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Changes and continuity in pottery production and use at Wujiafentou in the core zone of Youziling and Shijiahe cultures in central China

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Abstract
The Wujiafentou site is located at the heart of the Youziling (5900–5500 cal BP) and Shijiahe (4500–4200 cal BP) cultures in the Handong region, a core area to understand the relationship among economic networks, sociopolitical integration, and regional identity in the middle Yangtze River valley (MYRV) of central China during the Late Neolithic times. Its pottery assemblages are important clues to understanding the pottery production and use before and after the extensive walled town construction activities in the Neolithic MYRV. Wujiafentou is less than 5 km from the Shijiahe walled town, the largest city of its time in the MYRV. This paper applies microscopic examination and chemical and mineralogical analyses to a sample of 152 sherds of the Youziling-period and Shijiahe-period utilitarian vessels unearthed from the Wujiafentou site, revealing the changes and continuity in pottery production and use over time. We also probe into the socio-economic ties between Wujiafentou and the Shijiahe walled town mainly through *hong tao bei* (red clay cups), which were widely distributed and presumably highly symbolic items of the Shijiahe culture related to drinking, feasts, and rituals. We propose that the Wujiafentou inhabitants produced their red clay cups by mimicking those made within the Shijiahe walled town. Our study highlights an alternative interpretation of the formation of a regional identity during the Shijiahe period.

Keywords Wujiafentou, Pottery, Youziling culture, *Hong tao bei* (red clay cups), Chemical composition, Microscopic examination, Shijiahe walled town, Sanfangwan

Introduction

Pottery production, distribution, and use provide important insights into societal changes during the Neolithic times. However, the topic has remained vaguely understood in the middle Yangtze River valley (MYRV), a key region for exploring the beginnings of Chinese civilization. Wujiafentou is a recently excavated site in the Handong region of MYRV. Pottery artifacts dating to the Youziling (5900–5500 cal BP) and Shijiahe (4500–4200 cal BP) cultures have been discovered from Wujiafentou, presenting an avenue to probe into societal changes in Neolithic MYRV in temporal and geographical dimensions. On one hand, the evidence from Wujiafentou may help us understand the process of regional

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sociopolitical and cultural integration before and after the extensive walled-town construction activities in the MYRV, as reflected by the organization of pottery production and distribution. On the other hand, given Wujiafentou's proximity to the Shijiahe walled town, the largest city of its time in the MYRV demonstrating the highest level of social complexity, Wujiafentou's pottery may reveal the relationship between the Shijiahe walled town and its neighboring settlements.

The Handong region and its role in Neolithic MYRV

The relationship between craft production and social complexity has been discussed extensively since Vere Gordon Childe (1892—1957), who, during the 1940s-50s, pioneered in investigating the relations among craft production, patronage, market demands, and technological innovation to understand social evolution in ancient Near East and Europe [1–3]. Using China as a case study, many studies have examined the political economy of ceramic production and shown that the production, distribution, and consumption of pottery are correlated, to varying degrees, with the formation and development of social complexity [4–8, 8–13]. This emphasis on craft production and its relation to societal changes is largely due to the widespread adoption of Marxist interpretative models in Chinese archaeology [14, 15]. Specialized craft production could cause social complexity in one case but result from the latter in another. Therefore, it is important to examine the archaeological data of craft production against different lines of evidence for social complexity rather than assuming a default cause-and-effect relationship between the two. However, such discussions have been insufficient in the Neolithic archaeology of China and, in particular, largely missing from the middle Yangtze River valley (MYRV), one of the six regions comprising much of the later Chinese civilization [16, 17].

In the MYRV, 19 earthen-walled towns have been discovered, 18 of which were constructed, rebuilt, and/or modified for habitation purposes between 5500 and 4200 cal BP [16, 18]. (See Fig. 1 for the geographic locations of 19 Neolithic walled towns in the MYRV. A more detailed introduction can be found in [18].) Such a large concentration of earthen-walled towns is unique in this era in East Asia. Researchers suggested that the extensive construction of these walled towns was correlated with the emergence and development of social complexity in the Neolithic MYRV [18–21], exemplified by the influential Shijiahe regional state. As the center of the Upper Qujialing—Shijiahe cultures (5300–4200 cal BP), the Shijiahe site once expanded to approximately 180 hectares at its peak, and its excavation has yielded strong evidence of extensive regional social-political and cultural integration [e.g., 8,19,20,22,23]. While past studies have delved into the impact of climate change [24–29], population dynamics [30–33], conflicts and warfare [34, 35], and religion [23, 36, 37] on the formation and development of social complexity in MYRV, the current understanding of the interplay of social dynamics and economic networks and their influence on the rise and decline of complex societies such as Shijiahe remains limited [38].

As shown in Fig. 1b, the Handong region refers to the area in the MYRV that lies to the east of the lower Hanshui River, to the south of the Dahongshan Mountain, and to the west of the Yunshui River. It was home to ten Neolithic walled towns identified at the sites of Shijiahe, Tanjialing, Longzui, and Xiaocheng in Tianmen City; Taojiahu and Menbanwan in Yingcheng City; Yejiamiao in Xiaogan City; Wanguliu in Anlu City; Zhangxiwan in Huangpi District of Wuhan City; and Tucheng in Dawu County. These account for about half of the earthen Neolithic walled towns discovered thus far in MYRV [16, 18–22, 39]. During the Late Neolithic period, the Handong region appeared to have functioned as the primary center in China for developing large-scale walled towns [40, 41]. Therefore, this region is crucial for understanding the emergence and collapse of social complexity and regional states in MYRV.

Within the Handong region, the southern foot of Dahongshan Mountain is the core zone for a succession of Neolithic cultures, including the Youziling culture (5900–5500 cal BP), the Lower Qujialing culture (5500–5300 cal BP), the Upper Qujialing culture (5300–4500 cal BP), and the Shijiahe culture (4500–4200 cal BP). The site of Longzui in Tianmen City is believed to have served as a regional center during the Youziling culture period [42]. During the Upper Qujialing and Shijiahe culture periods, the earthen-walled town at Shijiahe and the cluster of settlements in its vicinity stood out as the largest city and the largest site group in MYRV, respectively [8]. Surveys in 2008 identified 73 clustered sites of the Upper Qujialing and Shijiahe cultures within an area of 150 square kilometers around the Shijiahe walled town, making it the most densely-settled region known within the Neolithic MYRV [43]. Sanfangwan, a pottery production site, is located within the Shijiahe walled town. The excavated artifacts from Sanfangwan primarily consist of *hong tao bei* (red clay cups), a highly symbolic item characterizing the Shijiahe-period pottery assemblages across the MYRV (see Fig. 2). The Sanfangwan site has been widely accepted as a location dedicated to the intensive production of Shijiahe-style red clay cups [44], which may have held symbolic significance reflecting a region-wide identity [8]. Our study included some *hong tao bei* unearthed from Layer 6 at Sanfangwan for comparison purposes.

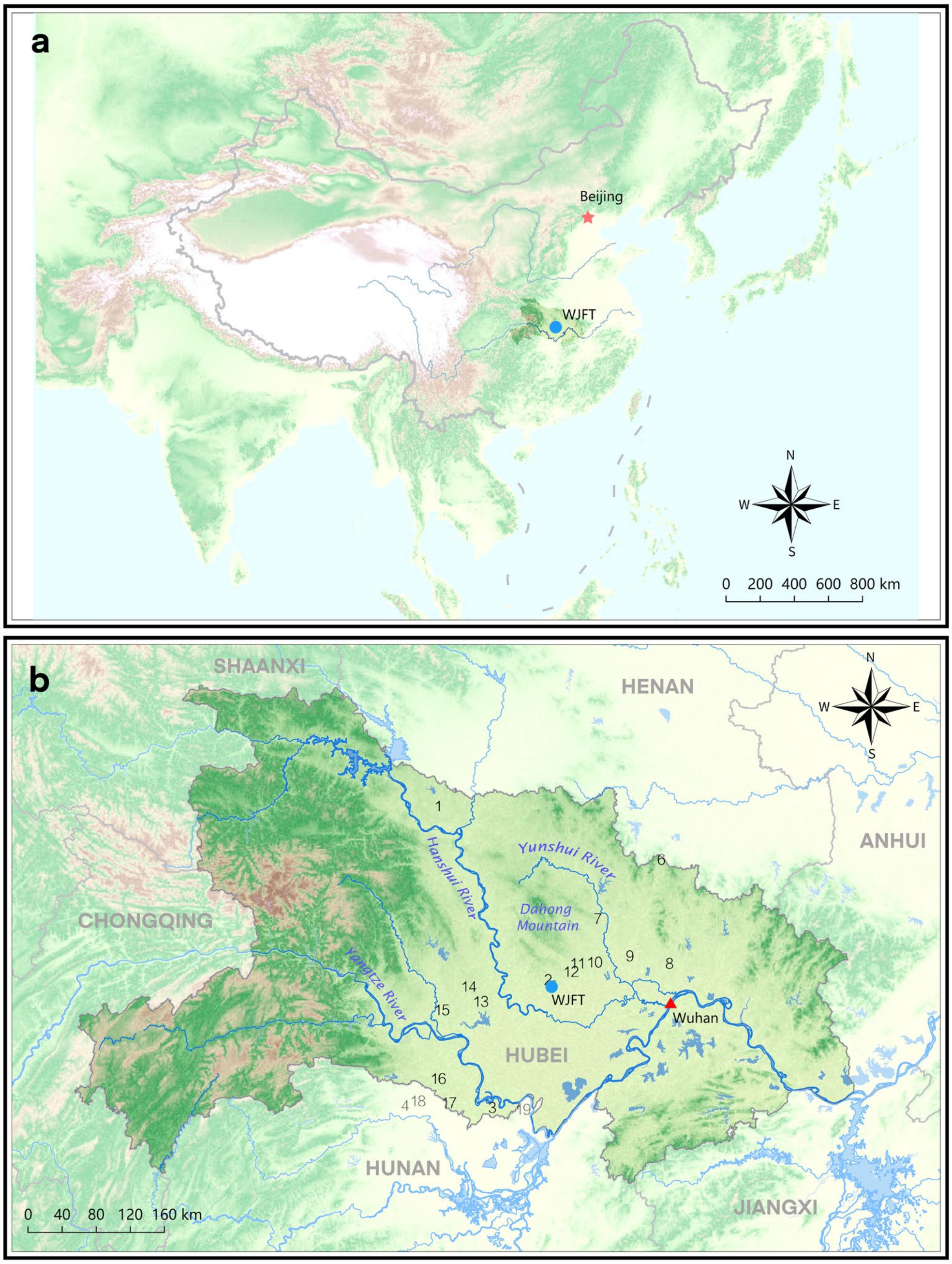

Fig. 1 Geographical locations of **a** the Wujiafentou (WJFT) site (blue dot) in China and **b** the 19 Neolithic walled towns identified in the middle Yangtze River valley (1, Fenghuanzgui; 2, Shijiahe; 3, Zoumaling; 4, Chengtoushan; 5, Longzui, overlapped with Shijiahe and Wujiafentou due to the spatial proximity; 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

Pottery production and use in the Handong region

The understanding of the scale and organization of Neolithic pottery production in the Handong region has been generally limited, and much of the focus was on special items such as the Shijiahe-period *hong tao bei* (red clay cups) and human and animal figurines. Guo proposed that a highly specialized pottery production center was developed within the site clusters around the Shijiahe walled city during the Shijiahe culture period. He argued that a large amount of broken red clay cups discovered at the Sanfangwan site were produced specifically for distribution. Guo believed that red clay cups was

Fig. 2 An enormous number of the Shijiahe-period *hong tao bei* (red clay cups) unearthed from Layer 6 at Sanfangwan within the Shijiahe walled town (**a** red clay cups preserved in situ, **b** stratigraphic profile showing cultural strata at Sanfangwan, **c** broken and complete red clay cups)

mass-produced within the Shijiahe walled city and some (if not all) were distributed, in smaller quantities, to more distant loci around the Shijiahe walled city [45].

Other studies focus on technical examination. For example, W. Li visually inspected the pottery unearthed from the Qujialing site in Jingshan City, arguing that the proportion of fine-paste black and gray-black pottery increased from Phase I through Phase III of the Qujialing culture [46]. W. Li also analyzed pottery unearthed from the Xiaojia Wuji site near the Shijiahe walled town, arguing that most vessels were fired at 800–900 ℃ and only a few might have been fired close to 1000 ℃ [47]. W. Li also investigated the Shijiahe-period pottery unearthed from the Guanmiaoshan site in Zhijiang City and the Honghuatao site in Yidu City, arguing that common, fusible clays were used to make pottery, either using the wheel-throwing technique or shaped by hand [48]. X. Li et al. analyzed the red pigment on painted pottery unearthed from the Longzui site, using a scanning electron microscope coupled with an X-ray dispersive analyzer (SEM–EDS) and attenuated total reflectance infrared spectroscopy (ATR-FTIR). They confirmed that cinnabar (HgS) and hematite (Fe_2O_3) were applied on the red-painted *bo*-bowl while hematite was applied on the *pan*-plate as a red pigment [49]. Recently, Xiao et al. investigated the black-painted and black-slipped pottery unearthed from the Qujialing site using X-ray fluorescence (XRF) and SEM–EDS. They suggested that the black-painted pottery was fired at high temperatures, transforming the black paint into a glassy material, probably involving three phases of firing (oxidizing-reducing-oxidizing) [50].

Despite existing studies on Neolithic pottery from the Handong region, details of pottery production, distribution, and use in the region await further investigation. Particularly, the organization of pottery production (e.g., *hong tao bei*) in the Handong region needs to be testified to by scientific analysis.

The Wujaifentou site in the Handong Region: discoveries and significance

The Wujiafentou site is located in the Yaoling Village of Shijiahe Town in Tianmen City, Hubei Province (see Fig. 3 for an aerial view). This 3-hectare area has undergone extensive surveys by the Hubei Provincial Institute

Fig. 3 An aerial view of the Wujiafentou site

of Cultural Relics and Archaeology, notably during the Third National Survey on Cultural Heritage between 2007 and 2011. Archaeologists revealed a dense distribution of ashy deposits beneath rice fields, indicative of substantial ancient human activities. The collected artifacts included pottery fragments and complete vessels such as *ding*-tripod, *weng*-urn, *guan*-jar, vessel lids, and *hong tao bei* (red clay cups). Stone tools such as axes and chisels were also collected at the site. Typological analysis of pottery and stone tools suggests that Wujiafentou was inhabited during the Youziling and Shijiahe cultural periods.

From July to October 2022, a joint excavation was conducted at the Wujiafentou site by the Wuhan University's Archaeological Institute for Yangtze Civilizations (AIYC) and Hubei Provincial Institute of Cultural Relics and Archaeology. This excavation revealed cultural deposits of approximately 1.6 m in depth, dating to the Youziling and Shijiahe periods. The Youziling-period remains consist of *ding*-tripods with wide and flat feet, ring-footed *pan*-plates with an attached cup, and house foundations and ash pits indicating residence. By contrast, the Shijiahe-period remains consist of many red clay cups, *ding*-tripods with wide and flat feet, *gang*-vats with thick walls, animal figurines, ash pits, and ditches. It seems that pottery vessels were mainly used in domestic activities such as food storage, preparation, and serving during the Youziling period, but their usage expanded over time and included feasts and rituals in the Shijiahe period. Figure 4 shows some restored Youziling-period and Shijiahe-period pottery vessels related to food preparation, consumption, and storage (*dou*-stemmed bowl, Fig 4a; *gui*-tureen, Fig. 4b; painted *wan*-bowl, Fig. 4c; vessel lid, Fig. 4d, e; ring-footed *pan*-plate, Fig. 4f; *wan*-bowl with deep belly, Fig. 4g; *leibo*, Fig. 4h; *gang*-urn, Fig. 4i; *wan*-bowl with shallow belly, Fig. 4j; *bo*-bowl, Fig. 4k, l). Figure 5 shows red clay cups unearthed from the Shijiahe-period context at Wujiafentou, presumably used for drinking. It is evident that these red clay cups differ in shape and other physical dimensions; that is, some have a slim and tall body with small straight mouth (Fig. 5a, b, h), others have a wide body with trumpet mouth (Fig. 5c–g, i–j), and still others have a shape in between the former two categories (Fig. 5k, l). The typological classification of the red clay cups is beyond the scope of this paper. Therefore, the variations in shape and other physical dimensions of the red clay cups and their implications are not pursued further.

The findings from Wujiafentou hold profound archaeological significance. Archaeological investigations in the Handong region used to concentrate on a few sites associated with the Youziling culture, including Longzui, Tanjialing, and Youziling. Compared to other large-scale, contemporaneous cultures such as the Miaodigou culture in the Central Plain, the Dawenkou culture in the Lower Yellow River valley, the Songze culture in the Taihu Lake area, and the Daxi culture in the western Hubei and Dongting Lake area, our understanding of the Youziling culture remains rather limited. The new materials from the Wujiafentou site in the core zone of the Youziling culture offer an opportunity to probe into the sociopolitical and economic life of the Youziling period in the MYRV.

Moreover, the geographical proximity of Wujiafentou to other major settlements in the region is likely to have influenced Wujiafentou's cultural development. Wujiafentou is less than 2 km from the Longzui site, a regional center of the Youziling culture period. Also, it is less than 5 km from the Shijiahe site. Region-wide sociopolitical integration peaked during the Upper Qujialing and Shijiahe periods, with the Shijiahe walled town emerging as the central hub of the Handong region [18, 41]. Wujiafentou was likely under substantial influence from the Shijiahe walled town, particularly during the Shijiahe period. By analyzing the Youziling-period and Shijiahe-period pottery found at Wujiafentou, we can better understand the dynamic interactions between Wujiafentou and the prominent settlements nearby.

Geological background

Tianmen City, where Wujiafentou, Longzui, and Shijiahe are located, is located on the northern edge of the Jianghan Basin, which has long been subject to inland sedimentation since the Yanshan Orogeny. The sediments brought by two major rivers, the Yangtze River and the Hanshui River, along with the gradual shrinking of numerous lakes once widespread in the region, have given rise to sedimentary strata mainly characterized by fluvial-lacustrine facies. These strata exhibit a typical binary structure: strata composed of thick-bedded riverine facies, which are comprised mainly of gravel and sandy materials, alternate with those with thinner, lacustrine bog facies, which primarily contain clay, silt, and silt clay. With extensive historical reclamation, the Jianghan Plain was gradually formed. The fertile soil layer is thick. Lenticular silt clay layers are discontinuously distributed at different depths within 50 m below the surface throughout the Jianghan Plain. [51, 52]

Most of this area, including the locations of Wujiafentou and Sanfangwan, is covered by Quaternary strata, according to the National 1:200,000 Digital Geological Map Spatial Database (H-49-11 and H-49-12 sections). The Wujiafentou site is situated on a platform layer of Pleistocene pluvial-alluvial deposits (Qp^{pal}). The stratum primarily contains an accumulation of grey-yellow

Fig. 4 Restored pottery vessels of the Youziling and Shijiahe cultures unearthed at Wujiafentou (**a**–**g** and **j**–**l**, serving vessels; **i** *gang*-urn for storage; and **h** *kecao pen*-grooved basin for food processing)

to grey-white sandstone (mainly quartz sandstone), sandy clay, as well as chert and limestone. The Sanfangwan site is situated on the Holocene alluvial deposit layer (Qh^{al}) where the Zhu River flows. The stratum displays an accumulation of grey-white to grey-yellow sandy-loamy clay. The loose sand and fine sand are composed of quartz, feldspar, mica, and a small amount of dark-colored minerals.

The strata at both Wujiafentou and Sanfangwan, although slightly varying in rock properties, share a common Quaternary origin, both primarily consisting of Quaternary sediments, i.e., long-grained sedimentary rocks and their weathering products. Figure 6 displays the geological background of the two sites.

Materials and methods

Pottery and sherds unearthed at Wujiafentou

We collected 152 Youziling-period and Shijiahe-period pottery sherds from Wujiafentou (see Table 1 for a summary of the sherds). These samples encompass a diverse

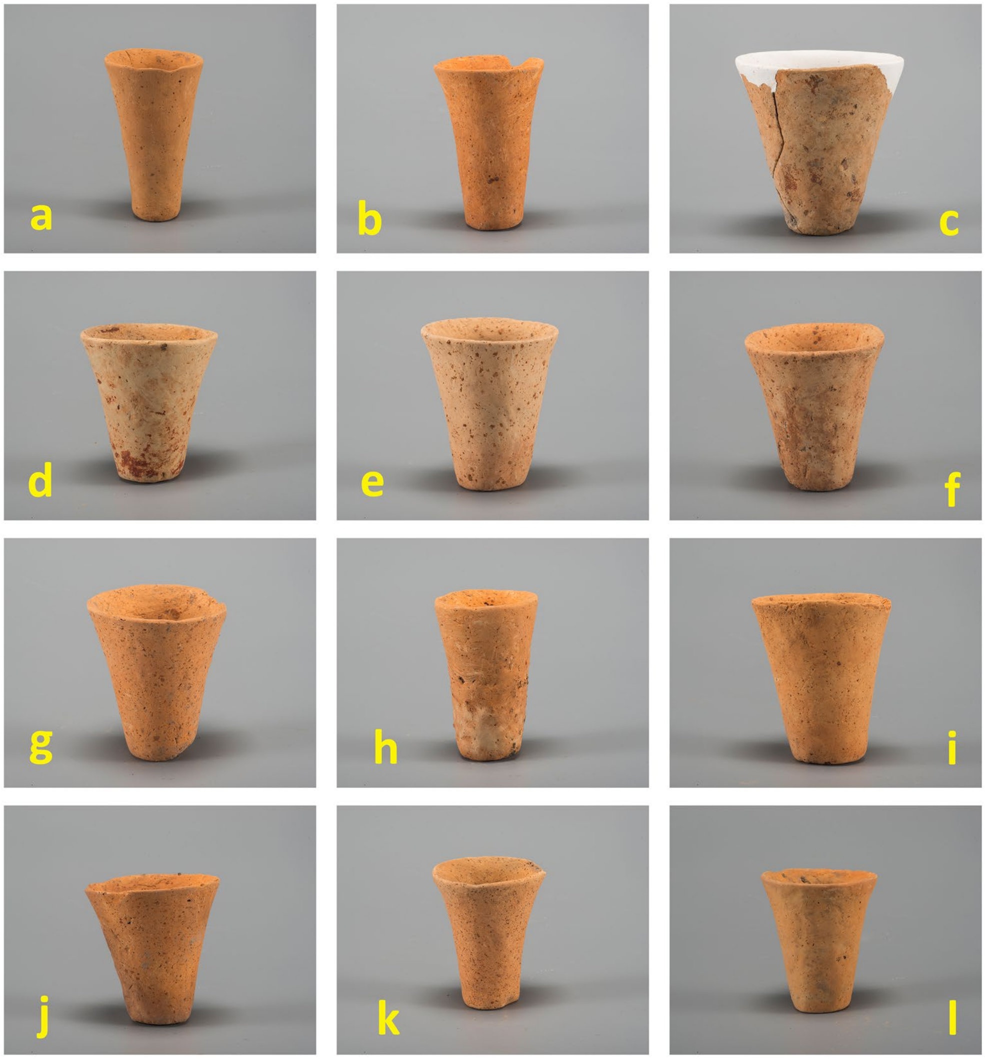

Fig. 5 The Shijiahe-period *hong tao bei* (red clay cups) unearthed at Wujiafentou show variations in shape and other physical dimensions (**a**, **b**, and **h** slim and tall with small straight mouth, **c**–**g** and **i**–**j** wide body with trumpet mouth, **k** and **l** *hong tao bei* with a shape in between the former two categories)

range of pottery types used for different purposes, including cooking wares, serving and storage vessels, and red clay cups presumably used for drinking. (It is worth noting that our work presented here is the first archaeological report on the Wujiafentou site. All data regarding the recent excavation at Wujiafentou are firsthand. The excavation at Wujiafentou will be detailed in another paper.)

Among these, 63 sherds are dated to the Youziling period, all excavated from a residential structure F2. These sherds belong to utilitarian vessels typically associated with household food preparation and serving, based on their shape-deduced functions: cooking vessels (*ding*-tripod and *fu*-caldron), serving vessels (*gui*-tureen, *pen*-basin, *dou*-stemmed bowl, and *pan*-plate), and storage vessels (*guan*-jar and *gang*-urn). Most sherds are made of fine-paste (n = 39), followed by coarse-paste (n = 13), and then by a small number of variants that are tempered with shell and/or charcoal (shell-tempered, n = 2; charcoal-tempered, n = 3; and shell-charcoal-tempered, n = 6).

The remaining 89 sherds from Wujiafentou, dating to the Shijiahe period, were discovered in ditch G3. This ditch was likely part of an encircling trench, and the sherds were probably discarded as trash. Although the Shijiahe-period sherds lack a clear domestic context, 54 of them belong to utilitarian vessels, ranging from *ding*-tripod, *bo*-bowl, and *guan*-jar, to pitcher-like forms and three-legged cups. Forty-two (42) of the 54 sherds are of fine paste, while the remaining 12 are of coarse paste. In

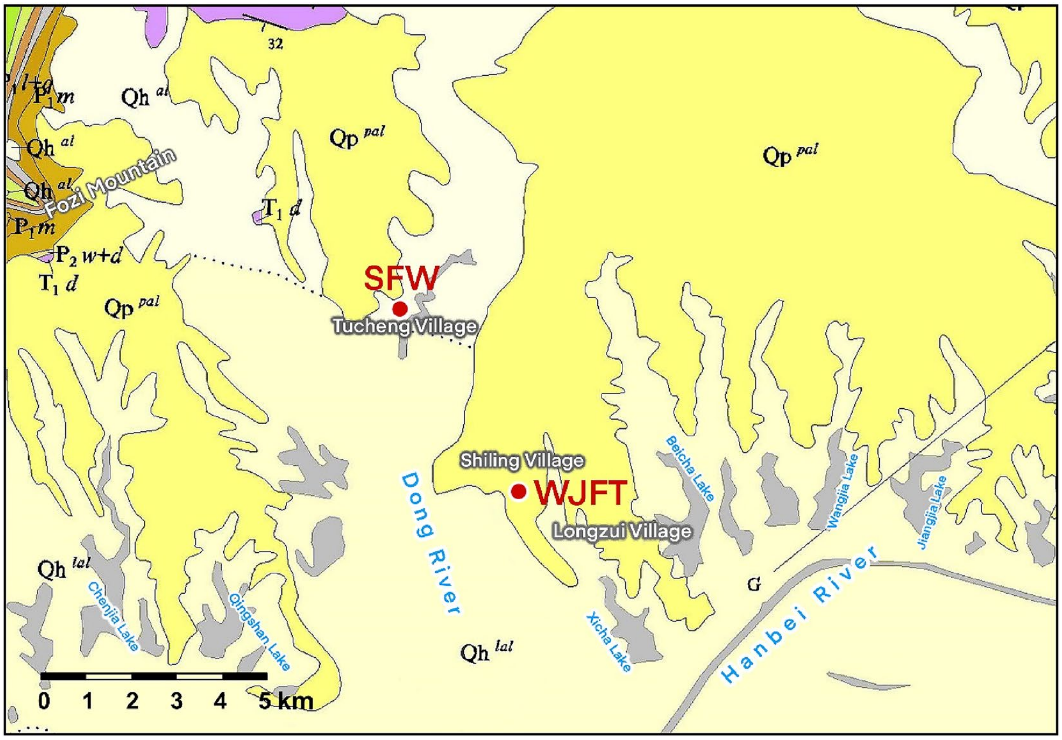

Fig. 6 Geological background of the Wujiafentou and Sanfangwan sites mentioned in the text

addition, 31 red clay cups and four burnt daubs, all from the Shijiahe period, were taken from the remaining samples unearthed from the G3 ditch. To our knowledge, red clay cups have not been found in the Youziling-period pottery. They are unique to the Shijiahe period.

Analytical methods

Examination of the cross-section by optical microscope

Our analysis began with a microscopic examination of each sherd's cross-section. The goal is to classify them by the thickness, color, and texture of their fabrics, as well as by surface treatment and/or mineral inclusions [53–56]. This qualitative characterization of the pottery's fabric facilitates sample selection for further chemical and mineralogical analyses [57]. We prepared each sherd by slicing and polishing. Upon achieving a polished finish, the sherds were set aside to dry, which resulted in a smooth surface. Subsequently, they were examined under a Dino-Lite Edge 3.0 Stereo Microscope (AM73915MZT). We examined the distribution, particle size, degree of sorting, and roundness of mineral inclusions in the sherd. Wherever possible, minerals were identified by their shape, color, transparency, crystal form, and cleavage. Conducted by Y. Hu, the second author, who was trained in gemology and materials science, the microscopic examination of each sherd took approximately 10 min. The full descriptions and results of the microscopic examination of the 152 sherds (omitted here due to space limit) can be obtained from the corresponding author (T. Li) upon request. Table 2 shows the subgroups of the 25 coarse-paste sherds (Youziling, n = 13; Shijiahe, n = 12) by their mineral inclusions.

Thin-section petrography by polarized light microscope

Thin-section petrography reveals the mineralogical composition of ceramic artifacts, allowing for differentiation based on tempering materials. The types and quantities of tempering materials indicate technological choices, household or community identities, and economic networks [58–60]. All the 25 coarse-paste sherds in microscopic examination (see sample information in Table 2), except SJH-47, were subject to petrographic examination. After a process of cutting, mounting, and polishing, slices with a thickness of 30 μm (0.03 mm) were made from the aforementioned sherds. These thin sections were examined under a Leica DMS1000 digital microscope, using magnifications ranging from 6× to 300× under plane-polarized light (PPL) and crossed-polarized light (XPL). PPL reveals the natural colors of minerals, while XPL shows interference colors, both of which are important for mineral identification [61]. Our focus was on the individually visible grains of silt size (20 μm) and larger sizes.

Table 1 Information regarding the 152 selected sherds

	Youziling					Shijiahe		Subtotal
	Fine	Coarse	Shell	Charcoal	Shell-charcoal	Fine	Coarse	
Bo-bowl						2		2
Dailiuqi-spouted vessel						1		1
Ding-tripod	9	3	2	1	4	1	3	23
Dou-stemmed bowl	3					4		7
Fu-caldron				1				1
Gang-urn		4				1	5	10
Guan-jar	2	3		2		8	3	18
Gui-tureen	4							4
Kecao pen-grooved basin						3		3
Pan-plate	1					6		7
Pen-basin	2	3				2		7
Vessel lid	18			1		5		24
Wan-bowl						3		3
Weng-urn						1	1	2
Gui-pitcher						2		2
Pitcher-like forms						1		1
Three-legged cups						1		1
Red clay cups						31		31
Burnt daub						4		4
Unidentified						1		1
	39	13	2	5	4	77	12	
Total	63					89		152

Youziling: Youziling-period; Shijiahe: Shijiahe-period; fine: fine-paste; coarse: coarse-paste; shell: shell-tempered; charcoal: charcoal-tempered; shell-charcoal: shell-charcoal-tempered

Surface elemental analysis by hhXRF and data processing

Chemical analysis has been a valuable tool for investigating the provenance and technologies of archaeological ceramics. Multi-elemental techniques such as instrumental neutron activation analysis (INAA), X-ray fluorescence (XRF), and inductively coupled plasma mass spectroscopy (ICP-MS) have been employed [62–65] to address crucial archaeological questions, particularly those concerning technological choices, social and economic organization, identity, and complex societies. Non-invasive handheld or portable X-ray fluorescence analysis (hhXRF or pXRF) has gained significant attention due to its affordability and in particular, its capacity to discern chemical variations among pottery samples, thus shedding light on pottery production and distribution [6, 7, 11, 66–71].

We employed a Thermo Fisher Scientific Niton XL3+950 handheld X-ray fluorescence (hhXRF) analyzer to gather compositional data from the exterior and interior surfaces of the 152 sherd specimens. The hhXRF analyzer, equipped with a 50 kV X-ray tube featuring an Ag anode and a Large Drift Detector (LDD), employs an active zone fitted with a polymer winder (specifically a MOXTEK AP 3.3 film) which facilitates superior X-ray transmission even in the low-energy range, extending down to the Mg Kα. The X-ray beam had a spot diameter of approximately 3 mm, with the detection limits determined from a cumulative analysis time of 120 s (40 s for the high filter; 40 s for the low filter; and 40 s for the main filter), operating in the Soil mode.

We collected six hhXRF readings for each sherd and calculated the mean. While we identified up to 33 elements, most were excluded in further analysis due to large relative standard deviations [6, 7, 41, 72]. The final compositional dataset comprises ten major, minor, and trace elements (zirconium, Zr; strontium, Sr; rubidium, Rb; zinc, Zn; iron, Fe; chromium, Cr; titanium, Ti; calcium, Ca; potassium, K; and barium, Ba). The readings for these elements were consistent, demonstrating a relative error of under 15%. The 10-element chemical compositional dataset, obtained from the 152 sherds from Wujiafentou and the 25 red clay cups from Sanfangwan, can be found in Additional file 1.

Figure 7 compares the 152 Youziling-period and Shijiahe-period pottery sherds from Wujiafentou, including *hong tao bei* (red clay cups) from the Shijiahe period, by

Table 2 Subgroups of the 25 Youziling-period and Shijiahe-period coarse-paste pottery by their mineral inclusions

Period	Mineral composition	Sherd IDs	Color	Vessel form
Youziling (YZL)	Subgroup I			
	Mafic igneous rocks	YZL-27	Black	*Gang*-urn
	Felsic mineral, felsic rocks, mafic rocks and sedimentary rocks	YZL-22	Gray-black	*Gang*-urn
		YZL-23	Black	*Pen*-basin
		YZL-24	Black	*Pen*-basin
		YZL-25	Yellow	*Guan*-jar
		YZL-30	Gray-black	*Guan*-jar
	Subgroup II			
	Felsic mineral and rocks	YZL-19	Gray-black	*Kecao pen*-grooved basin
		YZL-20	Gray-black	*Ding*-tripod
	Felsic mineral, felsic rocks, and sedimentary rocks	YZL-17	Yellow	*Ding*-tripod
		YZL-18	Gray	*Guan*-jar
		YZL-28	Yellow	*Ding*-tripod
	Felsic mineral, mica, felsic rocks, and sedimentary rocks	YZL-16	Red	*Gang*-urn
		YZL-29	Red	*Gang*-urn
Shijiahe (SJH)	Subgroup I			
	Felsic mineral, felsic rocks, mafic rocks and sedimentary rocks	SJH-07	Red	*Ding*-tripod
		SJH-48	Gray	*Gang*-urn
	Felsic mineral, felsic rocks, mafic rocks, sedimentary rocks, and chalcedony	SJH-10	Yellow	*Ding*-tripod
	Subgroup II			
	Felsic mineral, felsic rocks, and sedimentary rocks	SJH-34	Red	*Guan*-jar
		SJH-36	Black	*Guan*-jar
		SJH-39	Black	*Weng*-jar
		SJH-44	Red	*Gang*-urn
		SJH-47	Red	*Gang*-urn
	Felsic mineral, felsic rocks, sedimentary rocks, and chalcedony	SJH-45	Red	*Gang*-urn
	Felsic mineral, mica, felsic rocks, and sedimentary rocks	SJH-09	Red	*Ding*-tripod
	Felsic mineral, mica, felsic rocks, sedimentary rocks	SJH-50	Red	*Gang*-urn
	Felsic mineral, felsic rocks, and sedimentary rocks	SJH-31	Red	*Guan*-jar

the ten elements' concentrations obtained from hhXRF. For comparison, we included hhXRF data of 25 red clay cups collected from Sanfangwan. Certain elements, namely Zr, Rb, Sr, Cr, and Ca, demonstrate greater potential to characterize chemical variations among different archaeological assemblages of sherds, compared to other elements. According to previous literature review, 23 elements (Al, Ca, Ce, Co, Cs, Cr, Cu, Fe, Hf, La, Mg, Mn, Na, Ni, Rb, Se, Si, Sr, Ti, Th, V, and Zr) were said to be "most important for meaningful classification of pottery" for provenancing purposes [73], but not all of these elements are available in hhXRF data. The elements highlighted here consist of a representative subset that is promising to capture the chemical variations among the analyzed sherds.

Biplots of log-transformed elemental concentrations [74, 75] were constructed using the selected elements (Zr, Rb, Sr, Cr, and Ca, see Fig. 8). In each biplot, an 80% or 90% confidence ellipse is drawn to help us evaluate the likelihood that a subgroup of sherds were made from the same clay source (to be precise, the same clay paste) and that two subgroups of sherds were sourced from the same clay source or from two different clay sources. The patterns of chemical variations remain largely consistent, regardless the use of 80% or 90% confidence ellipse. Our discussions in this paper are based on biplots drawn with an 80% confidence ellipse. Biplots drawn with a 90% confidence ellipse can be found in Additional file 1.

The biplots in Fig. 8 show that (1) the pottery from the Youziling and Shijiahe periods at Wujiafentou largely overlap in composition; and (2) the Shijiahe-period red clay cups unearthed from Wujiafentou significantly differ in chemical composition from the other Youziling-period and Shijiahe-period potteries at the same site, but they overlap in chemical composition with those from Sanfangwan. These patterns of chemical variations are consistently demonstrated by biplots

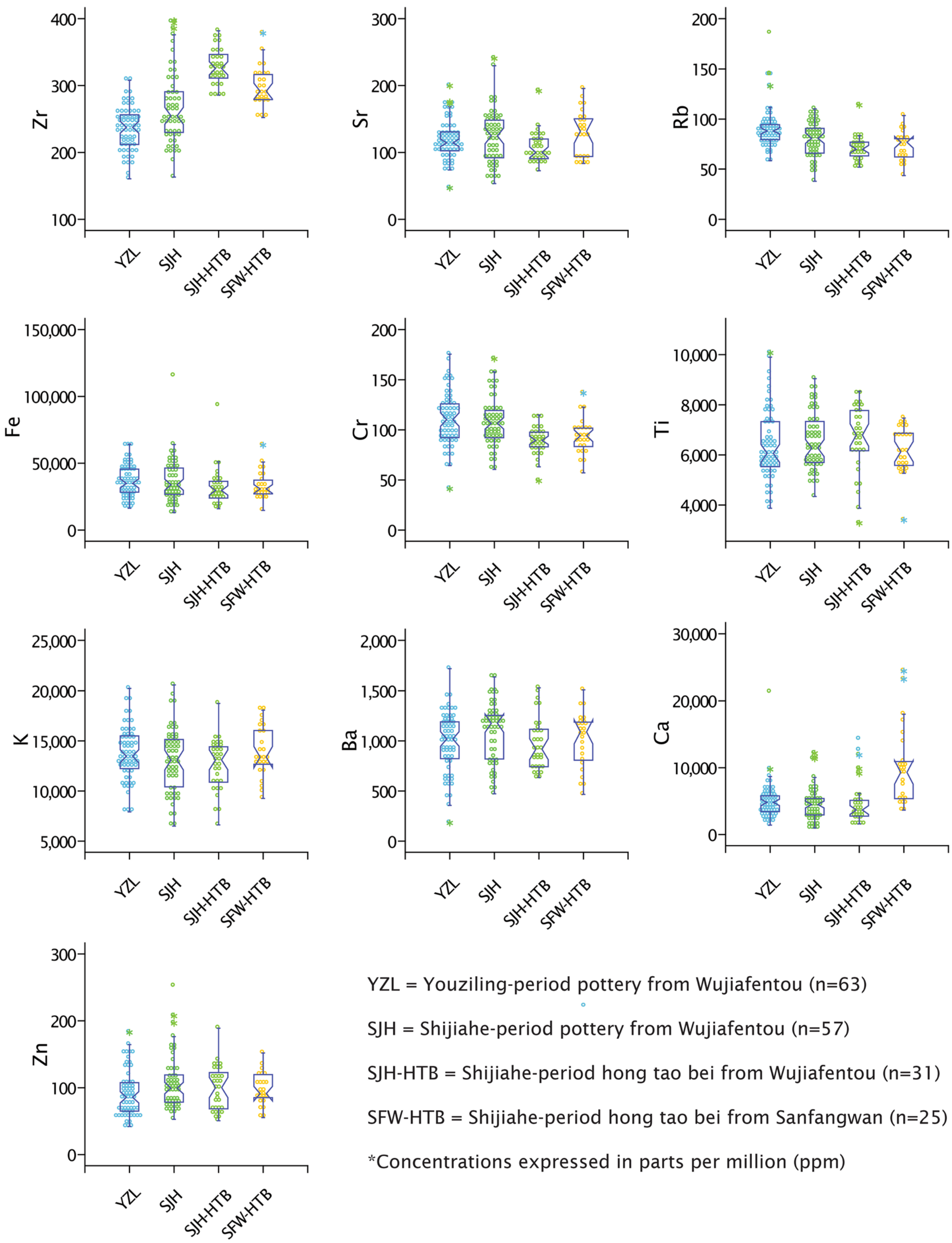

Fig. 7 Comparing the 152 Youziling-period and Shijiahe-period pottery from Wujiafentou and 25 *hong tao bei* from Sanfangwan by the ten elements' concentrations

of log-transformed concentrations of Zr, Rb, Sr, Cr, and Ca. In subsequent discussions, we further narrow down the elements of concern to Zr and Rb (sometimes also Ca) as they exhibit clearer patterns of chemical variations that inform about the use of clay source(s).

Results

The Youziling period (5900–5500 cal BP)

Microscopic examination by optical microscope

We classified the 63 Youziling sherds into coarse-paste (n = 13), shell-tempered (n = 2), charcoal-tempered

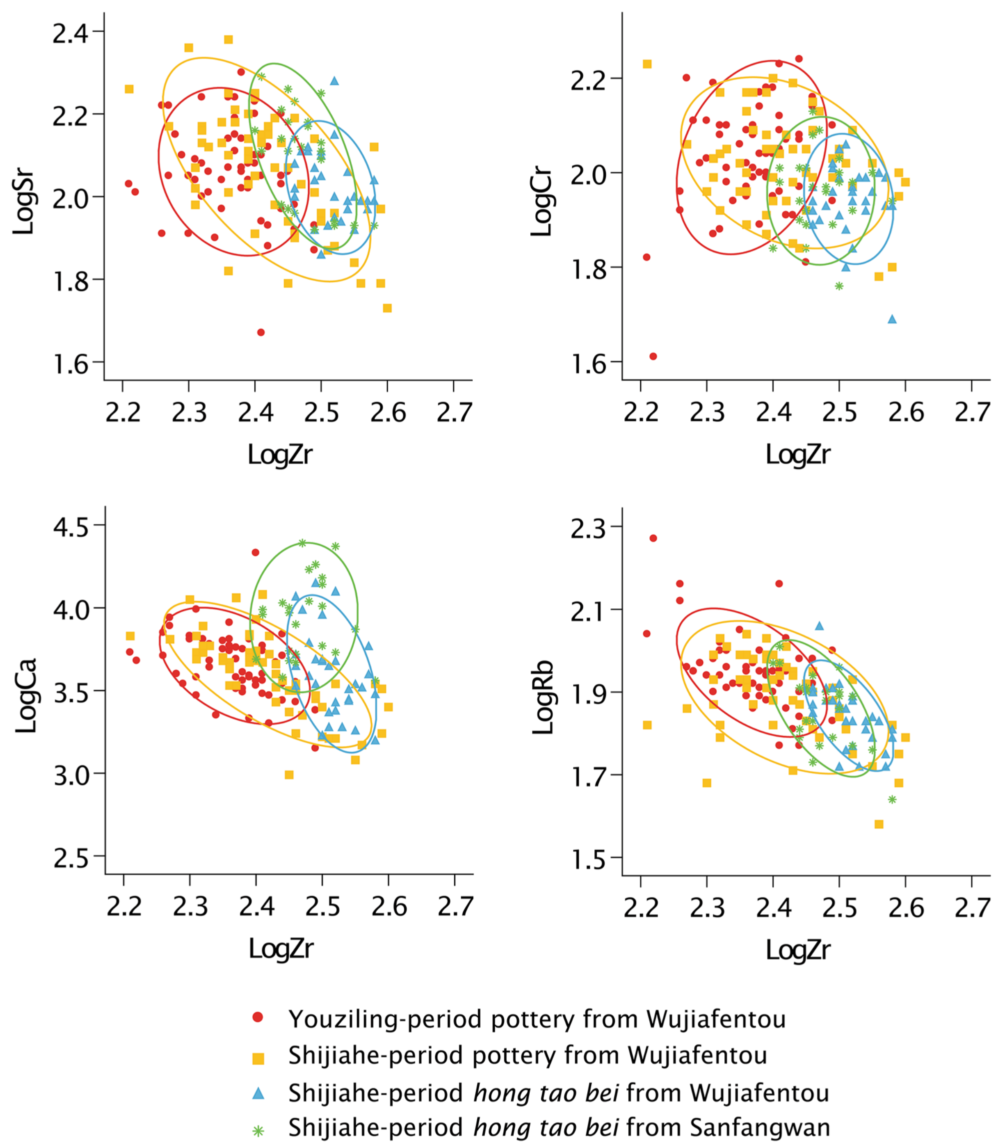

Fig. 8 Biplots of log-transformed concentrations of Zr, Rb, Sr, Cr, and Ca for the Youziling-period and Shijiahe-period pottery from Wujiafentou and 25 *hong tao bei* from Sanfangwan. Drawn with an 80% confidence ellipse

(n = 3), shell-charcoal-tempered (n = 6), and fine-paste (n = 39) by the sherd's paste and the types of inclusions.

The microscopic examination results of 13 coarse-paste Youziling sherds are shown in Table 2. These 13 sherds can be grouped into three types (referred to as S1, S2, and S3) by mineral inclusions. S1 is characterized by dark-colored (e.g., black, brownish-red, or dark green) opaque inclusions, which comprise mafic minerals (e.g., amphibole, pyroxene, and epidote) and also include rocks they comprise, such as basalt and gabbro. Translucent inclusions in S1 sherds are likely chert. S2 is characterized by light-colored (grayish white and light yellow) transparent inclusions consisting of felsic minerals such as quartz, feldspars, and the various rocks they form, including rhyolite and granite. S3 is characterized by light-colored (beige and light brown) opaque inclusions, largely consisting of mudrock or siltstone, with a texture closely resembling the clay matrix. The Youziling-period coarse-paste sherds with mineral inclusions typical of S1, S2, and S3 are shown in Fig. 9.

The 13 coarse-paste sherds can be divided into two subgroups (I and II), based on the mineral inclusions' morphology, granularity, angularity, and distribution frequency (Fig. 10). Subgroup I consists of

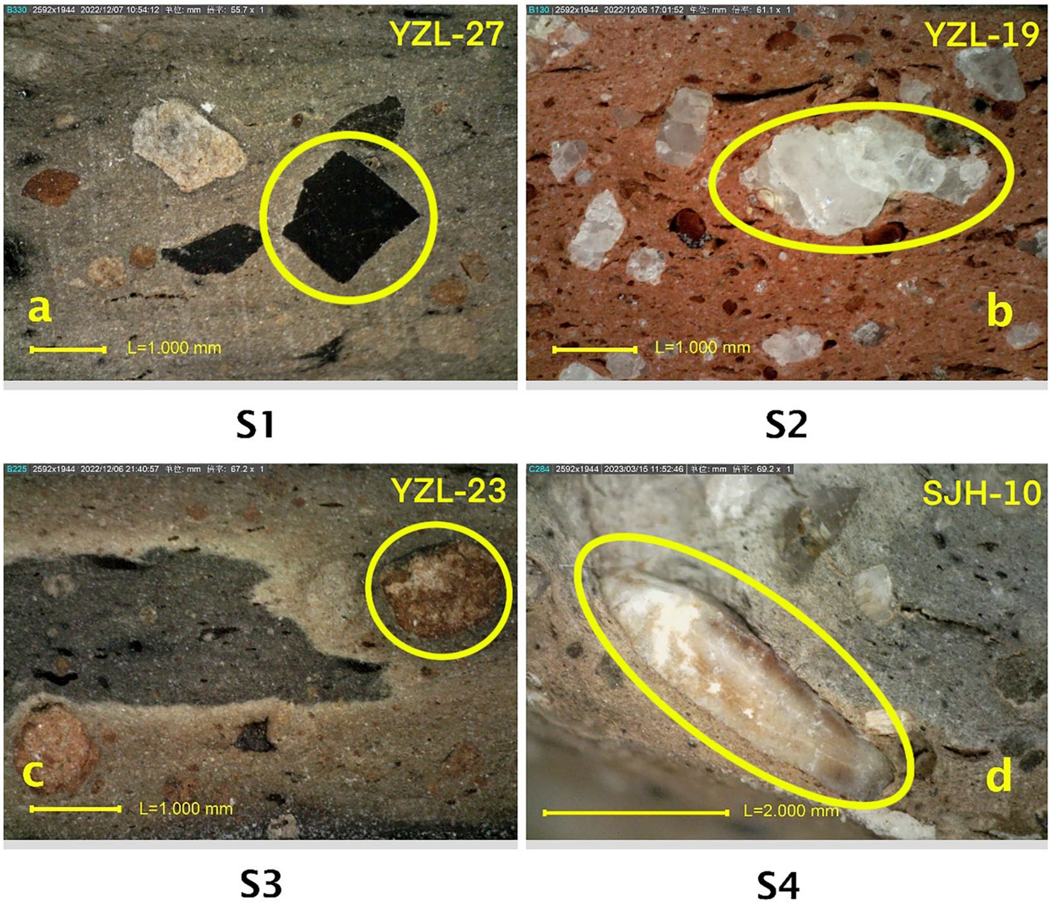

Fig. 9 Mineral inclusions characterizing the 25 coarse-paste Youziling-period and Shijiahe-period pottery (**a** to **c**, mineral inclusions noticed in pottery of both periods; **d**, mineral inclusions only noticed in the Shijiahe-period pottery)

six sherds (Fig. 10a–f) belonging to two *gang*-urns, two *pen*-basins, and two *guan*-jars. Some sherds (e.g., YZL-27, Fig. 10a) contain inclusions of coarse to very coarse sand sizes, with an angular to subangular shape and being moderately sorted. Others such as YZL-23 (Fig. 10c) and YZL-30 (Fig. 10f) in Subgroup I contain inclusions of fine to medium sand sizes, with a subrounded to rounded shape. Still, sherds belonging to S3 (e.g., YZL-22, Fig. 10b) contain inclusions of coarse sand sizes, with subrounded to rounded grain angularity. Large inclusions surpass 1 mm granulometry, while smaller ones are approximately 0.2 mm.

Subgroup II consists of seven sherds (Fig. 10g–m) belonging to one *kecao pen*-grooved basin, three *ding*-tripods, two *gang*-urns, and one *guan*-jar. Diverse grain sizes and subrounded angularity characterize the inclusions. Most samples in Subgroup II—including one *kecao pen*-grooved basin (YZL-19, Fig. 10g), one *ding*-tripod (YZL-28, Fig. 10k), one *gang*-urn (YZL-16, Fig. 10l), and one *gang*-urn (YZL-29, Fig. 10m)—contain a higher frequency of mineral inclusions than those in Subgroup I. Intact muscovite is present (notably in YZL-16 and YZL-29). The largest granularity inclusions reach 2 mm or more, while the smaller ones are between 0.1 and 0.5 mm.

There are two shell-tempered sherds (YZL-04 and YZL-09), both belonging to *ding*-tripods for cooking. YZL-04 (Fig. 11c) shows a significant proportion of shell debris on the cross-section, while YZL-09 has fewer shell-derived inclusions.

Three charcoal-tempered sherds belong to a vessel lid (YZL-03, Fig. 11d), a *ding*-tripod (YZL-06), and a *fu*-cauldron (YZL-21). The two cooking vessels, *ding* and *fu*, contain voids of varied forms. Some are long and straight, others short and curved, possibly associated with different types of plant fibers or different ways of paste preparation.

Six samples belonging to *ding*-tripods and *guan*-jars contain both shell and charcoal temper. Shell shavings and associated voids concentrate on the sherd's exterior surface, while charcoal shavings and associated voids appear more frequently on the cross-sections. These

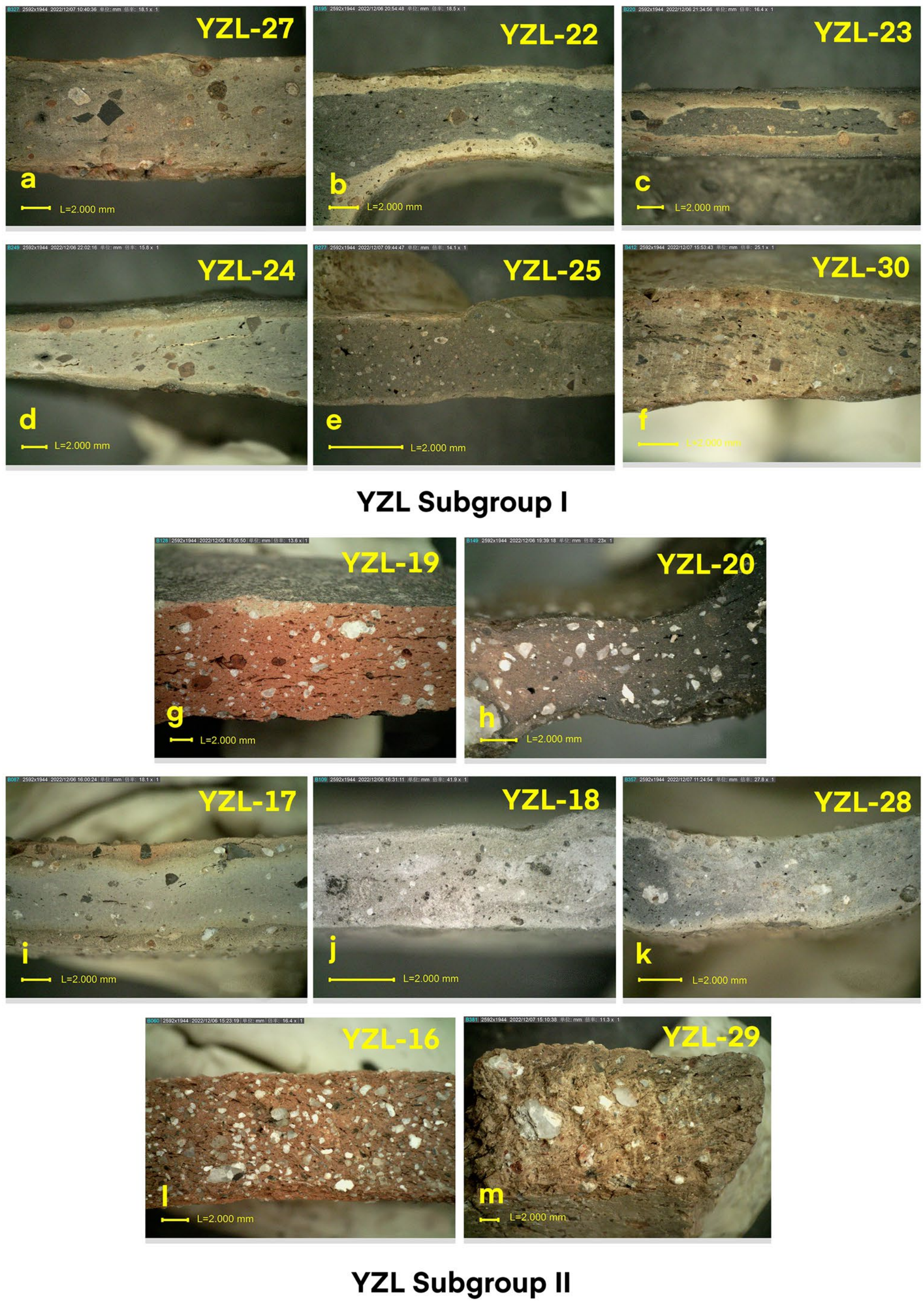

Fig. 10 Two subgroups are identified in the 13 coarse-paste Youziling-period pottery based on mineral inclusions (**a**–**f** Subgroup I, **g**–**m** Subgroup II)

inclusions or voids also appear in various shapes, which can be either straight or curved (e.g., YZL-05, Fig. 11e).

In fine-paste sherds, which belong to vessel lids, *ding*-tripods, and *pan*-plates, the visible "glitter" in the clay matrix likely consists of crystalline quartz, feldspar, and other unweathered minerals presumably occurring in the clay naturally. Some sherds (e.g., YZL-44, Fig. 11f) show a layered (or core–edge) structure, with contrasted colors, on their cross-section. The outer layers

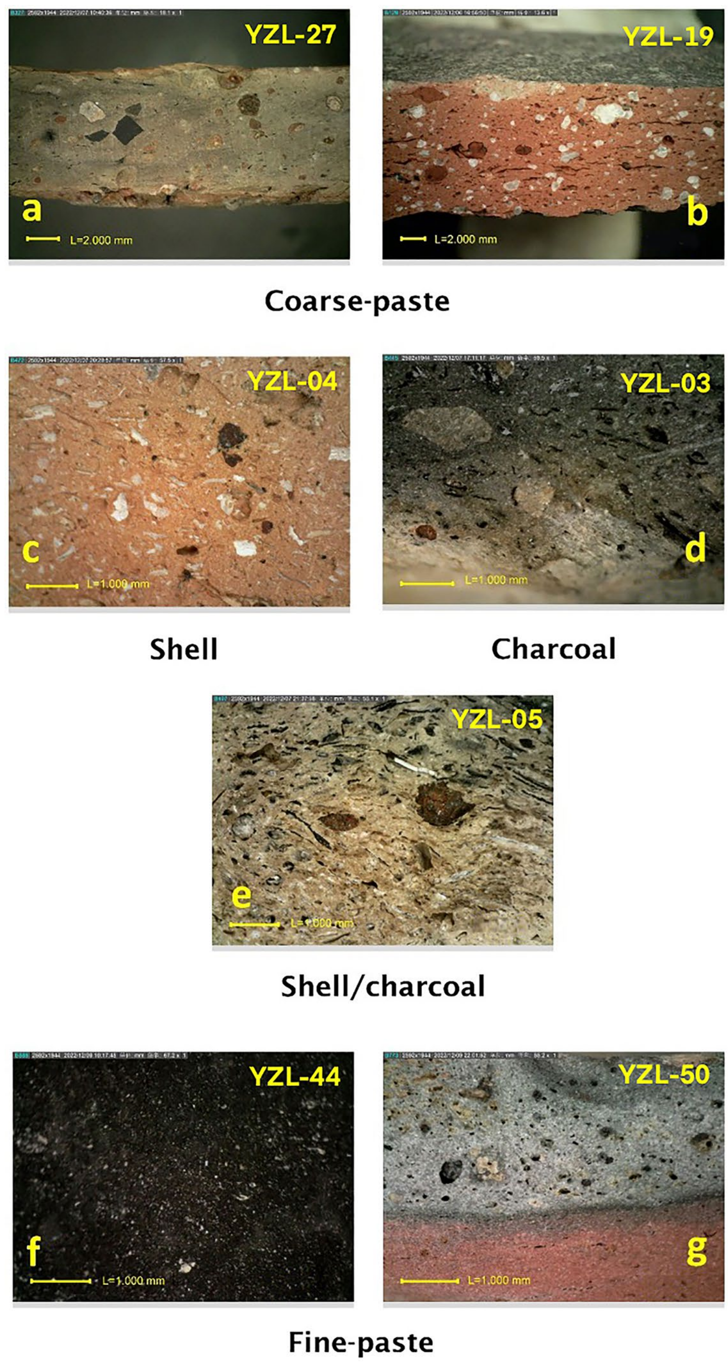

Fig. 11 Microstructures and pastes of representative Youziling-period pottery (**a**, **b** coarse-paste, **c** shell-tempered, **d** charcoal-tempered, **e** shell-charcoal-tempered, **f**, **g** fine-paste)

('edge') show a texture similar to the main fabric ('core') but the two differ significantly in color (Fig. 11g).

To summarize, coarse-paste sherds can be categorized into two subgroups based on the mineralogical characteristics of inclusions. The inclusions in storage vessels (*gang*-urns) are densely distributed, with larger grain sizes; while those in cooking vessels such as *ding*-tripods are more likely angular in shape. Pottery tempered with both shell and charcoal outnumbers those tempered with shell or charcoal only. Finally, some fine-paste sherds show a 'core–edge' structure on their cross-section.

Table 3 Thin-section petrographic results of the 13 coarse-paste Youziling-period sherds

F2 Samples	Inclusions								Pore		Clay matrix	
	Sand (> 0.0625 mm)			Slit (≤ 0.0625 mm)					P.S (mm)	Content (%)	Clay mineral	Content (%)
	Types		P.S (mm)	Content (%)	Types		P.S (mm)	Content (%)				
	M	R			M	R						
YZL-16 *gang*	Qz, Ms, Fs	SR, SAS, MS,Gr, Qzt	0.5–1.5	50	FMR		0.01–0.04	5	< 0.1	< 1	Ill	45
YZL-17 *ding*	Qz, Fs	MS	0.2–2.5	20	–		–	–	–	2	Ill, Kao	78
YZL-18 *guan*	Qz, Fs	MS	0.1–1	10	–		–	–	0.1–1	< 1	Kao, FMR	90
YZL-19 *kecaopen*	Qz, Fs	Qzt, MS	0.5–3	20	FMR		0.01–0.05	30	–	5	Kao, FMR	45
YZL-20 *ding*	Qz, Fs	SAS, MS, Che	0.5–1.5	20	FMR		0.01–0.05	5	–	3	Ill	72
YZL-22 *gang*	–	MS	0.2–2	5	FMR		< 0.05	50	–	< 1	Ill, Kao	45
YZL-23 *pen*	–	MS	0.2–1	5	FMR		< 0.05	50	–	2	Il, Kao	43
YZL-24 *pen*	–	MS	0.2–1	5	FMR		< 0.05	50	–	< 1	Ill, Kao	45
YZL-25 *guan*	Qz, Fs,	SR, MS	0.1–0.5	12	Qz		0.01–0.05	8	–	< 1	Ill, Kao, FMR	80
YZL-27 *gang*	–	MS, Che	0.2–2	10	FMR		0.01–0.05	30	0.1–0.3	< 1	Ill	60
YZL-28 *ding*	Qz, Fs	Qzt	0.1–2	20	Fs		> 0.01	< 1	0.2–1	< 1	Kao	80
YZL-29 *gang*	Qz, Ms, Fs	Qzt, Gr, MS	0.5–4	16	FMR		< 0.05	–	–	2	Ill	73
YZL-30 *guan*	Qz, Fs	MS, Gr	0.2–1	5	FMR		< 0.05	30	–	5	Ill	60

M: mineral; R: rock; FMR: felsic minerals or rocks; Qz: quartz; Ms: muscovite; Fs: feldspar; SAS: sandstone; SIS: siltstone; MS: mudstone; SR: siliceous rock; Gr: granite; Qzt: quartzite; Ill: illite; Kao: kaolinite; Che: chalcedony (beekite). P.S.: particle size

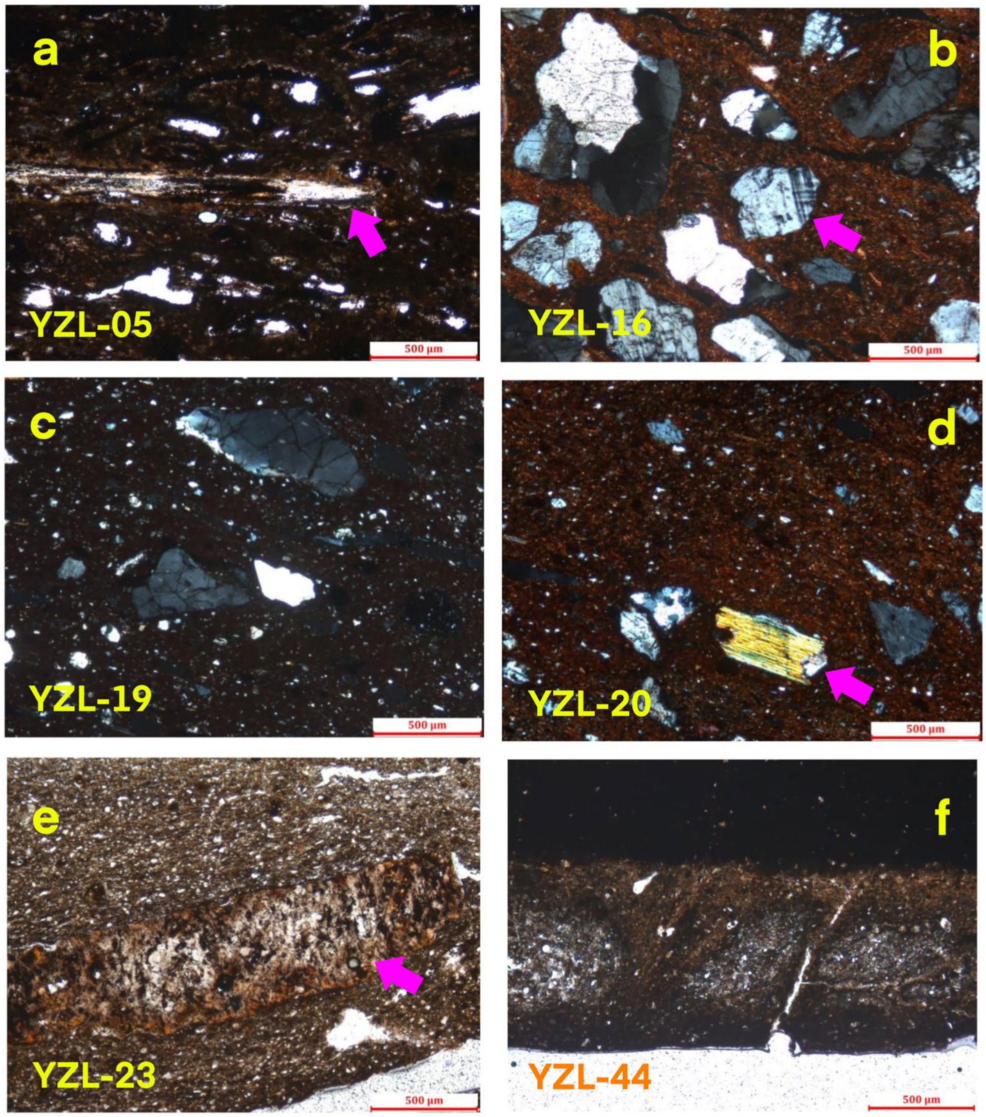

Fig. 12 Representative petrographic images of the Youziling-period pottery. Arrows indicate **a** long shell debris, **b** microcline with lattice twinning, **d** mica with a light-yellow interference color, and **e** dark-colored mudrock inclusions. **f** a core-edge structure noticed on fine-paste *ding*-tripod (YZL-44)

Microscopic examination by polarized light microscope

Sixteen (16) sherds from the Youziling period were selected for petrographic observation. Among these, 13 are of coarse paste, one shell-tempered, and the other two of fine paste. The petrographic identification results of the 13 coarse-paste sherds are shown in Table 3, which lists information for predominant or representative mineral inclusions.

The microstructure of each sherd can be divided into three parts, namely clay matrix, inclusions, and pores (minute holes). The clay matrix mainly comprises fine sand-sized felsic minerals (quartz, feldspar, etc.) and clay minerals (illite and kaolinite, etc.). Different sherds contain different types and amounts of minerals in the matrix, with varying degrees of recrystallization. The inclusions are mostly fine sand-sized (sub-angular, small particle size) or sand-sized (sub-angular to sub-rounded, varying particle sizes) felsic minerals (feldspar, quartz, etc.), mica, as well as mudstone, sandstone, silicate rocks, granite, chalcedony. There are more samples containing mudstone than those containing other mineral inclusions. Three examples (YZL-22, Fig. 10b; YZL-23, Fig. 10c; YZL-24, Fig. 10d) show no sand-sized debris of felsic minerals, and their petrographic features are consistent. The pores are mostly irregular and elongated,

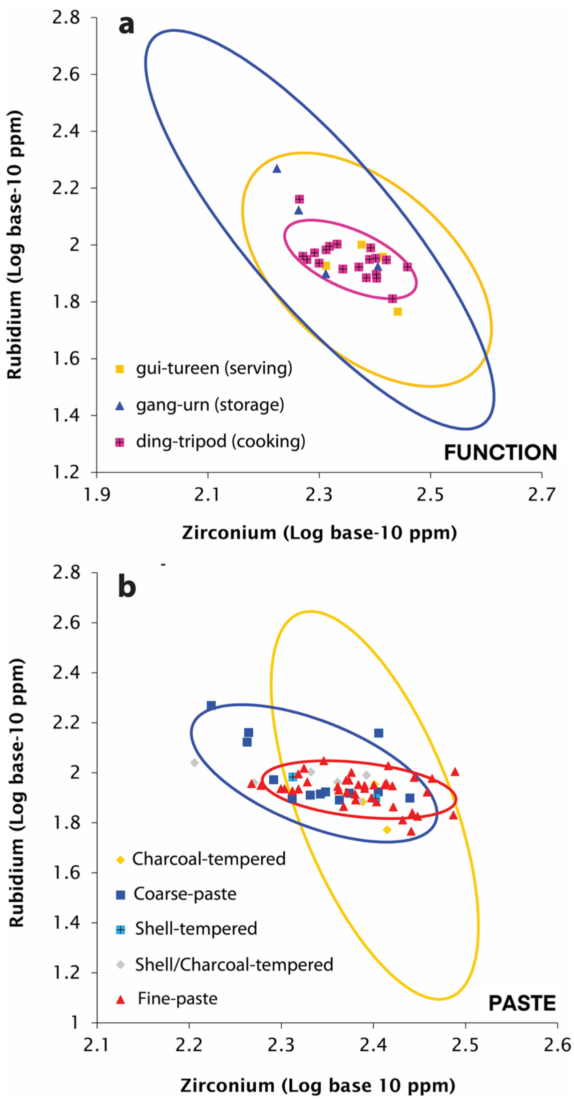

Fig. 13 Chemical variations among the pottery of the Youziling period (**a** vessel by function; **b** vessel by paste). Drawn with an 80% confidence ellipse

all below 5% of the volume, and the majority are between 1 and 2%.

Figure 12 shows representative petrographic images of the Youziling-period pottery. Figure 12a shows long shell debris and pores in a coarse-paste sherd (YZL-05) under PPL. Figure 12b shows that under XPL the mineral inclusions in YZL-16, a coarse-paste *gang*, consist of plagioclase minerals and rock fragments. The center of the field of view is a microcline with obvious lattice twinning. The matrix shows recrystallization, which is directional, and possibly related to the shaping process in pottery production. Figure 12c shows that under XPL the mineral inclusions in the *kecao pen*-grooved basin (YZL-19) are composed of a mixture of fine sand-sized plagioclase fragments and kaolinite, without noticeable crystallization. In Fig. 12d, mica is indicated by a light-yellow interference color in the field of view (under XPL) in YZL-2o, a coarse-paste *ding*-tripod. Under PPL, Fig. 12e shows that the coarse-paste *pen*-basin (YZL-23) contains dark-colored mudrock inclusions while Fig. 12f shows the core–edge structure in a fine-paste (YZL-44) *ding*-tripod.

Chemical variability by hhXRF

The chemical composition of the Youziling-period pottery, as illustrated in the Zr vs. Rb relationship (Fig. 13a), shows minimal differences among various forms associated with specific functions. Cooking vessels, such as *ding*-tripod, exhibit relatively homogeneous chemical composition, displaying a tight cluster in the biplot and suggesting intensive use of a particular clay source for their production. On the other hand, pottery used for serving (e.g., *gui*-tureen) and storage (e.g., *gang*-urn) show greater chemical variability. Nevertheless, the Youziling-period pottery from Wujiafentou, regardless of vessel forms or functions, demonstrates an overall chemical uniformity, suggesting that most, if not all, of the pottery was likely produced from a common source of clay [76, 77].

Figure 13b supports this argument. We are 80% certain that approximately 70% of the 13 coarse-paste pottery samples cannot be distinguished chemically from over 80% of the 39 fine-paste pottery samples, indicating the use of a primarily shared clay source for both paste types. Furthermore, despite small sample sizes, the shell- and shell-charcoal-tempered pottery also chemically overlap with fine- and coarse-paste pottery.

In brief, we propose that during the Youziling period, the Wujiafentou residents extensively utilized a common clay source to produce pottery with different pastes and for different functions. The diversity and combinations of mineral inclusions indicate that the potters understood the importance of incorporating minerals for tempering. However, establishing a strong correlation between tempering materials and specific vessel forms is challenging. We infer that the potters did not adhere to a standardized approach in producing tempered pottery.

The Shijiahe period (4500–4200 cal BP)

Macroscopic examination

The analyzed Wujiafentou samples from the Shijiahe period are either coarse-paste or fine-paste. Shell-tempered and charcoal-tempered pottery are absent (at least not present in our samples).

As with the Youziling period, the inclusions within the 12 Shijiahe-period coarse-paste samples can be primarily attributed to the S1, S2, and S3 types (see Table 2).

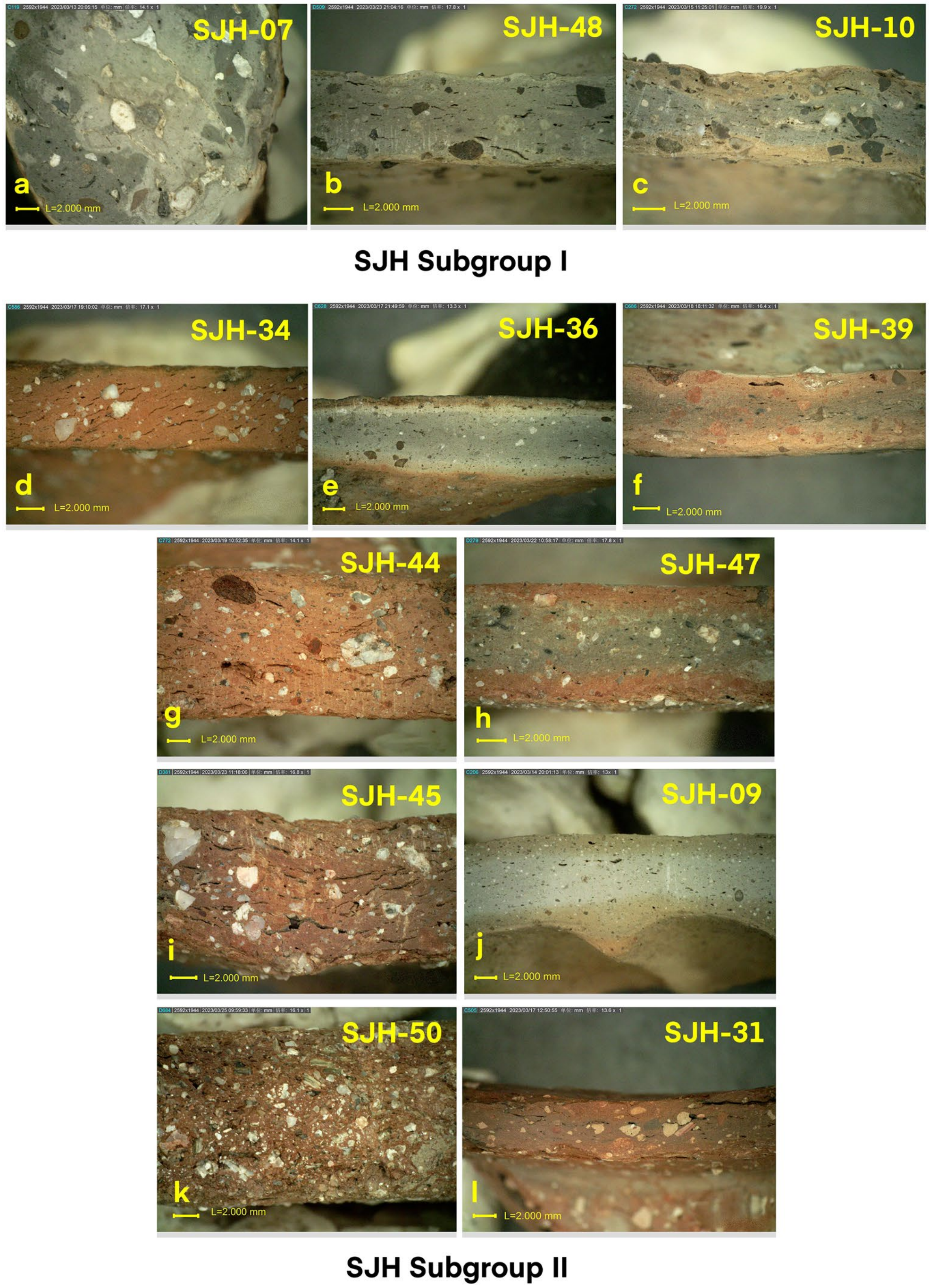

Fig. 14 Two subgroups are identified in the 12 coarse-paste Shijiahe-period pottery based on mineral inclusions (**a**–**c** Subgroup I, **d**–**l** Subgroup II)

However, the forms of the S1 and S2 type inclusions in Shijiahe-period pottery are more diverse than those of the Youziling-period pottery.

Similarly, the Shijiahe-period coarse-paste sherds can also be categorized into two subgroups (I and II) by inclusion types (Fig. 14). Subgroup I consists of three sherds (Fig. 14a, b, c), belonging to two *ding*-tripods and one *gang*-urn. S1-type inclusions are more densely distributed compared to the Youziling-period samples, while S2- and S3-type inclusions display increased grain sizes and angularity. Small inclusions are present in limited quantities. In addition, light-colored, translucent, more rounded minerals are observed, along with a brown crust (SJH-10), which are provisionally labeled as

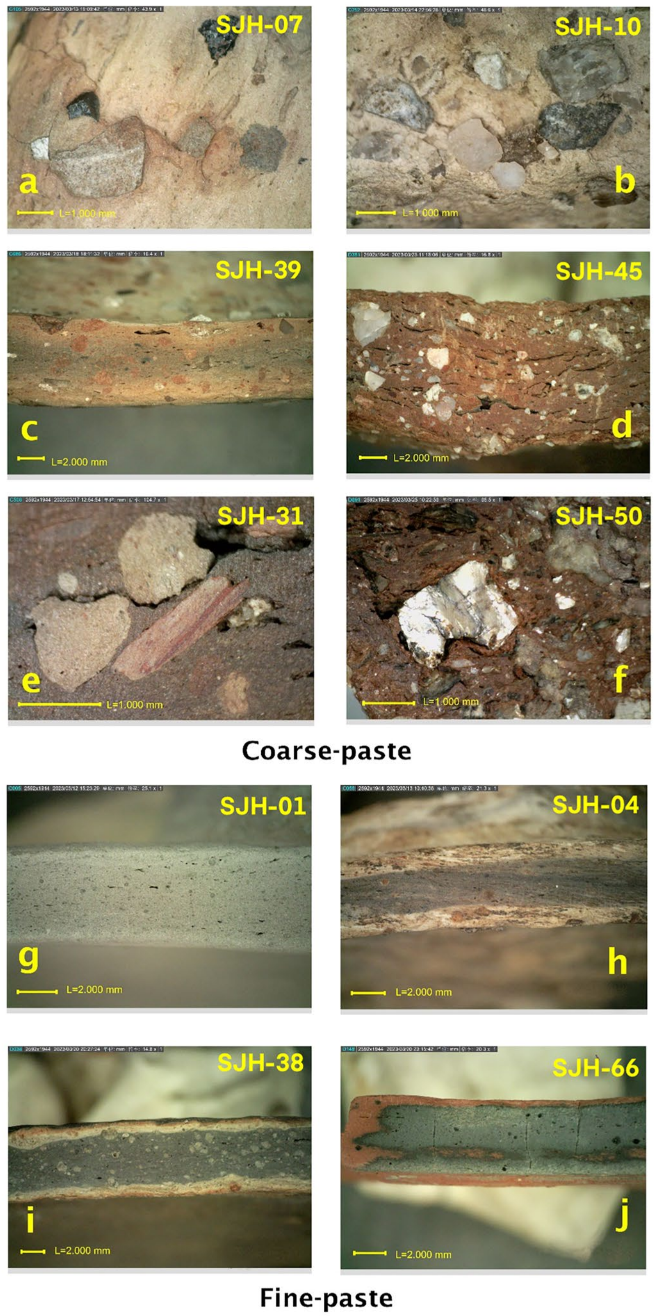

Fig. 15 Microstructures and pastes of representative Shijiahe-period pottery (**a**–**f** coarse-paste, **g**–**j** fine-paste).

S4 and could be cryptocrystalline minerals such as chalcedony. Compared to the foot of the *ding*-tripod (SJH-07, Fig. 15a), the rim of the *ding*-tripod (SJH-10, Fig. 15b) shows inclusions with more rounded angularity. Whether this reflects different technological choices in shaping different parts of vessels remains to be assessed by further analysis of different parts of the same vessel.

Subgroup II (Fig. 14d–l) consists of nine sherds, including four *gang*-urns, three *guan*-jars, one *weng*-jar, and one *ding*-tripod. The inclusions are predominantly of S2-type, showing varied granulometry and angularity. Most samples contain subrounded inclusions with larger grain sizes of around 1 mm. Their distribution frequency in the analyzed sherds ranges from low (SJH-39 *weng*-jar, Fig. 14f; SJH-44 *gang*-urn, Fig. 14g), to medium (SJH-34 *guan*-ja, Fig. 14d; SJH-36 *guan*-jar, Fig. 14e), then to high (SJH-47 *gang*-urn, Fig. 14h; SJH-45 *gang*-urn, Fig. 14i). A few samples (e.g., SJH-47) contain S1-type inclusions with smaller grain sizes and increased roundness, while others (e.g., SJH-45) seem to contain S4-type inclusions. Very few samples (such as SJH-09 *ding*-tripod, Fig. 14j) contain inclusions with smaller grain sizes (a diameter of around 0.1 mm), rounded shapes, high distribution frequencies, and the presence of mica.

Two samples stand out (SJH-50 *gang*-urn and SJH-31 *guan*-jar). SJH-50 (Fig. 14k) mainly contains S2-type inclusions with varying grain sizes and mica of larger particle sizes. The layered mica structure is visible on the cross-section. The grains in SJH-31 (Fig. 14l) range from 0.5 to 1 mm, rather rounded (partly elongated) and sparsely distributed. No S1-type inclusions were observed.

Most of the 19 fine-paste pottery sherds show the same "glitter" as seen in their Youziling-period counterparts. The sherds SJH-04 (Fig. 15h) and SJH-16 contain light-colored transparent mineral fragments (mainly quartz and feldspar), sand likely from riverine sediments, and flocculent charcoal particles, among other tiny inclusions that appear natural. Other sherds (e.g., SJH-22) show a loose texture on the cross-section with large pores. Sherds such as SJH-15, SJH-41, and SJH-38 (Fig. 15i) show a layered structure on the cross-section. Pinkish-colored pottery, similar to the pinkish *ding*-tripod from the Youziling period, is possibly manufactured from a mixture of two types of clay.

To summarize, the main categories of Shijiahe-period pottery are largely consistent with the pottery of the Youziling period. Although the coarse-paste Shijiahe-period sherds are similarly divided into two subgroups based on mineral inclusions, the second subgroup of Shijiahe-period pottery contains a wider variety of inclusions compared to Youziling-period pottery. The inclusion-rich *gang*-urns and *ding*-tripods with angular inclusions are abundant. Notably, a *guan*-jar with a sauce-red coating, containing multicolored sedimentary rocks, is noticed for the first time. Fine-paste pottery of the Shijiahe period can be divided into two subgroups based on the layered structure observed on cross sections, and the layers are often more complex than pottery from earlier periods.

Microscopic examination by polarized light microscope

The 11 coarse-paste and three fine-paste Shijiahe-period sherds were selected for thin-section petrographic examinations. The microstructural and mineralogical compositional characteristics of the 11 Shijiahe-period coarse-paste sherds can be summarized as follows (also see Table 4). The clay matrix is mainly composed of fine sand-sized felsic minerals (such as quartz and feldspar) and clay minerals (such as illite and kaolinite). The occurrence of recrystallization phenomena is evident, and some sherds are mixed with iron oxide compounds, likely responsible for the reddish-brown color in the pottery body. The inclusions are mainly fine sand-sized (sub-angular, less rounded, good sorting, small particles) and sand-sized (sub-angular to sub-rounded, varying particle sizes) felsic minerals such as feldspar and quartz, mica, along with mudstone, silicate rocks, granite, chalcedony, and others. The pores are mainly irregular and elongated, with the amount often less than 5% of the volume.

Fig. 16 shows petrographic images of the selected Shijiahe-period sherds (a to e, coarse-paste sherds under XPL; f, fine-paste sherd under PPL).

Figure 16a shows chalcedony debris as mineral inclusions at the center of the field of view in SJH-07, a coarse-paste *ding*-tripod.

Figure 16b shows that felsic mineral debris are visible as inclusions in SJH-09, showing uniform shapes. The arrow points to plagioclase debris with a polysynthetic twin, and the recrystallization of the matrix is not evident.

Figure 16c shows that the inclusions in SJH-31 mainly consist of silty mudstone, which has a uniform structure. The matrix is predominantly illite with apparent recrystallization.

Figure 16d shows feldspar and mudstone as inclusion in SJH-45. Recrystallization is also observed in the matrix.

Figure 16e shows felsic mineral debris and a large amount of mica as inclusions in SJH-50. Finally,

Figure 16f shows a core–edge structure in the fine-paste SHJ-66.

Chemical variability by hhXRF

As shown in Fig. 17a, we are 80% certain that 75% of the 12 coarse-paste pottery fall outside the compositional cluster defined by the fine-paste pottery, meaning a quarter of the coarse-paste pottery overlaps chemically with the fine-paste pottery. That said, a decreased chemical uniformity is noticed between the two types of ceramics (coarse-paste and fine-paste) for the Shijiahe period. This observation still holds when biplots with a 90% confidence ellipse are examined (see Additional file 1): we are 90% confident that 50% of the 12 coarse-paste pottery still differ in chemical composition from the fine-paste pottery.

Notably, a significant distinction is observed between the chemical composition of the fine-paste red clay cups and that of the coarse-paste pottery, with 90% certainty (see Additional file 1). Meanwhile, these cups overlap with the fine-paste pottery in chemical composition. The clay sources used to make the coarse-paste pottery is likely different from those for making the fine-paste

Table 4 Thin-section petrographic results of the 11 coarse-paste Shijiahe-period sherds

G3① Samples	Inclusions								Pore		Clay matrix	
	Sand (> 0.0625 mm)				Slit (≤ 0.0625 mm)				P.S (mm)	Content (%)	Clay mineral	Content (%)
	Types		P.S (mm)	Content (%)	Types		P.S (mm)	Content (%)				
	M	R			M	R						
SJH-07 *ding*	—	MS, MR, Qtz	0.5–3	10	FMR		< 0.05	50	–	< 1	Ill, Kao	40
SJH-09 *ding*	Qz, Fs	MS, MR	< 0.3	15	–		–	–	0.05–0.2	< 1	Kao, FMR	85
SJH-10 *ding*	Fs	Gr, MS, MR, SAS	0.5–3.5	15	FMR		0.01–0.04	30	–	5	Kao	50
SJH-31 *guan*	Qz, Fs	MS, Gr, Qtz	0.1–2	20	FMR		0.01–0.05	25	–	< 1	Ill	55
SJH-34 *guan*	Qz, Fs	MS, Gr, Qtz	0.5–4	25	–		–	–	–	5	Ill	70
SJH-36 *guan*	Qz, Fs	MS, Gr	< 0.1	6	–		–	–	0.05–0.1	4	Ill, Kao	90
SJH-39 *weng*	—	MS	0.5–3	10	–		–	–	–	< 1	Ill, FMR	90
SJH-44 *gang*	Qz, Fs	MS, Gr, Qtz	0.5–3	15	FMR		0.01–0.05	15	–	5	Ill	60
SJH-45 *gang*	Qz, Fs	MS, Gr, Qtz	0.2–3.5	20	FMR		0.01–0.05	15	–	5	Ill	60
SJH-48 *gang*	Qz, Fs	MS, Qtz	0.2–1	5	FMR		< 0.05	50	–	< 1	Kao	45
SJH-50 *gang*	Qz, Fs, Ms	MS, Gr, Qtz	0.2–3.5	45	–		–	–	–	2	Ill	43

M: mineral; R: rock; FMR: felsic minerals or rocks; Qz: quartz; Ms: muscovite; Fs: feldspar; SAS: sandstone; SIS: siltstone; MS: mudstone; SR: siliceous rock; Gr: granite; Qzt: quartzite; Ill: illite; Kao: kaolinite; Che: chalcedony (beekite). P.S.: particle size

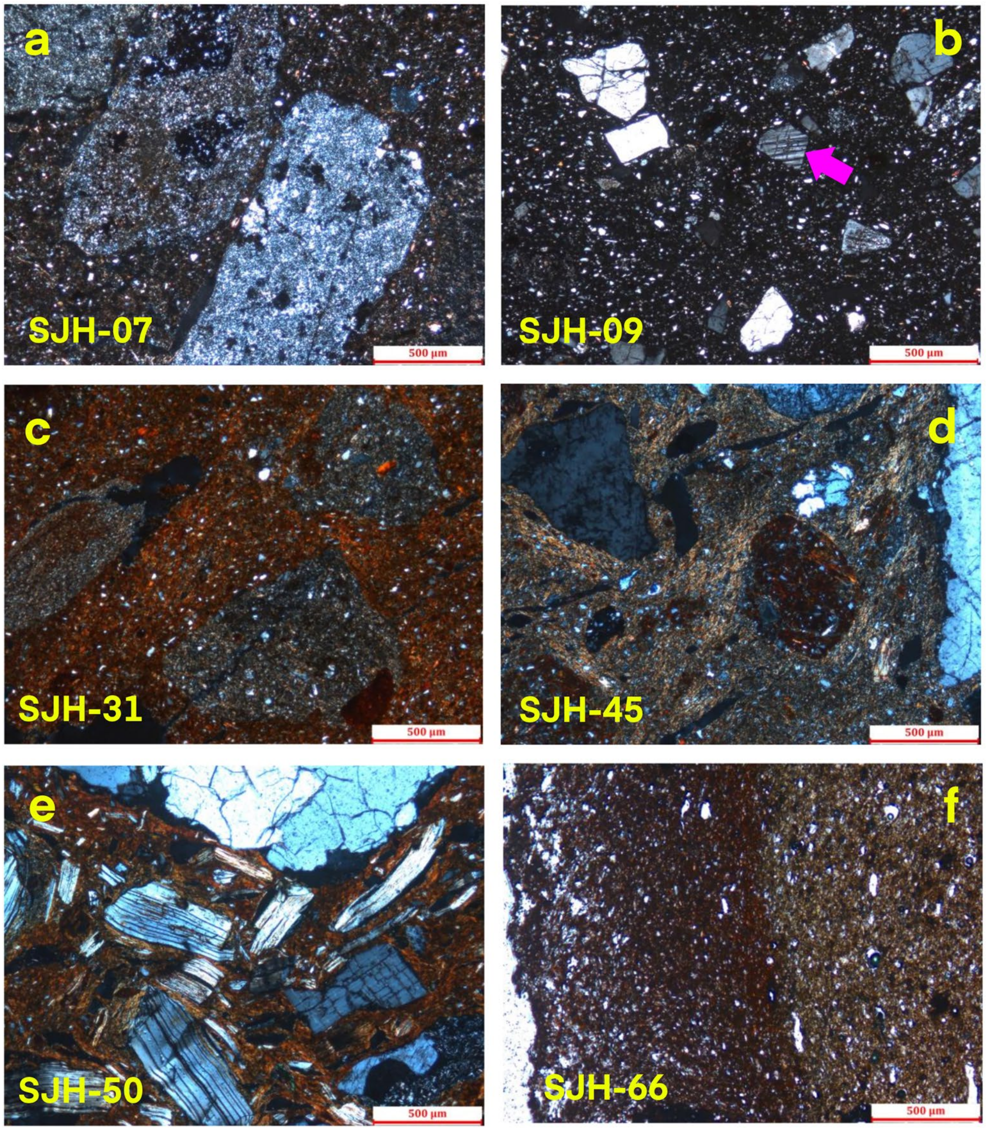

Fig. 16 Petrographic images of representative Shijiahe-period pottery. Arrow indicates plagioclase debris with a polysynthetic twin

red clay cups. Interestingly, at least one of the four burnt daubs from the Wujiafentou site chemically align with the red clay cups but definitely not with the coarse-paste pottery. The clay source for the Wujiafentou red clay cups could be very similar to this burnt daub in chemical composition.

Figure 17b shows a similar pattern of chemical variations among the sherds. It remains challenging to identify unequivocal correlations between clay sources and vessel functions. However, fine-paste pottery such as red clay cups chemically overlap with at least one burnt daub collected at Wujiafentou. In the meantime, we are 90% confident that all four burnt daubs are chemically different from the Sanfangwan red clay cups (see Additional file 1). Therefore, we propose that the Wujiafentou fine-paste vessels were made using locally procured clays, indicating a local origin.

Discussions

Changes and continuity in pottery production and use

Microscopic observations reveal both changes and continuity in pottery inclusions from the Youziling to the Shijiahe period. Shell-tempered and charcoal-tempered pottery were manufactured in the Youziling period but not in the Shijiahe period. Coarse-paste pottery, in which the inclusions are primarily igneous rocks and sandstone, consistently contributed a significant proportion from

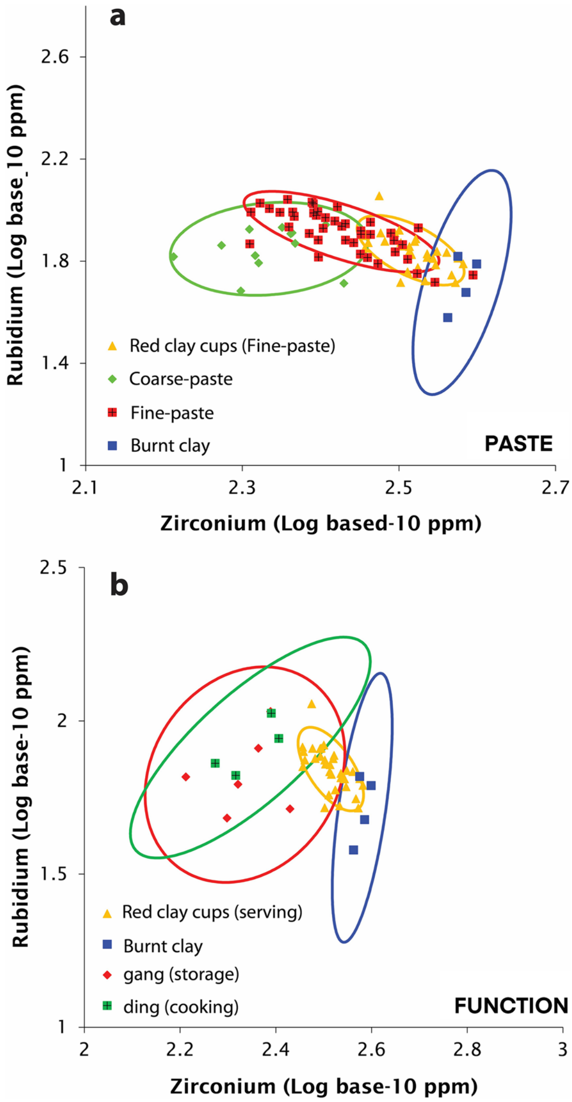

Fig. 17 Chemical variations among the Shijiahe-period pottery (**a** vessel by paste; **b** vessel by function). Drawn with an 80% confidence ellipse

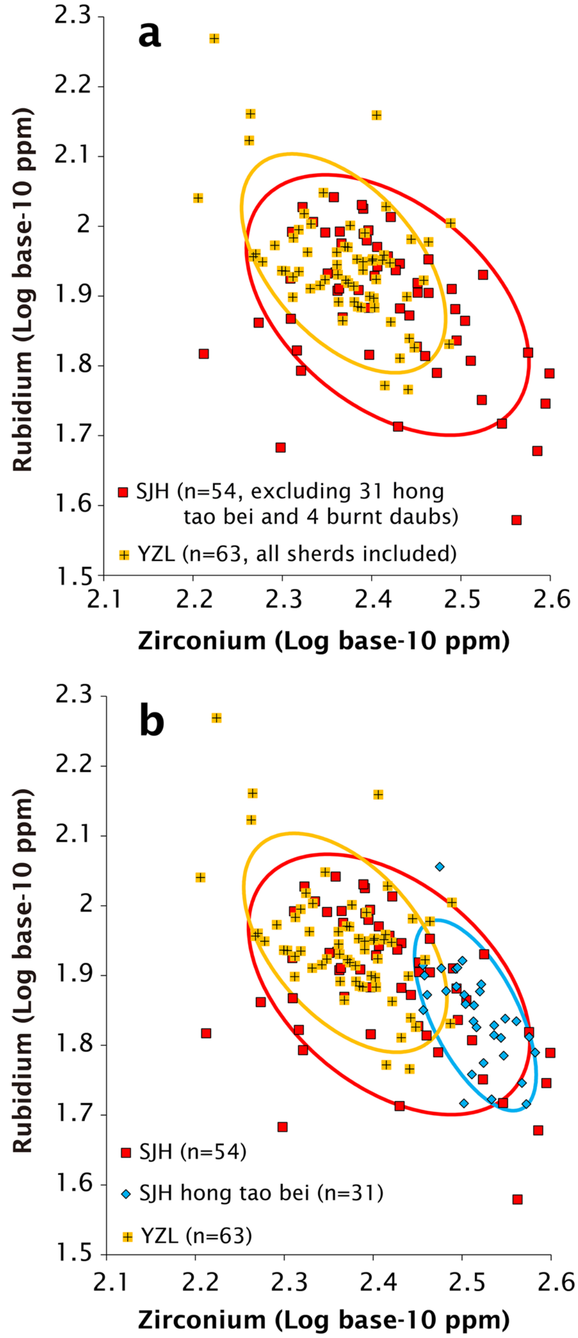

Fig. 18 Biplot showing chemical variations among the Youziling-period and Shijiahe-period pottery unearthed at Wujiafentou (**a** excluding the Shijiahe-period *hong tao bei*, **b** including Shijiahe-period *hong tao bei*). Drawn with an 80% confidence ellipse

Youziling through Shijiahe, although inclusions appeared in more types and larger quantities in the Shijiahe period. Among different vessel forms, *guan*-jars from both periods contain inclusions with the largest granulometry and density, and the occasional presence of dense patches of mica is a feature rarely seen in other vessel forms. Furthermore, large-granule dark magnesian igneous rocks are rarely seen in vessels that contain large fragments of transparent white feldspathic rocks as inclusions.

The inclusions in *ding*-tripods from both periods show a lower sphericity. Generally, these vessels contain larger-granule magnesian igneous rocks as inclusions, possibly reflecting the continuation of certain pottery-making traditions (e.g., the intentional addition of certain types of rock fragments or debris for tempering purposes). Fine-paste pottery vary little between the two periods, but several fine-paste vessels in both periods are composed of pinkish, dense clay and grey, loose clay. We infer that this distinct contrast in texture and color on the same pottery resulted from the paste preparation rather than from the firing itself. But further analysis is required to test this possibility.

Comparing the petrographic results of the sherds from the Youziling and Shijiahe periods, we notice that the firing temperature of these samples was not high, as there is no obvious glassy phase or mullite crystals in the clay matrix. However, the Shijiahe pottery is mostly manufactured from illite clay and shows apparent recrystallization; by contrast, recrystallization is only occasionally observed for the Youziling pottery that were made using kaolinite and illite clays. A higher firing temperature or a longer firing duration would result in the recrystallization of clay minerals [78]. Thus, we infer that the Shijiahe-period pottery was fired at higher temperatures or for longer duration than the Youziling-period pottery.

Pottery from the two periods contain similar types of inclusions. The inclusions in the Youziling-period and Shijiahe-period pottery are mostly felsic mineral rocks and sedimentary rocks, with a few chalcedonies, which aligns with the local geological conditions. The roundness and sorting characteristics suggest that the mineral inclusions were introduced either naturally (e.g., river sand) or intentionally, with the latter possibility likely involving sieving rather than crushing and mixing.

In addition, a few Youziling-period and Shijiahe-period fine-paste sherds show a core–edge structure (such as YZL-44 and SJH-66). This corresponds with their layered structure on the cross-section and may indicate a paste preparation method different from those without the core–edge structure.

According to the chemical compositional analysis (Fig. 18), we are 80% certain that the Youziling-period pottery (n = 63) and Shijiahe-period pottery (n = 54, excluding 31 red clay cups and four burnt daubs) unearthed from Wujiafentou heavily overlap in chemical composition. 84% (53/63) of the Youziling-period pottery and 61% (33/54) of the Shijiahe-period pottery fall within the same range, suggesting that they likely used the same or similar sources. This corroborates the consistency in pottery-making at this site, as indicated by microscopic observation. However, 98% (62/63) of the Youziling-period pottery and 84% (26/31) of the Shijiahe-period red clay cups fall within two different compositional ranges, implying that in the Shijiahe period potters must have used a new clay source to make red clay cups in addition to the source used for the Youziling-period and some of the Shijiahe-period pottery. These observations are valid with a higher confidence level (90%, see Additional file 1).

In summary, we suggest that the inhabitants of Wujiafentou during the Youziling period were able to produce pottery of different textures and for different functions, using the same or similar locally procured clay(s). However, in the Shijiahe period, although the inhabitants at Wujiafentou continued to make pottery using similar local clay(s), a new clay source was exploited primarily for making a new form of vessel—*hong tao bei* (red clay cups).

Implications for the Wujiafentou-Shijiahe relationship: a *hong tao bei* perspective

The consistency in chemical uniformity from the Youziling period through the Shijiahe period suggests a degree of stability or even standardization in the pottery production practices, possibly related to the consistent exploitation and use of a particular clay source or clay sources at specific loci. In particular, a new clay source was exploited and mainly designated for making *hong tao bei* (red clay cups), hinting at the significance they may have possessed. These cups might have been used as drinking vessels similar to the bronze and pottery goblets for elites of the Shang and Zhou dynasties [79], or may have been used for religious rituals [80]. Although these cups were found across the wider region under the influence of Shijiahe culture, the core zone of the Shijiahe culture yielded the largest collection. Red clay cups were discovered in astonishingly large quantities in the pottery production area of the Sanfangwan site within the Shijiahe walled town. More than 10,000 red clay cups were collected in just the 6th layer (Layer 6) of the 250 square meters area excavated in 2016. It is estimated that the total number of red clay cups in the entire 5510 square meters of the Sanfangwan area could be as high as more than two million [44]. The astonishingly large number of red clay cups at Sanfangwan, if confirmed, far exceeded the demand of the walled town itself, implying that these products may have supplied the surrounding areas. This suggests that Sanfangwan was reserved for the production of red clay cups. Thus, we suggest that red clay cups played a central role in the formation of regional identity and is crucial for understanding the formation and development of the Shijiahe culture, A more though analysis focusing on the Shijiahe-style red clay cups will be published in another paper.

As shown in Fig. 19, a good proportion of the 31 Wujiafentou red clay cups fall within the chemical variations delineated by the 25 Sanfangwan red clay cups while also, not surprisingly, overlapping with the Youziling-period and Shijiahe-period pottery from the same site—Wujiafentou. We are 80% confident that 71% (22/31) of the Wujiafentou red clay cups overlap with 56% (14/25) of the Sanfangwan red clay cups (see Fig. 19a). In Fig. 19b, which is plotted by log-transformed Zr, Rb, and Ca, 31% (12/39) of the fine-paste Youziling pottery overlap in

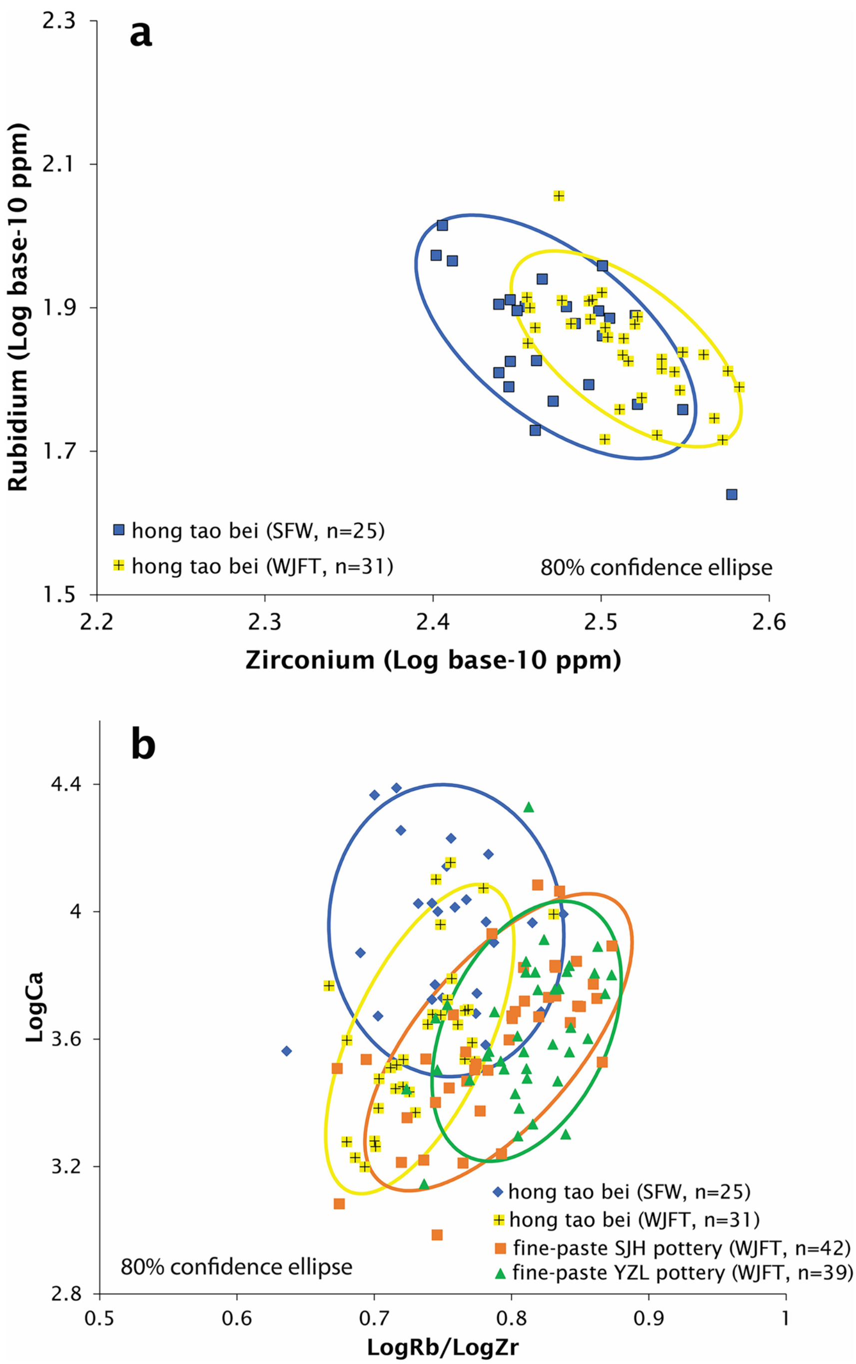

Fig. 19 Biplot showing chemical variations among the Shijiahe-period red clay cups unearthed from Wujiafentou and Sanfangwan (**a** biplot of logZr versus logRb, **b** biplot of logCa versus the ratio of logRb to logZr). Drawn with an 80% confidence ellipse

chemical composition with 28% (7/25) of the Sanfangwan red clay cups; meanwhile, 40% (17/42) of the fine-paste Shijiahe pottery overlap in chemical composition with 36% (9/25) of the Sanfangwan red clay cups. On the other hand, 68% (21/31) of the Wujiafentou red clay cups overlap in chemical composition with 29% (12/42) of the other fine-paste Shijiahe-period pottery unearthed at Wujiafentou, and only 19% (6/31) of the Wujiafentou red clay cups overlap with 15.4% (6/39) of the fine-paste Youziling-period pottery at Wujiafentou.

Compared to the Sanfangwan red clay cups, the Wujiafentou red clay cups demonstrate a higher chemical uniformity characterized by an overall higher level of zirconium (Zr) and lower level of calcium (Ca). By contrast, the Sanfangwan red clay cups seem to be chemically more diverse, and a good proportion (approximately 1/3) of them contain a lower level of Zr but higher level of Ca. More importantly, potteries unearthed from Wujiafentou—namely the fine-paste Youziling-period and Shijiahe-period pottery and the Shijiahe-period red clay cups—are more similar in chemical composition. (We shall also mention that our interpretations of data above are supported by biplots drawn with a 90% confidence ellipse. See Additional file 1.)

Given the chemical and mineralogical data, we are inclined to believe that all investigated Wujiafentou sherds were produced from locally procured raw materials. There appears to be at least two possible ways of interpreting the chemical similarity between Wujiafentou red clay cups and Sanfangwan red clay cups.

The first scenario hypothesizes that the provenance postulate [76] holds, assuming that Wujiafentou and Sanfangwan clays can be well distinguished from each other by chemical composition, and that Wujiafentou red clay cups were imported from Sanfangwan as final products. This would explain (1) the stronger chemical uniformity among the Wujiafentou red clay cups, as well as the difference in chemical composition between the Wujiafentou red clay cups and the fine-paste Youziling-period pottery, the latter of which exhibits chemical composition that likely characterizes the clay sources at or near Wujiafentou; and (2) the chemical similarity between Wujiafentou red clay cups and Sanfangwan red clay cups, the latter of which is characterized by more diverse clay sources. However, it fails to explain why the chemical composition of the fine-paste Shijiahe-period pottery, while largely overlapping with the fine-paste Youziling-period pottery, also fall within the ranges of the Sanfangwan red clay cups.

The second scenario, by contrast, considers the possibility that the postulate provenance does not always hold for the study sites. That is to say, their clay sources' chemical composition may distinguish the Wujiafentou and Sanfangwan loci if the potters made pottery at each location, using local raw materials; however, the degree to which the two differ from each other depends on the exact loci and the depth of clay deposit procured for pottery-making. This is not unlikely given (1) the geographical proximity between Wujiafentou and Sanfangwan and (2) the similar geological formations (see Sect. "Geological background"). This interpretation is compatible with the chemical variations among the fine-paste Youziling-period and Shijiahe-period pottery. Meanwhile, it explains the chemical similarity between the Wujiafentou red clay cups and those from Sanfangwan, implying the potters at each site used clay sources sharing similar chemical compositions. We could further suggest that Wujiafentou and Sanfangwan potters adopted the same procedures or standards to ensure that the 'same' colored and textured red clay cups were produced. This hypothesis leads us to a different conclusion about the nature of the Wujiafentou red clay cups: imitated items instead of imported products.

At this point, we find the second interpretation more appealing because it is compatible with chemical and mineralogical data and discloses a new perspective on the potential relation between Wujiafentou and Sanfangwan. During the Shijiahe period, the inhabitants at Wujiafentou decided to produce or imitate the red clay cups, which probably became part of an identity on the regional level. Several kilometers away from Wujiafentou, potters produced an enormous number of red clay cups at Sanfangwan. In the area centered around the Shijiahe walled city, red clay cups, along with other symbolic clay items (e.g., animal figurines and *gang*-vats), were likely used in feasts, rituals, and ceremonies to help create and maintain the community's identity and cohesion [8]. By producing and using red clay cups as drinking ware, people residing beyond the Shijiahe walled town, such as the inhabitants of Wujiafentou, showed their attraction to the Shijiahe walled town as well as their dedication to a common identity [8], which we now understand as the backbone of the Shijiahe culture.

Some researchers may find it tempting to consider the Shijiahe walled town as the most important, if not the only, center for producing and distributing red clay cups in the south foothills of the Dahongshan Mountain or even the entire Jianghan Plain [44]. Our data and interpretation do not reject this speculation. However, we point out another possibility—imitation, which may be equally important to understand the mechanism underlying social dynamics and economic relations in the core zone of the Shijiahe culture. Further studies on red clay cups from other settlements surrounding the Shijiahe walled town are needed to test our arguments and to help understand the organization of red clay cup production and the sociopolitical relations between Shijiahe and its neighbors.

Concluding remarks

The recent archaeological excavations at the site of Wujiafentou in Tianmen City of Hubei Province yielded rich materials dating to the Youziling and Shijiahe culture periods. We analyzed 152 pottery sherds, selected from the Youziling-period and Shijiahe-period pottery assemblages, and conducted microscopic examination and chemical and mineralogical analyses. The results demonstrated both changes and continuity in pottery production and use at the Wujiafentou site. We propose that during the Youziling period, the Wujiafentou residents made pottery of different textures and functions, using locally-procured clay. Over 1000 years later in the Shijiahe period, the inhabitants of the Wujiafentou site produced utilitarian pottery using local clay sources, too; however, they also began to make red clay cups, a drinking vessel characteristic of the Shijiahe culture, using a different clay source.

Given the short distance between Wujiafentou and the Shijiahe walled town, the Shijiahe core area likely exerted significant influence on Wujiafentou. This is especially evident in the production and utilization of red clay cups at Wujiafentou. However, with data solely derived from a handheld X-ray fluorescence analyzer, we cannot draw definitive conclusions regarding the overall picture of the socio-economic relationship between Wujiafentou and Shijiahe. Quantitative compositional data obtained from a carefully designed sampling of sherds from Wujiafentou and Shijiahe will shed more light on this issue.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-024-01181-w.

Additional file 1: Table S1. Sample information and 10-element chemical compositional dataset for the 152 Wujiafentou sherds and the 25 Sanfangwan hong tao bei. **Figure S1.** Chemical variations among the pottery of the Youziling period (**a** vessel by function; **b** vessel by paste). Drawn with a 90% confidence ellipse. **Figure S2.** Chemical variations among pottery of the Shijiahe period (**a** vessel by paste; **b** vessel by function). Drawn with a 90% confidence ellipse. **Figure S3.** Biplot showing chemical variations among the Youziling-period and Shijiahe-period pottery. Drawn with a 90% confidence ellipse. **Figure S4.** Biplot showing chemical variations among the Shijiahe-period red clay cups unearthed from Wujiafentou and Sanfangwan. Drawn with a 90% confidence ellipse. The pattern of chemical variations remains stable as noticed with an 80% confidence ellipse. **Figure S5.** Comparing the chemical composition of burnt daubs unearthed from Wujiafentou with those of the Shijiahe-period hong tao bei from Sanfangwan and Wujiafentou. Drawn with a 90% confidence ellipse. At least one burnt daub is chemically the same as the Wujiafentou red clay cups but none of the burnt daubs aligns with the Sanfangwan red clay cups in chemical composition. This additional line of evidence supports our argument that the Wujiafentou hong tao bei were locally produced rather than being imported from Sanfangwan as final products.

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Author contributions
TL, FYY, ZCX, SW Shan, and QQL conceived the study, analyzed and interpreted the data, and were significant contributors to the writing of the manuscript. ZCX and YH collected the sherds, carried out the microscopic examination, and prepared the samples for handheld X-ray fluorescence analysis. YH gathered the geological information and prepared the geological map. All authors reviewed and approved the final manuscript.

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Availability of data and materials
All data supporting the conclusions of this article can be obtained from the corresponding author Tao Li upon request.

Declarations

Competing interests
The authors declare no competing interests.

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