Università degli Studi di Padova

Dipartimento dei Beni Culturali: Archeologia,
Storia dell'Arte, del Cinema e della Musica

Master Degree in
ARCHAEOLOGICAL SCIENCES

Curriculum in
APPLIED SCIENCES TO CULTURAL HERITAGE MATERIALS AND SITES

Painting and colours on the pottery of Shahr-i Sōkhta 3000-2000 BC

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ACADEMIC YEAR 2023/2024

To my beloved mother, who may no longer be with me, but her presence is felt in every step of this journey.

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Acknowledgments

First and foremost, I would like to express my heartfelt gratitude to my supervisor, Prof. Lara Maritan, and my co-supervisor, Prof. Massimo Vidale, for their exceptional guidance, support, and invaluable insights throughout this research journey. Their mentorship has been instrumental in shaping both the direction and success of this thesis.

I am profoundly grateful to my father and brother for their unwavering support throughout my years of study. Their encouragement and advice have been my anchor, and without their belief in me, this accomplishment would not have been possible. I owe much of my perseverance and success to their constant presence by my side.

I also wish to honor my late mother, whose memory has been my greatest source of strength and inspiration. Though she is not here to share in this accomplishment, I know she would have been proud. I carry her with me always, and this thesis stands as a testament to her enduring influence on my life.

I would like to extend my heartfelt thanks to my dear friends, whose companionship, encouragement, and understanding have meant the world to me during this journey. Your presence made the difficult moments easier and the successes even sweeter. I am truly grateful for the support we shared along this path. A special thank you goes to Shima Pourmomeni, whose invaluable help and support throughout this research made a significant difference. I am truly fortunate to have had such wonderful friends beside me during this process.

Last but certainly not least, I want to thank myself—for never giving up, for pushing through the tough times, and for staying committed to this journey, no matter how difficult it became. This accomplishment is a result of hard work, resilience, and belief in my own ability to succeed.

Abstract

This thesis explores 13 pottery shards unearthed from the Eastern Residential Area of Shahr-i Sōkhta, a Bronze Age early city of the Helmand Civilization, extending from the valleys of the Kandahar region in Afghanistan to the endoreic basin of Sistan, in Iran. This part of the site, which situated at the highest point and to the north of the Burnt Building, has yielded a wealth of pottery artifacts through significant excavations. The focus is on pottery fragments dating from early Period II to Period III (about 3000-2500 BC).

The primary objective of this study is to chemically characterize these pottery shards and to trace possible changes over time of the composition of the clay slips used for painting. Additionally, the research examines the interaction between firing technology and ceramic properties, as well as how the ceramic body interacts with the applied colours. Detailed analyses using scanning electron microscopy (SEM) were conducted to understand the microstructural and compositional attributes of the pottery. The findings aim to provide preliminary insights into the technological advancements and aesthetic developments in pottery production during this significant period of the Shahr-i Sōkhta urban life.

This study is expected to contribute preliminary to our understanding of the cultural and technological developments in Shahr-i Sōkhta. By linking the chemical, technological, and visual aspects of the pottery, this research provides a holistic view of the craftsmanship and innovation of this Bronze Age society, enhancing our appreciation of their contributions to the ancient coeval civilizations.

Riassunto

Questa tesi esplora 13 frammenti di ceramica rinvenuti nell'Area Residenziale Est di Shahr-i Sōkhta , uno dei principali centri urbani della Civiltà dell'Hilmand, una civiltà dell'età del bronzo situata dalle valli della regione di Kandahar in Afghanistan al bacino endoreico del Sistan, in Iran. Questa parte del sito, situata nel punto più alto, a nord dell'Edificio Bruciato, ha restituito un'abbondanza di manufatti ceramici grazie a significativi scavi. L'attenzione è rivolta a frammenti di ceramica risalenti agli inizi del Periodo II fino al Periodo III (3000-2500 a.C.).

L'obiettivo principale di questo studio è caratterizzare chimicamente questi frammenti di ceramica e tracciare possibili cambiamenti nel tempo delle argille semiliquide uusate per la decorazione dipinta. Inoltre, la ricerca esamina l'interazione tra la tecnologia di cottura e le proprietà ceramiche, nonché il modo in cui il corpo ceramico interagisce con i colouri applicati. Sono state condotte analisi dettagliate tramite microscopia elettronica a scansione (SEM) per comprendere gli attributi microstrutturali e composizionali della ceramica. I risultati mirano a fornire approfondimenti sui progressi tecnologici e sugli sviluppi artistici nella produzione ceramica durante questo periodo significativo della vita di Shahr-i Sōkhta .

Si prevede che questo studio contribuisca in modo preliminare alla nostra comprensione degli sviluppi culturali e tecnologici a Shahr-i Sōkhta. Collegando gli aspetti chimici, tecnologici e artistici della ceramica, questa ricerca fornisce una visione olistica dell'artigianato e dell'innovazione di questa società dell'età del bronzo, arricchendo il nostro apprezzamento per i suoi contributi alle civiltà urbane del-mondo antico.

1 Shahr-i Sōkhta: A Bronze Age urban centre in Sistan, Iran

1.1 Historical and Geographical Context

Shahr-i Sōkhta (Persian: شهر سوخته, meaning "Burnt City"), also spelled as Shahr-e Sukhte and Shahr-e Sūkhté, is a significant Bronze Age archaeological site located in the Sistan-Baluchestan province of southeastern Iran. The city, situated near the ancient delta of the Helmand River, was strategically positioned along ancient trade routes that connected Mesopotamia, the Indus Valley, and Central Asia (Fig. 1). The name " Shahr-i Sōkhta" or "Burnt City" originates from evidence of multiple fires that left a layer of reddened clay, charcoal and ash across the site (Ascalone and Fabbri, 2022). This strategic location, combined with an extensive urban construction and a rich material culture, makes Shahr-i Sōkhta a key site for understanding the complexity and interconnectedness of early Bronze Age civilizations. Covering an area of approximately 150 hectares (taking both settlement and graveyard), it is one of the largest and most important archaeological sites of its era in the region. Recognizing its historical significance, the site was added to the UNESCO World Heritage List in June 2014 (https://whc.unesco.org/en/list/1456)

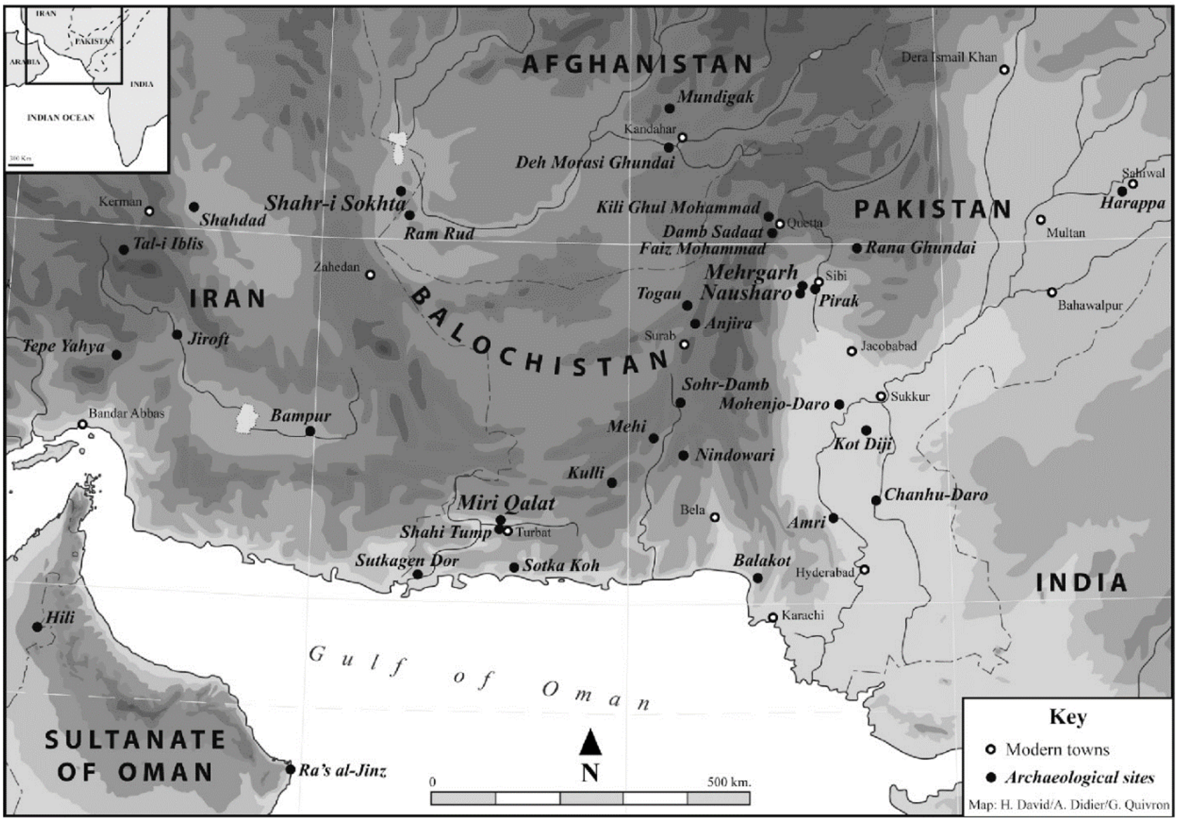


Fig.1 Map of Shahr-i-Sōkhta location and other Bronze age sites (After: Jarrige et al. 2011)

Shahr-i Sōkhta is believed to have undergone four distinct periods of occupation and experienced three major fires before its eventual abandonment. While the Italian archaeological mission initially dated the city's abandonment to around 1800 BC, recent research based on calibrated radiocarbon samples from the nearby site of Tappeh Graziani, led by Helwing, Fazeli Nashli and vidale, has revised the date to approximately 2400-2350 BC (Kavosh et al., 2019).
Currently, the site's abandonment is considered to have occurred around 2400 BC. New chronological and stratigraphical sequences, derived from excavations conducted between 2018 and 2019 in areas 26, 33, 35, and 36, were published in 2022, providing updated insights into the site's timeline, are as outlined below (Ascalone and Sajjadi, 2022, p. 152, Fig. 10):

Period	Dating	Phase
IA	3550–3350 BC	10-9
IB	3350–3100 BC	8
IC	3100–3000 BC	7
IIA	3000–2850 BC	6A-B
IIB	2850–2620 BC	5A-B
IIC	2620–2600 BC	4
IIIA	2600–2450 BC	3
IIIB	2450–2400 BC	2
IV	2400–2300 BC	1
GAP	2300–2100 BC	
V	2100–2000 BC	0

While these new dates offer a more updated timeline, in particular for the earlier dates from Period I, for simplicity, I will continue to reference the older chronological framework for consistency with earlier publications that rely on the four-stage periods, however corrected in the light of the Tappeh Graziani new absolute dating's for Periods III and IV. This approach ensures alignment with the established body of research. The four periods are:

Period	Dating	Phase
I	3200–3000 BC	10-9-8
II	3000–2700 BC	7-6-5a-5b
III	2700–2600 BC	4-3
IV	2600–2400 BC	2-1

The settlement at Shahr-i Sōkhta can thus be subdivided into four distinct periods, long identified through eleven structural horizons of occupation or phases spanning from 3200 to 2400 BC (Tosi 1976; Biscione et al. 1977; Sajjadi 2004)

Pottery from Period I (ca. 3200–2800 BC, phases 10, 9, and 8) is characterized by light-coloured paste bodies and in part, elaborate geometric decorations, closely resembling coeval ceramics from Mundigak III in Kandahar and other sites in Baluchistan (Biscione 1974; Festuccia 2011). This suggests a shared cultural influence, trade connections and possibly migrating groups among the involved regions during this time.
These decorative styles persisted into the early part of Period II (ca. 3000–2800 BC, phases 7, 6, and 5), distinguished by the, use of finer raw materials and improved firing techniques. These latter resulted in denser body-paste ceramics, which bore similarities to those found in Bampur III-IV (Vidale and Bennici 1995; Festuccia 2011). During this period, the majority of ceramics, whether locally produced or imported, consisted of buff and gray wares adorned with brown and black decorations (Biscione 1979).
During Period III (circa 2700–2500 BC, corresponding to phases 4 and 3), pottery production at Shahr-i Sōkhta experienced important transformations in both forms and decorative motifs, setting them apart significantly from those of earlier Periods (Vidale and Bennici 1995). At the onset of this

Period, the previously rich decorative patterns on ceramics evolved into simplified, smaller and less intricate designs (Biscione 1979; Salvatori and Vidale 1997). There was also a marked increase in the production or circulation of finer gray-paste ceramics adorned with black-painted decorations, similar to ceramics from Bampur IV and Tappeh Yahya IV (Festuccia 2011). Additionally, by the end of Period III, small, mass-produced wheel-thrown undecorated bowls with thin walls began to appear, indicating a marked shift in ceramic styles and preferences (Biscione 2010).

By Period IV (2500-2400 BC, phases 2, 1, and 0), the forms of ceramics at Shahr-i Sōkhta changed further in a significative way (Vidale and Bennici 1995). This Period saw the introduction of undecorated, more porous pottery, cream to red in colour, closely resembling the ceramics produced in the Namazga VI and V complexes of southern Turkmenistan (Salvatori and Tosi 2001). This shift marks a radical departure from the more decorative styles of earlier times, reflecting changes in both production techniques and possibly the functional needs of the society (Vidale 2010).

The occupation area of Shahr-i Sōkhta has been divided into five main parts, as mentioned by Sajjadi et al., 2003 (Fig. 2):

- *The Eastern Residential Area*

The Eastern Residential Area, corresponding to the highest topographic elevation of the site, is one of the most significant sections of this ancient city. This area is characterized by a dense concentration of housing structures and daily life artifacts, offering invaluable insights into the domestic life and social organization of its inhabitants. Pottery from Period I was found during excavations within this Eastern Residential Area, particularly to the north of the Burnt Building (Amiet and Tosi, 1978). The pottery shards analyzed in this thesis were specifically discovered in this location, known for its rich archaeological finds.

- *The Great Central Area or Central Quarters*

The Great Central Area, or Central Quarters, is the heart of Shahr-i Sōkhta, separated from the western, southern, and eastern areas by deep, apparently void-depressions. Significant large buildings and spaces were probably located here, indicating a well-organized urban layout and governance system (Salvatori and Tosi, 2005, p. 285).

- *The Craftsman Quarters (industrial zone)*

The Craftsman Quarters, located in the northwestern part of the site, was home to various workshops where artisans engaged in metalworking, pottery-making, bead-making, and other crafts. The artifacts and tools found in this area provide evidence of the sophisticated techniques and high-quality craftsmanship that were hallmarks of this city. (Salvatori and Tosi, 2005, p. 285; Vidale and Lazzari, 2017)

- The Monumental Area

The so-called Monumental Area, east of the Craftsman Quarters features several distinct low mounds representing grand structures and buildings that have been elite residence, or even seats of ceremonial or administrative significance. The scale and construction techniques of these structures reflect the architectural prowess and organizational capacity of the society (Sajjadi et al., 2003).

- The Graveyard Area

The Graveyard, occupying the southwestern part of the site and covering almost 80 hectares, offers insights but also manifold unsolved questions about the burial practices, beliefs about the afterlife, and more generally the forms of social segmentation shared by the city's inhabitants. More than one thousand graves have been excavated, revealing a variety of burial practices, buried goods and human remains. Most of the burials are dated to Period I and Period II (Sajjadi et al., 2003).

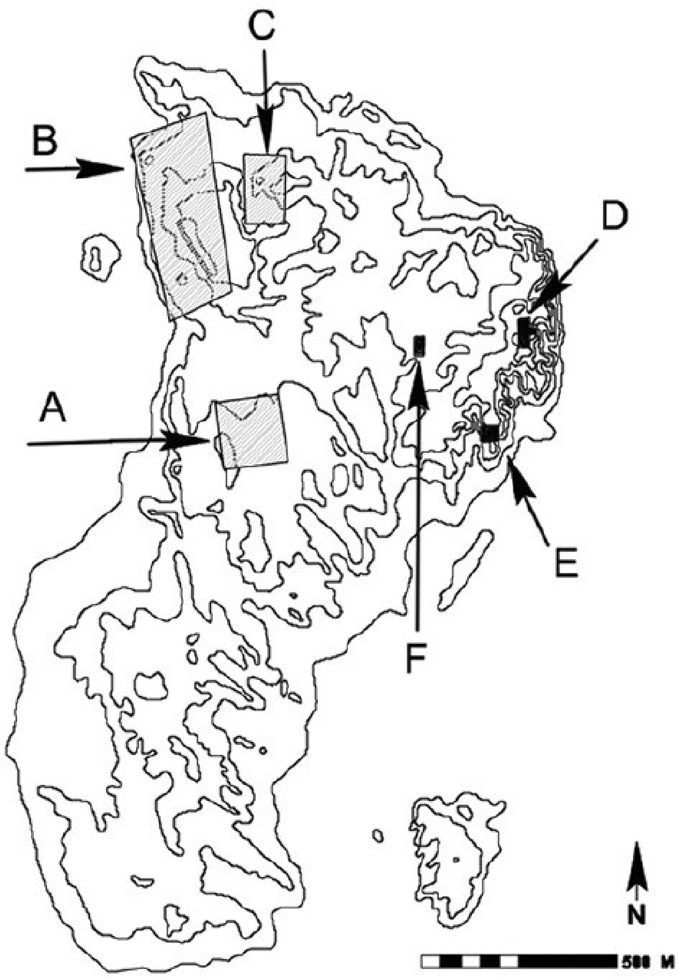


*Fig. 2**:** The main excavation sites at Shahr-i Sōkhta. A, Graveyard; Industrial zone; C, Monumental area; D, Eastern Residential Area (ERA); E, Burnt Building; and F, Central Residential Area. Source: Eftekhari et al. (2021).*

1.2 ARCHAEOLOGICAL EXCAVATIONS AND DISCOVERIES

Archaeological exploration of Shahr-i Sōkhta began in 1916 when British archaeologist Aurel Stein conducted a preliminary survey. Although Stein did not carry out extensive excavations, his observations highlighted the potential significance of the site, paving the way for future archaeological interest (Stein, 1928; Stein, 1938).

From 1967 to 1978, the first large scale excavation and research efforts were led by an Italian archaeological team from IsMEO, headed by Maurizio Tosi, then, in the last years, by Marcello Piperno and Sandro Salvatori. These comprehensive excavations uncovered a well-organized urban settlement with distinct residential, commercial, and industrial areas, indicating a high level of social organization and complexity (Tosi, 1968, 1969; Salvatori and Vidale, 1997; Amiet and Tosi, 1978).

Archaeological work resumed in 1997, led by Iranian archaeologists in collaboration with international teams. These more recent excavations have continued to reveal new aspects of Shahr-i Sōkhta's history and culture (Sajjadi et al., 2003; Sajjadi and Casanova, 2008). Advanced technologies, such as satellite imagery, chemical analyses of pottery and bioarcheological studies have been employed to deepen our understanding of the site's significance.

The excavations at Shahr-i Sōkhta, from the early 20th century to the present, have significantly affected our understanding of early urbanization in southeastern Iran. The site's overwhelming pottery record is still poorly studied, while it might help illuminating the cultural, economic, and technological adaptations of the Helmand Bronze age people. As research continues, Shahr-i Sōkhta remains a vital source of knowledge about the prehistoric cultures of the region.

1.3 POTTERY: FORMS AND COLOURS

The clay-based artifacts from Shahr-i Sōkhta include a diverse range of items, such as small anthropomorphic and zoomorphic figurines of uncertain use, semiprecious stones ornaments, copper artifacts and slag, and a unique abundance and variety of wicker and wooden objects, along with a substantial assortment of pottery, including jars, bowls, cups, beakers, and in the later centuries, plates (Sajjadi 2005).

The pottery was primarily crafted using various combination of molding, coiling and wheel-throwing (Vidale and Tosi 1996; Laneri and Vidale 1998), with paste colours ranging from buff to gray and red, reflecting a broad range of firing conditions in ceramic production (Tosi 1969; Vidale and Bennici 1995; Mugavero 2008; Sajjadi 2009; Biscione 2010; Festuccia 2011).

Painted pottery from Shahr-i Sōkhta showcases several technical solutions, including:

- Monochrome ware, characterized by single-colour motifs in black or brown traced before firing, usually referred to in the literature as "Black-on-buff ware".

- Bichrome ware, featuring decorations painted post-firing in both black and white.

- Polychrome ware, distinguished by a vibrant palette of white, red, black, yellow, green and rarely blue.

These were all crafted and eventually fired in various atmospheres and through different manufacturing cycles, resulting not only in the colours of the painted motifs but also in various colours of the paste (Eftekhari et al. 2018).

Trade and cultural interactions with other civilizations and coeval urban knots in the region are evident

- through comparisons with the geometric black-on-buff painted pottery of Namazga III of southern Turkmenistan, in Period I;

- with the black-on-buff painted Quetta ware of northern Baluchistan (Pakistan), again in Period I.

- with various classes of pottery found in the "twin site" of Mundigak in Afghanistan (Casal 1961) across the late IVth and the IIIrd millennium BC.

- with the early Harappan settlements of Punjab and Sindh in Pakistan in the Indus Valley (Cortesi et al. 2008).

- with some very distinctive forms of the Jiroft civilization in the Halil Rud basin of the Kerman province (Iran) in Period III (Biscione 1974; Salvatori 2006; Mugavero 2008).

Given the notable similarities between the ceramics found at Shahr-i Sōkhta and those from other contemporary sites across southwestern Asia, some scholars have wondered whether some of the ceramics under scrutiny were imported (Salvatori 2006).

However, recent investigations indicate that the almost totality of the ceramics discovered at Shahr-i Sōkhta were predominantly manufactured locally (Sarhaddi-Dadian et al. 2015; Pourzarghan et al. 2017; Javanshah 2018). Nonetheless, the possibility that an absolute minority of ceramic items were imported into the city remains under exploration (Moradi et al. 2013).

2 Material and Methods

2.1 SAMPLES

In this study, we analyzed a collection of 13 black-on-buff painted ceramic fragments from the archaeological site of the Eastern Residential Area of Shahr-i Sōkhta, dating primarily to the Periods II and early III. These fragments were originally excavated in the mid-70s near the Burnt Building by Maurizio Tosi, and brought to Italy for study after a specific permission of the Iranian Centre for Archaeological Research and currently deposited for study at the Archaeological Laboratories of the Department of Cultural Heritage of the University of Padua.

To structure the analysis, the ceramic samples were categorized into four groups based on their chronological placement:

- Group A: samples from the early part of Period II (potsherds 1, 2, 3, 6);
- Group B: samples from the later stages of Period II (potsherds 4, 5, 7);
- Group C: samples from Period III (potsherds 8, 9, 10, 11);
- Group Out: fragments of uncertain dating (potsherds 12, 13).

All the ceramics exhibit monochrome designs, characterized by the application of a single kind of paint to the surface before firing (Figure 3, Table 1): the monochrome black-on buff (sometimes overlapping with black-on-red background) technique remains a consistent decorative feature across all samples.

The 13 ceramic samples were selected among the smallest ones of the Eastern Residential Area collection, in order to minimize physical damages unavoidably brought about by archaeometric studies. They were categorized into four Groups based on their chronological placement, inferred by M. Vidale (personal communication) on the base of the stylistic features of the brushstrokes and texture of the biscuit. After a textual description of each fragment, Table 1 specifies the size and provenience of the 13 selected potsherds.

The samples in Group A, are from the early part of Period II, include potsherds 1, 2, 3, and 6. Below, I will describe these forms in more detail:

Sample 1 is a rim fragment belongs to a wide-mouthed beaker typical of the earliest production of the city. It features a painted frieze running below the rim, incorporating both oblique traits and curvilinear stepped motifs, which vary in thickness to create a dynamic rhythm of alternating thick and thin strokes. It encircled its entire circumference forming a distinct decorative band, emphasizing the artisan's intent to imbue the small vessel with fluidity and movement, thus adding an expressive touch. The ceramic body (as presently observed after unknown burial changes) maintains a consistent very dark grayish brown colour, noted as Munsell 10YR 3/2, while the paint itself is a lighter brown, recorded as Munsell 7.5YR 4/4; the contrast was carefully obtained with precise choices

Pottery shard (Sample) 2 features a painted surface characterized by a pinkish-white biscuit colour (Munsell 7.5YR 8/2) and a light reddish-brown painted decoration (Munsell 2.5YR 6/3). The design incorporates a curved, sweeping line that suggests part of a larger, possibly continuous motif. The paint is applied in a fluid, freehand manner, forming an arch-like shape that covers a substantial portion of the fragment's surface. The painted area is broad at one end and gradually tapers, designs being part of an expansive pattern that extended, of course, beyond the shard's current boundaries. However, the fragment does not permit a full reconstruction of the original motif.

Sample 3 (made of two refitting shards) exhibits a bodily surface colour Munsell 7.5YR 8/4, a subtle pink tone, while the painted decoration is rendered in a light reddish-brown (Munsell 2.5YR 6/4). The decorative pattern on these pottery shards consists of two neatly aligned horizontal lines that stretch across the width of the fragments. These bands are relatively uniform in width, due to a precise and controlled application technique, with a brush or similar tool that evenly distributed the light reddish-brown clay-based paint onto the pink surface. The bands are parallel, very regular, enhancing the contrast but also the overall visual appeal of the design.

The final sample from Group A, ceramic sherd 6, bears two oblique lines painted in a reddish-brown colour (Munsell 5YR 5/4) sharply contrasting with the sherd's very pale brown surface (Munsell 10YR 8/3). The paint on this sherd is dense and uniform.

Group B consists of samples from the later stages of Period II, including potsherds 4, 5, and 7:

Sample 4 exhibits significant surface wear and erosion, which obscures much of the detailed decorative elements. Although the very dark gray paint remains visible, the small size and degraded condition prevent discerning specific patterns or motifs clearly. The background colour of the ceramic is classified as Munsell 10YR 6/3, a pale brown, contrasting starkly with the painted areas, which are described as Munsell 7.5YR 3/1, a very dark gray.

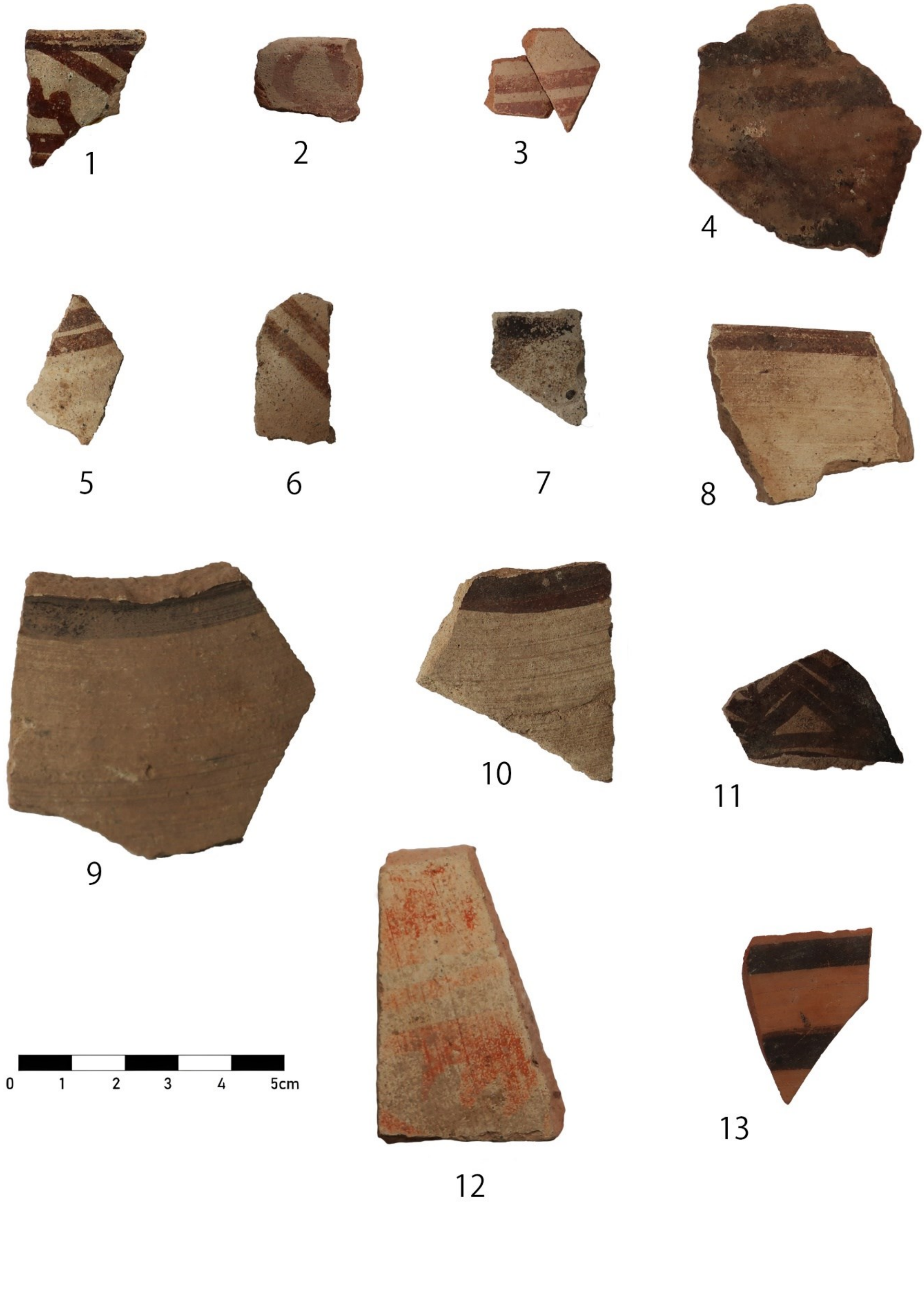


Fig. 3: Photographs of the studied painted potshards from Shahr-i Sōkhta

Ceramic sherd (Sample) 5 featuring two horizontal bands painted in a medium brown shade (Munsell 7.5YR 4/2). Contrasting against the sherd's very dark grayish brown background (Munsell 10YR 3/2). Each band is well painted, maintaining consistent thickness across the sherd's surface. The edges of these bands are sharply defined, indicating the use of a fine brush or a similar tool that facilitated precise and clean line work. This level of precision suggests a deliberate aesthetic intent, where the uniformity of the bands may have been aimed at conveying a specific visual message or adhering to a commonly accepted decorative style within the cultural context of its creation.

Sample 7 belongs to the rim of a container. The surface shows a blotchy and irregular alteration. What survives of the original painted decoration displays an area with a very dark gray (Munsell 7.5YR 3/1) colouration, in striking contrast against the predominant pale yellow (Munsell 2.5Y 8/2) surface. Again, the design is part of a more complex pattern that once adorned the vessel, now only partially preserved.

Group C consists of samples from Period III, specifically potsherds 8, 9, 10, and 11. In this group, the painted decorations on three of the shards are predominantly positioned on the upper part of the ceramic body, usually the rim, confirming that the mouth of the vessels continued to be an aesthetic focus also in Period III. key elements in the pottery's overall design and possibly having particular significance in their cultural context.

The first shard in Group C, Sample 8, showcases a horizontal reddish-brown band (Munsell 5YR 4/3) painted along the top edge of the rim. This band contrasts vividly against the very pale brown (Munsell 10YR 7/3) background of the ceramic, creating a clear visual distinction. The band's width and the consistency of its application indicate a careful execution, ensuring the line was straight and uniform. Rim decoration, was a common practice in many ceramic traditions designed to accentuate the vessel's opening and enhance its visibility and appeal.

Sample 9 features a decorative line in a very dark gray (Munsell 5YR 3/1) visible onto the very pale brown (Munsell 10YR 7/4) background of the ceramic surface. Extending horizontally across its width, like in previous cases, the line is broad and regular. It was applied uniformly to the shoulder of a necked jar. The band's dark colour provides a striking visual contrast against the lighter background. Other similar lines emphasizing the rim should have run along the rim, but they are now lost from the vessel.

Sample 10 displays a dark reddish-brown painted band (Munsell 5YR 3/3) set against a very pale brown background (Munsell 10YR 8/4), echoing the decorative positioning found in the previous samples. Situated on the rim of a restricted pot, this line might have been part of a more complex design. Its width, consistency, and sharp definition reflect a competent application technique. The deep, rich colour of the thick line strongly contrasts with the lighter surface, rendering the decoration visually striking.

The last shard, Sample 11, markedly differs from the previous examples. It features a decorative motif painted in very dark gray (Munsell 10YR 3/1) against a pinkish white background (Munsell 7.5YR 8/2). The surface is darkened by firing in use or post-depositional contacts. The design is bold and consists of a frieze of superimposed zig-zag lines, whose segments progressively decrease in size to produce a layered visual effect. The painted lines are thick, uniform, and sharply defined and thanks to a skilled application, likely using a fine-tipped brush or another tool. The placement and structure of the design are intended to be visually engaging, drawing the observer's eye and creating a rhythmic interplay through its repeated shapes.

This geometric design occupies most of the visible surface area of the sherd: usually these designs run on the shoulder of small-sized necked vessels, underscoring their visual impact.

The final group, classified as "Out" includes two Samples that are distinctively different from the others, which leaves open the possibility of an external origin. This distinction is based on the visual appreciation of an anomalous material composition, and different decorative techniques.

In fact, the painting on the surface of sherd (Sample) 12 is noticeably worn and exhibits significant fading. Although the residual outlines are not sharply defined, the original design might have featured motifs inspired by leaves.

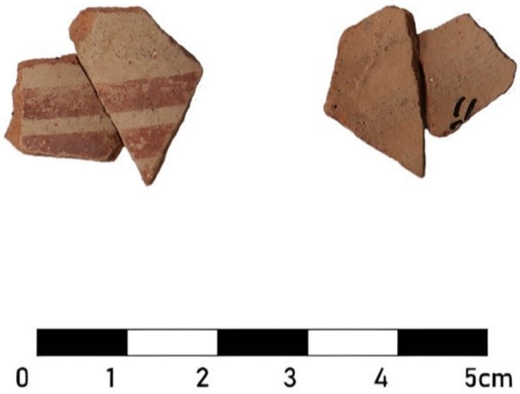
The patterns are rendered in a unique light red paint (Munsell 2.5YR 6/8), which imparts a delicate, almost textured appearance against the pink background (Munsell 7.5YR 8/4). The leaf-like motifs may have once been part of a larger, more intricate design that adorned the vessel.

The final Sample we will discuss, labeled 13, features a surface Munsell colour of 7.5YR 6/4, described as light brown, contrasted by painted decorations in black (Munsell 10YR 2/1) (Black-on-red ware). The design consists of two bold, wide horizontal bands that stretch across the width of the sherd, with a particularly strong contrast against the light brown background of the biscuit.

Both bands are similar in width and exhibit a consistent application, indicative of a careful execution. The placement and repetition of these parallel lines suggest they were part of a larger pattern that likely encircled the entire vessel.

<table>
<tr><td rowspan="5">
</td><td>Lab no: 1</td></tr>
<tr><td>Room: .s.ss</td></tr>
<tr><td>Group: A</td></tr>
<tr><td>Size
Length: 27 mm
Width: 23 mm
Thickness: 4 mm</td></tr>
<tr><td>Munsell colour
Surface:10YR 3/2
Very dark grayish brown
Painting: : 7.5YR 4/4
brown</td></tr>
</table>

<table>
<tr><td rowspan="5">
</td><td>Lab no: 2</td></tr>
<tr><td>Room: -</td></tr>
<tr><td>Group: A</td></tr>
<tr><td>Size
Length: 21 mm
Width: 16 mm
Thickness: 3 mm</td></tr>
<tr><td>Munsell colour
Surface: 7.5YR 8/2
Pinkish white
Painting: 2.5YR 6/3
light reddish brown</td></tr>
</table>



Lab no: 3

Room: II?

Group: A

Size

Length: 24 mm

Width: 23 mm

Thickness: 3 mm

Munsell colour

Surface: 7.5YR 8/4

pink

Painting: 2.5YR 6/4

light reddish brown

Lab no: 4

Room: -

Group: B

Size

Length: 46 mm

Width: 45 mm

Thickness: 6 mm

Munsell colour

Surface: 10YR 6/3

Pale brown

Painting: 7.5YR 3/1

very dark gray

	**Lab no:** 5
	Room: II
	Group: B
	Size Length: 36 mm Width: 20 mm Thickness: 4 mm
	Munsell colour Surface: 10YR 3/2 very dark grayish brown Painting: 7.5YR 4/2 brown

	**Lab no:** 6
	Room: -
	Group: A
	Size Length: 45 mm Width: 25 mm Thickness: 4 mm
	Munsell colour Surface: 10YR 8/3 Very pale brown Painting: 5YR 5/4 reddish brown

Lab no: 7

Room: B

Group: -

Size

Length: 23 mm

Width: 18 mm
Thickness: 5 mm

Munsell colour

Surface: 2.5Y 8/2

Pale yellow

Painting: 7.5YR 3/1
very dark gray

Lab no: 8

Room: CXLIV 5

Group: C

Size

Length: 41 mm

Width: 40 mm
Thickness: 9 mm

Munsell colour

Surface: 10YR 7/3

Very pale brown

Painting: 5YR 4/3
reddish brown

Lab no: 9

Room: CXLIV 5

Group: C

Size

Length: 52 mm

Width: 59 mm
Thickness: 11 mm

Munsell colour

Surface: 10YR 7/4

Very pale brown

Painting: 5YR 3/1
very dark gray

Lab no: 10

Room: HXD 2

Group: C

Size

Length: 46 mm

Width: 39 mm
Thickness: 8 mm

Munsell colour

Surface: 10YR 8/4

Very pale brown

Painting: 5YR 3/3
dark reddish brown

Lab no: 11

Room: VIII 10

Group: C

Size

Length: 34 mm

Width: 26 mm
Thickness: 4 mm

Munsell colour

Surface: 7.5YR 8/2

pinkish white

Painting: 10YR 3/1
very dark gray

Lab no: 12

Room: XHE

Group: out

Size

Length: 56 mm

Width: 36 mm
Thickness: 9 mm

Munsell colour

Surface: 7.5YR 8/4

Pink

Painting: 2.5YR 6/8
light red

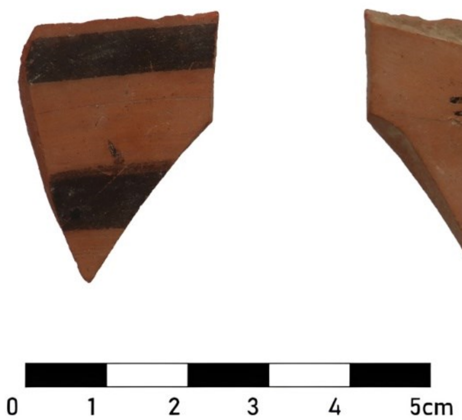
<table>
<tr><td rowspan="5">
</td><td>Lab no: 13</td></tr>
<tr><td>Room: II 8</td></tr>
<tr><td>Group: out</td></tr>
<tr><td>Size
Length: 33 mm
Width: 25 mm
Thickness: 6 mm</td></tr>
<tr><td>Munsell colour
Surface: 7.5YR 6/4
Light brown
Painting: 10YR 2/1
black</td></tr>
</table>

Table 1: photograph and brief description of the macroscopic aspect of the potsherds, reporting their chronology, place of finding, size and colour according to Munsell classification.

2.2 Analytical Methods

The study of ceramic artifacts offers a unique window into the past, providing insights into the cultural, technological, and artistic practices of ancient civilizations. In this chapter, we delve into the analytical techniques employed to examine the pottery shards unearthed from Shahr-i Sōkhta, focusing on how these methods illuminate the production processes and aesthetic choices of the artisans.

The comprehensive analysis of ceramic materials encompasses a series of distinct phases, each characterized by specific analytical procedures that aim to unravel the wealth of information embedded within an artifact. This information spans from the initial extraction of the clay to the ultimate burial of the finished object. Since the late 19th century, scientific methods such as petrographic and chemical analyses have been extensively utilized to investigate ancient ceramics. These techniques serve as powerful tools for answering critical questions about the provenance and production technologies of these artifacts (Maritan, 2019).

Each technique selected for this study is aimed at uncovering different facets of the ceramic fragments. From macroscopic observations to advanced microscopic analyses, the methods are chosen to complement each other, ensuring a comprehensive understanding of the material's composition and decorative techniques. Macroscopic observation serves as the preliminary assessment tool, providing initial insights into the physical characteristics of the shards, such as colour, texture, and overall morphology.

Advancing beyond the visible, we employ stereomicroscopy to capture finer details that escape the naked eye. The Zeiss Stemi 305 stereomicroscope, equipped with an Axiocam 208 camera, plays a pivotal role in this detailed examination. This instrument allows for a magnified view of the pottery’s surface, revealing subtle features such as tool marks, wear patterns, and the intricacy of painted decorations. Through high-resolution imaging, we can observe and document these details in a non-destructive manner, preserving the integrity of these precious artifacts.

Scanning Electron Microscopy (SEM), coupled with Energy Dispersive X-ray Spectroscopy (EDX), further extends our analytical reach into the elemental composition of the ceramic paints and bodies. This technique elucidates the chemical makeup of the materials used by the ancient potters, offering clues about the technological choices and resource availability during the period of production.

This chapter aims to outline these methods in detail and demonstrating how each contributes to our broader understanding of ancient ceramic production.

2.2.1 STEREOMICROSCOPY

The initial analytical method typically employed for ancient ceramics involves macroscopic observation. This preliminary examination allows for an assessment of the morphology, colour, fabric, and their categorized shape type (Maritan, 2024) before delving into more detailed methods.

All the pottery shards were examined and photographed using a Zeiss Stemi 305 microscope, equipped with an Axiocam 208 (1.2 Megapixel Wi-Fi camera). With a magnification range of 4x to 200x, this setup allowed for detailed and high-resolution visual documentation of the samples. Images were acquired via WLAN through the Labscope imaging app, enabling precise observation of the surface features and textures of the pottery fragments.

The Zeiss Stemi 305 stereomicroscope is an advanced optical instrument tailored for high-quality analysis and documentation of delicate artifacts, such as pottery shards. It is particularly suited for non-destructive examination, providing a three-dimensional view that allows detailed observation of surface textures, tool marks, and other critical features of archaeological samples.

The Stemi 305 is built with a Greenough optical system, which creates a true stereoscopic effect by delivering slightly different images to each eye, enabling a three-dimensional perception of the object under study. This 3D capability is essential for analyzing the texture, depth, and structure of surfaces, particularly in pottery analysis where fine details such as cracks, paint layers, and inclusions play a key role in interpreting production techniques and usage (Carl Zeiss Microscopy GmbH, 2015, p. 4).

The microscope has a magnification range of 4x to 200x, which allows flexibility in zooming in on specific details or viewing broader sections of a sample. The magnification can be continuously adjusted through its zoom system, making it easier to shift from an overall surface view to a more focused examination of intricate features, such as decorative elements or tool marks left during the pottery-making process (Carl Zeiss Microscopy GmbH, 2015, p. 9). The system is equipped with integrated LED illumination that provides uniform lighting across the sample surface. The reflected light option is particularly useful for opaque samples like pottery shards, allowing the surface to be illuminated without the need for transmitted light, which is typically used for transparent or translucent materials. The uniform LED ring light minimizes shadows, ensuring that even the finest surface details are well-lit and clearly visible, making it easier to spot irregularities such as surface wear, pigments, or remnants of decoration (Carl Zeiss Microscopy GmbH, 2015, p. 21).

A significant feature of the Zeiss Stemi 305 is its integration with the Axiocam 208 camera, a high-resolution 1.2-megapixel Wi-Fi-enabled camera designed to capture images of the samples under study. This camera is seamlessly integrated with the microscope, enabling real-time visual documentation of observations. Images are captured through the Labscope imaging app, which operates via WLAN, allowing live streaming of the sample view to connected devices. This setup enables researchers to capture, annotate, and save high-quality images of the pottery fragments for detailed analysis and archiving. The camera ensures that no detail is missed, providing crisp, detailed images that can later be used for further study or publication. (Carl Zeiss Microscopy GmbH, 2015, p. 10)

In terms of functionality, the stereomicroscope operates by positioning the pottery shard on the stage under the objective lens. The large working distance of the microscope allows easy handling of the sample, accommodating even larger or thicker fragments without the need to alter or damage the pottery. The sample is illuminated, and the focus is adjusted using the precision focus knob to bring out surface features such as cracks, inclusions, or paint layers. Once the sample is in focus, the zoom knob allows for smooth transitions between low and high magnifications, enabling a detailed examination of both general and specific features.

As the user manipulates the sample under the microscope, the stereoscopic view provides depth perception, which is vital for understanding the surface morphology of the pottery. The ability to perceive depth helps in identifying the extent of surface wear, the technique used in decoration, or the presence of applied pigments or tool marks.

Once the sample is observed in the desired magnification, high-resolution images are captured using the Axiocam 208 camera and transferred directly to the Labscope app. This process ensures that every observed detail is documented in real-time, providing a visual record for later reference. The Labscope app allows researchers to annotate the images, making it easier to highlight specific areas of interest.

The first step in our analysis involved observing and capturing detailed images of all the ceramic samples using stereomicroscopy. I focused on different parts of each fragment, particularly the painted areas and the clay paste, to document fine details such as tool marks, textures, and small scratches or abrasions. Stereomicroscopy was chosen for its ability to provide a three-dimensional view of the surface, making it particularly useful for examining surface decorations and manufacturing techniques. It is especially well-suited for analyzing the surface characteristics of opaque objects like pottery fragments.

2.2.2 Scanning electron microscopy (SEM)

For a detailed analysis of both the ceramic body and the painted surfaces of the ceramic fragments, a tabletop scanning electron microscope (HV and LV SEM), COXEM EM 30AX plus model, equipped with tungsten filament (W), SE Detector, BSE Detector (Solid type 4 Channel), energy dispersive X-ray detector (EDX) EDAX Element- C2B, was used.

The COXEM EM 30AX Plus is equipped with multiple detectors that enhance its analytical capabilities. The Secondary Electron (SE) Detector provides high-resolution images by capturing secondary electrons emitted from the sample surface. This detector is particularly useful for analyzing the topography of the sample, revealing fine details such as texture, surface wear, and any surface treatments applied to the pottery (Artioli, 2010). Additionally, the microscope includes a Backscattered Electron (BSE) Detector with a solid type 4-channel configuration, which is highly effective for imaging the compositional contrast within the sample. The BSE detector is sensitive to atomic number differences, allowing for a clear distinction between different elements or compounds within the ceramic material (Artioli, 2010). This feature is crucial for identifying areas of different mineral compositions within the pottery, especially in painted surfaces where pigments may differ from the base clay.

To further enhance the analysis, the SEM is paired with an Energy Dispersive X-ray Detector (EDX), is a powerful tool for determining the elemental composition of the sample. By detecting the characteristic X-rays emitted from the sample when bombarded by electrons, EDX provides quantitative and qualitative data on the elements present (Artioli, 2010). This is particularly important for studying the painted surfaces of pottery, as it allows for the identification of pigments, such as iron or manganese oxides, used in decoration, as well as the elemental composition of the clay matrix.

To avoid scattering and absorption by air particles, samples must be analyzed in a vacuum; they also require a metal coating for imaging and graphite for chemical analysis to prevent the accumulation of charge. If the samples cannot be coated or are hydrated, measurements can be conducted at low pressures (up to 2.5 kPa) using environmental scanning electron microscopes (ESEM) (Artioli 2010).

In practice, the SEM works by focusing a beam of electrons onto the sample surface. These electrons interact with the atoms in the sample, causing various signals to be emitted. The SE detector captures secondary electrons, which are emitted from the surface and give detailed topographic images, revealing the microstructure of the pottery. The BSE detector captures electrons that have been backscattered by the atoms in the sample, providing compositional contrast images, where heavier elements appear brighter and lighter elements appear darker (Artioli 2010). This makes it easier to identify different materials and inclusions within the pottery.

Once the sample is placed in the microscope's vacuum chamber, the electron beam scans across the surface. The SE and BSE images provide detailed views of the sample's surface features and compositional differences, while the EDX analysis provides a precise breakdown of the elements present (Artioli 2010). This combination of imaging and elemental analysis is key to understanding the materials and techniques used in the production of ancient pottery, particularly in identifying the materials used for pigments in painted decorations and assessing the quality of the clay paste.

By utilizing the COXEM EM 30AX Plus, we are able to obtain a comprehensive understanding of both the structural and elemental composition of pottery fragments. The versatility of the SEM, combined with high-resolution imaging from the BSE detector and detailed elemental analysis through the EDX system, offers crucial insights into the technological choices and materials used by ancient artisans in pottery production.

2.2.3 Scanning electron microscopy (SEM) of Pottery Thin Sections

The next step involved preparing thin sections from three selected samples. The decision to conduct thin section analysis, with a focus on the decorated/painted surfaces, was driven by the need to closely examine the microstructural and compositional properties of the ceramics.

These thin sections were analyzed using the same table bench scanning electron microscope (SEM), specifically the COXEM EM 30AX Plus model, equipped with a tungsten filament (W), Secondary Electron (SE) Detector, Backscattered Electron (BSE) Detector (solid type, 4 channels), and an energy dispersive X-ray detector (EDX), the EDAX Element-C2B, to provide detailed elemental composition and surface analysis.

Thin sections were prepared by selecting small, representative samples from the decorated areas of the pottery fragments. These samples were embedded in resin and the section were polished and Au coated (Maritan, 2024).

In this study, SEM was used to analyze the cross-sections of the painted surfaces, providing insight into the material composition.

This method is particularly well-suited for analyzing ceramic fragments from archaeological contexts, such as those from Shahr-i Sōkhta, where the preservation of surface decoration is critical for interpreting production techniques.

3 Results

3.1 MACROSCOPIC ANALYSIS UNDER THE STEREOMICROSCOPE

Through the use of stereomicroscopy, I observed various surface characteristics across the pottery samples from each group. The first group was Group A, which includes Samples 1, 2, 3, and 6.

In examining Sample 1 through stereomicroscopy, a detailed observation of the painted surface reveals contrasting states of preservation which highlight both the techniques and the probably environmental impacts on the pottery. The left image of Sample 1 (Fig. 4) shows a section of dense paint, neatly applied with clean brush lines. This area exemplifies a well-preserved portion of the design, where the paint has maintained its integrity and colour saturation over time.

Conversely, the right image of the same Sample shows significant erosion within the painted layers, leading to the exposure of the underlying biscuit or ceramic body.

The surface of the entire sample is rough, the same textural quality of the clay clearly visible in areas where the paint has eroded and along fractures. In traditional ceramic industries, imperfections and the variability in surface preparation contribute to the individual aesthetics of each pottery artifact.

In Sample 2, the left image (Fig. 4), the paint remains good, with the colour appearing dense and well-preserved, with much of its original vibrancy and coverage.

However, in contrast to the more preserved sections, the right image of the same sample reveals faded areas. The degradation of the painted surface highlights the vulnerability of the paint layer to environmental factors or the aging process.

What distinguishes Sample 2 from Sample 1 is the smoothness of the ceramic body. Unlike the rough texture seen in Sample 1, the substrate in Sample 2 appears smoother, suggesting a more refined preparation of the clay before painting. This difference affects the aesthetic appearance but also possibly the longevity and durability of the painted surface. The smoother substrate of Sample 2 highlights a variance in material preparation, perhaps reflecting a higher level of craftsmanship or different aesthetic intentions.

In both Samples 3 and 6, the stereomicroscopic examination reveals an irregular distribution of paint, with varying densities of pigment application across the surfaces. These denser areas could correspond to parts of the pottery that were less exposed to handling or environmental factors that typically contribute to paint degradation (Fig. 4).

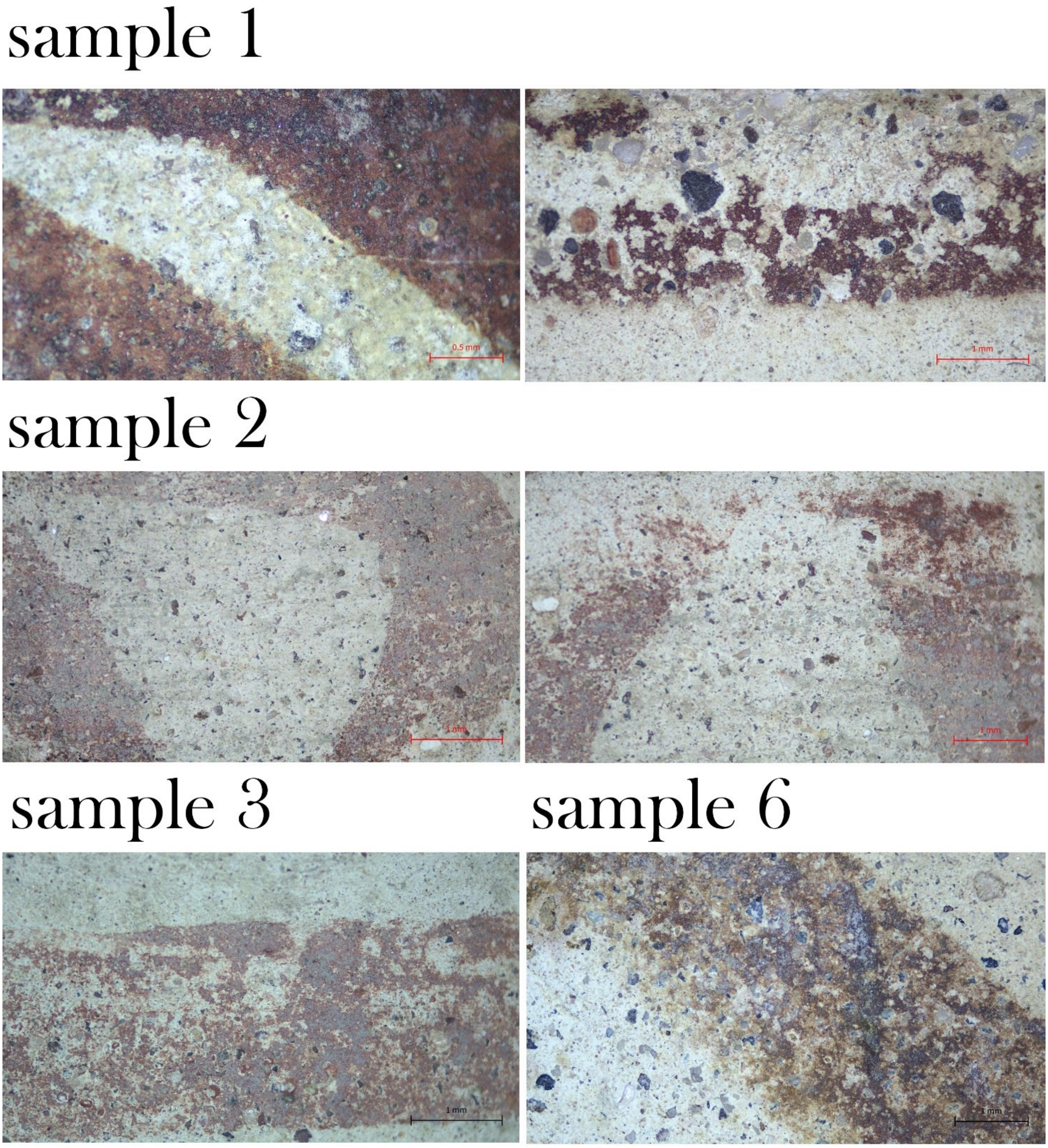


Fig. 4: Stereomicroscope images of Samples 1, 2, 3, and 6 belonging to Group A. The images reveal varying surface textures and states of paint preservation. Sample 1 and 2 shows a clear contrast between well-preserved vivid paint and significantly eroded sections exposing the ceramic body. Samples 3 and 6 display irregular paint distribution with varying pigment densities, highlighting the unique impacts of environmental exposure and handling on each pottery piece.

Group B, which includes Samples 4, 5, and 7, notable distinctions in the state of the painted surfaces compared to group A were observed. This Group shows more pronounced signs of fading and erosion, with the paint layer largely diminished across much of the pottery, revealing the underlying ceramic body more extensively.

Sample 4, in fact, exhibits significant fading and erosion across its painted surface, highlighting the vulnerability of the paint to taphonomic factors (Fig. 5). The ceramic body, which appears relatively rough and unsmoothed, indicates minimal surface preparation before the application of the paint. Despite this extensive wear, there are still isolated patches where the paint remains relatively dense, offering a glimpse into the original colour intensity and application technique.

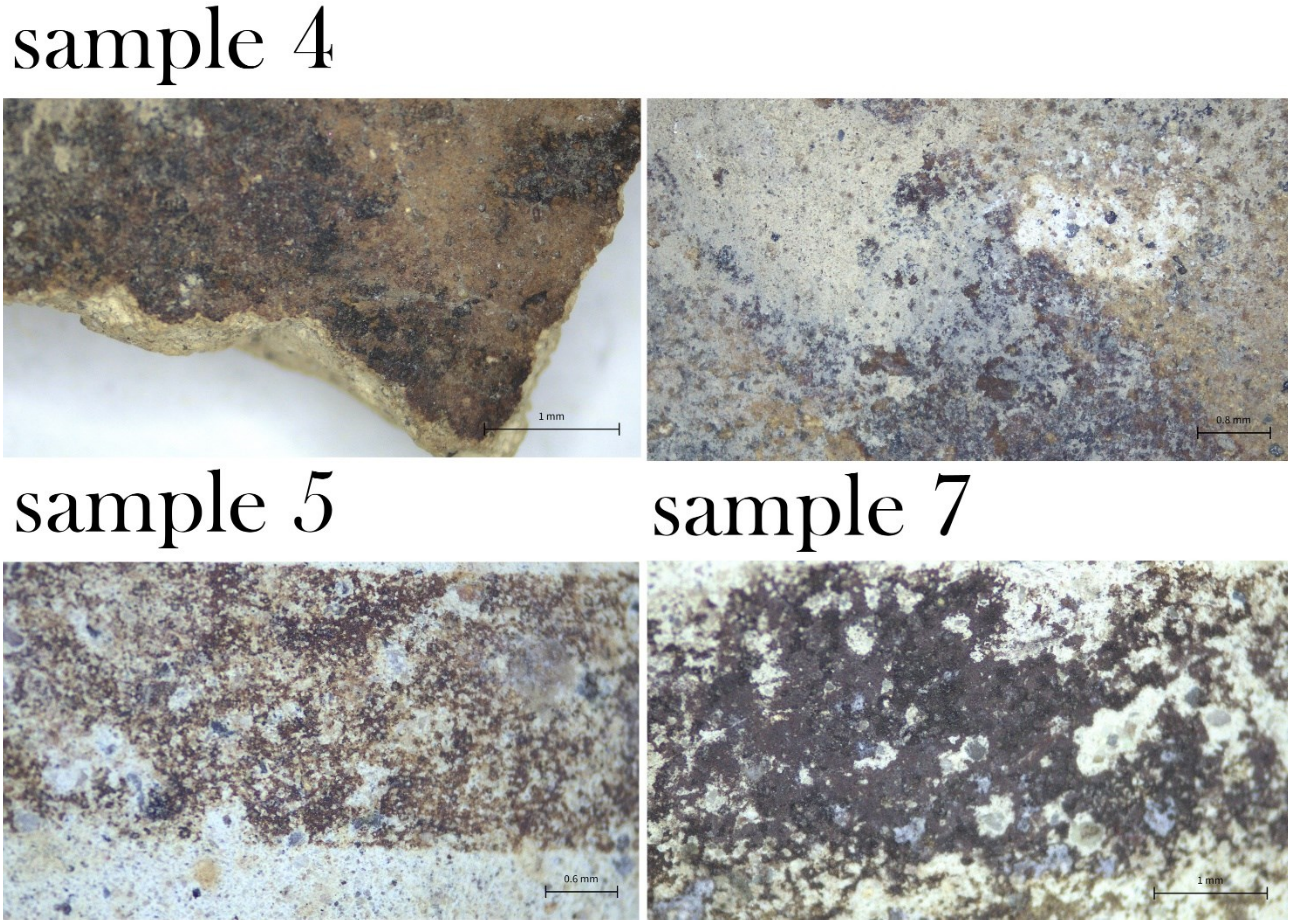


Fig. 5: Stereomicroscope images of Sample 4, 5 and 7 of Group B. Sample 4 exhibits significant fading and isolated patches of dense paint, revealing the original colour intensity. Sample 5 shows a speckled pattern of erosion, suggesting variations in paint thickness. Sample 7, while retaining more consistent paint coverage, is extensively faded and exhibits a mottled appearance, indicating uneven degradation and the impact on the visibility of original designs.

The erosion in Sample 5 is less uniform compared to Sample 4, allowing for a better understanding of the degradation patterns. The paint here appears speckled, with numerous small patches where the underlying biscuit is visible, interspersed among areas where the thicker paint has held better.

Unlike Samples 4 and 5, Sample 7 retains a more consistent paint coverage, though extensively faded. The surface is mottled where the paint density varies, creating another patchwork of more and less preserved areas. (Fig. 5).

For Group C, which encompasses Samples 8, 9, 10, and 11 from Period III, there are distinct features indicating advancements in pottery techniques, particularly the introduction of the potter's wheel.

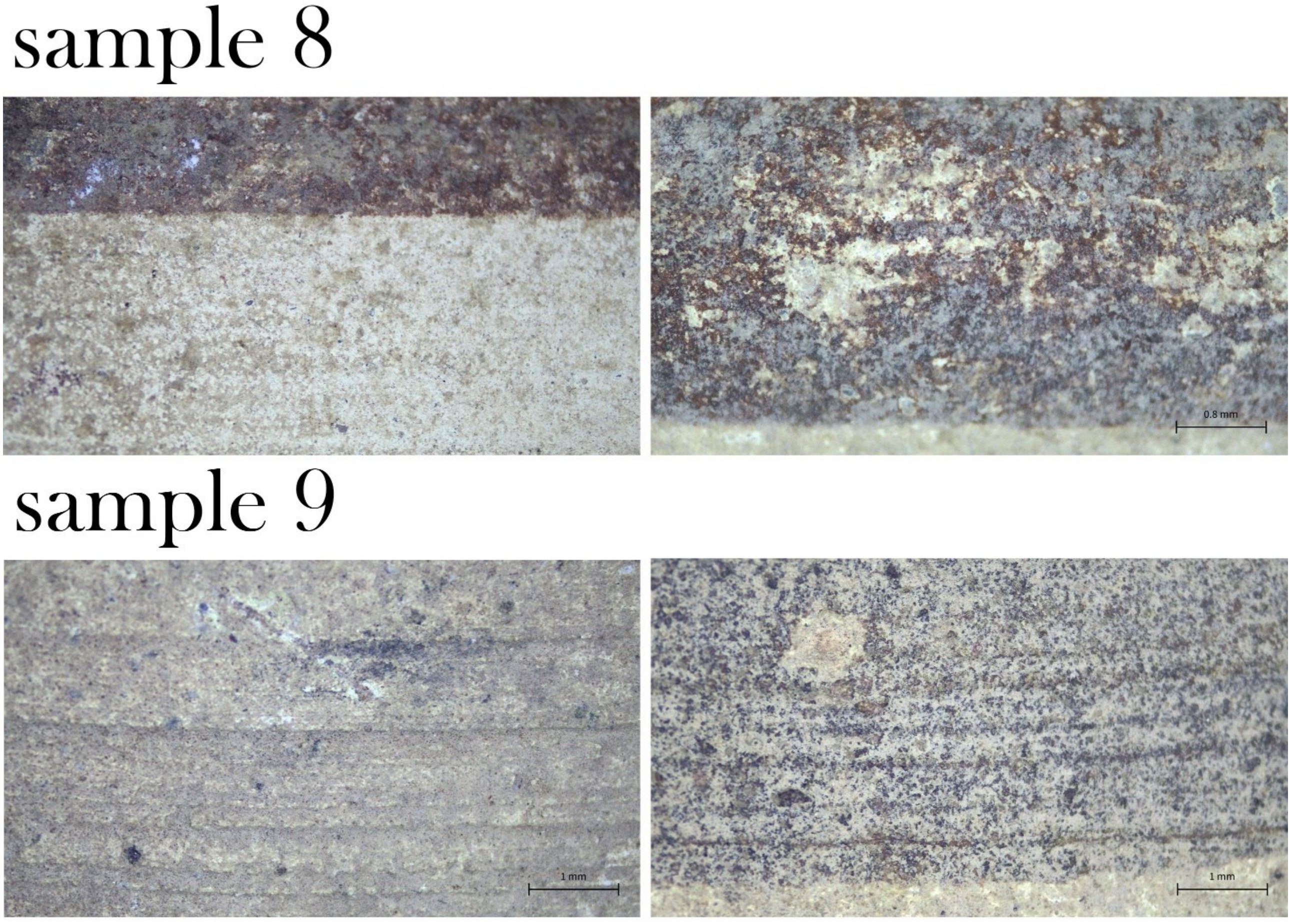


Fig. 6: Stereomicroscope images of Samples 8 and 9 from Group C. Sample 8 is notable for its painted rim that shows a consistent, clean line, indicative of high craftsmanship and the use of durable pigments that retain dense colour despite aging. Sample 9, exhibits wheel-throwing lines, clear evidence of the technological advancement with the introduction of the potter's wheel.

Sample 8 features a painted rim that exhibits a clean, consistent line indicative of being drawn with a steady hand using a brush. This demonstrates a high level of craftsmanship and control in the application of paint. Despite some fading over time, the majority of the painted area retains its dense colour, suggesting the use of durable pigments designed to withstand environmental factors and aging. In both Samples 9 and 10, wheel-throwing lines are prominently displayed on the ceramic body, marking a significant technological shift in Group C from Period III (Fig. 6 and 7). These marks clearly indicate the use of a pottery wheel, allowing for more uniform and symmetrical forms in pottery production. This transition to wheel-thrown containers represents a technological evolution, reflecting changes in production methods that likely influenced both the efficiency and the styles of ceramic creation.

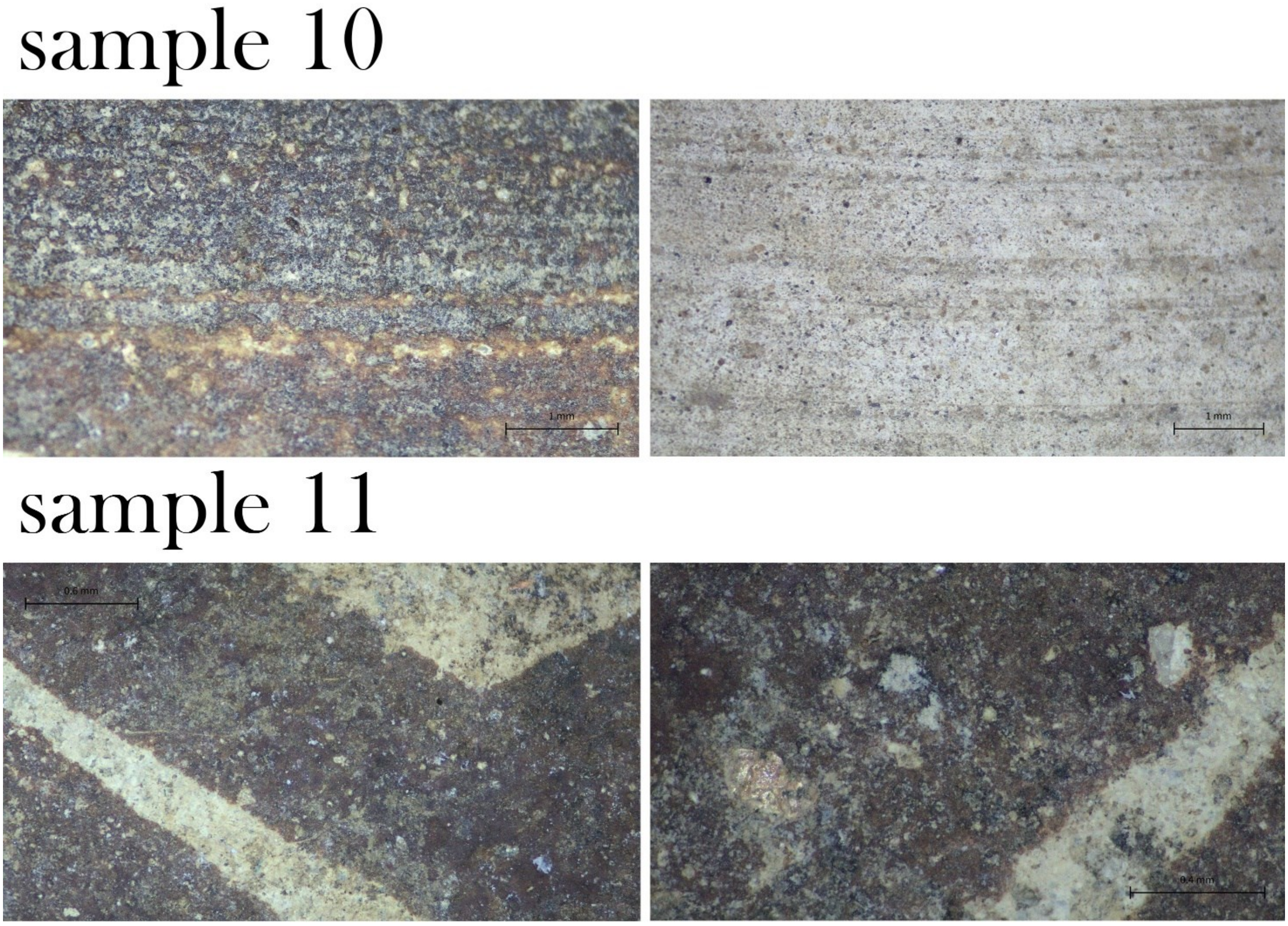


Fig. 7: Stereomicroscope images of Samples 10 and 11 from Group C. Sample 10 shows pronounced wheel-throwing lines, indicative of uniform pottery production. Sample 11 showcases precise, sharp geometric patterns in its decoration, reflecting advanced artistic skill with excellent preservation allows to designs stand out vividly, suggesting careful handling and minimal exposure to environmental damage.

Sample 11 is in a good state of preservation compared to other samples and demonstrates a high level of skill and control in decoration, evident in the precise painted lines that were presumably part of geometric patterns. The clean and sharp lines, whose original colors and designs stand out more vividly, attest to the artisans' craftsmanship (Fig. 7).

The last two samples, designated as part of a Group "out" might suggest that these pieces are not local.

Painting on Sample 12 is notably eroded and faded over time. However, upon closer examination, there are still small areas where the paint remains dense, suggesting that the original colouration was solid. The visible reddish streaks and blotches across the pottery surface highlight areas where paint was applied, though its uneven distribution and the patchy nature of the remaining paint suggest extensive wear and exposure to harsh conditions.

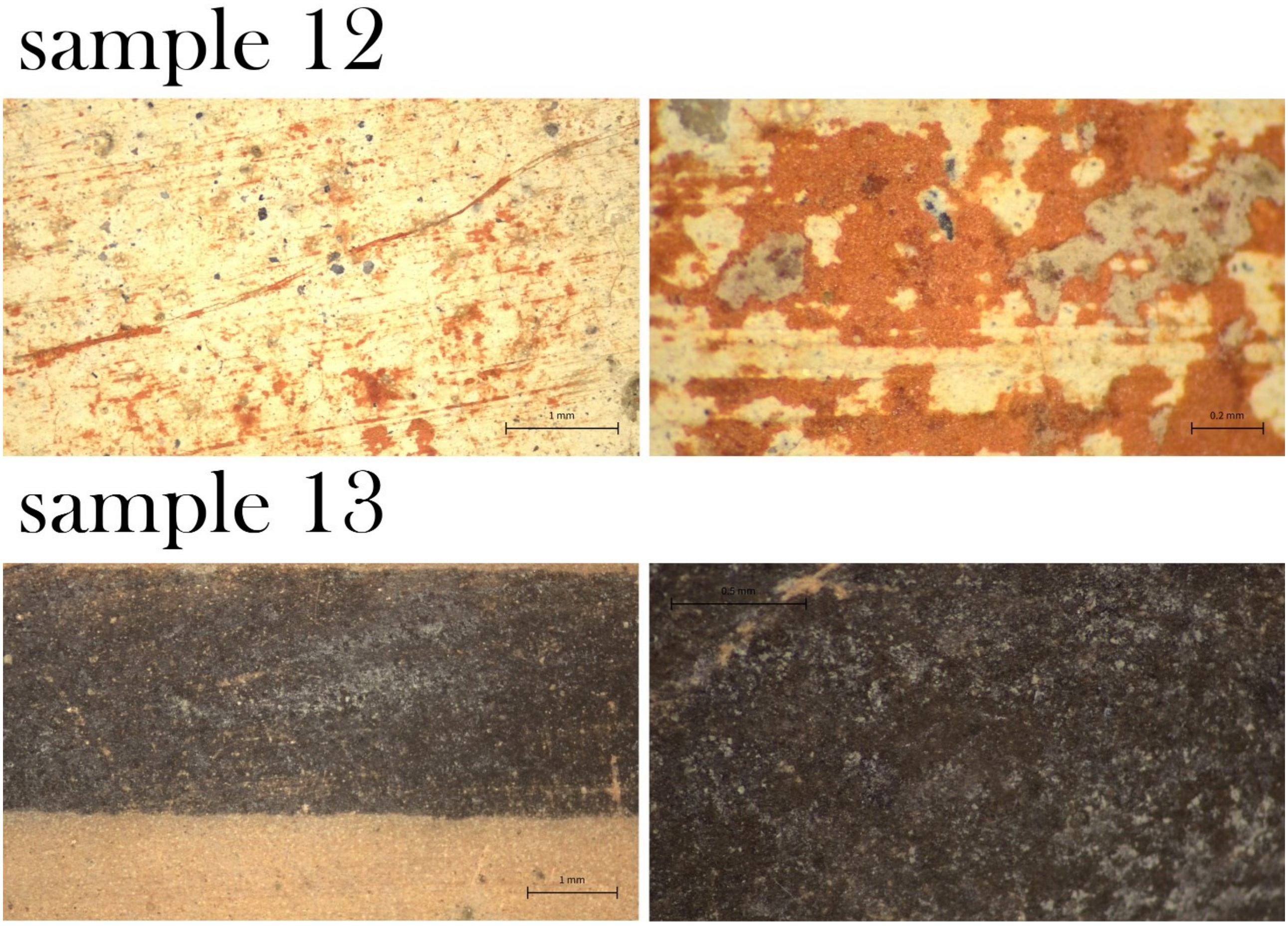


Fig. 8: This image illustrates pottery Samples 12 and 13 from Group "Out," potentially non-local artifacts, under stereomicroscopy. Sample 12 shows significant paint erosion and fading, yet retains small areas with dense, robust original colouration, marked by reddish streaks and blotches indicating extensive wear and exposure. In contrast, Sample 13 displays paint in remarkably good condition, suggesting either enhanced protection from environmental factors or the use of more durable materials and techniques.

In contrast to Sample 12, Sample 13 displays paint that is in remarkably good condition. The paint's preservation suggests that this piece was either fired at higher temperatures, or/and better protected from environmental stressors. The surface of the ceramic body is quite smooth, indicative of careful preparation and finishing processes prior to painting (Fig. 8).

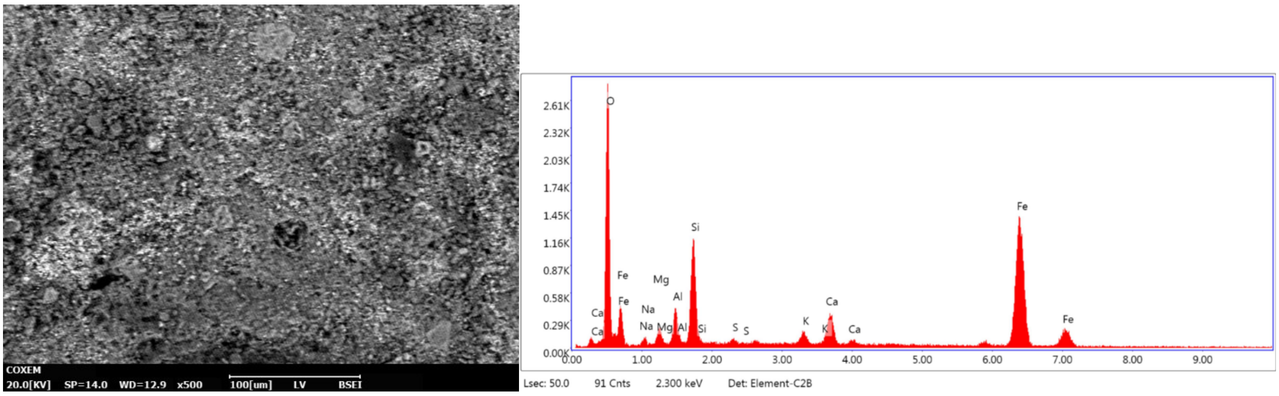
The observations and images obtained through stereomicroscopy serve as a foundational reference for selecting samples for more advanced analytical methods, such as scanning electron microscopy (SEM), which was the next step in our analysis.

3.2 MICROSTRUCTURAL ANALYSIS BY SCANNING ELECTRON MICROSCOPY (SEM)

To begin the presentation of the individual sample analysis, first we selected several representative pottery fragments for SEM examination. The following sections provide detailed results for selected samples, including their SEM-BSE images and SEM-EDX spectra. Each sample was chosen to highlight key variations in composition across different pottery fragments, particularly focusing on the painted areas.

The Scanning Electron Microscopy (SEM) analysis conducted on Sample 2 from Group A has revealed significant differences in the elemental composition between the painted and unpainted areas, as the painted sections exhibit elevated levels of iron, affirming the use of iron-based paints. In contrast, the unpainted portions of the pottery display markedly lower amounts of iron and a higher quantity of silicon, aluminum, magnesium and calcium (Fig. 9). This is certainly due to the deliberate application of iron paints (such as iron-rich earths).

Sample 2 (Painted surface)



(Unpainted surface)

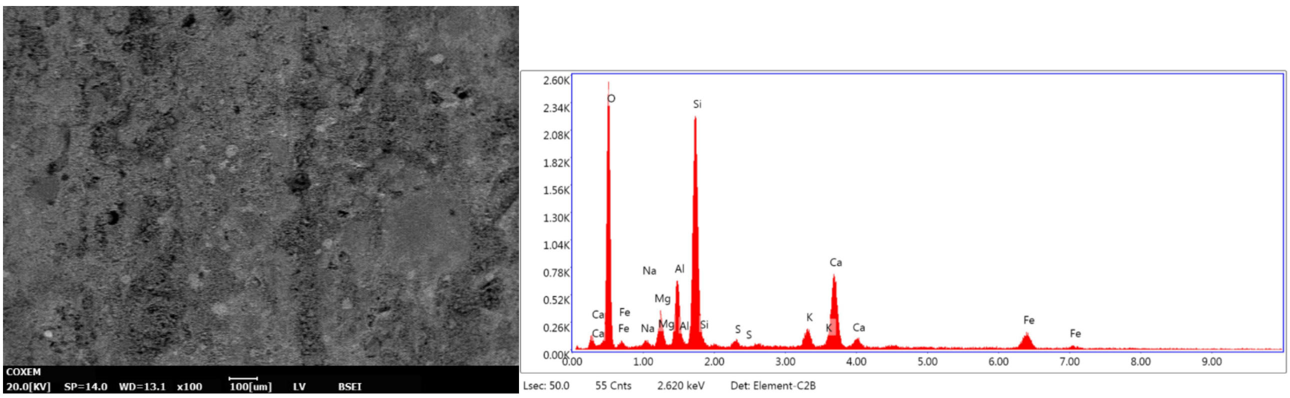
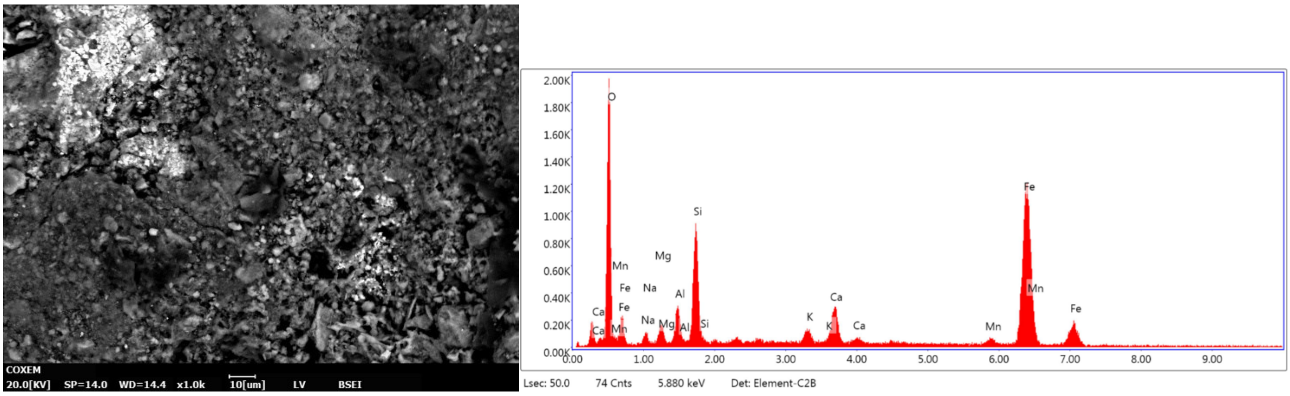


Fig. 9: SEM-BSE image (left) and SEM-EDX spectrum (right) for Sample 2, comparing the elemental composition of painted and unpainted surfaces. The image reveals microstructural details of the pottery surface, while the graph displays the elemental composition, prominently featuring a significant peak for iron (Fe). The high concentration of iron observed in the spectrum confirms that the painted surface is iron-based.

Sample 4 from Group B, shares the iron-based paint composition of the previous sample, but it also show the occurrence of some manganese in the painted area, indicating that the material used was probably a mix of iron and manganese (probably from a natural earth rich in this second element) (Fig. 10).

Sample 4 (Painted surface)



(Unpainted surface)

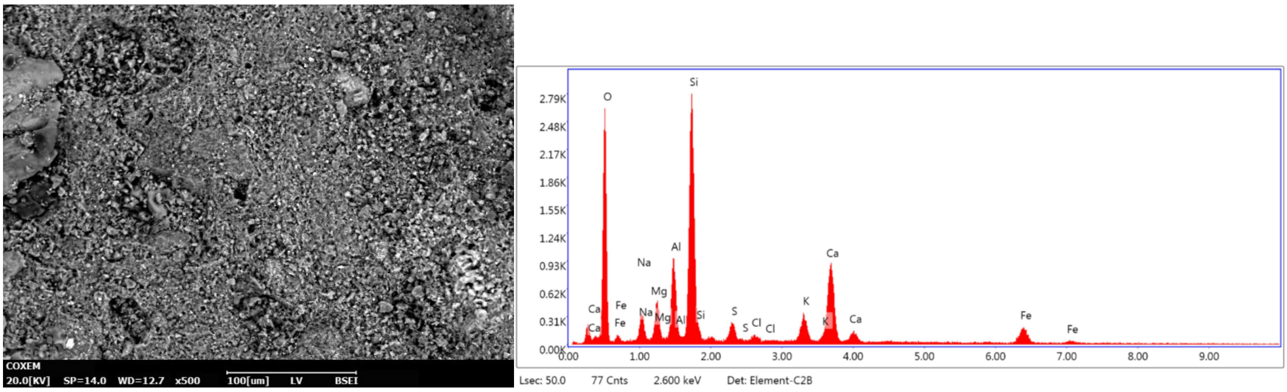


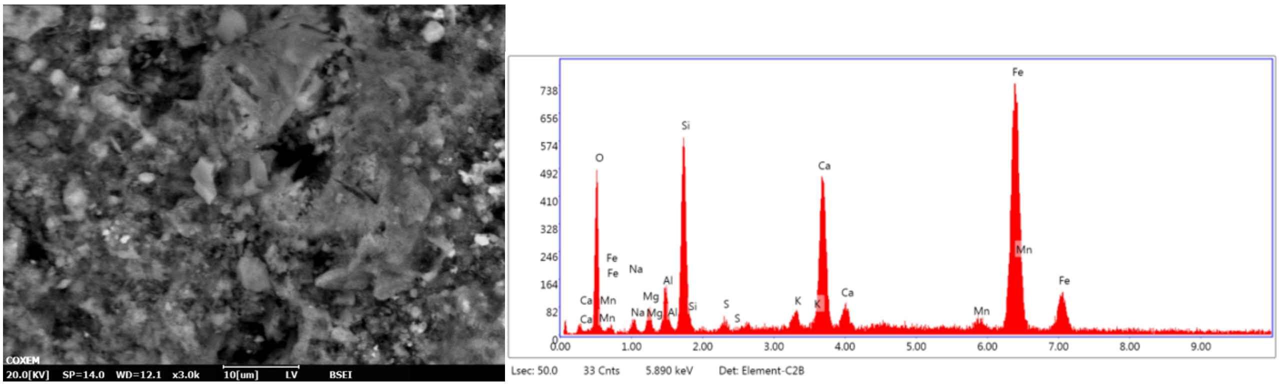
Fig. 10: SEM-BSE image (left) and SEM-EDX spectrum (right) for Sample 4, comparing the elemental composition of painted and unpainted surfaces. The images reveal microstructural details, while the spectrum identifies elevated levels of iron (Fe), indicating iron-based paint, enriched with an earth containing manganese.

Samples 5 and 7, both belonging to Group B, provide further evidence of the use of iron-based paint. These samples contain some of the highest levels of iron detected across all analyzed groups. The prominence of iron in both the painted and unpainted areas highlight its dual role in contributing to the pottery's colours and durability.

In Sample 5, the elevated levels of iron detected across multiple regions underscore the intentional use of an iron rich material like a earth rich in hematite or limonite (Fig.11). This material was selected for decorative qualities that could yield vivid reddish to black/brown hues.

Such a purposeful inclusion of iron oxides as a fundamental material in the pottery-making process is further supported by the findings in Sample 7, which mirrors the compositional characteristics of Sample 5, exhibiting a high level of iron, This further support the use of iron-rich materials as pigments to achieve the desired reddish to black/brown hues in the decoration.

Sample 5 (Painted surface)



(Unpainted surface)

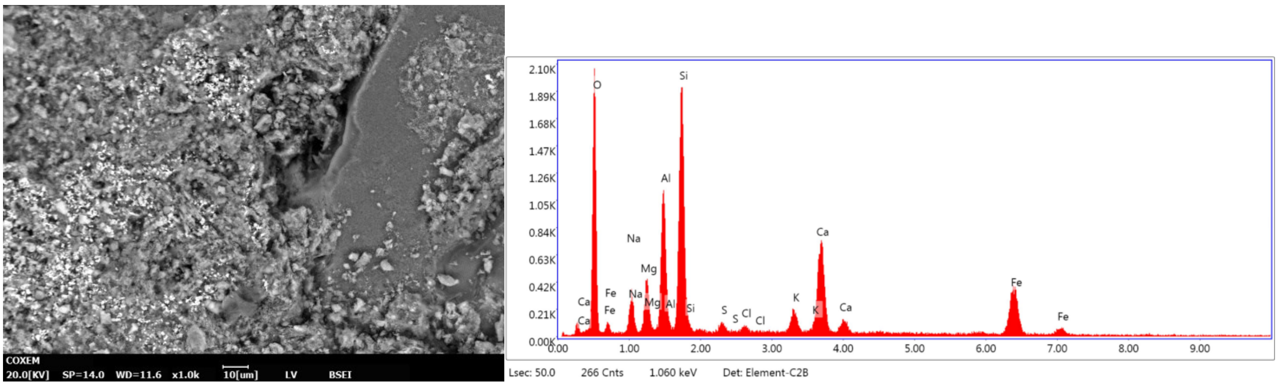
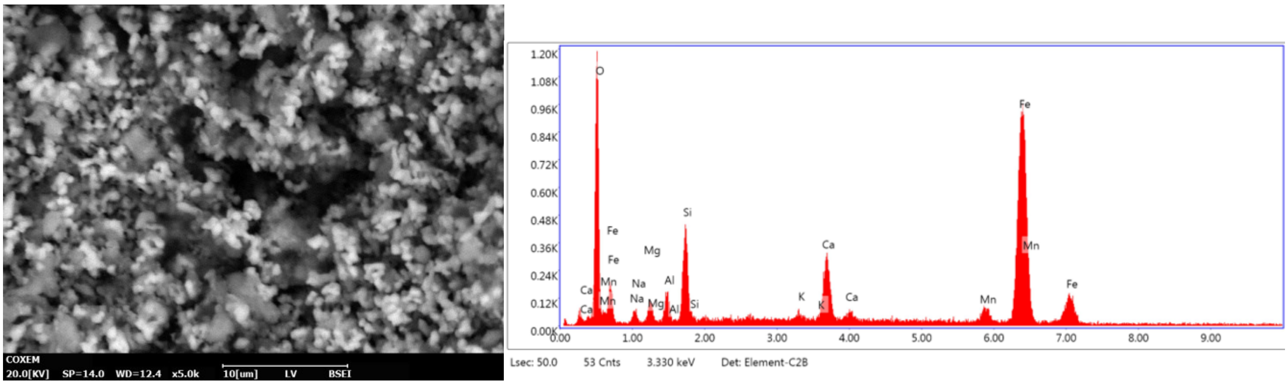


Fig. 11: SEM-BSE image (left) and SEM-EDX spectrum (right) for Sample 5. The image shows the microstructural details of the pottery surface, while the graph highlights the elemental composition, with a significant peak for iron (Fe). The high concentration of iron observed in the spectrum confirms that the painted surface is iron-based.

Additionally, Sample 7 revealed notable levels of salt, indicated by the presence of sodium and chlorine, across several areas of the ceramic. Salts are a distinctive, recurrent presence in the strongly alkaline deposits that cover large portions of the prehistoric site. Silicon, oxygen and aluminum were also consistently present, reflecting the use of phyllosilicates in both the ceramic body and the paint. The presence of calcium and magnesium suggests the use of carbonate-rich clays (carbonatic clays) (Fig.12).

Sample 7 (Painted surface)



(Unpainted surface)

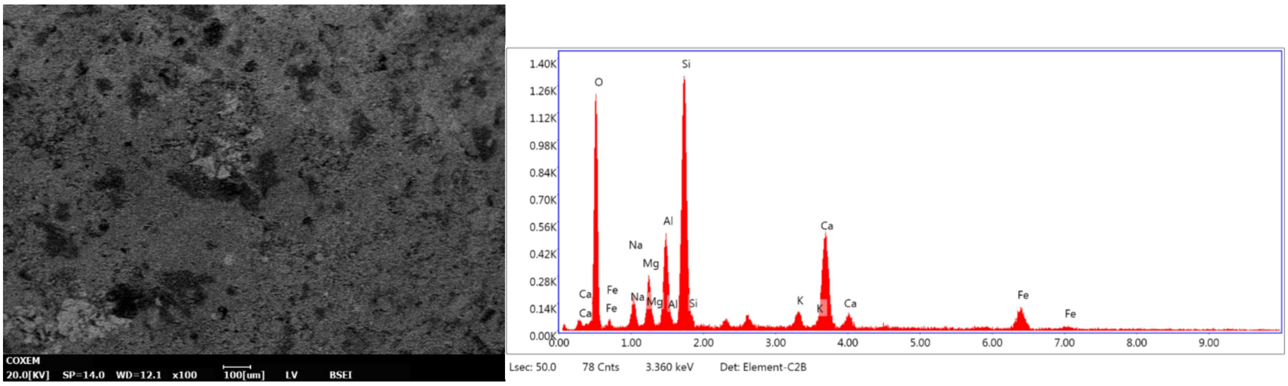


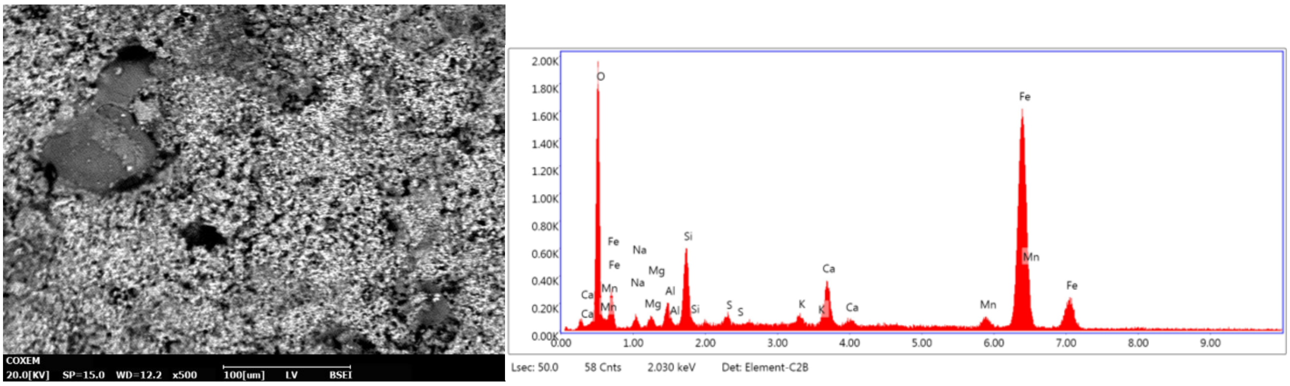
Fig. 12: SEM-BSE image (left) and SEM-EDX spectrum (right) for Sample 7. The image shows the microstructural details of the pottery surface, while the graph highlights the elemental composition, with a significant peak for iron (Fe). The high concentration of iron observed in the spectrum confirms that the painted surface is iron-based with trace of manganese.

The significant levels of iron are coupled to a small amount of manganese, like in the case of Sample 4.

In Sample 11, which is one of the samples from Group C, results show a similarly complex composition. Along with iron, elements such as silicon, calcium, and sodium are present in substantial amounts, pointing to the use of silicate and carbonate minerals, therefore a earth rich in iron. Sample 11, composition is dominated by iron, similar to last samples in Groups A and B, reinforcing the conclusion that iron oxides-rich materials were extensively used as pigments for the painted surfaces of the pottery (Fig. 13).

While many of the other samples analyzed are iron-based as well, these three—Sample 5, Sample 7, and Sample 11—stand out due to their very high levels of iron in the decorated areas. This indicates that the use of iron oxides was a well-established practice at Shahr-i Sōkhta, highlighting the kind of material selection and production techniques employed by the artisans of this ancient urban site.

Sample 11 (Painted surface)



(Unpainted surface)

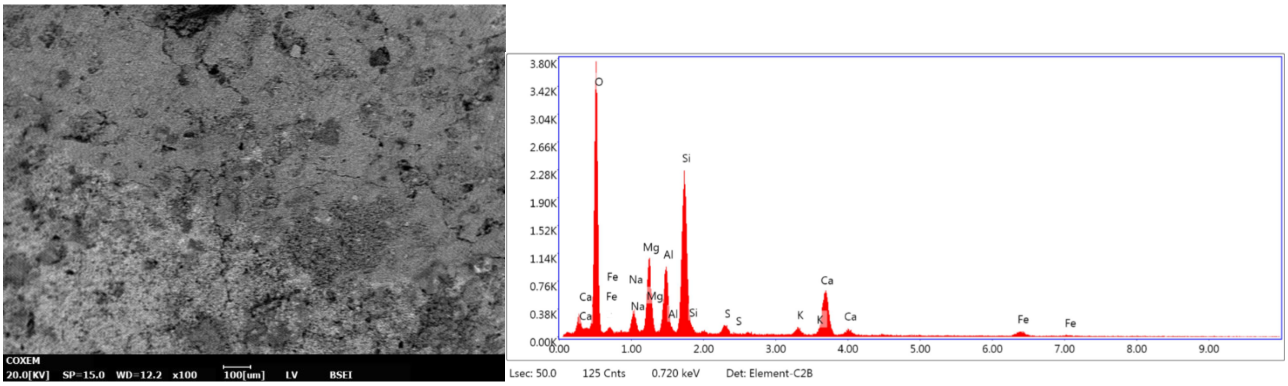
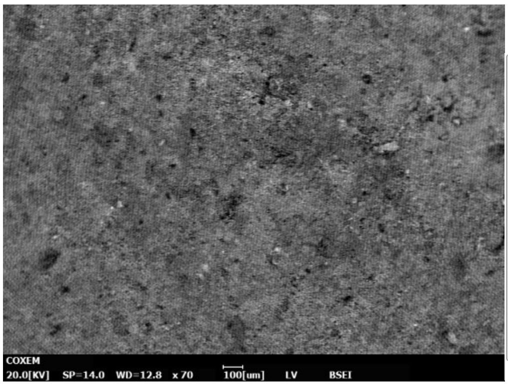


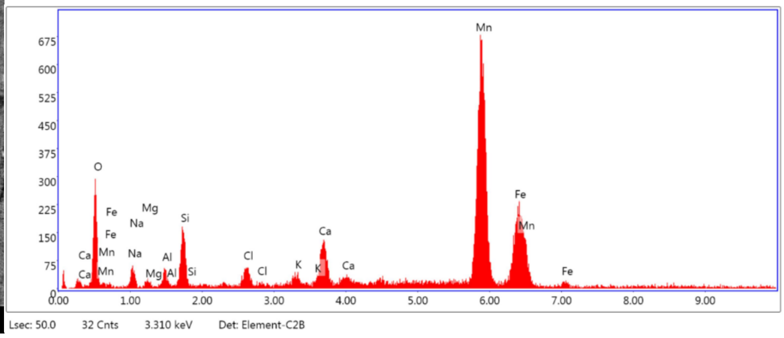
Fig. 13: SEM-BSE image (left) and SEM-EDX spectrum (right) for Sample 11. The image shows the microstructural details of the pottery surface, while the graph highlights the elemental composition, with a significant peak for iron (Fe). The high concentration of iron observed in the spectrum confirms that the painted surface is iron-based.

One notable exception is Sample 13 of Group "out", which is a black-on-red ware, that might be not local. The paint on this sample, in fact is different from the rest by being manganese-based. This sample is the only one among all 13 analyzed fragments to show manganese as the predominant component, setting it apart from the otherwise iron-dominated group of samples (Fig. 14).

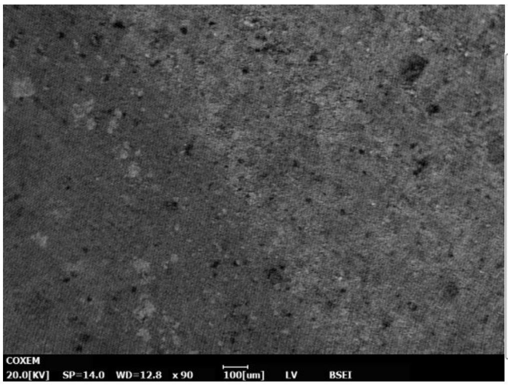
SEM-EDX analysis, indicates that manganese oxides were likely used deliberately in the pottery's painted surface, potentially for both colour and mechanical properties. Although there is a trace presence of iron, it is minimal compared to the dominant manganese.

Sample 13 (Painted surface)





(Unpainted surface)



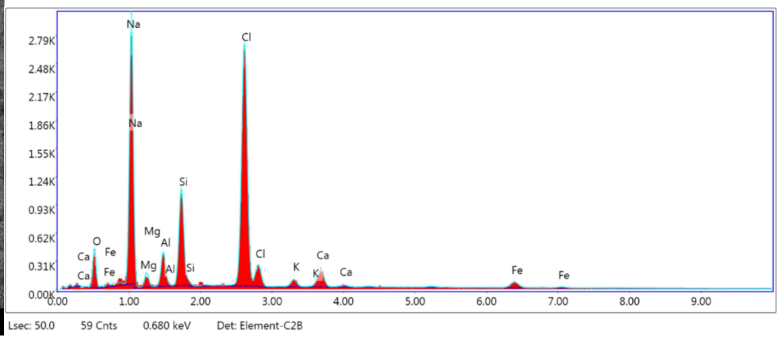


Fig. 14: SEM-BSE image (left) and SEM-EDX spectrum (right) for Sample 13. The image shows the microstructural details of the pottery surface, while the graph highlights the elemental composition, with a significant peak for manganese (Mn). This confirms that the painted surface of this sample is manganese-based, distinguishing it from other samples that are primarily iron-based.

3.3 MICROSTRUCTURAL ANALYSIS BY SCANNING ELECTRON MICROSCOPY (SEM) OF POTTERY THIN SECTIONS

We selected three samples for thin-section analysis, aiming to obtain more detailed information on their composition and production techniques. Sample 8 and Sample 11 were chosen due to the dense colouration in their painted areas, which suggested they could reveal valuable insights. Sample 13, as the only black-on-red ware among the collection, was included for its unique characteristics, making it an ideal candidate for deeper analysis.

The painted portion of the pottery's surface of Sample 8**,** consists on a layer about 10-15 μm thick, composed by a partially glassy material, showing pores, mineral phases rich in iron (light grey hues in the image) with cubic habit, as well as prismatic crystals of a lower average atomic number (darker grey hue) (Fig. 15). The painted layer, therefore was obtained using a clay material rich in iron and carbonates, which, during firing, led to the crystallization of Ca-rich prismatic phases (pyroxene) and hematite, the latter providing the red color to the decorative motifs (Fig. 15).

The painted surface of Sample 11 show analogous features to those of the previous sample, indicating the use of the same type of raw material for the decoration. The microstructure is less well-preserved and appears more porous, probably in relation to lower firing temperatures, which did not allow the extensive formation of a glassy matrix of the painted layer. The chemical composition shows the predominance of iron and small quantities of manganese contributing to the dark colour of the decoration (Fig. 16).

The last sample that was thin-sectioned, Sample 13, confirms that the painted surface of the pottery is manganese-based, with high concentrations of manganese as the primary component. Silicon and calcium suggest the use of a clayey material rich in carbonate, like in the case of the previous samples, the decomposition of which, during firing enhanced the structural integrity for the glassy material that formed which determined bridging in the layer (Fig. 17).

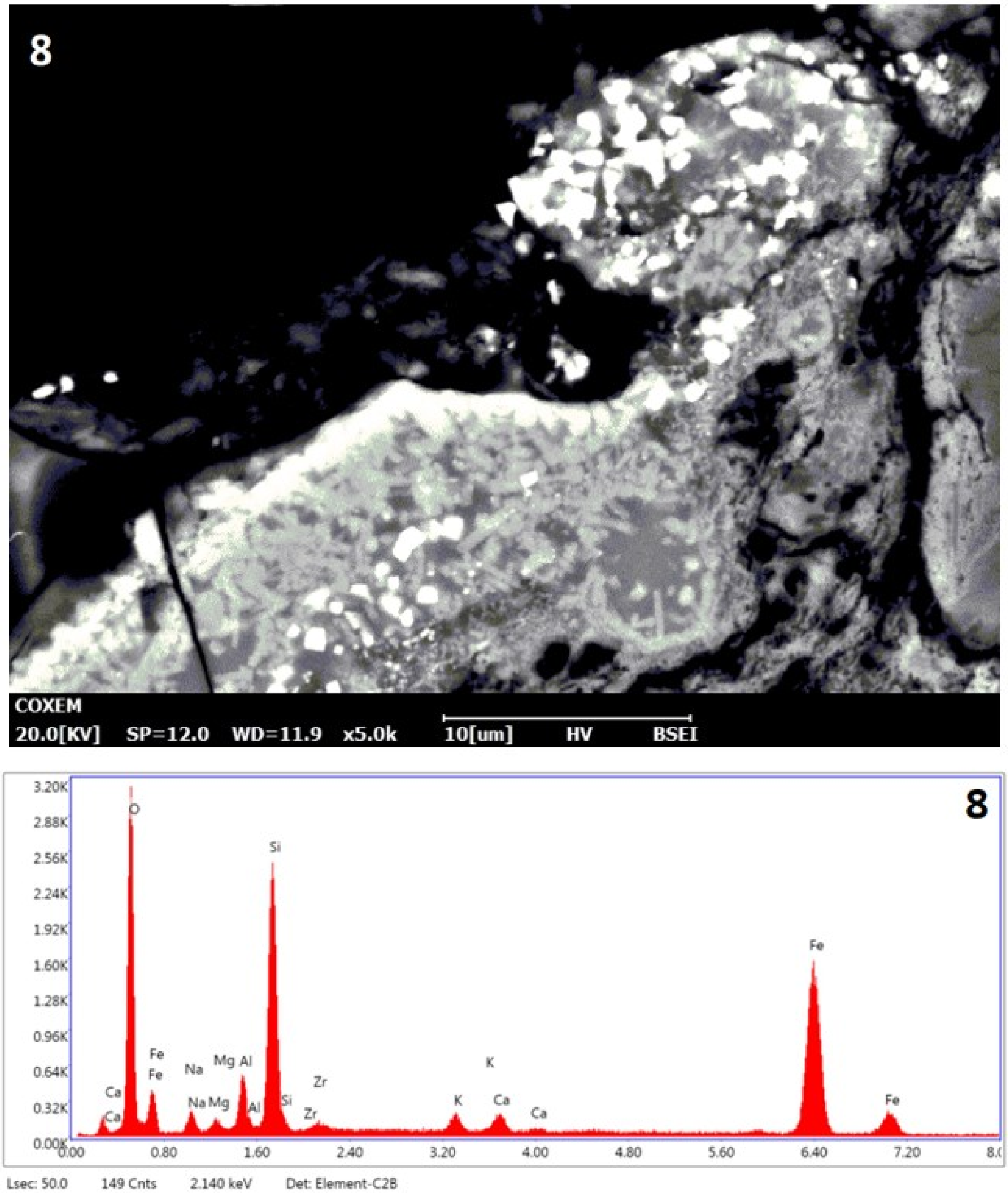


Fig. 15: Sample 8. The top image (SEM-BSE) reveals the microstructural details of the pottery surface, providing compositional contrast, the bottom graph (SEM-EDX spectrum) shows the elemental composition of the painted surface, indicating a predominantly iron-based composition.

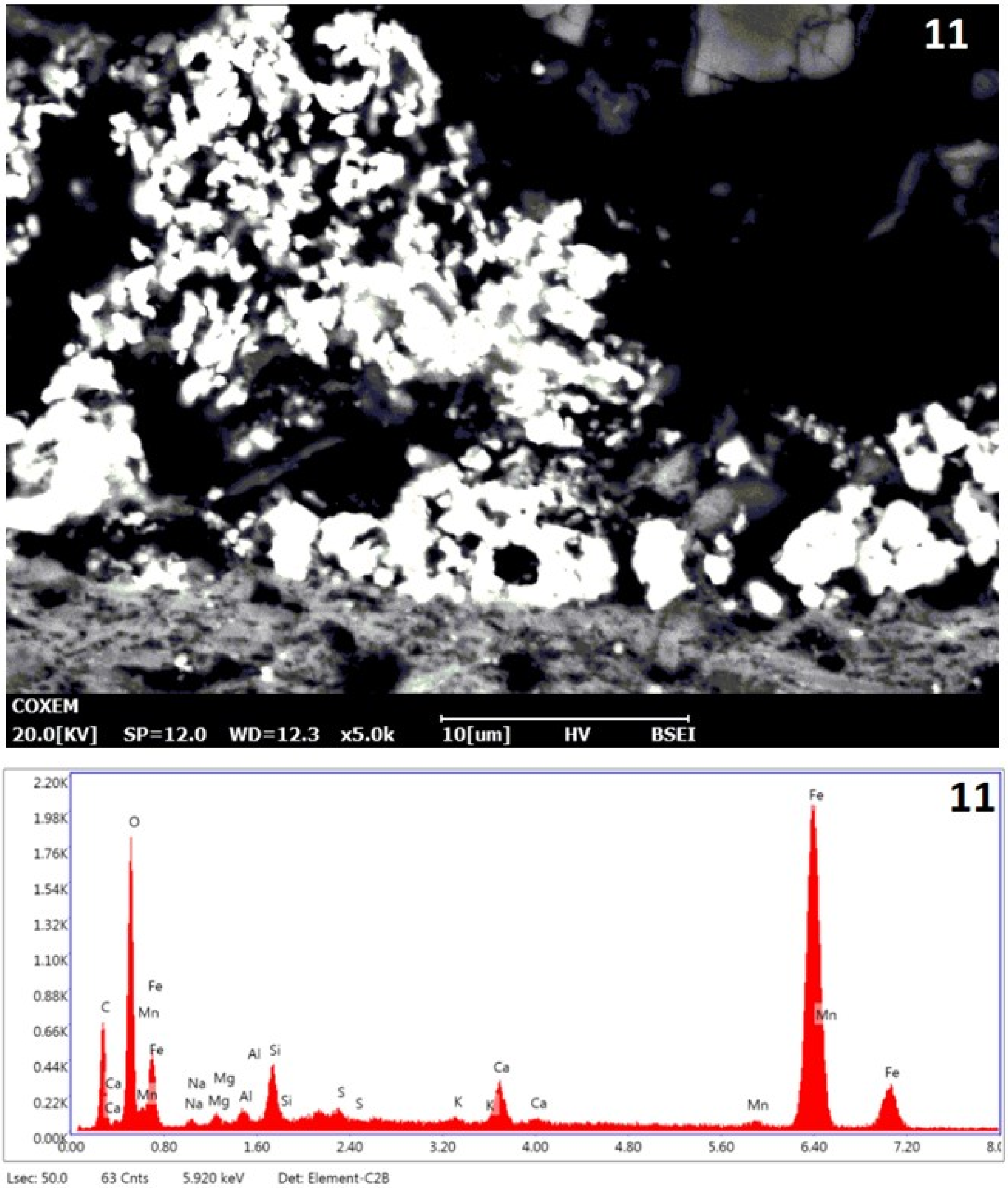


Fig. 16 : Sample 11. The top image (SEM-BSE) reveals the microstructural characteristics of the pottery surface, while the bottom graph (SEM-EDX spectrum) presents the elemental composition, confirming that the painted surface is predominantly iron-based.

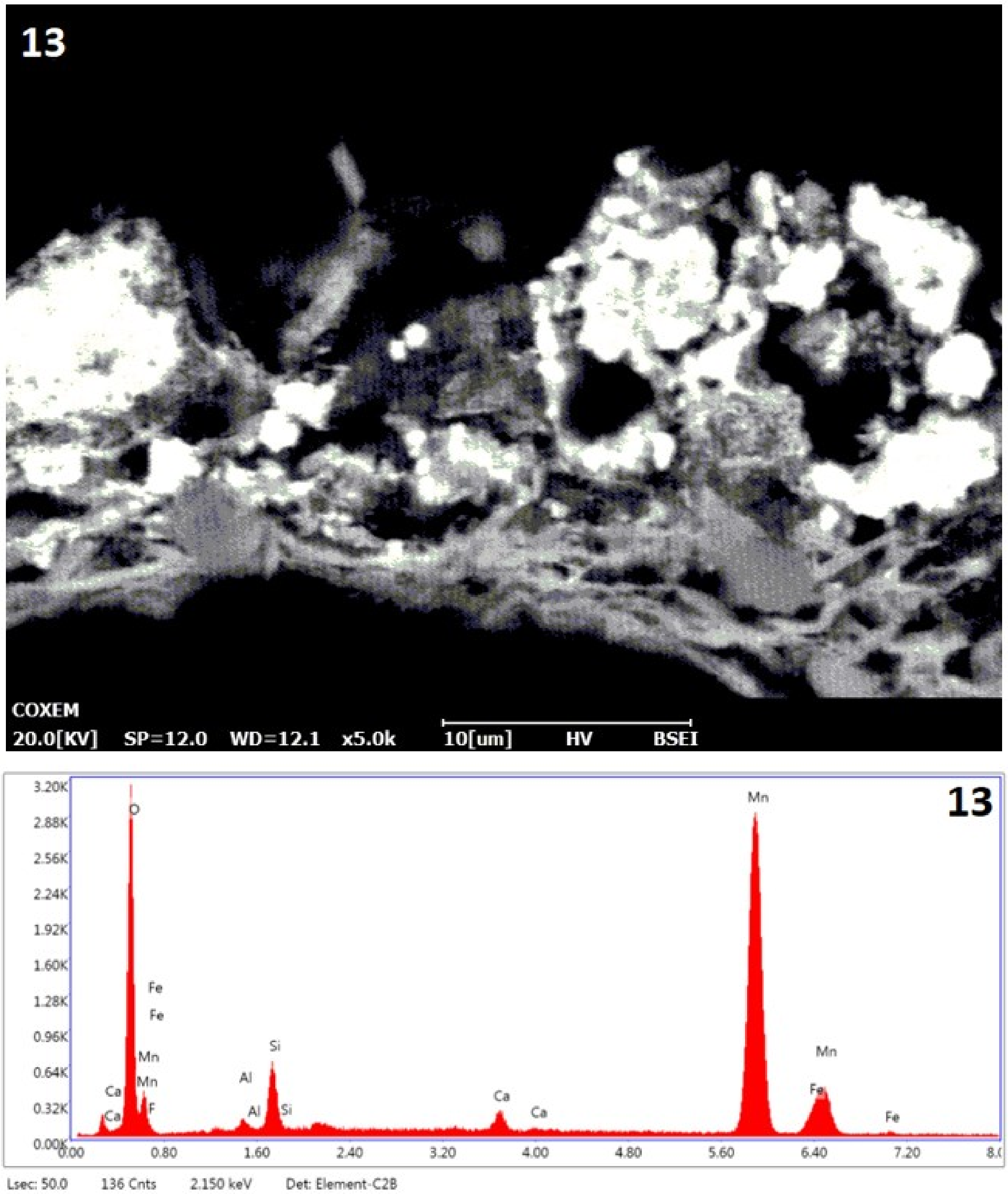


Fig. 17 : Sample 13. The top image (SEM-BSE) shows the microstructural details of the pottery surface, while the bottom graph (SEM-EDX spectrum) highlights the elemental composition of the painted surface, revealing a manganese-based composition.

Conclusions

The present study provides the results of a preliminary archaeometric analysis of pottery fragments from the site of Shahr-i Sōkhta, offering critical insights into the technological choices, materials, and production techniques employed by ancient artisans for the decoration. Through analytical methods, such as Scanning Electron Microscopy (SEM) coupled with Energy Dispersive X-ray Spectroscopy (EDX), this research has revealed the elemental composition of the pottery's clay paste and painted surfaces. These findings will contribute to our understanding of ancient ceramic production at Shahr-i Sōkhta and, in a broader context, will aid in interpreting the technological sophistication of Bronze Age societies, particularly in southeastern Iran. The iron-based compositions detected in pottery highlight the artisans' understanding of their material environment and their ability to manipulate natural resources to achieve desired aesthetic outcomes.

This aligns with broader archaeological evidence suggesting that ancient communities often relied on locally available materials for their crafts. The consistent use of iron-based pigments across many pottery fragments suggests that the artisans had developed a well-established technique for incorporating these pigments into their ceramic production process.

While iron-rich earths dominate the painted surfaces of the pottery, this study also uncovered the use of manganese-based pigments, although to a lesser extent. The presence of manganese in certain samples suggests a more diverse use of materials in the pottery production process. Manganese, like iron oxides/hydroxide-rich materials, was likely chosen for its pigmenting properties, providing shades of black and dark brown, which would complement the red and brown tones achieved through the use of iron oxides/hydroxide-rich earth. The samples in which manganese was the primary pigment provide an interesting counterpoint to the iron-based pieces, demonstrating that the artisans who made the vases were not limited to a single method or material when decorating their pottery.

The use of manganese in certain samples raises questions about the sourcing and use of materials in the region. It is possible that manganese-rich sediments or minerals were not as readily available as iron-rich ones, which could explain the less frequent appearance of manganese-based pigments. This relative scarcity might have led to the selective use of manganese, possibly reserved for specific types of pottery or particular purposes in different locations. Although the number of shards considered in this preliminary study is very limited.

In the Sample 2, manganese is almost absent, while its quantities, coupled with iron, appear to become more evident in the later Samples. In Samples 5, 7, 11 the amounts of iron in the paint are so abundant that they have been ascribed to a deliberate use of iron oxides-rich earths or minerals, thus reflecting what might have been a well-established craft routine.

Finally, the unique manganese-based paint of Sample 13 may witness the expansion of the economic procurement sphere of the potters of Shahr-i Sōkhta to areas where manganese outcrops were available; or simply that the vase from which the shard was actually imported.

However, to fully understand the extent of manganese use in comparison to iron, a larger sample size and further examination of pottery fragments are necessary.

The analysis has also shed light on the broader production processes employed by the artisans. The consistent use of silicate-based clays, as indicated by the presence of silicon and oxygen in the EDS spectra, suggests that the artisans were working with high-quality raw materials that provided a solid foundation for their ceramic production. The presence of other elements, such as calcium, aluminum, and magnesium, further supports the idea that the clay used in the pottery was carefully selected and processed to ensure durability and functionality. The presence of these elements also suggests that the artisans were aware of the properties of different clays and how they could be manipulated to achieve specific outcomes, whether in terms of the pottery's structural integrity or of its aesthetic appearance.

In conclusion, the analysis of pottery fragments from the site has provided useful insights into the materials, techniques, and cultural practices associated with ceramic production in the Bronze Age. The predominance of iron-based pigments in the painted surfaces, followed by the use of manganese-based pigments, is not surprising but reflects, with other technical details, the technological expertise and resourcefulness of the ancient artisans. The diversity of surface treatments, firing techniques, and temper materials observed in the pottery fragments further underscores the complexity of pottery production at the site. These findings contribute to a deeper understanding of the social and technological context of Shahr-i Sōkhta and offer valuable information for future studies of ancient ceramic production in the region.

As we continue to explore the rich archaeological heritage of Shahr-i Sōkhta, it is essential to build upon the findings of this study by expanding the scope of research to include a wider range of samples and integrating additional analytical methods. By doing so, we can continue to uncover the technological innovations and cultural practices that defined the Helmand civilization and its contributions to the broader history of the early Bronze age in the Near East and across the Iranian Plateau.

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