



An exploration of potential raw materials for prehistoric pottery production in the Tao River Valley, Gansu Province, China

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Abstract

Northwest China is known for its Majiayao-style Neolithic painted pottery which has received much praise for its high level of craftsmanship, yet its chain of production, in particular the step of raw material selection, is still poorly understood. To fill this lacuna, the present study explores the raw materials used in producing these wares from a geological and technological perspective. At its core stands the first geoarchaeological survey conducted around the eponymous site of Majiayao which collected 47 samples of raw materials suitable for ceramic production including clay, loess and rocks, which were all analysed macroscopically. A selection was analysed using thin-section petrography, and a subset of the clay and loess samples were subjected to firing experiments. Additionally, three clay samples were analysed by scanning electron microscope with energy-dispersive X-ray spectrometer to understand their composition and behaviour in ceramic production. These were then compared to archaeological ceramics, thus providing insights into raw-material availability and selection that will be of importance not only for research on Majiayao-style pottery but also for later-period ceramics produced in the area. This research shows how an archaeologically informed geological survey can contribute insights into human–environment interaction in early pottery production, especially the interplay between raw-material availability, technological know-how and potters' choices.

KEYWORDS

ceramic technology, experimental archaeology, Majiayao style, Northwest China, petrographic analysis, raw material sources

1 | INTRODUCTION

The Neolithic painted pottery of northwest China has long received much attention for its high-quality craftsmanship and beautiful designs entailing contrasting black and red paint on red to yellow

vessel bodies. Pottery similar in outward appearance to that discussed in this paper, referred to as Majiayao-style and conventionally dated to 5300–4000 cal. B.P. (Dong et al., 2013), can be found over large parts of Gansu and Qinghai provinces. Majiayao-style pottery comprises two types of wares: fine and coarse, the

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former predominantly painted and the latter often decorated with cord impressions (Figure 1).

While earlier work in the region has focused on typological comparisons with the aim of establishing local chronologies, recent years have seen increasingly more research on technological aspects of ceramic production and trade using archaeometric techniques (e.g., Hein & Stilborg, 2019; Hung, 2011, 2021; Ma, 2000; Stilborg & Hein, 2021; Womack, 2017). The present paper provides a case study of how an archaeologically informed geological survey can contribute insights into human–environment interaction in early pottery production, especially the interplay between raw-material availability, user expectations, technological know-how and choices made in raw-material selection and processing as well as object production and consumption. Raw material prospection in the vicinity of archaeological sites is a widely used approach to study provenance and ancient pottery production technologies (e.g., Albero Santacreu, 2017; Harrad, 2004; Michelaki et al., 2015). Exploration of available raw materials is crucial for distinguishing between paste recipes and identifying manually added materials in archaeological ceramics (e.g., Ho & Quinn, 2021; Kreiter et al., 2017), which is one of the main aims of the present paper. It can also help with identifying specific clay sources past potters may have used (e.g., Nodarou, 2011; Roux & Courty, 2019, p. 138), although this is of less concern to the present study. Rather, we are interested in decision-making processes in pottery production, more specifically which raw materials potters selected, how they processed them and why (e.g., Albero Santacreu, 2014; Gauß & Kiriati, 2011) and issues on which raw material prospection in connection with experimental work and analysis of archaeological samples can provide answers.

Previous petrographic analyses of Majiayao-style pottery from the Tao River Valley (Dammer, 2023; Hein & Stilborg, 2019; Womack, 2017) provide a point of departure for geological sampling and identification of raw materials used in ceramic production. These studies show that the

Majiayao-style fine ware paste is mostly homogeneous with all inclusions being below 0.2 mm. The coarse pottery paste shows prominent inclusions of different sizes up to 2 mm of crushed granitic rock or rounded fragments of river sand. The pastes of Majiayao-style pottery across different sites in Gansu and Qinghai follow the same pattern (Dammer, 2023), though there are some minute differences in silt levels and larger inclusions that have been used to suggest pottery exchange between prehistoric sites in the Tao River Valley (Womack, 2017; Womack et al., 2021, 2019).

Previously, most scholars have relied on chemical analyses to trace production locations (e.g., Hong et al., 2011, 2012; Hung, 2021; Hung et al., 2014), while only a few have focused on petrographic thin-section analysis (e.g., Womack, 2017; Yu et al., 2017). Hong et al. (2011) and Hung (2021) analysed archaeological ceramics from Gansu, Qinghai and Sichuan and a limited number of samples of modern-day pottery made using local clays using laser ablation inductively coupled plasma atomic emission spectroscopy. They suggested trade in ceramics across western China, but as only very few samples of ceramics with known clay origin and no actual geological samples had been taken and the archaeological samples span vast regions, the results have been called into question (e.g., Huan, 2021; Ren et al., 2013; Xiang & 向金辉, 2018).

One underlying issue with provenancing archaeological ceramics from this region lies in the relative homogeneity of windblown sediment deposits across large parts of northwest China, both the loess and the likewise aeolian quaternary red clay that is the preferred base clay used by modern potters in the region (Hein et al., 2020; Ma et al., 2020; Quinn, 2022, p. 8; Quinn et al., 2017, p. 975). In response to the studies published by Hung Ling-yu and colleagues, Ren et al. (2013) suggested that chemical analysis and statistical evaluation of major and minor elements were not enough, as did Huan (2021) who argued that trace elements and potential raw-material processing needed to be taken into account.



FIGURE 1 Majiayao-style pottery: (a) fine and painted K-05058, Bانشan (b) coarse, decorated with cord impressions K-06384, Zhujiashai; Museum of Far Eastern Antiquities, Stockholm, Sweden. (Photographs by E. Dammer).

Nevertheless, several teams conducted X-ray fluorescence analyses on Majiayao pottery, and this methodology was also applied to other prehistoric pottery styles in northwest China (e.g., Qijia and Yangshao) likewise suggesting long-distance exchange, though with similar methodological problems (e.g., Cui et al., 2015; Hou et al., 2016; Xiang & 向金辉, 2018). The ceramics analysed in these studies were predominantly fine ware dating to the Neolithic and Bronze Age (mostly Majiayao and Qijia style) with only a few samples for each site and not much consideration of clay processing or variations in local geology.

Recent years have seen increasingly more research taking a technology-focused and/or community-of-practice approach and using a petrographic rather than geochemical approach (e.g., Dammer, 2023; Stilborg & Hein, 2021; Womack, 2017; Womack et al. 2019, 2021). Among them is an extensive study of Neolithic Majiayao-style and Bronze Age Qijia-style pottery in the Tao River Valley by Womack (2017) which includes a geological survey around the sites of Qijiaping and Dayatou. Here, 24 samples of unfired clay, rocks, sand and loess, as well as four modern pottery samples were collected (Womack, 2017, figs. 2.14, 4.1, tab. 4.1, 4.2). Womack analysed coarse and fine wares by thin-section petrography and was able to identify different types of clay preparation and tempers. The base clays largely matched the clay samples retrieved on his geological survey: fine clay with feldspar, quartz and carbonate sand-sized inclusions; sand with clay pellets and small amounts of calcite, biotite, muscovite and rare epidote and hornblende. The rock samples, however, did not match what appeared in the archaeological ceramics, so Womack concluded that river sand has been used as tempering material (Womack, 2017, p. 1172; Womack et al., 2019). He also identified a fabric with coarse biotite and hornblende, feldspar and quartz but did not mark it as temper. Similar inclusions were found in recent analyses of Neolithic and Bronze Age pottery from the region, but here the researchers categorised them as temper (Hein & Stilborg, 2019). Distinguishing between temper and natural inclusions can be difficult; here, raw material prospection can help us to understand what kind of material occurs naturally and what type of inclusions are more likely the result of clay processing. This is one aspect of the work presented here.

The present study is an exploratory study of potential raw materials for pottery production collected during a geological survey around the pottery type-site Majiayao. The primary aim of this study was to assess natural raw material variation by leaving the collected clays largely in their natural state, removing only plant matter and other coarse impurities and then conducting the first macroscopic assessment followed by clay processing and experimental firing. Various types of lab-based analyses were conducted on both collected raw materials and archaeological ceramics to address the following questions:

1. Which clays available around the site of Majiayao are suitable for use in vessel shaping and firing without much processing?
2. How do the geological samples compare to the archaeological pottery? Do they match petrographically and can they, therefore,

be regarded as raw materials used for pottery production in prehistory?

3. What technological choices in paste preparation can be inferred from the comparison with archaeological pottery?

To address these questions, the collected clay samples were subjected to experimental firing at various temperatures, followed by macroscopic analysis, optical microscopy and scanning electron microscope with energy-dispersive X-ray spectrometer (SEM-EDX), with the aim of characterising locally available raw material sources for pottery making and evaluating their performance to see which materials could realistically have been used and how they appear in a fired state. The results of these analyses were compared with data from archaeological samples to assess actual versus possible potters' choices.

2 | MATERIALS AND METHODS

2.1 | Geological setting of the study area

The Tao River Valley is situated between the Maxian Mountains in the northeast and the Xiqing Mountains in the southwest (Figure 2). Coming from the north, the Tao River flows from the Xiqing Mountain into the Yellow River near Lanzhou. From the Xiqing Mountains, the river carries predominantly sedimentary material: sandstone, limestone and fluvio-lacustrine sediments (Table 1).

The bedrock of the Xiqing Mountains is rich in granite (Figure 3; Ma & Liu, 2002, pp. 326–327). There are several modern dams built on the upper reaches of the Tao River. This means that most of the sediment mass and large boulders eroded from the Xiqing Mountains do not reach the Tao River Valley where the Majiayao site is located. The sediments distributed along the riverbank in the valley closer to Majiayao consist mostly of unconsolidated sand and clay and rocks of different sizes scattered over it. The closest source of granite, granodiorite and gabbro for Majiayao are the Maxian Mountains (Figure 3; Ma & Liu, 2002, pp. 326–327).

A few dried-out tributaries of the Tao River are located at the foot of the Maxian Mountains, running through granite bedrock and hills consisting of bands of loess and red clay deposits. These tributaries could have been transporting sediment and eroded material into the Tao River. Manganese deposits were found in proximity to the Maxian Mountains: in Kanjiayao and at Nanpu (or Nanbao), both in Lintao County (Su, 2006, p. 61). Other deposits are located near Lanzhou city. Previous research has shown that manganese was used to prepare paint to decorate Majiayao-style pottery (Li et al., 2018, p. 50; Ma, 2000, pp. 54–58; Palmgren, 1934, p. 174, ft-note 2).

The Majiayao site is located at ca. 1982 m above sea level. The landscape around the site is defined by hills, gullies and ravines (Figure 4). The sediment forming the hills shows a natural separation in red-brown clay at the bottom and greenish-yellow brown loess on the top. Over the last century, the hills have been altered by artificial terracing for agricultural use; however, the overall geology remained

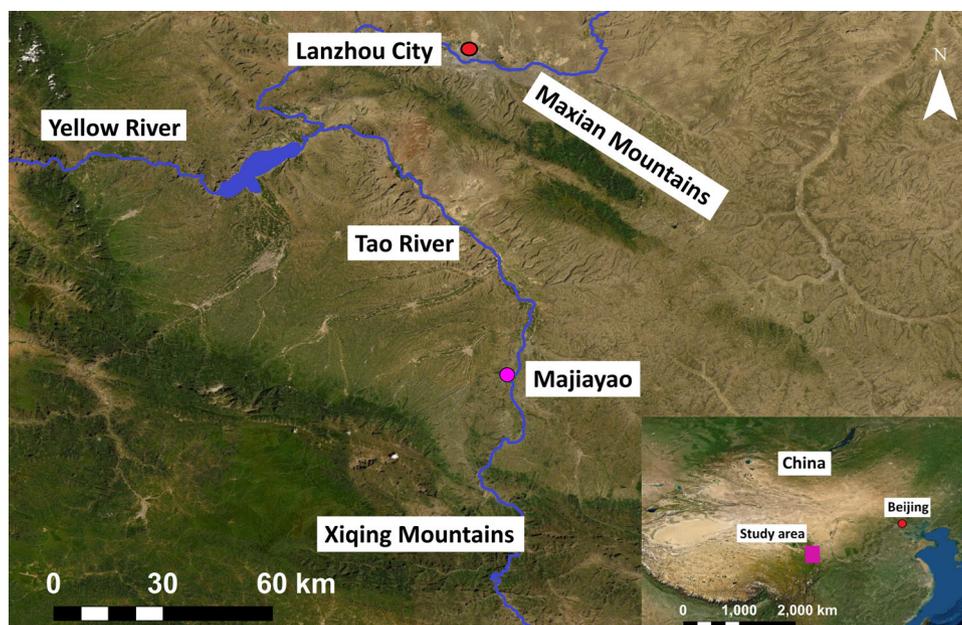


FIGURE 2 Satellite view of the Tao River Valley.

TABLE 1 Summary of geological characteristics of the Tao River Valley.

Sediment
<ol style="list-style-type: none"> 1 Deposits of aeolian red clay with deposits of loess on top. 2 Alluvial deposits of red clay along the river. 3 Layers of loose river sand visible in the lower red clay deposits in the dried-out river tributaries suggesting a higher river level in the past.
Rocks
<p>Sedimentary: orange-red sandy mudstones, conglomerates and red mudstones with calcareous concretions; sandstones, quartzite, siltstone, chert, clastic rocks, gypsum, limestone.</p> <p>Igneous: granite, granodiorite, gabbro, rocks with porphyritic texture.</p>

the same from prehistory until modern times (Andersson, 1925, pp. 7–8). The rivers are cutting increasingly deeper into the mountains, though, and the ancient river level which was higher than the current one can be observed in the geological profiles as sand layers mixed with large stones.

2.2 | Field sampling

According to ethnographic studies, around 70% of potters collect their raw materials within 4 km of where they live and 86% within 7 km (Arnold, 2006, p. 8). Based on this data and the local geomorphology, the geological survey was conducted within a ca. 5 km radius of the Majiayao site. The field sampling route went along the road cuts with accessible geological profiles at the top and bottom of the hills and included a survey of the riverbank near the site (Figure 5).

Raw material prospection in the field was conducted during 2 days of survey in 2019. Laboratory analyses were conducted at Xibei University over 10 days. Therefore, the testing of the suitability for pottery making of clay samples included only essential tests of (a) plasticity, that is, the ability of the clay to be formed into a shape and keep it without collapsing (Hamer, 1991, p. 243; Roux & Courty, 2019, p. 18), performed in the field, (b) workability (or malleability), that is, the ability of the clay to withstand stress and stretching without tearing (Hamer, 1991, p. 346; Roux & Courty, 2019, p. 17), performed in the laboratory, and (c) the assessment of macroscopic changes in clay after firing at different temperatures. The limited timeframe did not allow for experimental replication of the various paste types observed in archaeological samples, nor was it possible to replicate entire vessels to see how the material would perform with various complex forms. It was not possible to export unfired clay in the amount necessary to produce replica pottery elsewhere. Instead, we explored how the clay would perform by mixing it with water and shaping it into briquettes which were then fired and subsequently thin-sectioned for further analysis. This approach allowed us to answer the research questions listed above and therefore provide a basis for future analytical, experimental and comparative work (see also Sections 4 and 5).

In total, 47 geological samples were collected at 22 locations (Table 2). These are 14 samples of clay, three of loess, 29 rocks and one sand sample. Each sample was labelled Geological Sample China (GSC) with a location number from 1 to 22. Where multiple rock samples were taken at the same location, they were labelled using two numbers; for example, GSC22-2, the first number designating the location and the second, the sample. In addition to the clay samples from Majiayao, two other clay sources (GSC5 and GSC6; Table 2) were sampled at a distance of ca. 21.5 km north from the site as these were used by a local potter to make replicas of Qijia and Majiayao style pottery (Figure 6).

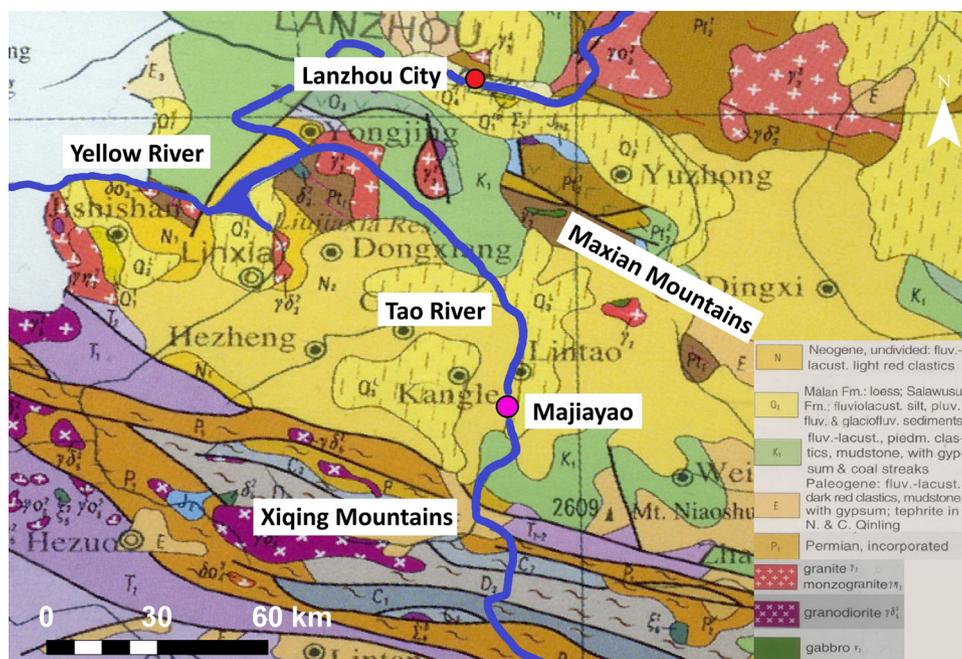


FIGURE 3 Geological map of the Tao River Valley, north oriented (after Ma & Liu, 2002); for full legend see Appendix S2.



FIGURE 4 Area around the Majiayao site (view from the northwest).

2.3 | Clay processing and experimental firing

All 47 samples of sediment and rock materials were analysed and described macroscopically and microscopically using a Brunel DM-2 stereomicroscope at $\times 30$ magnification (Appendix S2). Thirteen clay samples and three loess samples were selected for the firing experiment to see how they would perform in ceramic production. The clay samples were selected based on their plasticity after being mixed with a small amount of water in the field during sample collection. Each clay sample was kneaded and rolled into a coil to see if it would keep its shape, a major basic prerequisite for any further attempts at using the material in vessel making. While it is possible that prehistoric potters created their clays by mixing plastic and less plastic materials (Ho & Quinn, 2021), this pilot study mostly focused on raw materials which are naturally plastic, as there are plenty of such materials available in the area. We also collected three loess

samples, which are less plastic, because loess is widespread in the study area and it has been suggested that it may have been used in prehistoric ceramic production (Ma et al., 1991).

The experimental work was then conducted following the procedures described by Gauß and Kiriati (2011, p. 78). In accordance with the aims of this study and its exploratory nature, the clay samples were minimally processed, using only sedimentation by settling clay in water (Hamer, 1991, p. 285) to separate coarse materials, for example, vegetation and pebbles, from the clay, while retaining any rock fragments of up to 5 mm in diameter that were not easily seen by the naked eye and would have visibly torn the clay mass during vessel construction. Further refining of the clay would have compromised the comparative study with the archaeological pottery, as one of the aims was to explore if the coarse ceramics could have been made from naturally occurring coarse materials or if they must have been the result of adding temper. After mixing one

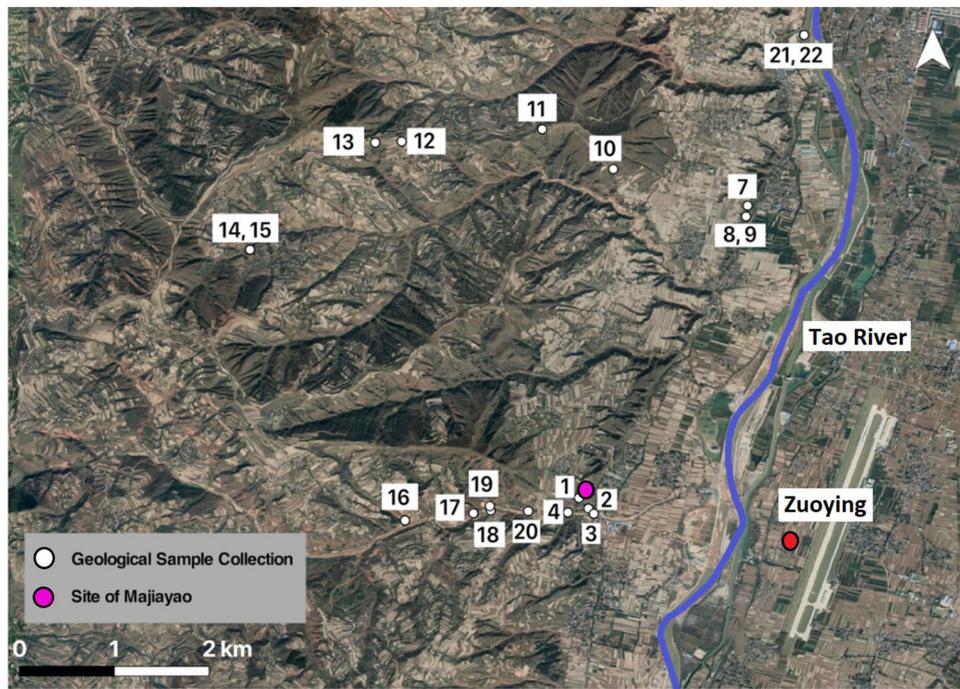


FIGURE 5 Geological field sampling itinerary in the Tao River Valley; see Table 2 for the number ID.

part water with three parts clay, the material required ca. 72 h at room temperature to dry to a workable state. Workability was assessed by rolling the clay into a ball, then pressing and stretching it out into a slab or coil and observing whether it would keep its shape or easily tear. Four tiles ca. 80 × 20 × 55 mm were formed from each sample; one tile was left unfired as a control and the others were later fired at various temperatures (Figure 7).

After 24 h of drying at room temperature (ca. 20°C in Xi'an in July 2019, air humidity average of 40%–60% outside [Past weather in Xi'an, 2022]), the tiles were placed in the electric oven ZRD-A5210 to dry between 0.5 and 1 h at temperatures between 60°C and 100°C (depending on how moist they were to the touch) to ensure even drying (Table 3).

The first kiln firing was conducted a day after the samples had been dried in the oven. The tiles were loaded into the electric kiln SHIMPO DFA-06 and fired at 700°C, 900°C, or 1050°C, temperatures that were chosen based on estimated firing temperatures for Majiayao-style pottery (see Ma, 2000; Ma et al., 1991, pp. 21, 31). (Table 4). After the tiles were fired at the desired temperature for 1 h, the kiln was left closed to cool down overnight and the performance of the tiles was observed the next day (Figure 8).

2.4 | Thin-section petrography

Thin-section petrography was conducted on eight experimentally fired briquettes, 14 rock samples and one sand sample using a 'James Swift MP3500' polarised light microscope. Photomicrographs were taken using a Brunel LCMOS 14-megapixel eyecam,

with TouPTek TouPView v3.7 processing software. The aim of the petrographic study was to assess the mineralogical composition of the clay and loess samples for comparison with the archaeological pottery fabrics, and of the sand and rock samples for comparison with coarse inclusions in these fabrics to investigate potential tempering materials (Carney, 2010; Quinn, 2022). The petrographic analysis focused on the visual assessment of the nonplastic inclusions under the microscope following the visual estimation chart (Terry & Chilingar, 1955) and following the ISO standard for grain size (International Organization for Standardization [ISO], 2017). Since the sediments in the study area are predominantly of aeolian origin and show natural well-sorted silty mineral inclusions mainly consisting of mica, quartz and feldspar. The coarse poorly sorted ceramics show stark differences in size and amount of mineral inclusions to fine ceramics. Therefore, in this case, visual estimation and identification were preferred to collecting quantitative data through, for example, point counting, to estimate mineral proportions; point counting was not considered as an efficient method to investigate and identify tempering materials. Individual petrographic description of each geological sample is provided in Appendix S1.

2.5 | SEM-EDX

A scanning electron microscope fitted with the Oxford Instruments AZtec energy-dispersive X-ray spectrometer (SEM-EDX) in the Department of Scientific Research of the British Museum (London, UK) was used to measure the chemical composition of three clay samples fired at 1050°C to assess the calcium oxide content, which

TABLE 2 List of geological samples.

ID	Sample number	Sample type	Lat Long	ID	Sample number	Sample type	Latitude Longitude
1	GSC1	Aeolian clay	35.30938 103.806257	12	GSC12	Loess	35.350733 103.785684
2	GSC2	Sand	35.308157 103.807363	13	GSC13	Aeolian clay	35.350604 103.782612
3	GSC3 (1-9)	Rocks	35.307563 103.807987	14	GSC14	Aeolian clay	35.338178 103.768071
4	GSC4	Aeolian clay	35.307704 103.804975	15	GSC15 (1-3)	Rocks	35.338178 103.768071
5	GSC5	Aeolian clay	35.495781 103.825364	16	GSC16	Aeolian clay	35.306781 103.786066
6	GSC6	Aeolian clay	35.495688 103.825367	17	GSC17	Alluvial clay	35.307615 103.794006
7	GSC7 (1-4)	Rocks	35.343292 103.825845	18	GSC18	Alluvial clay	35.307945 103.796016
8	GSC8	Aeolian clay	35.342039 103.825665	19	GSC19	Alluvial clay	35.30845 103.795912
9	GSC9	Aeolian clay	35.342039 103.825665	20	GSC20	Alluvial clay	35.307861 103.80037
10	GSC10	Loess	35.347527 103.810245	21	GSC21	Alluvial clay	35.363078 103.832407
11	GSC11	Loess	35.352146 103.802001	22	GSC22 (1-13)	Rocks	35.363078 103.832407

Note: For sample locations consult the maps in Figures 5 and 6. The sample location number is identical to the sample number unless more than one sample was collected at the same location, which is then specified by numbers in brackets.

Abbreviation: GSC, Geological Sample China.

was not possible to assess accurately by polarised microscopy (Dammer, 2023, p. 78).

The clay fabric SEM-EDX analyses were run via a Hitachi S-3700N variable pressure (VP) SEM at an accelerating voltage of 20 kV at a low vacuum of 40 Pa, with a count rate of 10,000 cps and a 150 s counting time for high spectrum count-rate statistics. Detection limits for different elements vary but are typically in the range of 0.1%–0.4%. Based on 30 EDX measurements of Corning Standard Glass A, the major oxide, SiO₂, was measured to an accuracy of 0.30% and a precision of 0.11% (one sigma) or 0.33% (three sigma). The precision and accuracy for minor element concentrations in the range of 5%–20% is around 10% relative, and it reduces as the detection limits are approached.

The uncoated clean flat fracture surfaces were analysed. The VP mode enables a wide range of nonconducting samples (such as these fired briquettes) that cannot be examined in a conventional high vacuum SEM to be studied at a range of voltages, without

being coated with a thin layer of carbon or gold (see Spataro et al., 2009, p. 39). Ideally, samples to be studied by SEM-EDX should be polished in thick or thin sections to improve the geometry of the sample, but the VP SEM used in this research has already been tested on unpolished surfaces (fractures), and the results are highly reproducible (e.g., see Falcone et al., 2006; Spataro et al., 2009, 2013, 2019). This technique is therefore appropriate for obtaining data accurate and precise enough to answer our research questions.

SEM-EDX measures the concentrations of major and minor oxides. As the samples were manually smoothed fractures, not polished thin sections and were uncoated, seven bulk analyses of areas c. 1.4 × 1.0 mm were carried out on each sample. Nine elements (Na, Mg, Al, Si, K, Ca, Ti, Mn, Fe) were quantified; the results were converted into oxide percentages, which were normalised (oxygen by stoichiometry) (e.g., Spataro, 2011, pp. 256–257).

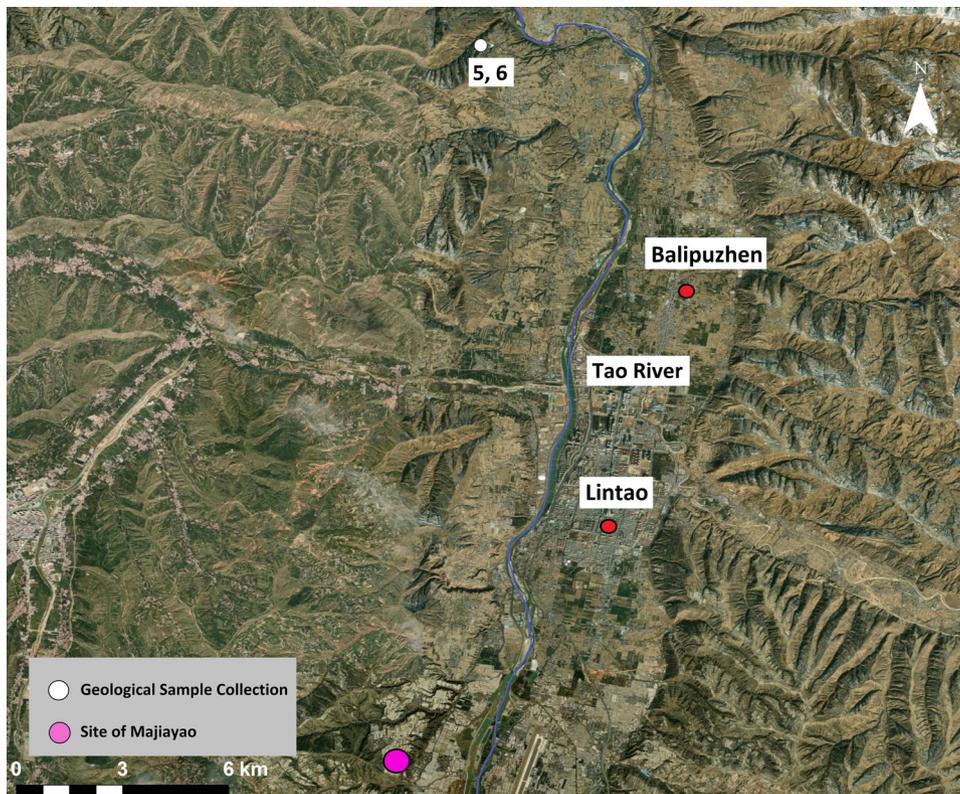


FIGURE 6 Sampled clay sources used by the local potter Mr Ma. See Table 2 for a reference to the ID numbers.



FIGURE 7 Examples of briquettes made for the firing experiment, dimensions of each piece ca. $8 \times 2 \times 5$ cm. (Photograph by E. Dammer).

2.6 | Archaeological ceramics used for comparison

In a recent study, Dammer (2023) identified seven main fabric groups using thin-section polarised light microscopy in 71 sherds from the Majiayao site kept at the Museum of Far Eastern Antiquities. These sherds were collected during the first archaeological fieldwork on the site in the 1920s (Andersson 1973, p. 264). Typologically the painted sherds fall into the Majiayao (5300–4650 cal. yr. B.P.) and Banshan

(4650–4300 cal. yr. B.P.) phases of the Majiayao period based on the painted ornaments and black and white. The sherds decorated with cord impressions were collected with the painted sherds and fall roughly into the same time period, although the unpainted Majiayao pottery does not have typo-chronological sequences as detailed as the painted ware. Based on the size of the designs and comparison to the complete vessels, the sherds predominantly belonged to large, rounded vessels as seen in Figure 1.

The fabrics of the analysed sherds consist of fine, coarse and semicoarse pastes (Table 5 and Figure 9). The main fabric types of the fine pastes are rich in mica, quartz and feldspar. The main coarse fabric types consist of granodiorite fragments and rounded sedimentary rock fragments. The semicoarse fabric has quartz as the dominant mineral inclusion type. Below, these pottery fabrics will be used for comparison with the geological samples.

3 | RESULTS

3.1 | Macroscopic analysis and results of the firing experiment

The unfired samples were macroscopically divided into three groups based on their plasticity and workability; the fired samples were divided into three groups based on their condition after firing (Table 6). The following observations were made:

TABLE 3 Drying process of the briquettes made from the clay collected during the survey.

Oven temperature (°C)	Duration (h)	Samples GSC	Notes
80–100	1–1.5	1, 6, 9, 10, 11, 12, 13, 16, 17, 18, 19, 20	These briquettes were put in the oven after 24 h of drying at room temperature.
100 60	0.5 1	5, 8, 14, 21	These briquettes were made a day later because this clay dried at a slower pace. The briquettes were put in the oven after one day of drying. The temperature was lowered after 0.5 h because GSC5 and GSC21 started to dry unevenly and crack.

Abbreviation: GSC, Geological Sample China.

TABLE 4 Three firings conducted for this study.

Firing 1		Firing 2		Firing 3	
Temperature (°C)	Duration	Temperature (°C)	Duration	Temperature (°C)	Duration
Start 35, end 700	3 h 35 min	Start 80, end 900	2 h 45 min	Start 90, end 1050	3 h 35 min
Hold 700	1 h	Hold 900	1 h	Hold 1050	1 h
Cool-down	ca. 15 h (overnight)	cool-down	ca. 15 h (overnight)	Cool-down	ca. 15 h (overnight)
Notes		Notes		Notes	
After firing all samples remained intact except for GSC5, which exploded at ca. 600°C.		After firing all samples remained intact except for GSC5, which exploded at ca. 600°C.		After firing all samples remained intact except for GSC5, which exploded at ca. 600°C.	

Abbreviation: GSC, Geological Sample China.

**FIGURE 8** State of the sample after the first firing; GSC5 exploded into small pieces. (Photograph by E. Dammer). GSC, Geological Sample China.**TABLE 5** Overview of the petrographic fabrics identified in the Neolithic Majiayao pottery samples.

Fine fabrics	Coarse fabrics	Semicoarse fabrics
1 Mica-quartz-feldspar	4A Quartz-feldspar and granodiorite fragments	7 Quartz dominant
2A Mica-quartz-feldspar with lesser inclusion frequency	4B Quartz-feldspar and granodiorite fragments, less porous	
2B Mica-quartz-feldspar with calcite fraction	4C Quartz-feldspar and granodiorite fragments with clay pellets	
3 Quartz dominant	5A Quartz-feldspar and granodiorite fragments	
	5B Calcite and quartz with sedimentary rock fragments, less coarse fraction and low porosity	
	6A Quartz and sedimentary rock fragments	
	6B Quartz and sedimentary rock fragments with high volcanic rock fraction	

- All samples in Fired Group 2 showed different degrees of damage caused by lime particles after firing. The cracking of briquettes turned a few samples into fine powder while others broke into chunks (Table 6, Fired Group 2). The poorest performance was observed with sample GSC5, which exploded in the kiln at around 600°C, based on loud pops heard during all three firings (Figure 8).
- None of the samples showed a naturally present high fraction of coarse rock or mineral inclusions (except for lime). It is possible, however, that there was a naturally coarse clay source in the study area which has not been identified.

- Samples GSC10, GSC11, and GSC12 show a higher silt fraction than all the other samples, which affects their plasticity and the ability to stay in a solid state after firing (Table 6, Unfired Group 3 and Fired Group 3). GSC10, GSC11, and GSC12 dissolved in water

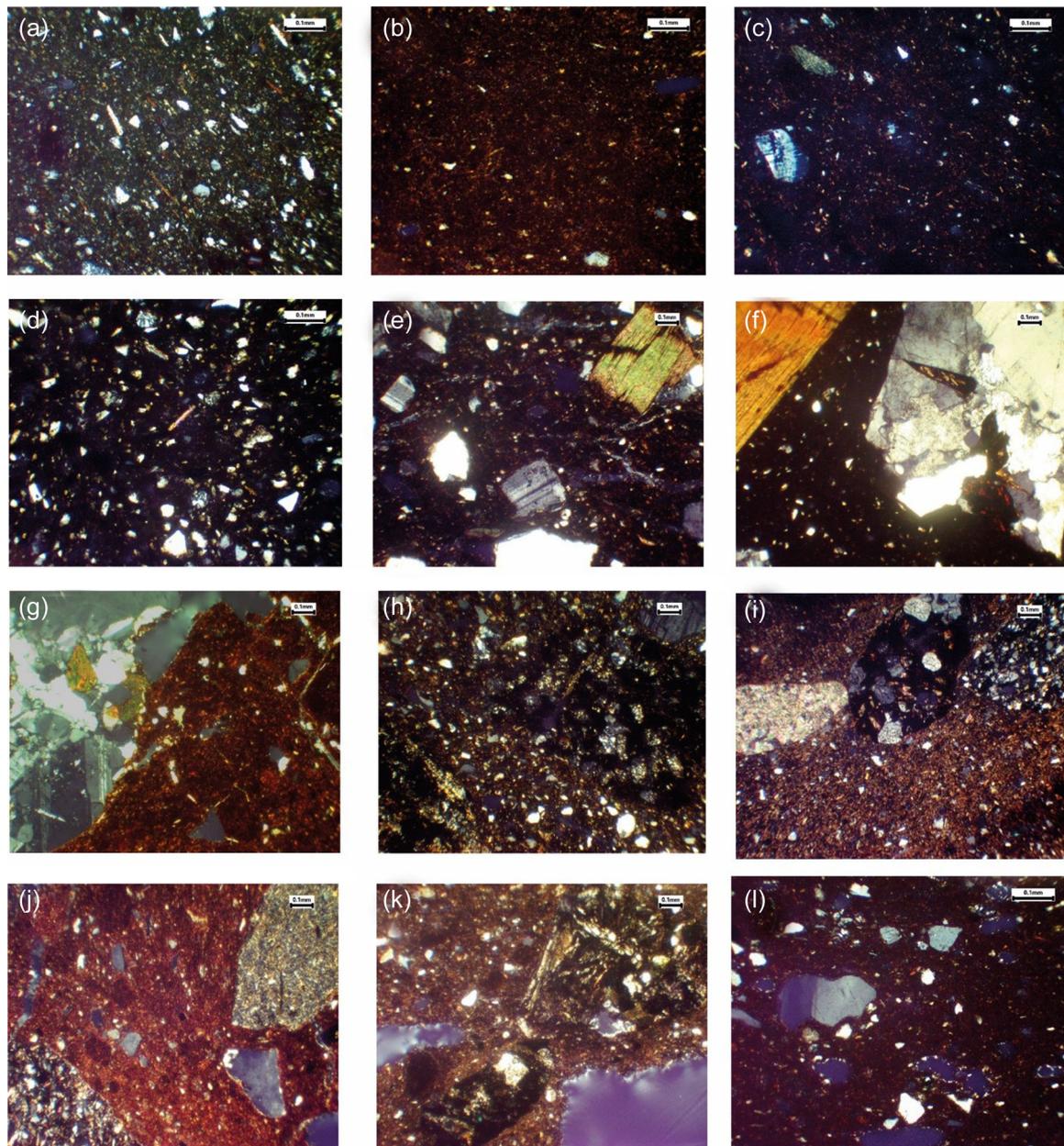


FIGURE 9 Photomicrographs of Majiayao ceramic thin sections taken under cross polarised light, scale size = 0.1 mm; (a) Fabric 1, CNP50; (b) Fabric 2A, CNP69; (c) Fabric 2B, CNP43; (d) Fabric 3, CNP64; (e) Fabric 4A, CNP24; (f) Fabric 4B, CNP9; (g) Fabric 4C, CNP35; (h) Fabric 5A, CNP22; (i) Fabric 5B, CNP34; (j) Fabric 6A, CNP10; (k) Fabric 6B, CNP13; (l) Fabric 7, CNP58. (Photomicrographs by E. Dammer).

within seconds, meaning that most particles in this material are coarser (silty) and water can permeate it faster.

4. The clay particle content has a direct influence on plasticity. The higher the proportion of fine clay, the higher the plasticity. GSC10, GSC11, GSC12 are comprised of silty loess material which had the lowest plasticity of all samples. It was not possible to form coils without tearing them. After firing, the briquettes of these samples fired below 1050°C can leave fine powder residue on the hands when touched.
5. None of the experimental briquettes acquired the yellow surface colour which is characteristic of the painted Majiayao-style

vessels. Most of the clay samples showed shades of brown and orange colours which were observed on surfaces of plain vessels and vessels decorated with impressions and appliqué.

The sand sample GSC2 was collected at the ancient river level in the geological profile of the hill on top of which the Majiayao site is located. Shell fragments, sedimentary rock fragments and minerals such as quartz and feldspar, were identified macroscopically.

There is no protruding natural bedrock around the site, and all collected rocks have rounded shapes: they were thus deposited

TABLE 6 Macroscopic analysis of unfired and fired clay samples (GSC4 not fired).

	GSC samples	Macroscopic description
Unfired Group 1	1, 5, 6, 8, 9, 13, 14, 17, 18, 19, 20, 21	Fine red clay; found in a hard dry and a soft wet state. It is plastic and holds its shape when manipulated by hand.
Unfired Group 2	4, 16	Red clay with a high proportion of coarse white carbonate rock or mixed rocks. Because of the high coarse fraction, these samples were less plastic.
Unfired Group 3	10, 11, 12	Silty creamy/light brown loess; low plasticity and malleability.
Fired Group 1	1, 5, 6, 8, 17	All samples except for GSC5 remained undamaged and in solid shape; no lime spalling; GSC5 exploded in the kiln at about 650–700°C during all three firing experiments. All samples showed various shades of brown and red-brown.
Fired Group 2	9, 13, 14, 16, 18, 19, 20, 21	All samples showed lime building after firing at 900°C and 1050°C. GSC13, GSC14 and GSC16 disintegrated into fine powder within a minimum period of 8 weeks. Samples fired at 700°C showed similar characteristics to the samples in Fired Group 1 by staying undamaged and turning brown in colour.
Fired Group 3	10, 11, 12	These are the same samples as in the Unfired Group 3. Silty loess stayed intact after firing; however, the samples fired at 700°C and 900°C are slowly disintegrating into fine powder. Briquettes fired at 1050°C remain whole.

Abbreviation: GSC, Geological Sample China.

TABLE 7 Rock types identified among the samples collected in the Tao River Valley.

<i>Igneous</i>
Gabbro; granodiorite; andesite; felsic rock sample with K-feldspar, quartz, mica—possibly granite.
<i>Sedimentary</i>
Gritstone (fine and coarse); intraclastic carbonate rock from shallow marine environment (limestone); claystone or shale; chert; chert with iron oxide/reduced iron staining; conglomerate with chert, mica, gneiss and bioclastic carbonates; sandstone; fine-grained sandstone; fault breccia.

either by ancient or still active streams around Majiayao. Most rocks observed here are sedimentary as is generally the case for the load carried by the Tao River (Table 7).

3.2 | Thin-section petrography

3.2.1 | Clay samples

The petrographic analysis showed that the differences between the different fired clay and loess samples are mostly in the amount and size of mineral inclusions but not in the type. All samples show fine mineral inclusions of size below 0.2 mm, except for GSC17, GSC20 and GSC21, which contain inclusions larger than 0.2 mm in length (Table 8 and Figure 10). The clay samples are predominantly fine; GSC17, GSC20 and GSC21 are semicoarse with a $\geq 30\%$ fraction of medium sand-sized inclusions of quartz and feldspar (0.2–0.63 mm). Although GSC20 and GSC21 both showed lime damage, no coarse calcium-based inclusions were observed.

Most of the geological samples show clay pellets taking up >5%–10% of the clay matrix (Table 8). Such a high amount of clay pellets in the experimental samples might be the result of poor kneading or insufficient slaking time. For example, when hydrated, sample GSC6 formed hard argillaceous lumps which were not completely dissolved after 2 days of being in suspension and the subsequent kneading (Figure 11). During the kneading process, GSC6 showed higher viscosity than the other samples. The characteristic of clays to form argillaceous lumps or clay pellets, which later appear as pellets in the thin section, and the viscosity degree of the clays can only be identified when clays are mixed with water and not given sufficient time to fully hydrate before being used for pottery making (Quinn, 2022, p. 238). In his study of unfired clay samples from the region, Womack (2017, p. 139) did not find clay pellets to be a significant characteristic, but some of the thin sections of archaeological ceramics he analysed did contain a high percentage of clay pellets. This difference between geological and archaeological samples likely arose because the clay samples Womack used for his study were not mixed with water or fired but left in their raw state; lump building and slow slaking of clays has a direct impact on the production process, requiring extensive kneading (Shepard, 1985, p. 17).

Further notable characteristics of the clay matrices after firing include changes in optical activity and porosity. The samples fired at 1050°C show moderate optical activity or are optically inactive and some show partial vitrification. The porosity in all samples is less than 3%, which is very low compared to the analysed fine pottery from Majiayao (3%–5% on average) (Dammer, 2023, tab. 4.4).

Comparing the GSC samples to the petrographic characteristics of the prehistoric pottery found at Majiayao, it becomes apparent that the GSC samples do not naturally contain coarse rock fragments in the same high quantity as the coarse Majiayao pottery. Mineral and rock inclusions in the geological clay are less than 0.02 mm in size whereas the coarse pottery has large inclusions up to 2 mm in size.

TABLE 8 Summary of petrographic characteristics of fired clay samples from the Tao River Valley (Appendix S2).

Characteristic	Samples
Inclusion frequency (based on the graphics in Terry and Chillingar [1955])	
20%–40%	GSC1, GSC5, GSC6, GSC8, GSC11
40% or more	GSC17, GSC20, GSC21
Inclusion size (after ISO [2017]) and type	
≤0.2 mm; Quartz 55%, mica 40%, feldspar 5%	GSC1
≤ 0.02 mm; Quartz 60%, mica 39.9%, feldspar 0.1%	GSC5
≤ 0.02 mm; Quartz 50%, mica 49.9%, feldspar 0.1%	GSC6
≤0.2 mm; Quartz 55%, mica 35%, feldspar 10%	GSC8
≤0.2 mm; Quartz 45%, mica 45%, feldspar 10%	GSC11
0.063–0.63 mm (35%) Quartz 69.4% Feldspar 30% Vitrified inclusions with quartz fragments 0.5%, sandstone 0.1%	≤0.2 mm (65%) Quartz 60% Mica 25% Feldspar 15% GSC17
0.063–0.63 mm (30%) Quartz 80% Feldspar 20%	≤0.2 mm (70%) Quartz 50% Mica 35% Feldspar 15% GSC20
0.063–0.63 mm (30%) Quartz 70% Feldspar 30%	≤0.2 mm (70%) Quartz 70% Mica 10% Feldspar 20% GSC21
Clay pellet amount	
No clay pellets	GSC11
1%–3%	GSC8
5%–10% and more	GSC1, GSC5, GSC6, GSC17, GSC20, GSC21
Optical activity of the clay matrix under cross-polarised light	
Moderately active	GSC1, GSC5, GSC6
Inactive	GSC17, GSC20, GSC21, GSC8, GSC11
Void amount	
3% or less	GSC1, GSC5, GSC6, GSC8, GSC11
3%–5%	GSC17, GSC20
5%–10%	GSC21

Abbreviation: GSC, Geological Sample China.

Coarse inclusions in the GSC clays are well sorted and mostly rounded (e.g., Figure 10d); the inclusions in coarse Majiayao pottery are poorly sorted: the fabric with dominant granite inclusions shows sharp edges, and the fabric with dominant sedimentary rocks shows large rounded inclusions. This suggests that local clay was used as base clay and tempered with crushed granite or river sand, confirming suggestions by Stilborg and Hein (2021) and Womack (2017, Womack et al. 2019).

The absence of carbonate inclusions in the GSC samples in the thin section is notable, but they were observed in ceramic fabrics. Even

samples GSC20 and GSC21, which showed light lime spalling after firing at >900°C, do not show any carbonate inclusions in the thin section. This means that the calcite content of the geological samples in this study is of very fine size and is not detectable by optical microscopy. Womack identified carbonate-rich clay among the geological samples he collected in the Tao River Valley. He suggested that this type of clay could have been used to make pottery paste with coarse carbonate inclusions (Womack, 2017, p. 140). However, Womack did not conduct a firing experiment to find out whether this type of clay would be damaged by lime formation postfiring.

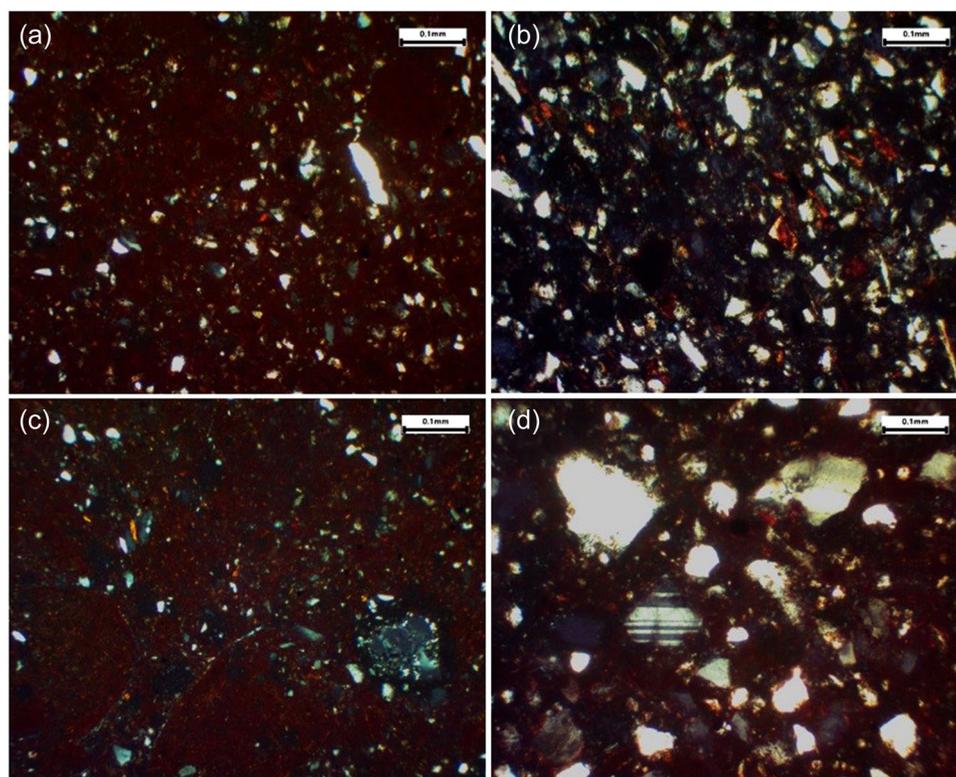


FIGURE 10 Examples of composition of clay and loess samples from the Majiayao site area. Samples fired at 1050°C; photomicrographs taken under cross-polarised light, scale size = 0.1 mm; (a) clay GSC1, (b) loess GSC11, (c) clay GSC5 and (d) clay GSC20. (Photomicrographs by E. Dammer). GSC, Geological Sample China.



FIGURE 11 GSC6, fired sample (1050°C), thin-section scan. The dark areas of different sizes are clay pellets. (Photoscan by E. Dammer). GSC, Geological Sample China.

Coarse carbonate inclusions have been identified in coarse pottery from Majiayao (Dammer, 2023, p. 38). These inclusions were found together with river sand temper. As no geological sample contained coarse carbonate inclusions, it is likely that the clay source sampled by Womack was not sampled in this study, leaving two possible interpretations. Either carbonate-rich clay was used as base clay for the coarse pottery as Womack (2017) argues, or carbonate inclusions were part of the river sand temper added to the clay paste by potters, as Dammer (2023, p. 82) suggests.

3.2.2 | Sand and rocks samples

Besides quartz and feldspar, the sand sample mainly consists of sedimentary rock fragments with few metamorphic rock fragments such as quartz-mica schist (Figure 12). Fragments of calcite, micrite and rounded black opaque inclusions (e.g., haematite) were found among the sand grains. The rock samples include sedimentary and igneous rocks (Table 9) as they have been identified as tempering material in coarse Majiayao-style pottery (Dammer, 2023; Stilborg & Hein, 2021, p. 84).

No metamorphic rocks were identified among the collected samples. Black opaque inclusions, similar to those found in the sand sample, were also identified in sedimentary rocks. As suggested for the sand sample composition, these inclusions could be ore fragments or organic matter. Sedimentary rocks such as sandstones, where the space between the individual mineral inclusions is large, show different types of matrices: calcareous (GSC3-1) or micaceous clay (GSC7-2) (Figure 13).

3.3 | SEM-EDX

Three samples of clays collected from the Tao River Valley were analysed: an aeolian red clay (GSC1), an alluvial clay (GSC21; see above Figure 10a) and a clay used by a contemporary local potter (GSC6) (see Table 2, Figures 5 and 6). They were all fired at 1050°C. The samples

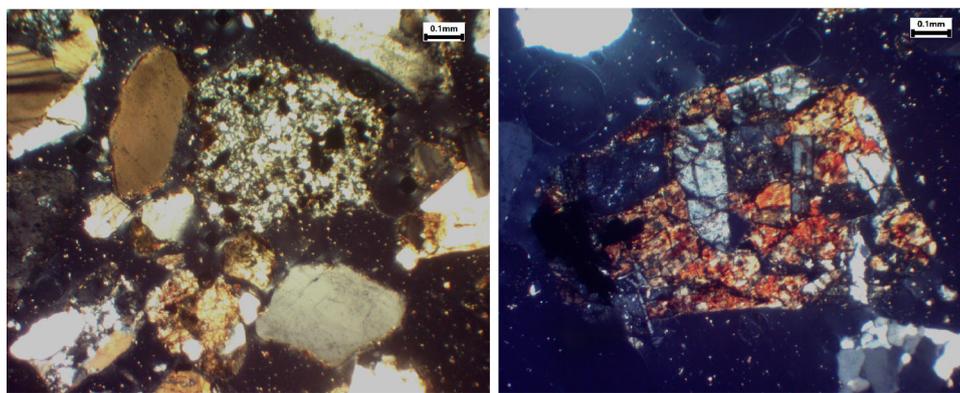


FIGURE 12 Sand sample GSC2 from the Tao River Valley; unfired, photomicrographs taken under cross polarized light, scale size = 0.1 mm. Identifiable grains are quartz, feldspar, sedimentary and carbonate rock fragments as well as black opaque fragments and volcanic(?) rock fragments. (Photomicrographs by E. Dammer). GSC, Geological Sample China.

TABLE 9 Thin-sectioned rocks and their location of collection.

Location	Thin-sectioned rocks
South of the Majiayao site, west tributary of the Tao River	<ul style="list-style-type: none"> • GSC3-1 fine sandstone • GSC3-2 coarse sandstone
North of the Majiayao site, at the foot of a loess hill	<ul style="list-style-type: none"> • GSC7-1 coarse sandstone • GSC7-2 fine sandstone
West of the Majiayao site; hill/mountain top	<ul style="list-style-type: none"> • GSC15-1 carbonate rock
North of the Majiayao site; Tao River riverbed	<ul style="list-style-type: none"> • GSC22-1 conglomerate • GSC22-2 gabbro • GSC22-3 limestone • GSC22-4 andesite • GSC22-5 marine limestone • GSC22-6 coarse sandstone • GSC22-7 carbonate rock • GSC22-8 granodiorite • GSC22-9 fine sandstone

Abbreviation: GSC, Geological Sample China.

fired at this temperature were chosen because they were not damaged by lime spalling when fired above 900°C. The aim of the SEM-EDX analysis was to measure and compare the calcium oxide (lime) content in these samples. The areas of the samples to be analysed were positioned as close as possible to the ideal geometry for analysis, that is, normal to the electron beam, to give the appropriate take-off angle for the X-ray detector (30°) (Spataro et al., 2009, p. 39).

The SEM backscattered image analyses revealed the fine microstructure of samples GSC6 and GSC21 and that the fabric of sample GSC1 contained more inclusions (Figure 14). Although the samples were manually smoothed fractures, the high magnification images allowed the observation of vitrification of the matrices (Figure 15).

The SEM-EDX results of the 21 bulk analyses are consistent within samples (Table 10). The three samples are different from each other, although they have similar magnesia, alumina, silica and iron oxide contents. The alluvial clay (GSC21) is richer in calcium oxide (c. 17% vs. 10%–11%) and poorer in potash (2.5% vs. 3.2%–3.5%) than the other

two samples (Table 9 and Figure 16). The aeolian clay used by the contemporary potter (GSC6) is slightly richer in potash, calcium and iron oxides than the aeolian clay (GSC1) collected at the Majiayao site.

4 | DISCUSSION: CLAY, SAND AND ROCKS: AVAILABILITY OF RAW MATERIALS AND POTTERS' CHOICES

In this study, the suitability for pottery production of geological clays available around the archaeological site of Majiayao was assessed based on their workability, plasticity, reaction to a range of temperatures that can be reached in kiln firing and their behaviour after firing. Furthermore, the composition of various types of raw material was assessed via thin-section petrography and SEM–energy-dispersive X-ray spectroscopy analysis and compared with the composition of Majiayao-period ceramics from Majiayao site to gain further insights into the raw material selection, processing and other aspects of prehistoric ceramic production at the site.

In terms of workability, firing and postfiring behaviour, the clays making up Fired Group 1 (Table 5) seem most suitable for pottery production. These clays are plastic and can easily be worked into coils without tearing. Furthermore, all of them except for GSC5 retained their shape throughout firing at all temperatures. The reason GSC5 exploded in the kiln is still unknown but may relate to its high calcium content. The clays of Fired Group 1 were not affected by post-firing lime formation, but this was more commonly seen with Fired Group 2. SEM-EDX analysis showed that the alluvial GSC21 had a higher CaO content (c. 17%) than the two aeolian samples, but the high calcium oxide content of GSC21 would not necessarily have stopped specialised potters using it to make fine ceramics. In Mesopotamia, fifth millennium B.C. Neolithic painted ceramics were consistently made with depurated and calcium-rich clays (Spataro & Fletcher, 2010, tab. 4). Sample GSC1, which has the lowest calcium oxide content of all samples, produced the hardest briquette even when fired at only 700°C and needed the least labour investment

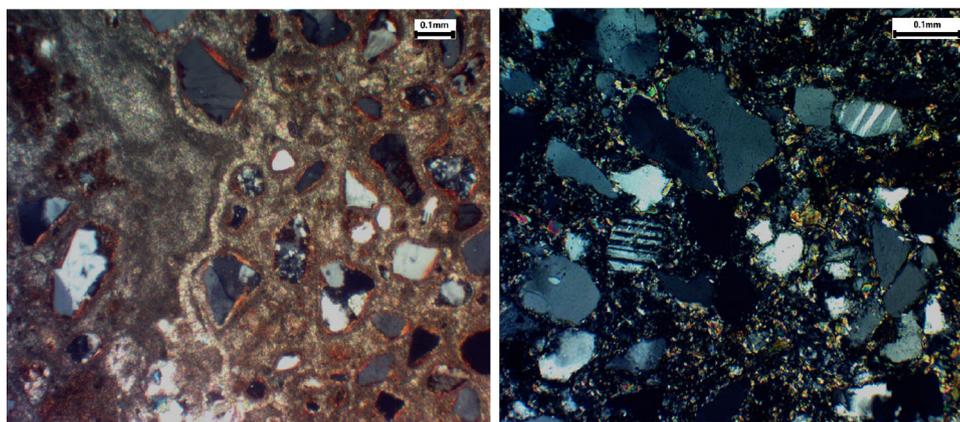


FIGURE 13 Matrices in the sedimentary rock samples, photomicrographs taken under cross-polarized light, scale size = 0.1 mm; left—calcareous matrix, GSC3-1; right—micaceous matrix, GSC7-2. (Photomicrographs by E. Dammer). GSC, Geological Sample China.

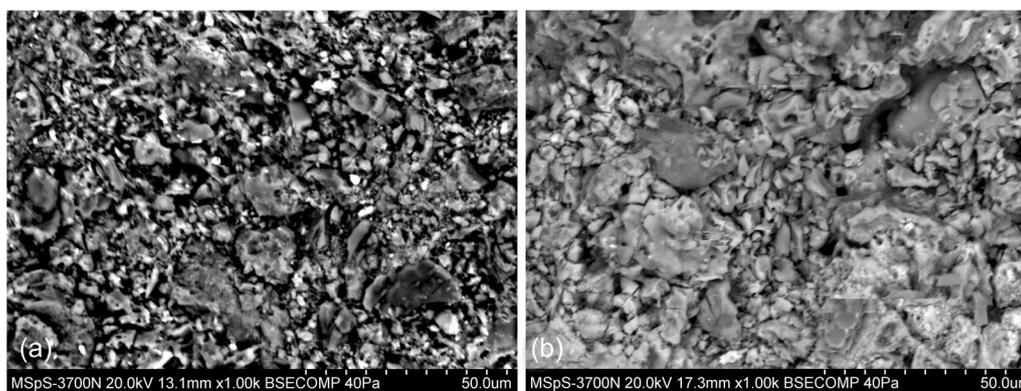


FIGURE 14 SEM backscattered electron images of (left) sample GSC1 (aeolian red clay fired at 1050°C) showing the very fine grains of the sediment and (right) sample GSC21 (alluvial clay fired at 1050°C) at the same magnification, showing the coarser quartz inclusions (darker inclusions) (©Trustees of the British Museum. Shared under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International [CC BY-NC-SA 4.0] licence). (Photographs by M. Spataro).

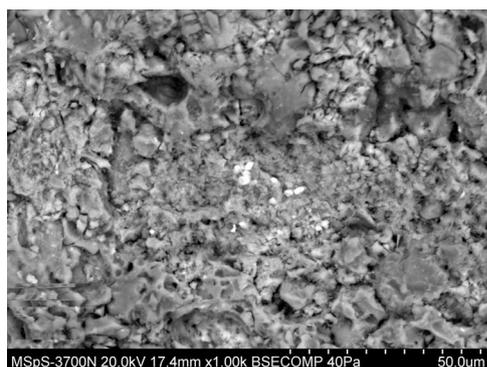


FIGURE 15 SEM backscattered electron image of GSC21 (alluvial clay fired at 1050°C) at high magnification, showing some vitrification of the clay (©Trustees of the British Museum). (Photograph by M. Spataro). Shared under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence.

during processing, due to its considerable malleability and the fact that it dried quickly. Hung (2021, p. 134) suggested that Tertiary red clay was used in the production of Majiayao-style pottery. Tertiary red clay is an aeolian sediment below the silty quaternary loess layers on the hills described above. Hung conducted a comparative study of chemical data collected from Majiayao-style pottery with the chemical data of Tertiary red clay from a geological study by Chen et al. (2001). However, the data provided by Chen et al. (2001) is limited to the Xifeng area in south-eastern Gansu, about 350 km east of Majiayao, so it is problematic to use material collected there as a proxy for sites located in the Tao River Valley. Furthermore, alluvial red clays were not considered in Hung's analysis. The present study has shown that both types of clay can be used for pottery production, as the alluvial sample GSC21 was one of the samples in Fired Group 2 least affected by lime formation.

As for the present study, the clay was not processed beyond removing large organic material and rocks, crushing and hydrating; the

TABLE 10 Compositional data from SEM-EDX analysis of three briquettes from the fired clays (at 1050°C) from the Tao River and their SD.

Sample	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	K ₂ O	CaO	TiO ₂	MnO	FeO
GSC21 bulk analysis	0.8	3.2	15.8	52.2	2.7	17.8	0.8	0.0	6.8
GSC21 bulk analysis	0.8	3.6	15.9	52.9	2.4	16.9	0.7	0.0	6.8
GSC21 bulk analysis	0.8	3.2	15.8	52.2	2.7	17.8	0.8	0.0	6.8
GSC21 bulk analysis	0.6	3.0	14.9	56.3	2.5	15.7	0.9	0.0	6.1
GSC21 bulk analysis	0.8	3.1	14.9	55.4	2.5	15.0	1.6	0.0	6.7
GSC21 bulk analysis	0.8	3.2	15.2	53.9	2.5	17.4	0.7	0.0	6.3
GSC21 bulk analysis	0.7	2.9	14.6	53.9	2.5	18.8	0.7	0.0	6.0
GSC21 mean of 7 bulk analyses	0.8	3.2	15.3	53.8	2.5	17.1	0.9	0.0	6.5
GSC21 SD of 7 analyses	0.1	0.2	0.5	1.6	0.1	1.3	0.3	0.0	0.4
GSC1 bulk analysis	1.9	3.6	16.2	57.0	3.3	10.1	0.9	0.1	6.9
GSC1 bulk analysis	2.0	3.6	16.5	56.7	3.1	10.4	0.8	0.1	6.8
GSC1 bulk analysis	2.0	3.7	16.3	56.7	3.2	10.5	0.8	0.2	6.8
GSC1 bulk analysis	2.0	3.7	16.9	56.3	3.1	10.4	0.8	0.1	6.8
GSC1 bulk analysis	2.1	3.5	16.3	57.5	3.3	9.7	1.0	0.0	6.7
GSC1 bulk analysis	2.0	3.6	16.4	57.1	3.3	10.2	0.8	0.1	6.5
GSC1 bulk analysis	2.0	3.5	16.7	57.5	3.2	9.6	0.8	0.1	6.6
GSC1 mean of 7 bulk analyses	2.0	3.6	16.5	57.0	3.2	10.1	0.8	0.1	6.7
GSC1 SD of 7 analyses	0.1	0.1	0.2	0.5	0.1	0.3	0.1	0.1	0.1
GSC6 bulk analysis	1.4	3.1	16.6	55.1	3.9	11.6	1.0	0.0	7.5
GSC6 bulk analysis	1.2	3.6	17.2	54.4	3.5	11.6	0.9	0.2	7.5
GSC6 bulk analysis	1.3	3.6	16.7	55.8	3.4	11.8	0.8	0.0	6.8
GSC6 bulk analysis	1.3	3.5	16.4	56.7	3.5	11.2	0.8	0.0	6.7
GSC6 bulk analysis	1.2	3.4	16.2	57.7	3.4	10.6	0.9	0.2	6.6
GSC6 bulk analysis	1.2	3.5	16.6	56.3	3.5	11.1	0.8	0.1	7.0
GSC6 bulk analysis	1.2	3.3	16.1	57.4	3.5	11.1	0.8	0.1	6.5
GSC6 mean of 7 bulk analyses	1.2	3.4	16.5	56.2	3.5	11.2	0.8	0.1	6.9
GSC6 SD of 7 bulk analyses	0.1	0.2	0.4	1.2	0.2	0.4	0.1	0.1	0.4

Note: Results are reported as normalised oxides.

Abbreviations: GSC, Geological Sample China; SD, standard deviation; SEM-EDX, scanning electron microscope with energy-dispersive X-ray spectrometer.

successful shaping and firing of samples in Fired Group 1 suggest that these materials were suitable for making pottery without requiring levigation (i.e., removal of coarser fraction using water; see Rice, 2015, p. 121), aging, or mixing with other materials. The samples of the clays used by the local potter analysed in the present study also fall into Fired Group 1, which shows that clays from this group are indeed suitable for pottery production. A levigated clay contains few or scarce mainly fine inclusions, as most coarser inclusions are artificially removed, but the result may look similar to naturally occurring materials (Rice, 2015, p. 121), so it can be difficult to assess via thin-section analysis if the material had been levigated. The fact

that some of our minimally processed geological clay samples resembled archaeological ceramic fine ware samples suggests that these fine pastes could have been obtained without extensive levigation.

The far less workable loess samples, GSC10, GSC11 and GSC12, did not exhibit any similarities with the prehistoric pottery fabrics. The behaviour of these samples during the forming of the experimental briquettes, crumbling after firing and the low amount of clay matrix in the thin section suggest that loess is not suitable for vessel building, at least not without further clay processing. It might have been used as opening material for very sticky clays such as

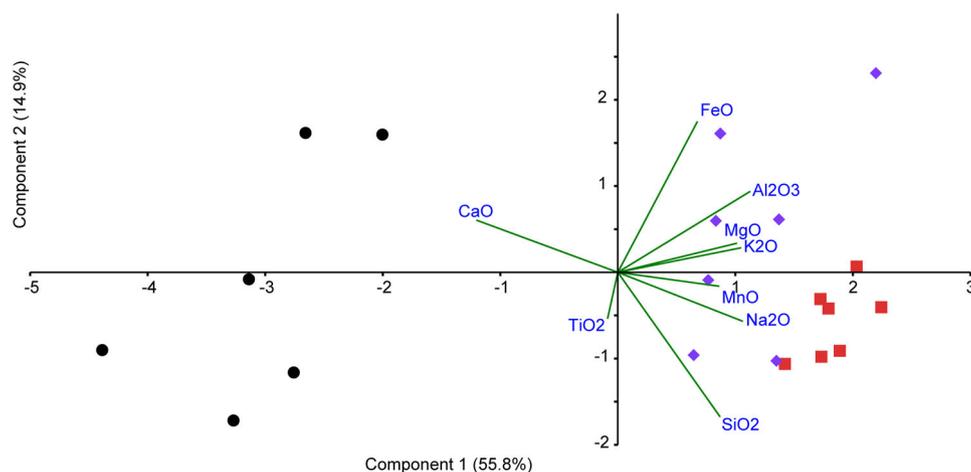


FIGURE 16 Principal component analysis output (components 1 and 2), based on SEM-EDX compositional data of three geological samples from the Tao River Valley, fired as briquettes. Legend: black dot: sample GSC21 (alluvial clay); purple diamond: GSC6 (clay used by contemporary potters); red square: GSC1 (aeolian red clay). Each symbol represents one bulk analysis (c. 1.4×1.0 mm). Principle Component Analysis was carried out using Past v. 3.18 (Hammer et al., 2001). (Figure M. Spataro). GSC, Geological Sample China; SEM-EDX, scanning electron microscope with energy-dispersive X-ray spectrometer.

GSC6. As the inclusions in loess and red clay are very similar in size, it is not possible to infer petrographically whether loess was added to clay or not. There is also the possibility of mixing different types of clays by prehistoric potters to produce Majiayao pottery. The aim of the present study was to examine whether there are natural clays that can be used for pottery production without adding temper or clay mixing.

On the whole, this study has shown that the clays around the site of Majiayao are fine with mostly fine sand-sized mineral inclusions. The petrographic analysis of archaeological pottery from the Majiayao site revealed a clear distinction between fine and coarse fabrics, whereas none of the clay samples had naturally occurring coarse granitic rock fragments or coarse sand fragments of comparable diameter up to 2 mm (Table 5 and Figure 9). The fine pottery fabrics show a homogeneous groundmass and well-sorted silt-sized inclusions of quartz, feldspar and mica. The petrographic composition of the coarse archaeological fabrics is dominated either by angular granitic rock fragments or rounded river sand inclusions up to the fine-gravel size (2–3 mm max length). This difference between the geological and archaeological fabrics supports the conclusions of previous research, that the coarse Majiayao-style pottery was tempered with crushed rocks or river sand (Hein & Stilborg, 2019; Stilborg & Hein, 2021; Womack, 2017). The mineralogical composition of collected rocks and river sand is similar to the types of coarse inclusions present in local prehistoric pottery.

Granite fragments are not as frequent in the sand sample as they are in some pottery fabrics and the shape of these inclusions in pottery is not rounded but has sharp edges indicating that the rock was crushed by external force and then manually added to the clay rather than being a natural part of it. Granite or granodiorite can be found among the rocks in the river area and were likely part of the sediment load transported by the Tao River. Adding materials to the

base clay is an action known as tempering (Hamer, 1991, p. 318; Roux & Courty, 2019, p. 30). The type of temper can vary depending on the materials available to the potter and the intended function, for example, making the clay more plastic or improving the thermal shock resistance of the pot (Roux & Courty, 2019, p. 36). In the analysed Majiayao coarse wares, granite/granodiorite and river sand were consistently chosen as temper. Besides quartz, feldspar is the main mineral component in granitic rocks: coarse feldspar fragments can serve as a flux and lower the melting point of the clay paste (Rice, 2015, p. 108). If feldspar was added as a fluxing agent to the clay, then it would suggest that coarse pottery was exposed to high temperatures, that is, used for cooking. Granite tempering of cooking pots has been identified in coarse pottery in different parts of the world, for example, the Mediterranean region, where experimental studies have shown that granite temper in moderate amounts increases the thermal conductivity of pottery through oblate pore formation aiding the heat flux (Hein et al., 2008, p. 42). It is generally assumed that at least some of the coarse Majiayao wares served as cooking vessels, but this hypothesis has yet to be tested via use-wear and residue analysis.

Besides being easily accessible and widely available, river sand also contains feldspar particles and thus might also have fulfilled a similar function as suggested for granite. Still, the clear differentiation between these two types of temper is noteworthy. Granite additionally contains coarse biotite flakes with a golden shimmer that can be visible to the naked eye. It is possible that granitic fragments were chosen for aesthetic reasons—if the glimmer translated to the pottery—or if it was imbued with a special cultural/ritual/religious meaning that is no longer possible to know.

The fine fabrics have similar petrographic characteristics to the clay samples: well-sorted silt-sized quartz, mica and feldspar. These also match petrographically with the groundmass of the coarse

fabrics, which suggests that the fine and coarse pottery pastes have the same base clays. This differs from what an analysis of the earlier Neolithic Yangshao pottery found at Dadiwan, in Tianshui, Gansu Province, observed, where different raw materials seem to have been used to make the fine and the coarse wares (Ma et al., 2020, p. 11). Similar observations were made at the Majiayao period site of Zongri in Tongde County, Tibet Autonomous Region (Hong et al., 2012). While both sites also held painted pottery and it is generally accepted that Majiayao stylistically developed from Yangshao pottery, it thus seems that approaches to raw material selection for coarse vs fine ware differed between different locations and periods. For the material from Majiayao, additionally, a semicoarse clay type was identified petrographically in GSC17, GSC20 and GSC21, which otherwise looked and behaved like fine clay. Only three pottery samples out of 71 were classified as semicoarse, which suggests that prehistoric potters might not have differentiated between fine and semicoarse clay (Dammer, 2023, p. 84). At the other end of the spectrum of fine materials, there is a type of very fine clay with inclusions less than medium silt in size (<0.02 mm, GSC5 and GSC6), which can be also found in the pottery samples. The existence of semicoarse and very fine raw clays suggests that prehistoric potters might have used these clays in their natural state without refining them. The question here remains for future experimental and chemical studies whether these clays were used to produce Majiayao-style pottery. As suggested above, based on the experimental, petrographic and chemical study, GSC1 would be most suitable for pottery making. GSC1 did not form into lumps when mixed with water and did not require a long time to knead into a malleable state. Other clays that showed high malleability, such as GSC21 or GSC6, required a longer time to settle after being mixed with water due to their high clay content. GSC6 (Figure 11) formed lumps, which appear as clay pellets in the thin section. Womack (2017) interpreted clay pellets in pottery fabrics as a temper; however, pellets probably indicate a clay type similar to GSC6, which needed longer soaking and kneading to produce a homogenous paste and which had a tendency to produce clay pellets.

Comparing the fired clay to the prehistoric pottery, it is obvious that none of the clay samples acquired the yellow colour, which is generally seen as characteristic of painted Majiayao-style pottery. The origin of this colouration is still unclear. There are cases where the yellow is the result of firing, as seen in cross-section, but there also are examples of vessels where the yellow could be the result of surface coating, indicating different technological choices to create similar results (Dammer, 2023, p. 112). Experimental research by Michelaki et al. (2015) has shown that desired pottery colour can be achieved by choosing a particular type of clay and firing it at an exactly known temperature or a temperature range. The colour might not appear if the firing temperature is too low or disappear if the temperature rises too high. Either could have been the case here. This matter will require further research.

Another characteristic of the clay samples analysed in this study that became apparent after firing was their different calcium carbonate contents. Most of the clay samples were damaged to

different degrees by lime forming after firing. This suggests that natural clays in the study area have predominantly high calcium content, with few outcrops of clays having a lower calcium content. Given how much the presence and type of calcium in clay will influence firing behaviour, it can be assumed that the potters were aware of these differences between clays in terms of their suitability for pottery production.

All in all, based on the results of this study, it can be concluded that the prehistoric potters producing Majiayao-style pottery made deliberate technological choices in tempering materials, even if the underlying reasoning for some of their choices, such as the addition of granite and sand temper is not yet entirely clear. They were aware of technological issues in shaping, firing and postfiring alterations, such as lime formation, as well as the resulting body colours (even if the chemical processes involved were not understood in detail), and they chose, processed and fired raw materials accordingly.

In summary, five main insights into prehistoric Majiayao-style pottery production were gained from this exploratory study into the local raw materials:

1. The firing experiments showed that the available workable clays in the study area have a wide range of natural contents of calcium. This is significant because high calcium content leads to lime formation after firing, which in turn can lead to vessel failure. Potters can prevent this by various means, but they have to be aware of the issue and act accordingly. Given the considerable scale of high-quality ceramic production at Majiayao and contemporaneous sites in the region, the results of this study thus suggest that the potters had the awareness and technological skill to address this issue and fire pottery made from high-calcium material successfully.
2. All sampled clays are naturally fine and no particularly coarse clays were observed. The comparison with archaeological materials, some of which had angular coarse inclusions, suggests tempering with coarse granite and river sand, which confirms hypotheses on tempering behaviour from previous research.
3. The colour of the clay samples after firing is different from the fired colour of the archaeological sherds. This difference indicates knowledge of pyrotechnology and the ability to control firing atmosphere and temperature.
4. Different firing temperatures have different effects on the hardness of the different clay samples: some became brittle or even exploded, while others, such as GSC1, were robust and difficult to break, which likely played a role in raw material selection among prehistoric potters. Given that Majiayao-style pottery—at least the painted fine wares—tends to be hard and shiny, it seems likely that potters specifically selected raw materials that would fire this way.
5. GSC5, a sample from a source used by a local potter to make Majiayao-style replicas, with high clay content and high workability, exploded in all three firings when used in its natural state. The potter did not report using any form of processing, but he must have done something, as he regularly fires pottery successfully.

Alternatively, he may not have revealed his actual raw material source to protect his livelihood. In the future, it would be advisable to talk to him further, observe his work if possible, and conduct further experiments with this raw material to see if it can indeed be used to successfully make vessels.

5 | CONCLUSION

While most previous studies on archaeological ceramics from northwest China have tended to use either only chemical (Cui et al., 2015; Hong et al., 2012; Hung, 2021; Hung et al., 2014) or only petrographic analysis (Womack, 2017) to develop models of ceramic production and circulation in Neolithic northwest China (for rare exceptions see Hein & Stilborg, 2019; Hein et al., 2020), the present exploratory study has taken a combined approach of experimental, petrographic and geochemical work to understand raw material availability, selection and processing in prehistoric pottery production. Rather than focusing on the archaeological ceramics and adding at most a few geological samples as previous research has done, the present study has taken the opposite approach of focusing on the locally available raw materials and conducting a systematic geological study around one specific site followed by experimental and analytical work. Analysing geological clay samples in their fired rather than their natural state as previous studies have carried out and comparing them to archaeological ceramics from the same site has allowed this study to test previously held assumptions such as classifying clay pellets as tempering material (they appear only with processing and firing), the general problem of calcite in the raw material (it seems to depend on the overall composition of the clay, as well as the size and shape of its inclusions rather than the general presence/absence of significant amounts of calcite), or the preference for only one type of clay or deposit. Additionally, this study has also been able to provide insights into the nature of the coarse clays used in Majiayao pottery production, namely that large inclusions were likely the result of tempering, rather than naturally present materials. Similar geological studies conducted around other archaeological sites—especially if combined with experimental and comparative petrographic and geochemical analyses—would help greatly in resolving the long-standing debate on patterns and directions of pottery circulation across northern and western China which at present is still largely based on typological arguments and highly contested chemical data. The type of in-depth knowledge of the surroundings of specific sites presented here and the focus on the interplay between local geology and human decision-making can then serve as a basis for comparing pottery production (and raw material availability) at different sites, resulting in a much more comprehensive “fingerprinting” of prehistoric ceramics, not merely based on chemical composition but a combination of geology and technological tradition. This study has identified the following issues needing further in-depth analysis:

1. Based on this study, it seems likely that the properties of local aeolian clay (e.g., sample GSC1) were known to the prehistoric potters, moving them to make specific choices when selecting raw

materials for pottery making. Experimental coarse and fine pottery making using the clays from the Fired Group 1 would be the next step in testing the hypotheses about the raw material choices presented in the present study.

2. It is unclear whether the archaeological fabrics with coarse calcium carbonate inclusions observed among Majiayao ceramics belong to a source not samples in this study or are part of tempering material such as river sand. Experimental making of coarse pottery fabrics with river sand from the study area could help shed light on this issue.
3. Refiring experiments of the archaeological pottery and the experimental clay briquettes would help in the investigation of clay body colours, specifically in exploring how the yellow colour of the fine-painted Majiayao ware was achieved.
4. Clays that were damaged by lime spalling represent the highest number of samples in this study. If these clays were used for pottery making, then the potential prevention of the pottery being damaged after firing needs further investigation.

All in all, using a combination of experimental clay preparation and firing, thin-section optical microscopy and SEM-EDX analysis on geological samples and archaeological ceramics, the present study has been able to answer successfully the research questions asked in the beginning and develop a series of new questions to be answered in future experimental and lab-based analytical work. The study has furthermore served to show that such a combination of analytical methods and the use of both geological and archaeological samples can go a long way towards understanding past pottery production and its embeddedness in the local landscape.

AUTHOR CONTRIBUTIONS

Evgenia Dammer: Conceptualisation; investigation; methodology; formal analysis; writing—original draft; writing—review and editing; visualisation. **Anke Hein:** Conceptualisation; funding acquisition; writing—review and editing; writing—original draft; project administration; supervision; resources; methodology. **Michela Spataro:** Conceptualisation; investigation; funding acquisition; writing—original draft; writing—review and editing; visualisation; methodology; formal analysis; project administration; supervision; resources.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the Supporting Information Material of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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