

Raw Materials and Body-Glaze Technology in Qingbai Porcelain Production at the Fanchang Kiln

Zitian Li

Peking University

Kaiwen Zuo

91004@n.jnu.edu.cn

Nanjing Normal University

Jianfeng Cui

Peking University

Zhigao Wang

Nanjing Normal University

Research Article

Keywords: qingbai porcelain, Fanchang kiln, binary formula, body and glaze formula

Posted Date: October 23rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11282680/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Raw Materials and Body-Glaze Technology in Qingbai Porcelain Production at the Fanchang Kiln

Zitian Li^{1†}, Kaiwen Zuo^{2†*}, Jianfeng Cui¹, Zhigao Wang²

¹ School of Archaeology and Museology, Peking University, Beijing, China

² School of History and Archaeology, Nanjing Normal University, Nanjing, China

† First Author and Second Author contributed equally to this work.

*Corresponding author

Email: 91004@njnu.edu.cn

ORCID: 0009-0008-6205-7738

First Author

Email: 2601211052@stu.pku.edu.cn

ORCID: 0009-0001-3293-3548

Abstract

The emergence of the ‘binary formula’ is an important issue in the development of porcelain raw material technology in southern China, and both its date of emergence and the criteria for its identification have long been debated. This study examines raw materials from porcelain workshops, qingbai porcelain sherds and underfired specimens excavated at the Fanchang kiln in 2025, analysing their chemical compositions, mineralogical compositions, firing temperatures and colouration mechanisms from a production-chain perspective. The results show that the $\text{SiO}_2\text{-Al}_2\text{O}_3$ trends of the porcelain bodies are broadly consistent with those of the workshop raw materials. Considered together with the mineralogical and microstructural evidence, these results provide no clear evidence for the deliberate addition of kaolin. The relatively high Al_2O_3 contents of the bodies are more likely to be associated with kaolin naturally occurring in the porcelain stone and with raw material processing. The glazes are high-fired lime glazes containing plant ash, with firing temperatures of approximately 1150-1250 °C. Differences in glaze colour are mainly influenced by Fe_2O_3 and TiO_2 contents and the firing atmosphere. This study provides new evidence for reassessing the ‘binary formula’ debate at the Fanchang kiln and the raw material technology of early qingbai porcelain.

Keywords

qingbai porcelain; Fanchang kiln; binary formula; body and glaze formula

Introduction

The Fanchang kiln in Anhui province was a highly representative kiln centre in southern China during the Five Dynasties and Northern Song periods (Fig. 1). Some scholars have argued that it should be identified as the ‘Xuanzhou kiln’, an official kiln of the Southern Tang recorded in historical documents. As the earliest qingbai porcelain production site currently known from archaeological discoveries, the Fanchang kiln is of considerable academic importance for investigating the emergence and development of qingbai porcelain technology and clarifying the processes of exchange and integration between northern and southern porcelain-making traditions.

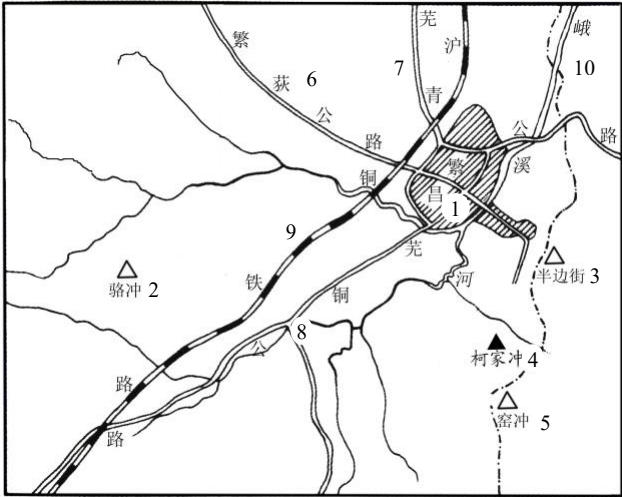


Fig. 1 Geographical location of the Fanchang kiln and distribution of the main kiln sites(Adapted from Anhui Provincial Institute of Cultural Relics and Archaeology, 2016)

Map key: 1, Fanchang; 2, Luochong; 3, Banbianjie; 4, Kejiachong; 5, Yaochong; 6, Fandi Road; 7, Wuhu-Qingyang Road; 8, Wuhu-Tongling Road; 9, Shanghai-Tongling Railway; 10, Exi River.

The central controversy in research on the Fanchang kiln concerns whether its potters had already adopted a ‘binary formula’ involving the deliberate addition of kaolin. The term ‘binary formula’ refers to a body-preparation technique in which alumina-rich materials such as kaolin are deliberately added to porcelain stone. Combining porcelain stone and kaolin in specific proportions can increase the refractoriness and strength of porcelain bodies and reduce deformation at high temperatures during firing. The emergence of the binary formula marked a shift in southern porcelain technology from the use of naturally suitable raw materials towards the deliberate control of body properties. Closely associated with the exploitation of kaolin resources and improvements in kiln technology, it represented an important advance in the history of Chinese ceramic technology.

Discussions concerning the origins of the binary formula have focused primarily on Jingdezhen, with the central issue being how to distinguish a formula using porcelain stone alone from a binary formula involving the deliberate addition of kaolin. Natural porcelain stone generally contains less than 18% Al_2O_3 , and both levigation and the addition of kaolin can increase the Al_2O_3 content of porcelain bodies. Previous research has argued that, under ancient production conditions, levigation alone would have been unlikely to raise the Al_2O_3 content above 20%, and has therefore inferred that the binary formula was already in use at Jingdezhen during the Yuan dynasty (Liu and Bai 1982). Other research has noted that the Al_2O_3 content of Yuan-dynasty Jingdezhen porcelain bodies never exceeded 23%. Considered alongside other archaeological and documentary evidence, this observation suggests that porcelain stone containing naturally associated kaolinite was more likely to have been used. According to this interpretation, the true binary formula originated in the late Ming and early Qing periods and began to be widely used only during the Qing dynasty (Xiao et al. 2020).

The Fanchang kiln successfully produced qingbai (bluish-white) porcelain as early as the Five Dynasties period, providing important material for investigating the early development of ‘binary formula’ technology. Since the 1980s, scholars have sampled and analysed porcelain stone from the vicinity of the Fanchang kiln site. They identified a substantial difference in Al_2O_3 content between the porcelain bodies and the raw materials and proposed that ‘binary formula’ technology might already have existed at that time (Hu 1994; Wang 2022; Yang and Zhang 2006). In 2014, a research team conducted a field survey near the site. They found that kaolin deposits near Mount Maren, more than 10 km from the kiln site, contained over 25% alumina, providing a possible source of alumina-rich raw materials (Wang 2022).

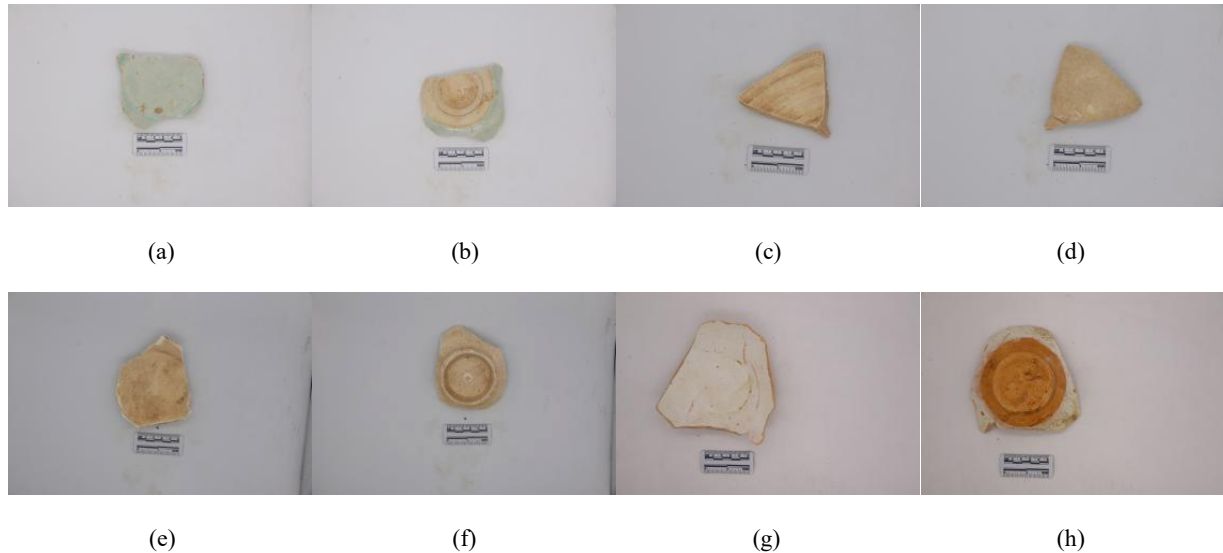
By contrast, Dong Wenkai argued, on the basis of ceramic science, that the kaolin deposits near Fanchang County could not yet explain the substantial difference in alumina content between the porcelain bodies and the raw materials. Moreover, no kaolin extraction sites dating to the Five Dynasties or Northern Song periods have been identified at Fanchang, and a direct chain of evidence supporting the ‘binary formula’ has yet to be established (Dong 2019). More importantly, the ‘raw materials’ examined in previous studies generally consisted of porcelain clay deposits near the site or rock debris excavated in the workshop area. These do not necessarily represent the materials that actually entered the porcelain-making process after levigation, settling and other operations. Direct comparison of such samples with porcelain body compositions may therefore be insufficient to establish whether kaolin was deliberately added.

Accordingly, this study examines sediment samples collected from porcelain-making tanks at the Fanchang kiln, using raw materials from workshop production stages to reassess the hypothesis that the binary formula had already emerged. On this basis, it also discusses body and glaze recipes, firing technology and colouration.

Materials and methods

(1) Materials

82 The materials examined in this study comprise 74 ceramic sherds and five sediment samples from porcelain-making
 83 tanks discovered during the 2025 excavations at the Fanchang kiln site in Fanchang District, Anhui Province, dating from the
 84 early to middle Northern Song period. The sherds were numbered FCYYP1-74; nine were intrusive earlier pottery sherds
 85 and are excluded from the discussion. The remaining 65 samples were divided into four categories according to glazing,
 86 degree of sintering and glaze colour: 18 bluish qingbai sherds, 26 yellowish qingbai sherds, 12 underfired sherds and nine
 87 underfired sherds with slip coatings. The five porcelain raw material samples were collected, respectively, from the bottom
 88 of levigation tank C2, the upper part of C2, settling tank C3, the bottom and sidewall of C5, and the interior of C5, and were
 89 numbered FCYTY1-5. All samples were photographed before analysis (Fig. 2).



94 **Fig. 2** Selected ceramic sherds recovered from the excavation of the Fanchang kiln site

95 (a) FCYYP5-concave; (b) FCYYP5-convex; (c) FCYYP13-concave; (d) FCYYP13-convex; (e) FCYYP48-concave; (f) FCYYP48-convex;
 96 (g) FCYYP71-concave; (h) FCYYP71-convex.

97 (2) Methods

98 The colours of the qingbai porcelain samples were measured using a WR-10 precision colourimeter manufactured by
 99 China Weifu Optoelectronic Technology Co., Ltd., in the CIE $L^*a^*b^*$ colour space. Sample surfaces were cleaned and
 100 levelled before measurement, and measurements were performed after instrument calibration. L^* represents lightness, a^* the
 101 red-green coordinate and b^* the yellow-blue coordinate. Differences in lightness and colour were used to evaluate colour
 102 variation among the samples.

103 The surfaces and cross-sections of all sherds were examined by stereomicroscopy and photographed using a Keyence
 104 VHX-5000 3D digital microscope with an extended depth of field.

105 A Hitachi TM3030 tabletop scanning electron microscope equipped with a Bruker QUANTAX 70 energy-dispersive
 106 spectrometer was used to examine the microstructures and analyse the chemical compositions of the sherds included in this
 107 study. Standardless analysis was performed at an accelerating voltage of 15 kV with an acquisition time of 120 s. Sample
 108 morphology and structure were observed under vacuum, and areas with a homogeneous structure on the cross-sections were
 109 selected for chemical analysis of the porcelain bodies.

Experimental firing of the five porcelain raw material samples was conducted in a muffle furnace. The samples were heated in air at a rate of 5-10 °C/min and held at 1100 °C for 3 h. The resulting specimens were used for LA-ICP-AES analysis.

A DIL806 dilatometer was used to record dimensional changes in eight samples with increasing temperature. Curves of dimensional change during heating and their derivatives were obtained to assess firing temperatures. As the results were broadly consistent, the study presents two representative curves.

The chemical compositions of the glazes and experimentally fired sediment samples were analysed by laser ablation inductively coupled plasma atomic emission spectrometry (LA-ICP-AES), using a Prodigy High Dispersion inductively coupled plasma atomic emission spectrometer coupled to a UP-266 Macro laser ablation system. The laser beam diameter was 780 µm, and calibration was performed using Corning D as the reference material. The data were processed using a single-standard normalisation method and are reported as oxides.

An OLYMPUS TERRA-0677 portable X-ray diffractometer was used to analyse the mineralogical compositions of the sediment samples from the porcelain-making tanks, the bodies of the underfired specimens and their surface slip coatings. The X-ray tube was operated at 30 kV and 300 µA.

(3) Data processing

Statistical analysis of the colourimetric data was performed in R. The three colour parameters L^* , a^* and b^* were used as variables in k-means clustering. The number of clusters was set to two according to the glaze colours of the samples and the aims of the study.

Principal component analysis (PCA) of the chemical composition data for both bodies and glazes was performed in R. The Fanchang samples were combined with the corresponding comparative datasets. Samples with missing values were excluded, and all variables were standardised before PCA.

Results

(1) Visual characteristics

The k-means clustering results based on L^* , a^* and b^* indicate that the qingbai porcelain samples can be divided into two groups. The groups are relatively well separated in colour space and broadly correspond to the bluish and yellowish glaze colours visible to the naked eye (Figs. 3 and 4).

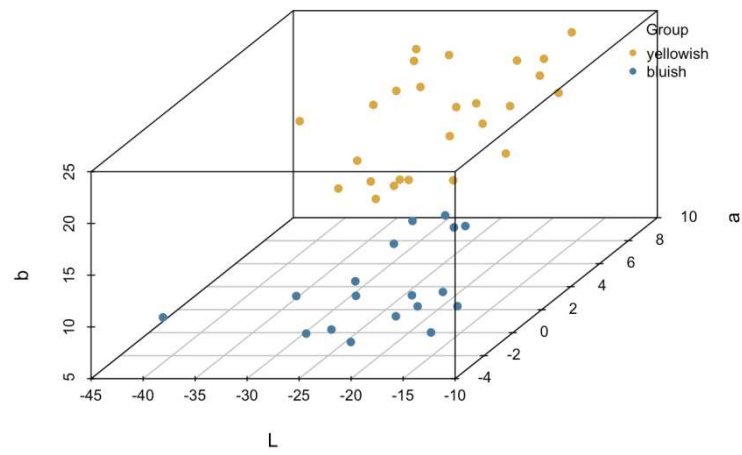


Fig. 3 Three-dimensional visualisation of the colourimetric measurements and clustering results

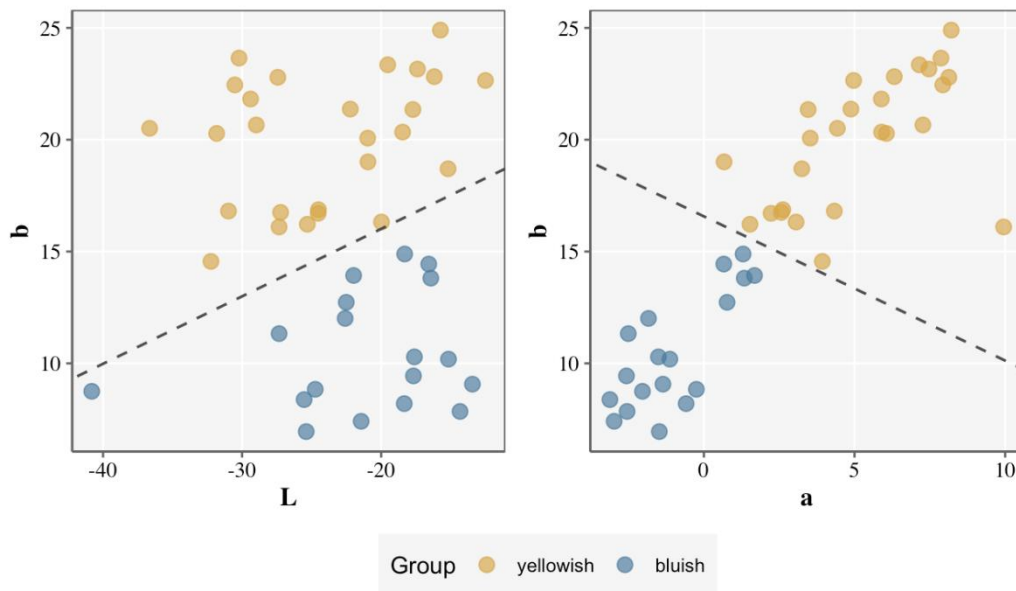
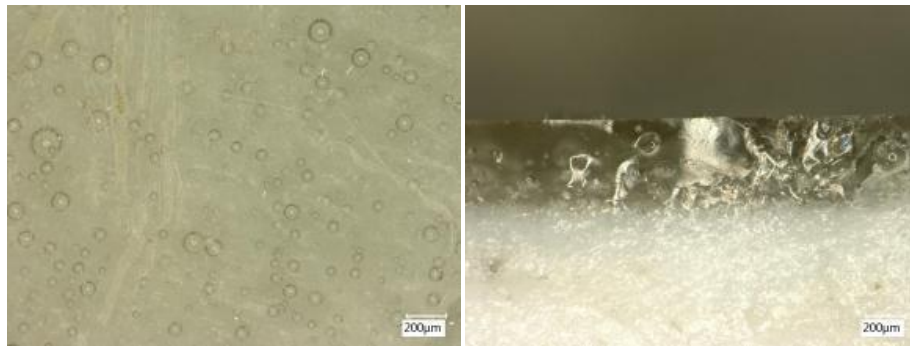


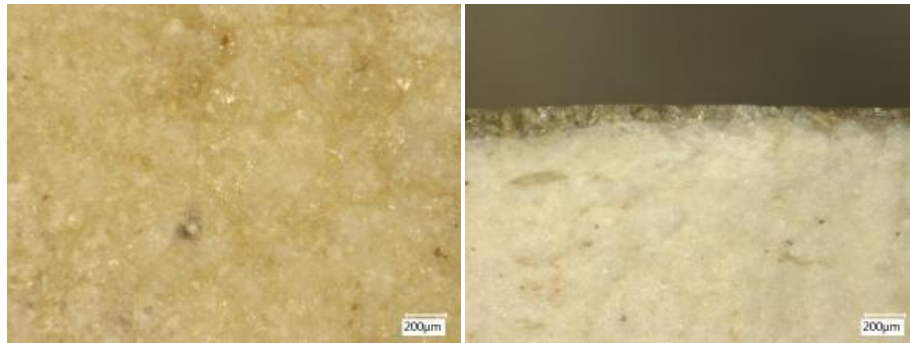
Fig. 4 Two-dimensional scatter plots of the colourimetric measurements and clustering results

Microscopic examination (Fig. 5) shows that the bluish qingbai specimens generally have thicker, more highly vitrified glaze layers, with frequent crazing and a few bubbles on the surfaces, and relatively dense bodies. The yellowish qingbai specimens have relatively thin glaze layers of uneven thickness and a lower degree of vitrification; some show no obvious vitrification. Their bodies are mostly yellowish and contain more impurities. Most underfired specimens have reddish bodies, and a few have white bodies. The slip-coated specimens have a white surface layer approximately 0.1 mm thick.



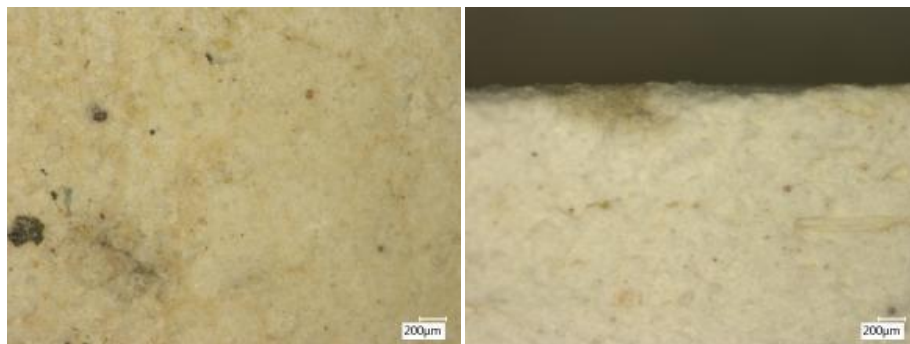
(a)

(b)



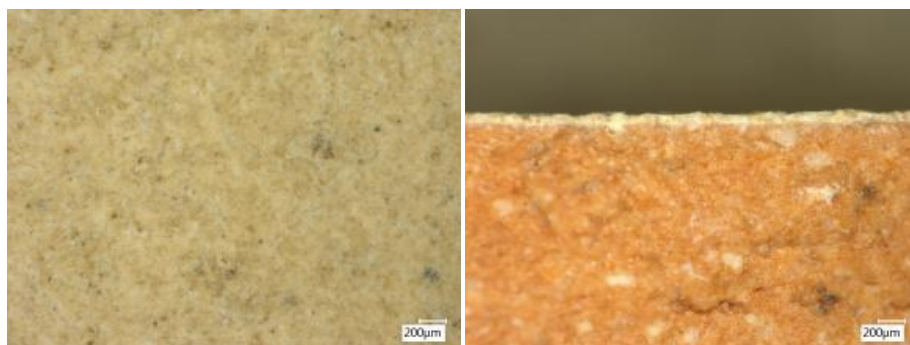
(c)

(d)



(e)

(f)



(g)

(h)

Fig. 5 Microscopic images of ceramic sherds from the Fanchang kiln

(a) FCYYP17 surface; (b) FCYYP17 cross-section; (c) FCYYP38 surface; (d) FCYYP38 cross-section; (e) FCYYP48 surface; (f) FCYYP48 cross-section; (g) FCYYP52 surface; (h) FCYYP52 cross-section.

(2) Chemical composition

Chemical analysis of the porcelain raw materials indicates SiO₂ contents of approximately 73-81% and Al₂O₃ contents of approximately 14-20%, with some variation among samples (Table 1).

Table 1. Chemical compositions of porcelain raw materials from the Fanchang kiln determined by LA-ICP-AES.

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO ₂
FCYTY1	80.50	14.44	0.74	0.49	0.39	1.30	1.63	0.13	0.16	0.04
FCYTY2	75.90	17.18	1.60	0.48	0.83	0.10	3.41	0.18	0.11	0.03
FCYTY3	80.68	14.41	0.86	0.20	0.58	1.94	0.73	0.15	0.21	0.02
FCYTY4	73.00	19.81	1.66	0.55	1.42	1.43	1.42	0.21	0.24	0.04
FCYTY5	78.35	15.69	2.62	0.51	0.54	0.68	0.97	0.18	0.15	0.03

Chemical analysis shows that the porcelain bodies contain 67-77% silica, 18-25% alumina and approximately 1% iron oxide (Table 2). The glaze samples generally contain 60-70% silica and 12-30% alumina, with mean calcium oxide and iron oxide contents of 8.96% and 2.26%, respectively. Titanium dioxide contents range from 0.12% to 0.62%, and the mean sodium oxide content is 1.40% (Table 3). The slip coatings on the underfired specimens generally have low alumina contents, mostly below 10%, together with relatively high calcium oxide contents and approximately 2-4% phosphorus pentoxide (Table 4).

Table 2. Chemical compositions of porcelain bodies from the Fanchang kiln determined by SEM.

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO ₂
FCYYP2	72.21	22.96	1.05	0.49	0.51	1.34	1.21	0.14	0.04	0.04
FCYYP3	74.82	19.97	0.74	0.42	0.31	2.47	1.10	0.15	0.00	0.02
FCYYP4	70.66	22.84	1.39	0.57	0.49	0.90	2.88	0.21	0.00	0.07
FCYYP5	71.07	23.35	1.23	0.65	0.40	1.33	1.63	0.24	0.08	0.03
FCYYP6	74.07	21.30	0.80	0.39	0.64	1.53	1.18	0.09	0.00	0.00
FCYYP7	72.85	22.09	0.94	0.46	0.45	1.24	1.67	0.17	0.12	0.00
FCYYP8	71.85	23.01	1.27	0.45	0.35	1.48	1.25	0.25	0.00	0.10
FCYYP9	70.89	23.54	1.22	0.61	0.42	1.54	1.19	0.21	0.33	0.05
FCYYP10	76.24	18.69	0.98	0.53	0.38	1.47	1.39	0.27	0.00	0.04
FCYYP11	75.89	19.02	0.97	0.44	0.97	1.27	1.44	0.00	0.00	0.00
FCYYP13	74.69	19.54	0.99	0.50	0.58	1.98	1.23	0.27	0.17	0.05
FCYYP14	72.56	21.86	1.44	0.61	0.59	1.11	1.51	0.10	0.21	0.00
FCYYP15	73.87	20.41	1.26	0.80	0.48	1.36	1.64	0.18	0.00	0.00
FCYYP16	75.50	19.20	1.06	0.55	0.50	1.21	1.38	0.17	0.36	0.07
FCYYP17	75.02	20.14	0.88	0.57	0.53	1.26	1.26	0.29	0.00	0.05
FCYYP18	77.19	18.75	0.86	0.04	1.07	0.93	1.11	0.05	0.00	0.00
FCYYP23	74.56	20.79	0.97	0.57	0.37	0.78	1.71	0.25	0.00	0.00
FCYYP24	70.45	23.52	1.25	0.57	0.59	1.63	1.69	0.18	0.12	0.00

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO ₂
FCYYP25	73.60	22.86	0.61	0.36	0.45	0.84	1.08	0.03	0.16	0.00
FCYYP26	71.70	22.73	1.25	0.53	0.57	1.81	1.26	0.15	0.00	0.00
FCYYP27	72.65	22.50	0.93	0.47	0.56	1.24	1.47	0.18	0.00	0.00
FCYYP28	71.40	23.39	1.44	0.53	0.61	0.60	1.56	0.16	0.32	0.00
FCYYP29	71.99	22.69	0.93	0.58	0.34	1.42	1.68	0.27	0.08	0.02
FCYYP30	71.11	22.85	0.82	0.49	0.32	3.06	1.18	0.10	0.00	0.06
FCYYP31	70.70	22.92	1.31	0.67	0.62	1.49	1.90	0.31	0.00	0.08
FCYYP32	70.76	23.77	1.22	0.57	0.39	1.34	1.75	0.21	0.00	0.00
FCYYP33	72.62	21.96	1.01	0.61	0.47	1.70	1.49	0.14	0.00	0.00
FCYYP34	73.51	21.61	0.91	0.41	0.51	1.23	1.61	0.16	0.00	0.06
FCYYP35	74.87	20.84	0.94	0.32	0.53	0.97	1.29	0.24	0.00	0.00
FCYYP36	72.40	22.40	1.28	0.56	0.29	1.35	1.43	0.30	0.00	0.00
FCYYP37	75.44	20.09	0.89	0.52	0.53	0.86	1.26	0.34	0.00	0.07
FCYYP38	71.13	22.54	1.21	0.54	0.80	0.78	2.81	0.20	0.00	0.00
FCYYP39	69.26	24.40	1.21	0.34	0.68	1.78	1.49	0.27	0.56	0.00
FCYYP40	70.38	23.95	1.56	0.50	0.66	1.08	1.55	0.28	0.00	0.02
FCYYP41	72.36	22.37	1.45	0.22	0.54	1.28	1.45	0.26	0.00	0.07
FCYYP42	72.55	21.30	1.08	0.40	0.38	2.27	1.80	0.21	0.00	0.02
FCYYP43	75.81	20.49	1.45	0.00	0.47	0.22	1.36	0.18	0.00	0.00
FCYYP44	75.82	18.80	0.95	0.50	0.77	1.78	1.19	0.19	0.00	0.00
FCYYP45	73.41	22.03	0.89	0.48	0.51	0.61	1.84	0.23	0.00	0.00
FCYYP46	75.31	19.78	0.90	0.54	0.64	1.47	1.21	0.10	0.00	0.06
FCYYP47	75.77	18.93	0.87	0.61	0.68	1.56	1.24	0.29	0.00	0.07
FCYYP48	76.10	19.88	0.89	0.31	0.58	0.42	1.46	0.36	0.00	0.00
FCYYP49	75.72	19.29	0.73	0.71	0.38	1.51	1.32	0.26	0.00	0.08
FCYYP50	73.60	20.13	1.03	0.38	1.14	2.06	1.51	0.15	0.00	0.00
FCYYP51	75.24	19.44	1.02	0.40	0.59	1.47	1.45	0.36	0.00	0.04
FCYYP52	72.72	21.02	1.47	0.19	1.08	2.07	0.91	0.53	0.00	0.00
FCYYP53	73.98	20.24	0.92	0.55	0.53	1.65	1.55	0.16	0.29	0.13
FCYYP54	74.07	20.74	0.94	0.61	0.44	1.26	1.69	0.18	0.08	0.00
FCYYP55	75.61	20.01	0.90	0.22	0.80	0.57	1.69	0.21	0.00	0.00
FCYYP57	76.90	19.10	0.55	0.62	0.41	0.78	1.18	0.16	0.29	0.00
FCYYP58	73.48	21.90	0.88	0.54	0.48	1.14	1.33	0.10	0.08	0.08
FCYYP59	76.15	20.50	1.17	0.06	0.38	0.32	1.38	0.04	0.00	0.00
FCYYP60	73.71	21.79	0.78	0.57	0.43	1.19	1.12	0.21	0.20	0.00

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO ₂
FCYYP61	67.71	25.29	1.62	0.70	0.54	1.12	2.67	0.24	0.12	0.00
FCYYP62	73.33	22.19	0.90	0.43	0.60	1.05	1.31	0.19	0.00	0.00
FCYYP63	72.83	21.90	1.27	0.43	0.43	1.12	1.70	0.33	0.00	0.00
FCYYP64	71.89	22.63	1.09	0.50	0.63	1.29	1.31	0.38	0.28	0.00
FCYYP65	75.40	21.40	0.47	0.25	0.31	0.90	1.08	0.20	0.00	0.00
FCYYP66	70.19	23.13	1.54	0.37	0.57	1.78	1.90	0.52	0.00	0.00
FCYYP67	77.14	18.51	1.37	0.35	0.52	0.52	1.39	0.16	0.00	0.05
FCYYP68	73.50	21.16	1.33	0.37	0.45	1.18	1.86	0.14	0.00	0.00
FCYYP69	67.66	25.33	1.58	0.65	0.67	1.59	1.75	0.22	0.53	0.03
FCYYP71	72.61	22.11	1.08	0.51	0.48	1.29	1.74	0.13	0.00	0.05
FCYYP72	73.96	21.75	0.74	0.53	0.31	1.40	1.11	0.16	0.00	0.05
FCYYP74	71.58	23.19	0.85	0.52	0.57	1.71	1.23	0.22	0.12	0.00

Table 3. Chemical compositions of glazes from the Fanchang kiln determined by LA-ICP-AES.

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO ₂
FCYYP3	66.49	15.50	2.26	1.63	9.67	2.11	0.74	0.21	0.86	0.24
FCYYP5	61.26	13.84	2.55	1.93	16.25	1.29	0.48	0.31	1.24	0.30
FCYYP10	65.35	14.86	2.36	2.31	9.63	1.79	0.56	0.60	1.03	0.42
FCYYP15	59.32	15.40	2.35	2.13	16.26	0.99	0.67	0.37	1.20	0.30
FCYYP17	68.02	15.17	2.06	1.49	9.87	1.13	0.89	0.17	0.85	0.15
FCYYP23	67.63	15.79	2.62	1.46	9.37	0.77	1.06	0.14	0.65	0.24
FCYYP29	61.04	22.73	2.76	1.49	1.76	5.14	4.30	0.23	0.20	0.13
FCYYP30	71.30	14.06	0.92	0.95	8.09	2.79	0.88	0.15	0.58	0.09
FCYYP32	67.21	12.73	1.98	1.84	12.32	1.31	1.04	0.14	0.96	0.23
FCYYP33	71.98	13.89	1.48	1.54	6.86	1.71	1.26	0.16	0.78	0.14
FCYYP42	59.15	13.69	2.27	1.44	17.37	2.06	1.73	0.62	0.74	0.16
FCYYP57	71.77	13.69	1.69	1.43	8.27	0.89	1.00	0.17	0.75	0.13
FCYYP60	69.68	14.20	1.64	1.43	8.91	0.92	1.72	0.19	0.77	0.20
FCYYP62	69.92	13.94	1.76	1.66	8.86	1.03	1.12	0.16	1.03	0.25
FCYYP65	71.45	15.80	1.68	1.11	6.56	1.16	1.01	0.14	0.61	0.22
FCYYP68	63.22	28.90	2.56	0.79	0.65	1.12	2.11	0.23	0.19	0.03
FCYYP72	69.55	15.70	1.94	1.35	7.95	1.26	0.85	0.12	0.83	0.22
FCYYP6	69.63	14.48	1.66	0.89	9.36	1.92	0.68	0.15	0.75	0.26
FCYYP13	60.88	18.95	3.34	1.80	9.58	1.30	1.37	0.40	1.53	0.30
FCYYP27	70.20	13.45	1.76	0.85	9.75	1.43	1.20	0.26	0.60	0.18
FCYYP31	73.02	13.72	2.72	1.13	5.68	1.21	1.48	0.22	0.48	0.13

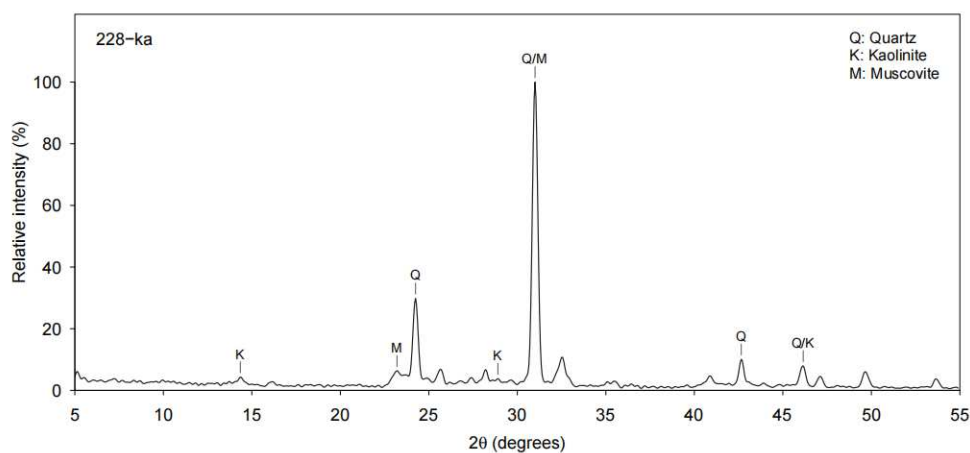
FCYYP35	61.49	30.77	2.27	0.54	1.83	0.97	1.32	0.31	0.20	0.08
FCYYP36	65.49	14.57	3.16	1.18	8.86	1.87	3.22	0.22	0.95	0.16
FCYYP37	74.02	13.15	2.29	0.98	5.83	0.99	1.40	0.28	0.58	0.12
FCYYP38	62.05	17.43	2.48	1.74	11.54	0.77	2.02	0.38	0.92	0.23
FCYYP40	62.99	17.03	2.78	1.26	5.68	1.32	7.44	0.21	0.85	0.19
FCYYP41	60.41	18.63	3.62	1.26	10.18	1.35	1.20	0.46	1.79	0.16
FCYYP43	67.15	14.10	2.55	1.38	10.43	1.15	1.62	0.24	0.77	0.23
FCYYP44	72.22	14.60	2.12	0.97	5.58	1.84	1.37	0.31	0.51	0.19
FCYYP45	63.13	14.69	2.35	1.74	14.37	0.75	1.08	0.21	1.15	0.22
FCYYP47	67.53	13.19	1.59	1.71	11.17	1.61	0.99	0.21	1.37	0.34
FCYYP49	66.83	14.78	2.12	2.03	9.67	1.35	1.20	0.31	1.05	0.26
FCYYP50	58.75	31.77	3.44	0.81	0.91	1.59	1.59	0.28	0.41	0.08
FCYYP51	60.73	14.52	2.19	2.24	15.25	1.40	0.99	0.28	1.62	0.36
FCYYP53	66.81	14.20	1.89	2.30	9.09	1.24	1.35	0.27	2.01	0.43
FCYYP54	65.69	14.40	1.88	2.52	10.07	0.95	1.20	0.32	1.89	0.51
FCYYP58	69.85	13.78	1.13	1.33	10.09	1.04	0.79	0.31	0.83	0.25
FCYYP61	67.17	15.84	1.82	1.48	8.77	1.03	2.08	0.28	0.90	0.28
FCYYP63	70.39	13.94	2.28	1.33	7.92	1.18	1.52	0.17	0.71	0.27
FCYYP66	60.24	21.90	3.82	1.17	6.90	1.59	2.07	0.42	1.35	0.14
FCYYP67	71.42	14.41	1.67	1.41	7.09	0.75	1.97	0.17	0.66	0.17
FCYYP74	60.52	17.48	3.11	1.79	12.13	1.10	1.28	0.26	1.71	0.26

Table 4. LA-ICP-AES results for the surface slip coatings on underfired specimens from the Fanchang kiln.

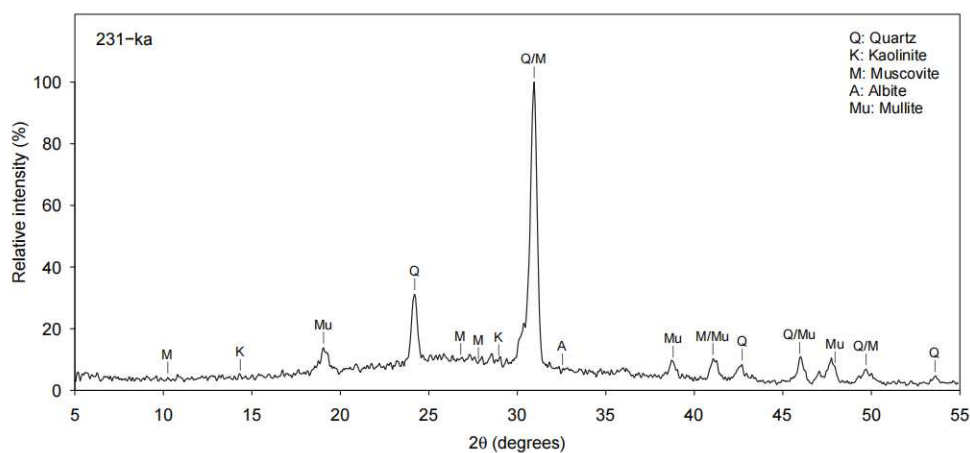
Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO ₂
FCYYP4	63.37	14.77	2.62	1.25	10.88	1.11	1.42	0.79	2.95	0.25
FCYYP7	64.94	9.90	2.06	3.20	12.69	1.01	0.98	0.32	4.17	0.35
FCYYP11	75.70	9.23	1.83	1.38	7.49	0.73	0.80	0.16	2.26	0.14
FCYYP18	75.71	9.69	0.70	0.59	8.13	0.82	0.49	0.12	3.29	0.13
FCYYP26	78.58	7.14	0.80	1.50	7.02	0.63	0.57	0.21	3.14	0.12
FCYYP28	79.23	6.59	1.48	2.46	6.28	0.24	0.37	0.20	2.71	0.20
FCYYP52	62.48	18.18	2.19	1.05	8.28	2.04	0.98	0.30	3.63	0.19
FCYYP71	70.07	11.92	1.22	1.63	9.11	0.86	0.98	0.18	3.53	0.23

(3) Mineralogical composition

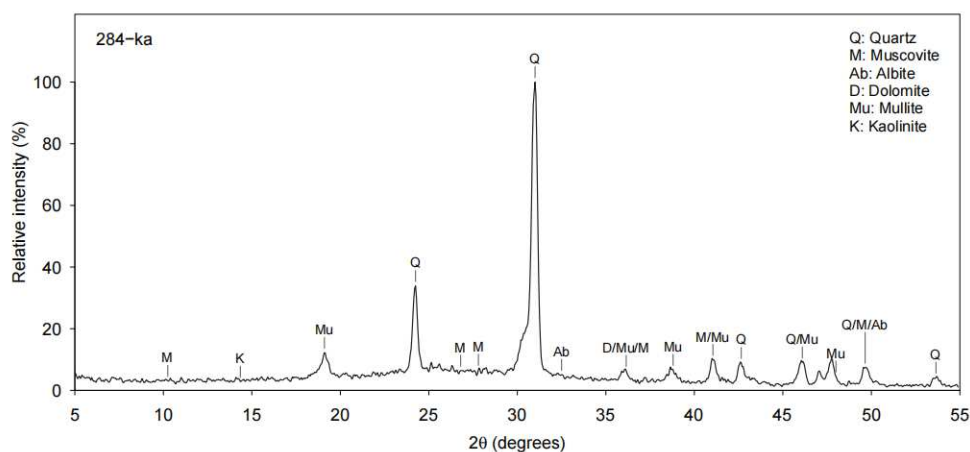
The XRD results are shown in Fig. 6. Phase identification indicates that the porcelain raw materials from the Fanchang kiln consist mainly of quartz, muscovite and kaolinite. Quartz is the principal constituent, whereas kaolinite is present in very small amounts and is unevenly distributed; it was not detected in some sediment samples. The bodies of the underfired specimens are likewise dominated by quartz and muscovite, together with minerals including albite, dolomite, montmorillonite and mullite. Some samples contain small amounts of kaolinite. In addition to quartz/cristobalite and albite, calcium-bearing minerals such as gismondine and anorthite were identified in the surface slip coatings of the underfired specimens.



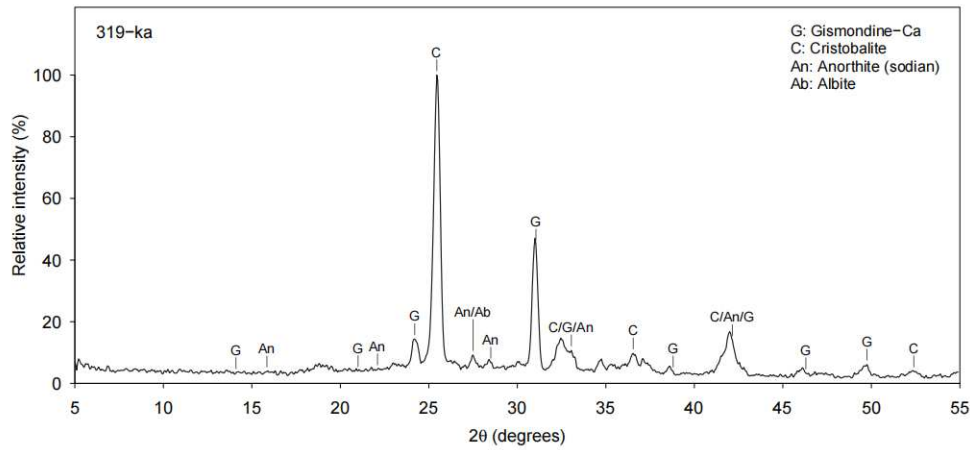
(a)



(b)



(c)



(d)

Fig. 6 XRD patterns and phase identification for samples from the Fanchang kiln (horizontal axis: diffraction angle 2θ ; vertical axis: diffraction intensity)

(a) FCYTY5; (b) FCYYP7 body; (c) FCYYP59 body; (d) FCYYP11 slip coating.

Analysis and discussion

(1) The emergence of qingbai porcelain

Population movements between northern and southern China and exchanges in kiln technology during the Five Dynasties and Northern Song periods provided an important historical context for the emergence of qingbai porcelain in southern China. To examine the relationships between Fanchang and other major kilns of the same period in terms of body and glaze compositions, principal component analysis (PCA) was performed using published data for white porcelain from the northern Ding kiln, celadon from the southern Yue kilns and qingbai porcelain from the Hutian kiln at Jingdezhen.¹

The PCA results for the bodies (Fig. 7) show substantial overlap between the Fanchang and Hutian body samples in principal component space, indicating a high degree of similarity in their chemical compositions. This may reflect similar approaches to selecting and processing raw materials. Fanchang samples lie closer to those from the northern Ding kiln than to those from the southern Yue kilns in principal component space. Although porcelain body compositions are constrained by local raw material resources, Fanchang and Yue show greater differences despite both being located in southern China. This suggests that differences in physical geography between northern and southern China may be insufficient to explain the variation in body composition among kiln centres. Considered alongside previous research on the spatial distribution of qingbai and celadon production in southern China (Huang 2010), the differences between Fanchang and Yue body compositions may reflect distinct porcelain-making traditions.

¹ The Hutian data are taken from Jiangxi Provincial Institute of Cultural Relics and Archaeology and Jingdezhen Museum of Folk Kilns (2007) and Wu et al. (2019). The Ding data are taken from Chen et al. (2025) and Zhou (2011). The Yue data are taken from Xiong et al. (2010).

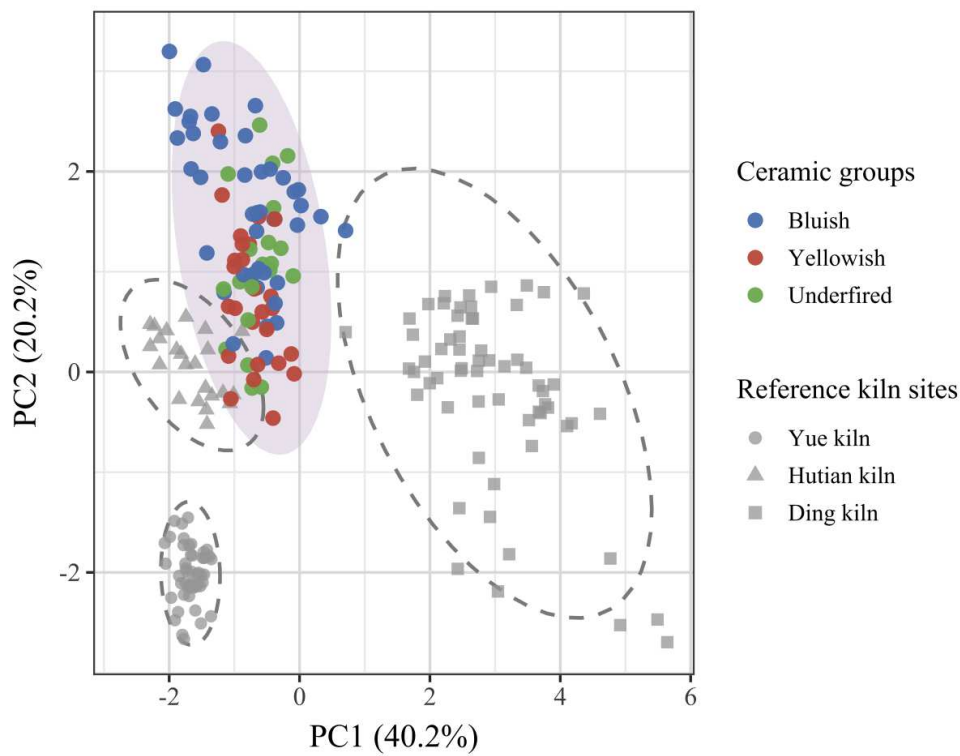


Fig. 7 PCA of Fanchang porcelain bodies in comparison with body compositions from other kiln sites

The PCA results for the glazes (Fig. 8) show that the samples from Fanchang and Hutian at Jingdezhen occupy relatively similar positions in principal component space, suggesting possible common features in their glaze-making technology. Overall, the Fanchang samples lie between those from Yue and Ding, with some overlap with both, but are closer to Ding. This distribution indicates that Fanchang glaze compositions differ from those of typical southern celadon and may reflect the incorporation of elements from other porcelain-making traditions. Because glaze chemistry is determined jointly by raw materials and manufacturing techniques, the conclusion drawn in previous studies, based solely on PCA, that Fanchang qingbai glaze formulas were learned from the northern Ding kiln remains open to question. The specific technological connections between the two require further discussion at the level of porcelain manufacturing processes.

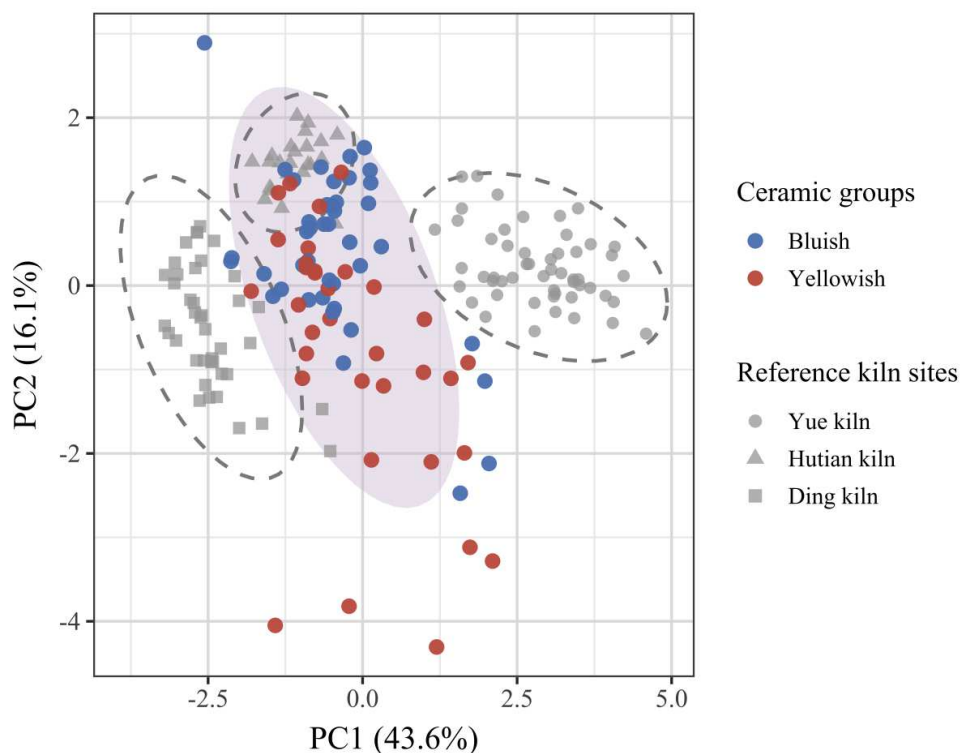
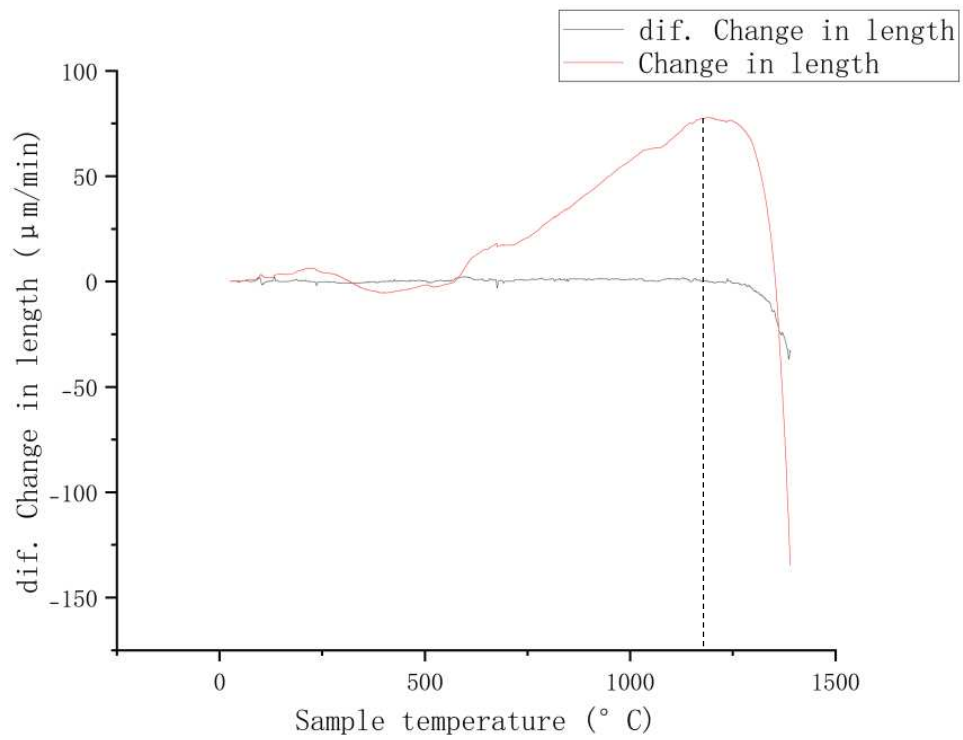


Fig. 8 PCA of Fanchang glazes in comparison with glaze compositions from other kiln sites

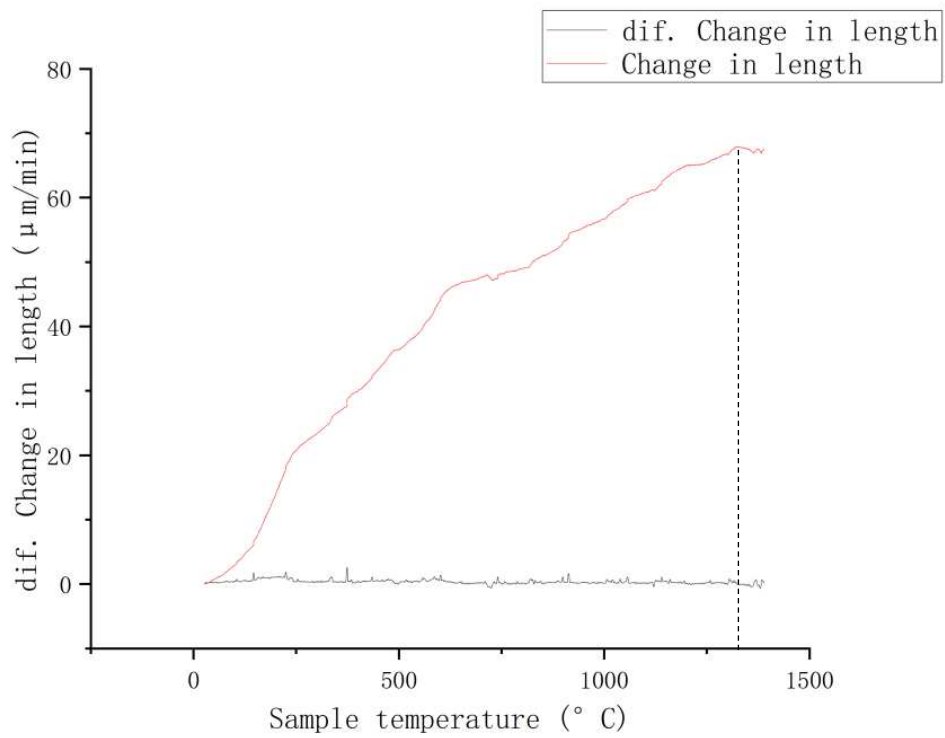
(2) Glaze recipes and colouration mechanisms

The ‘slip’ on the surfaces of the slip-coated underfired specimens from Fanchang is likely to be a glaze layer that had not completely melted. Its chemical and mineralogical compositions can provide a useful indication of the state of the glaze materials before firing and thus offer important evidence for investigating Fanchang glaze recipes.

The slip coatings on the underfired specimens generally have high CaO contents and contain approximately 2-4% P_2O_5 (Table 4). These characteristics suggest that plant ash may have been added to the glaze raw materials at Fanchang. XRD phase identification (Fig. 6) reveals minerals including cristobalite, gismondine and anorthite in the coatings. The presence of calcium-bearing minerals is consistent with the relatively high CaO contents of both the underfired coatings and the finished glazes. Together, the chemical and mineralogical compositions indicate that Fanchang probably employed high-fired lime glaze technology involving the addition of plant ash. High-fired lime glazes typically melt at 1150-1250 °C. The derivative dilatometric curves for the eight samples were broadly consistent and show that their estimated firing temperatures generally fall within the melting range of plant ash glazes; two representative examples are presented in Fig. 9. The estimated firing temperatures of the yellowish qingbai specimens are slightly lower than those of the bluish specimens. Combined with the lower degree of glaze vitrification observed microscopically in the former, this suggests that firing temperature may have been one of the factors influencing glaze vitrification.



(a)



(b)

Fig. 9 Representative derivative dilatometric curves for Fanchang samples

(a) FCYYP13; (b) FCYYP60.

Analysis of the chemical compositions of Fanchang qingbai glazes shows that², among the principal colourant elements in the glazes, only Fe₂O₃ and TiO₂ differ significantly between the bluish and yellowish groups ($p < 0.05$; Figs. 10 and 11). The colour of an iron-bearing melt results from the combined contributions of Fe²⁺ and Fe³⁺ and depends on both oxidation state and concentration. In an oxidising atmosphere, the proportion of Fe³⁺ is higher, producing a more yellowish-brown colour; in a reducing atmosphere, some Fe³⁺ is reduced to Fe²⁺, producing a more bluish-green colour. The generally lower Fe₂O₃ contents of the bluish Fanchang qingbai glazes may also contribute to their whiter appearance. Previous studies have shown that TiO₂ can affect the colouration behaviour of iron ions in glazes (Kerr and Wood 2025, p. 390; No et al. 2014). Experimental simulations showed that TiO₂ contents of 0.2-0.3% could change a slightly bluish celadon glaze to grass green (Ishii 1930). The TiO₂ contents differ significantly between the bluish and yellowish qingbai glazes from Fanchang, and the two groups generally fall on opposite sides of 0.2%. This suggests that differences in TiO₂ content may also have contributed to glaze colour variation at Fanchang. Overall, the distinction between bluish and yellowish Fanchang qingbai is not determined by a single factor but results from the combined effects of Fe₂O₃ and TiO₂ contents and the firing atmosphere.

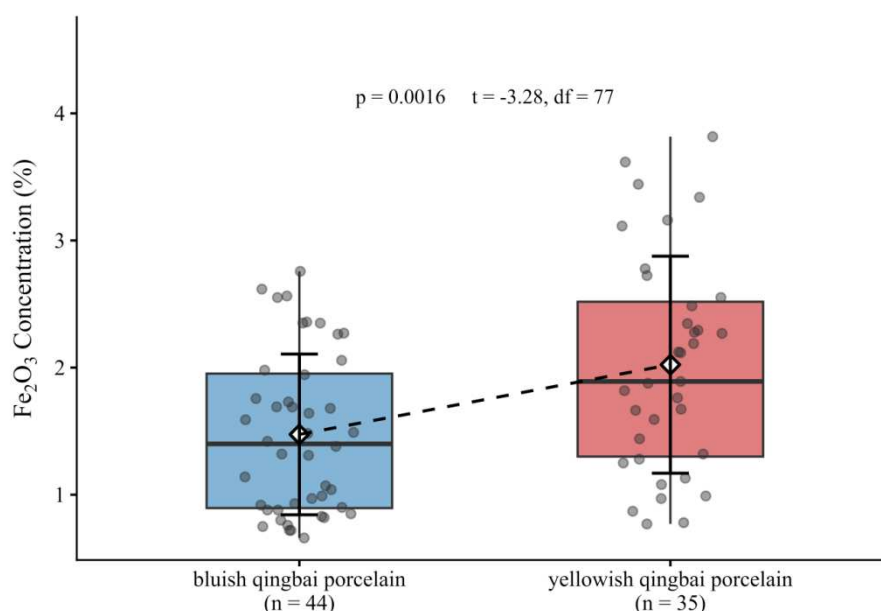


Fig. 10 t-test and box plots comparing Fe₂O₃ contents in bluish and yellowish qingbai porcelain

² During data compilation, this study also consulted previously published datasets (Yang et al. 2017; Cui et al. 2018; Zhu et al. 2024) to minimise the possibility that the analytical results were fortuitous. Elements that were not detected or were detected at ppm levels in the published datasets were assigned a content of zero.

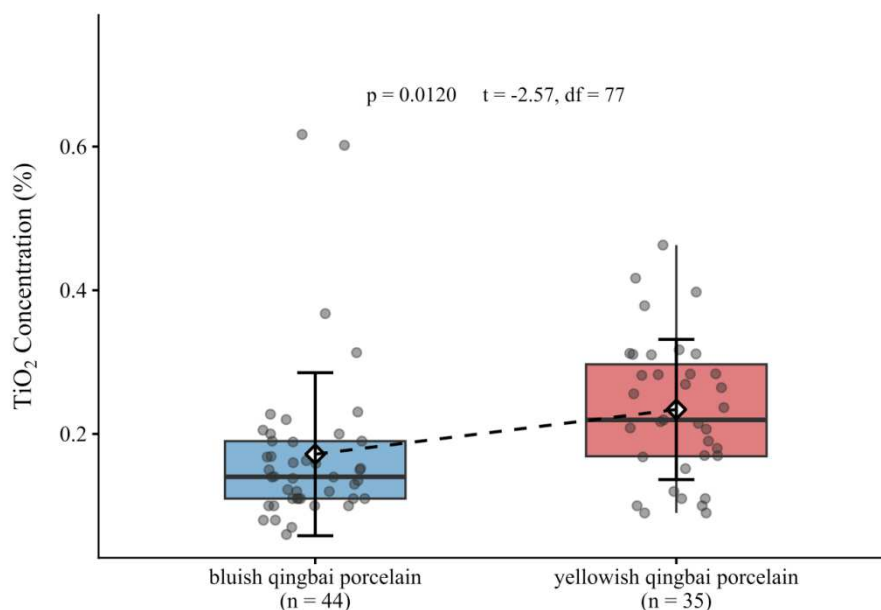


Fig. 11 t-test and box plots comparing TiO₂ contents in bluish and yellowish qingbai porcelain

This study compares the compositions of Fanchang glazes with those from other contemporary kiln centres (Table 5). Compared with white porcelain glazes from the northern Ding kiln, Fanchang glazes have markedly higher mean Fe₂O₃ and CaO contents. Compared with celadon glazes from the southern Yue kilns, they have lower mean P₂O₅ and CaO contents. A distinctive feature of Fanchang is its relatively high Na₂O content, averaging 1.41%, which exceeds that of the other kiln centres listed in Table 5. Together with the identification of albite in the underfired specimens, this characteristic may be related to the mineralogical composition of the local glaze raw materials.

Table 5. Comparison of means and variances for selected chemical components at Fanchang and other kiln centres.^a (Jiangxi Provincial Institute of Cultural Relics and Archaeology and Jingdezhen Museum of Folk Kilns 2007; Wu et al. 2019; Chen et al. 2025; Zhou 2011; Xiong et al. 2010)

Kiln site	Period	Fe ₂ O ₃ (%)		TiO ₂ (%)		P ₂ O ₅ (%)		CaO (%)		Na ₂ O (%)	
		Mean	Variance	Mean	Variance	Mean	Variance	Mean	Variance	Mean	Variance
Fanchang	Northern Song	2.33	0.60	0.29	0.05	0.89	0.73	10.93	15.83	1.41	0.52
Yue	Five Dynasties-Northern Song	2.10	0.19	0.27	<0.01	1.83	0.23	17.88	4.01	0.21	0.01
Ding	Five Dynasties-Song	0.87	0.04	0.11	<0.01	0.28	0.02	4.75	1.59	0.74	0.13
Jingdezhen	Song	1.09	0.06	0.04	<0.01	0.11	0.01	14.80	4.28	0.90	0.21

a. 'Five Dynasties–Northern Song' includes all samples dating from the Five Dynasties through the Northern Song, whereas 'Five Dynasties–Song' includes all samples from the Five Dynasties, Northern Song and Southern Song periods.

(3) Body recipes and 'binary formula' technology

'Binary formula' technology represented an important advance in the history of ceramic production, and its date of emergence and process of development have long been central concerns in the study of ancient ceramics.

The principal minerals in porcelain stone commonly used in southern porcelain manufacture are sericite and quartz. Sericite provides kaolin-like plasticity and feldspar-like fluxing properties, allowing porcelain stone to be used directly in porcelain production. This provided the natural geographical basis for the long-standing use of a single-component formula

272 using porcelain stone as the raw material in southern China. Previous research has argued that recipes based on porcelain
273 stone alone generally contain less than 18% Al_2O_3 , and an Al_2O_3 content exceeding 20% in porcelain bodies has therefore
274 often been regarded as important evidence for the deliberate addition of alumina-rich materials such as kaolin. However, this
275 criterion is not conclusive. Porcelain stone is formed by the weathering of volcanic rocks; the sericite within porcelain stone
276 subsequently undergoes further weathering, ultimately transforming into kaolin (Kerr and Wood 2025, p. 39). More intensely
277 weathered porcelain stone deposits therefore often occur in association with kaolin. Consequently, Al_2O_3 content and the
278 presence of kaolin are insufficient to establish whether kaolin was deliberately added during porcelain production.

279 To clarify this issue further, the SiO_2 and Al_2O_3 contents of the porcelain bodies and workshop raw materials were
280 plotted and analysed (Fig. 12).³ The body compositions form a continuous band in SiO_2 - Al_2O_3 space, with no clear grouping
281 or change in trend associated with variations in Al_2O_3 content. Both the bodies and the raw materials show a clear negative
282 linear relationship between SiO_2 and Al_2O_3 , with similar slopes, suggesting a relatively high degree of similarity in their
283 chemical compositions. The raw materials generally plot on the high- SiO_2 , low- Al_2O_3 side of the bodies. This offset could
284 reflect either the addition of alumina-rich materials or mineral sorting during processing. However, achieving the observed
285 body Al_2O_3 contents of 18-25% through the addition of kaolin would require kaolin proportions varying from approximately
286 0% to 30%,⁴ implying substantial differences in mixing ratios among samples. Moreover, the bluish qingbai, yellowish
287 qingbai and underfired specimens are interspersed on the plot, with no clear differences between groups. In other words, the
288 different product types do not show clearly distinct body compositional systems. None of these findings provides evidence
289 for the deliberate addition of kaolin.

290 Previous studies analysed yellowish-white rock fragments excavated within the site as raw materials and found that
291 their alumina contents were approximately 10%, making them unlikely to form porcelain on their own. On this basis,
292 scholars proposed that the workers had added alumina-rich materials such as kaolin during manufacture (Yang and Zhang
293 2006). By contrast, the raw materials from the porcelain-making tanks analysed in this study had already entered the
294 workshop production process, providing evidence for an intermediate stage in the production chain that was not documented
295 in earlier studies. The Al_2O_3 contents of these raw materials overlap with those of the bodies, and some compositional
296 differences are also present among raw materials collected from tanks associated with different stages of porcelain
297 production. This indicates that differences between the bodies and raw materials could indeed have resulted from production
298 processes such as levigation and settling. The specific causes require further assessment through changes in raw material
299 composition during production, together with mineralogical and microstructural evidence.

³ During data compilation, this study also consulted previously published datasets (Yang and Zhang 2006; Cui et al. 2018) to minimise the possibility that the analytical results were fortuitous. Elements that were not detected or were detected at ppm levels in the published datasets were assigned a content of zero.

⁴ In ‘Analysis of the bodies and glazes of Southern Song and Yuan qingbai porcelain from the Luomaqiao kiln site at Jingdezhen: A discussion of the origins of the “binary formula”’, Weng et al. (2015) calculated the proportion of kaolin added to the body raw materials from the approximate relationship between body Al_2O_3 content and the amount of kaolin added during body preparation. The present study follows this method, estimates kaolin additions using the composition proposed in previous research and expands the sample size. It suggests that kaolin additions of approximately 0–30% would be required to achieve the observed range of body Al_2O_3 contents.

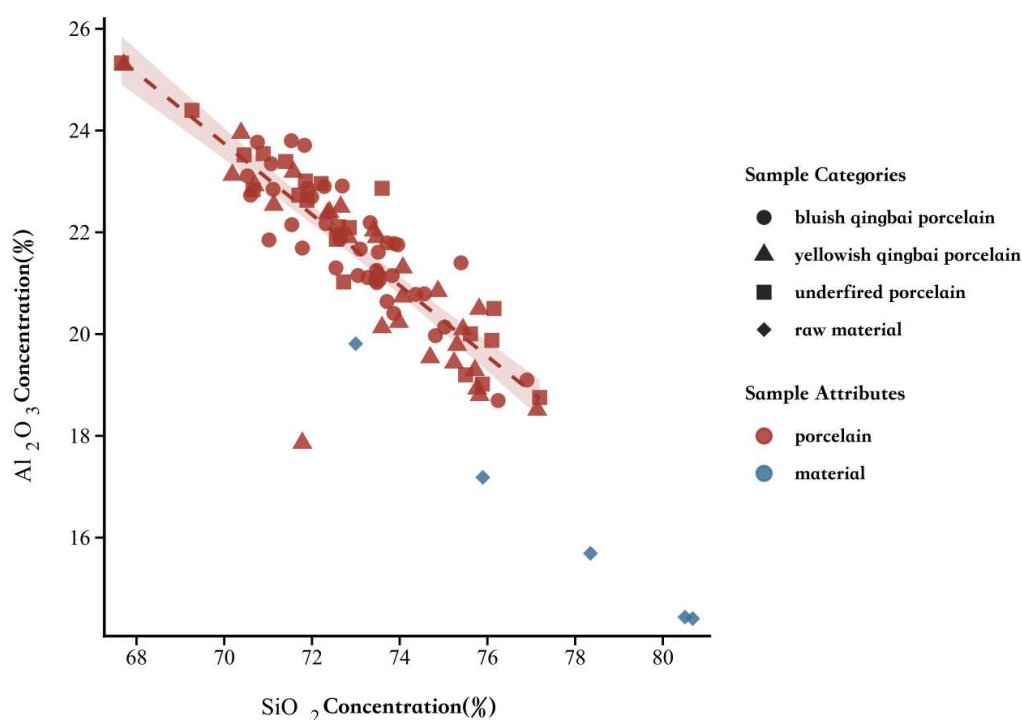


Fig. 12 SiO_2 - Al_2O_3 scatter plot and linear fits for porcelain raw materials and bodies from the Fanchang kiln

XRD analysis provides information on the principal minerals in raw materials and bodies of Fanchang porcelain (Fig. 6). The raw materials have relatively simple mineralogical compositions, consisting mainly of quartz and muscovite with small amounts of kaolinite (no more than 10%). Quartz is likewise the principal mineral in the underfired specimens, accompanied by muscovite, albite, montmorillonite and mullite; mullite is a product of high-temperature clay sintering. Kaolinite contents in the raw materials are generally low and unevenly distributed, and kaolinite was not detected in some samples. The materials therefore do not show consistently kaolinite-rich characteristics. These results are consistent with the natural occurrence of small amounts of kaolinite during the weathering of porcelain stone and do not provide clear mineralogical evidence for the systematic, deliberate addition of kaolin.

Selected samples were examined and analysed by scanning electron microscopy (Fig. 13). The images show that Fanchang porcelain bodies are relatively porous and consist principally of clay and residual quartz with dissolution rims. The residual quartz grains are relatively large, reaching 0.4 mm, and show extensive dissolution at their margins, most of which have distinct, partially melted rims. The bodies also contain an abundant glassy phase and very small amounts of mullite crystals. Porcelain stone consists of weathered feldspar and quartzite. Its chemical composition is close to the eutectic composition, favouring the formation of abundant glassy phase. Where the liquid phase is abundant and its viscosity is low, quartz undergoes strong dissolution at high temperatures, readily producing large quartz grains with embayed margins. By contrast, the addition of kaolin shifts the bulk system away from the eutectic proportions, reducing liquid-phase formation and resulting in less extensive dissolution of residual quartz. Moreover, mullite formation also requires high Al_2O_3 contents and sufficient high-temperature solid-state reaction. Fanchang porcelain bodies contain only small amounts of short, needle-like mullite crystals, which are poorly developed. Taken together, the available evidence does not indicate widespread, systematic and deliberate addition of alumina-rich materials such as kaolin during body preparation at Fanchang. The chemical characteristics of Fanchang porcelain bodies may instead be related to the properties of the porcelain stone itself and to production and processing.

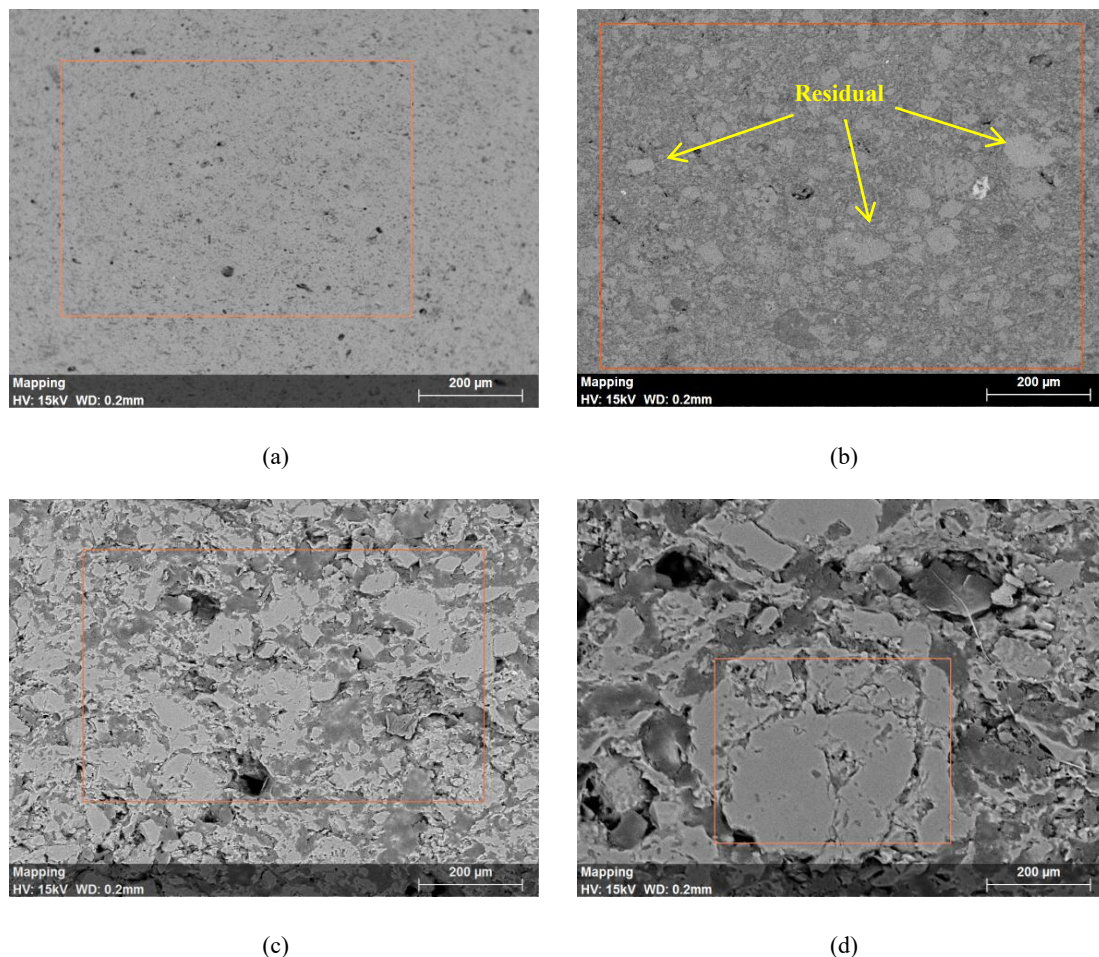


Fig. 13 Scanning electron micrographs of Fanchang samples at different magnifications

(a) FCYYP43 body ($\times 50$); (b) FCYYP48 body ($\times 120$); (c) clay in the FCYYP52 body ($\times 400$); (d) residual quartz grains in the FCYYP52 body ($\times 800$).

On the basis of the excavation report and related studies, Fanchang porcelain can be divided into two broad chronological groups: the early Northern Song to the early-middle Northern Song transition, and the middle Northern Song.⁵ From the former period to the latter, the Al_2O_3 content of Fanchang porcelain bodies decreases markedly, with a significant difference between the two groups ($p < 0.01$; Fig. 14). This change indicates a pronounced chronological shift in the chemical composition of body raw materials during production. Notably, Al_2O_3 contents do not increase progressively over time as might be expected from the deliberate addition of alumina-rich materials, but instead decrease substantially. Together with the preceding analysis of the raw materials and body mineralogy, this suggests that the relatively high alumina contents of Fanchang porcelain may well derive from more intensely weathered porcelain stone. As extraction continued, the more strongly weathered porcelain stone near the surface may have been exhausted, and less weathered stone from deeper parts of

⁵ The three periods distinguished in ‘Preliminary report on the 2025 excavations at the Fanchang kiln site in Fanchang District, Anhui’ (unpublished report)—the early Northern Song (T11, layers ⑮–⑳), the transition between the early and middle Northern Song (T11, layers ⑥–⑭), and the middle Northern Song (T11, layers ②–⑤)—were combined into two because most related studies do not distinguish the transitional period. This grouping was adopted to avoid differences in data dispersion arising from that discrepancy and to ensure a sufficient sample size for analysis in each period. The transitional-period samples examined in this study came from T10, layers ⑩, ⑬ and ⑭, which are stratigraphically closer to the early Northern Song. The transitional period was therefore combined with the early Northern Song.

the deposit may have become the principal raw material, resulting in lower Al_2O_3 contents in the bodies. This interpretation still requires further validation through systematic surveys of raw material deposits in the vicinity of the kiln site and across different weathering horizons.

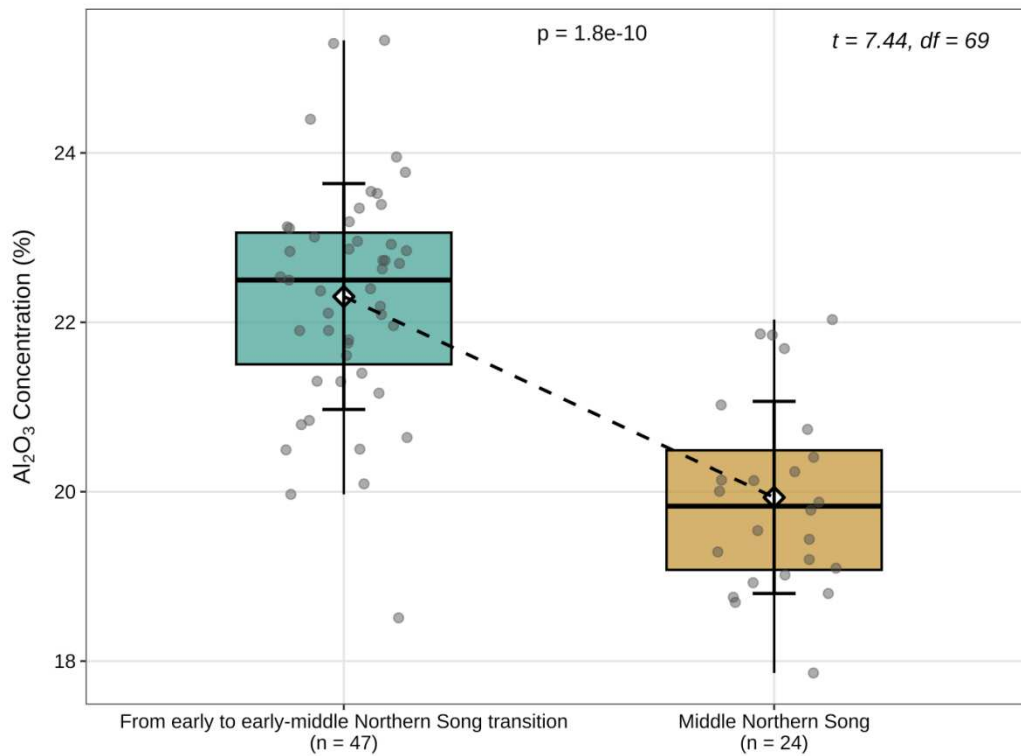


Fig. 14 Changes in Al_2O_3 content in Fanchang porcelain from earlier to later periods

Conclusions

Using archaeological materials recovered during the latest excavations at the Fanchang kiln in 2025, this study combines archaeometric methods including chemical, structural, colourimetric and firing-temperature analyses to investigate key issues concerning the body and glaze recipes, firing practices, colouration mechanisms and technological origins of Fanchang qingbai porcelain during the Northern Song period. The main findings are as follows.

First, the available evidence does not indicate that a ‘binary formula’ involving the deliberate addition of kaolin was widely used at Fanchang. Taken together, the analytical results show a continuous distribution of body SiO_2 - Al_2O_3 compositions and a degree of compositional similarity to the workshop raw materials. The bodies are dominated mineralogically by quartz and muscovite, with very low and unevenly distributed kaolin contents, and their microstructures show no features that clearly support the addition of alumina-rich raw materials. This conclusion clarifies the long-standing debate over the ‘binary formula’ at Fanchang and provides new production-chain evidence for reassessing the raw material technology of early qingbai porcelain production.

Second, Fanchang employed a plant ash lime glaze system, with glaze colour determined jointly by iron and titanium contents and the firing atmosphere. The CaO and P_2O_5 contents of the glaze materials clearly indicate the use of plant ash in glaze preparation, continuing the southern tradition of high-fired lime glazes. Firing temperatures of approximately 1150-1250 °C correspond to the melting range of plant ash lime glazes, indicating that glaze recipes were suited to kiln conditions. This correspondence suggests that the emergence of qingbai porcelain was likely the result of the combined effects of multiple technological advances. The bluish and yellowish glaze colours are mainly attributable to differences in

359 Fe₂O₃ and TiO₂ contents. TiO₂ generally occurs at very low concentrations in porcelain glazes, and its role has received
360 comparatively little attention in studies of colouration. Drawing on earlier research, this study proposes that even small
361 changes in TiO₂ content may have important effects on glaze colour, extending our understanding of colouration mechanisms
362 in porcelain.

363 Third, the emergence of qingbai porcelain at Fanchang reflects exchange and integration between northern and southern
364 porcelain technologies. The PCA results show close similarities in body and glaze compositions between Fanchang and
365 Hutian at Jingdezhen, indicating some common features in raw material selection and porcelain processing. Fanchang body
366 and glaze compositions are closer to those of the northern Ding kiln than to those of the southern Yue kilns. Together with
367 similarities in vessel types and kiln-loading and firing practices between Fanchang and Ding identified in previous studies,⁶
368 this suggests that Fanchang very likely adopted northern white porcelain technology. Drawing on local raw materials with
369 low iron and titanium contents and the firing advantages of dragon kilns, it gradually developed a distinctive qingbai
370 technological system and became an important kiln centre in the formation and transmission of early qingbai technology.

371 References

- 372 Anhui Provincial Institute of Cultural Relics and Archaeology, Fanchang County Cultural Relics Bureau (2016) The
373 excavation of the Kejiachong kiln site at Fanchang County, Anhui Province in 2013–2014. *Wenwu* 3:19–35.
374 <https://doi.org/10.13619/j.cnki.cn11-1532/k.2016.03.002> (in Chinese)
- 375 Chen D, Cui JF, Qin DS, Huang X, Li X (2025) Scientific analysis of porcelain raw materials excavated at the Ding kiln site.
376 *Spectrosc Spect Anal* 45:72–81. [https://doi.org/10.3964/j.issn.1000-0593\(2025\)01-0072-10](https://doi.org/10.3964/j.issn.1000-0593(2025)01-0072-10) (in Chinese)
- 377 Cui MF, Zhu JH, Xu F (2018) Origin of Qingbai porcelain technology of Fanchang kiln from the aspect of body and glaze
378 crafts. *J Univ Sci Technol China* 48:770–776. <https://doi.org/10.3969/j.issn.0253-2778.2018.09.012> (in Chinese)
- 379 Dong WK (2019) A discussion of the sources of alumina-rich raw materials in the ‘binary formula’ at the Fanchang kiln.
380 *Identification and Appreciation of Cultural Relics* 2:69–71 (in Chinese)
- 381 Han Q (2012) Report on the Palace Museum’s 2012 survey of kiln sites in Anhui. Palace Museum.
382 https://www.dpm.org.cn/forum_detail/100134.html. Accessed 2 October 2026 (in Chinese)
- 383 Hu YQ (1994) The Fanchang kiln in the Jiangnan region of Anhui. *Southeast Culture*, Supplement 1:70–75 (in Chinese)
- 384 Huang YJ (2010) A historical geographical study of Song-dynasty qingbai porcelain. Cultural Relics Press, Beijing (in
385 Chinese)
- 386 Ishii T (1930) Experiments on the tenriuji yellow celadon glaze. *J Trans Br Ceram Soc*, Wedgwood Bi-centenary Memorial
387 Number:360–387
- 388 Jiangxi Provincial Institute of Cultural Relics and Archaeology, Jingdezhen Museum of Folk Kilns (2007) The Hutian kiln
389 site at Jingdezhen: Report on the archaeological excavations of 1988–1999. Cultural Relics Press, Beijing (in Chinese)

⁶ In A Study of the Fanchang Kiln (Wang 2022), Wang Fazhi argues that some of the principal products of the first phase at Fanchang display the styles of the northern Xing and Ding kilns. According to ‘Report on the Palace Museum’s 2012 survey of kiln sites in Anhui’ (Han 2012), large numbers of saggars and setter discs, together with a small number of setter rings, were found at the site. In A Historical Geographical Study of Song-Dynasty Qingbai Porcelain (Huang 2010), Huang Yijun argues that Fanchang’s early use of northern-style funnel-shaped saggars, setter discs and setter rings constitutes direct evidence of technological exchange.

390 Kerr R, Wood N (2025) *Science and civilisation in China*, vol 5, chemistry and chemical technology, part 12, ceramic
391 technology, translated into Chinese by Chen T et al. Science Press, Beijing

392 Liu XY, Bai K (1982) A historical study of kaolin: Porcelain stone, kaolin and porcelain production at Jingdezhen from the
393 tenth to nineteenth centuries. *China Ceramics* 7 (in Chinese)

394 No H, Kim U, Kim J, Cho W, Kim C, Kim C (2014) Effect of TiO₂ on the color generation in celadon glaze. *J Korean*
395 *Ceram Soc* 51:150–155. <https://doi.org/10.4191/kcers.2014.51.3.150>

396 Wang FZ (2022) *A study of the Fanchang kiln*. Anhui Normal University Press, Wuhu (in Chinese)

397 Weng YJ, Cui JF, Jiang JX (2015) Analysis of the bodies and glazes of Southern Song and Yuan qingbai porcelain from the
398 Luomaqiao kiln site at Jingdezhen: A discussion of the origins of the ‘binary formula’. *Oriental Museum* 3:97–106 (in
399 Chinese)

400 Wu JM, Ma HJ, Qian W, Zheng NZ, Hai JX (2019) Composition and coloration characteristics of Song-dynasty qingbai
401 porcelain from the Hutian kiln. *Spectrosc Spect Anal* 39:3855–3860.
402 [https://doi.org/10.3964/j.issn.1000-0593\(2019\)12-3855-06](https://doi.org/10.3964/j.issn.1000-0593(2019)12-3855-06) (in Chinese)

403 Xiao HY, Ai QZ, Cui JF (2020) The invention of Jingdezhen porcelain’s ‘binary formula’ and the history of kaolin mineral
404 exploitation. *Palace Museum Journal* 5:23–33 (in Chinese)

405 Xiong YF, Gong YW, Xia JD, Wu JW (2010) EDXRF analysis of the chemical compositions of celadon bodies and glazes
406 from the Yue kilns at Shanglin Lake. *Sciences of Conservation and Archaeology* 22:28–34.
407 <https://doi.org/10.16334/j.cnki.cn31-1652/k.2010.04.002> (in Chinese)

408 Yang YZ, Zhang JZ (2006) The emergence of the ‘binary formula’ technique viewed through qingbai porcelain production at
409 the Fanchang kiln. *Archaeology and Cultural Relics* 2:89–92 (in Chinese)

410 Yang YZ, Zeng LY, Wang FZ, Cui W, Xu F, Zhang JZ (2017) Chemical compositions and sources of glaze-making
411 technology of bluish-white glaze fired at Fanchang kiln, Anhui Province. *Spectrosc Spect Anal* 37:1009–1015.
412 [https://doi.org/10.3964/j.issn.1000-0593\(2017\)04-1009-07](https://doi.org/10.3964/j.issn.1000-0593(2017)04-1009-07) (in Chinese)

413 Zhou LJ (2011) Chemical analysis of sherds and raw materials recovered from archaeological excavations at the Ding kiln
414 site. Master’s thesis, Peking University, Beijing (in Chinese)

415 Zhu J, Yao ZQ, Luo H, Ma HJ, Zhang WJ (2024) Chemical compositions and Sr isotopic characteristics of qingbai glazes
416 from the Fanchang kiln. *Southern Cultural Relics* 5:252–257 (in Chinese)