ویژه‌ای دارند. به نظر می‌رسد که معادن کبالت ایرانی برای سفالگران چینی نیز اهمیت داشته‌اند. در این پژوهش، آنالیز XRF پورتابل (p-XRF) بر روی ظروف مینایی، کاشی‌های لاجوردینه و سرامیک‌های آبی و سفید از ایران و چین انجام شد. نتایج نشان داد که در دوران سلسله مینگ، همانطور که پیشتر توسط محققان پیشنهاد شده بود، کبالت محلی با محتوای منگنز بالا در چین استفاده می‌شد. اما در مورد لعاب‌های آبی در ایرانٍ بین سده‌های ۱۲ تا ۱۷ میلادی، مشخص شد که حداقل دو معدن مختلف برای استخراج کبالت استفاده شده است. یکی از معادن اصلی احتمالاً قمصر کاشان است که قبلاً در متون اسلامی فارسی به کبالت آن اشاره شده بود. با این حال، دومین معدنی که در این پژوهش پیشنهاد شده، معدن تخت سلیمان است که ترکیب شیمیایی آن با لعاب‌های آبی پیش از دوران مینگ در چین مطابقت بیشتری نسبت به معدن قمصر دارد. علاوه بر این، نام کبالت در متون قدیمی فارسی ”سنگ سلیمانی“ و در متون قدیمی چینی ”سو-ما-لی-چین“ ذکر شده است که از این نظر با نام تخت سلیمان شباهت بیشتری دارد. قابل توجه است که معدن کبالت تخت سلیمان در طول جاده ابریشم قرار دارد، که تجارت آن با چین را ساده‌تر از دیگر معادن کبالت ایرانی می‌کند. بنابراینٍ، برای نخستین بار در این مطالعه پیشنهاد می‌شود که معدن تخت سلیمان منبعی احتمالی برای کبالت تجاری در چین بوده باشد، معدنی که احتمالاً نقش مهمی در معرفی اولیه کبالت ایرانی به سفالگران چینی ایفا کرده است. با این حال،p-XRF یک ابزار تحلیل سطحی است و با توجه به محدودیت‌های آن بهترین گزینه برای تعیین دقیق تفاوت‌های معادن کبالت نیست.

واژگان کلیدی: ظروف مینایی، سرامیک‌های آبی و سفید، کاشی لاجوردینه، معدن کبالت، p-XRF.

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The Origin of Cobalt: A Review of Blue Glazed Ceramics in Iran and China from the 12th to the 17th Centuries CE

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Abstract

The exploitation of cobalt mines for the use of its blue colorant in vitreous materials dates back to the second millennium BCE in Egypt and Iran. For this reason, cobalt mines in Iran hold significant value for studying the blue color of glazed ceramics. Evidence suggests that these Iranian cobalt mines were also important for Chinese potters. In this research, portable X-ray fluorescence analysis (p-XRF) was conducted on Mina'i ware, Lajvardina tiles, and blue and white ceramics from both Iran and China. The results further corroborate what scholars have previously suggested, revealing that during the Ming Dynasty (1365-1644 CE), locally sourced cobalt with a distinctive high manganese content was used in China. However, the cobalt used for the blue glazes in Iran dating from the 12th to 17th centuries CE was determined to have been obtained from at least two different mines. One of the key mines is likely Qamsar in Kashan, which has been mentioned in Persian texts regarding its cobalt. The second mine proposed in this research is the Takht-e Soleyman mine, the Takht-e Soleyman mine, which has a chemical composition that aligns with that of the blue glazes predating the Ming dynasty in China. Additionally, its name corresponds to "Soleymani stone" in Persian texts and "Su-ma-li-qin" in old Chinese texts. Notably, the Takht-e Soleyman cobalt mine is located along the main Silk Road, making its trade with China more straightforward than that of other Iranian cobalt mines. This study suggests, for the first time, that the Takht-e Soleyman mine should be considered a potential source of traded cobalt in China and played a role in the initial introduction of Chinese potters to Iranian cobalt. Although p-XRF is a surface analysis tool with limitations in accurately determining differences in cobalt sources, this study provides new insights into cobalt trade and the interaction between Iranian and Chinese potters.

Keywords: Mina'i ware; Blue and White ceramics; Lajvardina tile; Cobalt mine; p-XRF.

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Introduction

The use of cobalt as a blue colorant in vitreous material dates back to at least the second millennium BCE in Egypt, Mesopotamia and Iran. It appears that cobalt from mines in Iran and Egypt was utilized in the production of blue vitreous materials.(Matoïan & Bouquillon, 2021). Therefore, Iran and Egypt can be considered among the regions with the earliest use of cobalt as a coloring agent for glass and faience. Additionally, the use of cobalt as a blue color agent in vitreous materials was reported during the second millennium BCE in Mesopotamia (Walton *et al.*, 2012; Shortland *et al.*, 2006). The use of cobalt as a color agent in the faience and other vitreous materials in Iran and Egypt was mentioned in the second millennium BCE and during the Achaemenid empire (Shortland *et al.*, 2006; Yousefnejad, 2023). In the early Islamic period, during the Abbasid dynasty (9-10th centuries CE), blue and white ceramics were used, and the possibility of using these kinds of cobalt blue in Oman, Saudi Arabia or Yemen was raised (Wood *et al.*, 2007a). In China, the production of vitreous materials with a cobalt blue color seems to have (re)started in the Tang Dynasty (around the 7th century CE) (Zhang & Pollard, 2022; Colomban *et al.*, 2021a). Blue and white porcelain are the most famous brands in China worldwide, and Yuan (1279-1368 CE) and early Ming Dynasties (1368-1644 CE) may have used imported cobalt materials from Persia (Jiang *et al.*, 2020). It appears that the production of blue and white ceramics, which continued in Iran until the Qajar dynasty, eventually reached a stage where the blue color developed into dark blue and even black shades. Additionally, the use of chromium as a coloring agent has also been reported in Qajar dynasty blue and white ceramics (Ma *et al.*, 2022). Regarding the cobalt mine used in the ancient world, it seems that the most famous mine according to ancient texts should be a mine in Kashan (Qamsar) in the central region of Iran (Fig. 1), which is known as the Sulaimani mine in Persian texts (14th century CE) and known as the su-ma-li-qin mine in Chinese texts (15th century CE); also, in European texts, this mine has been mentioned recently (Watt, 1979; Matin & Pollard, 2015).

This research focused on the time span from the 12th to the 17th centuries CE and glazed wares with blue coloration in Iran and China. The reason for the significance of the time span from the 12th to the 17th century CE lies in the hypothesis that in the 15th century CE, coinciding with the rule of the Xuande Emperor (1426-1435 CE), locally sourced Chinese cobalt completely replaced Iranian cobalt for the production of blue and white porcelains (Jiang *et al.*, 2020).

In addition, the amount of manganese in cobalt blue glazes in China seems to be slightly greater than that in cobalt blue glazes in Iran. This issue is clear by comparing the cobalt blue glazes of Iran and China in the 13th and 14th centuries CE (Holakooei *et al.*, 2023; Jiang *et al.*, 2018). This difference is especially clear for manganese, as in Iranian blue glazes from

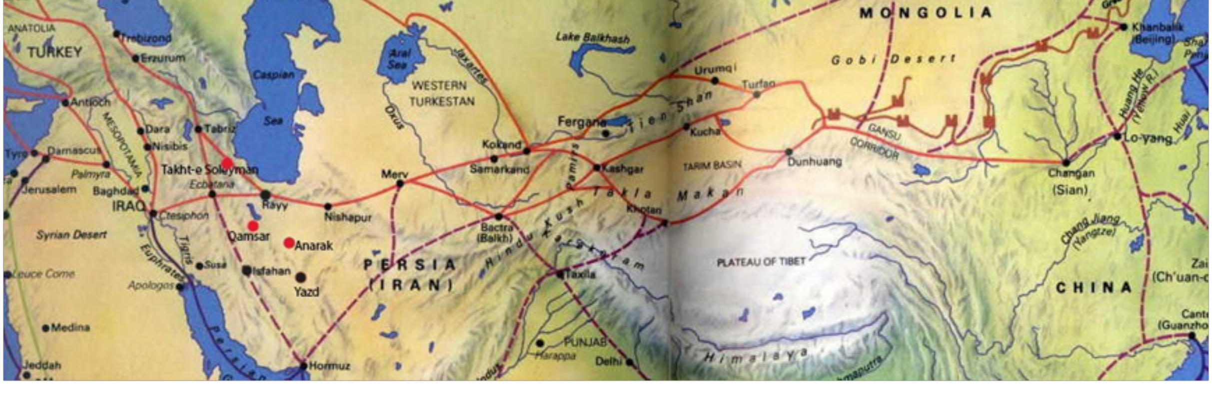

Fig. 1. The geographical locations mentioned in the text, along with the main route of the Silk Road in the Iranian plateau (The red circles indicate mining areas). Adapted from (Boucharlat & Azarpay, 1999) with minor modifications.

the 12th to the 17th centuries CE (Holakooei, 2016; Gradmann, 2016), the average manganese content is less than 0.1%; however, in Chinese glazes, the average manganese content is close to that in Iran only during the Yuan dynasty; however, in the Xuanda imperial and Qing (1644-1911 CE) glazes, the average manganese content in cobalt blue glazes is close to 2.5% (Jiang *et al.*, 2020). However, studies conducted on cobalt mines in Qamsar, Kashan, have indicated that one of the key characteristics of Qamsar cobalt is its high arsenic content (Matin & Pollard, 2017). This is in contrast to analyzed samples from the blue and white porcelains of the Yuan dynasty, where arsenic levels are not elevated (Simsek Franci, 2020). Consequently, the question arises regarding how the cobalt trade between Iran and China, emphasized in ancient texts, could have occurred while the evidence for this trade during the period from the 12th to the 17th centuries CE seems somewhat unclear.

Thus, if we acknowledge the use of Iranian cobalt in Chinese potters for creating a blue color, uncertainties remain regarding the specific Chinese dynasties that employed this practice. Additionally, we lack clarity on the particular cobalt mine in Iran that, if the trade between Iran and China did occur, supplied the cobalt stone for the production of blue and white porcelains in China. To address this issue comprehensively, it is imperative to conduct a study on Iranian vitreous materials and compare them with Chinese samples.

Materials and methods

A total of 28 glazed ceramic samples were selected for this study (Fig. 2). The glazed ceramics under investigation were chosen from three distinct collections, including 8 Mina'i ceramic sherds and 8 blue and white ceramic sherds with Safavid seals from the Iran National Museum collection. Additionally, 9 blue and white porcelain samples from the archaeologi-

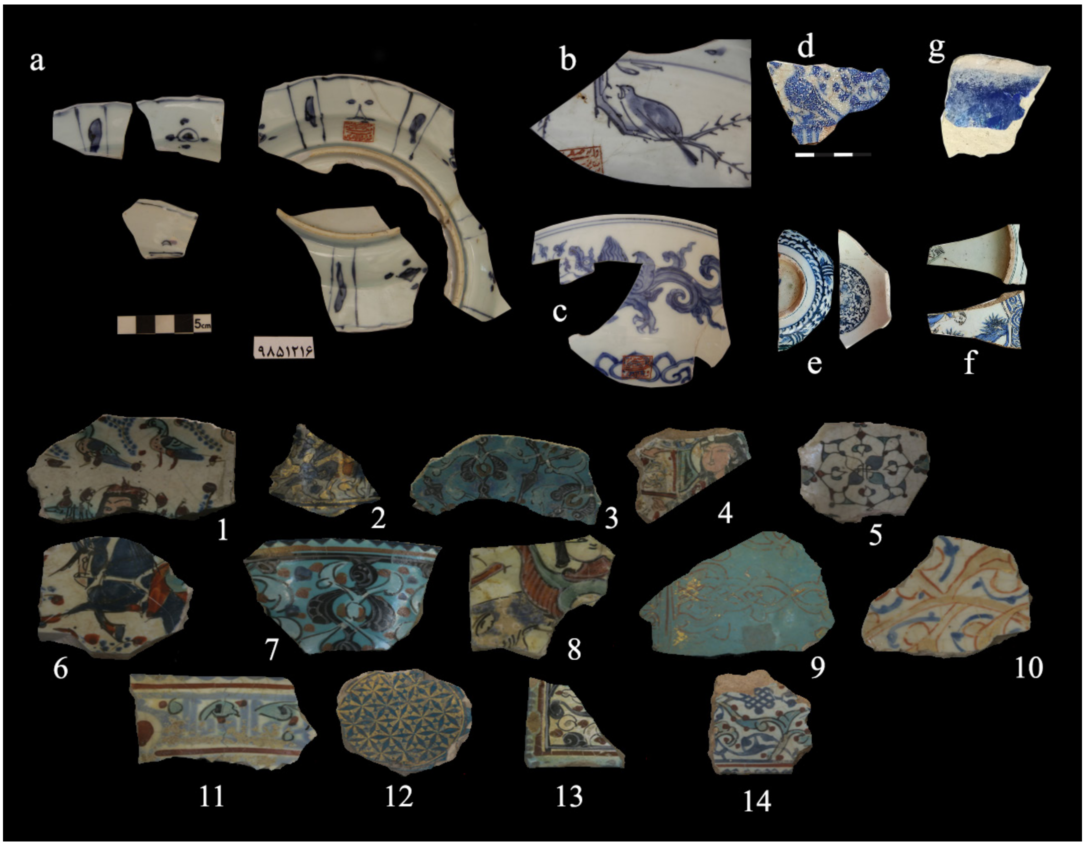

Fig. 2. A selection of the studied samples (a, b, and c) correspond to CH-1, CH-4, and CH-5; (d, e, and f) JN-4, JN-2, and JN-7; (g) Sample LA-1; and (H) the set of ceramic fragments from the Mina'i pottery collection of the Iran National Museum, which in this study includes samples 2, 4, 5, 7, 8, 10, 11, and 14, were investigated. These patients were designated MI-1 to MI-8, respectively, in this study.

cal excavations of the Jahan-Nama site in Isfahan were selected, with 1 stonepaste blue and white ceramic shred at that site. Furthermore, 2 samples of lajvardina tiles from Yazd were also included in the selection. The collection of blue-and-white porcelains in the National Museum of Iran, which is the subject of the study, belongs to the shrine of Sheikh Safi al-Din Ardabili. All the studied samples bear the red seal of Shah Abbas Safavi, symbolizing the dedication of these items to the shrine of Sheikh Safi al-Din Ardabili. These ceramics are part of the precious collection of Shah Abbas I (1588-1629 CE) of the Safavid dynasty and are considered Chinese-made blue-and-white porcelains. To facilitate the identification of samples, abbreviations were used such that "MI" denotes Mina'i samples, "JN" represents samples from the Jahan-Nama site, "CH" indicates samples from the shrine of Sheikh Safi al-Din Ardabili, and "LA" signifies Lajvardina samples from Yazd (Table 1).

X-ray fluorescence spectroscopy analysis was carried out utilizing a handheld X-ray fluorescence spectrometer (Skyray Explorer 7000) equipped with a silver target end window-integrated miniature X-ray tube. The primary filter operates at a voltage of 50 kV and a current of 200 μA, with a detection window diameter of 4 mm, resulting in a measurement area of approximately 16 mm² per test. The acquisition time for compositional data collection was

Table 1. Information related to the studied samples

Number	Sample Name	Type	Ceramic body	Dynasty (period)	Place of discovery
1	MI-1	Mina'i	Stonepaste	Late 12th- 13th century	Rey
2	MI-2	Mina'i	Stonepaste	Late 12th- 13th century	Rey
3	MI-3	Mina'i	Stonepaste	Late 12th- 13th century	Rey
4	MI-4	Mina'i	Stonepaste	Late 12th- 13th century	Saveh
5	MI-8	Mina'i	Stonepaste	Late 12th- 13th century	Saveh?
6	MI-6	Mina'i	Stonepaste	Late 12th- 13th century	Saveh
7	MI-7	Mina'i	Stonepaste	Late 12th- 13th century	Saveh
8	MI-8	Mina'i	Stonepaste	Late 12th- 13th century	Rey
9	JN-1	B&W	Porcelain	Ming/Safavid	Isfahan
10	JN-2	B&W	Porcelain	Ming/Safavid	Isfahan
11	JN-3	B&W	Porcelain	Ming/Safavid	Isfahan
12	JN-4	B&W	Stonepaste	Ming/Safavid	Isfahan
13	JN-5	B&W	Porcelain	Ming/Safavid	Isfahan
14	JN-6	B&W	Porcelain	Ming/Safavid	Isfahan
15	JN-7	B&W	Porcelain	Ming/Safavid	Isfahan
16	JN-8	B&W	Porcelain	Ming/Safavid	Isfahan
17	JN-9	B&W	Porcelain	Ming/Safavid	Isfahan
18	JN-10	B&W	Porcelain	Ming/Safavid	Isfahan
19	CH-1	B&W	Porcelain	Ming/Safavid	Ardabil
20	CH-2	B&W	Porcelain	Ming/Safavid	Ardabil
21	CH-3	B&W	Porcelain	Ming/Safavid	Ardabil
22	CH-4	B&W	Porcelain	Ming/Safavid	Ardabil
23	CH-5	B&W	Porcelain	Ming/Safavid	Ardabil
24	CH-6	B&W	Porcelain	Ming/Safavid	Ardabil
25	CH-7	B&W	Porcelain	Ming/Safavid	Ardabil
26	CH-8	B&W	Porcelain	Ming/Safavid	Ardabil
27	LA-1	Lajvardina	Clay body	Ilkhanid	Yazd
28	LA-2	Lajvardina	Clay body	Ilkhanid	Yazd

set at 60 seconds, with 30 seconds each for the high and low filters. A minimum of three valid readings were obtained from the same portion of each sample. If the initial three readings exhibited simultaneous fluctuations in the content of multiple elements significantly different from the other two readings, the reading was deemed invalid and subjected to reanalysis until a minimum of three valid readings were obtained. The average of these readings was then accepted as the result for the test area. An inherent challenge with portable X-ray fluorescence (p-XRF) systems lies in conducting the analysis in an atmospheric environment, which poses difficulties in analyzing light elements in glazes (Simsek, Demirsar Arli, *et al.*, 2019). Consequently, the data on the contents of light elements are intentionally rendered incomparable across different devices, allowing for reproducible data only when using a specific selected analyzer. Therefore, the focus of interest in this study encompasses elements above calcium (Ca). Instrument calibration was meticulously controlled using mineral standards, ensuring a high detection capability for the measurement of ceramic materials.

Results

Research on cobalt blue coloring in ancient vitreous materials has indicated the variety of cobalt ores used for blue coloring (Gratuze *et al.*, 2018; Molera *et al.*, 2021). Cobalt occurs in nature in three main forms, either as an impurity of manganese ores, such as asbolane ($(Ni,Co)_{2-x}Mn^{4+}(O,OH)_4 \cdot nH_2O$), or as sulfides ($CoAsS$, Co_3S_4) and arsenide ($CoAs_{2-3}$), which are usually associated with iron, copper or silver ores (Gratuze *et al.*, 2018). Based on the studies conducted thus far on cobalt in glass and glazes in western Asia and China, the cobalt used in glaze can be divided into 5 groups: a) Fe-Co (Zn, Cu), which is mentioned in the Abbasid blue and white glazes. b) Fe-Co (Cu) in Tang Sancai glazes (Wood *et al.*, 2007b). c) Mn-Co (cobalt rich in manganese) from the Ming and Qing dynasties, d) cobaltite (CoAsS) from medieval Islamic glazes (Matin & Pollard, 2017) and e) Ni-Co-As-Cu from Sassanid and early Islamic glazes and glasses (Jiang *et al.*, 2020). As shown, there is high variation between the types of cobalt pigments in the glazes of western Asia and China. In Iran, the two mines of Qamsar and Anark have been mentioned as the mines producing cobalt in vitreous materials (Matin & Pollard, 2017; Jiang *et al.*, 2020). Alongside all these considerations, the possibility of mixing different cobalt ores with each other should not be overlooked (Simsek, Unsalan, *et al.*, 2019). For this purpose, p-XRF nondestructive analysis was performed on the samples. The chemical composition results corresponding to the blue color of the glazed ceramics are presented in Table 2. It appears that cobalt, iron, copper, zinc, arsenic, and manganese can be useful in identifying cobalt mines used as blue coloring agents in glazed ceramics (Colomban *et al.*, 2021b). Considering Figure 3, it is possible to categorize all the samples into two main groups based on the origin of the utilized cobalt. The first group comprises cobalt pigments employed in porcelain bodies whose origin traced back to China and whose origin was positioned along the iron-manganese axis. The second category consists of cobalt pigments/glazes found in clay and stonepaste ceramic bodies originating from Iran and positioned along the iron–cobalt axis. In other words, there is a discernible difference between the cobalt sources in China and Iran, and the ternary diagram of iron, manganese, and cobalt can be instrumental in delineating this distinction (Colomban *et al.*, 2021b).

However, considering the amounts of cobalt, manganese, arsenic, and copper (Fig. 4 a, b), it can be asserted that samples related to the Iranian Plateau can also be classified into at least two broad groups. In other words, based on Figure 4a, the studied samples exhibit three distinct dispersion ranges. The first range corresponds to the apex of the diagram, near the manganese element, where samples of Chinese blue and white porcelain are situated. Considering the findings of previous studies indicating elevated levels of manganese in locally used cobalt ores for the production of Chinese blue and white ceramics (Du & Su, 2008), this finding was expected. The second category com-

Table 2. Chemical composition of the blue color in the glazed ceramic samples determined via p-XRF analysis (wt%)

Sample	Mn	Fe	Co	Ni	Cu	Zn	As
MI-1	0.04	2.43	0.43	0.28	0.24	0.01	0.01
MI-2	0.08	1.6	0.36	0.38	0.72	0.03	0.63
MI-3	0.05	1.63	0.8	0.26	0.12	0.01	0.62
MI-4	0.04	2.43	0.9	0.27	1.57	0.02	0.04
MI-8	0.09	3.52	1.19	0.36	0.19	0.02	0.97
MI-6	0.06	0.93	0.28	0.38	0.17	0.02	0.03
MI-7	0.04	0.76	0.17	0.32	0.2	0.02	0.02
MI-8	0.1	4.21	1.36	0.42	0.71	0.04	0.11
JN-1	0.08	0.31	0.01	0	0	0	0
JN-2	0.004	0.25	0.01	0	0.009	0	0
JN-3	0.007	0.49	0.01	0	0.008	0.008	0
JN-4	0.009	0.28	0.13	0	0.08		0.1
JN-5	0.007	0.45	0.02	0	0.009	0	0
JN-6	0.001	0.22	0.01	0	0.01	0	0
JN-7	0.01	0.46	0.02	0	0.01	0.009	0
JN-8	0.003	0.22	0.05	0	0.07	0	0
JN-9	0.01	0.24	0.02	0	0.08	0	0
JN-10	0.009	0.26	0.03	0	0.08	0	0
CH-1	0.17	0.43	0.02	0	0	0	0
CH-2	0.09	0.68	0.09	0	0	0	0
CH-3	0.23	0.44	0.06	0.008	0	0	0
CH-4	0.11	0.4	0.02	0	0	0	0
CH-5	0.05	0.33	0.009	0	0	0	0
CH-6	0.05	0.24	0.009	0	0	0	0
CH-7	0.09	0.29	0.01	0	0	0	0
CH-8	0.21	0.31	0.04	0	0	0	0
LA-1	0.02	1.5	0.18	0	0.63	0.02	0.15
LA-2	0.02	2.12	0.19	0	0.67	0.02	0.12

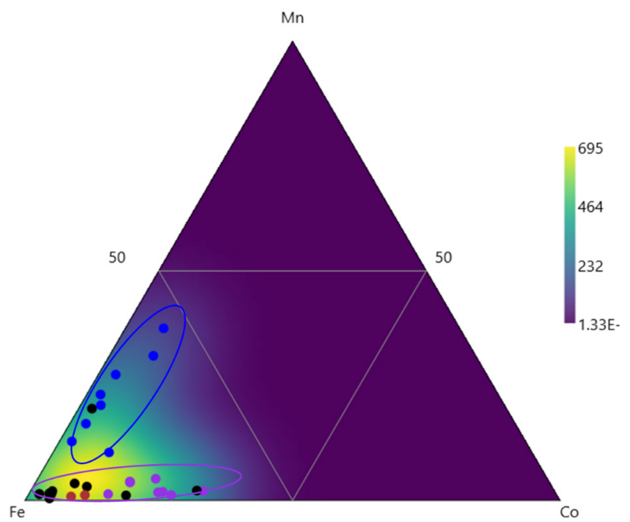

Fig. 3. Ternary diagram of manganese-iron-cobalt; The magenta circles represent Mina'i samples, red circles indicate Lajvardina samples, black circles denote blue-and-white samples from the Jahan-Nama site, and blue circles signify blue-and-white samples from the shrine of Sheikh Safi al-Din.

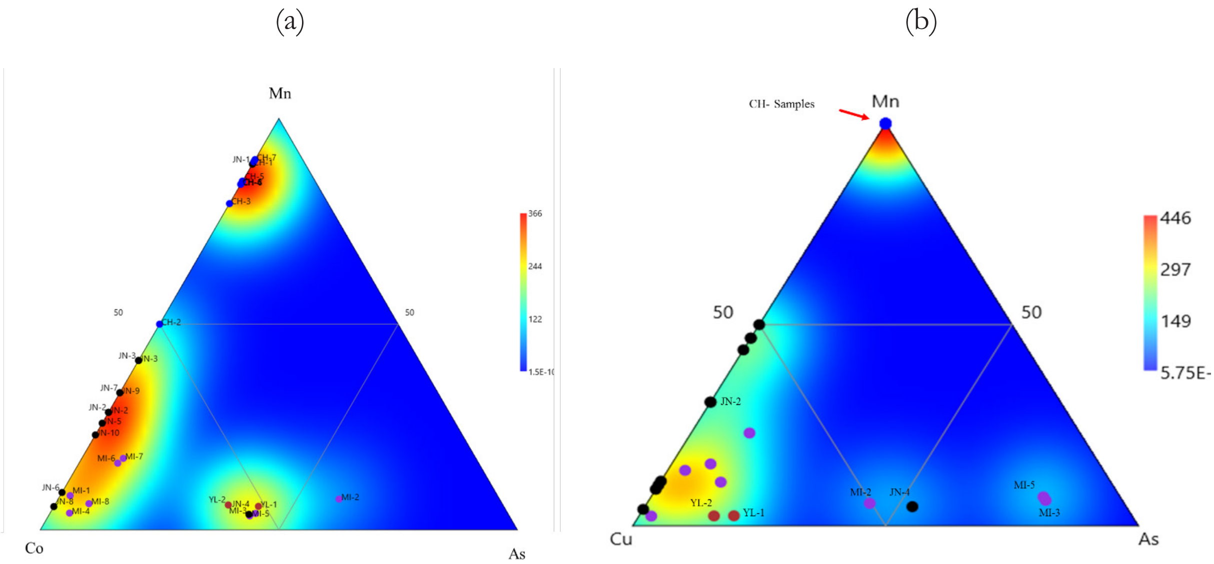

Fig. 4. (a) Ternary diagram of manganese-cobalt-arsenic. (b) Ternary diagram of manganese-copper-arsenic. The magenta circles represent Mina'i samples, the red circles indicate Lajvardina samples, the black circles denote blue-and-white samples from the Jahan-Nama site, and the blue circles signify blue-and-white samples from the shrine of Sheikh Safi al-Din.

prises samples located closer to the arsenic content range. It seems that in these samples, the arsenic content is high, which is characteristic of the cobalt mines in Kashan (Matin & Pollard, 2017). The third category falls within the range near the cobalt element, and according to Table 1, these samples have higher copper contents than do the other samples. To illustrate this phenomenon, a ternary diagram of manganese-copper-arsenic materials was constructed (Fig. 4b), revealing that the Iranian blue glaze samples can be divided into two groups: (a) samples with high arsenic and low copper percentages and (b) samples with high percentages of both arsenic and copper. Additionally, the ternary diagram of manganese-nickel-arsenic (Fig. 5) indicates that the Iranian cobalt blue samples can be classified into at least two distinct groups based on the levels of arsenic and nickel. Considering the studies conducted on the Qamsar Kashan cobalt mine (Matin & Pollard, 2017), the presence of nickel in the cobalt blue samples suggested that it cannot be directly associated with the Qamsar mine. Therefore, it appears that on the Iranian Plateau, at least one other cobalt mine, apart from Qamsar, has been utilized. This observation is crucial because the samples that have shifted toward the copper axis in Figure 4b also exhibit a tendency toward the axis associated with nickel (Fig. 5). In other words, the cobalt mine utilized for these samples simultaneously had elevated levels of both copper and nickel. Therefore, according to Figure 5, the cobalt blue samples from China are distinctly separated from the other samples due to their high manganese content. To further examine and categorize the remaining samples more precisely, particularly the mina'i and lajvardina types, a ternary diagram of nickel, arsenic, and zinc was utilized (Fig. 6). As illustrated, the 12th to 14th century samples can be divided into two main groups: some samples have higher arsenic levels, while others have higher nickel levels. It is worth noting that two lajvardina samples (samples LA-1 and LA-2) from the 13th -14th century contain a notable amount of zinc in addition to high arsenic. This characteristic is also observed in some of the high-nickel samples (top of the diagram in Fig. 6), such as sample MI-8. However, in general, all samples can be categorized into two groups: those with high nickel and those with high arsenic.

Discussion

Several hypotheses have been proposed regarding the source of cobalt used in the production of blue glaze ceramics in pre-Ming dynasties

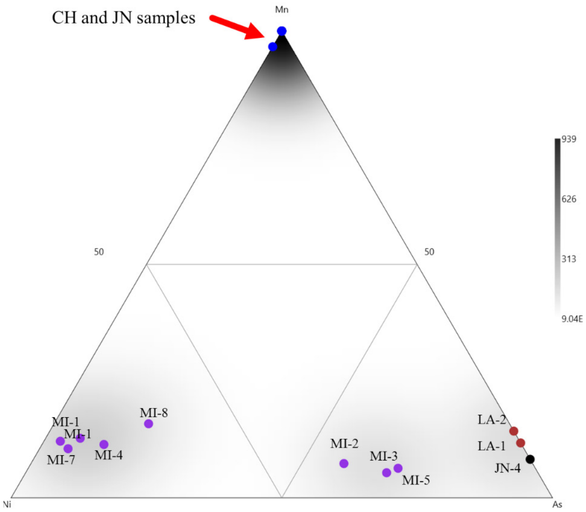

Fig. 5. Ternary diagram of the manganese-nickel-arsenic. The magenta circles represent Mina'i samples, the red circles indicate Lajvardina samples, the black circles denote blue-and-white samples from the Jahan-Nama site, and the blue circles signify blue-and-white samples from the shrine of Sheikh Safi al-Din.

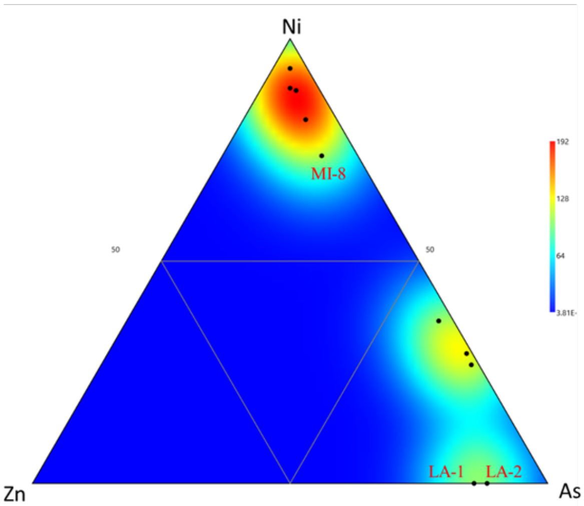

Fig. 6. Ternary diagram of the nickel-arsenic-zinc of 12th to 14th century samples (Lajvardina and Mina'i samples).

in China, suggesting that it may have been imported from Persia (Wen *et al.*, 2007). However, there is much debate about the origin of cobalt mines. Several researchers have attributed cobalt sources in China to the Qamsar mine of the Kashan mine in central Iran (Wen & Pollard, 2016). In contrast, others dismiss the possibility of using the Qamsar of the Kashan mine due to the lack of chemical compatibility with the blue glaze in Chinese ceramics (Kessler, 2012). They propose that the Qamsar mine might not have been a supplier of cobalt to China before the Ming dynasty. For this reason, some mines, such as the Anarak cobalt mine, located southeast of the Qamsar mine, have been suggested as potential sources for China's cobalt supply from Iran (Jiang *et al.*, 2020). As indicated in Figure 3, at least two distinct cobalt sources were utilized on the Iranian Plateau during the period from the 12th to the 17th centuries CE. Considering that cobalt contains a percentage of copper and nickel, geologically, cobalt in the Takht-e Soleyman region is suggested. The cobalt mine in this area is known as "Bayche-Bagh" and contains cobalt, nickel, arsenic and copper mineralization (Rezazadeh *et al.*, 2020).

Therefore, the presence of a high level of copper along with cobalt can be considered one of the indicators of the Takht-e Soleyman cobalt mine. Although the Anarak cobalt mine has also been reported to contain nickel, arsenic, and copper (Jiang *et al.*, 2020), there are several significant reasons for the greater importance of the Takht-e Soleyman mine compared to the Anarak mine. First, Takht-e Soleyman is situated along the main road known as Silk Road, making its trade with China much more straightforward than that of Anarak. Second, the chemical composition of the Lajvardina tiles from Takht-e Soleyman in blue glaze contains a high percentage of copper along with cobalt (Holakooei *et al.*, 2023), likely sourced from the nearby Takht-e Soleyman cobalt mine rather than from a more distant location such as Anarak. Furthermore, the mineral samples studied in the present research, obtained from ancient Rey (Table 1), also exhibit a blue composition containing cobalt-nickel-copper. Given Rey's location on the main Silk Road (Fig. 1), it is plausible to expect the probable use of cobalt from Takht-e Soleyman. However, the third and most significant reason for utilizing cobalt from Takht-e Soleyman is its name. In ancient Persian texts, such as Abu al-Qasim's treatise, cobalt was introduced as a "Soleymani" stone (Kashani, 1966). This name is the same name mentioned in ancient Chinese texts as "Su-ma-li-qin," which is associated with Persia (Du & Su, 2008). This may indicate the use of cobalt from Takht-e Soleyman rather than Anarak or Qamsar for trades between Iran and China. Regarding the term "Su-ma-li-qin" in ancient Chinese texts, two main hypotheses exist. The first suggests that Su-ma-li-qin should be associated with Indonesia and Sumatra (Watt, 1979). The second hypothesis links "Su-ma-li-qin" in Chinese texts to Samarra in Iraq (Du & Su, 2008). However, considering the presence of cobalt mines in Takht-e Suleiman, it seems more probable, in both ancient Chinese and Persian texts, that the association of Su-ma-li-qin is with Takht-e Soleiman rather than Somalia and Samarra.

As is evident, the intertwining of the name "Soleymani" in both ancient Persian and Chinese texts suggests that the initial acquaintance of Chinese potters with Iranian cobalt may be attributed to the cobalt from Takht-e Soleyman. This likely explains why Iranian cobalt is referred to as "Su-ma-li-qin" in Chinese texts and has been well recognized among Iranian potters. Moreover, the chemical composition of the blue glazes from the Tang Dynasty indicates that the early blue and white glazes in China contained a high percentage of copper. Hence, a hypothesis can be proposed that the initial encounter of Chinese potters with Iranian cobalt, particularly from Takht-e Soleyman, led to the use of this name in both ancient Chinese and Persian texts. Furthermore, the utilization of the name "Takht-e Soleyman" might date back to the early Islamic period when Muslims entered the Iranian plateau. To safeguard pre-Islamic religious sites in the Sasanian Empire, Iranians associated these places with prophet Sulayman (Solomon), a revered figure among Muslims, for their protection (Nikoei & Javadi, 2022). It is now evident that Takht-e Soleyman, known as Ganzaka or Shiz in the Sasanian empire (Jackson, 1909), was one of the significant religious centers and fire temples of the Sasanians. Considering the proposed hypothesis of a name change, the commencement of using the name Takht-e Soleyman instead of Shiz could be linked to the early Islamic era. Additionally, during the Ilkhanate dynasty, Hamdollah Mostaufi mentioned the name "Satūriq" for this region (Mustaufi, 1892). This provides further historical evidence of the diverse names associated with Takht-e Soleyman over different periods. Thus, despite previous discussions centering around the cobalt mines of Qamsar and Anarak on the central Iranian Plateau as potential sources of cobalt exported from Iran to China, due to various reasons, such as linguistic similarity, chemical composition, and the strategic location of Takht-e Soleyman along the main Silk Road, it is proposed that the likelihood of utilizing cobalt from Takht-e Soleyman for this trade is greater. However, this hypothesis is at its preliminary stage and requires further focus on the collection of cobalt blue glaze samples and diverse analytical studies to validate its feasibility.

It should also be noted that XRF analysis, aimed at identifying various mines, has limitations, as discussed earlier (Ma *et al.*, 2021). Therefore, it is recommended to conduct analyses such as LA-ICP–MS or even isotope analyses on samples from the Anarak, Takht-e Suleiman, and Qamsar mines in conjunction with analyses of glaze samples. Additionally, it is important to consider that the techniques used for Mina'i ware and Lajvardina tiles involve overglaze and in-glaze types, while the techniques used for blue and white wares are underglaze, adding to the limitations of p-XRF analysis, which is a surface analysis technique. However, what is now evident is the difference in the chemical composition of blue glazes on the Iranian Plateau between the 12th and 17th centuries CE, and the main cause of this difference needs to be determined.

Conclusion

In conclusion, despite the long history of using blue in glassware, one of the challenges in accessing dark blue ceramic glazes has been the limited availability of cobalt mines. Consequently, the cobalt trade has consistently been a focal point for ancient potters, with references to this trade from Iran found in ancient Chinese texts. The question of which Iranian mine supplied cobalt for blue ceramics in China before the Ming dynasty was significant. The Qamsar and Anarak mines have historically been mentioned as sources for cobalt; however, the chemical composition of Qamsar's cobalt is different from that of the cobalt ores used in China. Moreover, Anarak's cobalt industry faces logistical challenges related to trade.

Through the analysis of blue glazes on enamelware, lapis lazuli tiles, and blue and white vessels from both Iran and China in this study, it was determined that during the Ming Dynasty in China, a locally sourced mine characterized by a high manganese content compared to that of other elements, such as cobalt, was used. Many blue and white vessels found at the Jahan Nama site in Isfahan were clearly of Chinese origin and exhibited characteristics of Chinese cobalt. However, it was revealed that Iranian-produced cobalt blue glazes can be categorized into at least two major groups. The first group contains a higher percentage of arsenic than of the other elements, indicating the potential use of cobalt from the Qamsar mine. The second group, characterized by elevated percentages of nickel, copper, and arsenic, suggests probable utilization of cobalt from the Takht-e Soleyman region, which likely supplied cobalt to China during various periods.

Three reasons support this hypothesis: First, the chemical composition of blue glazes in Tang Dynasty ceramics and blue and white vessels from early Islamic Iran and Iraq showed a high copper content, indicating the potential use of mines other than Qamsar in Iran. Second, ancient Chinese and Persian texts both mention a mine in Iran for cobalt extraction; these texts are referred to as "Su-ma-li-qin" and "Soleymani,", respectively, and even the name "Soleymani stone" is associated with cobalt in Iran. Among the mines considered for cobalt supply in the Iranian Plateau, the Takht-e Soleyman mine bears a name similar to what is mentioned in Persian and Chinese texts. Third, the Takht-e Soleyman cobalt mine is located along the main Silk Road, making its trade much more feasible and cost-effective than that of other mines not situated along this route. Additionally, the chemical composition of the blue glazes on Takht-e Soleyman's lapis lazuli tiles contains a high percentage of copper and arsenic, aligning with the expected composition from the Takht-e Soleyman mine.

Therefore, it is suggested that the Soleymani stone likely refers to cobalt from the Takht-e Soleyman mine, exported to China and serving as the initial introduction of Chinese potters to Iranian cobalt. This is reflected in ancient Chinese texts mentioning the mine as "Su-ma-li-qin."

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