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Blurred boundaries: Exploring the complexity of the production system at the Luomaqiao kiln in Yuan-dynasty Jingdezhen

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ABSTRACT

The conceptual framework of attached and independent production has long shaped archaeological studies of ancient craft organization. While this dichotomy is often regarded as an oversimplification, the nuanced variations within ancient craft production systems remain insufficiently explored. This study addresses the complexities of attached production through a case study of the Luomaqiao kiln site in Yuan-dynasty Jingdezhen (1271–1368 CE) —a state-affiliated workshop that produced high-quality porcelain. By integrating high-resolution compositional analysis (LA-ICP-MS) with archaeological and historical evidence, the study examines raw material selection and use, as well as the associated organizational dynamics. Specifically, it identifies three major porcelain styles—egg-white (*luanbai*), bluish-white (*qingbai*), and grayish-green (*huiqing*) glazed porcelain—each produced with geochemically distinct raw materials, reflecting deliberate choices in sourcing and production strategy. Notably, the *luanbai* porcelains bearing five-clawed dragon motifs—symbols strictly reserved for imperial use—exhibit exceptional chemical purity and homogeneity, suggesting the possible use of the *yutu* (imperial clay) as described in historical records. However, this special clay was also employed in the production of ordinary *luanbai* wares, implying that imperial resources were not strictly confined to official products but circulated more broadly within the kiln system. These findings reveal a production system in which the boundaries between attached and independent modes are blurred, reflecting significant artisan agency within a state-controlled framework. Recognizing the duality and fluidity inherent in Yuan-dynasty porcelain production in Jingdezhen underscores the need for more nuanced frameworks that capture the dynamic interplay between state control and artisan agency, thereby offering broader insights for archaeological interpretations of ancient craft production systems.

1. Introduction

Craft production has long been a focal point in archaeological studies for understanding the socio-economic and political dynamics of ancient societies (Costin, 2001, 2005; Underhill, 2015). Central to this discourse is the conceptual framework distinguishing between attached and independent specialization (Brumfiel and Earle, 1987; Costin and Lynne, 1991; Earle, 1981). Attached specialists are artisans sponsored by elites or state institutions, producing goods—often prestige or luxury items—under direct control to fulfill the demands of their patrons. In contrast, independent specialists operate autonomously, with unrestricted access to resources and markets, creating utilitarian goods for general consumption.

While this dichotomy between attached and independent production has been instrumental in understanding the role of craft production in the development of social complexity, it often oversimplifies the diversity and fluidity inherent in these systems (Clark, 1995; Hayashida and Mariko, 1995; Inomata, 2001; Sinopoli, 2003; Stein, 1998). The

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distinction between attached and independent production is far from clear-cut, as both contexts frequently overlap, and the degree of elite control can vary significantly across different scenarios. In many cases, the production and distribution of goods for elites, even valuable ones, were not always subject to strict elite control (Sinopoli, 2003). Even in cases of attached production, artisans did not always exclusively craft high-value items but also produced utilitarian goods (Stein, 1996; Stein and James Blackman, 1993; Wright and Johnson, 1975; Zeder, 1988). Moreover, the physical context of production does not necessarily reflect the underlying social relationships, making it difficult to determine whether a particular craft was practiced by attached or independent specialists (Stein, 1998). Independent specialists could produce valuable goods that were later used by elites (Arnold and Munns, 1994). Even within elite households, artisans were not always attached specialists under elite control; they could themselves be elites engaged in production for personal use (Inomata, 2001; Reents-Budet, 1998). Furthermore, artisans could navigate between independent and attached roles, indicating that these categories are not mutually exclusive at the individual level (Clark, 1995; Clark and Parry, 1990; Inomata, 2001).

Recognizing the limitations of the rigid dichotomy, Costin and Lynne (1991) proposed early on that attached and independent specialization should be viewed as idealized endpoints along a continuum, characterized by varying degrees of control and autonomy. While this continuum model has gained wide acceptance (Sinopoli, 2003; Underhill, 2015), the exact nature of these intermediate states remains unclear, making their definition and identification challenging. Clark (1995) emphasizes the need to shift focus from rigid evolutionary models to the activities of individual agents, a perspective further advanced by Inomata (2001), who advocates for a micro-scale approach—concerning the specific actions and behaviors of individual producers—to better capture the nuances of craft production systems rather than limiting analysis to macro-scale classifications of independent or attached specialization. Therefore, to advance our understanding of the complexities of craft production, it is essential to conduct in-depth case studies across diverse temporal and regional contexts.

This study addresses these issues through a case study of the Luomaqiao kiln site in Jingdezhen, China, during the Yuan dynasty (1271–1368 CE). Porcelain production in imperial China, particularly at sites with potential state involvement, offers a valuable opportunity to explore complex production systems and, more specifically, the dynamics between state control and artisan agency. However, much of the existing research on official kilns has focused primarily on traditional artifact analysis and using archaeological findings to verify historical records, often with an emphasis on highlighting the significance of official kilns and elite-related wares (Liu, 1993, 2001; Lu, 2005; Xiao et al., 2001). While these studies have greatly contributed to understanding porcelain artifacts and the historical context of official kilns, they have not addressed broader questions of craft specialization, production organization, and artisan agency within an anthropological archaeology framework.

This study seeks to address these gaps by examining the Luomaqiao kiln not only as a potential site of state-regulated production but also as a space where artisan practices and state policies may have intersected in ways that reflect a more nuanced understanding of production dynamics during the Yuan dynasty. Historical records mention the establishment of the *Fuliang Ciju* (Fuliang Porcelain Bureau) in Jingdezhen—then administratively part of Fuliang—by the Yuan government (Song, 1976), along with the use of the *yutu* (imperial clay) and the dedicated *yutu yao* (imperial-clay kiln) (Cao, 1986; Kong, 1987), highlighting state's formal involvement in porcelain manufacturing and its efforts to secure and regulate high-quality resources for imperial production. However, recent archaeological excavations at Luomaqiao present a more nuanced picture. The assemblage of Yuan dynasty porcelain sherds includes not only high-status wares adorned with the exclusive five-clawed dragon motif—a symbol reserved for imperial use—but also ordinary wares of varying qualities (Weng, 2017; Weng et al., 2017; Xu, 2014). This evidence indicates a highly complex production system at Luomaqiao, where diverse products that range from elite-sponsored wares to more utilitarian items were produced within the same kiln context, raising questions about the nature of production organization and the interplay between state control and artisan agency during the Yuan dynasty.

This study aims to investigate the complexities of the production system at Luomaqiao by integrating high-precision compositional analysis using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) with historical records. It addresses the following research questions: (1) Did the Luomaqiao kiln use special raw materials, such as the *yutu* (imperial clay), for producing high-status wares like those bearing the exclusive five-clawed dragon motif reserved for imperial use? (2) If such special raw materials were used, were they reserved solely for high-status items, or were they also available across various styles of wares? (3) How was production at Luomaqiao organized, and what does this reveal about the interaction between state control and artisan practices during the Yuan dynasty? By examining the raw materials, production techniques, and organizational practices at Luomaqiao, this study aims not only contributes to our understanding of craft production in this specific historical context but also underscores the importance of developing more nuanced frameworks that account for the dynamic interplay between state control and artisan agency in archaeological interpretations of ancient production systems.

2. Porcelain production in Yuan-dynasty Jingdezhen

Research on Yuan-dynasty porcelain production in Jingdezhen has attracted considerable attention, largely due to historical records linking it to state involvement. According to the *History of Yuan*, we translate the passage as follows: "The Fuliang Porcelain Bureau, ranked as the ninth official grade, was established in the 15th year of Zhiyuan (1278 CE). It was responsible for the production of porcelain, lacquered goods, horsehair, palm fiber hats, and other items. The bureau had one director and one deputy director" (Song, 1976:1479). However, historical accounts are somewhat vague and inconsistent, with discrepancies even in aspects such as the official rank and personnel structure of the bureau across various sources (Li, 1994; Shi, 2014; Xu, 2013; Zeng, 2012). This ambiguity has led to ongoing scholarly debates regarding the bureau's exact responsibilities and supervision methods in porcelain production. Some scholars propose that the bureau established its own kiln sites to produce porcelain for imperial use, indicating the existence of official kilns (Chen, 2019; Liu, 1981, 1993; Lu, 2012; Xiao et al., 2001), with its significant achievements occurring during the reign of Emperor Wenzong of Yuan (1328–1332 CE) (Liu, 2001; cf. Ma, 2005). Others suggest that the bureau did not establish its own kilns but instead functioned as a supervisory agency, overseeing porcelain production while relying on civilian kilns or independent artisans for the actual manufacturing—a system later known as 'officially sponsored, civilian-operated firing' (Cao and Xu, 2009; Jiang, forthcoming; Kanazawa, 2000). Another view contends that the primary function of the bureau was tax collection, particularly in its early period (Lu, 2005; Lv, 2008), though others argue that the lack of direct evidence makes this unlikely (Chen, 2019; Shang, 2017; Xu, 2013).

Further evidence of state involvement in porcelain production comes from the *Raozhou Fuzhi* (*Gazetteer of Raozhou Prefecture*), which records that during the Taiding reign (1324–1328 CE), the local provincial governor supervised porcelain production, with orders supplied only upon command; otherwise, production ceased (Huang and Tong, 1989). This document has sparked additional debates, particularly regarding whether there was a potential reorganization or shift in management practices, and about the duration of the Fuliang Porcelain Bureau—specifically, whether it was replaced by the provincial governor's supervision during this period (Chen, 1990, 2019; Li, 1994; Liu, 1981, 2001; Wang, 2000; Xiong, 1986; Yu, 2016; Zeng, 2012).

In addition to these records, historical documents about Yuan dynasty porcelain production in Jingdezhen mention the use of the *yutu* and the existence of the *yutu yao*. In the late Yuan dynasty, Kong Qi's *Zhizheng Zhiji* (True Records of the Zhizheng Era) included an entry titled "*Raozhou Yutu* (Raozhou Imperial Clay)," which we translate as follows: "Raozhou imperial clay is as white as power. Each year, officials are assigned to oversee the production of vessels for tribute, which are referred to as the Imperial-Clay Kiln. Once the firing is completed, the kilns [or possibly the clay deposits or the processed clay in the workshop] are sealed, and private use of the clay is prohibited. If there is any surplus clay from the tribute production, it is used to make items such as plates, basins, bowls, dishes, pots, ewers, cups, and goblets. Thers wares are white and lustrous, very appealing" (Kong, 1987:80). Shortly thereafter, in the early Ming dynasty, the *Gegu Yaolun* (The Essential Criteria of Antiques) also mentions the Imperial Clay Kiln, which we translate as follows: "The Imperial Clay Kiln produces pieces that are thin and lustrous, of the highest quality. There are plain, folded-waist styles with slightly thick bodies, but their color is white and lustrous, especially fine, and their price is lower than Ding ware. Yuan dynasty pieces with small feet and incised designs, some marked with *shufu* characters, are highly valued" (Cao, 1971, 1986:107). These records collectively suggest direct state involvement in porcelain manufacturing in Jingdezhen, particularly underscores the importance of specific raw materials in producing high-quality wares for the court. However, the true nature of *yutu*—including whether it existed as described, which specific clay qualified as imperial clay, and how it was managed and used—remains unclear. Additionally, the existence and function of the *yutu yao* mentioned in records are also uncertain, raising questions about whether it was an actual dedicated facility or a general term for kilns producing imperial wares.

Scholars often associate the production of egg-white (*luanbai*) glazed porcelain with the Fuliang Porcelain Bureau or Yuan-dynasty official kilns. Widely considered an innovation of the Yuan period, *luanbai* porcelain is characterized by a thick, opaque glaze that produces a distinctive bluish-white hue resembling egg white, from which its name is derived. Because some *luanbai* wares are molded with the characters *shufu*—generally thought to refer to the *shumi yuan* (Privy Council), an official military department—these porcelains are sometimes called *shufu* wares (Chinese Ceramic Society, 1982; Xiao, 2006; Yu, 2020). In addition to *shufu*, other inscriptions such as *taixi* and *dongwei* have been found, with *taixi* commonly interpreted as an abbreviation for *taixi yuan* or *taixi zongyin yuan*, an official institution overseeing rituals for former emperors and empresses (Liu, 2001; Sun, 1963), while *dongwei* is associated with the imperial guards of the Eastern Palace (Song, 1987). Moreover, some items are stamped with double-horned, five-clawed dragons (Liu 2001; Sun 1963; Xiao et al., 2001)—a motif that, in the Yuan dynasty, was reserved exclusively for imperial use (Chen et al., 2011:1968; Fang, 2001:358; Song, 1976:1942). Some scholars believe that the large-scale production of *luanbai* porcelain catered to the Yuan dynasty's needs for ritual vessels, aligning with the cultural preference of the Yuan court for the color white (Jiang and Jiang, 2008; Liu, 1981, 2001; Lu, 2000; Shang, 2015; Wang, 2000). Meanwhile, other researchers have pointed out that *luanbai* porcelain encompassed various categories; besides those used by the royal court and government offices, there were also large quantities of commercial porcelains, which were not only popular domestically but also exported overseas (Shang, 2015).

Based on current archaeological evidence, fragments with five-clawed dragon motifs—characteristic of imperial wares—have been found at multiple locations in Jingdezhen, including Fengjing Road, located at the northern end of the Imperial Kiln Factory during the Ming and Qing periods, as well as at the Liujiawu area of the Hutian kiln district and the Luomaqiao kiln site (Liu, 2001; Weng et al. 2017; Xiao et al., 2001). However, only the Luomaqiao kiln site has undergone systematic archaeological excavation, providing valuable data for understanding this production.

The Luomaqiao kiln site, located in the southern part of Jingdezhen city, Jiangxi province, approximately 0.6 km east of the Changjiang River and 1.9 km north of the Nanhe River (Fig. 1). Archaeological excavations conducted between 2012 and 2015 revealed substantial evidence of porcelain manufacturing, including kiln structures, workshops, architecture remains, and a diverse assemblage of porcelain artifacts, spanning multiple dynasties from the Northern Song to the late Qing dynasty (Li, 2014; Qin et al., 2020; Weng, 2017; Weng et al., 2017; Weng and Li, 2021; Xu, 2014). While production at Luomaqiao continued over centuries, the Yuan period stands out for its remarkable diversity and technical sophistication of porcelain, significantly shaping Jingdezhen's historical development as a renowned porcelain production center. Yuan-period artifacts excavated from the site primarily include porcelains with egg-white (*luanbai*) glaze, bluish-white (*qingbai*) glaze, and grayish-green (*huiqing*) glaze (Fig. 2), collectively accounting for over 95 % of all porcelain fragments recovered from the site dated to this period (Weng, 2017; Xu, 2014). Additionally, although produced in smaller quantities, notable innovations such as blue-and-white porcelain, blue-glazed porcelain, porcelain with underglaze copper-red decoration, and red-and-green enameled porcelain also emerged during the Yuan dynasty. Some of the egg-white glazed porcelain fragments bear high-status symbols, such as five-clawed dragon motifs (Fig. 3) and *shufu* inscriptions, indicating the kiln was likely involved in producing wares for the imperial court. The discoveries at the Luomaqiao kiln site underscore its significance in understanding the structure and organization of Jingdezhen's porcelain production during the Yuan dynasty, providing crucial archaeological evidence for examining the interactions among official and private kilns, as well as the regulatory frameworks governing porcelain production and distribution (Li, 2014).

3. Materials and methods

3.1. Materials

This research focuses on the main porcelain products of the Luomaqiao kiln site during the Yuan dynasty. A total of 135 Yuan-dynasty porcelain samples were analyzed, classified into three main styles: egg-white (*luanbai*) glazed porcelain, bluish-white (*qingbai*) glazed porcelain, grayish-green (*huiqing*) glazed porcelain (Fig. 2). Detailed information on their vessel forms and decorations is available in the Mendeley Data repository (see Dataset_S3). *Luanbai* porcelain is distinguished by its fine-grained white paste and an opaque glaze, often exhibiting a milky or semi-transparent quality. *Qingbai* porcelain, in contrast, features a relatively fine white paste and a highly transparent glaze, giving it an overall bluish-white appearance. *Huiqing* porcelain differs markedly, with a coarser paste bearing a grayish tint and a relatively thin, slightly opacified glaze, resulting in an overall grayish-green appearance. While there are discernible differences between the glazes of *luanbai* and *qingbai* porcelain, these distinctions are often subtle, and the visual differences—primarily the greater transparency of *qingbai* compared to the opacified nature of *luanbai*—are not always pronounced, making them challenging to differentiate with the naked eye. Both *luanbai* and *qingbai* porcelain exhibit a variety of vessel forms, including bowls, stem cups, cups, plates, vases, jars, etc. In contrast, all *huiqing* porcelain products are limited to bowls.

3.2. Methods

This study used Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) to analyze the elemental composition of porcelain samples, focusing on both the paste and glaze components. All analyses were conducted at the Elemental Analysis Facility (EAF) of the Field Museum in Chicago. The equipment included a Thermo Scientific iCAP Q quadrupole ICP-MS paired with a New Wave UP213 laser ablation system. Analytical procedures and parameters followed well-established approaches and adhered to the EAF's standard protocol (Dussubieux et al., 2007; Niziolek, 2015; Oka et al., 2009; Xu et al., 2021).

Fig. 1. Location map of the Luomaqiao Kiln site in Jingdezhen, Jiangxi province, China.

Fig. 2. Examples of Yuan dynasty porcelain from the Luomaqiao kiln site. (a) egg-white (*luanbai*) glazed bowl, (b) bluish-white (*qingbai*) glazed stem cup, and (c) grayish-green (*huiqing*) glazed bowl. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

For the paste analysis, samples were examined in cross-section to facilitate a precise assessment of their compositional characteristics. Ten ablation spots were selected on each specimen, with a pre-ablation pass of 20 s performed to remove surface contaminants that could potentially affect the results. Each ablation was carried out using a laser spot size of 100 μm, with a wavelength of 213 nm, energy output at 80 %, and a pulse frequency of 20 Hz. The dwell time for each spot was set to 60 s to accumulate sufficient signal intensity for accurate measurement. To account for potential instrument drift and ensure data accuracy, standard reference materials (SRMs) NIST SRM 610 (glass) and NIST SRM 679 (brick clay) with known elemental concentrations were analyzed at regular intervals—specifically, after every five to ten samples. Ohio Red Clay was used as a quality control measure to monitor consistency and precision throughout the study.

For the glaze analysis, four ablation spots were selected on each glaze sample, avoiding visible inclusions, cracks, or defects to ensure representative results. A pre-ablation pass was performed with a laser spot size of 110 μm, pass speed of 70 μm/s, and a dwell time of 60 s to remove potential surface contamination and eliminate transient signals. Subsequently, an ablation pass was executed with a laser at 213 nm, operating at 80 % energy, a pulse frequency of 10 Hz, a spot size of 100 μm, pass speed of 10 μm/s, and a dwell time of 60 s. Five samples were processed per ablation cycle, with glass standard materials—NIST SRM 610, Corning B, and Corning D—used for instrument drift correction and elemental concentration calculation. These standards and controls were each ablated four times at different locations.

Element concentrations for each sample and control were calibrated using silicon (^{29}Si) as an internal standard, following the method described by Dussubieux et al. (2007), to improve measurement precision. To ensure data reliability and minimize the effects of instrument drift or surface contamination, anomalous values were identified and removed, with no more than one measurement per element excluded for glaze samples and no more than three measurements per element for paste samples. The final composition for each element was then calculated as the average of the remaining measurements, with the majority of relative standard deviation (RSD) values falling below 10 % and often under 5 %. The spectrometer measured 58 elements for each sample: Li, Be, B, Na, Mg, Al, Si, P, Cl, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Y, Zr, Nb, Mo, Ag, Cd, In, Sn, Sb, Cs, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, W, Au, Pb, Bi, Th, and U. Certain elements were excluded from further statistical analysis due to consistently low readings or high relative standard deviation (RSD) values. For

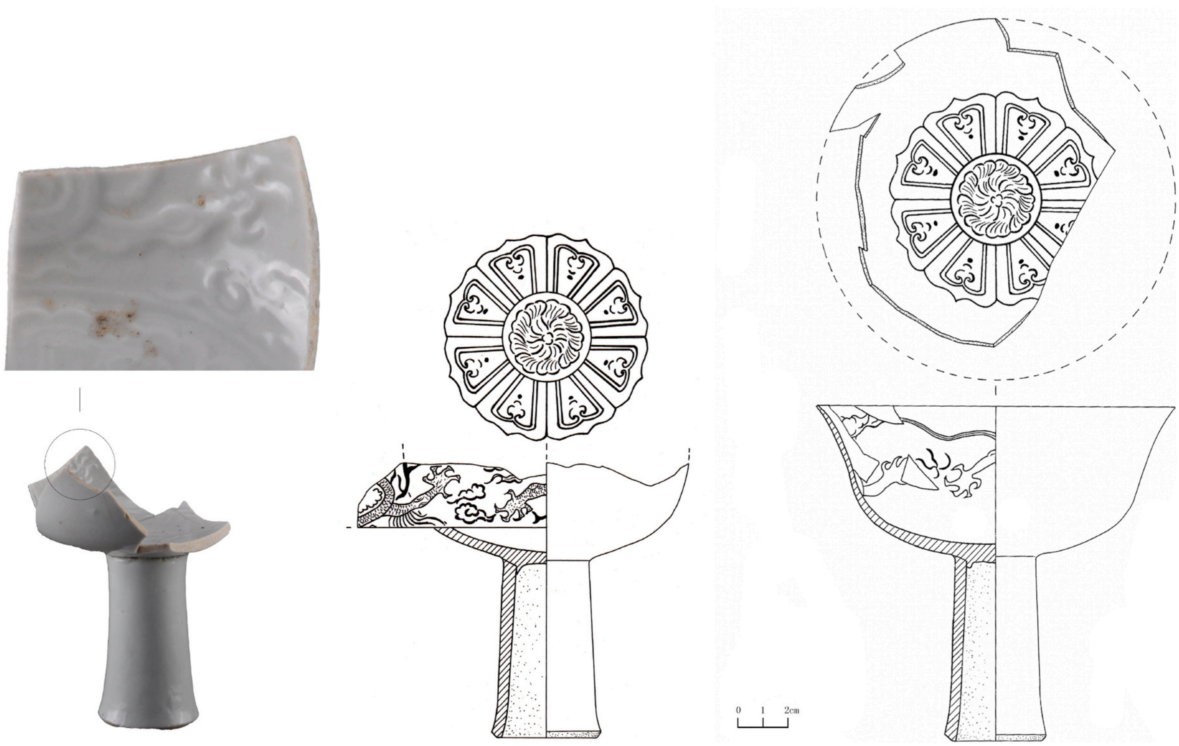

Fig. 3. Examples of egg-white (*luanbai*) glazed stem cups featuring five-clawed dragon motifs from the Luomaqiao kiln site. The left side shows a photograph of a *luanbai* porcelain fragment with a close-up of the dragon motif. The center and right sides present illustrations, including a detailed line drawing of the interior pattern and a cross-sectional view of the stem cup, showcasing its structure and ornate design.

paste analyses, selenium (Se) and cadmium (Cd) were excluded; for glaze analyses, chlorine (Cl), selenium (Se), cadmium (Cd), and tin (Sn) were excluded. As a result, 56 elements were retained for paste analysis and 54 for glaze analysis. Full compositional data for paste and glaze are accessible in the Mendeley Data repository (see files Dataset_S1 and Dataset_S2).

To uncover compositional patterns, multivariate statistical methods, including principal component analysis (PCA) and hierarchical cluster analysis (HCA), were employed. The log base-10 transformation of elemental data was used to reduce variation between major, minor, and trace elements (Baxter, 2006; Bishop and Neff, 1989; Glascock, 1992). Most statistical analyses, including PCA, HCA, the generation of boxplots, enrichment–depletion plots, and bivariate plots, were conducted using R version 4.4.0 (R Core Team, 2024). Group membership probabilities based on Mahalanobis distance calculations were calculated using MURRAP statistical routines, developed and maintained by Hector Neff and Michael Glascock at the University of Missouri Research Reactor Center (MURR) (Glascock, 1992).

4. Results and discussion

4.1. Compositional signatures and raw material selection in three porcelain styles

4.1.1. Paste composition

Although *luanbai* porcelain is widely recognized as a distinctive innovation of the Yuan dynasty—often associated with official or imperial use—its distinction from *qingbai* porcelain is not always clear-cut. As noted above, the visual differences between the two are often subtle: while *qingbai* porcelain typically features a more transparent glaze, and *luanbai* is characterized by a more opacified, white appearance, these differences are not always pronounced to the naked eye. Moreover, existing compositional analyses have yet to yield a clear differentiation between the two styles. Studies employing Energy-Dispersive X-ray Fluorescence (ED-XRF) have identified some differences in the concentrations of fluxing agents such as potassium, calcium, and sodium (Li, 1998; Ming et al., 2014; Wood, 1999; Xu et al., 2017), yet these findings have not conclusively established whether *luanbai* and *qingbai* porcelains were made from fundamentally different raw materials. LA-ICP-MS, capable of analyzing over 50 elements—including trace elements such as rare earth elements (REEs)—offers a more refined means of assessing compositional differences and may provide a clearer basis for distinguishing between the two porcelain styles.

To better capture the nuanced differences between *luanbai* and *qingbai* porcelains, we begin by analyzing these two visually similar styles before turning to *huiqing* wares, which are more visually distinct. HCA, an unsupervised clustering algorithm that groups samples based solely on compositional similarity (Baxter, 1994, 2006; Bishop and Neff, 1989; Glascock Michael, 2014), was first applied to the dataset restricted to these two visually similar styles to assess whether they could be distinguished without relying on prior stylistic classification. The resulting dendrogram identifies two distinct compositional groups (Fig. 4), indicating clear differences in paste chemistry. A closer inspection reveals that the two clusters correspond closely with the known stylistic classifications: *luanbai* samples dominate the left cluster, while *qingbai* samples are concentrated on the right. To further assess the robustness of this separation, PCA was performed on the same dataset, using the HCA-derived groupings as a reference. The resulting biplot of the first two principal components displays a similarly distinct separation, with *luanbai* and *qingbai* samples forming well-defined, non-overlapping clusters (Fig. 5). This convergence between HCA and PCA results provides strong support for the interpretation that the two styles are compositionally distinct in terms of their paste chemistry.

Having established a clear compositional distinction between *luanbai* and *qingbai* porcelains, we then incorporated *huiqing* samples into the analysis to assess their overall compositional position within the dataset. The results (Fig. 6) reveal a clear tripartite separation, with all three porcelain styles forming distinct clusters in PCA space. *Luanbai* samples

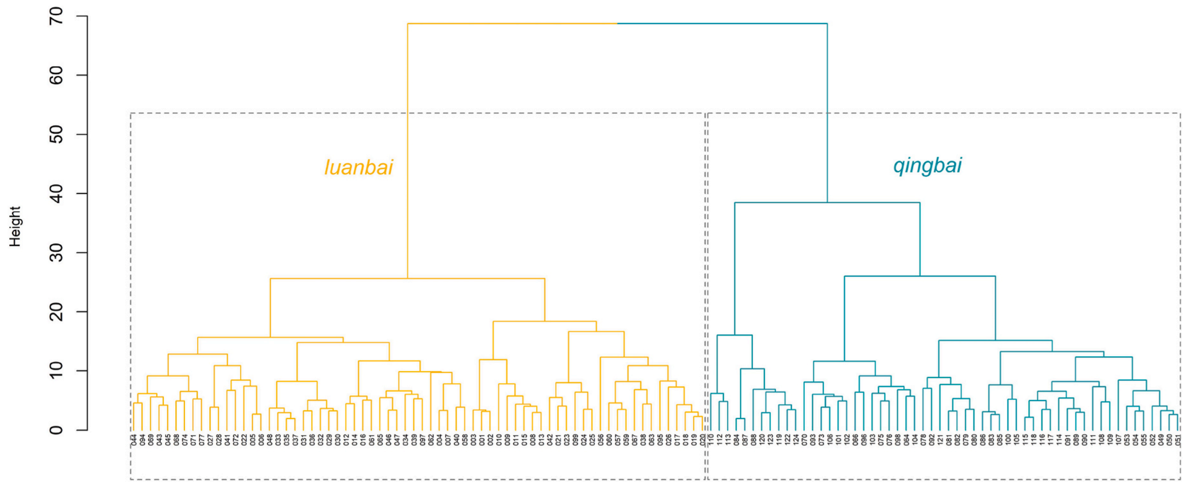

Fig. 4. Dendrogram from Hierarchical Cluster Analysis (HCA) of paste samples, illustrating two primary clusters based on compositional similarity. The left cluster corresponds to egg-white (*luanbai*) glazed porcelains, while the right cluster corresponds to bluish-white (*qingbai*) glazed porcelains.

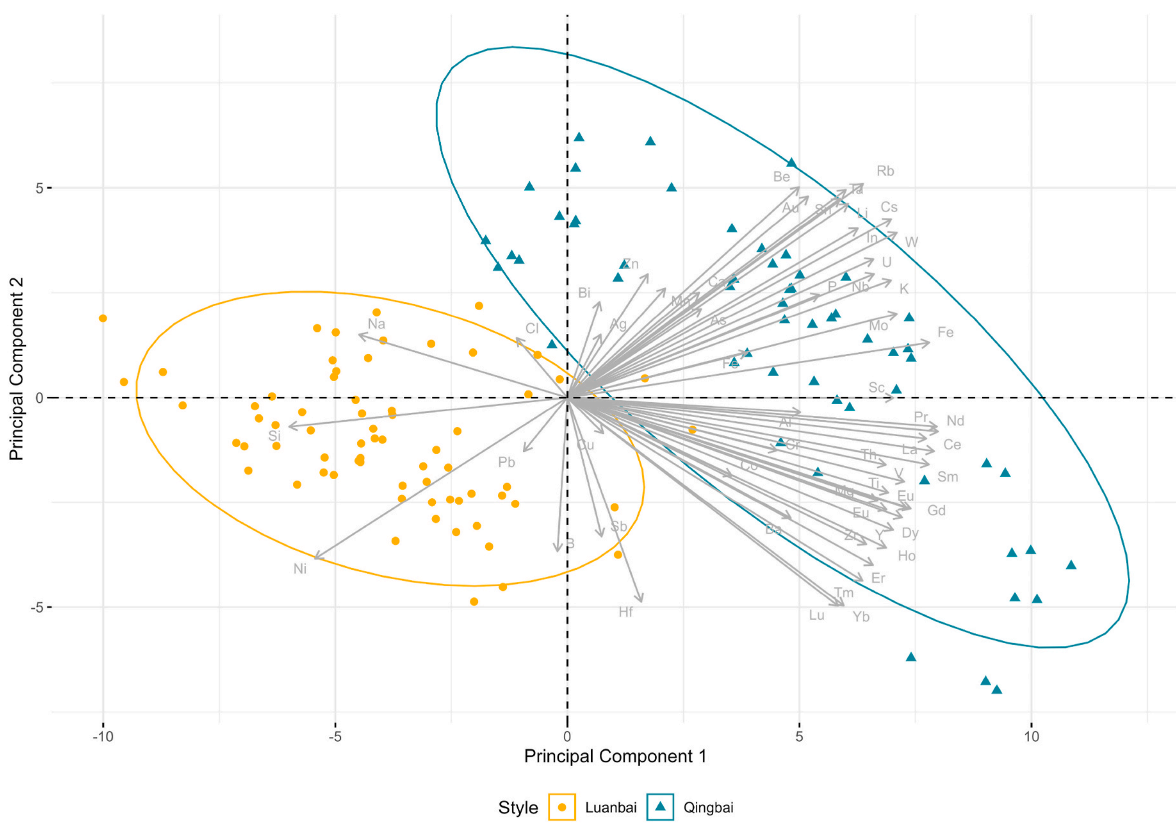

Fig. 5. PCA biplot of the full elemental composition (56 elements) in the paste for egg-white (*luanbai*) glazed and bluish-white (*qingbai*) glazed porcelain samples. PC1 accounts for 47.3 % of the total variance, and PC2 for 13.1 %. The ellipses represent 90 % confidence intervals for each group.

form a particularly tight cluster, indicating a high degree of chemical uniformity that likely reflects the use of more homogeneous raw materials or tighter control over material selection. In contrast, *qingbai* samples exhibit a broader spread, suggesting greater variability in either the composition or selection of their source materials. *Huiqing* samples show the greatest internal dispersion, consistent with a more compositionally heterogeneous or mineralogically complex source material. The loadings of principal components provide further insight into the elemental dimensions driving this separation. *Huiqing* samples are aligned with elevated levels of Fe, Ti, REEs, and heavy trace elements such as Zr and Hf. *Qingbai* samples are more closely associated with alkali-enriched elements such as Rb, Cs, and Li. In contrast, *luanbai* samples are positioned toward high Si and Na, and away from vectors corresponding to clay-derived or heavy mineral elements. These trends suggest that the three porcelain styles were likely derived from geochemically distinct sources of raw materials.

Building on the results of the multivariate analyses, a detailed comparison of the paste compositions among the three porcelain styles reveals systematic differences across major, minor, and trace elements (Fig. 7 and Table 1). *Luanbai* porcelains exhibit the highest SiO_2 content (mean = 75.43 %, SD = 2.34 %), significantly higher than both *qingbai* (mean = 73.04 %, SD = 2.14 %) and *huiqing* (mean = 72.66 %, SD =

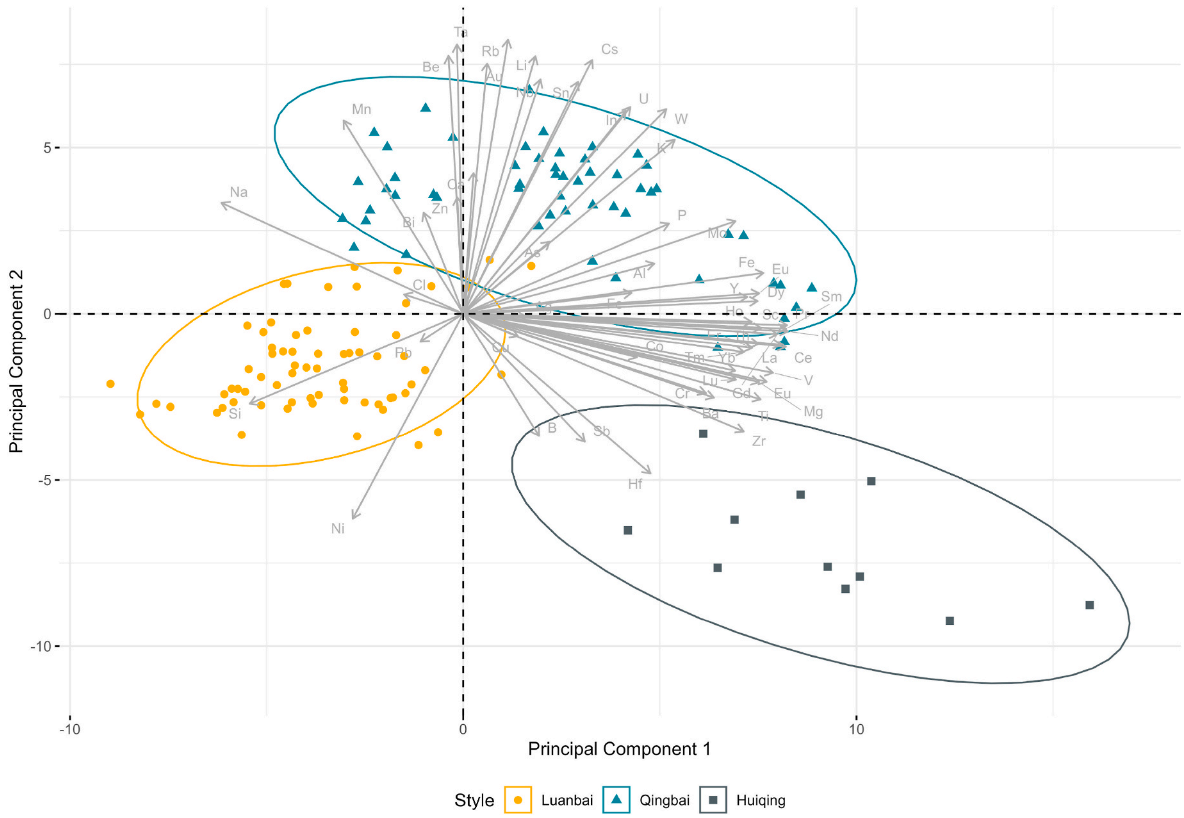

Fig. 6. PCA biplot of the full elemental composition (56 elements) in the paste for egg-white (*luanbai*), bluish-white (*qingbai*), and grayish-green (*huiqing*) glazed porcelain samples. PC1 accounts for 42.8 % of the total variance, and PC2 for 21.4 %. The ellipses represent 90 % confidence intervals for each group. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

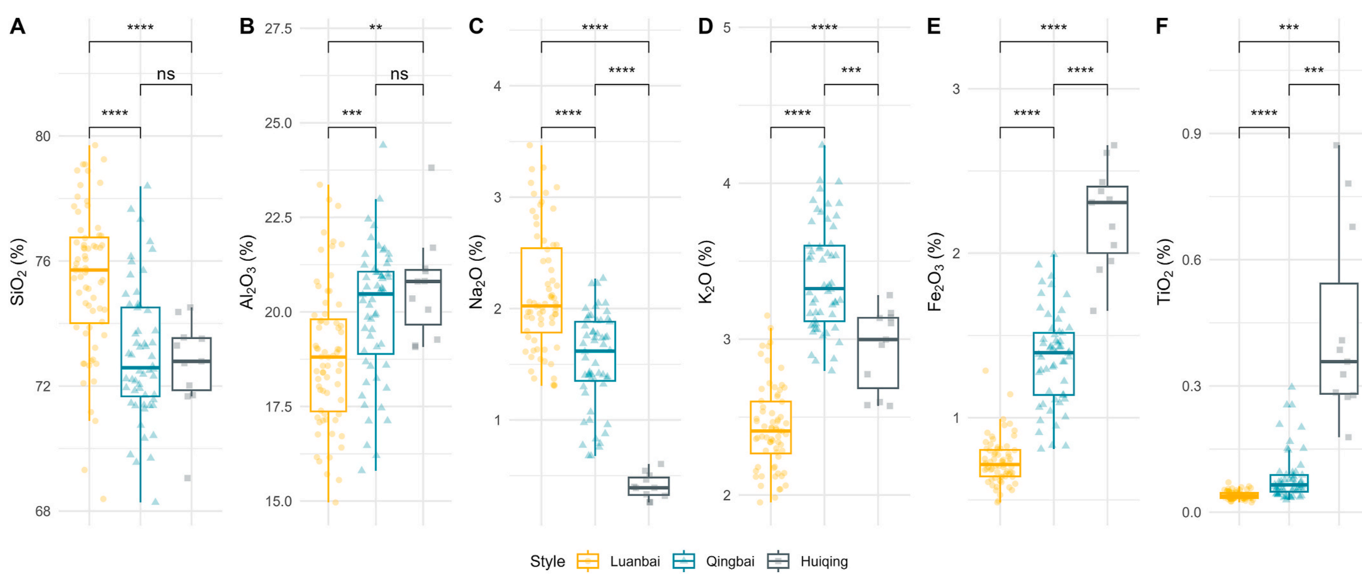

Fig. 7. Boxplots showing the concentrations of SiO_2, Al_2O_3, Na_2O, K_2O, Fe_2O_3, and TiO_2 in the pastes of egg-white (*luanbai*), bluish-white (*qingbai*), and grayish-green (*huiqing*) glazed porcelain samples. The asterisks indicate the significance levels from pairwise t-tests: ns ($p > 0.05$), ** ($p \leq 0.01$), *** ($p \leq 0.001$), and **** ($p \leq 0.0001$). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

1.54 %). Conversely, Al_2O_3 content is lowest in *luanbai* porcelains (mean = 18.84 %, SD = 1.86 %), significantly lower than both *qingbai* (mean = 20.01 %, SD = 1.77 %) and *huiqing* (mean = 20.66 %, SD = 1.37 %). These contrasting trends suggest that *luanbai* pastes were formulated from a more quartz- and feldspar-rich, clay-poor porcelain stone, whereas *qingbai* and *huiqing* pastes incorporated higher proportions of alumina-bearing clay minerals. Sodium and potassium contents also differ markedly. Na_2O concentrations are highest in *luanbai* (mean = 2.15 %, SD = 0.54 %), followed by *qingbai* (mean = 1.54 %, SD = 0.42 %) and *huiqing* (mean = 0.41 %, SD = 0.11 %), with all pairwise differences statistically significant ($p < 0.0001$). Conversely, *qingbai* porcelains have the highest K_2O concentrations (mean = 3.39 %,

Table 1
Average elemental concentrations, standard deviation (SD), and relative standard deviation (RSD) in pastes for *luanbai* (egg-white), *qingbai* (bluish-white), and *huiqing* (grayish-green) groups.

Element	*Luanbai* Group (n = 68)			*Qingbai* Group (n = 56)			*Huiqing* Group (n = 11)		
	mean	**SD**	**RSD (%)**	**mean**	**SD**	**RSD (%)**	**mean**	**SD**	**RSD (%)**
Oxide %									
SiO_2	75.43	2.34	3.10	73.04	2.14	2.93	72.66	1.54	2.11
Al_2O_3	18.84	1.86	9.88	20.01	1.77	8.82	20.66	1.37	6.63
NaO	2.15	0.54	25.35	1.54	0.42	27.65	0.41	0.11	27.63
MgO	0.12	0.03	21.76	0.19	0.07	38.09	0.45	0.07	15.99
K_2O	2.43	0.27	11.20	3.39	0.34	10.12	2.94	0.26	8.94
CaO	0.15	0.08	51.55	0.23	0.12	53.35	0.12	0.13	102.04
Fe_2O_3	0.74	0.14	18.97	1.37	0.28	20.66	2.22	0.31	13.98
MnO	0.07	0.02	30.40	0.08	0.02	24.06	0.02	0.01	36.55
TiO_2	0.04	0.01	23.47	0.08	0.06	71.23	0.44	0.23	52.46
ppm									
Li	52.79	27.72	52.50	134.92	37.45	27.76	31.94	13.37	41.86
Be	7.82	1.94	24.80	13.45	3.96	29.43	4.08	1.29	31.70
B	99.85	81.18	81.30	83.78	62.58	74.70	190.07	59.77	31.44
P	46.65	25.52	54.70	160.09	40.47	25.28	173.50	30.59	17.63
Cl	364.14	188.77	51.84	391.52	316.65	80.88	235.96	48.29	20.47
Sc	2.79	0.59	21.01	5.26	1.49	28.35	10.41	3.72	35.73
V	3.58	1.85	51.65	11.84	10.90	92.10	72.87	31.43	43.13
Cr	2.10	1.24	58.98	6.05	7.63	125.96	44.04	31.94	72.53
Ni	7.99	3.23	40.45	2.90	1.22	41.96	8.01	3.49	43.56
Co	2.23	1.25	55.91	2.81	2.11	75.04	4.82	1.67	34.65
Cu	4.41	1.39	31.48	3.93	0.86	21.93	4.76	1.05	22.05
Zn	57.57	13.73	23.85	69.42	18.08	26.04	53.81	15.91	29.57
As	1.70	1.79	105.21	3.46	3.09	89.12	4.40	5.68	129.18
Rb	269.47	76.30	28.32	546.07	99.91	18.30	144.59	41.20	28.49
Sr	24.92	5.69	22.83	28.92	7.40	25.59	37.70	20.94	55.56
Zr	23.54	3.77	16.03	31.46	11.37	36.15	116.44	29.17	25.05
Nb	14.41	2.84	19.73	23.48	5.03	21.40	9.65	3.56	36.90
Ag	0.04	0.02	51.95	0.04	0.02	53.88	0.05	0.01	12.57
In	0.05	0.03	65.75	0.15	0.04	28.69	0.06	0.01	16.85
Sn	9.36	7.88	84.14	30.60	9.26	30.25	6.45	2.52	39.13
Sb	2.33	0.95	40.60	2.33	1.31	56.51	9.08	4.02	44.34
Cs	25.20	8.19	32.52	64.25	13.15	20.46	21.08	5.41	25.68
Ba	92.15	21.78	23.64	121.17	46.63	38.49	243.13	67.40	27.72
La	4.10	1.38	33.68	8.19	3.59	43.85	25.05	8.73	34.84
Ce	7.05	2.20	31.24	14.47	6.52	45.05	45.97	16.71	36.34
Pr	1.12	0.34	30.14	2.27	0.85	37.58	5.64	2.12	37.63
Ta	3.06	0.84	27.40	6.56	1.85	28.22	1.01	0.50	49.93
Au	0.02	0.01	32.02	0.04	0.01	27.80	0.01	0.01	50.81
Y	8.54	2.20	25.73	12.06	3.97	32.95	13.94	5.76	41.31
Pb	36.60	9.93	27.14	33.31	10.93	32.80	37.00	14.82	40.06
Bi	0.05	0.07	156.33	0.06	0.07	131.91	0.03	0.06	217.65
U	3.81	0.90	23.64	7.75	2.19	28.27	4.41	0.82	18.70
W	1.66	0.50	30.10	6.54	1.38	21.07	3.09	0.95	30.91
Mo	0.17	0.10	58.75	0.49	0.17	34.14	0.64	0.33	51.96
Nd	4.74	1.33	28.16	9.65	3.51	36.35	24.91	9.49	38.08
Sm	1.76	0.39	22.39	2.74	0.70	25.61	4.87	1.78	36.63
Eu	0.23	0.08	36.23	0.38	0.17	44.03	1.12	0.26	23.42
Gd	1.85	0.42	22.52	2.65	0.69	25.97	4.08	1.47	35.92
Tb	0.30	0.07	22.88	0.40	0.10	24.13	0.49	0.18	36.22
Dy	1.92	0.44	22.88	2.67	0.68	25.32	3.26	1.29	39.53
Ho	0.30	0.07	22.64	0.41	0.13	31.05	0.52	0.22	43.42
Er	0.87	0.20	22.83	1.19	0.39	32.82	1.68	0.77	46.21
Tm	0.11	0.03	23.83	0.15	0.05	35.59	0.21	0.10	48.70
Yb	0.90	0.20	22.19	1.15	0.43	37.63	1.67	0.86	51.70
Lu	0.11	0.03	24.11	0.14	0.06	41.02	0.22	0.11	52.71
Hf	2.03	0.38	18.50	1.95	0.39	20.14	3.81	0.92	24.05
Th	4.74	1.29	27.16	7.02	1.63	23.17	12.61	2.55	20.25

SD = 0.34 %), significantly higher than those in *huiqing* (mean = 2.94 %, SD = 0.26 %) and *luanbai* (mean = 2.43 %, SD = 0.27 %) ($p < 0.001$). These differences in alkali element concentrations likely reflect variations in the feldspar composition of the porcelain stones used, with elevated Na_2O suggesting a dominance of albite-rich sources and higher K_2O indicating the presence of potassic feldspar. In terms of iron and titanium contents, *luanbai* porcelains display the lowest average Fe_2O_3 (mean = 0.74 %, SD = 0.14 %) and TiO_2 contents (mean = 0.04 %, SD = 0.01 %), followed by intermediate values in *qingbai* (Fe_2O_3 mean = 1.37 %, SD = 0.28 %; TiO_2 mean = 0.08 %, SD = 0.06 %) and the highest levels in *huiqing* (Fe_2O_3 mean = 2.22 %, SD = 0.31 %; TiO_2 mean = 0.44 %, SD = 0.23 %), all differences statistically significant ($p < 0.001$). The progressive increase in Fe_2O_3 and TiO_2 contents across the three styles likely contributed to the corresponding shift in paste color, from subdued creamy white in *luanbai* porcelains, to a slightly grayer white in *qingbai* porcelains, and to the darker gray tones characteristic of *huiqing* porcelains.

Trace element comparisons further underscore the compositional divergences among the three porcelain styles, with rare earth element (REE) patterns offering particularly compelling evidence. *Luanbai* porcelains exhibit the lowest total REE content (ΣREE) and flattest distribution (low LREE/HREE), *huiqing* porcelains display the highest ΣREE and strongest LREE enrichment, and *qingbai* porcelains consistently occupy an intermediate position (Fig. 8). These differences are statistically significant across all pairwise comparisons ($p < 0.001$ or 0.0001). REEs are widely recognized as robust geochemical tracers for determining the geological origins of clay materials, as their distribution patterns typically remain stable even after post-depositional processes such as crushing, sieving, and sedimentary transport, and are largely unaffected by firing conditions or human processing (Fleet, 1984; Glascock, 1992; Wilson and Pollard, 2001). These patterns in REE distribution thus provide critical support for the broader interpretation that distinct geological sources were used in producing different porcelain styles.

The results of the multi-level elemental analysis provide compelling evidence that the three porcelain styles produced at the Luomaqiao kiln site were made from geochemically distinct raw materials. Notably, recent studies have shown that porcelain production in Yuan-dynasty Jingdezhen typically relied on a single raw material—porcelain stone—rather than the traditionally assumed mixture of porcelain stone and kaolin clay (Weng et al., 2015; Xiao et al., 2020; Xu et al., 2017). Within this technological context, the observed geochemical divergences likely reflect the selection of different sources of porcelain stones for each style. *Luanbai* pastes are characterized by elevated Si and Na, low Al, Fe, and Ti, and notable depletions in trace elements—particularly REEs, suggesting the use of a highly refined, albite- and quartz-rich porcelain stone. In contrast, *qingbai* pastes exhibit higher Al and K, as well as enrichments in alkali-related trace elements such as Rb, Li, and Cs, indicating a distinct geological source enriched in potassic feldspar and secondary clays. *Huiqing* pastes exhibit the highest levels of Fe, Ti, ΣREE, and LREE/HREE fractionation, indicating the use of a compositionally and mineralogically impure source material, likely enriched in heavy accessory minerals. These differences likely reflect strategic choices in raw material selection and preparation, tailored to distinct technical objectives or production constraints. The pronounced chemical homogeneity and high-purity signature of *luanbai* pastes suggest a more rigorous approach to material selection, potentially associated with higher-value or more standardized products. In contrast, the greater compositional variability observed in *qingbai* pastes—and even more so in *huiqing* pastes—points to a descending gradient in raw material quality and processing control, indicative of increasingly flexible or lower-tier production strategies. Taken together, the geochemical divergences among the three styles offer insight into the internal production organization at the Luomaqiao kiln site in Yuan-dynasty Jingdezhen, where stylistic distinctions were likely underpinned by deliberately differentiated raw material supply systems and production practices.

4.1.2. Glaze composition

While paste compositions of the three porcelain styles show significant differences, their glaze compositions exhibit a certain degree of compositional similarity, as reflected in the partial overlap observed in the PCA plot (Fig. 9). Nonetheless, a more detailed examination reveals consistent and statistically significant differences in flux-related oxides among the three styles (Fig. 10 and Table 2). *Luanbai* glazes contain the highest average Na_2O content (mean = 3.28 %, SD = 0.37 %), significantly higher than in *qingbai* (mean = 2.32 %, SD = 0.57 %) and *huiqing* (mean = 1.73 %, SD = 0.26 %) glazes, with all pairwise differences statistically significant ($p < 0.0001$). Conversely, K_2O levels are lowest in *luanbai* glazes (mean = 2.99 %, SD = 0.52 %), higher in *qingbai* (mean = 3.81 %, SD = 0.45 %), and highest in *huiqing* (mean = 4.32 %, SD = 0.5 %). CaO contents show comparatively modest variation across glaze styles, with *qingbai* (mean = 6.38 %, SD = 1.94 %) and *huiqing* (mean = 6.11 %, SD = 1.34 %) glazes slightly higher than *luanbai* (mean = 5.15 %, SD = 1.78 %). To clarify the origins of these elemental differences in flux oxides, enrichment–depletion plots and Al_2O_3-normalized oxide ratios were used to compare glaze and paste compositions (Figs. 11 and 12). Both Na_2O and K_2O show systematic enrichment in glazes relative to pastes across all three styles, with Na_2O/Al_2O_3 and K_2O/Al_2O_3 ratios in glazes consistently elevated above those in the corresponding pastes.

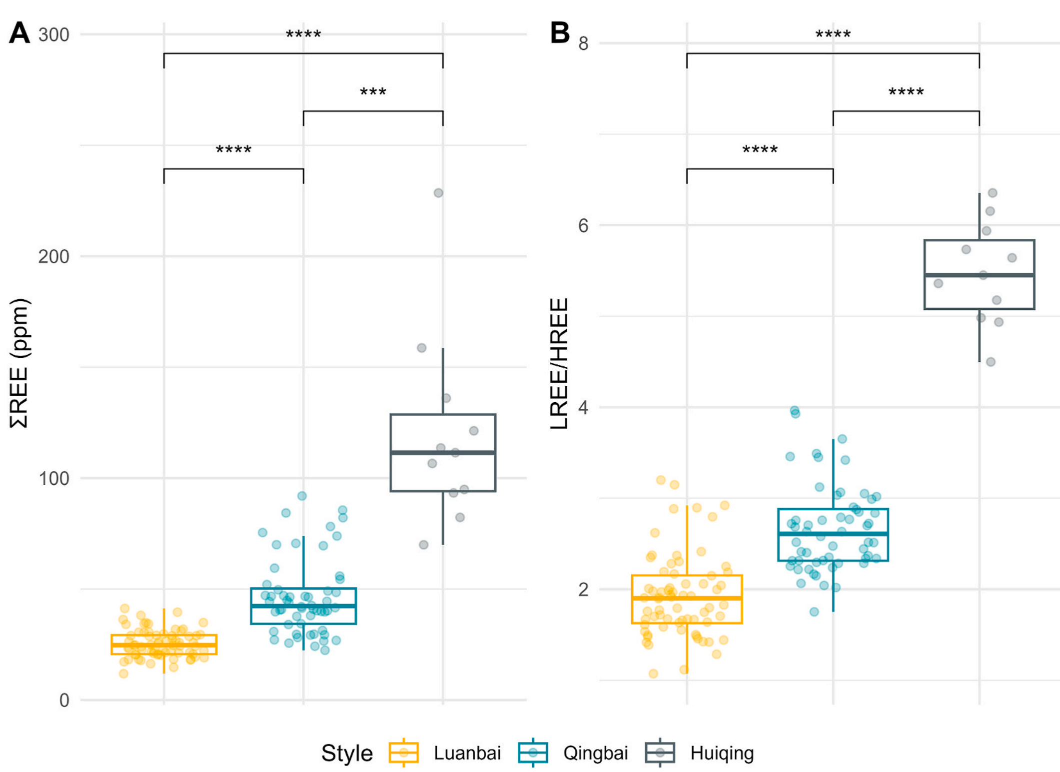

Fig. 8. Boxplots showing (left) the total REE concentrations (ΣREE) and (right) the LREE/HREE ratios in the pastes of egg-white (*luanbai*), bluish-white (*qingbai*), and grayish-green (*huiqing*) glazed porcelain samples. The asterisks indicate significance levels from pairwise t-tests: *** ($p \leq 0.001$) and **** ($p \leq 0.0001$). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

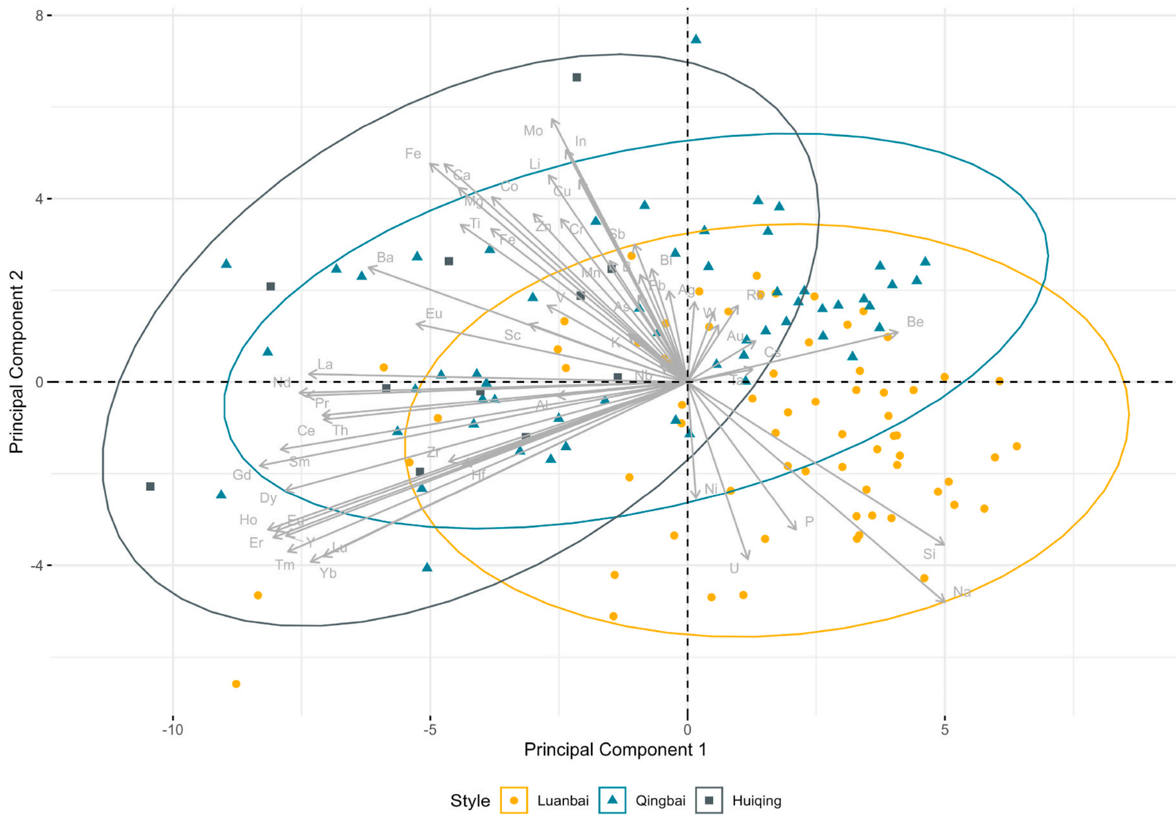

Fig. 9. PCA biplot of the full elemental composition (54 elements) in the glaze for egg-white (*luanbai*), bluish-white (*qingbai*), and grayish-green (*huiqing*) glazed porcelain samples. PC1 accounts for 26.9 % of the total variance, and PC2 for 9.9 %. The ellipses represent 90 % confidence intervals for each group. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

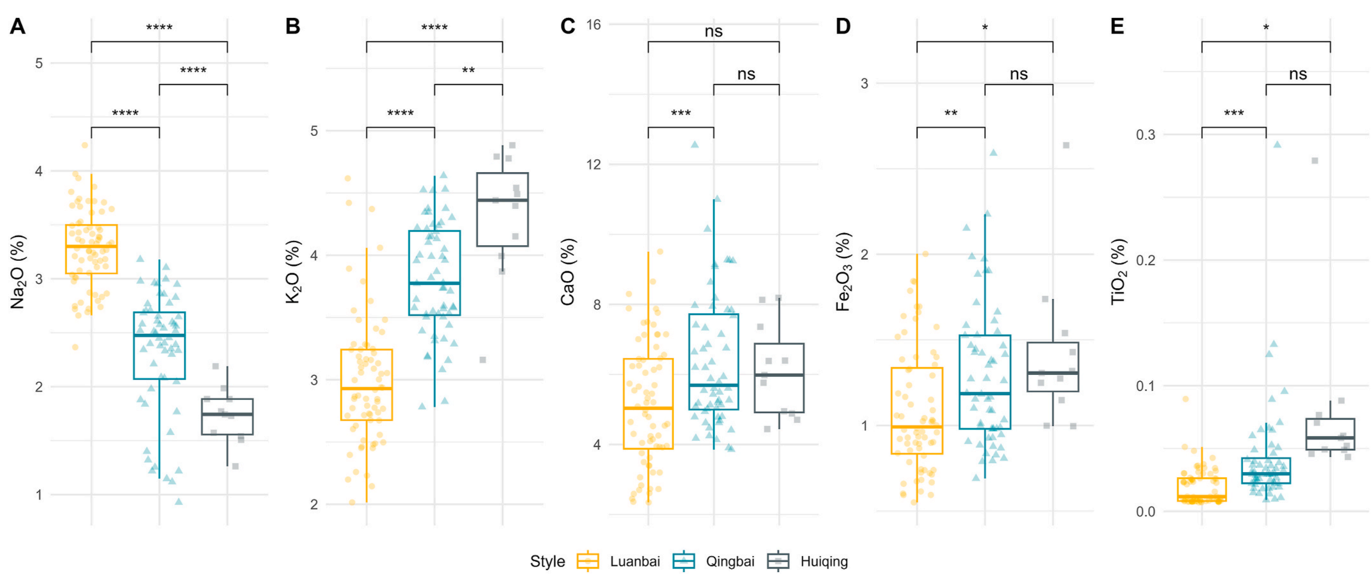

Fig. 10. Boxplots showing the concentrations of Na_2O, K_2O, CaO, Fe_2O_3, and TiO_2 in the glazes of egg-white (*luanbai*), bluish-white (*qingbai*), and grayish-green (*huiqing*) glazed porcelain samples. The asterisks indicate the significance levels from pairwise t-tests: ns ($p > 0.05$), * ($p \leq 0.05$), ** ($p \leq 0.01$), *** ($p \leq 0.001$), and **** ($p \leq 0.0001$). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Notably, the degree of this enrichment is relatively uniform across styles, suggesting a common underlying mechanism. In contrast, CaO displays a markedly different pattern: all three styles show substantial increases in CaO content from paste to glaze—often exceeding an order of magnitude—as evidenced by strong vertical displacements in enrichment plots and significantly elevated CaO/Al_2O_3 ratios in the glazes.

These patterns offer important insights into glaze formulation practices. The consistently elevated levels of sodium and potassium in glazes relative to their corresponding pastes—coupled with the relatively uniform magnitude of enrichment across all three porcelain styles—strongly suggest that these alkalis were not primarily introduced

Table 2
Average elemental concentrations, standard deviation (SD), and relative standard deviation (RSD) in glazes for *luanbai* (egg-white), *qingbai* (bluish-white), and *huiqing* (grayish-green) groups.

Element	*Luanbai* Group (n = 68)			*Qingbai* Group (n = 56)			*Huiqing* Group (n = 11)		
	mean	**SD**	**RSD (%)**	**mean**	**SD**	**RSD (%)**	**mean**	**SD**	***RSD (%)***
Oxide %									
SiO_2	73.47	2.00	2.73	71.67	2.10	2.93	70.65	1.90	2.69
Al_2O_3	13.72	0.78	5.68	14.00	1.03	7.33	15.18	1.41	9.31
NaO	3.28	0.37	11.14	2.32	0.57	24.52	1.73	0.26	14.77
MgO	0.27	0.10	37.11	0.27	0.08	30.09	0.32	0.10	32.24
K_2O	2.99	0.52	17.50	3.81	0.45	11.86	4.32	0.50	11.65
CaO	5.15	1.78	34.55	6.38	1.94	30.41	6.11	1.34	21.89
Fe_2O_3	1.08	0.36	33.46	1.29	0.42	32.40	1.42	0.46	32.27
MnO	0.09	0.03	27.57	0.09	0.03	28.30	0.08	0.04	48.08
TiO_2	0.02	0.01	74.07	0.04	0.04	100.40	0.08	0.07	85.40
P_2O_5	0.14	0.07	48.92	0.09	0.07	80.92	0.10	0.10	105.40
ppm									
Li	119.55	41.59	34.79	316.39	82.91	26.21	186.01	66.11	35.54
Be	16.19	5.84	36.11	13.12	4.70	35.83	11.07	6.02	54.38
B	91.65	26.83	29.27	85.00	26.21	30.83	123.29	24.92	20.22
Sc	2.49	0.29	11.50	2.75	0.40	14.55	2.90	0.29	9.84
V	10.47	5.69	54.36	16.97	13.65	80.40	22.79	9.59	42.08
Cr	2.82	1.78	63.21	3.05	1.62	53.17	3.01	1.63	54.31
Ni	69.25	51.60	74.51	25.47	16.01	62.83	60.56	37.43	61.81
Co	1.45	1.49	102.72	1.61	1.31	81.74	2.72	2.64	97.09
Cu	32.62	39.49	121.05	62.05	189.02	304.60	66.65	16.51	24.77
Zn	67.32	26.76	39.75	82.09	43.98	53.57	78.66	54.87	69.76
As	2.24	2.44	108.62	3.71	5.11	137.69	10.55	14.91	141.35
Rb	330.72	54.02	16.33	467.49	115.32	24.67	248.32	45.84	18.46
Sr	95.63	17.98	18.80	96.38	20.40	21.17	104.07	7.91	7.60
Zr	22.76	21.27	93.45	22.97	12.42	54.08	31.68	11.20	35.34
Nb	18.56	8.28	44.64	16.89	6.88	40.75	19.22	8.25	42.94
Ag	0.12	0.16	138.67	0.17	0.49	280.62	0.08	0.02	19.96
In	0.12	0.11	91.23	0.66	2.03	306.63	0.72	1.69	232.88
Sb	6.41	13.14	204.85	11.20	43.28	386.64	8.76	12.37	141.27
Cs	18.22	4.75	26.06	23.20	6.72	28.97	17.04	4.68	27.45
Ba	70.38	20.68	29.38	87.96	39.42	44.81	144.74	24.91	17.21
La	4.40	5.64	128.26	4.74	3.75	79.20	7.65	5.90	77.11
Ce	10.16	14.98	147.46	10.19	9.14	89.68	13.79	9.75	70.75
Pr	1.16	1.49	127.89	1.23	0.88	71.91	1.76	1.22	69.53
Ta	3.97	1.89	47.75	3.25	1.63	50.14	3.67	2.71	73.75
Au	0.04	0.03	81.05	0.04	0.05	135.09	0.03	0.02	71.49
Y	7.59	4.88	64.35	8.46	3.88	45.90	10.09	4.47	44.30
Pb	142.49	358.93	251.90	112.63	315.95	280.53	39.51	18.83	47.66
Bi	0.26	0.90	347.80	0.21	0.92	434.69	0.44	1.37	309.86
U	8.25	2.26	27.39	6.88	1.84	26.70	6.18	1.77	28.66
W	9.30	5.57	59.92	7.38	4.19	56.80	4.95	1.62	32.72
Mo	1.14	0.74	65.15	1.85	0.90	48.51	1.83	0.77	42.38
Nd	4.42	5.13	116.12	4.88	3.65	74.87	6.98	4.82	69.09
Sm	1.36	1.15	84.14	1.54	0.78	50.98	1.96	1.04	53.06
Eu	0.33	0.42	125.35	0.38	0.20	52.74	0.54	0.25	46.13
Gd	1.23	0.67	54.27	1.50	0.73	48.25	1.90	0.94	49.59
Tb	0.23	0.21	89.57	0.25	0.11	44.79	0.30	0.13	44.67
Dy	1.39	0.43	31.12	1.69	0.77	45.36	2.05	0.90	43.70
Ho	0.22	0.18	78.11	0.25	0.12	45.72	0.32	0.13	41.93
Er	0.67	0.50	74.58	0.75	0.34	44.70	0.95	0.40	41.53
Tm	0.09	0.06	65.76	0.10	0.04	41.57	0.12	0.05	39.77
Yb	0.76	0.47	61.55	0.78	0.31	39.32	0.97	0.35	36.44
Lu	0.09	0.06	71.05	0.09	0.04	40.42	0.11	0.04	34.32
Hf	1.86	1.90	102.34	1.78	0.83	46.84	1.92	0.32	16.77
Th	1.81	0.81	44.75	2.96	1.85	62.55	4.93	1.28	26.02

through the selective addition of sodium- or potassium-rich fluxing agents. Rather, they likely reflect a combination of firing-induced interdiffusion, whereby sodium and potassium migrate from the paste into the glaze during high-temperature processing (Pradell and Molera, 2020), and the inherently alkali-bearing composition of the porcelain stones used in both paste and glaze formulations. In contrast, the markedly higher CaO contents in glazes relative to pastes—often exceeding paste levels by more than an order of magnitude—point to an exogenous source of calcium. Previous studies have shown that Yuan dynasty Jingdezhen glazes were typically prepared by mixing certain clay material—commonly porcelain stone (also referred to as "glaze-stone")—with a flux composed primarily of plant ash and lime (Wood, 1999; Wu, 2020). While glaze ash serves as a major source of calcium, it contributes negligible amounts of sodium or potassium. These patterns thus support the conclusion that sodium and potassium in the glazes were primarily sourced from the same porcelain stone used in the paste—reflecting a shared raw material base—whereas calcium was introduced separately through the addition of glaze ash.

Additional support for this interpretation is provided by the levels of Fe_2O_3 and TiO_2 in the glazes, which closely mirror the patterns observed in the pastes (Fig. 10). *Luanbai* glazes exhibit the lowest levels of these impurities (Fe_2O_3 mean = 1.08 %, SD = 0.36 %; TiO_2 mean = 0.02 %, SD = 0.01 %), *huiqing* the highest (Fe_2O_3 mean = 1.42 %, SD = 0.46 %; TiO_2 mean = 0.08 %, SD = 0.07 %), and *qingbai* intermediate value

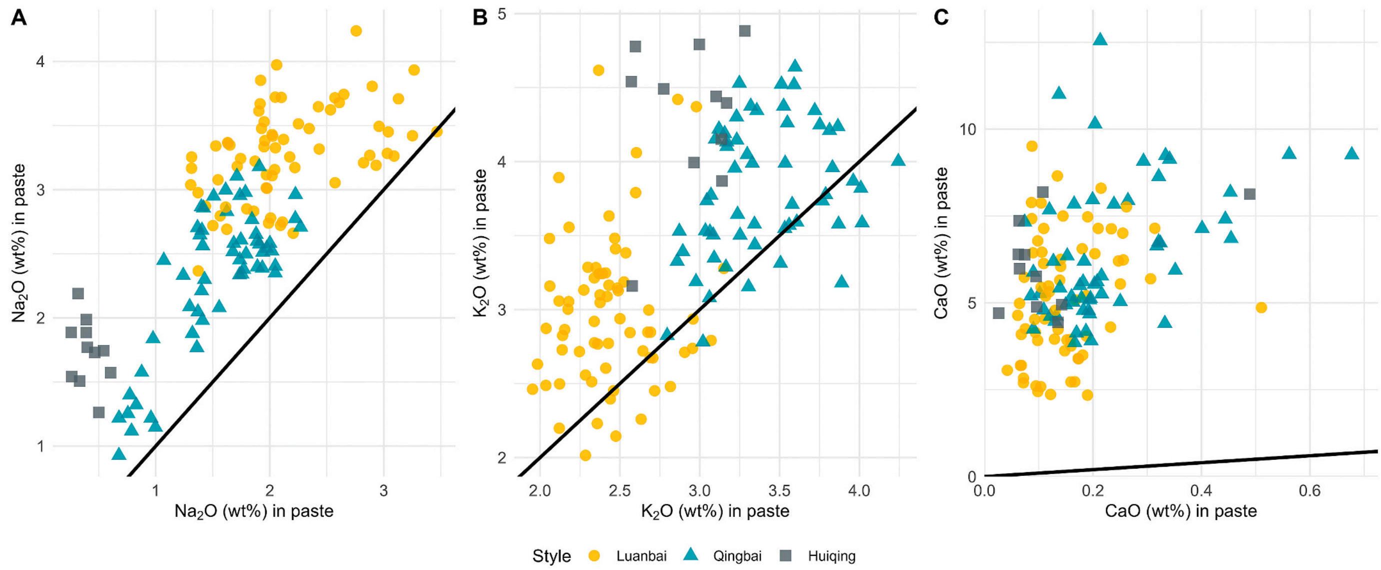

Fig. 11. Enrichment-depletion plots comparing the concentrations of Na_2O, K_2O, and CaO in glaze and paste samples from egg-white (*luanbai*), bluish-white (*qingbai*), and grayish-green (*huiqing*) glazed porcelains. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

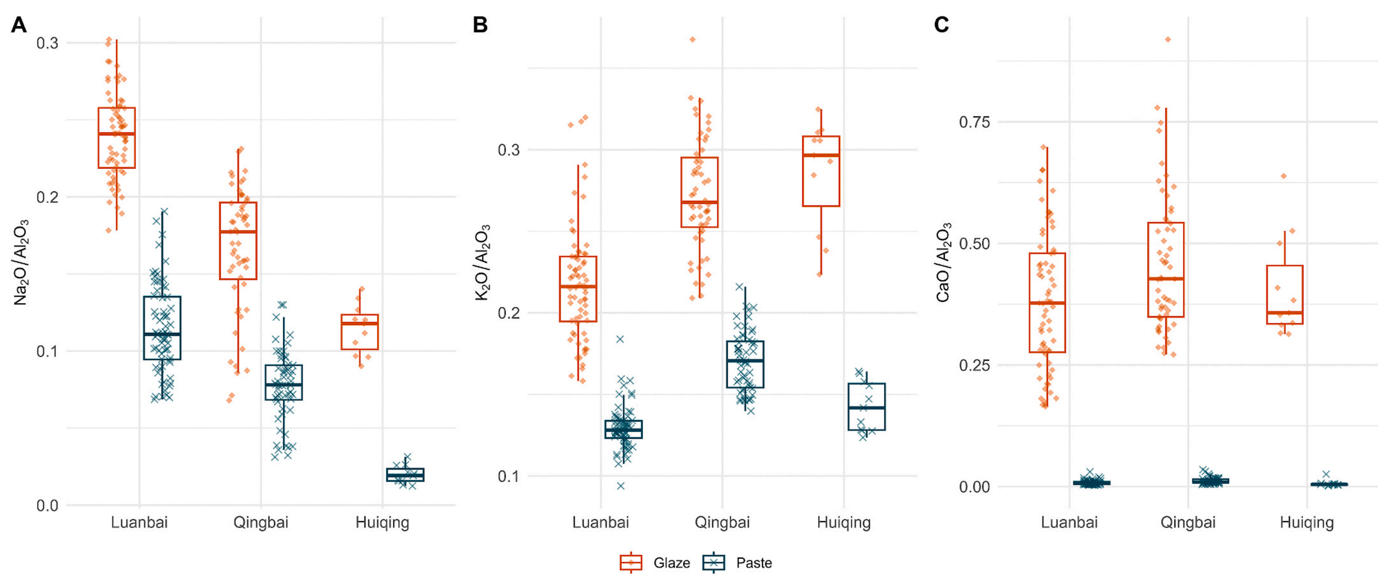

Fig. 12. Boxplots comparing the oxide-to-alumina ratios (Na_2O/Al_2O_3, K_2O/Al_2O_3, and CaO/Al_2O_3) in glazes and pastes from egg-white (*luanbai*), bluish-white (*qingbai*), and grayish-green (*huiqing*) glazed porcelains. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(Fe_2O_3 mean = 1.29 %, SD = 0.42 %; TiO_2 mean = 0.04 %, SD = 0.04 %). This parallel trend further reinforces the inference that the same geological sources of porcelain stone were used in both paste and glaze.

In summary, while all three porcelain styles likely employed a broadly similar glaze formulation strategy—based on the combination of porcelain stone and glaze ash—the primary differences in glaze composition appear to reflect variations in the types of porcelain stone selected. *Luanbai* glazes were formulated using a highly refined, soda-rich, low-impurity porcelain stone; *qingbai* glazes were based on a potassic-rich feldspathic source; and *huiqing* glazes were prepared from porcelain stones with higher impurity levels. These distinctions underscore the style-specific adaptation of raw materials within a shared technological tradition and further highlight the differentiated production strategies employed at the Luomaqiao kiln site during the Yuan dynasty.

4.2. Five-clawed dragon pattern, imperial clay, and production organization at the Luomaqiao kiln

Building on the results of the compositional analysis, this section continues to address questions concerning the use of raw materials and the organization of production at the Luomaqiao kiln, with a particular focus on five-clawed dragon porcelains. Were porcelains bearing the five-clawed dragon motif produced using a special type of clay distinct from that used for ordinary *luanbai* wares, and if so, could this clay correspond to the *yutu* (imperial clay) described in historical records as reserved for official use? What do patterns of material usage reveal about the organization of production at Luomaqiao?

4.2.1. Did five-clawed dragon porcelains use a distinct clay source?

To address this question, we revisited the PCA results of paste compositions, this time marking the samples decorated with five-clawed and four-clawed dragon motifs to examine their distribution within the broader dataset (Fig. 13). The biplot shows that all dragon-decorated samples—including those bearing five-clawed and four-clawed motifs—cluster tightly within the main *luanbai* group, with no observable outliers or distinct sub-clusters. To verify this pattern and quantitatively assess this relationship, we further conducted Mahalanobis distance-based group membership probability calculations using the first six principal components derived from the PCA, which together account for approximately 85 % of the total variance. The results show that all five-clawed dragon motif samples (LMQ008–LMQ016) exhibit high probabilities of belonging to the *luanbai* group (see Dataset_S4 in the Mendeley Data repository). Specifically, samples LMQ009 and LMQ008 show particularly high alignment (92.84 % and 83.96 %, respectively), while most others exceed 60 %, confirming their compositional conformity with the broader *luanbai* group. Taken together, these findings demonstrate that despite their exclusive imperial symbolism, the five-clawed dragon porcelains were not made from a distinct clay source but rather from the same material used for *luanbai* wares more broadly.

Despite this compositional similarity, a more granular comparison of compositional variability in pastes reveals differences in the degree of material standardization. Five-clawed dragon porcelains exhibit the lowest degree of variability: in all 46 of the 58 analyzed elements in the pastes, their coefficients of variation (CV, expressed as '%RSD' in the tables) values are lower than those of the ordinary *luanbai* porcelains, and for 29 elements, they are also lower than those of the four-clawed group (see Dataset_S5 in the Mendeley Data repository). The four-clawed group also displays relatively low variability, with 40 elements showing lower CV values than the ordinary *luanbai* group. Together, these results reflect a stratification in material standardization, where five-clawed porcelains—intended for the imperial use—underwent the most rigorous quality control, followed by the four-clawed group likely associated with elite or high-ranking consumption, while ordinary *luanbai* wares were produced using a broader and less tightly regulated material base. This gradient of variability underscores a deliberate system of quality control tied to the symbolic and social status of each product category.

This finding raises a critical question: although five-clawed dragon porcelains did not use a distinct clay source, the material they share with ordinary *luanbai* wares is itself compositionally unique—clearly different from the clays used in other styles of porcelain. Could this distinctive material have been a state-supplied resource—perhaps the *yutu* described in historical records?

4.2.2. *Was the so-called yutu (imperial clay) used in production?*

To explore this possibility, we turn to the institutional context of Yuan-dynasty ceramic production, with particular attention to the structure and function of the Fuliang Porcelain Bureau. Historical sources describe the Bureau as an official handicraft institution responsible for the production of porcelain and other crafts (Chen et al., 2011; Song, 1976). Although its administrative and the exact number of artisans it oversaw vary across sources, scholarly estimates suggest it managed between 100 and 300 registered households (Li, 1994; Xu, 2013; Zeng, 2012). These artisans, known as *xiguan jianghu* (government-affiliated artisan households), were typically assigned to official workshops, received state provisions, and were either supplied with raw materials or allocated funds to procure them in order to fulfill mandated quotas (Chen, 2019; Fang, 2001; Gao, 1997; Ju, 1935). The Yuan government also exercised stringent oversight over material management in official bureaus or workshops, mandating the return of surplus materials and enforcing legal penalties for the theft of

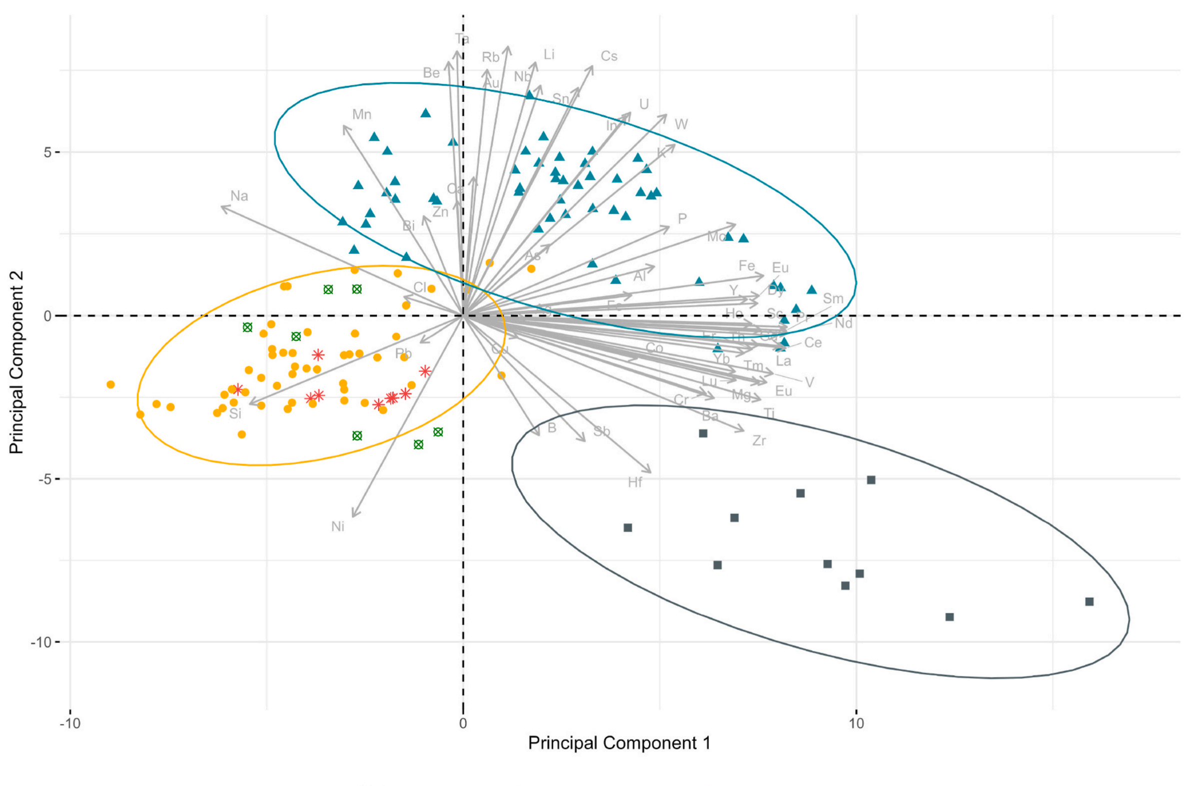

Fig. 13. PCA biplot illustrating the distribution of paste compositions (based on 56 elements) for egg-white (*luanbai*), bluish-white (*qingbai*), and grayish-green (*huiqing*) glazed porcelain samples, with the addition of markers for pieces decorated with four-clawed and five-clawed dragon motifs. PC1 accounts for 42.8 % of the total variance, and PC2 for 21.4 %. The ellipses represent 90 % confidence intervals for each group. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

government property (Chen et al., 2011:1953; Song, 1976:1765). As such, the Fuliang Porcelain Bureau did not function as a tax-collecting agent or supervisory body overseeing private kilns, but rather as a state-run handicraft institution with artisans working within its infrastructure and relying on government-supplied materials for regulated production tasks. Moreover, historical records consistently emphasize that the five-clawed, double-horned dragon motif was strictly reserved for imperial use (Chen et al., 2011:1968; Fang, 2001:358; Song, 1976:1942), indicating that the wares featuring this design produced at the Luomaqiao kiln were likely intended for the court. Given the exclusive symbolism of the five-clawed dragon, the administrative model of the Fuliang Porcelain Bureau, and the Yuan government's strict policies governing raw material distribution, it is reasonable to infer that the five-clawed dragon porcelains produced at Luomaqiao were made using raw materials directly supplied by the government.

This interpretation is also consistent with the results of the compositional analysis, which show that *luanbai* porcelains—including those bearing imperial motifs—were made from a geochemically distinct type of clay, clearly different from the materials used in *qingbai* and *huiqing* wares. The distinction extends to both the paste and the glaze, suggesting a coherent and deliberate choice of high-quality clay tailored to a specific production system. Given the convergence of compositional and historical evidence, it is highly plausible that this distinctive clay corresponds to the *yutu* referenced in Yuan-dynasty documents.

However, this special raw material was not used exclusively for five-clawed dragon porcelains. As the compositional data indicate, the same clay was also employed in the production of ordinary *luanbai* wares, implying that access to government-supplied materials may have extended beyond strictly regulated imperial products. This observation aligns with Kong Qi's notes that while private use of the *yutu* was prohibited, surplus clay was sometimes used to make everyday items (Kong, 1987). Yet this raises a further question: how did a material supposedly reserved for imperial production come to be used in non-imperial contexts?

4.2.3. How did the imperial clay end up in ordinary products?

Understanding this apparent contradiction requires a closer look at the Yuan dynasty's broader approach to porcelain governance and the actual conditions under which official workshops operated. Compared with bureaus responsible for crafting gold, jade, and agate items, the Fuliang Porcelain Bureau occupied a low position in the government hierarchy (Chen, 2019; Shi, 2003; Xu, 2013), and even ranked lower than other kilns responsible for producing building materials (Song, 1976:1515). The Yuan court placed the highest value on gold, jade, and agate vessels, with porcelain being less significant (Shi, 2003). Historical accounts mention that when the emperor discovered a minister using porcelain, he considered it too frugal and bestowed upon him luxurious items to encourage possessions befitting his rank (Song, 1976:2639–41). Additionally, porcelain was listed among items considered "of no use in our land," traded to foreign merchants for more valuable commodities (Chen et al., 2011:874). Moreover, scholars have found that official production quotas in the Yuan dynasty were not excessively burdensome, and even with additional orders, artisans did not need to work year-round in government workshops (Gao, 1997; Hu, 2003; Ju, 1935; Liu and Chen, 2003). The enforcement of material regulations appears to have been inconsistent in practice. While the surplus was supposed to be returned to the state, in practice it was often retained or informally redistributed. Instances of private production by attached artisans were not uncommon, and in some cases, even local officials requested such unauthorized work (Fang, 2001:104). In this context, it becomes more plausible that the *yutu*—though officially controlled—entered circulation beyond its intended imperial scope.

These institutional and administrative conditions also help explain the diverse range of products found at the Luomaqiao kiln, which does not conform neatly to either a fully state-controlled or an entirely independent model of craft production. While the kiln produced five-clawed dragon porcelains likely destined for the court—an indicator of state involvement—it also manufactured ordinary *luanbai* porcelains and even *qingbai* and *huiqing* wares using different raw materials. The simultaneous use of state-supplied clay for both imperial and non-imperial products reflects a hybrid mode of operation in which government oversight coexisted with considerable artisan autonomy. Although the Yuan dynasty established the Fuliang Porcelain Bureau, oversaw government-affiliated artisans, and provided raw materials such as the *yutu*, in practice it may neither have demanded large quantities of porcelain nor strictly enforced production regulations, allowing for instances of private production.

4.3. Fluidity in production roles: blurring boundaries between attached and independent production

The findings at the Luomaqiao kiln provide a compelling case study of the complexities within ancient craft production systems, illustrating that the boundaries between attached and independent production were far more fluid and dynamic than traditionally perceived. This fluidity is evident in the interplay between state control and artisan agency during the Yuan dynasty, where the distinctions between official policies and their implementation, as well as between state oversight and artisan autonomy, are often blurred.

In practice, the Luomaqiao production system did not conform to either extreme of complete state control or total artisan independence. Instead, it operated as a dynamic hybrid model in which production roles were highly adaptive and responsive, defined by a broad spectrum of overlapping control and agency. While the kiln was likely established and maintained by the government—with official artisans and allocated materials like the *yutu* for imperial items such as five-clawed dragon porcelains—it simultaneously engaged in activities beyond its official mandate. The same high-quality materials intended for imperial wares were used to produce ordinary *luanbai* porcelains, while the kiln also produced *qingbai* and *huiqing* wares using different sources of raw materials. This parallel production of official porcelains alongside ordinary products within a single facility illustrates how an ostensibly "attached" workshop could operate flexibly as a *de facto* hybrid system within a formal state framework.

This blending of official and private production modes within a single operational context suggests that the artisans at Luomaqiao actively navigated between fulfilling state-imposed duties and exploiting opportunities for broader economic engagement. Despite their formal status as attached specialists bound by state regulations, the Luomaqiao potters exercised considerable autonomy, engaging in private production with state-supplied materials and even appropriating restricted imperial motifs whenever oversight was minimal or enforcement lax. Such strategic behavior shows that artisans were not passive executors of state orders but active agents who made calculated decisions to advance their own interests within the attached system's constraints.

Moreover, the Luomaqiao evidence exposes a clear discrepancy between the intended policies of state control and how production actually operated in practice. Although the Yuan state had established strict regulations for its official kilns—requiring artisans to work exclusively in government workshops, forbidding any unauthorized private production, mandating the return of surplus materials to the authorities, and reserving certain prestigious motifs (such as the five-clawed dragon) for imperial wares alone—the enforcement of these edicts was likely far from absolute. Both historical records and archaeological evidence indicate that unauthorized private production, the covert use of state-supplied materials, and even the improper application of reserved imperial designs were not uncommon occurrences. These contradictions between policy and practice highlight the inherent flexibility of attached production systems and underscore the importance of considering how official regulations were implemented (or circumvented) on the ground. Recognizing this implementation gap enriches our understanding of production in complex societies, revealing that such systems were shaped not only by the rigidity of official rules but also by the adaptability and agency of those working within them.

Ultimately, in a broader comparative perspective, the Luomaqiao case contributes to a growing body of scholarship that challenges rigid, universal models of centralized control in imperial craft production contexts (Clark, 1995; Costin and Lynne, 1991; Inomata, 2001; Sinopoli, 2003). It demonstrates that even under formal state oversight, craft production could operate in surprisingly flexible, multi-tiered ways that accommodated both official and unofficial outputs. These findings encourage us to move beyond simple typological classifications and to adopt more nuanced analytical frameworks that account for the variability, negotiation, and artisan agency inherent in production systems. By integrating high-resolution compositional data with historical documentation, this study provides a concrete example that calls into question overly simplistic categorizations of craft organization, highlighting instead the complex, context-dependent nature of production under imperial regimes.

5. Conclusion

This study reveals a complex and fluid system of ceramic production at the Luomaqiao kiln site in Yuan-dynasty Jingdezhen. High-resolution LA-ICP-MS analysis reveals that the three major porcelain styles—*luanbai*, *qingbai*, and *huiqing*—were produced using geochemically distinct raw materials, reflecting deliberate choices in sourcing and production strategy. Notably, the *luanbai* wares bearing the five-clawed dragon motif exhibit exceptional purity and compositional homogeneity, suggesting the use of *yutu* (imperial clay) as described in historical records. Yet the same high-quality material was also employed in the production of ordinary *luanbai* wares. This finding reveals a disconnect between official regulations and on-the-ground practice: materials formally reserved for imperial porcelain were not confined to official products but circulated into common output. Such evidence suggests that artisans operated in a flexible institutional environment, one shaped not only by formal regulation but also by informal adjustments and situational decisions made in the course of production. In effect, the boundaries between “official” and “private” production at Luomaqiao were blurred, with imperial resources and motifs permeating beyond their prescribed domain.

Rather than a rigid system of centralized control, the Luomaqiao kiln exemplifies a hybrid model in which state oversight, symbolic restrictions, artisan agency, and different production practices coexisted in dynamic and sometimes contradictory ways. Artisans working within a state-managed framework were not passive executors of state-imposed duties but strategic agents who navigated, adapted, and at times reconfigured the institutional boundaries imposed upon them. This case therefore challenges the conventional binary division between attached and independent craft production. It reveals instead a continuum of production arrangements, where authority, resource access, and individual agency were continuously negotiated in practice.

By integrating high-resolution compositional analysis with archaeological context and historical documentation, this study highlights how ancient craft production could operate in flexible, multi-tiered ways that defy simplistic classification. Such insights call for more nuanced analytical frameworks that account for the dynamic interplay of state authority and artisan agency in ancient societies. Ultimately, the Luomaqiao findings not only deepen our understanding of Yuan-era porcelain production in Jingdezhen, but also provide a valuable comparative perspective. They illustrate that even under strong imperial oversight, craft production systems could be remarkably adaptable—a finding that resonates with studies of pre-modern craft organizations in other complex societies.

CRediT authorship contribution statement

Wenpeng Xu: Writing – review & editing, Visualization, Supervision, Resources, Methodology, Funding acquisition, Data curation, Writing – original draft, Validation, Software, Project administration, Investigation, Formal analysis, Conceptualization. **Dashu Qin:** Resources, Supervision. **Yanjun Weng:** Resources, Data curation, Project administration, Investigation. **Xianping Gao:** Data curation. **Yu Ding:** Funding acquisition, Project administration.

Data availability statement

All data and R scripts used in this study are publicly available in Mendeley Data (https://doi.org/10.17632/p49ncrb39k.1). The Associate Editor for Reproducibility downloaded all materials and could reproduce the results presented by the authors.

Declaration of competing interest

We have no conflict of interest regarding the research or entities involved in this research.

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