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Chemical insights into pottery production and use at Neolithic Fenghuangzui earthen-walled town in China

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Xinyue Ao[1,2,4], Jianfang Wu[1,2,4], Zichen Xie[1,2] & Tao Li[1,2,3]

Widespread earthen-walled town construction in the Neolithic middle Yangtze River valley reflects significant sociopolitical changes. The Fenghuangzui site, located far from the Jianghan Plain—the core area of Upper Qujialing and Shijiahe cultures—shows strong cultural influence from the plain through pottery styles. Comparing peripheral sites like Fenghuangzui to core areas offers insights into social differentiation and cultural identity, though research is limited. This study analyzes 129 sherds from Fenghuangzui using X-ray fluorescence, revealing continuity in pottery production with consistent clay sources despite cultural shifts. Comparisons with Zoumaling in the Jianghan Plain indicate independent pottery production at both sites using local materials but shared techniques in forming, shaping, and firing. We argue that the Jianghan Plain's social complexity arose not from elite control over pottery production but from its effective use for sociopolitical and ideological purposes. Further comparisons with core-area sites like Qujialing and Shijiahe will validate these findings.

In the middle Yangtze River valley, 19 Neolithic earthen-walled towns have been identified (see Fig. 1 for the geographic locations of these towns). Two towns were constructed for occupation during the Daxi–Youziling cultural period (6900–5100 cal BP), while the other seventeen were constructed or rebuilt for residential purposes during the Lower and Upper Qujialing (Lower Qujialing: 5500–5300 cal BP; Upper Qujialing: 5300–4500 cal BP) cultural periods[1,2]. Scholars have linked the formation of regional states in this region to the emergence and widespread construction of walled towns[3–5], arguing that social differentiation arose in response to both internal pressures (increased tension and conflict from a growing regional population) and external pressures (natural disasters such as floods and droughts and other environmental changes), ultimately leading to the changes in regional settlement patterns, the reorganization of regional populations, and the sociopolitical transformation during the Upper Qujialing cultural period and its successor, the Shijiahe cultural period[6,7]. Since the 1990s, Chinese archeologists have made great efforts to investigate the layout and structure, chronology, house structures, residential patterning, subsistence strategies, craft production, burial practices, and inter-household differentiation of these walled towns. Their goal is to better understand (1) when these towns were constructed, occupied, and abandoned; (2) how inhabitants sustained themselves; and (3) in what sociopolitical and economic aspects the towns differed from one another. While a general picture of Neolithic town life has emerged[2,5,8], town-to-town comparisons remain underexplored, particularly concerning the differences between walled towns in the core and those in the peripheral areas.

The core area of the Upper Qujialing culture and its successor, the Shijiahe culture (4500–4200 cal BP), is centered on the Jianghan Plain of the middle Yangtze River valley. This area is defined by a most impressive and dense distribution of distinct features and artifacts characteristic of the Upper Qujialing and Shijihae cultural periods. Pottery, the focus of this paper, is one of the most important indicators distinguishing between the core and the peripheral areas. At least five walled towns (Qujialing, Shijiahe, Chengtoushan, Chenghe, and Zoumaling; see Fig. 1 for geographic locations) in the core area have been studied for pottery-making evidence during the Upper Qujialing period. The Qujialing site unearthed the black-painted and black-slipped eggshell pottery artifacts dating to the Upper Qujialing cultural period, whose production requires an oxidation-reduction-oxidation firing atmosphere[9]. The Zoumaling site excavated thin-walled, burnished black serving wares fired in the kiln at 950 °C, presumably related to higher-status Upper Qujaling households and individuals[2]. Pottery kilns were discovered in most walled towns dating to the Upper Qujialing cultural period in the core area, including Chenghe and Chengtoushan. These studies offer initial insights into pottery-making in the core zone, highlighting the particularly impressive manufacture and use of black pottery in the Upper Qujialing cultural period.

During the Shijiahe cultural period, clear evidence of mass-produced pottery artifacts in the core area underscores a centralized mode of pottery

[1]School of History, Wuhan University, Wuhan, PR China. [2]Laboratory for Comparative Archaeology, Wuhan University, Wuhan, PR China. [3]Archaeological Institute for Yangtze Civilization (AIYC), Wuhan University, Wuhan, PR China. [4]These authors contributed equally: Xinyue Ao, Jianfang Wu. e-mail: tao-li@live.com

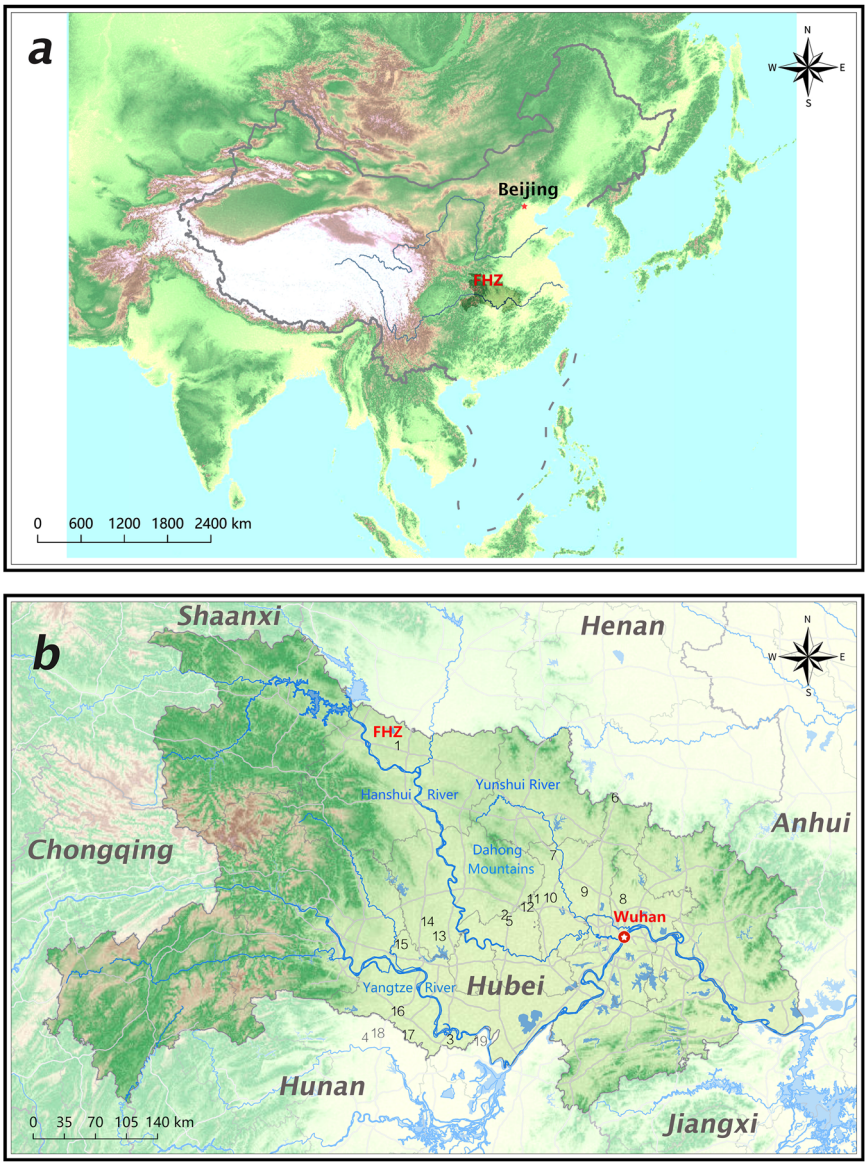


Fig. 1 | Maps showing the geographic locations of 19 Neolithic walled towns in the middle Yangtze River valley of China. a the study area and geographic location of Fenghuangzui. **b** geographic locations of 19 walled towns (1 Fenghuanzgui, 2 Shijiahe, 3 Zoumaling, 4 Chengtoushan, 5 Longzui, 6 Tucheng, 7 Wangguliu, 8 Zhangxiwan, 9 Yejiamiao, 10 Menbanwan, 11 Taojiahu, 12 Xiaocheng, 13 Chenghe, 14 Majiayuan, 15 Yinxiangcheng, 16 Jimingcheng, 17 Qinghe 18 Jijiaocheng, 19 Qixingdun).

production[1,10], while such evidence is absent in the peripheral areas. For instance, archeological excavations at the Dengjiawan and Sanfangwan loci within the Shijiahe walled town discovered a significant amount of red human and animal clay figures and red clay cups (*hong tao bei*) as drinking vessels, respectively[8]. The small clay figurines unearthed from Dengjiawan total over 5000, and in one single ash pit (H67), 1.48–1.8 m in diameter and 0.32 m deep, archeologists collected over 1000 animal figurines[11,p. 369]. The clay figurines were likely mass-produced and used in ritual and ceremonial contexts. Likewise, thousands of thousands of *hong tao bei*, highly standardized in shape and style, were unearthed at the Sanfangwan loci, associated with two kilns, a clay settling or levigation pit, pits for containing unprocessed clay, piles of burnt earth, and a large *gang*-jar probably used to hold water used for forming vessels[8]. Pottery production began at Sanfangwan in the late Upper Qujaling cultural period but intensified during the Shijiahe and Meishan cultural periods, peaking in the Shijiahe cultural period[10]. Many scholars believe that the production of *hong tao bei* was highly centralized and specialized, arguing that Sanfangwan was the largest —if not the only—production and supply center for the widespread discovery of *hongtaobei* in the Shijiahe cultural area[10].

Given the contrasting archeological indicators of pottery production and use between core and peripheral areas, some scholars believe that specialized pottery production developed alongside the advent of large settlements (earthen-walled towns) in the Jianghan Plain—the core area; by the Shijiahe cultural period, craft production was practiced not only in walled towns but also in small, ordinary villages[5] and production centers may have existed to supply the pots on a regional scale[10]. This viewpoint assumes a positive correlation between craft specialization and social complexity (i.e., as craft specialization develops, so does social complexity). Recently, an alternative perspective has been proposed, which encourages the interpretation of pottery findings within the framework of social and symbolic needs and highlights the significance of ritual or ceremonial use of pottery[8]. These two explanations are not necessarily mutually exclusive; however, neither has been scientifically tested.

Our study aims to investigate further how these regions differed in pottery production and use in the Upper Qujialing to Shijiahe transition. We conducted our research mainly by analyzing the chemical composition of domestic pottery, focusing on everyday vessels rather than more elaborate wares like black pottery. Previously, we performed a chemical compositional analysis of domestic pottery from the Upper Qujialing cultural period unearthed from the Zoumaling walled town in the core area[2,12]. In this study, we selected domestic vessel sherds from Fenghuangzui—the site located furthest from the core area of the Upper Qujialing and Shijiahe cultures—for

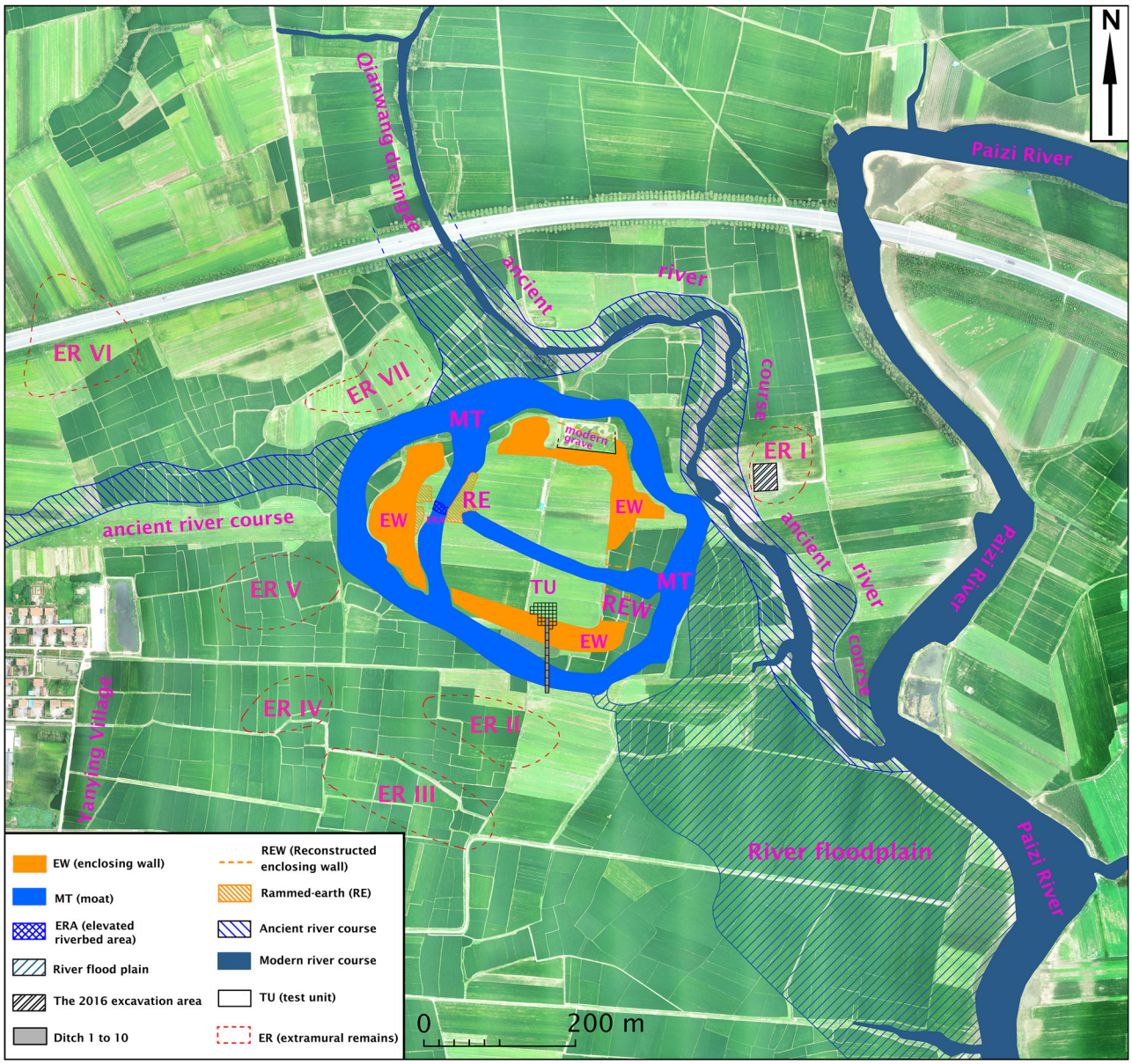


Fig. 2 | The layout and structure of the walled town at Fenghuangzui. Figure courtesy of Dr. Siwei Shan from Wuhan University's Archeological Institute of Yangtze Civilization.

another chemical analysis. Our objectives are threefold: (1) to reveal how pottery was produced in peripheral areas such as Fenghuangzui during the Upper Qujialing and Shijiahe cultural periods; (2) to examine pottery production and use between the two periods to understand continuity and changes at Fenghuangzui; and (3) by comparing our results to the Zoumaling case study, to tentatively discuss how pottery production and use may have related to the sociopolitical transformation of the Neolithic walled towns. Our study presents important new data and discussions from a poorly understood area. The comparison between Fenghuangzui and Zoumaling contributes to the establishment of a methodological framework for inter- and intra-regional comparative studies of craft production and its relationships to societal changes in the Neolithic middle Yangtze River valley.

The Fenghuangzui site (111°58'58.69"E, 32°14'49.58"N) is located in the middle Hanshui River valley and close to the southern edge of the Nanyang Basin in central China. Regarding administrative boundaries, the site spreads into the Yanying and Qianwang villages of Longwang Town in Xiangyang City, Hubei Province. The first test excavation was carried out at the Fenghuangzui site in 2016, delineating the site size and highlighting the possible presence of a walled town. In 2018, the site and its surrounding areas were systematically surveyed to confirm the walled town's layout, size, and spatial distribution of cultural deposits. Since August 2020, joint excavations have been conducted at Fenghuangzui, leading to the discoveries of significant features and artifactual remains by Wuhan University's Archeological Institute for Yangtze Civilizations, Hubei Provincial Institute of Cultural Relics and Archeology, Xiangyang Museum, and Fenghuangzui Conservation Center.

Archeologists have identified a Neolithic walled town with a nearly square plan at the Fenghuangzui site. The walled town was built in the early phase of the Upper Qujialing culture with an enclosing wall and a moat, but it was abandoned by the late phase of the Upper Qujialing culture and transformed into a moat-surrounded settlement[13]. The moat-surrounded settlement continued to be occupied in the Shijiahe (4500–4200 cal BP) and Meishan (4200–3900 cal BP) cultural periods. Residential remains discovered at the site include house foundations, post poles, and ash pits dating to the Upper Qujialing, Shijiahe, and Meishan cultures. Extramural remains outside the enclosing wall are also identified at several loci west of the walled town (Fig. 2). The Fenghuangzui site, along with its surrounding associated

Fig. 3 | Typical vessel forms unearthed from Fenghuangzui. The Upper Qujialing pottery vessels (**a** *bei*-cup, **d** *bo*-bowl, **g** *dou*-stemmed bowl) and the Shijiahe pottery vessels (**b** *bei*-cup, **c** *gui*-wine vessels, **e** *zeng*-steamer, **f** *ding*-tripod, **h** *gaoquanzu bei*-high steam cup, **i** *guan*-jar).

settlements, covers an overall area of ~50 ha, making it the largest settlement discovered to date in the middle reaches of the Hanshui River region. The site features a moat that dates back to the Upper Qujialing cultural period and preserves an enclosing wall and an extensive network of waterways inside and outside the walled town (Fig. 2). Additionally, the artifacts unearthed at Fenghuangzui show characteristics of cultural integration between southern and northern China (a topic we will elaborate further). Typical pottery vessels of the Upper Qujialing and Shijiahe cultural periods unearthed from the Fenghuangzui site are shown in Fig. 3. These remains provide evidence of the northward expansion of the Upper Qujialing culture into the Central Plains[14,15].

Geological settings are important for pottery production because they determine the types and locations of clay deposits, the contents of minerals in clay, the distribution of water and fuel sources, and the many choices the potters made in procuring raw materials and firing pots, e.g.,[16–18]. According to the Xiangfan Formation (I-49-35)[19] and the geological survey report by the Regional Geological and Mineralogical Survey of Hubei Provincial Bureau of Geology and Mineral Resources, the Fenghuangzui site is situated primarily within the valley plains of the Xiangyang-Yicheng Plain. The Xiangyang-Yicheng Plain is primarily a low-lying area with gentle slopes, bordered by the Wudang Mountains to the west and the Dabie Mountains to the north. The plain is part of the larger Yangtze River valley, well known for its extensive river systems and tributaries. The region is characterized by rich alluvial soils, primarily composed of loam and clay, that are highly fertile and suitable for agriculture. Numerous rivers and streams, including the Hanshui River, a major Yangtze River tributary, crisscrossed the plain. This network of waterways supports irrigation and plays a crucial role in transportation and trade. A diverse range of flora and fauna can also be found across the region due to its varied habitats, including wetlands, forests, and agricultural lands.

The Quaternary strata surrounding the Fenghuangzui site extend within a 10 km radius, as indicated by the National 1:200,000 Digital Geological Map Spatial Database (sections I-49-33 and I-49-34). As shown in Fig. 4, the site is located within Holocene alluvial deposits (Qh^{al}), which are often considered suitable for making pottery due to their high clay content, fine texture, the presence of organic matter and minerals, and easy access (typically found in river valleys and floodplains). At the same time, the surrounding areas expose Pleistocene alluvial deposits (Qp^{al}) and Pleistocene slope deposits (Qp^{dl}). The predominant exposed rocks are sedimentary, ranging from clay to silt to coarse sand. The mineral composition of these rocks primarily originates from Quaternary deposits, which are prevalent at the site and extend for several kilometers in the surrounding area[20,p. 113–115].

Methods

We sampled 129 sherds of utilitarian vessels from the Upper Qujialing ($n = 39$) and Shijiahe ($n = 90$) cultural periods at the Fenghuangzui site. All sherds were excavated in the 2020–2022 seasons, 106 of which were unearthed from the southern part of the Fenghuangzui walled town, while the remaining 23 were from the central part. Both excavation areas contained densely distributed residential features and remains. Sherds belonged to artifacts from different residential features, contextual uses, and cultural periods, thereby potentially representing the maximal compositional variations among the sherds consumed in the excavation area (see more sample details in Tables S1 and S2 in Supplementary Information). Features from which sherds were sampled include (1) H236, an ash pit dating to the early Qujialing cultural period; (2) F1 and H7, a house and an ash pit dating to the late Qujialing cultural period; (3) F5 and H13, a house and an ash pit dating to the early Shijiahe cultural period; and (4) H17 and H637, both being ash pits dating to the late Shijiahe cultural period. We focused on houses and ash

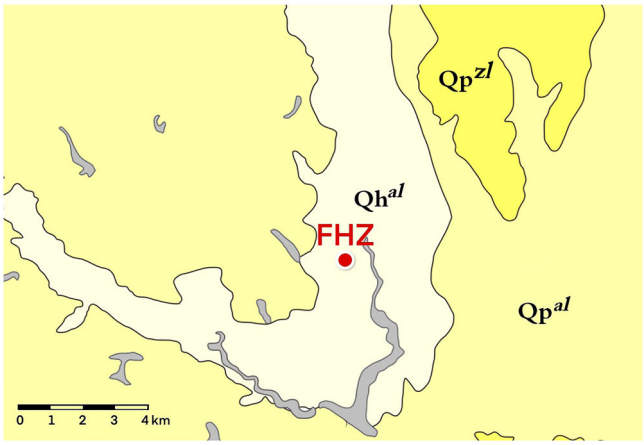


Fig. 4 | Geological background of the Fenghuangzui site.

pits because they were most closely related to human activities occurring on a regular basis.

While selecting sherds from Fenghuangzui, we focused on the fine paste rather than the tempering materials, hoping to explore the diversity of clay source(s) for pottery production. Thus, the selected sherds are mainly fine-paste ($n = 112$). A small sample of coarse-paste ($n = 4$) and shell-tempered ($n = 13$) sherds was also included for comparison. Pottery vessel forms include *fu*-caldrons and *ding*-tripods for cooking; *guan*-jars, *weng*-urns, and *gang*-urns for storage; *dou*-stemmed bowls, *quanzu pan*-ring-footed plates, *wan*-bowls, and *bo*-bowls for serving; and *gui*-wine vessels and *bei*-cups for drinking. Details of the sampled sherds are shown in Table 1.

We selected ten sherds dating to the Upper Qujialing cultural period from the Zoumaling site, located in the core area of the Upper Qujialing and Shijiahe cultures. Excavated from trench G6, these sherds include vessel forms such as serveing *dou*-stemmed bowls and *pen*-basin, drinking *gui*-wine vessels, storage *guan*-jars, and cooking *zeng*-steamer. Previously, we conducted a chemical analysis of 130 domestic pottery sherds from Zoumaling, which revealed minimal chemical variation among different household units, textures, vessel shapes, forms, and functions[12]. Assuming the ten sherds share similar chemical compositions, we compared them with the 129 sherds from Fenghuangzui to assess differences in pottery production and use between the two towns from a chemical perspective. This allows us to better understand the role of pottery production and distribution in the core vs. peripheral areas.

Wavelength dispersive X-ray fluorescence (WDXRF)

We performed a chemical compositional analysis of the 129 selected samples on an Axios mAX wavelength dispersive X-ray fluorescence spectrometer (WDXRF, Marvin Panaco, the Netherlands) at the Public Service Platform for Scientific Research of Wuhan University. This instrument has an ultra-sharp, non-tungsten filament X-ray tube with four filters to eliminate line interference and increase the detection limit of the analyzed element. The maximum power of the high voltage generator is 60 kV, 160 mA, 4 kW. The instrument determines the elemental content of ppm to 100%; the elements to be determined range from O_8 to U_{92}. The test of each powdered sample takes ~30 min.

Up to 50 elements were reported in every test; however, most were excluded from further statistical analysis due to their low concentrations (lower than the detection limit or less than 100 ppm). Fourteen (14) elements and oxides are considered reliable, including Al_2O_3, CO_3, CaO, Fe_2O_3, K_2O, MgO, Na_2O, SiO_2, Ba, Mn, P, Ti, Sr, and Zr. The 14-element compositional dataset can be found in Supplementary Tables 1 and 2. Statistical analysis of the 14-element compositional dataset was completed using SYSTAT software (version 13.0). PCA was applied to the compositional dataset of 14 elements and oxides. The 90% confidence ellipse was drawn in each scatter plot, with which we are reasonably confident that the sherd pool from which our samples were drawn would expect to fall within that ellipse. By observing the distribution of sherd specimens in or beyond the confidence ellipse, we could evaluate to what extent the sherd pool from which the studied specimens are sampled was compositionally similar or different from another sherd pool[21].

We performed principal component analysis (PCA) on the 39 Upper Qujialing and 90 Shijiahe sherds, respectively, using the 14-element composition dataset. Four principal components were extracted for each PCA. The first four principal components (PCA1, PCA2, PCA3, and PCA4, see component loadings in Supplementary Table 5) for the 39 Upper Qujialing sherds account for 82.3% of the total variance of original compositional data. By contrast, the first four principal components for the 90 Shijiahe sherds account for 82.2% of the total variance of original compositional data. Scatter plots were drawn to indicate the relative positions of sherd samples on the two axes using the PCA scores (PCA1 vs. PCA4 and PCA2 vs. PCA3, see component loadings in Supplementary Table 6).

We performed another chemical compositional analysis of the 10 sherds, all fine-paste, selected from Zoumaling using the same instruments and test conditions as described earlier. The dataset consists of 12 elements and oxides (Al_2O_3, CaO, Fe_2O_3, K_2O, MgO, Na_2O, SiO_2, Ba, Mn, P, Sr, and Zr, see Supplementary Tables 3 and 4), following the procedures described earlier. PCA was applied to the chemical dataset composed of 10 sherds from Zoumaling and 112 fine-paste sherds from Fenghuangzui. The three extracted principal components (PCA1, PCA2, and PCA3, see component loadings in Supplementary Table 7) for those 122 sherds account for 77.9% of the total variance of original compositional data. The 90% confidence ellipse was drawn in the scatter plot.

Results

Chemical analyzes often reveal that pottery and the clay paste from which it was made are most similar in chemical composition; in other words, assuming all other factors are equal, the chemical composition of clay paste is largely retained in the fired pottery, with minimal chemical changes e.g.,[22,23]. The archeological implication of this observation is significant: by examining the chemical variability among vessel sherds, we can assess the likelihood that two groups of sherds were produced from the same or different clay pastes. It is important to note that potters, whether from the same community or different ones, often employ varied methods in preparing the clay into a workable paste for shaping vessels e.g.,[24,25]. This variability complicates the chemical or elemental correlation between a clay source and the resultant clay paste (or pottery). Consequently, our approach does not aim to directly link specific chemical or elemental patterns to precise geographic loci. Instead, we focus on the chemical composition of the pottery and its implications for the diversity of clay pastes used in production.

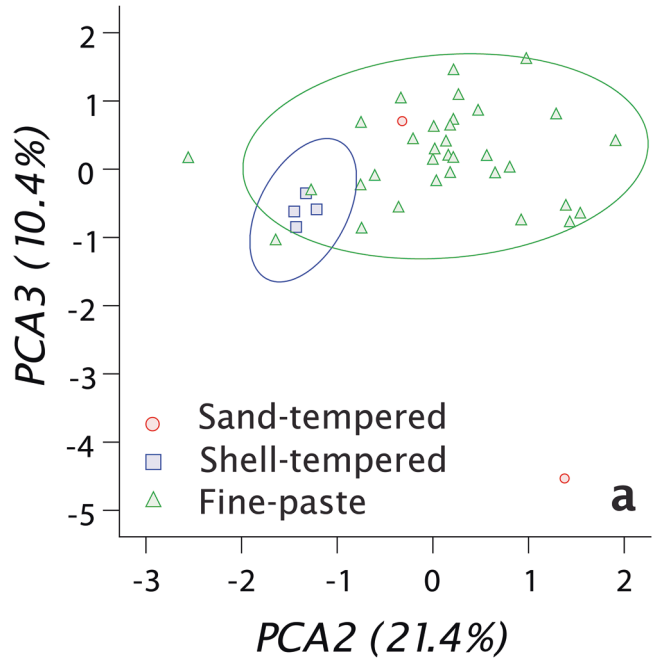
Chemcal variability among sherds from the Upper Qujialing period

Of the 39 Upper Qujialing sherds, 14 date to the early phase and 25 to the late phase of the Upper Qujialing cultural period (the distinction between the early and late phases of the Upper Qujialing or Shijiahe cultural period is made on pottery typology). Vessel sherds unearthed from ash pit H236 date to the early phase of the Upper Qujialing cultural period, while those from F1, a house structure, and H7, another ash pit, date to the late phase of the Upper Qujialing cultural period. As shown in Fig. 5, at the 90% confidence level, 36 (92%) of the 39 vessel sherds fall within the chemical variability delineated by fine-paste sherds, suggesting that the selected sherds are most similar in chemical composition. We may also argue that the addition of tempering agents, such as sand and crushed shells, did not cause significant changes to the pottery's chemical composition.

Figure 6 compares the chemical composition of sherds dating to the early and late phases of the Upper Qujialing period. Once again, nearly all (37 out of 39) sherds heavily overlap in chemical composition, indicating the same clay paste for making pottery from the early to the late phases. It

Table 1 | Archeological information of the 129 selected sherds

Intended uses	Vessel forms	Early upper qujialing			Late upper qujialing			Early shijiahe			Late shijiahe		
		Fine paste	Shell tempered	Coarse paste	Fine paste	Shell tempered	Coarse paste	Fine paste	Shell tempered	Coarse paste	Fine paste	Shell tempered	Coarse paste
Serving vessels (*N* = 56)	*dou*-stemmed bowl	4			4			10			8		
	quanzu pan-footed plate	1			2			1			3		
	wan-bowl	1			2			1			1		
	bo-bowl	1			2			3					
	pen-basin	1			2			4			5		
Cooking vessels (*N* = 22)	*jia*-wine vessel				1				1			1	
	zeng-steamer							1			3		
	fu-caldron		1			1			2			1	
	ding-tripod		1		1	1		2	1	1	1	2	
Storage vessels (*N* = 34)	*zun*-wine vessel							1			1		
	weng-urn	1									2		
	gang-urn			1			1	4					1
	guan-jar	1			2			3			5	1	
	gaoling guan-jar with high neck	1			3			1			4		
	ailing guan-jar with short neck							1					
Drinking vessels (*N* = 17)	*hu*-pot							1			1		
	bianfu hu-flat-bellied pot										1		
	xiefu bei-cup	1						5			2		
	gaoquanzu bei-high steam cup				2						1		
	gui-wine vessel										3		
Sum		39						90					



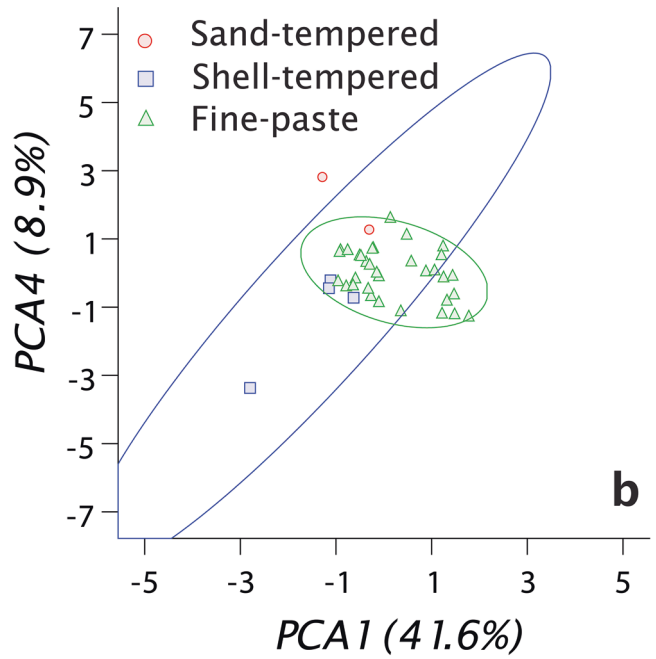
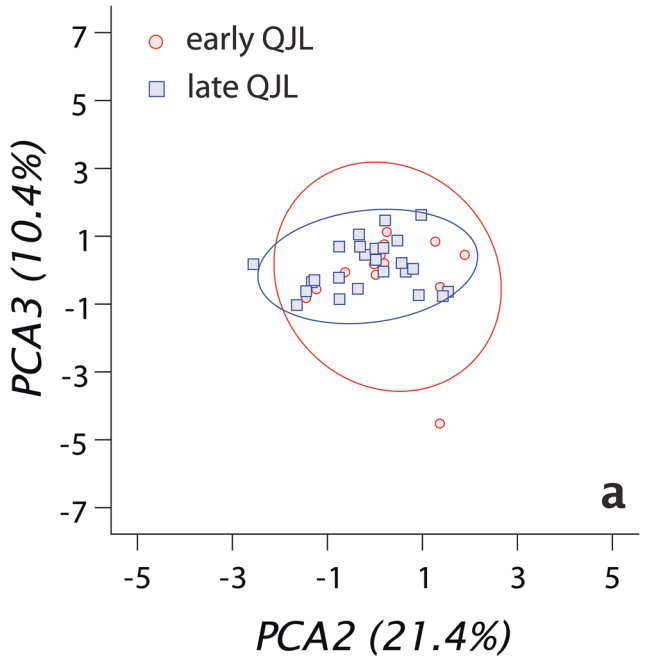


Fig. 5 | Chemical variability among the 39 Upper Qujialing vessel sherds (by paste). a PCA2 vs PCA3. **b** PCA1 vs PCA4. Drawn with a 90% confidence ellipse.



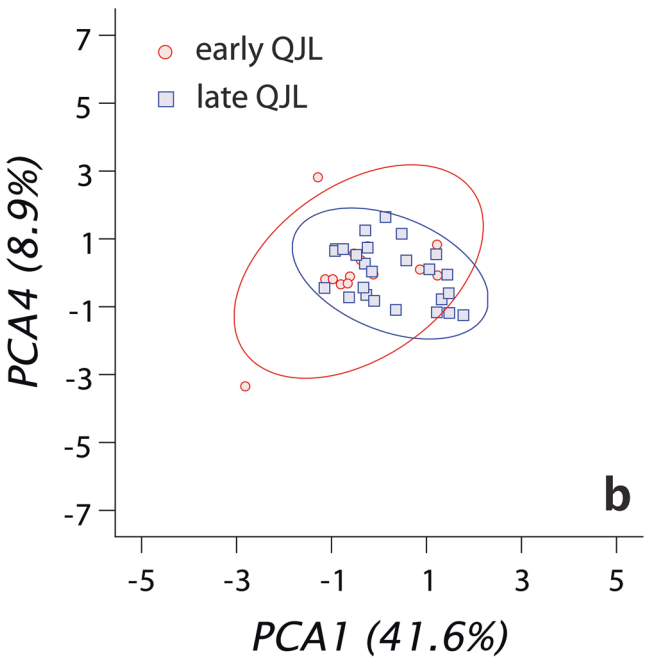


Fig. 6 | Chemical variability among the 39 Upper Qujialing sherds (by period). a PCA2 vs PCA3. **b** PCA1 vs PCA4. Drawn with a 90% confidence ellipse.

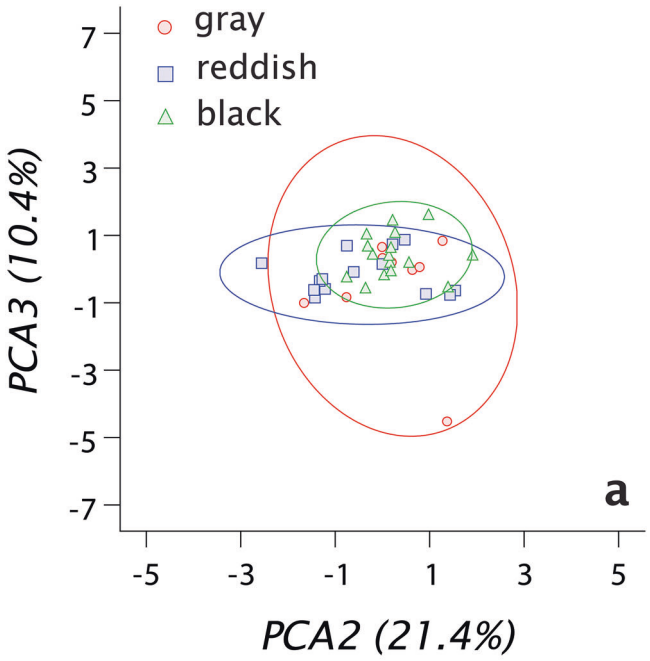
suggests a continuity in the paste preparation method, the exploited clay source, or both during the Upper Qujialing cultural period.

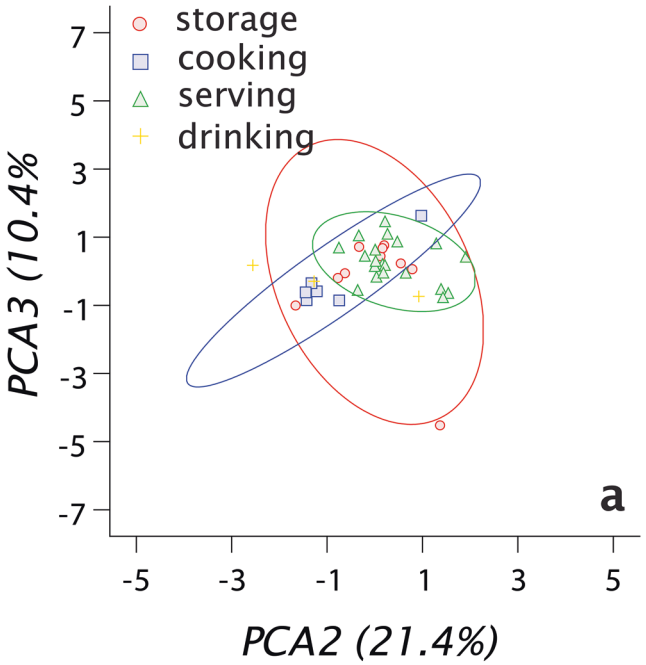
Figure 7 shows the differences in the chemical composition of the Upper Qujialing vessel sherds with different paste colors (gray, reddish, and black). We refer to "paste color" as the color of the pottery's body itself. The paste color often varies depending on the mineral content and the firing conditions, which may help distinguish different clay sources[26,27]. As shown in Fig. 7, black pottery has a more distinct chemical composition, showing a concentrated and, therefore, narrower range of chemical variability. In contrast, the gray and reddish pottery sherds significantly overlap in chemical composition. However, as a whole, vessel sherds with different paste colors are indistinguishable from one another, suggesting that the same clay paste and/or firing conditions apply to the investigated pottery vessels.

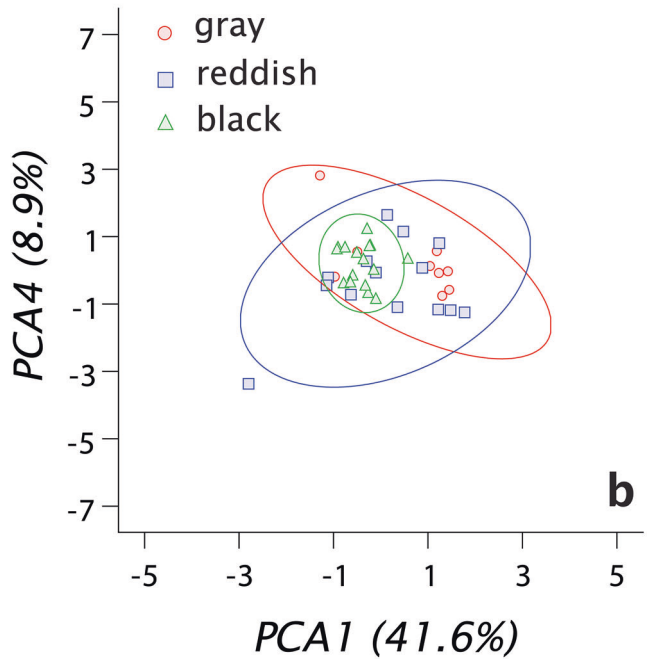
The same observation applies to Fig. 8. The serving vessels are more concentrated in chemical composition than vessels for other functional uses. Although some cooking vessels seem to differ from serving vessels in chemical composition, both functional uses are not chemically specific; that is, no clay paste seems to correspond to a specific, intended functional use. The potters made pottery from the same clay paste(s) to cook, serve, and store foods and drinks.

Chemcal variability among sherds from the Shijiahe period

Of the 90 Shijiahe vessel sherds, 44 date to the early phase and 46 to the late phase of the Shijiahe cultural period. Vessel sherds unearthed from ash pits H17 and H637 date to the early phase, while those from F5, a multi-room house, and H13, an ash pit, date to the late phase. Figure 9 shows that most







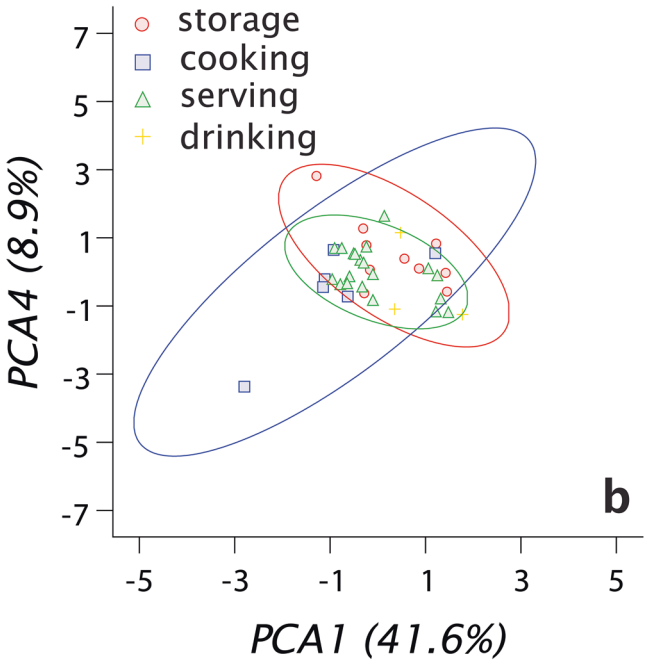


Fig. 7 | Chemical variability among the 39 Upper Qujialing sherds (by paste color). a PCA2 vs PCA3. **b** PCA1 vs PCA4. Drawn with a 90% confidence ellipse.

Fig. 8 | Chemical variability among the 39 Upper Qujialing sherds (by function). a PCA2 vs PCA3. **b** PCA1 vs PCA4. Drawn with a 90% confidence ellipse.

sherds fall within the same ranges of chemical variations, except for a few outliers. The addition of sand or crushed shells as tempering agents did not cause significant changes to the pottery's chemical composition. The same clay paste(s) are strongly indicated.

Additionally, Fig. 10 excludes the possibility that different clay pastes were used from the early to the late phases. However, vessel sherds of the late phase demonstrate a narrower range of chemical variations, suggesting a stronger focus on the more standardized clay paste, which may correspond to the most commonly exploited or more intensively used clay sources. Figures 11 and 12 investigate the chemical variability among vessels of different paste colors or intended functional uses. The same conclusions can be drawn from Figs. 11 and 12, just as from Figs. 7 and 8: neither the paste colors nor the intended functional uses are correlated to the pottery's chemical composition. The potters made pottery of different paste colors and with different intended uses from the same clay paste(s).

Diachronic perspective on the vessel sherds' chemical variability

We have shown that in both periods, the potters at Fenghuangzui made their pottery vessels from the same clay paste(s) and probably used the same firing techniques. An easier way to present this idea is to compare the chemical variability of the 129 Upper Qujialing and Shijiahe vessel sherds in the same biplots. As with earlier sections, we performed PCA and plotted the sherds using PCA scores. The biplots are omitted here but can be found in Supplementary Fig. 1. From the Upper Qujialing cultural period to the Shijiahe cultural period, the Fenghuangzui inhabitants made pottery from the same clay paste(s), and given this remarkable continuity in nearly 1000 years, we

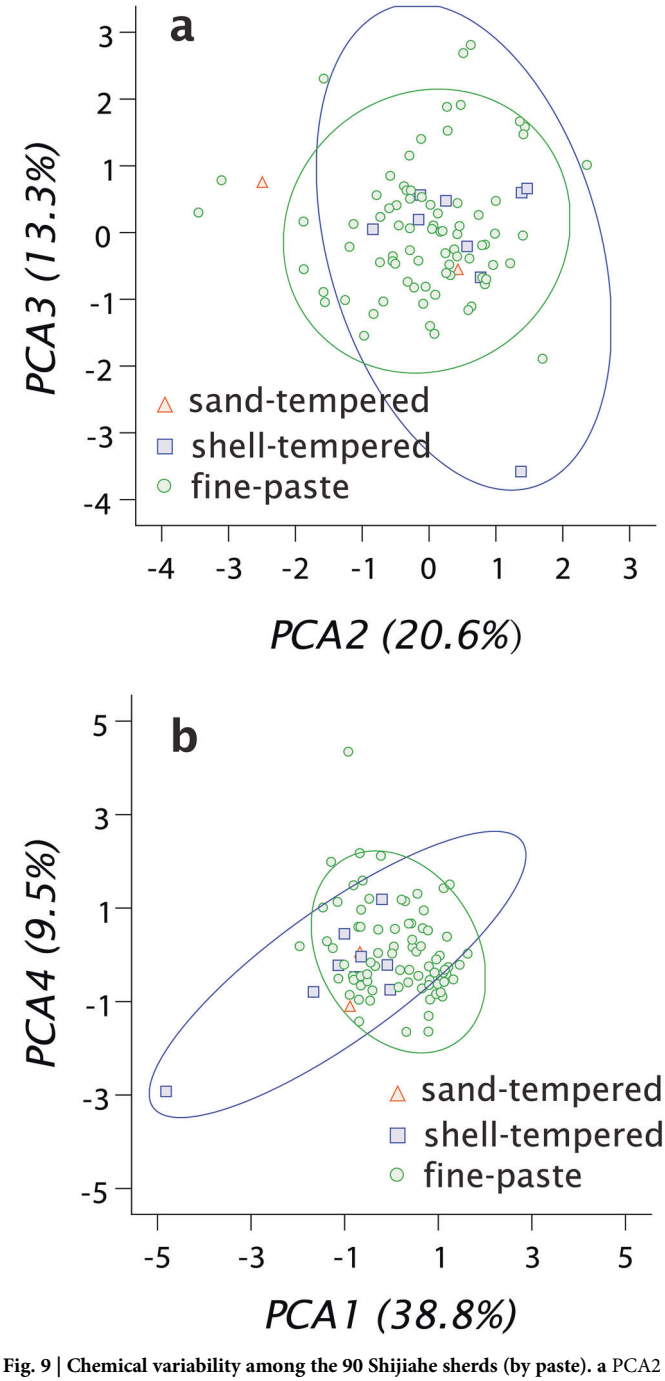


Fig. 9 | Chemical variability among the 90 Shijiahe sherds (by paste). a PCA2 vs PCA3. **b** PCA1 vs PCA4. Drawn with a 90% confidence ellipse.

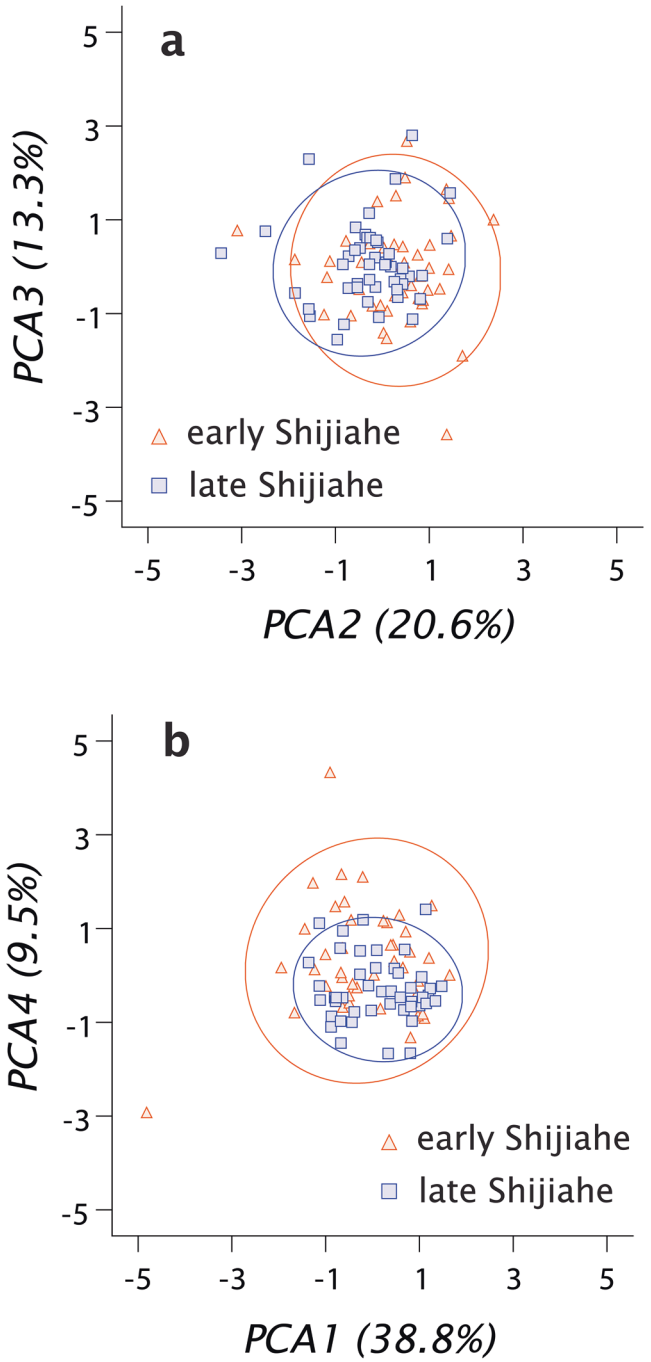


Fig. 10 | Chemical variability among the 90 Shijiahe sherds (by period). a PCA2 vs PCA3. **b** PCA1 vs PCA4. Drawn with a 90% confidence ellipse.

suggest that they very likely procured clay from the same loci consistently and practiced the same paste preparation method. They made pottery with different textures and paste colors for different functional uses. We also highlight that over time, the chemical composition of pottery vessels tends to show a higher level of chemical uniformity, implying that some clay sources were more favored or more intensively used than others.

Comparisons between Fenghuangzui and Zoumaling in a chemical perspective

The pottery artifacts from Fenghuangzui differ significantly in chemical composition from those from the Jianghan Plain, the core area of the Upper Qujialing and Shijiahe cultures. The biplots drawn with PCA scores (Fig. 13) show that the pottery artifacts unearthed from each walled town remain relatively uniform in chemical composition and, at the same time, differ significantly from those from the other walled town. Given the over 290 km straight-line distance between Zoumaling and Fenghuangzui, as well as their different geological settings (Qp^{l} for Zoumaling, Qh^{al} for Fenghuangzui), we conclude that the two walled towns are unlikely shared the same clay sources or the same pool of pottery artifacts. Therefore, we propose that pottery production developed independently at the sites of Fenghuangzui and Zoumaling, rather than manufactured at one centralized loci.

Discussions

The Fenghuangzui site is located at the periphery of the core area associated with the Upper Qujialing and Shijiahe cultures, within a region characterized by cultural diversity. By "cultural diversity," we refer to two or more distinct pottery styles at the same site, possibly resulting from interactions

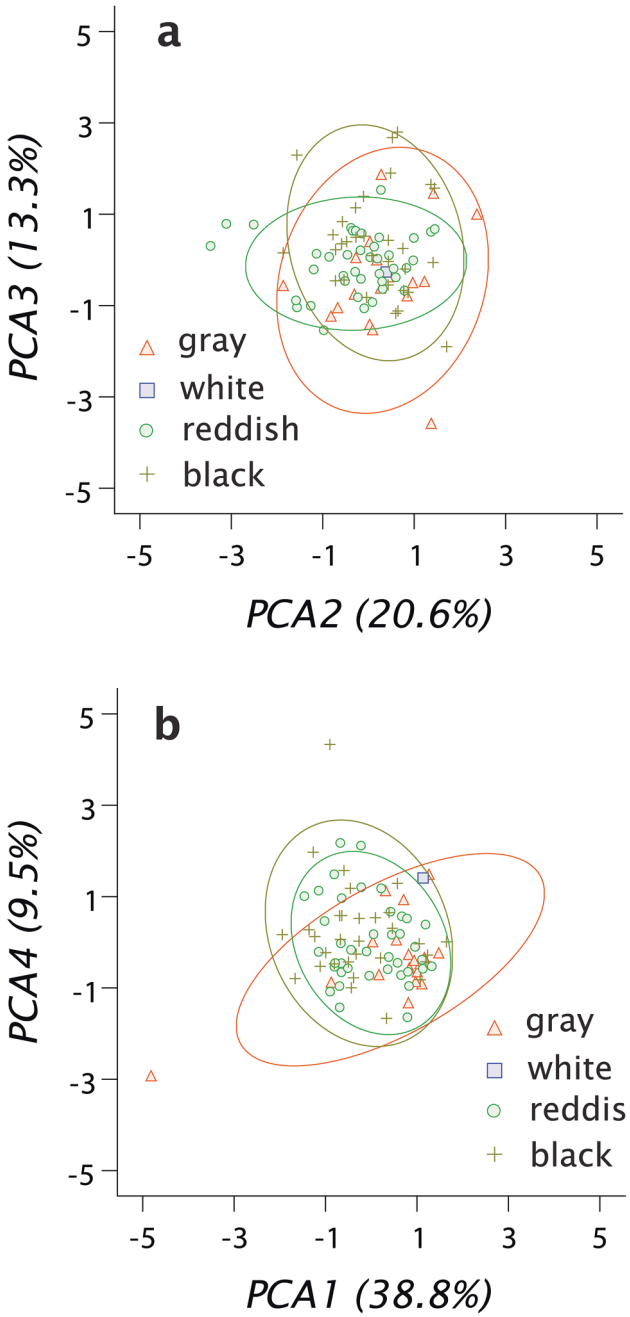


Fig. 11 | Chemical variability among the 90 Shijiahe sherds (by paste color). **a** PCA2 vs PCA3. **b** PCA1 vs PCA4. Drawn with a 90% confidence ellipse.

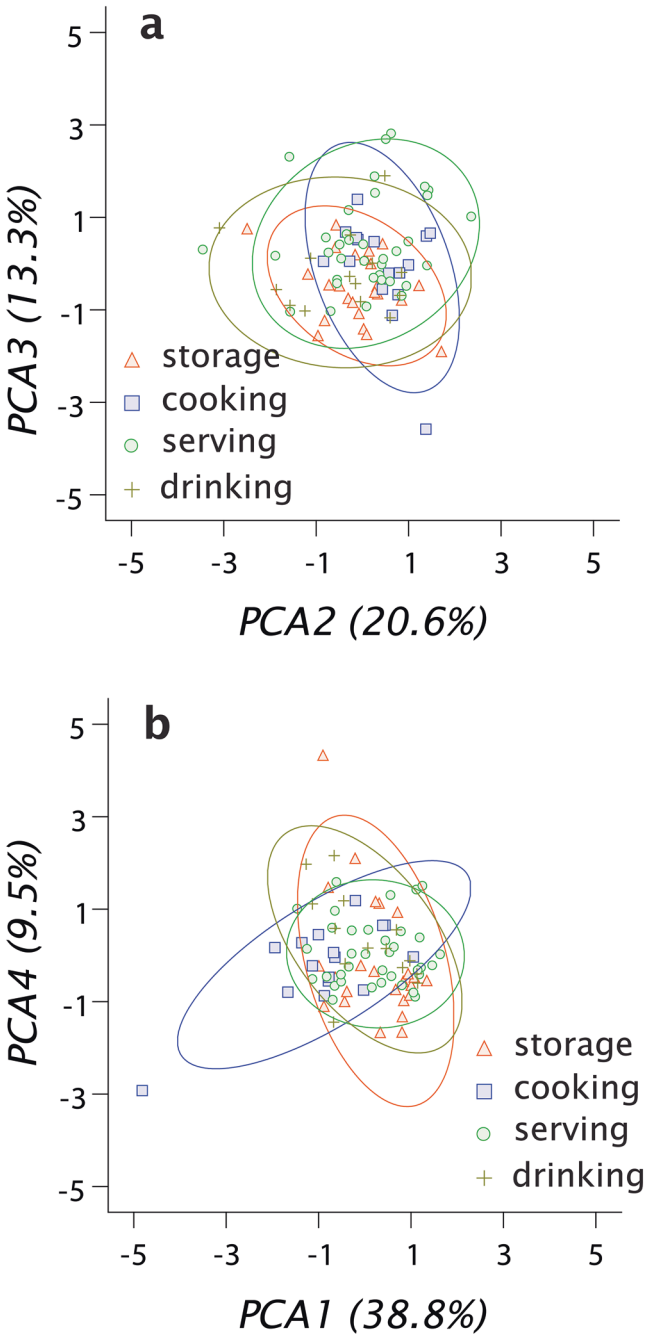


Fig. 12 | Chemical variability among the 90 Shijiahe sherds (by function). **a** PCA2 vs PCA3. **b** PCA1 vs PCA4. Drawn with a 90% confidence ellipse.

between different cultural groups involving exchange, trade, and/or migration[28]. Judging by vessel forms and styles, pottery unearthed from Fenghuangzui implies a strong cultural influence from the core zone, which may be considered the dominant culture. Meanwhile, some pottery shows elements of pottery-making traditions widespread in the Central Plains. However, the "Central Plains" elements reflect only a weaker and secondary source of influence.

For instance, at Fenghuangzui, the vessel forms dating to the Upper Qujialing cultural period primarily consist of basin-shaped *ding*-tripods, *guan*-jars with wide mouths, double-bellied *dou*-stemmed bowls, *bei*-cups with tall ring foot, red-topped *bo*-bowls, and lids decorated with floral designs. The vessel forms dating to the Shijiahe culture mainly include basin-shaped *ding*-tripods, high-necked *guan*-jars, medium-mouth *guan*-jars, *zeng*-steamers, ring-footed *pan*-plates, *leibo*-grinding bowls, *gui*-tripod pitchers, *hongtaobei* (red clay cups), and *qizuo*-stands. Despite its distance from the core area, the style, form, and combination of the Upper Qujialing- and Shijiahe-style pottery artifacts unearthed from Fenghuangzui demonstrate strong similarities to those found in the Jianghan Plain, which is considered the core area. This suggests significant cultural influence from the core area on the pottery traditions in the peripheral areas such as Fenghuanzgui.

Regarding the "Central Plains" influence, the Miaodigou Phase II culture (2900–2500 BCE) expanded from the Central Plains into the northwestern region of present-day Hubei Province, where the Fenghuangzui site is located, during the late phase of the Upper Qujialing period. It slightly influenced the pottery styles, mainly in pottery forms and decorations, and its impact lasted until the end of the Shijiahe cultural period. The jar-shaped tripods decorated with appliqué patterns unearthed from Fenghuangzui were influenced by Miaodigou II culture from the

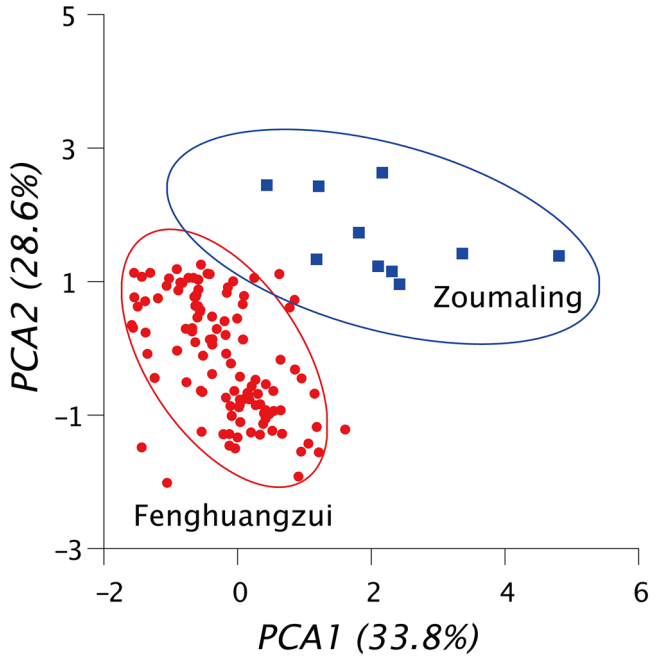


Fig. 13 | Chemical variability among the fine-paste sherds from Zouamling and Fenghuangzui (PCA1 vs PCA2). Drawn with a 90% confidence ellipse.

Central Plains. The three-legged kettle-shaped *jia* unearthed from Fenghuangzui was typical of the Miaodigou II culture.

Figure 14 compares the pottery assemblages unearthed from Fenghuangzui with those unearthed in the core area (especially the Jianghan Plain) of the Upper Qujialing and Shijiahe cultures as well as in the Central Plains. It is evident that through the Upper Qujialing to Shijiahe cultural periods, the Fenghuangzui site received a strong cultural influence from the core zone and was less influenced by the Miaodigou Phase II culture in the Central Plains.

With this background in mind, we proposed three research questions and aimed to illuminate pottery production and use at Fenghuangzui through chemical compositional analysis. To begin with, our chemical analysis indicates a high degree of consistency in the clay used from the early phase of the Upper Qujialing culture to the late phase of the Shijiahe culture[20, p. 113–115]. This suggests that the clay sources were stable and continuous across these periods, potentially obtained from nearby locations. Ethnographic and ethnoarcheological case studies reported worldwide support that potters typically procure clay near their production sites[29]. Arnold's threshold model for ceramic resources suggests that potters rarely source clay or tempering materials from distances greater than 7 km for pottery production[30]. Pottery-making ethnic groups in China match with Arnold's findings, showing that potters following traditional pottery-making practices generally accessed raw materials within a maximum distance of 10 km from their settlements[29]. The geology of the Fenghuangzui site is relatively uniform, with rock minerals primarily derived from Quaternary sediments distributed over an area of ~10 km (Fig. 4). Therefore, we infer that the potters at Fenghuangzui had access to stable sources of raw materials in the vicinity, potentially from one or several loci, during the Upper Qujialing and Shijiahe cultural periods. This assumption is compatible with our chemical results.

Furthermore, the tempering materials used in pottery at the Fenghuangzui site indicate the exploitation of local resources. Xie sampled 1449 sherds, including four different pastes, from household utilitarian vessels dating to the Upper Qujialing and Shijiahe cultural periods. These samples were collected from 21 excavation units at the Fenghuangzui site for microscopic examination. Her research reveals that the selection of tempering materials remained consistent in the Upper Qujialing and Shijihae cultural periods, featuring crushed shells, with significantly less use of minerals and rocks, and the primary mineral and rock types identified are quartz and feldspar, which conform to the site's geological context of predominantly Quaternary sediments[31]. The site of Fenghuangzui is located in a river valley plain, presently 300 meters from the Paizihe River. This geographical setting suggests that potters could have utilized river shellfish resources to make shell-tempered pottery, further underscoring the reliance on locally sourced raw materials. No significant changes in mineral types were observed from a diachronic perspective[31].

Third, archeological discoveries of kilns at the Fenghuangzui site also highlight on-site pottery production. During the 2020–2022 excavations, three pottery kilns (Y3, Y4, and Y5, see Fig. 15a for Y4), all dated to the Shijiahe cultural period, were uncovered. Despite poor preservation, each kiln's chamber, combustion chamber, and fire channel were identified. The kilns share structural similarities with those at Zoumaling (see Fig. 15b), supporting the local production of pottery at Fenghuangzui. Although kilns from the Upper Qujialing cultural period have not been found, we infer their existence at Fenghuangzui due to the high uniformity in the chemical composition of pottery and the consistent way of tempering pottery vessels.

Considering all evidence currently available, we conclude that the Fenghuangzui inhabitants made their pottery using local materials (e.g., clay, sand, and shell) during the Upper Qujialing and Shijiahe cultural periods. The clay sources remained stable and were used to make pottery of different textures, paste colors, and intended functional uses. This either suggests a continuous and stable practice for clay procurement and paste preparation, indicates that the clay procurement catchment was spatially limited or certain clay sources were most intensively used, or both. Further analytical and comparative studies of a systematic sampling of potential clays and sherd samples are required to address these questions.

Previously, we reported that during the Upper Qujialing period, pottery artifacts were made from local raw materials at Zoumaling, a walled town in the core area of the Upper Qujialing and Shijiahe cultures[2]. We further investigated the chemical variability of the pottery artifacts and clay sources within the Zoumaling walled town, arguing that the pottery-making clay was very likely sourced to the West Water Gate and that household units within the town, despite their differing status or wealth, had no difficulty accessing the potters (or the pottery pool)[12]. We argued that household units within the Zoumaling town worked as corporate groups and maintained close relationships and economic ties[32]. The Zoumaling inhabitants shared the same cultural identity, engaged in the same productive activities (e.g., rice farming supplemented by millet agriculture, pottery-making, and lithic production)[12,33], and demonstrated some degree of social differentiation, especially in household size, layout, and prestige items[2]. A sociopolitical landscape was developed over the Zoumaling walled town through time.

Similar to Zoumaling, potters at the Fenghuangzui walled town produced their own pottery for local consumption during the Upper Qujialing and Shijiahe cultural periods. Across different periods and units, Fenghuangzui inhabitants seemed to have differed little in their ability to access the pottery pool, mirroring the situation at Zoumaling. However, the tempering materials used at Fenghuangzui and Zoumaling differed. While both sites employed minerals as tempering agents, crushed shells were commonly used at Fenghuangzui, whereas fiber-tempered pottery was prevalent at Zoumaling.

Observations of well-preserved pottery reveal that both sites used similar forming and shaping techniques, employing wheeled and handmade methods. The method of forming and shaping vessels is correlated with the size and intended use of vessels. For instance, *hu*-pot, *bo*-bowl, and *wan*-bowl were thrown on the potter's wheel; *guan*-jars, *qigai*-vessel lids, and *qizuo*-stands can be formed and shaped either on the wheel or by hand, depending on the vessel size. Larger-sized artifacts such as *gang*-urns were handmade, constructed in two or more parts, and then joined together. Small vessels such as *bei*-cups can be manufactured in various ways. For example, some *xiefu bei*-cups with thin walls were wheel-thrown, others with thick walls were handmade, and high-stemmed *bei*-cups were joined by parts.

In terms of vessel styles, potters at Fenghuangzui demonstrated greater flexibility by producing new vessel styles and forms in addition to those

Fig. 14 | The cultural influence of the Upper Qujialing and Shijiahe cultures from the core area versus that of the Miaodigou Phase II culture in the Central Plains, at Fenghuangzui. (1 *ding*-tripod, 2 *bei*-cup, 4 *wan*-bowl, 5 *dou*-stemmed bowl both from Zoumaling, 3 *guan*-jar from Dengjiawan, 6 *ding*-tripod, 7 *bei*-cup, 8 *guan*-jar, 9 *wan*-bowl, 10 *dou*-stemmed bowl both from Fenghuangzui, 11 *ding*-tripod, 12 *bei*-cup, 14 *pen*-basin, 15 *wan*-bowl both from Zoumaling, 13 *guan*-jar from Xiaojiawuji, 16 *ding*-tripod 17 *bei*-cup, 18 *guan*-jar, 19 *pen*-basin, 20 *bo*-bowl, 21 *jia*-wine vessel both from Fenghuangzui, 22 *ding*-tripod, 23 *bei*-cup, 24 *guan*-jar, 25 *guan*-jar, 26 *pen*-basin, 27 *jia*-wine vessel both from Guchengdongguan).

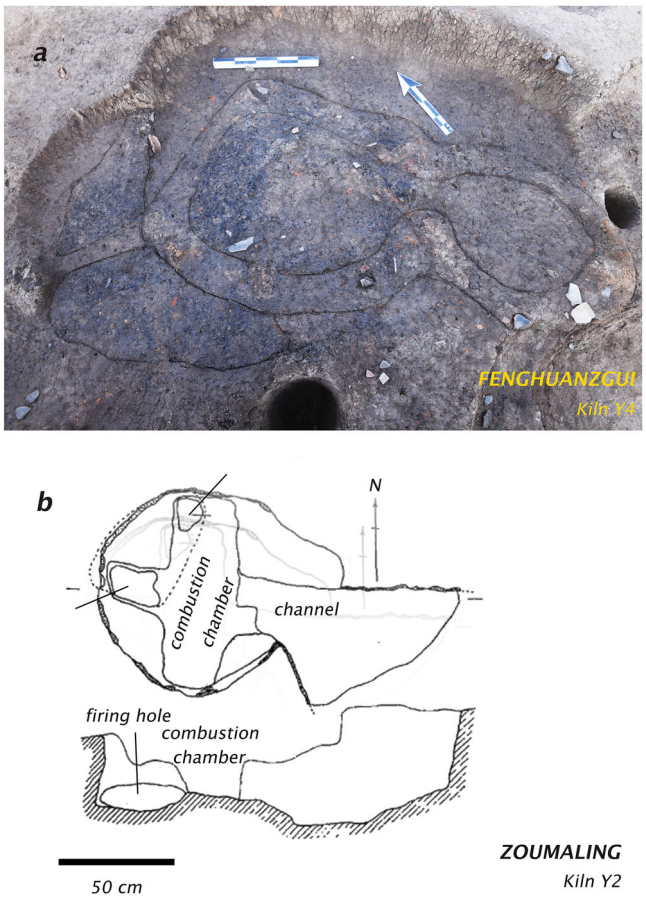


Fig. 15 | The structural features of pottery kilns dating to the Shijiahe cultural period identified at the walled towns. a Fenghuangzui. **b** Zoumaling.

characteristic of the Upper Qujialing and Shijiahe cultures. In contrast, the people of Zoumaling strongly focused on the core area's pottery traditions and rarely consumed or produced pottery with "exotic" styles or made from exotic materials[12]. All else being equal, we infer that diversity in pottery style may reflect innovation, specialization, and technological advancement in pottery-making[34]. Therefore, compared to Zoumaling, Fenghuangzui potters developed a higher degree of flexibility by creating new vessel styles or producing more vessels from consistently used clay sources to meet their needs. From the perspective of manufacturing techniques, Fenghuangzui potters were as advanced as those of Zoumaling, if not more so.

We conclude that domestic pottery was produced independently at Fenghuangzui and Zoumaling, using similar forming and shaping techniques with local raw materials. The peripheral communities practiced their own ways of life in regard to pottery production despite the broader sociopolitical transformation marked by the emergence of walled towns and the widespread influence of the Upper Qujialing and Shijiahe cultures from the middle Yangtze River valley. Researchers have argued that economic control was fundamental to the construction of walled towns and the development of social complexity in the middle Yangtze River valley[35]. Economic control can be achieved through, for example, securing access to important raw materials[36,37] and controlling technical knowledge[38–40]. And, it can extend beyond valuables like jade to include household goods such as utilitarian pottery[35]. For example, Dai Xiangming's regional survey of the Yuanqu Basin, Shanxi Province, provides evidence that Bronze Age elites controlled the regional manufacture and circulation of utilitarian pottery[41].

Our findings indicate that at both Zoumaling and Fenghuangzui, domestic pottery production remained localized and independent, highlighting a similar pattern of economic self-sufficiency (see earlier discussions). We hypothesize that the connections and interactions between Fenghuangzui and the walled towns of the core zone were established not through economic control but through other means. Some scholars have argued that the new form of society emerging during the Upper Qujialing and Shijiahe cultural periods was characterized by a large political entity unified by community cohesion achieved through shared ideology, manifested as rituals or ceremonial artifacts—thereby emphasizing the significance of pottery use rather than production[5,8]. We suggest that the Jianghan Plain developed a high degree of social complexity than elsewhere in the middle Yangtze River valley, not because elites maintained control over pottery production, but because they effectively utilized pottery to serve sociopolitical purposes through rituals and ceremonies. Further studies involving pottery from more walled towns in the core zone, particularly those at sites of Qujialing and Shijiahe, will help assess our observations and develop a more comprehensive understanding of how pottery production, distribution, and use are related to the increasing social complexity in the Neolithic middle Yangtze River valley.

Data availability

The chemical compositional datasets supporting this article's conclusions can be found in Supplementary Information.

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Author contributions

T.L., X.Y. A.o., and J.F. W.u. conceived the study, interpreted the data, and were significant contributors to the writing of the manuscript. T.L. and Z.C. Xie designed the sampling plan, collected the sherds, and prepared the samples for X-ray fluorescence analysis. All authors reviewed and approved the final manuscript.

Competing interests

Tao Li, the corresponding author of this manuscript, serves as an Associate Editor of NPJ Heritage Science and Guest Editor for the article collection 'Cultural Heritage of Neolithic Walled Towns in the Middle Yangtze River Valley: from Archeological Discoveries to Scientific Interpretation.' However, he has not been involved in the peer review process or editorial decisions regarding this submission. The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Tao Li.