https://doi.org/10.1038/s40494-025-01667-1

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

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Nineteen Neolithic walled towns, dating to 5500–4500 cal BP, have been discovered in China's middle Yangtze River valley. While their construction is linked to early state formation, the sociopolitical role of specialized production remains unclear. Recent excavations at Zoumaling, an early walled town, offer insights into craft production, sociopolitical integration, and social differentiation. We analyzed 222 pottery sherds from Zoumaling using EDXRF and multivariate statistics. Results show consistent clay sourcing from the West Water Gate area across the Lower (5500–5300 cal BP) and Upper Qujialing (5300–4500 cal BP) periods. Fiber-tempered pottery, used for cooking, dominated the Lower Qujialing, while coarse-paste pottery, used for storage, increased in the Upper Qujialing, reflecting evolving technological choices. Minimal household variation in pottery production and use suggests technological changes alone did not drive social differentiation. Findings support the 'corporate group' hypothesis, emphasizing household interdependence and community collaboration in shaping Zoumaling's sociopolitical landscape.

Some 5500 years ago, settled farmers in the middle Yangtze River valley began transforming their lifestyles by constructing earthen-walled towns, which triggered significant changes in regional demography, settlement patterning, and sociopolitical and cultural integration[1,2]. (In the text below, we will use "walled town" or "town" to refer specifically to "earthen-walled towns.") The construction of walled towns ceased by 4200 cal BP as the Shijiahe culture approached its end. Nineteen Neolithic walled towns were built in these 1300 years, including two constructed in the Lower Qujialing period (5500–5300 cal BP) and 17 constructed and modified in the Upper Qujialing (5300–4500 cal BP) and Shijiahe (4500–4200 cal BP) periods[1,3]. Nowhere else was there such a high density of man-built walled towns between 5500 and 4500 cal BP in East Asia[1]. Both internal and external factors have been discussed to account for the walled town construction and its causes and impacts, including (but not limited to) environmental changes[4,5], flooding events[6], regional settlement patterns[3,7], inter/intra-community competition and cooperation[1,8], population growth[9,10], and social differentiation and development of urbanism[3,11]. However, no single cause satisfactorily explains the significant reorganization of increased populations in the Lower to Upper Qujialing period.

The site of Zoumaling in Shishou City of Hubei Province is one of the oldest walled towns in the middle Yangtze River valley (see Fig. 1 for geographic locations of Zoumaling and other towns discovered thus far in the middle Yangtze River valley). Since its discovery in 1989, Zoumaling walled town has been surveyed and excavated in several seasonal fieldwork projects, yielding features such as enclosing walls, moat, house structures, hearths, ash pits, and community cemetery, as well as artifacts including pottery vessels, jade ornaments, and tools made of stone and bone[12,13]. These features and artifacts allow researchers to probe into site chronology, town structure and function, crop remains and subsistence strategies, and function and provenance of stone tools. Despite the advantages of shedding light on the daily life and productive activities of Zoumaling inhabitants, pottery did not attract scholarly attention until recently. Recently, Li and colleagues investigated the chemical composition of fine-paste pottery from two Upper Qujialing household units differing in status or wealth within Zoumaling town, offering insights into economic ties at the household and community scales[8]. However, a more thorough technical investigation is needed to develop a dynamic perspective on pottery production and use from the Lower Qujialing through the Upper Qujialing period.

This paper conducts a chemical compositional analysis of pottery from the Zoumaling walled town. It differs from the previous pottery study by Li and colleagues[8] mainly in three aspects: (1) Focus on continuity and changes. This study aims to investigate the continuity and changes in the production and use of pottery from the Lower Qujialing to Upper Qujialing, primarily through the lens of raw materials (clay and tempering materials such as fiber

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Fig. 1 | Maps showing the study area and geographic locations of Neolithic walled towns in the middle Yangtze River valley of China. **a** The study area. **b** Geographic locations of the 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).

and sand) and technological choices; (2) Larger sample size. This study focuses on a larger sample size ($n = 222$) involving pottery with different pastes and intended uses from various residential zones within the walled town. This approach is more likely to provide a fuller picture of pottery production and use on household and community scales; and (3) Synthesis of evidence. This paper mainly uses chemical evidence but also synthesizes archeological evidence with chemical interpretations, creating a multifaced perspective on the sociopolitical role of pottery production and use.

The Zoumaling walled town is located in the Zoumaling Village in the Shishou City of Hubei Province, south China (see Fig. 2 for an aerial view of the Zoumaling site and its surrounding areas), 50 ha in size, is the fourth largest of the nineteen Neolithic walled towns in the middle Yangtze River valley[1]. The stratigraphic excavation, pottery typological analysis, and radiocarbon dating results suggest that the town was constructed for occupation during the Lower Qujialing period (5500–5300 cal BP) and continued to be used for residence in the Upper Qujialing (5300–4500 cal BP), Shijiahe (4500–4200 cal BP), and Meishan (4200–3900 cal BP) periods[1]. The town became prosperous during the Upper Qujialing period but gradually weakened during the Shijiahe period. It was abandoned entirely after the Meishan period[12]. Paleoenvironmental studies support the above statements, indicating that the climate was warm and wet from 6400 to 5300 cal BP, coinciding with the construction of a walled town at Zoumaling. This was followed by a warm and humid period from 5300 to 4700 cal BP, which facilitated the development of rice agriculture and increased the regional population. From 4700 to 4200 cal BP, the climate turned cool and dry, correlating with the decline of the Shijiahe culture at the site. The period from 4200 to 2400 cal BP was characterized by the coolest and driest conditions, and the complete abandonment of Zoumaling town was witnessed[5].

Zoumaling walled town has an outer and an inner town area delineated by two enclosing walls (see ref. 1 for the town layout and structure). The inner town is recognized by a series of earthen platforms with a remaining height of 2 to 9.8 m above the surface and forming a near oval shape from the aerial view. In addition, a few earthen platforms to the north, west, and east of the inner town form a recognizable, ring-shaped enclosing wall, delineating the outer wall. A third, half-ring-shaped enclosing wall is noticed immediately adjacent to the outer wall on its northeast corner. Functionally, this third enclosing wall differs from the inner and outer walls and may have served as the barbican[1]. Throughout the Lower Qujialing to Meishan periods, residential zones consistently existed within the inner town[12]. At the same time, signs of residence in the form of very shallow cultural deposits were sparsely noticed within the outer town. Human occupation and activities mainly occurred in the inner town during the Upper Qujialing period. Both small and large households are discovered in the residential

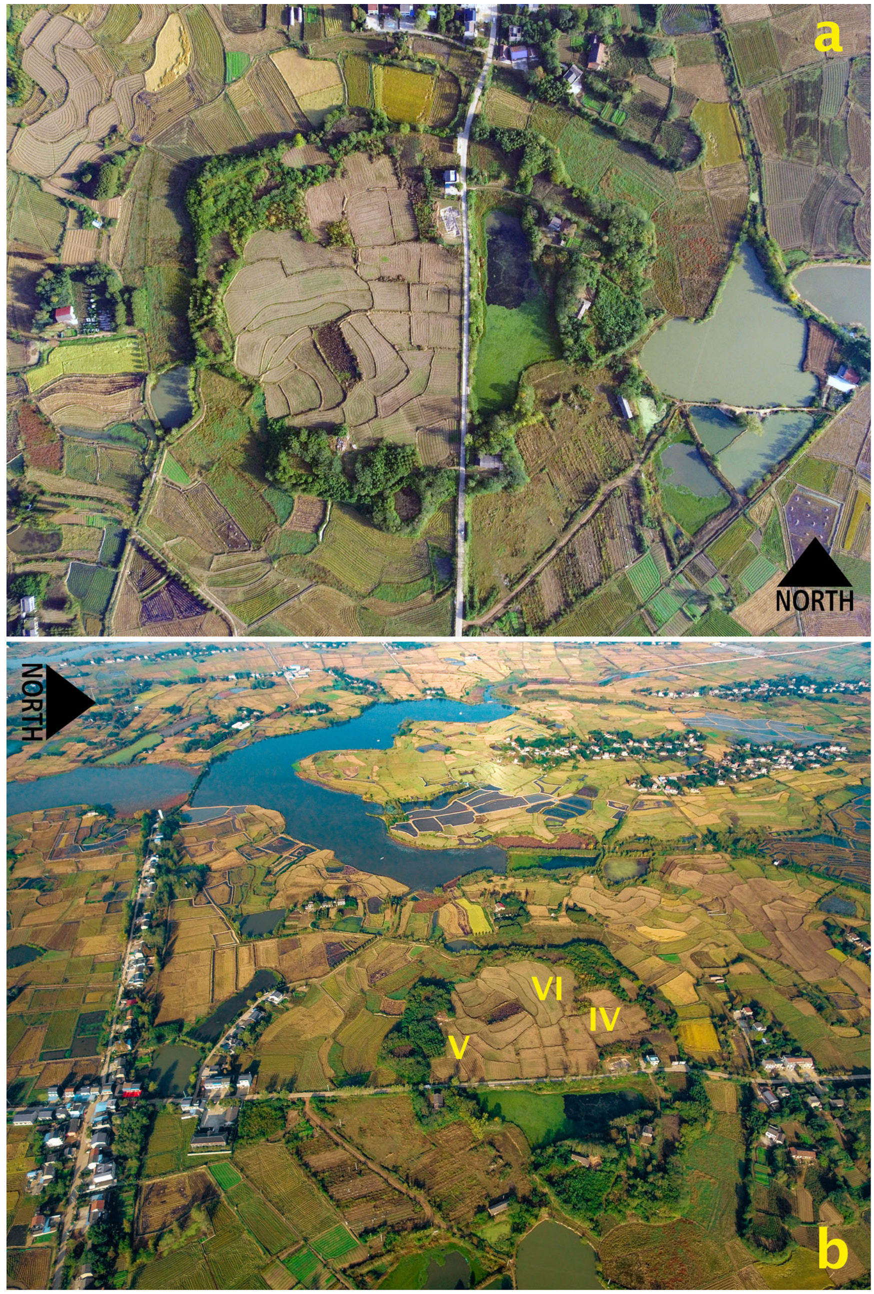

Fig. 2 | Aerial view. **a** The Zoumaling site. **b** The three excavation areas (VI, V, and VI).

zone, indicating wealth- or status-based differentiation[8]. Archaeobotanical remains identification results suggest that rice was the dominant crop at Zoumaling, complemented by small-scale foxtail millet cultivation[14]. The Zoumaling inhabitants also made pottery using clays procured at the West Water Gate and nearby areas within the town[8]. Analysis of lithic tools suggests that Neolithic inhabitants likely sourced metamorphic sandstone and slate for tool production from locations within 30 km of Zoumaling[15].

Methods

Our study focuses on the Lower Qujialing and Upper Qujialing periods, as it was during the Upper Qujialing period that the Zoumaling walled town first showed signs of social differentiation[1]. This research represents the initial attempt to investigate the transition from the Lower to the Upper Qujialing periods through the lens of pottery analysis. Focusing on the development of the Zoumaling walled town from its beginning to its prosperity, this paper is devoted to exploring the continuity and changes in the production and use of pottery from the Lower Qujialing to the Upper Qujialing. Utilitarian vessels of diverse shapes and functions were produced and used in both the Lower and Upper Qujialing periods, including cooking (*ding*-tripod, *fu*-cauldron), storage (*gang*-vat, *guan*-jar), serving (*gui*-tripod pitcher, *dou*-stemmed bowl, *wan*-bowl, *pen*-basin), drinking (*bei*-cup), vessel lids, *qizuo*-pedestals, etc. Typical pottery vessels of the Lower and Upper Qujialing periods unearthed from Zoumaling are shown in Fig. 3.

The sherds unearthed from Zoumaling can be categorized into three groups based on paste color: grey, reddish, and black. These colors are visually distinct, with each group characterized by a significantly different paste color. However, this does not imply that all sherds within the same group have identical paste colors; there is some variation within each color group, although it is minimal compared to the differences between the groups. Most sherds are fine-paste pottery, but coarse-paste and fiber-tempered pottery also account for a reasonable proportion of the pottery pool. Throughout this study, fine-paste pottery is characterized by the absence of (recognizable) inclusions. In contrast, coarse-paste pottery contains mineral inclusions (most often sand) used as tempering agents,

Fig. 3 | Typical pottery vessels unearthed from the Zoumaling walled town. The Lower Qujialing pottery vessels (**a** *gui*-tureen; **b** vessel lid; **c** *bei*-cup) and the Upper Qujialing pottery vessels (**d** *qizuo*-pedestal; **e** *fu*-cauldron; **f** *gang*-vat; **g** *ding*-tripod; **h** *bei*-cup; **i** *dou*-stemmed bowl).

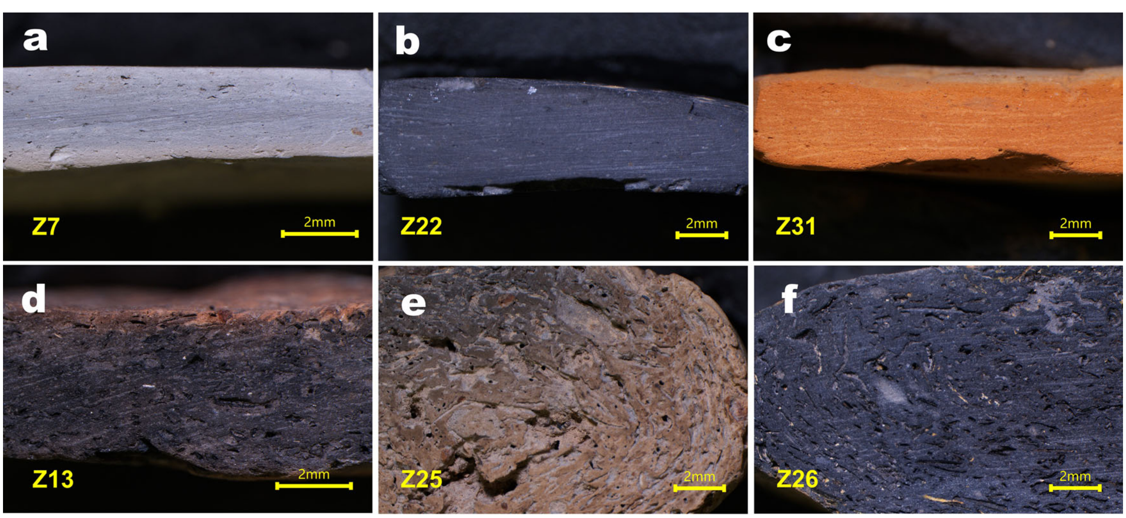

Fig. 4 | Microscopic structures of the cross-section of selected pottery. The Lower Qujialing fine-paste pottery (**a** z7, *wan*-bowl; **b** z22, vessel lid; **c** z31, *guan*-jar) and fiber-tempered pottery (**d** z13, *fu*-cauldron; **e** z25, *ding*-tripod; **f** z26, *ding*-tripod).

while fiber-tempered pottery incorporates inclusions originally sourced from plant fibers as tempering agents. The differences among the paste groups are shown in Figs. 4 and 5.

This paper selected 222 sherds from 56 excavation units (including ash pits, houses, and burials), in the hope of revealing the widest possible range of chemical variations among the pottery at Zoumaling. Sherds are primarily collected from the northern and southwestern parts of the inner town (excavation areas IV, V, and VI are indicated in Fig. 2b; details of the excavation areas are discussed in ref. 12), where the most densely packed residential areas are identified. The 222 sherds show a diversity in paste color, texture, shape, and form- or shape-induced function. Among them, 31 belonged to the Lower Qujialing pottery vessels, while the remaining 191 sherds belonged to the Upper Qujialing pottery vessels. Details of the sherds are shown in Table 1, and some are shown in Fig. 6.

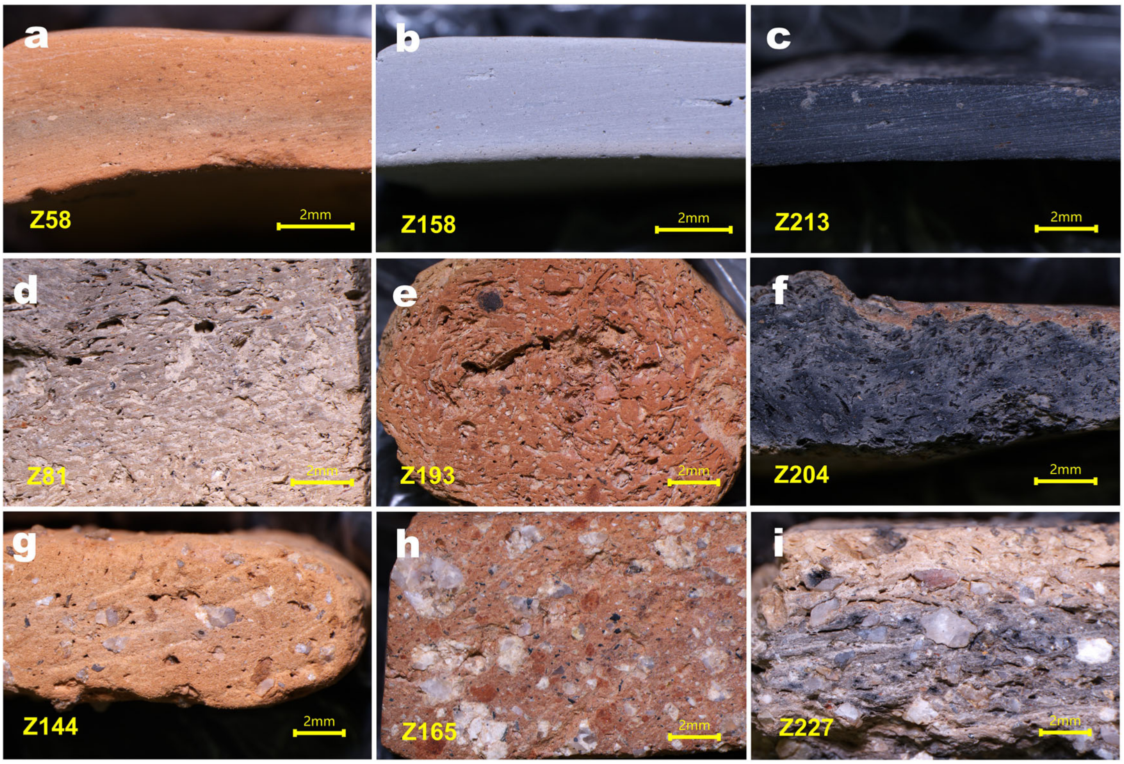

Fig. 5 | Microscopic structures of the cross-section of selected pottery. The Upper Qujialing fine-paste pottery (**a** z58, *bei*-cup; **b** z158, *guan*-jar; **c** z213, *dou*-stemmed bowl), fiber-tempered pottery (**d** z81, *ding*-tripod; **e** z193, *ding*-tripod; **f** z204, *fu*-cauldron), and coarse-paste pottery (**g** z144, *gang*-vat; **h** z165, *gang*-vat; **i** z227, *gang*-vat).

Table 1 | Archeological information of the 222 selected sherds

			Lower Qujialing (n = 31)	Upper Qujialing (n = 191)	Subtotal
Color N = 222	Gray		18	56	74
	Black		8	51	59
	Reddish		5	84	89
Paste N = 222	Fine-paste		27	117	144
	Coarse-paste		0	26	26
	Fiber-tempered		4	46	50
	Fiber/Coarse-paste		0	2	2
Vessel forms N = 222	Cooking n = 51	*ding*-tripod	4	38	42
		fu-cauldron	2	5	7
		zeng-steamer	0	2	2
	Storage n = 66	*gang*-vat	0	15	15
		guan-jar	11	40	51
	Serving n = 65	*dou*-stemmed bowl	2	25	27
		wan-bowl	2	2	4
		pen-basin	5	20	25
		gui-tureen	4	4	8
		die-plate	0	1	1
	Drinking n = 15	*bei*-cup	0	14	14
		yu-basin	0	1	1
	Others n = 25	vessel lid	1	13	14
		qizuo-pedestals	0	3	3
		qi'er-loop ear	0	3	3
		red burnt soil	0	1	1
		ring-foot	0	3	3
		indeterminate	0	1	1

Six fiber-tempered sherds (three Lower Qujialing and three Upper Qujialing) were selected from the 222 vessel sherds for phytolith analysis. For comparison, one fine-paste sherd, presumably containing no fibers, was selected from both the Lower and Upper Qujialing periods. The phytoliths found in fine-paste pottery are expected to reflect the natural soil composition. By comparing these phytoliths with those in fiber-tempered pottery, we can identify the source plant by analyzing the types and morphology of the phytoliths that were artificially introduced.

Chemical compositional analysis

Chemical composition was analyzed by an Orbis energy dispersive X-ray fluorescence analyzer (EDAX, USA). A sherd specimen of 2 cm by 2 cm was cut off from each sherd, and the cut surface was polished using sandpaper to ensure it was flat and smooth for testing. While conducting the chemical compositional analysis, we tried to avoid tempers or large mineral inclusions. Thus, the data primarily reflected the chemical composition of the clay matrix of the sherd, and the influence of temper or inclusions was avoided as much as possible. On each sherd, we collected at least three readings from separate spots. The tests were conducted with an X-ray spot diameter of 300 microns, an X-ray tube operating voltage of 50 kV, and a current of 800 mA. It took about two minutes to collect one reading and 8 to 10 min to complete a sherd.

We used the averaged composition to represent the analyzed sherd's chemical composition. The final compositional dataset consists of eight major elements (SiO_2, Al_2O_3, CaO, MgO, K_2O, P_2O_5, Fe_2O_3, and TiO_2) and seven minor and trace elements (MnO, CoO, CuO, ZnO, Rb_2O, SrO, and ZrO_2). The full compositional datasets can be found in Supplementary Tables 1 and 2 in Supplementary Information.

Principal component analysis (PCA) was applied to the compositional dataset of 15 major, minor, and trace elements[16–22]. The total cumulative contribution to the variance of the first four principal components is 72.1%. The first two components (PCA1 and PCA2) explained 47.2% of the total variance of original compositional data. Scatter plots were drawn to indicate the relative positions of sherd samples on the two axes (PCA1 vs. PCA2).

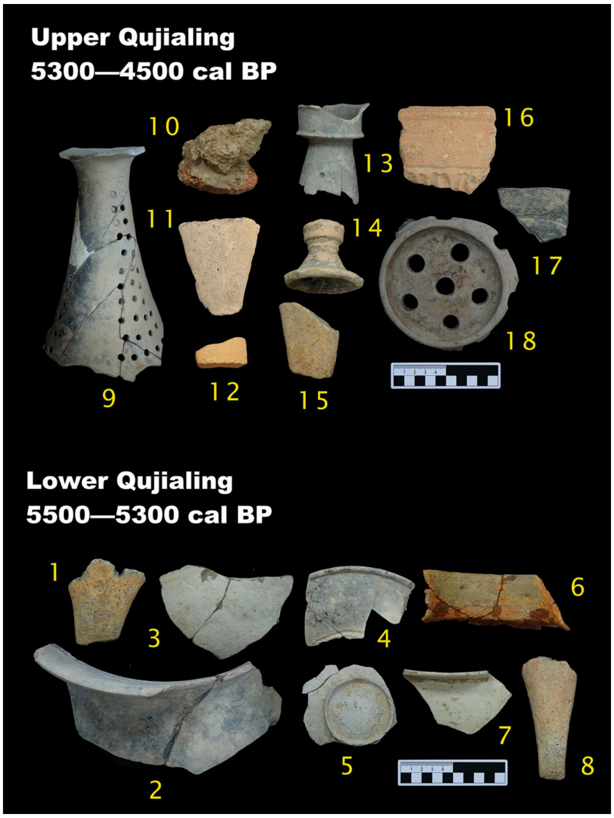

Fig. 6 | Sherds sampled from the Zoumaling site in this study (1, *ding*-tripod; 2, *guan*-jar; 3, *gui*-tureen; 4, *dou*-stemmed bowl; 5, *wan*-bowl; 6, *guan*-jar; 7, *gui*-tureen; 8, *ding*-tripod; 9, *dou*-stemmed bowl; 10, red burnt soil; 11, *ding*-tripod; 12, *bei*-cup; 13, *dou*-stemmed bowl; 14, vessel lid; 15, *ding*-tripod; 16, *gang*-vat; 17, *dou*-stemmed bowl; 18, *zeng*-steamer).

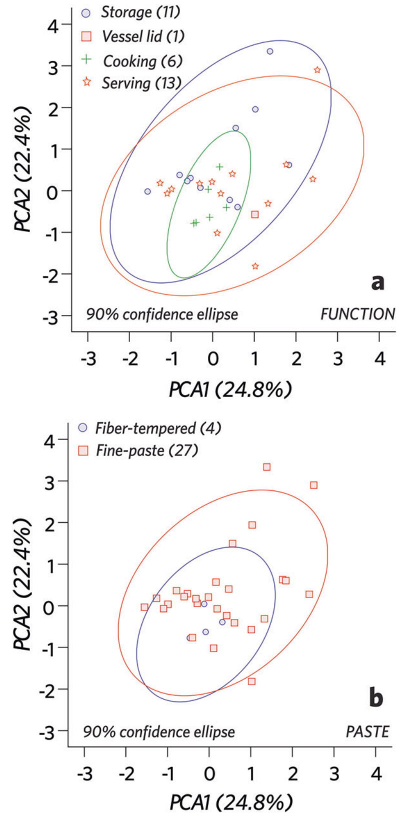

Fig. 7 | Chemical variability among the 31 Lower Qujialing vessel sherds. a Sherds by function. **b** Sherds by paste. Drawn with a 90% confidence ellipse.

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[23].

Phytolith extraction and identification

Phytoliths are microscopic silica formed by the deposition of solid silica—originating from groundwater and in a soluble state—within living plants[24,11–13]. Composed primarily of non-crystalline silicon dioxide, phytoliths vary in shape and size depending on the plant species, the type of cells that deposited the silica, and the location of these cells[25,16–20]. The distinct shapes, sizes, combinations, abundance, and relative frequency of phytoliths enable differentiation between plant species[26]. This study aims to identify the source(s) of fiber used as temper in pottery by analyzing the types and morphology of phytoliths present.

The extraction method for phytoliths followed the protocols established by Wang Yongji and Lü Houyuan[25]. The main procedures are as follows: (1) Grind the sherd specimen into a powder using a mortar and pestle. Weigh 5 g of the powder and place it in a 50 ml centrifuge tube. (2) Add 30 ml of 30% hydrogen peroxide (H_2O_2) solution and heat in a water bath to promote the reaction. (3) Once the reaction slows, add 20 ml of 10% hydrochloric acid (HCl) solution until the reaction stops. (4) Centrifuge for 5 min and then cleanse with distilled water three times. (5) Add 5 ml of heavy liquid ($ZnBr_2$, $d = 2.3$), mix thoroughly, and centrifuge at 3000 rpm for 5 min. Transfer 2 ml of the supernatant to a 15 ml centrifuge tube. (6) Add another 3 ml heavy liquid, fully mix, and centrifuge at 3000 rpm for 5 min. Transfer 2 ml of the supernatant to a new 15 ml centrifuge tube. (7) Wash the supernatant in the centrifuge tube with distilled water and centrifuge three times (3000 rpm; 5 min). (8) Wash with anhydrous ethanol and centrifuge (3000 rpm; 5 min), then dry and seal for storage.

Slides were prepared using Canada balsam as the mounting medium for observation. The samples were examined under an Olympus BX50 biological microscope at 200x and 500x magnification for identification, imaging, and quantitative analysis.

Results

Chemical variability among sherds from the Lower Qujialing period

Figures 7, 8 show the chemical variability among the 31 sherds from the Lower Qujialing period (5500–5300 cal BP). In Fig. 7a, there is no significant difference in the chemical composition of the pottery vessels that served different functions (cooking, serving, and storage). At the 90% confidence level, 93.5% (29 out of 31) of the sherds fall within the confidence ellipse delineated by serving or storage vessels, all being fine-paste pottery. The chemical composition of cooking vessels ($n = 6$) is more concentrated than others. Overall, the selected 31 sherds are similar in chemical composition. Figure 7b shows a further chemical compositional comparison among the 31 sherds. Only three of the 31 sherds (9.6%) fall beyond the 90% confidence ellipse delineated by the fine-paste sherds, indicating that fine-paste and fiber-tempered pottery are highly consistent in chemical composition. In other words, fine-paste and fiber-tempered pottery were produced from the same clay source(s) (This issue will be addressed in greater detail in Discussion).

Figure 8 shows the variation in the chemical composition of the pottery unearthed from different contexts (stratigraphic layer or stratum, burial, ash pit, and ash ditch). At the 90% confidence level, 87.1% (27 out of 31) of the sherds fall within the compositional group delineated by ash pits, which supposedly contain broken or dumped pottery vessels largely from domestic consumption. We are 90% confident that pottery (sherds) from different

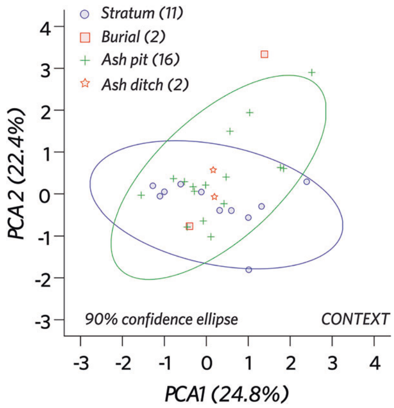

Fig. 8 | Chemical variability among the 31 Lower Qujialing sherds by the context of excavation. Drawn with a 90% confidence ellipse.

contexts differ little in chemical composition. The two sherds unearthed from the burial differ significantly in chemical composition, with one (z1 from a Lower Qujialing burial within the Zoumaling walled town) falling within the ellipse while the other (z31 from the Tunzigang cemetery—also dating to the Lower Qujialing period—outside of the Zoumaling walled town) beyond. It may suggest more significant chemical variations among the pottery artifacts as grave goods inside and outside the Zoumaling walled town. Typological analysis indicates the same vessel shapes and forms were shared between the burials within the town and those beyond the town (at the Tunzigang cemetery) (Dr. Siwei Shan, lead excavator of the Zoumaling site, Personal Communication). We infer that pottery artifacts as grave goods demonstrate more significant variations in the chemical composition because their production occurred infrequently and irregularly compared to utilitarian vessels, involving possibly more diverse clay sources. However, further investigation of a larger sample size is needed to verify this assumption.

We also noticed that sherds sampled from various locations (excavation areas VI, V, and VI) within Zoumaling walled town are not distinguishable by chemical composition, indicating an open pottery distribution network. It is compatible with a previous study by Li and colleagues[8] arguing for a shared pottery pool among corporate groups within the walled town.

Chemical variability among sherds from the Upper Qujialing period

Figure 9 shows the chemical variability among the 191 sherds of the Upper Qujialing (5300–4500 cal BP), revealing largely indistinguishable chemical compositions. In Fig. 9a, at the 90% confidence level, 93.2% (178 out of 191) of the sherds fall within the compositional group delineated by the 55 storage vessels (30 fine-paste, 17 coarse-paste, and eight fiber-tempered). 92.3% (51 out of 55) of the serving vessel sherds, 95.5% (43 out of 45) of the cooking vessel sherds, and 86.7% (13 out of 15) of the drinking vessel sherds fall within the 90% confidence ellipse drawn for storage vessels. This indicates that the shared clay source(s) was procured to make pottery vessels for domestic needs, especially food- and drink-related activities. The red-burnt clay (*hong shao tu*) sampled from inside the Zoumaling walled town, though just one, is chemically the same as the utilitarian vessels above. This is, again, compatible with the on-site production of pottery proposed by Li and colleagues[8].

Figure 9b compares the chemical composition of fine-paste, coarse-paste, and fiber-tempered pottery, leading to the same observation above. 93.5% (43 out of 46) of the fiber-tempered sherds and 88.5% (23 out of 26) of the coarse-paste sherds fall well within the 90% confidence ellipse drawn for the 117 fine-paste sherds. The sherds tempered with plant fibers and sand also fall within the chemical group delineated for fine-paste sherds. The pastes of the selected 191 sherds barely differ in chemical composition, again indicating the shared clay source(s).

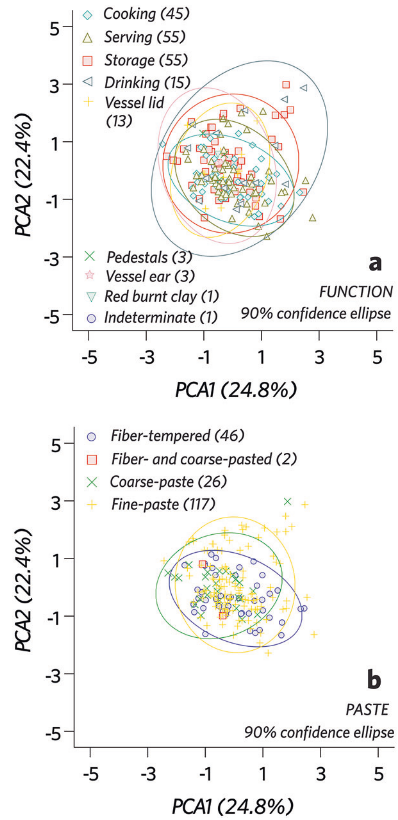

Fig. 9 | Chemical variability among the 191 Upper Qujialing vessel sherds. **a** Sherds by function. **b** Sherds by paste. Drawn with a 90% confidence ellipse.

Rice by-products as tempering materials

Potters at Zoumaling used plant fibers to temper the clay from the beginning of the walled town construction, and they continued this practice from the Lower Qujialing to the Upper Qujialing period. We extracted and identified phytoliths from the fiber-tempered pottery sampled from Zoumaling. Phytoliths are known for their high heat resistance and ability to survive even after firing at high temperatures[25]. As shown in Fig. 10, rice double-peaked phytoliths (Fig. 10a) are characteristic of the glume cells of rice husks, and rice bulliform phytoliths (Fig. 10b–d) are from rice leaves. In addition, square (Fig. 10e), rectangular (Fig. 10f), Acicular hair cells (Fig. 10g), Elongate sinuous (Fig. 10h), and Bilobate short cell phytoliths (Fig. 10i) are noticed, but their source plants can hardly be identified. The double-peaked and bulliform phytoliths specific to rice are noticed in fiber-tempered pottery only (fine-paste pottery contains no rice phytoliths), indicating that rice husks and straws were introduced to the pottery. This finding aligns with the archaeobotanical evidence of rice cultivation at the Zoumaling walled town[14].

Discussion

Based on the statistical analyses of chemical compositional data, we infer that during the Lower Qujialing period, the inhabitants of Zoumaling walled town produced pottery from similar clay sources. Regardless of paste type, function, or contextual use, the pottery consumed within the town demonstrated a strong consistency in chemical composition. This conclusion also applies to the Upper Qujialing period.

A further comparison of the chemical compositions of pottery from the Lower and Upper Qujialing periods (as shown in Fig. 11) reveals a high degree of consistency. At a 90% confidence level, 83.4% (26/31) of the pottery from the Lower Qujialing overlaps with 83.4% (166/191) of the pottery from the Upper Qujialing in chemical composition. This indicates that (1) pottery production during both periods involved sourcing clay from similar locations (or locations sharing a similar geological background), and

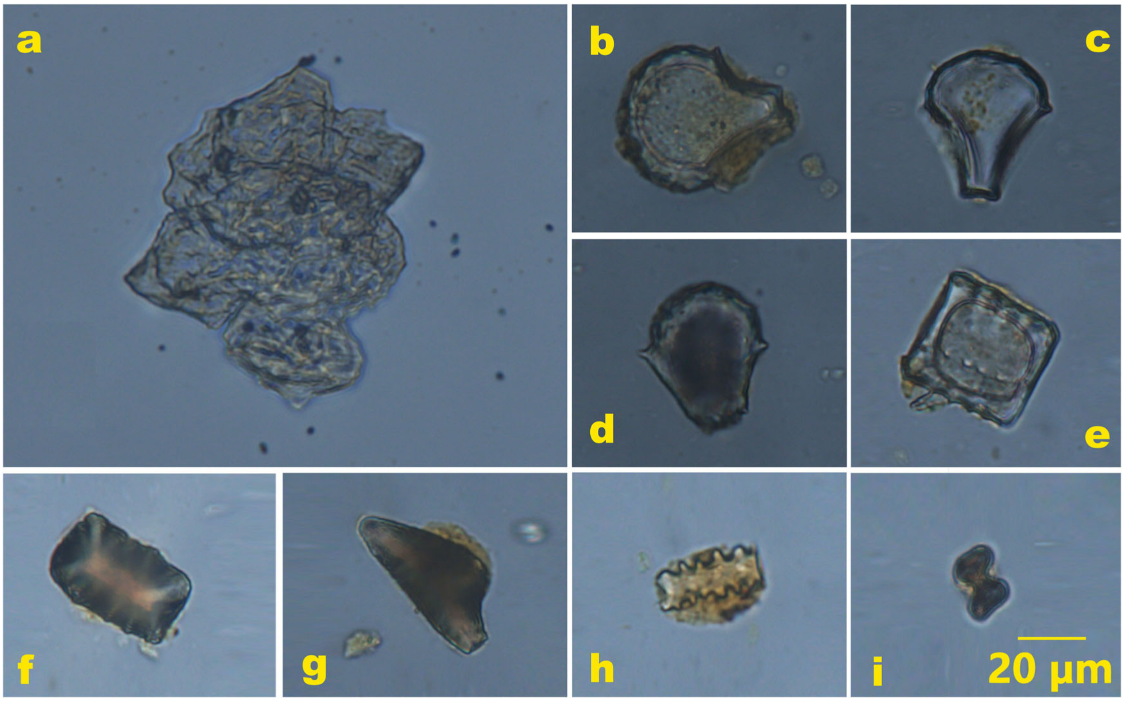

Fig. 10 | Phytoliths identified in two Upper Qujialing fiber-tempered pottery. **a** Rice double-peak, z59, *ding*-tripod. **b**–**i** z32, *ding*-tripod (**b**–**d** rice bulliform, **e** square, **f** rectangular, **g** Acicular hair cells, **h** Elongate sinuous, **i** Bilobate short cell).

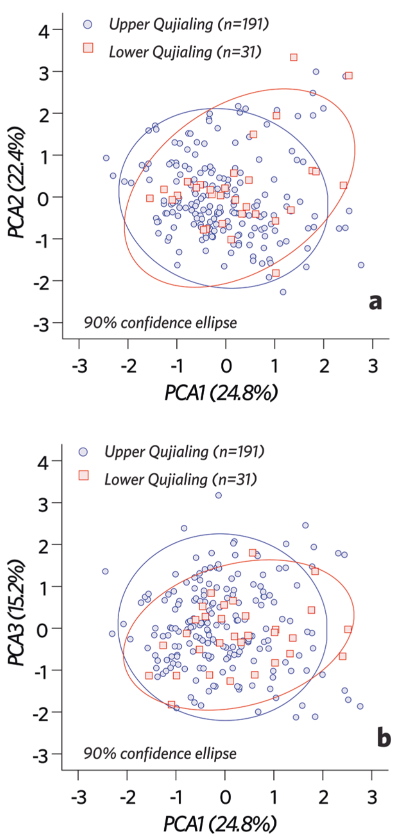

Fig. 11 | Chemical variability among the Lower and Upper Qujialing vessel sherds. **a** drawn with PCA1 and PCA2 scores. **b** drawn with PCA and PCA3 scores. Drawn with a 90% confidence ellipse.

(2) potters did not intentionally select distinct clay sources for specific functions or contexts. We argue for continuity in raw materials (clay) selection at Zoumaling from the Lower to the Upper Qujialing period.

In this study, we identified a clay source when most, if not all, of the investigated sherds are indistinguishable in chemical composition. This shared chemical composition indicates clay was procured from a common source or geographically close sources with similar sedimentary contexts[27]. It is important to clarify that "clay source," as used here, does not refer to a specific location. However, by relating our findings to previous probing surveys and chemical analyses of sherds and soil samples[8], we can infer potential areas for clay procurement during both periods. Previous research has investigated the chemical compositions of Upper Qujialing pottery and soil samples collected within Zoumaling walled town, suggesting that during the Upper Qujialing period, clay was likely sourced from the West Water Gate and nearby areas due to the matching chemical compositions of pottery sherds and soil samples[1,8]. Given the high consistency in the chemical composition of pottery from both periods, it is plausible that the inhabitants of Zoumaling consistently exploited clay from around the West Water Gate.

From a modern material science perspective, potters must have clay, water, and fuel to produce pots, and they may or may not require tempering materials to prepare the clay paste[28]. However, pottery studies worldwide indicate that both ancient and modern potters recognize that proper non-plastic materials (e.g., fibers, sand, and grog) as tempering materials can enhance pottery's chemical and physical properties, particularly the texture of the paste and the strength of the body[29–33]. There is significant diversity in tempering materials used globally for pottery production[34]. Plant fibers and mineral inclusions (such as sand) are commonly utilized due to their ease of procurement[29] or cultural learning[31]. The types of plant fibers or mineral inclusions used are closely linked to the geological history and natural environments in which the pottery-making community resided[35,36].

The inhabitants of Zoumaling consistently sourced clay from the West Water Gate and surrounding areas to produce pottery from the Lower Qujialing to the Upper Qujialing period. Furthermore, they likely recognized the role of non-plastic materials in enhancing the chemical and physical properties of fired pots, as evidenced by the consistently high proportions of fiber-tempered vessels in both periods and the increased quantity of coarse-paste vessels in the Upper Qujialing period. In the Lower Qujialing period, the sand-tempered, or coarse-paste as we referred to in this work, was nearly absent. 27 (87.1%) of the 31 potteries were fine-paste, and the remaining four (12.9%) were tempered with plant fibers. By contrast, in the Upper Qujialing period, 26 (13.6%) of the 191 vessel sherds were tempered with sand. The proportion of fine-paste decreased to 61.3% (117/191), and 24.1% (46/191) was fiber-tempered pottery. The potters used plant temper in two periods but selected more sand as temper in the Upper Qujialing period.

Based on the result of phytolith analysis, we argue that Neolithic potters at Zoumaling intentionally incorporated rice by-products (such as husks, leaves, and straws) into clay when preparing the paste. Fiber-tempered pottery was produced and used in the Lower and Upper Qujialing periods, and it continued to be produced and used—albeit in small quantities—in the subsequent Shijiahe and Meishan periods. We propose that the prevalence of fiber-tempered pottery likely stems from the easy availability of raw materials (rice by-products). Using rice by-products as tempering materials could well have characterized the pottery-making tradition at Zoumaling.

On the other hand, there was a shift in the favored tempering materials (i.e., from fiber-tempered to coarse-tempered pottery) alongside the Lower-Upper Qujialing transition. On a larger spatial scale, i.e., the middle Yangtze River valley, Li Wenjie concludes that fiber-tempered pottery emerged in the Chengbeixi (7800–6900 cal BP) culture period, peaked during the Daxi (5900–5300 cal BP) culture period, and then quickly declined during the Upper Qujialing (5300–4500 cal BP) culture period and became rare after the Shijiahe (4500–4200 cal BP) culture period[37]. His observation is compatible with the Zoumaling case: over time, the Neolithic potters at Zoumaling walled town favored coarse-paste pottery over fiber-tempered pottery. The excavations of the Zoumaling site from 1990 to 1992 suggested that although fine-paste pottery vessels dominated the pottery artifacts from the Lower to the Upper Qujialing period, coarse-paste vessels increased from 9.9% to 26% while fiber-tempered pottery decreased from 20.9% down to 2.7%[13]. The contrast between increasing coarse-paste and decreasing fiber-tempered is also noticed at Neolithic sites such as Guanmiaoshan and Qujialing in the middle Yangtze River valley, which we believe implies a shift in technological choices (we will return to this topic in Discussion).

Excavations have identified densely distributed house remains in northwestern, northern, and eastern parts of the inner town, characterizing these areas as residential zones[1]. The 222 sherds investigated in this work mainly came from northwestern (excavation area VI) and northern (excavation area IV) parts of the inner town, where interhousehold differences are noticed, especially in household size and exotic or fancy goods[8]. However, our analysis here shows that both residential areas consumed pottery vessels of the same shapes and forms and with the same (similar) chemical composition. This finding further validates the previous research that even though households inside Zoumaling walled town achieved different social statuses or wealth, they differed little in procuring and using pottery vessels for everyday life[8].

While continuity is primarily reflected in the artifactual assemblages and raw material (clay), changes are evident in two aspects. First, the increase in the number of *bei*-cups likely signals a growing demand for drinking vessels in the Upper Qujialing period. The *bei*-cups were presumably used as personal drinking vessels, and their use was closely related to ritual and sacrificial activities at this time in the middle Yangtze River valley[38]. The increased production and use of *bei*-cups could have resulted from a growing desire for fermented beverages during the Upper Qujialing period. According to our current knowledge of fermented beverages in prehistoric China, grains were most often used for brewing and making fermented beverages[39,40]. The Zoumaling inhabitants primarily relied on rice agriculture, and the warm and humid period from 5300 to 4700 cal BP facilitated the development of rice agriculture[5]. Many rice remains were found through flotation at Zoumaling, which accounted for 94.8% of the crop remains[14]. The discoveries of rice spikelet bases are also important evidence of rice cultivation at Zoumaling[14]. Furthermore, the pottery steamers (see Fig. 6:18) discovered at Zoumaling may have been used as brewing tools to prepare fermented foods and rice-based alcoholic beverages. We infer that the increasing number of *bei*-cups highlights the importance of brewing and fermented beverages (probably rice-based) at Zoumaling walled town during the Upper Qujialing period.

Table 2 | Percentages of fiber-tempered cooking vessels and coarse-paste storage vessels in the Lower and Upper Qujialing periods

Period	Paste	Vessel function	Counts	Percentage
Lower Qujialing N = 4	Fiber-tempered (*n* = 4)	cooking	4	100
		others	0	0
	Coarse-paste (*n* = 0)		0	0
Upper Qujialing N = 72	Fiber-tempered (*n* = 46)	cooking	36	78.3
		storage	8	17.4
		others	2	4.3
	Coarse-paste (*n* = 26)	storage	17	65.4
		cooking	2	7.7
		others	7	26.9

Second, from the Lower Qujialing to the Upper Qujialing period, fiber-tempered pottery continued to be used as cooking vessels, while coarse-paste pottery increased significantly, primarily for storage. Over time, fine-paste pottery was preferentially used for serving and drinking, coarse-paste pottery (such as *gang*-vats and *guan*-jars) was mainly utilized for storage, and fiber-tempered pottery (typically *fu*-cauldrons and *ding*-tripods) was predominantly used for cooking (see Table 2). The potters intentionally differentiated between coarse-paste, fiber-tempered, and fine-paste pottery based on their intended uses. As shown in Table 2, all four fiber-tempered potteries dating to the Lower Qujialing were cooking vessels. Of the 45 cooking vessels dating to the Upper Qujialing, 36 (80%) were tempered with plant fibers, suggesting a dominant role of fiber-tempered pottery for cooking foods. By contrast, 65.4% (17/26) of the coarse-paste pottery was used for storage, which possibly indicates a correlation between coarse-paste pottery and storage vessels. This situation reflects a technological choice in pottery use, influenced by potters' and consumers' preferences, advancements in technological knowledge, or new demands arising from agricultural development in the Upper Qujialing period.

We propose that over time, potters from the Lower and Upper Qujialing periods purposefully selected certain raw materials (clay, plant fibers, and sand) over others, a practice we refer to as 'technological choices.' This concept emerged in the 1970s and 1980s[41] and is used in pottery studies to describe the methods and decisions made by potters during production, particularly highlighting the diverse ways of manufacturing and producing pottery[42–44]. Technological choices in pottery production are often influenced by environmental settings, potters' technological knowledge, transportation methods, and the context of pottery use. Analyzing the pottery production process to identify these choices and their underlying reasons will enhance our understanding of pottery's role in politics, economics, and society[45–47]. Additionally, this analysis will facilitate discussions on technological change and its causes within the framework of continuity and changes in pottery production and use over time at Zoumaling.

As discussed earlier, fiber-tempered pottery was produced and used as cooking vessels, probably due to the intentional choice and the access to rice by-products (husks and straws) within Zoumaling walled town. We learn from the material science perspective that with the right selection and the proper amount of tempering materials, the thermal shock resistance of cooking vessels can be significantly improved[31,48,49]. Plant fibers as tempering agents have several advantages over other materials[50]—they help produce lightweight and easy-to-transport pottery vessels, speed up the drying process, and can be easily collected for mass production (especially in rainy and humid areas). In addition, making fiber-tempered pottery is easy to learn and master[51]. Some of the earliest pottery vessels in the world are characterized by thick walls, soft bodies, and plant fibers as tempering materials, such as those in the Russian Far East[52], Korea[53], North China[54], and South China[55].

However, coarse-paste pottery overshadowed fiber-tempered pottery during the Upper Qujialing period at Zoumaling. More coarse-paste vessels were tempered with sand for storage in the Upper Qujialing. Potters may have realized that coarse-paste pottery has superior properties and is more advantageous for producing larger, more endurable, and higher-quality storage vessels. In addition, pottery vessels tempered with sand have a denser body, better heat resistance, and superior thermal shock resistance than fiber-tempered pottery[50]. Wu Weihong and colleagues argue that the widespread sand-tempered *ding*-tripods in the Late Xuejiagang culture (5700–4800 cal BP) at the Sunjiacheng site (Anhui Province, south China) resulted from a cultural choice for better physical and functional performances[56]. We think this statement holds with the Zoumaling case. When potters had mastered the skills and knowledge to produce coarse-paste pottery, they did not stop producing and using fiber-tempered pottery immediately. They continued to make fiber-tempered pottery as cooking vessels (in decreasing proportion) but prioritized manufacturing coarse-paste vessels for storage purposes. They made their technological choices with the emergent new demands and technological advances.

Our chemical compositional analysis of a larger and more representative sample further supports the 'corporate group' hypothesis[8], which was primarily based on the construction of large public works (the Zoumaling walled town) and highlights the importance of shared identity, resources, and social responsibilities among its inhabitants. Our conclusions are drawn from a synthesis of chemical and archeological evidence.

Chemically, the pottery excavated from the Zoumaling site shows a high degree of consistency in chemical composition, indicating a common source of clay (from the West Water Gate and surrounding areas). In contrast, soil samples from the walled inner town at Zoumaling show significant variability in chemical composition[8]. This suggests that if potters sourced clay from different locations, the pots they made with these clays would likely show greater chemical variability. Therefore, the high consistency in chemical composition implies either a shared clay source, centralized pottery production, or both[27]. In this context, potters at Zoumaling likely shared knowledge and skills and maintained close social and economic ties with pottery consumers. Furthermore, consumers likely had similar access to the pottery pool, significantly reducing chemical variability in the pottery used within the town.

Archeologically, at least four independent lines of evidence indicate a shared community identity and close interdependence among the inhabitants of Zoumaling. First, archaeobotanical remains suggest that during the Upper Qujialing, Shijiahe, and Meishan periods, the agricultural base of Zoumaling town was primarily rice agriculture, supplemented by small-scale dryland millet cultivation[14]. Cross-cultural psychological studies indicate that rice farming fosters greater interdependence and collectivism[57]. The high labor demands and interdependent irrigation networks of paddy rice farming enhance social cohesion[58]. Second, identical vessel shapes and forms were found throughout the town, and pottery kilns, dating to the Shijiahe periods, were spatially restricted within Zoumaling town, suggesting some form of centralized pottery production[13]. Third, the cemetery discovered at Tunzigang revealed a shared burial form (rectangular vertical earthen pit tomb) and similar (combinations of) grave goods, strongly indicating a shared community identity. Lastly, provenance studies trace the raw materials of lithic tools unearthed from Zoumaling to locations up to 30 km away[15]. The procurement of these materials must have required collaboration and teamwork.

The combined findings from pottery chemical analysis and archeological evidence suggest that the inhabitants of Zoumaling maintained close social and economic ties through shared productive activities and cultural identity. Therefore, we believe the corporate group hypothesis is applicable to Zoumaling. It is important to note that pottery production and use show little variation among Neolithic households at Zoumaling. Pottery does not appear to significantly contribute to social differentiation within the Zoumaling walled town, a topic that warrants further discussion and analysis.

Data availability

The chemical compositional data supporting the conclusions of this article can be found in Supplementary Information.

Received: 6 August 2024; Accepted: 27 March 2025;
Published online: 19 April 2025

References

1. Shan, S. et al. The emergence of walled towns in prehistoric middle Yangtze River valley: Excavations at the Zoumaling site. *Archaeol. Res. Asia* **26**, 100285 (2021).
2. Zhang, C. The Qujialing-Shijiahe culture in the middle Yangzi River valley. in *A Companion to Chinese Archaeology* (ed. Underhill, A. P.) 510–534 (Wiley-Blackwell, Malden, 2013).
3. Li, T., Underhill, A. P. & Shan, S. Shijiahe and its implications for understanding the development of urbanism in Late Neolithic China. *J. Urban Archaeol.* **7**, 31–49 (2023).
4. Luo, J. Human activities and environment in the Two Lakes Region in the Neolithic Age. *Jianghan Archaeol.* **5**, 72–79 (2017).
5. Guo, A., Mao, L., Shan, S., Mo, D. & Yu, X. Environmental change and human adaptation at Zoumaling city since mid-Holocene, midstream of the Yangtze River, China. *Acta Geogr. Sin.* **79**, 1211–1230 (2024).
6. Liu, J. A preliminary study of Chinese prehistoric water management civilization. *Cult. Relics South China* **6**, 5–11 (2020).
7. Zhang, C. *Prehistoric Settlement Research in the Middle and Lower Yangtze River*. (Cultural Relics Publishing House, Beijing, 2003).
8. Li, T., Yao, S., He, L., Yu, X. & Shan, S. Compositional study of household ceramic assemblages from a Late Neolithic (5300-4500 cal BP) earthen walled-town in the middle Yangtze River valley of China. *J. Archaeol. Sci. Rep.* **39**, 103159 (2021).
9. Peng, X. An experimental analysis of the population growth patterns of the walled towns of the Qujialing Culture. *Cult. Relics South China* **6**, 35–39 (2022).
10. Li, D. The emergence of walled towns and social complexity in the Taojiahu-Xiaocheng region of Jianghan plain China. (University of Pittsburgh, Pittsburgh, PA, 2016).
11. Zhang, X. Discoveries and preliminary studies of walled-towns of the Qujialing period. *Archaeol* **7**, 629–634 (1994).
12. Shan, S. & Yu, X. The excavation report at the Neolithic Zoumaling walled-town in Shishou City, Hubei Province. *Archaeol* **9**, 3–24 (2018).
13. Jingzhou Museum, Shishou Municipal Museum & Wuhan University. The excavation report at the Neolithic Zoumaling walled-town in Shishou City, Hubei Province. *Archaeol*. **4**, 16–38 (1998).
14. Tang, L., Jiaqi, L., Shan, S., Yu, X. & Zhao, Z. Identification and study of prehistoric plant remains at the Zoumaling site in Shishou, Hubei Province. *Jianghan Archaeol.* **3**, 109–115 (2021).
15. He, C. et al. Provenance of the raw materials of stone tools at the Zoumaling site, Shishou City, Hubei Province. *Sichuan Cult. Relics* **6**, 43–51 (2021).
16. Baxter, M. J. *Exploratory Multivariate Analysis in Archaeology*. (Edinburgh University Press, Edinburgh, 1994).
17. Baxter, M. Principal component analysis in archaeometry. in *Choice, Representation and Structuring of Archaeological Information*, *Archaeologia e Calcolatori* (ed. Moscati, P.) **5**, 23–38 (1994).
18. Tite, M. S. Ceramic production, provenance and use: a review. *Archaeometry* **50**, 216–231 (2008).
19. Papachristodoulou, C., Gravani, K., Oikonomou, A. & Ioannides, K. On the provenance and manufacture of red-slipped fine ware from

ancient Cassope (NW Greece): evidence by X-ray analytical methods. *J. Archaeol. Sci.* **37**, 2146–2154 (2010).

20. Papachristodoulou, C., Oikonomou, A., Ioannides, K. & Gravani, K. A study of ancient pottery by means of X-ray fluorescence spectroscopy, multivariate statistics and mineralogical analysis. *Anal. Chim. Acta* **573–574**, 347–353 (2006).
21. Papageorgiou, I. Ceramic investigation: how to perform statistical analyses. *Archaeol. Anthropol. Sci.* **12**, 210 (2020).
22. Liritzis, I. et al. Characterization and provenance of ceramic artifacts and local clays from Late Mycenaean Kastrouli (Greece) by means of p-XRF screening and statistical analysis. *J. Cult. Herit.* **46**, 61–81 (2020).
23. He, L. et al. Ceramic raptors unearthed at the site of Shimao (2300–1800 BCE) in northern China: Production and use. *J. Archaeol. Sci. Rep.* **48**, 103844 (2023).
24. Piperno, D. R. *Phytolith Analysis: An Archaeological and Geological Perspective*. (Academic Press, Inc., San Diego, CA, 1988).
25. Wang, Y. & Lü, H. *Research and Application of Phytolith*. (China Ocean Press, Beijing, 1993).
26. Rovner, I. Plant opal phytolith analysis: major advances in archaeobotanical research. *Adv. Archaeol. Method Theory* **6**, 225–266 (1983).
27. Li, T. et al. Pottery production at the Miaodigou site in central China: Archaeological and archaeometric evidence. *J. Archaeol. Sci. Rep.* **41**, 103301 (2022).
28. Arnold, D. E. *Ceramic Theory and Cultural Process*. (Cambridge University Press, Cambridge, 1988).
29. Shepard, A. O. *Ceramics for the Anthropologist*. (Washington, DC: Carnegie Institute, 1957).
30. Rice, P. *Pottery Analysis: A Source Book*. (The University of Chicago Press, Chicago and London, 1987).
31. Rye, O. S. Keeping your temper under control: materials and the manufacture of Papuan pottery. *Archaeol. Phys. Anthropol. Ocean.* **11**, 106–137 (1976).
32. Vindrola-Padrós, B., Schuldt, T. & Wojcik, A. An Early Neolithic 'cracking technology': assessing the thermal shock behaviour of organic-tempered low-fired ceramics. *J. Archaeol. Sci. Rep.* **61**, 104893 (2025).
33. Bebber, M. R. Tempered strength: A controlled experiment assessing opportunity costs of adding temper to clay. *J. Archaeol. Sci.* **86**, 1–13 (2017).
34. Eramo, G. Ceramic technology: How to recognize clay processing. *Archaeol. Anthropol. Sci.* **12**, 164 (2020).
35. Arnold, D. E. Mineralogical analyses of ceramic materials from Quinua, department of Ayacucho, Peru. *Archaeometry* **14**, 93–102 (1972).
36. Arnold, D. E. The threshold model for ceramic resources: A refinement. in *Ceramic Studies: Papers on the Social and Cultural Significance of Ceramics in Europe and Eurasia from Prehistoric to Historical Times* (ed. Gheorghiu, D.) 3–9 (BAR International Series, Oxford, 2006).
37. Li, W. *History of Ancient Chinese Pottery Engineering Technology* (Shanxi Education Press, Taiyuan, 2017).
38. Xie, Z. et al. Changes and continuity in pottery production and use at Wujiafentou in the core zone of Youziling and Shijiahe cultures in central China. *Herit. Sci.* **12**, 64 (2024).
39. Liu, L. et al. Identification of 10,000-year-old rice beer at Shangshan in the Lower Yangzi River valley of China. *PNAS* **121**, e2412274121 (2024).
40. Liu, L., Li, Y., Zhao, Y., Chen, X. & Gu, W. Beyond subsistence: Evidence for red rice beer in 8000-year old Neolithic burials, north China. *J. Archaeol. Sci. Rep.* **51**, 104168 (2023).
41. Schiffer, M. B. Archaeology as Behavioral Science. *Am. Anthropol.* **77**, 836–848 (1975).
42. Roux, V., Bril, B., Goujon, A.-L. & Lara, C. Adaptive behavior within technological stability: field experiments with potters from five cultures. in *The Evolution of Techniques* (ed. Charbonneau, M.) 3–26 (The MIT Press, 2024).
43. Lemonnier, P. *Technological Choices: Transformation in Material Cultures since the Neolithic*. (Routledge, London and New York, 1993).
44. Schiffer, M. B. & Skibo, J. M. Theory and experiment in the study of technological change. *Curr. Anthropol.* **28**, 595–622 (1987).
45. De La Fuente, G. A. & Vera, S. D. Making vessels for the dead: pottery-making practices, *Chaîne Opératoire* and the use of grog (crushed sherds) as a technological and cultural choice during Late and Inca periods in the northwestern Argentine region (Southern Andes). *Open Archaeol.* **9**, 20220338 (2023).
46. Pérez-Monserrat, E. M., Maritan, L., Baratella, V. & Vidale, M. Production technologies and provenance of ceramic materials from the earliest foundry of Pre-Roman Padua, NE Italy. *Heritage* **6**, 2956–2977 (2023).
47. Dammer, E., Hein, A. & Spataro, M. An exploration of potential raw materials for prehistoric pottery production in the Tao River Valley, Gansu Province, China. *Geoarchaeology* **39**, 122–142 (2024).
48. Reid, K. C. Fire and ice: new evidence for the production and preservation of Late Archaic fiber-tempered pottery in the middle-latitude lowlands. *Am. Antiq.* **49**, 55–76 (1984).
49. Tite, M. S., Kilikoglou, V. & Vekinis, G. Strength, toughness and thermal shock resistance of ancient ceramics, and their influence on technological choice. *Archaeometry* **43**, 301–324 (2001).
50. Skibo, J. M., Schiffer, M. B. & Reid, K. C. Organic-tempered pottery: an experimental study. *Am. Antiq.* **54**, 122–146 (1989).
51. Rice, P. M. On the origins of pottery. *J. Archaeol. Method Theory* **6**, 1–52 (1999).
52. Dikshit, K. N. & Hazarika, M. The earliest pottery in East Asia: A review. *Purãtattva* **42**, 227–237 (2012).
53. Kim, M.-J., Go, J.-W., Bang, M.-B., Hong, W. & Lee, G.-K. Absolute chronology of Gosan-ri-type pottery, the oldest manufactured pottery in Korea. *Radiocarbon* **62**, 1715–1722 (2020).
54. Wang, L. & Sebillaud, P. The emergence of early pottery in East Asia: new discoveries and perspectives. *J. World Prehist.* **32**, 73–110 (2019).
55. Zheng, Y. & Jiang, L. Rice remains unearthed from the Shangshan site and implications. *Archaeol* **9**, 19–25 (2007).
56. Wu, W. & Qiu, Z. A preliminary study of fiber-tempered pottery at the Sunjiacheng site in Huaining, Anhui Province, China. *Jianghan Archaeol.* **4**, 92–101 (2020).
57. Talhelm, T. et al. Large-scale psychological differences within China explained by rice versus wheat agriculture. *Science* **344**, 603–608 (2014).
58. Talhelm, T. & Dong, X. People quasi-randomly assigned to farm rice are more collectivistic than people assigned to farm wheat. *Nat. Commun.* **15**, 1782 (2024).

Acknowledgements

The authors thank Jian Wang (Department of Archeology of Wuhan University) and Mr. Hong Zeng (Zoumaling Archeological Site Park Management Office) for their help with sampling the sherds. This study received financial support from the National Social Science Foundation of China (grant agreement number 19ZDA231, granted to Dr. Xiyun Yu) and the National Youth Talent Support Program (grant agreement number 1105-212200003, granted to Dr. Tao Li).

Author contributions

T.L., J.F.W., X.Y.A., and X.W. conceived the study, analyzed and interpreted the data, and were significant contributors to the writing of the manuscript. J.F.W., X.Y.A., and F.Y.L. collected the sherds, conducted the microscopic examination, and prepared the samples for X-ray fluorescence analysis. J.F.W., X.Y.A., and X.W. extracted and identified phytoliths in the selected sherds. 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

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s40494-025-01667-1.

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