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RESEARCH

Creating *Wusetu* ("Five-Coloured Clay"): Chronological changes in *Zisha* ware clay recipes and the complexity of potters' technological choices

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Abstract

Technological choices in pottery production, particularly the selection of raw materials, are much discussed for prehistoric periods but have received little scholarly attention in the case of Late Imperial China. In this paper, *zisha* teapots, which became China's main tea preparation vessels over the course of the 15th–twentieth century, are presented as a case study to explore the complexity underlying potters' raw material selection in historic periods. A total of 187 excavated *zisha* sherds was analysed using optical microscopy, semi-quantitative chemical analysis via scanning electron microscopy (SEM) combined with energy-dispersive X-ray (EDX) spectroscopy, and ImageJ analysis of SEM backscatter spectrum images. These *zisha* sherds date from the Ming dynasty to the Republican period (1368–1949) and were recovered from Shushan kiln site. SEM–EDX analysis combined with image manipulation in ImageJ revealed changes in the clay recipe over time, including an increase in iron oxide variation and increasing fineness of clay particle sizes, suggesting an expanded colour range and refinement of the clay paste. Combining these findings with an examination of the geological setting of the mining locations, the clay procurement sequence, the clay-processing techniques used by the potters, and texts discussing clay colour and texture appreciation, this study demonstrates the complexity of the potters' raw material choices in Late Imperial China and illustrates how these factors can be elucidated through a combination of scientific analysis of archaeological material, examination of geological samples, visual analysis, and reference to historical sources.

Keywords Potters' technological choice · *Zisha* clay · Shushan site · Ming and Qing dynasties · Colourant oxides · Particle sizes

Introduction

This study explores the complexity of potters' technological choices, particularly raw material choice in Late Imperial China, focusing on *zisha* teapot clay recipe changes. *Zisha* teapots, produced in Yixing, China, are unglazed tea-making vessels that started to gain popularity during the Late Ming period (Cai DY 2019; Liu S 2013; Fig. 1) and became internationally renowned in the seventeenth and eighteenth centuries, as they were exported across Asian and European markets (Li SY 2009; Teng XB 2017; Valfre 2000). "Potters' technological choices" refers to a series of interrelated decisions, including the selection of raw materials (such as clay sources and recipes), tools and equipment for shaping pottery, energy sources (e.g., hydro-powered clay mills and fuels for firing), and processing and shaping techniques (Hunt 2016 pp. 104–106; Lemonnier 1993, pp. 6–12;

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Schiffer and Skibo 1997; Sillar and Tite 2000). These decisions also intersect with broader cultural, economic, and social dynamics (Kudelić and Neral 2025a, b).

Potters' raw material selection is shaped by various factors, including the properties and availability of raw materials (Cumberpatch et al. 2001; Martineau et al. 2007; Sillar and Tite 2000), cultural values and community preferences (Arnold et al. 2007; Mahias 1993), mechanical performance (e.g., resistance to thermal shock and overall durability) (Bronitsky and Hamer 1986; Kilikoglou et al. 1998; Tite et al. 2001; Vekinis and Kilikoglou 1998), and regional crafting traditions (Dietler and Herbich 1989). The study of raw material choice in Chinese ceramic production has largely focused on the Neolithic period and especially on Majiayao and Yangshao ceramics (Dammer et al. 2024; Li et al. 2025; Spataro and Hein 2025; Womack et al. 2019). For instance, Dammer et al. (2024) demonstrated through geological surveying and experimental firing combined with petrographic and geochemical analyses on excavated sherds and experimental material that Majiayao potters intentionally selected clays with certain calcium contents and that they added granitic fragments or river sand as temper, demonstrating a nuanced understanding of raw material behaviour and environmental constraints.

Less attention has been given to raw material choice in Late Imperial China ceramic production. Most studies of Late Imperial ceramics have focused on analysing the chemical and mineralogical properties of clay recipes, including several studies on Jingdezhen (He, Zhang, and Zhang SY 2016; Wood 2021a, b; Yap and Hua 1992) and Dehua wares (Li et al. 2011; Wu et al. 2013), none of them considering the underlying decision-making strategies behind material use and processing techniques. For instance, Li (2011) examined porcelain samples from five Dehua kiln sites, and published detailed data on Song, Yuan, and Ming dynasty Dehua wares, concluding that their Fe_2O_3 and K_2O compositions varied. However, the author did not discuss potential reasons for the clay recipe changes. Thus, although compositional analyses are abundant, the decision-making processes of Late Imperial potters—why they chose certain clay sources over others—remain underexplored.

We argue that *zisha* teapots offer a rare and valuable lens through which to examine the complexity of these clay choices in Late Imperial China. First, *zisha* wares were

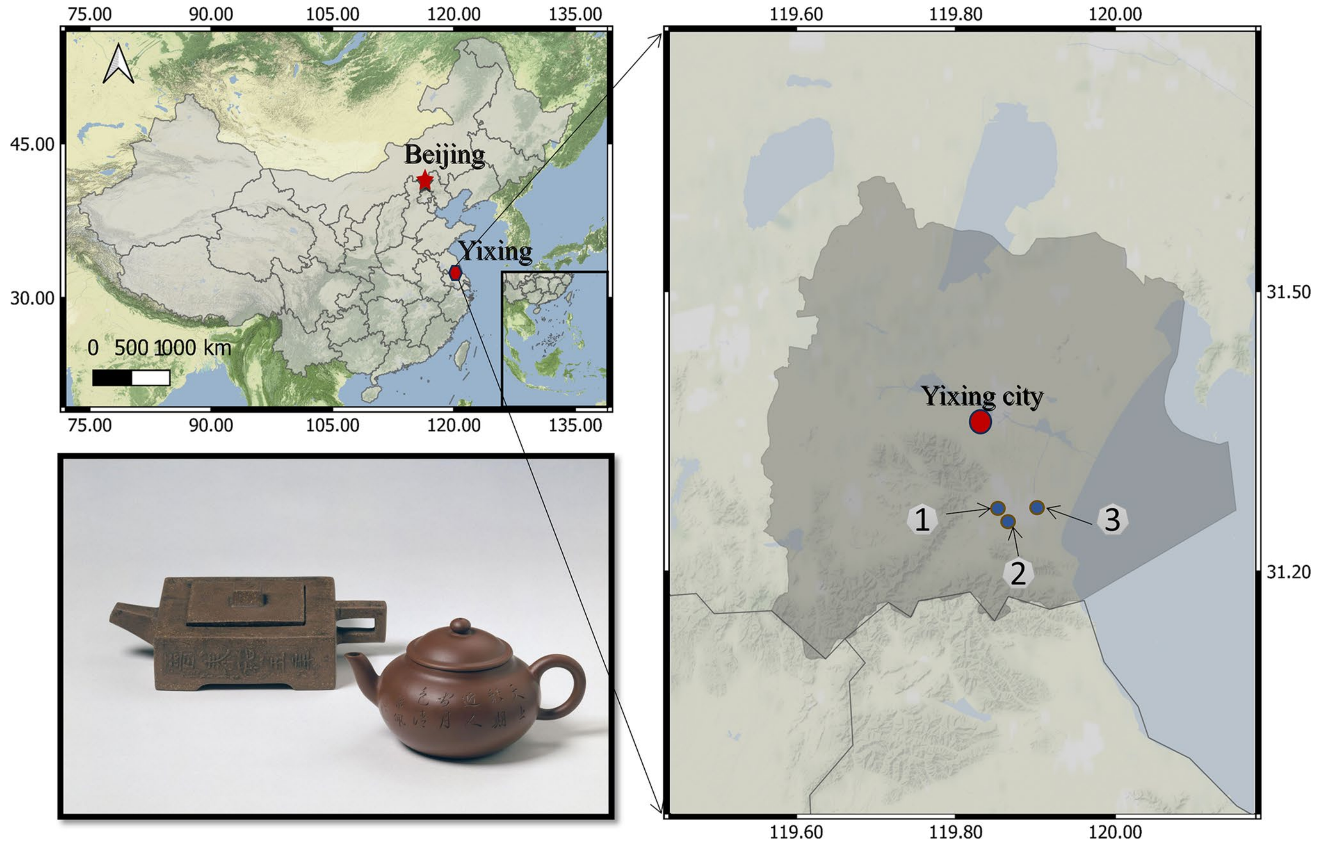

Fig. 1 Top left: the location of Yixing in China. Bottom left: Yixing zisha teapots with Yang Pengnian (楊彭年) inscriptions (a Ming dynasty potter), held by the Victoria & Albert Museum. Right: the location of the Zhaozhuangshan 趙莊山 mine (marked as), the Huanglongshan 黃龍山 mine (marked as), and the Shushan site 蜀山 (marked as) in Yixing

and continue to be produced in Yixing, China (Jiangsusheng 1992; Jiangsusheng dituji bianzuan weiyuanhui 2004) (Fig. 1), one of the main regional ceramic production centres in China during the Ming and Qing dynasties, comparable to Dehua and Shiwan (Kerr and Wood 2004; Liang 1991; Xu XT 2000). These wares, like the ones produced in Jingdezhen and Dehua, were exported to Asian and European countries like Japan, Thailand, Spain, Holland, and England during the seventeenth and eighteenth century (Valfre 2000). Second, in contrast to glazed wares, the clay body is of particular importance in *zisha* wares, as users and consumers can directly observe the colour and texture of the fired clay which is neither fully vitrified nor covered by a glaze that would obscure these properties. Their final appearance and texture are determined largely by the composition and treatment of the clay and the firing conditions (temperature and atmosphere). This unglazed feature makes *zisha* an ideal case study for investigations into how potters negotiated geological settings and procurement, clay processing, and technological and aesthetic preferences. Third, while the material properties of *zisha* ceramics have received some attention, previously the focus has been on the impact of the layered pores of this particular clay on thermal properties and thus ultimately the performance of these vessels in tea-making. Further, it has been argued that the structure of the pore system of *zisha* wares allows for the absorption of tea oils that over time lead to what the users of these wares perceive as improved flavour and an aesthetically pleasing patina. While these are important topics, the view of the users has overshadowed that of the makers. The present study thus focuses on the decisions made by the makers of these wares, providing new and different insight into the phenomenon of *zisha* pottery and the particularities of its raw material. Fourth, clay properties and origins are particularly important in *zisha* making and consumption. *Zisha* teapots are crafted from *zisha* clay, which is procured from different mining locations in Yixing. Certain mining locations, including the Huanglongshan 黄龙山 and Zhaozhuangshan 赵庄山 mines, are known for their "authentic" *zisha* clay (for a detailed discussion of *zisha* clay authenticity, see Hou et al. 2016; Xu XT 2009; Zhao and Lu 2013). The three main clay types are *Zini* (紫泥, "clay with purplish colour"), *Hongni* (红泥, "clay with reddish colour"), and *Lüni* (绿泥, "clay with greenish colour") (Han et al 1981; He 1988; Zhu ZW 2009, p. 38). Local potters call this clay *Wusetu* (五色土, "five-coloured clay"), due to its diverse colours (Wu Q 2014 [1786], p. 871; Zhou GQ 2014a [ca. 1640], p. 514). Ming and Qing dynasty texts document specific clay mining locations and make it clear that connoisseurship of clay sources added cultural significance to these *zisha* clay sources (Cai 2019; Li CP 2006; Yan 2016). As *zisha* ware from Yixing represents a well-known regional ceramic tradition in Late Imperial China, its specific mining locations, diverse clay colours, and rich cultural background present a unique opportunity to investigate diachronic changes in raw material use—an area that remains underexplored in the archaeological literature despite the prominence of *zisha* in Chinese ceramic production.

Previous studies and research gaps

Most existing *zisha* clay studies focus on its chemical and mineralogical composition (Cao et al. 2016; Hou et al. 2016; Jiang X 2011; Wu 1991; Zhu et al. 2019) and its uniqueness (Chen, Lu, and Zhan 2019; Luo JL 2016; Luo and Leng 2017; Ouyang et al. 2011; Wang et al. 2016a, b; Zhang 2020). Change in the clay recipe over time, however, is less frequently discussed. For example, the analysis of *zisha* sherds from the Yangjiaoshan site (a *zisha* kiln site investigated in 1976; see Sect. 3.1) does not include a discussion of *zisha* clay recipe changes (Gu et al. 1984, p. 2); instead, the main focus is on a comparison of the chemical compositions of Yangjiaoshan *zisha* sherds with modern *zisha* pieces.

Regarding colourant oxides and changes to their proportions, multiple studies have concluded that the main colourant oxides in *zisha* are Fe_2O_3, and that their proportion increased from the Late Ming to the Republican period (Wu et al. 2013; Zhang et al. 2016). These studies did not examine other factors resulting in fired piece colour changes, such as titanium oxide content (Wood 2021a, b) or firing atmosphere (Wakamatsu et al. 1985). If the results of these studies—which indicate an increasing proportion of Fe_2O_3 over the examined period—are correct, then, under consistent firing conditions, the differing clay compositions would likely lead to a greater prevalence of reddish hues in later periods compared to earlier ones. However, the *Yangxian shahu tukao* 陽羨砂壺圖考, composed in 1937, lists over 27 types of clay sources used by Yixing potters (Gao 2025, p. 123; Zhang and Li (1998 [1937]). The list includes clays described as *bai* (白; "white") and *lengjin* (冷金; "cold golden") in colour. The literature reflects a diversification in the colour of fired pieces in the early twentieth century and the appearance of lighter colours (presumably clays with a lower iron content). These texts contradict earlier findings that point to an increase in iron content in the later period. This discrepancy between chemical analyses and written sources calls for a re-examination of the colour changes in the *zisha* clay recipe.

The mineralogical properties and microstructures of *zisha* clay and fired pieces have been the subject of heated discussions in previous research, but changes in particle size have so far remained unexplored. This is where the present study sets in. It is commonly believed that *zisha* clay rock consists mainly of quartz, mica, feldspar, hematite, and kaolinite (Gao 2025; Li S 2018; Han et al. 1981; Yang et al. 2021; Zhu et al. 2019). The pore structure and microstructure of fired *zisha* pieces have been the focus of previous studies, and most researchers believe that *zisha*'s layered pores are one of the key factors leading to its superior tea-making qualities (Gao 2025; Han et al. 1981; Jiang X 2011, pp. 29–52). For instance, Jiang (2011) observed the layered pore structure in *zisha* cross-sections, with fewer pores on the exterior surface layers and more pores on the interior layers, concluding that this pore structure provides improved mechanical strength and thermal resistance. For the detailed analysis and responded to the *zisha* fired pieces porosities and its inner correlations to the tea flavours, is detailed discussed in author Gao's thesis (Gao 2025). Here, this research mainly focuses on its mineralogical properties, in order to better understand the colour and gain sizes which will detail address in later sections.

Previous research has also investigated a variety of factors that may affect potters' raw material choices, including local geological conditions (De Bonis et al. 2017, Gliozzo et al 2008), mining locations (Arnold 1991, p. 15; Arnold 2000; Kudelić and Neral 2025a, b), mining and clay deposit sequences (Hein and Kilikoglou 2020), clay-processing techniques (Eramo 2020; Gosselain and Livingstone Smith 2005; Spataro and Hein 2025), and various social and cultural factors (Sillar and Tite 2000). For instance, Eramo (2020) examined common clay-processing techniques (e.g. crushing, pounding, ageing) and their relationship to the properties of the clay sources, such as plasticity and workability. Hein and Kilikoglou (2020) observed that ceramic raw materials are a mixture of sedimentary rocks and that the composition of clay is related to its source rock as well as the weathering sequences of the clay deposit. Although these factors have been covered in some previous research, how sedimentary sequences and clay exploitation sequences relate to clay colours has rarely been discussed. Moreover, the appreciation of clay colour and texture is seldom addressed in studies concerning raw material selection. As an unglazed ware, *zisha* teapots provide an ideal case for examining the valuation of unglazed clay surfaces and their relationship to the choice of raw materials.

The inner complexity of the potters' raw material choice has been highlighted previous, and researchers have explored holistic methods for understanding potters' choices (Gualtieri 2020; Santacreu 2017; Van der Leeuw 1993). Santacreu (2017) considered environmental parameters (e.g. proximity and accessibility), use of energy, and the physical properties of the clay paste as well as its qualities and functional constraints to explain clay recipe changes. Adding to this discussion, this study further explores the correlations between geological conditions, exploitation sequences, clay-processing techniques, and the appreciation of the clay colour and texture. This study also reinforces the complexity of these factors and considers them not in isolation but jointly to investigate their effect on the potters' material choice and the changes to the clay recipe.

From the review of previous literature provided above, three primary research gaps require further examination: 1) whether there are chronological changes in the visual colour of the fired *zisha* pieces from the Shushan site and if so, what the main colourant oxides causing this are, 2) whether paste coarseness (the size and quantity of particles) changed over time and if so how exactly, and 3) what factors may have led the potters in Yixing to alter their clay recipes. To address these research gaps, this study focuses on 187 sherds excavated from the Shushan site (*zisha* kiln sites excavated in 2005–2007; see Sect. 3.1). This larger sample size allows a more comprehensive overview of chronological changes. Colourant oxides are re-examined to address the discrepancies discovered between previous chemical analyses and the written sources. In this analysis of colourant oxides, additional factors, including titanium oxides and firing atmosphere, are taken into consideration. Particle size changes in the *zisha* clay recipe are also examined here for the first time. This study explores the complex negotiations behind the clay recipe and its changes, addressing geological conditions, clay mining sequences, clay processing, and the appreciation of clay, as associated with changes in the *zisha* clay recipe from the Late Ming to the Republican period in terms of its colour and particle size.

The Shushan site, sampling, and methods of analysis

The Shushan site

The Yangjiaoshan and Shushan sites are the only two known *zisha* kiln sites. Dating at the Yangjiaoshan site (31°15′47" N, 119°50′39" E), investigated in 1976, is problematic, as *zisha* sherds were erroneously dated to the Song dynasty (Yixing Taoci Gongsi 1984). The dating is based on limited archaeological evidence and ambiguous literary references to *Zi'ou* 紫甌 ("purple-coloured bowl") in Song dynasty literature. Compared with the Yangjiaoshan site, the Shushan site (31°16′06" N 119°51′48" E), excavated in 2005–2007, provides precise archaeological dating based on stratigraphy (Hang and Ma 2008, Hang 2009). In addition, the Shushan site yielded over 30,000 ceramic sherds, most of which were identified as *zisha* ware (Fig. 2). The large quantities of *zisha* sherds found here which dated from the Late

Fig. 2 *Zisha* sherds from the Shushan site. All photographs taken by Xuyang Gao at Yixing Cultural Relic Committee (YCRC). Figure 2 (a) Ming dynasty teapot spout from the Shushan site. Figure 2 (b) Early Qing dynasty teapot lid. Figure 2 (c) Mid-Qing dynasty teapot body with handle. Figure 2 (d) Late Qing dynasty teapot lid

Ming to the Republican period, enable the reconstruction of changes to the *zisha* clay recipe over time. Therefore, this study is based on data and sherds from the Shushan site.

Between 2019 and 2022, author Gao documented, photographed, and sampled *zisha* sherds from Shushan. The meticulous documentation of the site's archaeological excavation allowed precise dating of artefacts across six distinct zones (A–F), spanning from the Late Ming dynasty to the Republican period. Zone A predominantly contained *zisha* ware dating from the Qianlong (1736–1796) to the Republican period, whereas Zone B held ceramics (including *zisha* teapots and glazed daily-ware sherds) dating to the Late Ming dynasty. Ceramic sherd accumulations in Zones C and D were dated to the Late Qing dynasty, while Zone E encompassed ceramic sherds spanning several centuries, from the Late Ming dynasty to the Republican period. Zone F contained daily-ware sherds, including a reddish-brown bowl and basin that were dated to the Late Qing dynasty.

Sampling

Sampling was conducted in collaboration with officers and archaeologists from the Office of the Yixing Municipal Cultural Relics Management Committee (宜興市文物管理委员会办公室) and Nanjing Museum (南京博物院). Following the sampling strategies described in existing ceramics studies (Orton 2000, pp. 142–147; Richardson and Gajewski 2003), 187 sherds were randomly selected for this study from different excavation layers, based on accessibility and preservation conditions. Sherds with limescale contaminations were avoided because limescale contains high levels of calcium carbonate, resulting in elevated calcium content in these samples.

Methods

To investigate changes in clay colour and coarseness, the sherds' chemical composition, the particle area within the cross-section of scanned sherds, and the average individual particle size were examined. Low-magnification optical quantitative analysis, applied Dino-Lite Digital Microscope with 10 magnifications, was used to characterize optical attributes, including colour and clay texture of the fresh cross-section cut from the samples (Ballirano et al. 2014; De Bonis et al. 2017). Following that analysis, the colour and coarseness (particle size and area in cross-sections of the samples) were assessed using optical and qualitative methods, referencing the *Munsell Soil Color Chart* as well as percentage diagrams for estimating composition by volume (Compton 1985; Munsell Color (Firm) 2018). The resultant data were compared with the findings from scanning electron microscopy combined with energy-dispersive X-ray spectroscopy (SEM–EDS) to identify the main colourant oxides. SEM–EDS analysis provided semi-quantitative chemical data on sherd composition, while SEM backscatter images facilitated particle and microstructure analysis, identifying for instance mineral crystals and pores (Freestone and Middleton 1987; Palanivel and Meyvel 2010; Tite et al. 1982). ImageJ (bundled with 64-bit Java 8) was used to statistically calculate the SEM backscattered imagery sources and quantify particle area and size (Marcomini and Souza 2011; Sheikhattar et al. 2016; Venkataraman et al. 2007). ImageJ analysis of the backscattered images was first tested for accuracy and then used to compute particle area and particle size in the scanned areas. This analysis was conducted at the University of Oxford Research Laboratory for Archaeology and History of Art (RLAHA), with Hitachi TM 4000Plus and Jeol JSM-5910 SEMs.

To investigate the geological and cultural factors that may have influenced Yixing potters' raw material choices, this study analyses geographical information, data collected during a research trip to local mining sites, and texts written during the Ming and Qing dynasties. Geological data gathered around Yixing is used to determine the nature of the geological formations and the distribution of clay deposits. Observations of present-day Yixing potters and their clay-processing practices—such as grinding, sieving, washing—also provides insight into possible changes in the clay recipe over time. In addition, historical texts from the Ming and Qing periods, including the earliest known monograph on *zisha* teapots, *Yangxian minghuxi* (陽羨茗壺系, Renowned Teapots in Yangxian) by Zhou Gaoqi (周高起) (Zhou GQ 2014b [ca. 1640]), were consulted. The aim of examining these written sources was to understand contemporaneous appreciation of *zisha* clay colour and fired texture, which is connected to shifts in clay selection and processing practices.

Chronological changes in *zisha* clay colour

Optical analysis of clay colour

The *zisha* samples were sorted into six colour groups based on visual analysis. A Munsell Soil Chart was used to assign sherds to the different colour categories: red, reddish brown, pale brown, dark reddish brown, dark grey, and reddish grey. The results of the optical quantitative analysis data are provided in Appendix 1. The number of clay colour categories increased from four during the Ming dynasty to five during the Early Qing dynasty and to six during the Mid-Qing and Late Qing/Republican period (Fig. 3). Shannon entropy is a statistical quantifier extensively used for the characterization of complex processes and to measure uncertainty regarding the occurrence of a particular event (Karaca and Moonis 2022; Shannon 1948). In the present study, it was used to measure colour diversity by calculating the unpredictability of the distribution, with higher values indicating more diverse and evenly distributed colours. The Simpson index quantifies diversity by focusing on the probability of two randomly selected items belonging to different categories (Gorelick 2006), with values closer to 1 representing greater diversity. In the ceramic colour analysis of the Shushan site samples, both metrics increase from the Ming dynasty (Shannon = 1.75, Simpson = 0.67) to the Late Qing/Republican period (Shannon = 2.35, Simpson = 0.79), scientifically confirming that ceramic colours became more diverse and evenly distributed over time, shifting from a red-dominated palette to a more balanced one that included a greater variety of colours.

Several factors, including the composition and proportion of colourant oxides in the clay paste, firing atmosphere, calcium content, and firing temperature, influence the optical colour of the fired pieces (De Bonis et al. 2017; Maniatis et al. 1983). As *zisha* wares are commonly fired in natural or oxidizing atmosphere around 1100–1200 degree (Gao 2016), colourant oxides are likely the key factors influencing changes in clay coloration. Therefore, further chemical analysis could help determine whether the observed colour variations in *zisha* clay recipes were caused by changes in the chemical composition of these colourant oxides.

SEM–EDS chemical analysis

SEM–EDS analysis was conducted at a fixed 200 × magnification for 15 s per area on each sample. To ensure sample representation by SEM mapping area, three areas were chosen on each sample, and the average was computed to obtain its EDS profile. One sample from each historical period and colour group was randomly selected for SEM–EDS analysis. The results of the SEM–EDS analysis are presented in Appendix 2.

The SEM chemical-composition data shows an increasing variation in iron composition from the Ming to the Late Qing period (Fig. 4). The iron composition of the Late Qing samples ranged from 2.1 to 7.59%, while that of the Ming dynasty samples exhibited less diversity, ranging from 5.03 to 6.87%. Iron oxides significantly affect the body colour of

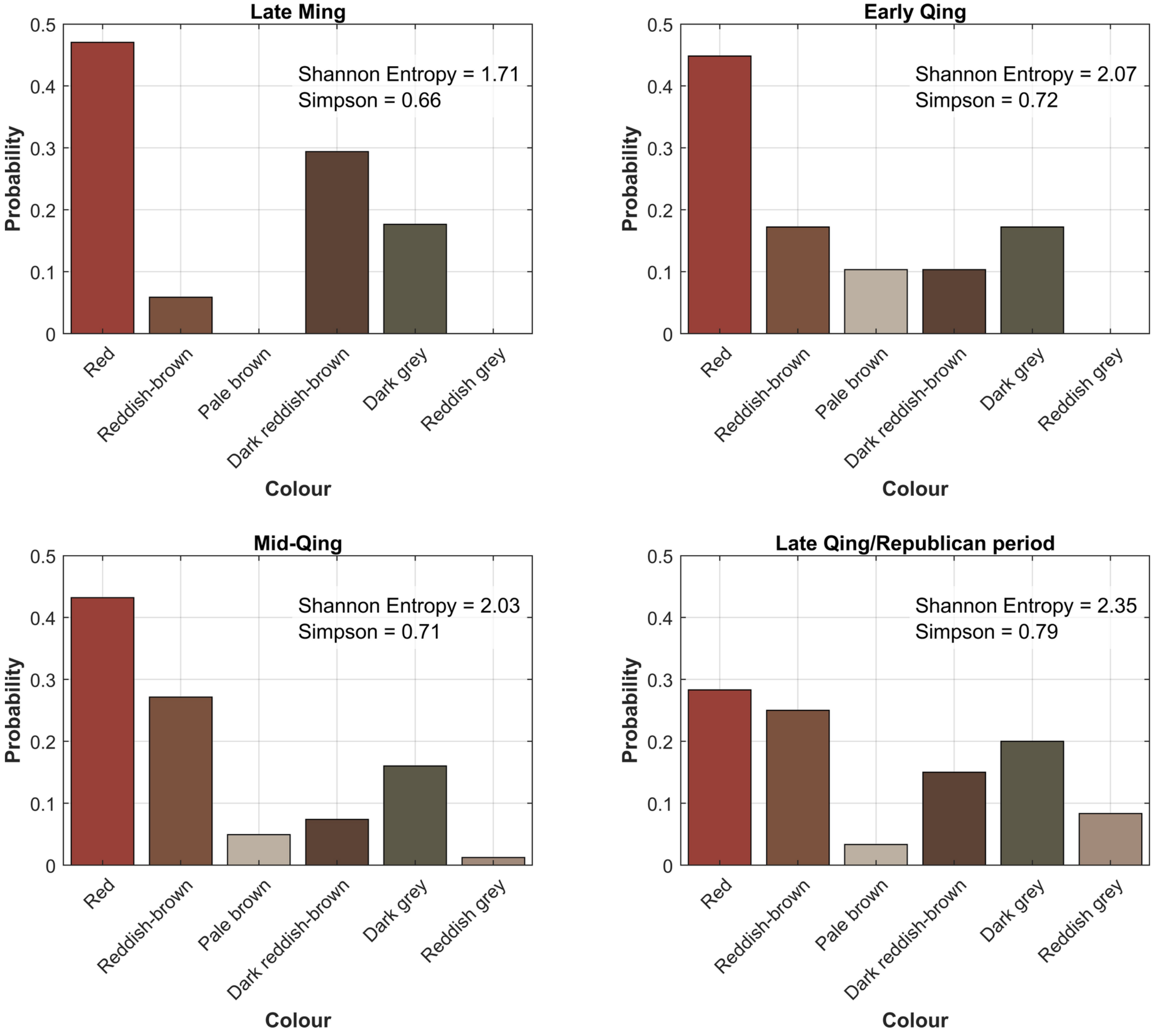

Fig. 3 The colours of the analysed fired pieces from Shushan. Colours marked 1–6 represent red, reddish brown, pale brown, dark reddish brown, dark grey, and reddish grey. Shannon entropy and Simpson index calculations quantify colour diversity

ceramic vessels (De Bonis et al 2017; Hradil et al. 2003). In oxidising firing environments (oxygen-rich environments), iron forms ferric oxide, yielding red tones. In reducing conditions (oxygen-poor environments), iron forms ferrous oxide, resulting in darker grey and black tones (Molera et al. 1998). Under identical firing oxidation–reduction conditions, the broad range of iron oxides observed in the pieces belonging to the Mid- and Late Qing dynasty periods indicates a wider spectrum of body colours among sherds from these periods than those from earlier periods. Thus, the findings corroborate the optical analysis results and suggest that iron composition is the principal contributor to colour diversity in *zisha* clay.

Furthermore, the standard deviation in iron percentages across each period notably increases from the Early Qing to the Mid- and Late Qing dynasty/Republican period (Tab. 1). The materials from the Ming dynasty exhibit a standard deviation similar to that of the Early Qing period, differing by only 0.05. This elevated standard deviation suggests greater internal diversity in iron content in later periods. These findings support the expansion of colour categories identified through optical analysis in Sect. 4.1.

Previous studies have discussed titanium as one of the chemical components affecting Fe–Ti reaction, as titanium oxides can transform iron-blue glazes into green by oxidising certain Fe2+ions to Fe3+when exposed to the high

Fig. 4 Iron percentage of samples from the Ming to Late Qing dynasties

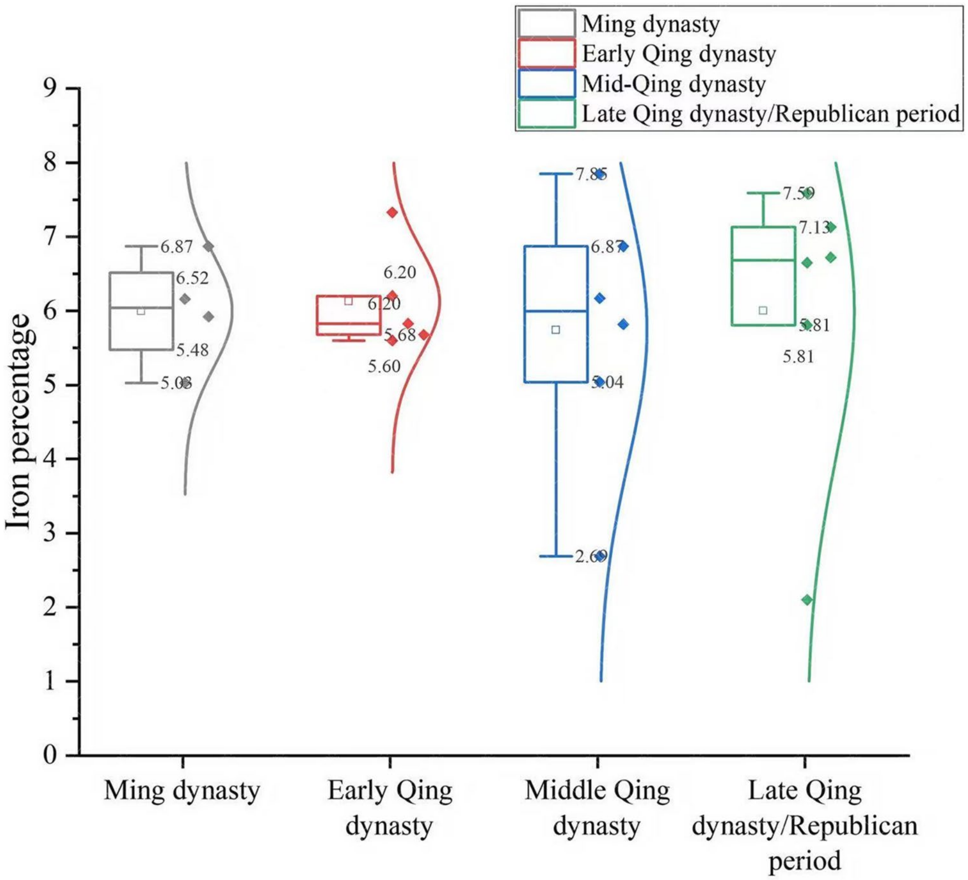

Table 1 Iron composition standard deviation in the examined samples from Shushan

Period	Iron percentage standard deviation	Iron percentage mean value	Colour of samples based on Munsell chart (detailed in Appendix 2)
Ming Dynasty	0.76	6.00	red, reddish-brown, dark reddish brown, dark grey
Early Qing Dynasty	0.71	6.13	red, reddish-brown, pale brown, dark reddish-brown, dark grey
Middle Qing Dynasty	1.77	5.74	red, reddish brown, pale brown, dark reddish-brown, dark grey, reddish grey
Late Qing/ Republican Period	2	6.00	red, reddish brown, pale brown, dark reddish-brown, dark grey, reddish grey

temperatures of a kiln (Wood 2011, 2021a, b). However, according to SEM backscatter imaging, titanium oxides in the *zisha* sherds manifested as particles suspended in the clay paste rather than dissolved in it (Fig. 5). Thus, the particles could not actively interact with iron oxides to alter the colour of *zisha* ware. Additionally, colourant oxides, including calcium oxide, could potentially influence optical colour under similar firing conditions. According to Maniatis et al. (1981), clay with over or equal to 5% is considered as the calcareous clay, and the calcareous will affect the iron oxides during firing. Given that the calcium percentage of the *zisha* sherds was below 1%, no significant contribution from calcium oxidation to the *zisha* sherd colour took place. Cr and Mn oxides, which are recognized as colorant oxides in ceramic studies, were not detected in the SEM–EDS analysis, likely due to their absence or concentrations below the instrument's detection limit.

SEM backscatter analysis showed that the iron oxides in the *zisha* clay paste come from iron oxide minerals (e.g. haematite, goethite) and iron-rich rock fragments. For example, sample 05BG1(4)_48 contained a sub-rounded rock fragment with a high concentration of iron, (Fig. 6) suggesting that in addition to pure minerals, iron-rich rock fragments also contributed significantly to the iron variability in the clay, potentially affecting its coloration.

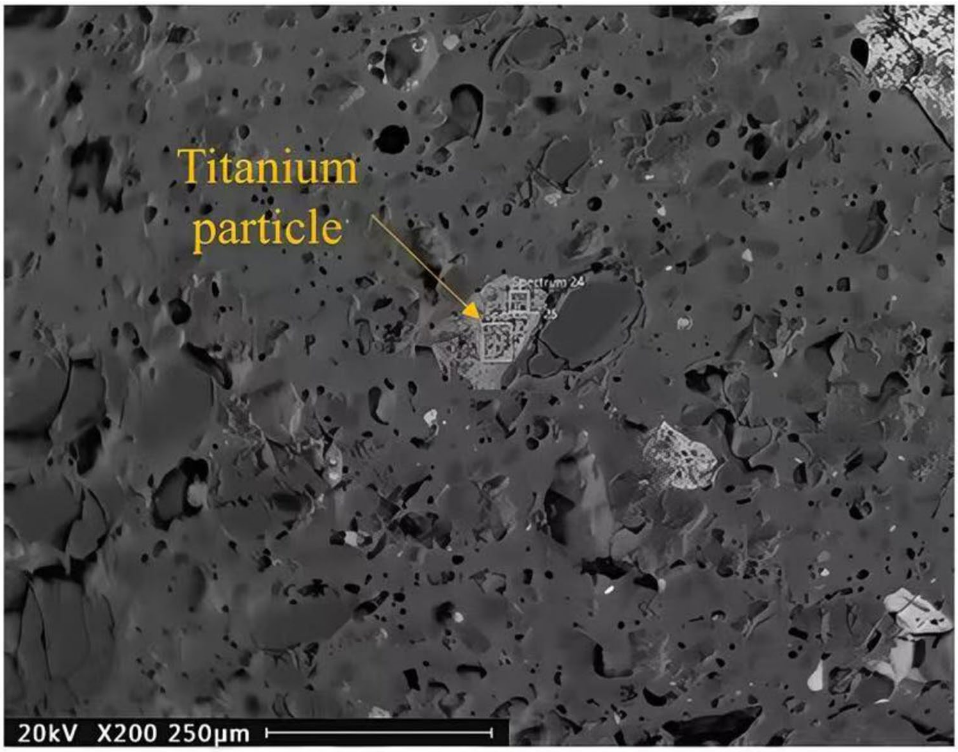

Fig. 5 Titanium particle in an SEM backscatter image of sample 05BG1(4)_80

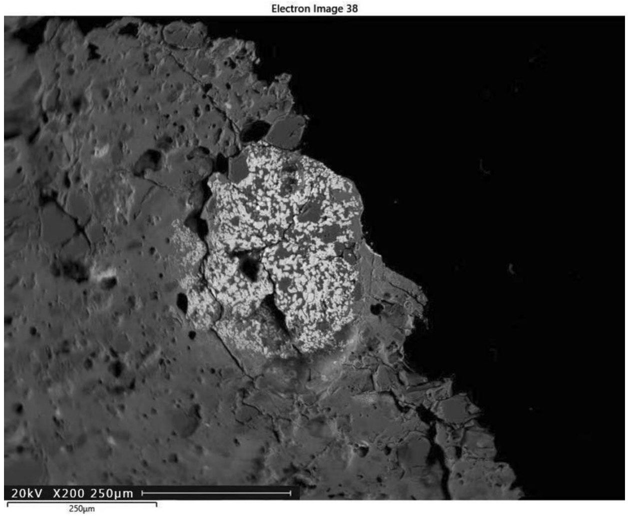

Fig. 6 Iron-rich rock fragments in SEM–EDS iron distribution mapping, from sample 05BG1(4)_48. The lighter grey colour suggests concentrated iron, demonstrating that the rock fragment has a high iron content

Chronological changes in *zisha* clay particle size

Optical analysis of sample coarseness

Optical quantitative analysis was conducted on cross-sections of the *zisha* sherds. The resultant data are presented in Appendix 1. Using percentage diagrams to estimate composition by volume, the coarseness of the cross-sections was categorized into five groups, ranging from very fine (group 1) to coarse (group 5). In contrast with the Early Qing–Late Qing/Republican sherds, a larger percentage of the Ming dynasty *zisha* sherds belong to the coarse group (Fig. 7).

The mean coarseness is calculated as the arithmetic average of the coarseness values of all samples within each time period. A pronounced decreasing trend can be observed from the Ming dynasty (approximately 2.64) to the Mid-Qing period (approximately 1.68), followed by a slight increase during the Late Qing/Republican period (approximately 1.88) (Fig. 8). The superimposed linear regression ($y = -0.258x + 2.69$) indicates an overall declining trajectory, suggesting a general improvement in surface smoothness across these periods.

Furthermore, SEM spectrum mapping using a HITACHI TM4000II at a fixed 200 × magnification with a count ranging between 16,000 and 25,000 cps was performed on 18 randomly chosen samples from three SEM coarseness categories (fine, medium, and coarse clay; see Appendices 1 and 3). The obtained mapping images were processed with ImageJ.

ImageJ calculation of particle size

ImageJ is widely used for processing images and converting them into quantifiable data (Collins 2007; Dal Sasso

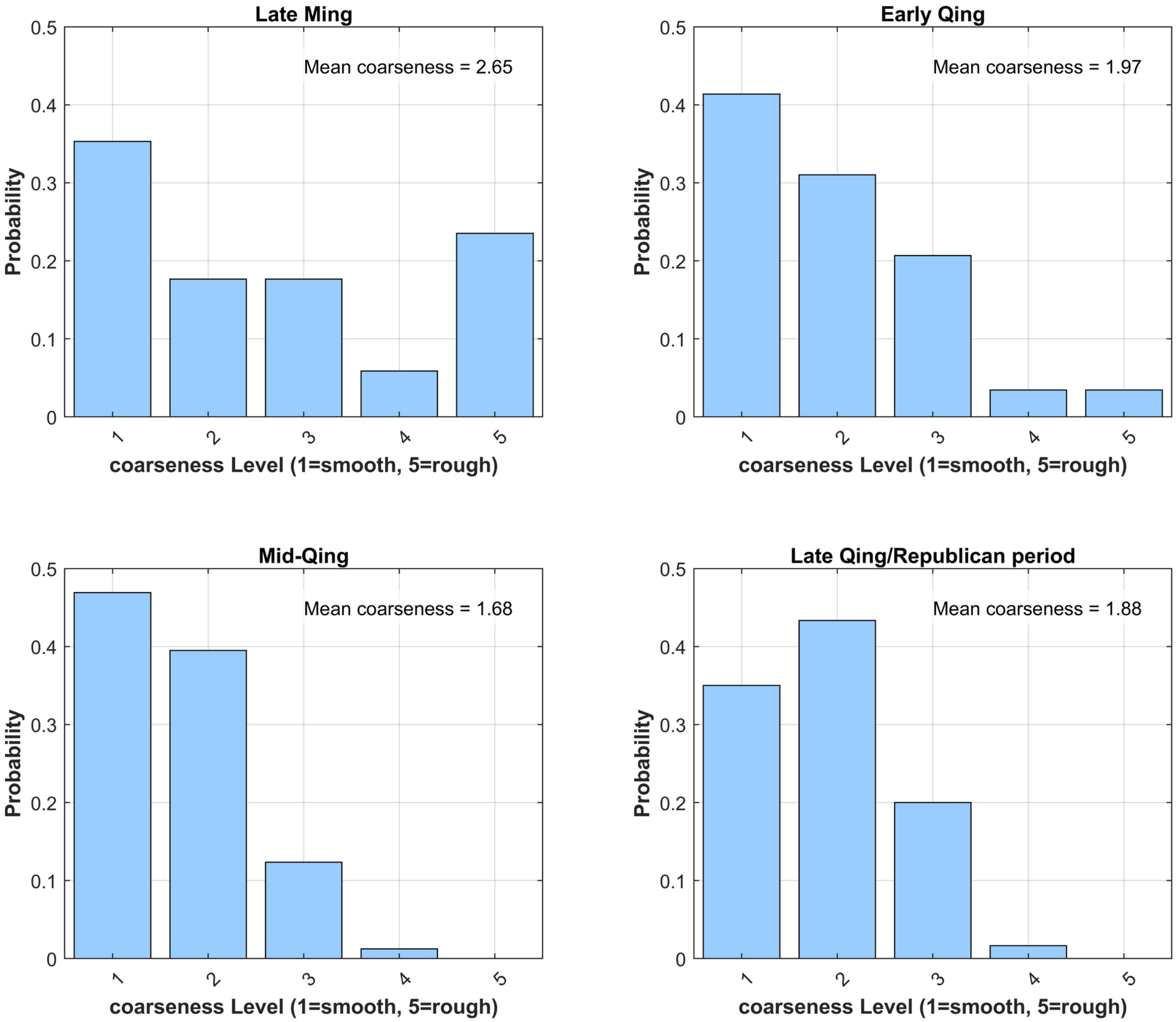

Fig. 7 Coarseness of fired pieces from Shushan. Coarseness was defined by optical analysis and categories are labelled 1 to 5, representing fine, fine-to-medium, medium, medium-to-coarse, and coarse

et al. 2014), for instance to determine particle shapes and sizes. Igathinathane and colleagues used ImageJ to calculate the dimensions of particles of various geometric shapes and concluded that particle shape does not affect dimension calculation in ImageJ (Igathinathane et al. 2008). Lormand and colleagues used ImageJ to analyse backscattered electron images of crystals in volcanic rock, providing a case study for the application of ImageJ in rock crystal analysis (Lormand et al. 2018). ImageJ has also been used in petrography; Berrezueta and colleagues used it to calculate pore size in microscopic images (Berrezueta et al. 2019). Based on these previous successful studies, this study uses ImageJ to calculate particle size in backscattered SEM images.

Beyond following the previous research, the accuracy of ImageJ in calculating particle size was validated in the context of the present study. To do this, two black squares, each consisting of 16 units (16 + 16 = 32 units), were generated on a white canvas measuring 324 grid units (18 × 18 units). Mathematically, these black squares encompass 9.87% of the white canvas. The ImageJ threshold function (which converts a grayscale image into a binary, black-and-white image) and area calculation function determined that the black area occupied 10% of the total area, reflecting a 0.13% error margin compared to the mathematical calculations. Additionally, two black circles on an identical white canvas were tested, revealing a 0.02% error margin between the areas determined via ImageJ and mathematical calculations. These results confirm that ImageJ's area calculation function provides reliable measurements and can thus accurately reflect particle areas in image analysis. A limitation

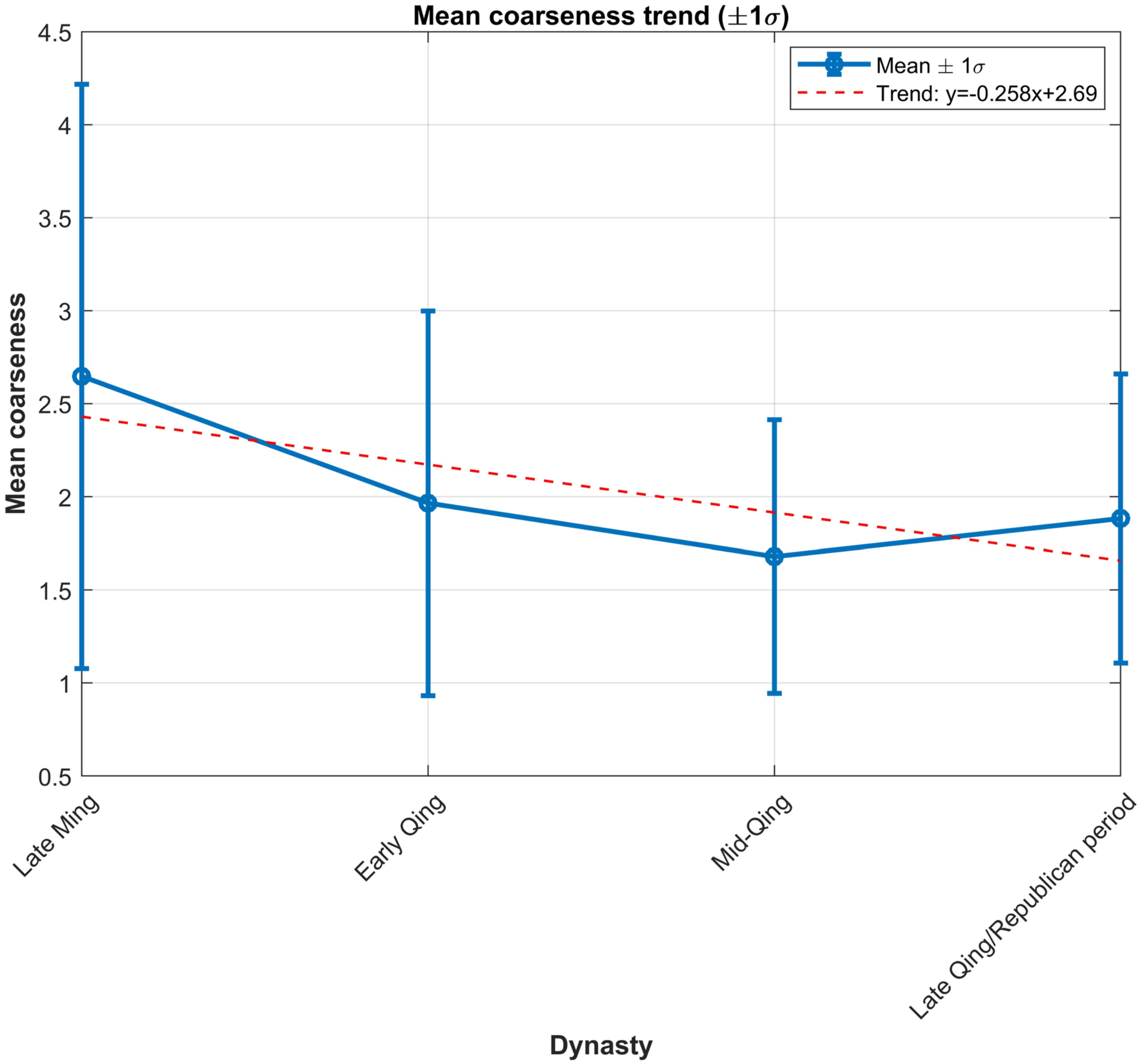

Fig. 8 Mean coarseness values of fired pieces from the Shushan site dating from the Late Ming to the Late Qing/Republican period

of the use of Image J to calculate particle area is that the particle area calculation in this study only accounts for particles that exceed 10 pixels in fineness on SEM backscatter images, which corresponds to particles larger than 10 µm in diameter. This was taken into account when evaluating the data.

Changes in clay particle size over time

Calculation of quartz particle size

The size of quartz particles in *zisha* clay serves as an ideal indicator for assessing clay paste coarseness. The primary reason for this is that quartz can be readily distinguished from other mineral crystals in SEM spectrum mapping due to its consistently high silicon content. Quartz is prominent component of *zisha* clay paste in the examined periods (Fig. 9). Therefore, although several other particles, including clay clumps, feldspar crystals, also contribute to the clay paste coarseness, quartz is analysed in this study as a representative particle. In the analysis below, the word “particle” in later discussion refers to quartz particles.

On the SEM, three silicon spectrum mapping images were captured from each sample and subjected to thresholding, binary conversion, and particle analysis processes in ImageJ to distinctly outline individual particles (Figs.9) and calculate the area of all outlined particles or individual outlined particles.

The total area of quartz particles in examined thin section reflects the size of all quartz particles and also provides insights into the coarseness of the sample. A comparison of the area of all outlined particles in samples from the Late Ming to the Late Qing/Republican period shows a decreasing trend in particle area size, ranging from 53,508–63,549

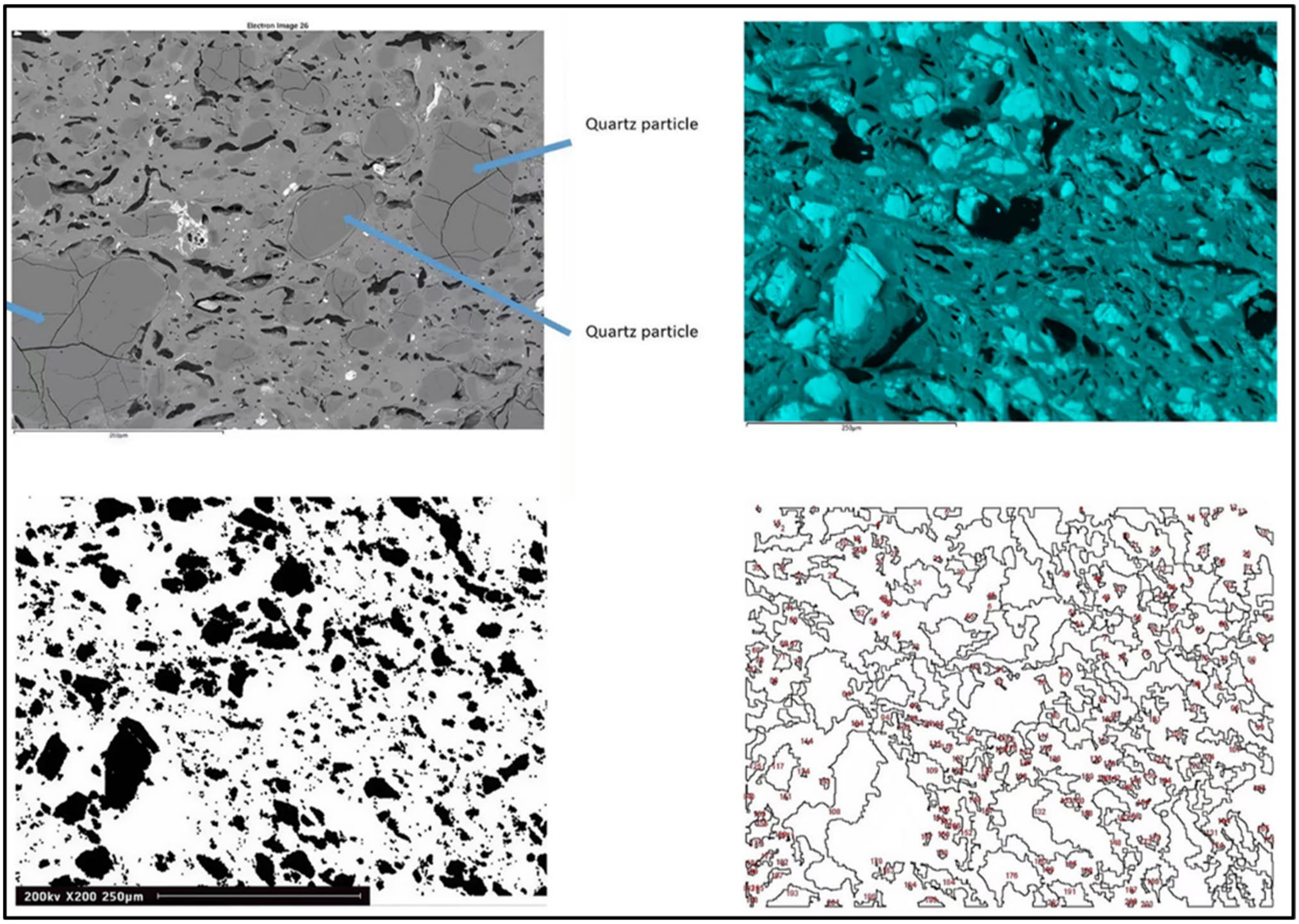

Fig. 9 Top left: Quartz particles in a fired *zisha* sherd. Sample 05BG1(4)_48; Top right: SEM silicon map of sample 06ET1K2(14)_24. The bright area shows the silicon distribution; Bottom left: SEM silicon map of sample 06ET1K2(14)_24 after application of the threshold function. The black area represents the silicon-rich area; Bottom right: SEM silicon map of sample 06ET1K2(14)_24 after application of the threshold function, binary (converts to black and white images based on the current threshold settings), and particle analysis, showing the outlines of particles and the number of counted particles

μm^2 in the Ming dynasty to 29,802–34,060 μm^2 in the Late Qing/Republican period (Fig. 10; Appendix 4). These findings indicate that fewer quartz particles or smaller quartz particles appeared in the later samples. *Zisha* potters in later periods clearly opted for finer clay than their predecessors.

To determine whether the decrease in quartz particle area was caused by a reduction in individual particle size or a reduction in particle quantity, the size of the average quartz particle and the standard deviation of particles in each sample were calculated in ImageJ. According to the ImageJ calculations, the average individual particle size during the Ming dynasty was within the range of 130–183 μm^2, while particles in pieces from the Mid-Qing and Late Qing/Republican periods measured between 77–123 μm^2 and 79–110 μm^2, respectively (Appendix 5; Fig. 11). Notably, Early Qing dynasty *zisha* clay exhibited the largest individual particle size, ranging from 205 to 260 μm^2. As shown in the figure, the Early Qing dynasty has a distinctive high average quartz particle size, which may be caused by dynastic transitions and sociopolitical unrest that may have influenced ceramic production practices. Limitations in particle measurements may also affect the particle counting results by counting the closely adjacent or touching grains as single particles, potentially inflating the size estimates. Therefore, further research employing refined image analysis techniques is needed to substantiate any historical correlations.

An examination of the standard deviation confirmed a reduction in size variation among quartz particles over time. Specifically, the range diminished from 630–1,665 μm^2 during the Ming dynasty, to 226–512 μm^2 during the Late Qing period (Appendix 6; Fig. 12). These findings suggest that the *zisha* paste used in the earlier periods was poorly sorted, with particles displaying substantial size disparities, while the paste used in later periods shows evidence of improved sorting, as the quartz particles had a more consistent appearance and were relatively homogeneous in size. In previous research on ceramic production, homogeneous

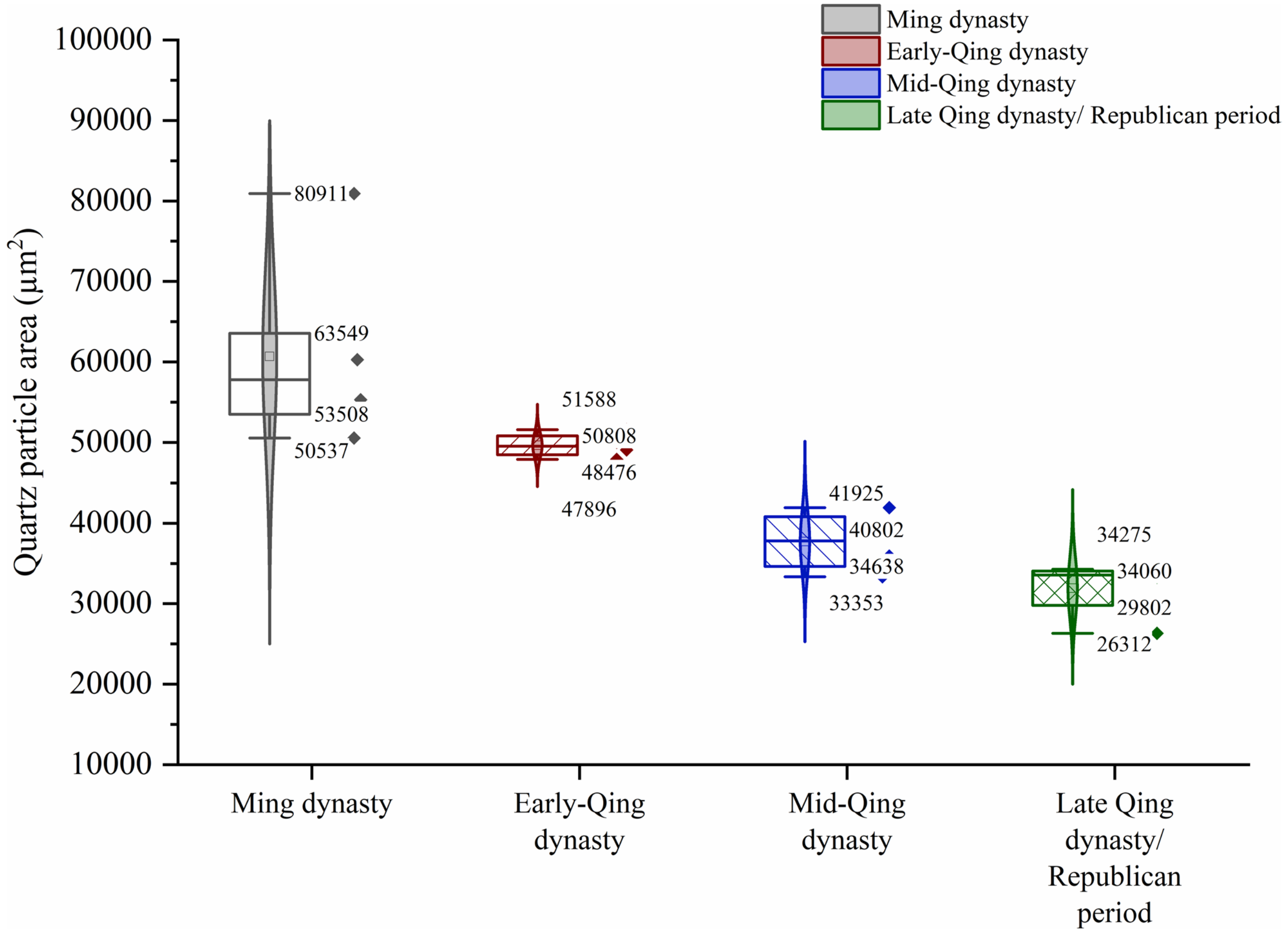

Fig. 10 Quartz particle area of ceramic pieces dating from the Ming to the Late Qing/Republican period

size of particles in clay pastes has generally been attributed to the use of certain clay-processing techniques (Eramo 2020; Gosselain & Livingstone Smith 2005). For instance, crushing clay rock and sieving clay paste breaks down or removes larger mineral particles, resulting in a more homogeneous particle sizes. *Zisha* clay-processing techniques and their relationship to the homogeneity of the clay paste are discussed in Sect. 6.3.

Factors that may have influenced potters' raw material choices

The following discussion of *zisha* teapot recipe changes focuses on the complexity of raw material choices and discuss the correlations between geological formations, clay exploration sequences, and clay-processing techniques, as well as cultural factors that may have led to the clay recipe changes—the growing diversity of colour, decrease in the number of quartz particles, and increasing homogeneity in particle size.

Geological formation and clay mining sequence

Geologically, *zisha* clay forms through sedimentary processes involving weathering, transportation, and deposition of silicate materials (Guggenheim and Martin 1995, p. 255; Rice 2015, p. 202). Like other sedimentary rocks, it develops when weathered fragments are carried by wind, rivers, or ocean currents to deposition sites, creating layers with varying grain sizes and textures (Allen 1970; Tucker 2001, p. 1). The characteristic reddish colouration of *zisha* clay stems primarily from the presence of iron oxide minerals—hematite, goethite, and limonite—whose different oxidation states produce colours ranging from black to red (McBride 1974; Rothwell 1989, p. 139). During formation, amorphous ferric hydroxide appears as the main weathering product and may recrystallize into goethite, yielding yellow to orange hues (Schmalz 1968, p. 277). Hematite's red colour can be modified through interactions with ferric oxyhydroxide or goethite.

In 2005 and 2010, Gao conducted field studies in Yixing, which confirmed the sedimentary deposit of the clay

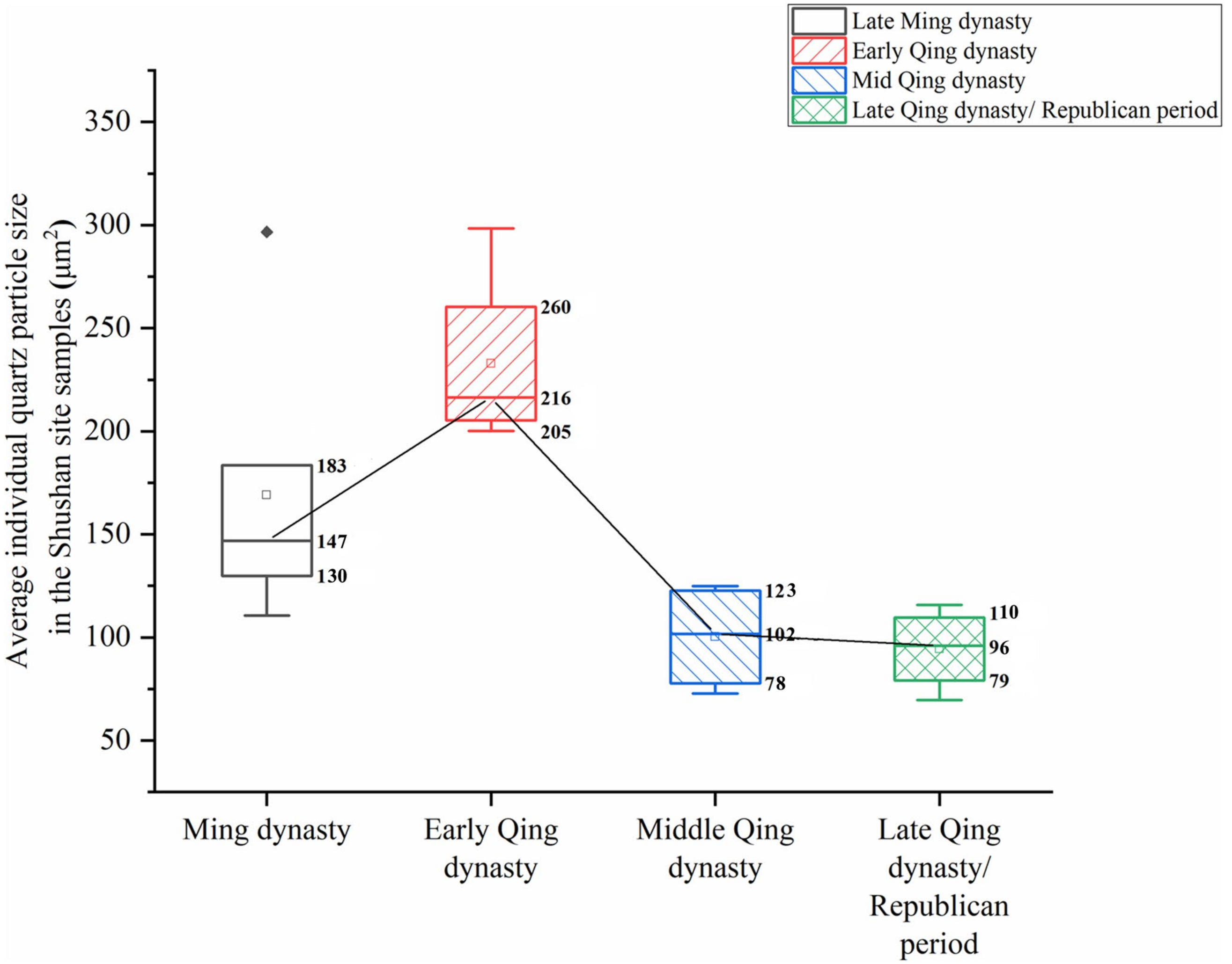

Fig. 11 Average quartz particle size in samples from the Ming to the Late Qing/Republican periods

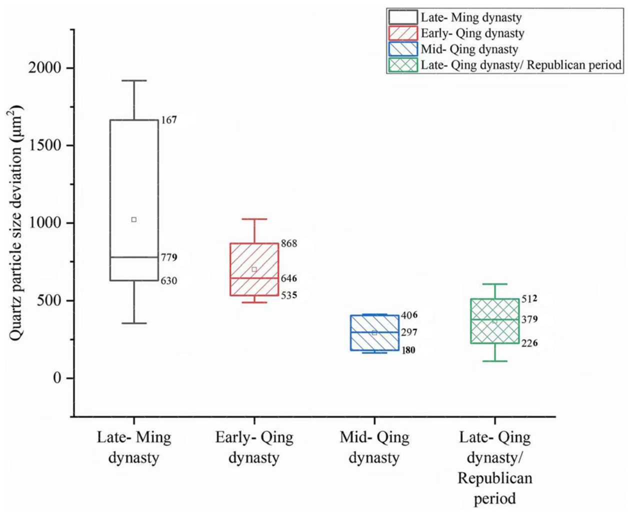

Fig. 12 Standard deviation of quartz particle size in samples from the Ming to the Late Qing periods

sources in Yixing. At the open-air clay mining site in Hufu town[1] (Fig. 13), southwest of Yixing, a clear cross-section from surface level to deeper clay bedding formation could be observed. Five clay layers with distinguishable colours can be identified in the stratigraphic cross-section of the mine (Fig. 14). Visual examination of the geological bedding revealed distinct belt-like sedimentary structures with diverse colour gradations. From top to bottom, the layers display pale brown, brownish yellow, brown, yellow, and greyish brown hues. This variation in colour within a single clay mine may be caused by differences in iron oxides between layers (e.g. variations in the presence and distribution of haematite, goethite, and limonite). The presence of hematite results in black to red colours (Torrent &

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[1] The Hufu mine was the only mining site examined in this study, as parts of the Huanglong mining area were flooded at the time and closed to public access (Gao 2016; Zhao 2010).

Fig. 13 Location of the Hufu mine in the southwestern mountains of Yixing, situated west of Dingshu village and the Huanglong mine

Schwertmann 1987). Both amorphous ferric hydroxide and goethite produce a colour range that includes yellow, yellowish brown and orange (Schwertmann 1993). This variation of oxides is one of the key factors contributing to the colour differences observed in the fired clay pieces from the Shushan site.

Due to the clay's layered sedimentary structure, with different iron compositions in each layer, access to clay containing various iron oxides depended heavily on the sequence in which Yixing potters or clay dealers extracted the clay deposit. In earlier periods, they extracted clay from surface layers only, as the deeper strata did not become accessible until later periods (see Zhao 2010). Ming dynasty potters accessed the clay in the uppermost quarry layers while subsequent potters and clay merchants gained access to both surface layers and deeper deposits (Fig. 14). As mining activities reached deeper levels, more sedimentary layers became accessible to later potters and clay dealers. Craftspeople in later periods, who had access to a greater number of geological strata, naturally had a wider range of clay colours available to them. The clay exploration sequences could thus partly explain the increase in clay colour diversity. Therefore, the increasing diversity in clay colour and the expanding range of iron oxides in the *zisha* clay recipe (as concluded in Sect. 3) can be attributed to the layered sedimentary geological structure of the deposit, as well as clay mining sequences.

Clay processing and selection

The physical properties of a clay paste correlate with raw material processing techniques and selection criteria (Arnold 1985, p. 20; Eramo 2020; Gosselain 1994, p. 102; Velde & Druc 1999). During field research in 2016, author Gao conducted systematic observations of the clay classification and processing methods used by contemporary potters and clay dealers (Gao 2016). *Zisha* clay dealers evaluate the colour and texture of the clay rocks and categorize raw clay materials with the same chromatic gradation and texture into a group destined for pottery making. During

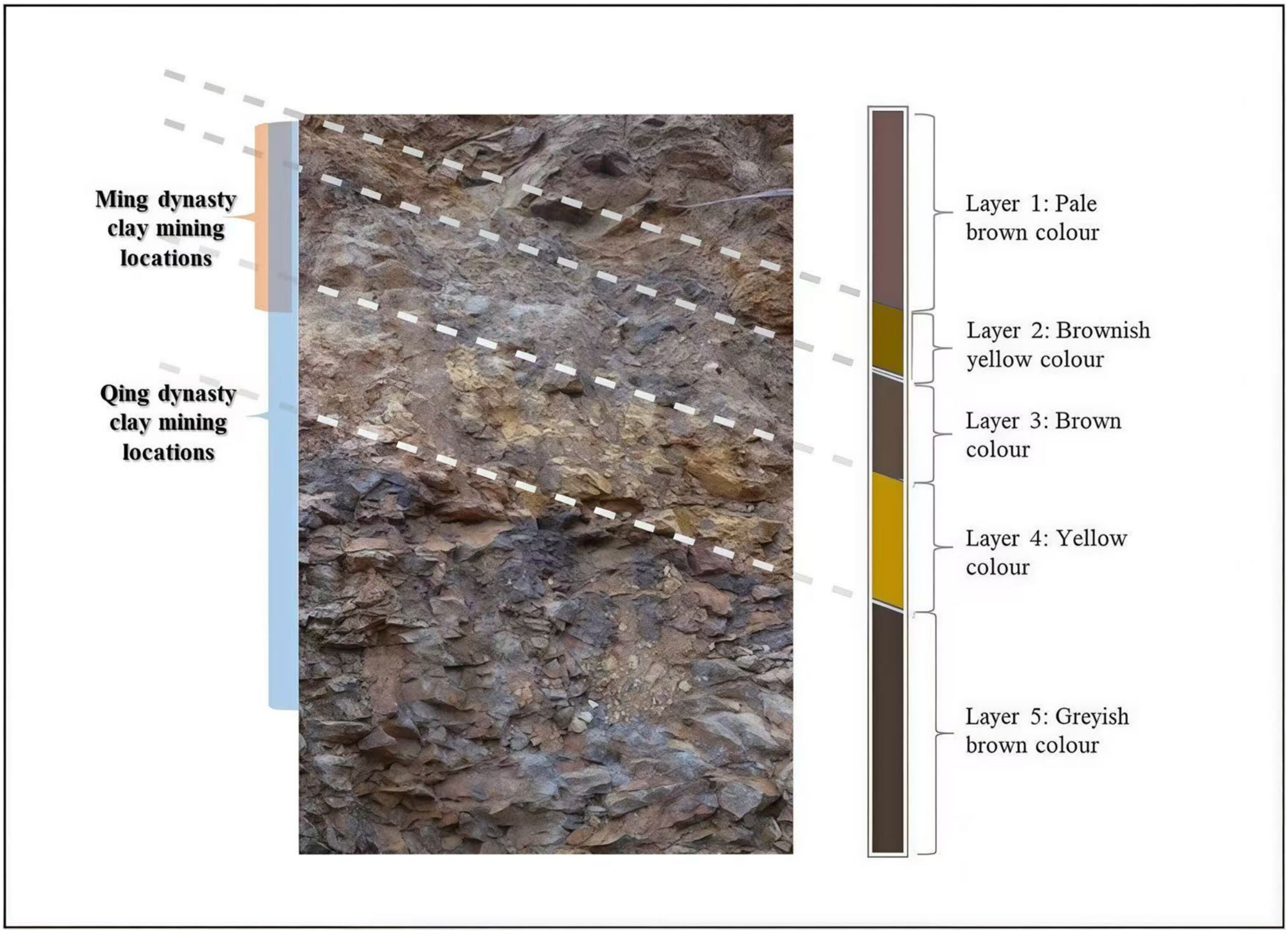

Fig. 14 The working face of a mining area at Hufu mine, showing all clay layers

the clay weathering process, the clay dealers' classification is predominantly based on two parameters: chromatic gradation and textural properties. The textural assessment, locally termed *cuci* (粗次, grade of coarseness), is based on the macroscopically observable granularity of the clay rock's cross-sectional surface (Gao 2016, p. 18). Therefore, the colour of the clay used for pottery making is ultimately determined by the clay dealers' classification, probably combined with their own experience with one or other of these types of clays and/or what they were told by their own teachers. These details of knowledge building and transfer would need to be the subject of further research.

The 2016 field research also made clear that traditional *zisha* clay-processing includes grinding, sieving and levigation. After grinding, a preliminary sieving process takes place, and a stone mill is used for clay-grinding. The weathered clay powder is placed in water, stirred with bamboo sticks, and washed to remove impurities and rock fragments (Gao 2016, p. 18–20). Potters then pour out the water on the upper level and add more clear water to wash the clay, repeating the previous steps. The clay is aged inside vessels, submerged in water for years or even decades, before it is dehydrated to create a clay paste ready for pottery making.

Ethnographic observations of contemporary Yixing potters and clay dealers indicate that the clay is typically processed without the tempers (Gao 2016). *Zisha* clay rock naturally contains a high proportion of quartz. Thus, in general, there is no need to add additional temper. For instance, Han et al (1981), examined *Zini* (紫泥, purple clay, a type of *zisha*) and found that the quartz content in the clay rock reached approximately 50%. Similarly, another study, Yang (2021) reported that the quartz content in *Dicaoqing* (底槽青, type of *zisha* clays) was 49.1 wt%. Given by the contemporary *zisha* teapots potters, sands are occasionally added to the clay paste not for enhancing the workability, but for aesthetic reasons—the contrasting color of the sand particles enriched the visual texture of the otherwise uniform clay surface. However, none of the samples in 187 sample set found sands in contrast colour. Therefore, tempers are not considered here to explaining the declining of the *zisha* clay raw material particle size. Techniques involving grinding, sieving, and levigation are used to alter dry consolidated clay rocks into pastes ready for use, a process that refines the clay by removing or crushing larger particles and homogenizing the clay paste (Eramo 2020; Quinn 2013, p. 154–155; Roux 2016). Therefore, the decreasing average particle size and increasing homogeneity of the clay paste reflect potters' deliberate efforts to refine and perfect their clay-processing techniques.

Appreciation of clay colours and textures

Zisha clay colours and textures are frequently mentioned in Ming and Qing dynasty texts such as *Jingxi shu* (荊溪疏, Annotated Commentary on Jingxi), *Yangxian minghuxi* (阳羡名壶系, Renowned Teapots in Yangxian), *Minghu tulu* (茗壶图录, Teapot Catalogue), *Yangxian mingtaolu* (阳羡名陶录, A Record of Renowned Teapots in Yangxian), and *Yixing taoqi gaiyao* (宜興陶器概要, An Overview of Yixing Pottery) (Ao 1998 [1874]; Siku Junhuishu 2000 [unknown];Wu Q 2014 [1786]; Zhou GQ 2014a [ca.1640]; Zhou and Zhou 1932).

To better understand the literati appreciation criteria of *zisha* teapots, the *Yangxian minghuxi*, a text known as the first *zisha* monograph, is examined here in some detail (Chen 2016, 2018; Li S 2008). This text was written by Zhou Gaoqi (周高起) in the late seventeenth century. Although he did not serve as an official at court, Zhou was a literatus and diligent writer. In addition to the *Yangxian minghuxi*, he also wrote texts for the local gazetteer *Jiangyin Xianzhi* (江阴县志, Gazetteer of Jiangyin County) (Feng, Xu, and Zhou 2003 [ca. 1640]) as well as a book on tea plants titled *Dongshan jiechaxi* (洞山岕茶系, Jie tea in Dongshan) (Zhou GQ 2014b [ca.1639]). Him writing the texts *Yangxian minghuxi* and *Dongshan jiechaxi* makes it clear that Zhou was an enthusiastic tea connoisseur who appreciated *zisha* teapot artisanship. His knowledge of *zisha* teapots was influenced by Wu Honghua 吳洪化, a *zisha* teapot collector from a prominent Yixing family. The details of Zhou's connection with Wu Honghua are analysed in an article by Gao and Hein (2024).

The *Yangxian minghuxi* focuses on documenting renowned potters, clay sources, mining locations, and the artistic styles and designs of teapots. The clay used to make *zisha* wares, and particularly its colour, is described in detail in the text, as shown in the passage quoted below.

> Original text: 嫩泥出趙莊山, 以和一切色, 上乃黏脂可築蓋陶壺之丞弼也。 石黃泥出趙莊山，即未觸風日之石骨也。陶之乃變朱 (硃) 砂色。天青泥出蠡墅。陶之變黯肝色。又其夾支, 有梨皮泥。陶現梨凍色。淡紅泥，陶現鬆花色。淺黃泥，陶現豆碧綠色蜜。泥陶現輕赭色。梨皮和白砂, 陶現淡墨綠色。山靈腠絡，陶冶變化，尚露種種光怪雲。老泥出團山。陶則白砂星星。按若珠琲。以天青石黃和之成淺深古色。白泥出大潮山, 陶缾盎缸用之。
>
> (Zhou GQ 2014a [ca.1640], p. 514)
>
> Translation: Nen (嫩, "soft")-textured clay is extracted from the Zhaozhuang Mountain and can be mixed with *zisha* of different colours to produce various categories of ceramic products from teapots to food containers. *Shihuang* (石黃, "rocky yellow") clay is found in the Zhaozhuang mountains, and is an unweathered clay rock. Fired pots made with shihuang clay are *zhusha* (硃砂, "cinnabar") coloured. *Tianqing* (天青, "bluish green") clay is sourced from the Lishu 蠡墅 area. Fired pots made with *tianqing* clay are *angan* (黯, "dark liver") coloured. Different types of *zisha* clay are collected from the *tianqing* clay layer(s), such as *lipi* (梨皮, "pear peel")-coloured clay. Fired pieces made from *lipi* clay are *dongli* (凍梨, "chilled pear peel") coloured, while those made from *danhong* (淡紅, "light red") clay are *songhua* (松花, "pine tree flower") coloured. Fired pieces made from *qianhuang* (淺黃, "light yellow")-coloured clay result in a *doubi* (豆碧, "bean green") colour, while unfired pieces are *qingzhe* (輕赭, "light reddish brown") coloured. When *lipi* clay is mixed with *baisha* (白砂, "white sand") clay, a greyish-green-coloured clay is produced. These strange phenomena of clays and changes in pots' colours are attributed to the spirits in the mountains. *Lao* (老, "aged")-textured clay is procured from the Tuanshan 團山 mine. The pots have star-like white spots. The surfaces of the pots resemble pearls. When *tianqing* and *shihuang* clays are mixed, two kinds of clays of a dark brown colour are produced. *bai* (白, "white") clay is excavated from Dachaoshan 大潮山 and is used to produce vessels, bowls, and jars.

This section underscores the importance of mining locations in the classification of *zisha* clay. It reveals that clay types were named according to both their chromatic or textural properties after firing. Sites such as Zhaozhuang Mountain (赵庄山), Lishu (蠡墅), Tuanshan (团山), and Dachaoshan (大潮山) are associated with at least eight distinct clay types—*nen* (嫩, "soft"), *shihuang* (石黃, "rocky yellow"), *tianqing* (天青, "bluish green"), *lipi* (梨皮, "pear peel"), *danhong* (淡紅, "light red"), *danhuang* (淡紅, "light red"), *lao* (老, "aged"), and *bai* (白, "white")—each bearing distinct colours and textures. For example, *shihuang* clay produces a vivid cinnabar red when fired, while *tianqing* yields a dark liver hue; *lipi* and *danhong* result in surface colours likened to chilled pear skin and pine pollen, respectively (Zhou GQ 2014a [ca. 1640], p. 514).

In the section titled *Mingjia* (名家, “renowned potters”), Zhou Gaoqi offers a critical appraisal of the teapots produced by Xu Youquan (徐友泉), framing the diversity of clay colours as both a marker of technical expertise and a vehicle for artistic expression. Zhou describes Xu as a distinguished artisan who deliberately selected clay bodies of varied hues to enhance the visual and material qualities of his ceramic works, as evidenced by the quoted text below.

> Original text: 泥色有海棠红、朱砂紫、定窑白、冷金黄、淡墨、沉香、水碧、榴皮、葵黄、闪色、梨皮诸名。种种变异, 妙出心裁。 (Zhou GQ 2014a [ca.1640], p. 513)
>
> Translation: The clay colours include crab apple red, cinnabar purple, ding-ware white, pale golden yellow, pale ink, agarwood, greenish water, pomegranate skin, sunflower yellow, *shan* (a mixture of contrasting colour tones), pear peel, etc. The colour changes form an exceptional and ingenious design.

The colours employed by Xu include *haitanghong* (海棠红, “crab apple red”), *zhushazi* (朱砂紫, “cinnabar purple”), *dingyaobai* (定窑白, “Ding-ware white”), *lengjinhuang* (冷金黄, “pale golden yellow”), *danmo* (淡墨, “pale ink”), *chenxiang* (沉香, “agarwood”), *shuibi* (水碧, “greenish water”), *liupi* (榴皮, “pomegranate skin”), *kuihuang* (葵黄, “sunflower yellow”), *shanse* (闪色, referring to variegated or iridescent colouration), and *lipi* (梨皮, “pear peel”). This wide chromatic range—encompassing shades of red, purple, yellow, and white—demonstrates an advanced level of material literacy and aesthetic refinement. Zhou’s use of the phrase *miaochu xincai* (妙出心裁), which connotes ingenuity and originality, further underscores the degree to which these colour variations were not incidental but rather the result of deliberate artistic design. In this context, clay colour selection functions as a key index of craftsmanship, creativity, and cultivated taste (Zhou GQ 2014a [ca. 1640], p. 513).

Zhou Gaoqi argues that the distinctive smooth and naturally matte finish of *zisha* teapots makes them particularly well-suited as refined objects for scholarly appreciation (Zhou GQ 2014a [ca. 1640], p. 515), which could be evident from the text as below.

> Original text: 壺入用久, 滌拭日加自發闇然之光, 入手可鑒。 此為書房雅供。 Translation: With prolonged use, the teapot gradually accumulates a natural patina through daily cleaning, emitting a subdued radiance when held. This is an elegant addition to the study. (Zhou GQ 2014a [ca.1640], p. 515)

This view underscores the central role of surface texture in the aesthetic evaluation of teapots, as the matte quality—achieved through the use of fine-textured clay—embodies both visual restraint and tactile subtlety. Zhou further notes that with prolonged use and regular cleaning, *zisha* teapots develop a subdued, lustrous patina that enhances their visual appeal, describing this glow as “a subdued radiance” (*anran zhiguang*, 闇然之光) that becomes evident when the teapot is held. Such a transformation is not only a result of material properties but also a sign of cultivated interaction between object and user over time. In this way, the teapot becomes more than a functional vessel—it evolves into a scholar’s object, appropriate for the refined atmosphere of the study (*shufang yagong*, 書房雅供). The frequent references to clay colour and surface finish in historical texts thus reflect more than technical concerns; they reveal an enduring cultural valuation of subtle material and colour variation aesthetics in *zisha* craftsmanship.

Discussion

This study set out to explore the complexity of potters’ raw material choices in Late Imperial China, with a particular focus on changes in the clay recipe for *zisha* teapots excavated from the Shushan site. Through a combination of archaeometric analysis, geological data, observation of contemporary practitioners, and written texts, this discussion synthesizes how geological formations, clay mining sequences, clay-processing practices, and aesthetic preferences intersected to shape technological choices. Rather than attributing material selection to any singular factor, this study frames raw material choice as the outcome of the interplay between environmental, technological, and cultural variables.

The geological origin of *zisha* clay as a sedimentary deposit—composed of stratified layers with varying iron oxide content—provides a foundational explanation for the observable increase in colour diversity over time. The results from SEM–EDS analysis demonstrate a broader range of iron oxide percentages from the Ming to the Late Qing period, while optical data reveal an expansion in the diversity of clay colours used to make *zisha* teapots. Field observations from the Hufu mine confirmed stratified beds of clay exhibiting chromatic gradations, suggesting that access to deeper deposits in later periods enabled potters to exploit layers with differing iron compositions. This progressive vertical mining strategy aligns with expansion of clay colours during the examined period, supporting the hypothesis that the mining sequence, determined by the local geological structure, influenced the composition of the clay recipe.

Clay processing techniques, particularly grinding, sieving, and washing, played a significant role in clay paste changes. The analysis result demonstrates a marked reduction in particle size and variability from the Ming to the Republican periods. This refinement of texture aligns with field observations of present-day Yixing clay-processing methods, which aim to remove impurities and produce more homogenous pastes. The historical shift toward finer, more uniformly processed clays suggests increasing control over the mechanical and visual properties of the final product, reflecting potters' growing technical proficiency and awareness of consumer preferences.

A key contribution of this study lies in highlighting the cultural valuation of clay appreciation as a driver of technological change. Unlike glazed wares, where surface decoration can obscure the clay body, *zisha* teapots rely entirely on the visual and tactile qualities of their clay. Historical texts from the Ming and Qing periods—particularly Zhou Gaoqi's *Yangxian Minghuxi*—emphasized appreciation of subtle colour tones and surface textures and catalogued the vocabulary of named clay types. These written texts provide evidence of the emphasis on clay colour and texture during the Ming and Qing dynasties. Therefore, the increased chromatic and textural variation can be seen, in part, as a result of clay appreciation shaped by literati taste and artisanal reputation. Potters such as Xu Youquan, praised for their innovative use of diverse clays, exemplify how aesthetic connoisseurship shaped production decisions. The increasing homogeneity and colour diversity of clay bodies must therefore be read as both technological and cultural responses to elite consumption practices.

Rather than treating geological conditions, clay processing, and cultural aesthetics as isolated determinants, this study proposes that it is their interaction which best explains the observed changes in *zisha* clay recipes. The expansion of mining activity into deeper strata offered the potters a broader palette of clays, while increasingly sophisticated processing methods enabled them to tailor their materials to meet changing aesthetic demands. Meanwhile, the enduring cultural emphasis on matte, fine-textured surfaces and nuanced hues motivated the continual refinement of clay selection. This integrated analysis aligns with broader discussions in ceramic studies that conceptualize technological choices as embedded within social, economic, and environmental contexts (Arnold 1985; Lemonnier 1993; Santacreu 2017).

Conclusion

This analysis of Shushan-site *zisha* sherds dating from the Ming dynasty to the Republican period reveals significant insights into the complex factors that influenced potters' raw material choices in Late Imperial China. Our multi-method investigation, combining SEM–EDS analysis, optical examination, and analysis of textual materials, demonstrates that the alteration of the *zisha* clay recipe was shaped by an intricate interplay of geological factors, clay-processing techniques, and clay appreciation.

The scientific analysis revealed two key chronological trends: an increasing diversity in clay colours and a shift toward finer clay textures. SEM–EDS analysis showed a growing variation in iron oxide composition (from 5.03–6.87% in Ming samples to 2.1–7.59% in Late Qing samples), while particle analysis demonstrated a reduction in average particle size (from 129–183 μm^2 in Ming samples to 79–109 μm^2 in the Late Qing/Republican period samples) and improvements in particle sorting techniques in clay processing.

While geological factors, mining sequences, and clay-processing techniques partially explain these trends, our research indicates that the appreciation of clay colour significantly influenced potters' raw material choices. Historical texts written during this period explicitly connect clay colour diversity and fine texture with artistic excellence, suggesting that potters actively selected and modified clay recipes to meet these aesthetic preferences. This study thus enriches our theoretical framework for understanding the complexity of technological choice, particularly when it concerns Late Imperial Chinese ceramic production. By considering the views of both makers and consumers, this paper furthermore shows that visual characteristics and aesthetic preferences may just be as important as functional properties when making decisions regarding raw material choice and processing or purchase and use. Future research also needs to explore how the characterization of clay in terms of colour and texture differs between clay dealers, potters, consumers/collectors, and archaeological scientists.

This study suggests that future research on ceramic technologies should consider not only the physical properties and functional requirements of materials but also the cultural context of appreciation and connoisseurship that may influence technical decisions. More broadly, this research illustrates the value of integrating scientific analysis with geological data, field trip observations, written texts to understand the potters' technological choice.

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