Letting the stones speak: An interdisciplinary survey of stone collection and construction at Liangzhu City, prehistoric Lower Yangtze River

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Abstract
Our interdisciplinary investigation of the stone collection and construction process of Liangzhu City walls offers important evidence to understand the engineering and organization behind the construction. We examined spatial distributions, physical and petrological characteristics of the stones discovered from our excavations of representative wall sections. These results were compared with similar aspects as well as sedimentation contexts and availability of the surveyed stones from the surrounding regions to identify the source areas for the stone collection. We developed criteria based on physical and petrological characteristics and spatial distribution of stones for the identification of construction units and estimated the volume of stones for each unit. We concluded that even though the overall scale of stonework construction was enormous, the actual tasks of stone collection and construction were likely completed by small individual working groups. Liangzhu workers preferred to collect directly available, hand-portable stones from source areas. However, some areas with suitable stone sources were neglected by Liangzhu workers. The total workforce may have followed a central organization, and many groups likely worked simultaneously. Through the repeated efforts of numerous small working groups, Liangzhu society constructed a massive, multicomponent infrastructure. Our study holds implications for wider archaeological research of ancient stone architecture.

Keywords
city walls, Liangzhu, Lower Yangtze River, Neolithic, petrology, stone collection

1 | INTRODUCTION

As enduring parts of archaeological landscapes, ancient stonework constructions and monuments worldwide have attracted considerable attention for studying how they were built, what they symbolized, and how they functioned in ancient societies. Although ancient architectural technologies and functions varied cross-regionally, they often shared the qualities of sophisticated planning, engineering, and logistics of large-scale construction. Among the many archaeological studies, prominent examples include the
Natifian stone houses in the Levant (Boyd, 2006; Finlayson et al., 2011; Richter, 2017), the Neolithic Stonehenge in the UK (Parker Pearson, 2012), the classical-period palaces and monuments in Mediterranean (Broodbank, 2013), and more. Previously, pre-dynastic China had been regarded as lacking stone architecture, but new discoveries of stone walls and buildings have radically changed these views. Among these discoveries in China, some of the most impressive examples include a Bronze Age fortified site of Sanzuoandian in Northeast China (Shelach, Raphael, & Jaffe, 2011), the late Neolithic stone-walled site of Shimao in the Northern Loess Plateau (Guo & Sun, 2018; Jaang, Sun, Shao, & Li, 2018; Sun, 2016; Zhejiang Provincial Institute of Cultural Relics and Archaeology, 2005), and the earthen walls built atop stone bases at Liangzhu City of the Lower Yangtze River (Renfrew & Liu, 2018).

Research programs at ancient stonework sites have attempted to unpack their roles in the diverse trajectories of social complexity, addressing critical issues concerning how ancient people acquired and transported the stones, how they designed and constructed the monumental architecture, and how their complicated labor projects could have been organized (Boyd, 2006; Parker Pearson, 2012; Richter, 2017; Shelach et al., 2011). At the widely known site at Stonehenge, the research focus has shifted from the stone circle itself, instead now considering the larger surrounding landscape for a holistic understanding of the construction process (Parker Pearson et al., 2015). With this conceptual expansion, the individual stone components of Stonehenge have been situated in their original provenances and interpreted as instruments in "feeding" the monument (Craig et al., 2015; Darvill, Marshall, Parker Pearson, & Wainwright, 2012). The bluestones and sarsen stones have been analysed in terms of their petrological properties, measurements of the stone tonnage, and other variables that in concert have depicted the ancient transportation routes and techniques of bringing these components to the site (Harris, 2017; Parker Pearson et al., 2015). While it may never be known about the exact actions during ancient times, the studies at Stonehenge and elsewhere have been instructive for establishing new research programs about ancient stonework sites such as in our current example at Liangzhu (5300–4300 B.P.).

To understand these similar issues, our interdisciplinary study examined the geophysical compositions and engineering design of ancient stone wall bases and other features of Liangzhu City, regarded as one of China’s most spectacular ancient cities. Liangzhu culture is characterized by its advanced jade industry, and its highly stratified society demonstrated by the rich jade-bearing elite tombs and a developed regional network on the distribution of elaborate jade items (Qin, 2013; Renfrew & Liu, 2018). While the control of jade resources and jade production at Liangzhu City is widely considered a unique trajectory to social stratification at Liangzhu and thus has received intensive scholarly attention, the acquisition patterns of stones and other construction and economic resources at the city are much less well understood. The labor organization and its implications to social complexity in Liangzhu society remain unclear.

Our research, conducted by field archaeologists, geologists, and petrologists, combined three lines of evidence to reconstruct the raw materials acquisition and mobilization into extensive stone wall bases at Liangzhu City. We obtained evidence of spatial distributions, physical characteristics, and petrological properties of construction stones through our excavation of selective stone wall sections and on-site observation. These multiple lines of information helped us identify construction units. We then surveyed possible source areas where the construction stones might have come from, focused on the physical and petrological characteristics as well as sedimentation contexts and availability of stones in these areas. Comparing this information with the examination of construction stones enabled us to determine stone collection procedure and provenance the construction stones. Here we present detailed information regarding how this study was conducted. We then discuss how the results helped us to comprehend the labor organization and construction process underpinning the construction of the enormous earthen and stone works at Liangzhu City.

### 1.1 Building Liangzhu City and its walls

Liangzhu City is situated in the so-called C-shaped basin to the south of the Taihu Lake region of the Lower Yangtze River (Figure 1a). It is surrounded by the Tianmu Mountain ranges to its north, west and south. The modern East Tiao River runs across the northwest and north corners of Liangzhu City (Figure 1b). Liangzhu society predominantly relied on rice agriculture, as attested by the discovery of thick carbonized rice deposits of several dozen 1,000 m² inside the city and a well-preserved paddy field (c. 80 hectares) at Maoshan (Zhuang, Ding, & French, 2014). The surviving architectural components at Liangzhu City include a palace compound built on a large artificial platform, several elite cemeteries on artificial platforms or altars, enormous storage facilities filled with abundant carbonized rice remains, piers, and numerous other features. The ancient piers were connected to an extensive water management system inside and surrounding the city, including at least 51 artificial and natural canals and ditches (Liu et al., 2017; Liu, Qin, & Zhuang, 2020; Figure 1b). Additionally, an enormous hydraulic enterprise was constructed just outside the city, where high and low dams formed large-sized reservoirs, along with extensive levees (Liu et al., 2017).

The massive constructions at Liangzhu City have prompted questions about the extent and organization of their underlying labor and resources (Liu et al., 2017). The entire enclosed area of the city measured around 290 ha. The central Mojiaoshan palatial compound occupied 30 ha and required about 2.28 million m³ of moved earth. On an even larger scale, around 2.88 million m³ of earth would have been dug and transported to build the Tangshan levees, low dams and high dams of the hydraulic enterprise (Liu et al., 2017).

These impressive constructions of Liangzhu City reflect two architectural technologies. First, people dug clay from swampy lands, and they wrapped the clay into bundles with grasses (Chen, 2019).
FIGURE 1  Geographic location (a) and distribution of key archaeological features at and surrounding the Liangzhu City (b). Black shades are distributions of the hydraulic system and the numerical numbers are locations of the high and low dams and levees outside the Liangzhu City [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 2  Flowchart demonstrating roles of different project members and how their results worked in concert toward accomplishing the research objectives of this project [Color figure can be viewed at wileyonlinelibrary.com]
These “sandbags” were stacked to raise the ground and to fill the cores of walls and mounds (Figure S1) which were then dressed or stacked by multiple layers of yellow silty clay. Second, people built stone bases as the supporting foundations for the stacked earthen layers. This technology can be seen in the construction of the city walls and the Tangshan levees (Figure S2).

The positions and layouts of Liangzhu’s city walls have been confirmed as two “circles” of inner and outer portions, as seen through aerial imagery and ground-truthing surveys (Figures 1b and 2e). The contiguous inner-circle walls formed an overall rounded-cornered square in plan-view, measuring around 1.8–1.9 km south-north by 1.5–1.7 km east-west. Extending outward to the east and south,
the outer-circle walls formed an irregular shape in plan-view, with maximum dimensions of 3 km × 1.7 km.

Excavation trenches have exposed the construction techniques of the city walls. Stone bases were observed in all cases, and those base constructions can be extrapolated as a total 29 ha of stonework for making the city walls. The single-layered stone bases, 40–60 m in width, were emplaced in a grayish clay (c.20 cm in thickness) that formed a mucky ground, at least during wet seasons, and therefore, a stone base solved the immediate concerns for creating usable foundations. Furthermore, stone material allowed water to drain downward through the stonework interstices and into the natural water table, whereas simple mounded earth would have slumped and subsided in this environment.

2 | METHODS AND MATERIALS

We considered spatial distributions, physical and petrological characteristics of the construction stones during our excavation and on-site observation. Similar features as well as sedimentation contexts and availability of stones were observed during the field geological survey. These different research activities were designed and conducted together by all the project members. Different lines of evidence were collected, shared, and discussed between different specialists, leading to our successful identification of construction units and stone provenance. The roles of project members are illustrated in the flowchart (Figure 2) and explained in detail below.

We excavated a total of more than 700 m² in representative portions of the eastern, western (two excavation trenches in the western wall), northern and southern walls of the inner circle (Figure 3 and Table 1). Excavation at the western wall was particularly informative, revealing about 500 m² of the stone bases. The excavation revealed how the stone bases were paved, whether the stones faced the same or different directions, and whether they can be divided into different piles or units. This information, combined with the measurement of the stone physical and petrological characteristics, provided key evidence for the identification of construction units. The measurement of physical and petrological characteristics of the construction stones was based on our extensive on-site examination of almost all of the 10,526 pieces of stones. The physical characteristics include size, shape, and roundness. Regarding the size, as we were not able to move or turn over the stones, we only measured the long and short axes and calculated the ratio of the long and short axes of the exposed surface of the stones. Square, elongated, or other shapes of the stones were documented. Stone roundedness was recorded in categories of subangular, subrounded, and rounded shapes that could be coordinated with the original depositional processes of the stones before they were collected. Stones of rounded shape are transported for a long distance, while angular shapes suggest stones are either broken in situ due to natural weathering and/or mined directly from bedrock. Stones of subangular or subrounded shapes indicate that they experienced a moderate degree of abrasion from short-distance transportation. In addition, for very few stones that showed damaged edges, we applied the technique of continuous shooting of high-magnification photographs to closely examine these sharp edges.

The petrological characteristics of the construction stones were recorded in situ during excavations, including color, texture, weathering, mineral assemblage, and structure. These attributes allowed the stones to be assigned in several objective groups. Those groups feedback to the information obtained regarding the spatial distribution and physical characteristics of the stones, corresponding with spatially distinctive patterns of construction units that were completed by different work groups during different events or tasks.

Our geological survey expanded on an initial analysis of geological maps and satellite images and results of previous field observations. Geologically, the Tianmu Mountain ranges are dominated by Cretaceous granites, intrusive rocks, volcanic rocks, middle Jurassic terrestrial sedimentary rocks, and early Paleozoic marine sedimentary rocks (Table S1). The field-walking routes prioritized locations with bedrock outcrops or other stone source exposures (Figure S3). We focused on three immediate areas surrounding Liangzhu City: (a) the Liangzhu–Guqiu plain, (b) the North Tiao River plain and the nearby mountains, and (c) the Mid-South Tiao River plain and the nearby mountains (Figure 4), approximate 200 km² in total. During the survey, we first observed the sedimentation context, distribution, and physical features (size, sorting, and roundness) as well as assemblage (whether stones in each landform unit tend to belong to limited or highly mixed rock types) of stones in the surveyed areas. We then identified and recorded characteristics of texture, structure, weathering, and other objective attributes of stone samples we found on the surface or embedded in the sediments in these areas. The physical and petrological characteristics of surveyed stones were then compared with those of construction stones. The comparison provided key evidence for stone provenance. Furthermore, the assessment of the stone availability helped us to determine stone collection preference and procedure. To further corroborate evidence on stone raw material provenances, we selected ten stone samples from both the construction areas and surveyed regions for detailed geochemical analysis. For more detailed definition of stone geochemistry, ten representative pieces were selected from the excavation and field survey, and the analysis produced corroborating evidence for stone provenances. From the excavations, construction stones were selected from the underside portions to maximize integrity and minimize possible contamination. The analytical procedures, conducted at the State Key Laboratory for Mineral Deposits Research of Nanjing University, are described in the supplementary information, concentrating on analysis of

| Location       | Excavated area (m²) | Number of stones |
|----------------|---------------------|-----------------|
| Eastern wall   | 32.8                | 407             |
| Southern wall  | 120.5               | 1,618           |
| Northern wall  | 25.6                | 742             |
| Western wall-1 | 495                 | 6,257           |
| Western wall-2 | 40                  | 1,502           |
| Total          | 713.9               | 10,526          |
their oxide components and rare elements. While the sample size was admittedly small, the geochemical results were cross-checked and compared with results of the observations of physical and petrological characteristics of the construction and surveyed stones, consistently corresponding strongly with our provenance.

3 | RESULTS

3.1 | Characterizing the construction stones

Our on-site observation shows that individual stone pieces were predominantly square or nearly square, while elongated pieces were selected only rarely. The ratios between the length (long axis) and width (short axis) mostly were between 1 and 1.8, but a few outliers reached values of 2 or more (Figure 5b). The ratio of the length (long axis) and width (short axis) indicates whether the stone is of square or spheroid shape (when the ratio is close to 1) or elongate shape (when the ratio is larger than 1). As shown in Table 2, the majority of stones measured between 10 and 35 cm in length and weighed around 5 kg, while only small percentages were either larger than 40 cm or smaller than 10 cm (Figure 5a). Differential groupings of stone dimensions can be discerned for the separate walls and construction segments. The sizes of the stones generally were smaller (10–15 cm) in the east wall, while they were longer (mostly 15–20 cm but occasionally 50+ cm) in the south, north and west walls (Figure S4).

According to our recording of their roundedness (Table 3), most of the construction stones had subangular and subrounded shapes, subjected to little or moderate abrasion in their sedimentary processes, before their acquisition for construction material in the Liangzhu walls. Very few long-distance transported stones were
FIGURE 5 Dimension of the construction stones. (a) long axis or diameters of the measured construction stones, x-axis: actual length, y-axis: percentage; (b) ratios between the long axis and width. E, eastern wall; N, northern wall; S, southern wall; W-1, western wall-1; W-2, western wall-2 [Color figure can be viewed at wileyonlinelibrary.com]
identified, and they could be described as rounded pebbles (Figure 6).

Our observations furthermore revealed that the majority of the stones were not altered by mining tools that otherwise would have created angular edges. Except for a few rare larger chunks of stones that were broken into smaller suitable pieces, nearly all of the construction stones had been used in their raw forms from surface collection. The very few broken pieces showed signs of damaged edges, possibly attributable to breakage during collection or transport. Of 20 samples that appeared to have been edge-damaged, detailed examination with the technique of continuous shooting of high-magnification photographs under microscope confirmed that 16 of those 20 pieces indeed were chipped and smashed. It also should be noted that some stones experienced severe postconstruction weathering, which caused sharply broken edges. Such edges, however, can be easily differentiated from the edges created by chipping or smashing during stone collection just described.

In our petrological examination, the construction stones belonged to a diversity of sedimentary, metamorphic, and igneous rock types in 11 distinctive categories (Table S2). Among these 11 categories, trachyandesite ignimbrite was used most frequently, both in terms of quantity and distributional areas (frequency), to build the excavated stone bases at the western, eastern, and southern walls (Figure 7a–c). Other types of stones were used in less frequency, and their distributions were more concentrated in smaller areas. For instance, the stone bases at the western wall-2 were built exclusively by andesite (Figure 7e).

TABLE 2

| Long axis (cm) | Eastern wall (n and %) | Southern wall | Northern Wall | Western wall-1 | Western wall-2 | Subtotal |
|---------------|------------------------|---------------|---------------|---------------|---------------|----------|
| ≤5            | 1 (0.06)               | –             | 2 (0.03)      | 2 (0.13)      | 5 (0.05)      |
| 5–10          | 65 (4.02)              | 27 (3.64)     | 233 (3.72)    | 200 (3.13)    | 530 (5.04)    |
| 10–20         | 437 (27.01)            | 216 (29.11)   | 1,844 (29.43) | 366 (4.37)    | 2,986 (28.37) |
| 20–25         | 313 (19.34)            | 147 (19.81)   | 1,401 (22.40) | 175 (11.65)   | 2,110 (20.05) |
| 25–30         | 205 (12.67)            | 87 (11.73)    | 730 (11.65)   | 73 (4.86)     | 1,135 (10.78) |
| 30–35         | 98 (6.09)              | 60 (8.09)     | 427 (6.82)    | 28 (1.86)     | 621 (5.90)    |
| 35–40         | 45 (2.78)              | 19 (2.56)     | 172 (2.75)    | 7 (0.47)      | 251 (2.38)    |
| 40–45         | 42 (2.60)              | 14 (1.89)     | 73 (1.17)     | –             | 132 (1.25)    |
| 45–50         | 23 (1.42)              | 11 (1.48)     | 23 (0.37)     | –             | 58 (0.55)     |
| 50–55         | 1 (0.13)               | 16 (0.26)     | –             | 24 (0.23)     |
| 55–60         | 3 (0.40)               | 1 (0.02)      | –             | 8 (0.08)      |
| 60–65         | 1 (0.06)               | 2 (0.03)      | –             | 3 (0.03)      |
| 65–70         | 1 (0.13)               | 1 (0.02)      | –             | 2 (0.02)      |
| 70–75         | 1 (0.06)               | 1 (0.02)      | –             | 2 (0.02)      |
| 75–80         | 1 (0.06)               | –             | –             | 1 (0.01)      |
| Total         | 407                    | 1,618         | 742           | 6,257         | 1,502         | 10,526   |

TABLE 3

| Roundness      | Eastern wall (n and %) | Southern wall | Northern wall | Western wall-1 | Western wall-2 | Subtotal |
|----------------|------------------------|---------------|---------------|---------------|---------------|----------|
| Angular        | 8 (1.97)               | 18 (1.11)     | 51 (6.87)     | 25 (0.40)     | 13 (0.87)     | 115 (1.09) |
| Subangular     | 251 (61.67)            | 1,139 (70.40)| 446 (60.11)   | 3,975 (63.53) | 1,310 (87.22) | 7,124 (67.68)|
| Subrounded     | 135 (33.20)            | 315 (19.47)   | 177 (23.85)   | 1,636 (26.15) | 176 (11.72)   | 2,439 (23.17)|
| Rounded        | 13 (3.19)              | 146 (9.02)    | 68 (9.16)     | 621 (9.92)    | 3 (0.20)      | 851 (8.08)  |
| Total          | 407                    | 1,618         | 742           | 6,257         | 1,502         | 10,526    |
3.2 | Identification of construction units

In most of the excavated trenches, the stones were more or less evenly and horizontally aligned (Figure 3c,d). The underlying and overlying earthen layers were either stacked over or interlocked with the stone bases (Figure 3). The outer slopes of the walls were made in gradients of 20–27°, comparable with the angles of the modern levees along the Tiao River. Some distribution patterns can be observed (e.g., Figure 3c,d and see below). Stones of similar geological properties tended to be concentrated in specific construction areas with similar alignments. These areas were separated by clear boundaries according to their different rock types and stone alignments. In the southern-wall excavation trench, the exposed stone bases were identified as belonging to 10 construction units (Figure 8). Most of the identifiable construction units were 1.5–3 m in width. Only two of the construction units were significantly larger than the others, measuring 5 m (unit 9) and 9 m (unit 10) in width, respectively. Each unit tended to use a limited range of stone raw materials, but there were exceptions. Stones in unit 2 (1.5 m in width) were divided into two piles. While most stones belonged to rhyolitic vitric tuff (blue colors in Figure 8), there were a few rounded-shaped quartz-sandstones, trachyandesitic crystal ignimbrite, and silicified rock scattered in the small pile in the west. More than 50% of the stones in unit 6 (2 m in width) were quartz-sandstones, with many rhyolitic vitric tuff and silicified stones mixed in them. Unit 9 is 5 m wide, but only covered by some silicified stones.

Another kind of distinctive construction event was exposed in the northern-wall trench, where monzonite porphyry was used to build the core body of the stone bases, then finished with other stone types randomly positioned in the corners (Figure 3b). Other positioning patterns of rock types can be seen in other excavated areas. Most cases appeared to be the work of single labor groups or events, thereby suggesting that the individual construction events can be traced back to the stone collection processes and construction organization during the construction of the walls.

3.3 | Sourcing the stones

The geological field surveys of Areas A, B, and C contain wide-range geomorphologic units (Table 4). Area A, where Liangzhu City is located, consists of low-lying alluvial plains and isolated hills of less than 200 m above the sea level. Heavily weathered rocky outcrops can be seen on the surface of these hills, while the foothills are covered by yellowish clay, over which many Liangzhu period sites were situated. Area B includes the upper catchment of the North Tiao River and the mountains along the headwater of the river.
**FIGURE 7** The distributional frequency (pie charts) of different stone types at different excavated trenches. (a) eastern wall; (b) western wall-1; (c) southern wall; (d) northern wall; and (e) western wall-2 [Color figure can be viewed at wileyonlinelibrary.com]

**FIGURE 8** Division of construction units with the different types of construction stones at the southern-wall excavation trench. (a) Elevation view of some construction units shown on the left-hand side (southern part) of (b); (b) ten construction units with stone types highlighted in different colors. Numerical numbers are different construction units. Note the green excavation partition column (near the steps) in the middle of (b), which blocked the elevation view taken for the southern part; the boundaries shown in (a) and (b) are slightly different, this was caused by the visual difference between different views. Also note that unit 6 can be divided into two subunits and see discussion in the text [Color figure can be viewed at wileyonlinelibrary.com]
Its geology was more complicated than in Areas A and C, and accordingly it was divided into geological subareas. The loose bedrock is eroded and redeposited on the foothills and valleys of Area B1, which was closest to Liangzhu City and likely attractive for stone collection. Area B2 received abundant colluvium including gravels from upstream, redeposited along wide river channels that would have been convenient for the Liangzhu workers to transport the collected stones via water. The other subareas (B3, B4, and B5) offered little potential for stone construction supplies due to their low availability of stones and inconvenient hilly terrain for transportation. Area C is the farthest from Liangzhu City and likely unattractive for stone collection. The information of sedimentation, distribution, physical features, and assemblage documented during our survey provides key evidence to compare with the same variables of the construction stones. As introduced in Section 3.1, most construction stones are square or nearly square, subangular or subrounded, and c.10–35 cm in length. Based on this information and the fact that stones of the same petrological features tend to appear in the same construction units (Table 4), the roundness of most stones falls into the categories of subangular to subrounded, while their sorting varies between different landform units (Table 4).

The information of sedimentation, distribution, physical features, and assemblage documented during our survey provides key evidence to compare with the same variables of the construction stones. As introduced in Section 3.1, most construction stones are square or nearly square, subangular or subrounded, and c.10–35 cm in length. Based on this information and the fact that stones of the same petrological features tend to appear in the same construction units (Section 3.2), mountainous valleys and low mountains in the surveyed areas A and B must have been the most likely source areas supplying stones to the five excavated construction sites. The characteristics of stones from these two landform units (Table 4) are similar to those of most construction stones revealed in our excavation. In terms of lithological origins, these stones belong to eight of the 22 lithological groups (Table 5).
FIGURE 9  Observations of different stone types and petrological characters during the geological surveys. Note that Qz are absent in the ZS group and the Fel displays different colors in the YB group, while most Fel in the TMS group are of light reddish color. Bit, biotite; Fel, feldspar; Kf, potassium feldspar porphyritic crystals; KM, Kangmen lithological group; Qz, quartz porphyritic crystals; TMS, Tianmushan lithological group; YB, Yaobei lithological group; ZS, Zhaoshan lithological group [Color figure can be viewed at wileyonlinelibrary.com]
Further details were ascertained through thin-section and geochemical compositional analyses. Thin-section analysis showed nearly identical microscopic petrological properties between the construction stones and some of the surveyed stones (Figures 11, S7, and S8).

The geochemical analyses concentrated on the main oxide compositions and trace elements of the rhyolitic vitric tuff, rhyolitic crystal ignimbrite, trachyandesite crystal ignimbrite, monzonite porphyry, and quartz andesite in both the construction stones and

![Image](https://wileyonlinelibrary.com)

**FIGURE 10** Distributions and depositions of rocks at different surveyed areas. (a) Subrounded pebbles, of mixed rock types, on the floodplain at the Shuangxi village; (b) angular or subangular pebbles on the channel bed of small creeks in the mountainous area; (c) weathered rocks well embedded in yellowish sediments on the southern slope of the Dazhe Mountain; and (d) angular or subangular pebbles on hill slopes. [Color figure can be viewed at wileyonlinelibrary.com]

| Lithological group | Location | Main rock types |
|--------------------|----------|----------------|
| Yaobei (YB)        | Foothills of the Dazhe Mountains, north Pingyao town | Trachyandesite crystal ignimbrite |
| Shishanxia (SSX)   | Shishanxia village, southeast to the Liangzhu City | Rhyolitic vitric tuff |
| Yanshan (YS)       | Yanshan village | Rhyolitic vitric tuff |
| Liangbo (LB)       | Daxiong Mountains, near the Liangzhu Museum | Rhyolitic vitric tuff |
| Yushanjian (YSJ)   | Daxiong Mountains and Upper South Tiao River | Rhyolitic vitric tuff |
| Zhaoshan (ZS)      | Zhaoshan village, near east Kangmen Reservoir | Monzonite porphyry |
| Zhishan (ZS)       | Zhishao Mountain and the Qianshan Mountain | Andesite |
| Near Kangmen (KM)  | Near Kangmen (KM) group, Luojiashan and the Fengshan (FS) group | Quartz-fluorite vein and silicified/ altered rocks |
FIGURE 11  Microphotographs of thin sections of the construction and surveyed rocks. (a) construction stone (no. E283 from eastern wall), rhyolitic vitric tuff, PPL, scale bar 1 mm; (b) surveyed stone from the Yanshan (YS) lithological group (no. 001-1), rhyolitic vitric tuff PPL, scale bar 1 mm; (c) construction stone (no. N591 from northern wall), andesite, PPL, scale bar 1 mm; (d) construction stone (no. N591 from northern wall), andesite, XPL, scale bar 400 μm; (e) surveyed stone from the Zhishan mass, andesite, PPL, scale bar 1 mm; (f) surveyed stone from the Zhishan mass, andesite, XPL, scale bar 400 μm; (g) construction stone (no. N209 from northern wall), monzonite porphyry, XPL, scale bar 1 mm; (h) surveyed stone from the Zhaoshan (ZS) lithological group, monzonite porphyry, XPL, scale bar 1 mm. PPL, plane polarized light [Color figure can be viewed at wileyonlinelibrary.com]
surveyed stones, affirming close matches (see Tables 6 and 7). The SiO$_2$ compositions of the rhyolitic vitric tuff as a kind of acid, silicon-rich pyroclasts, showed a match of close to 80% for samples from the eastern walls and the Yanshan group. Moreover, they both showed high Na$_2$O and K$_2$O (>6%), medium aluminum (Al$_2$O$_3$ = 11%), and low CaO (<0.04%) and MgO (<0.05%). For the monzonite porphyry from the northern wall and from the Zhaoshao group, their SiO$_2$ components deviated slightly (65.07% and 63.83%, respectively), while their TiO$_2$, TFe$_2$O$_3$, Na$_2$O, and K$_2$O all were very close, indicating their similar petrological origins.

The trace elements also showed similar matches between the stones in wall construction and the geological survey areas. Particularly significant were the nearly identical curves showing the ratios between the trace elements of the measured samples and those of chondrites between the construction and surveyed stones, as shown in Figure S5. More detailed results are summarized in Tables 6 and 7.

4 | DISCUSSION

4.1 | Stone collection and selection preferences

The Liangzhu workers must have surveyed their surrounding environment intensively and developed ongoing knowledge of the stone qualities in different source areas. The loosely distributed surface-accessible stones would have been convenient and effective for use as construction material, and accordingly they matched with the dimensions, petrology, and geochemical compositions of the stones found during our excavations. As mentioned above, most of the construction stones were measured at 10–35 cm length and weighed around 5 kg. Smaller stones of less than 10 cm in length were in fact abundant in the natural source areas, but they were not commonly found in the excavated walls. It can be surmised that Liangzhu workers had preferences for selecting readily available, hand portable size stones that did not require extra steps of chiselling or other processing with specialized tools. As already mentioned, the mountainous valleys and low hills provided abundant such stones and indeed our study confirmed that most of the construction stones came from such landforms in the Zhaoshan (ZS) group, the Zhishan and Fengshan groups of the surveyed areas A and B, with various distances to the city (Figure 4). We identified a number of natural stone sources that could have been convenient for the Liangzhu builders, yet they were not used in the excavated stone bases. One such instance was on the 30-m wide riverbed at Shuangxi village at the western surveyed area, where poorly sorted gravels were abundant, including rounded to subrounded pieces mostly 10–20 cm in length that were consistent with the overall preferred wall construction material (Table 4 and Figure 10a). Another anomaly was the Pingyao lithological group (PY), easily available in outcrops close to Liangzhu City, yet these outcrops were not at all used in the excavated wall construction. A similar situation applied to the Fengshan group (FS) and the Dongshan (DS) group. At the Kangmen (KM) group, one part of this source was merely 20–30 m distance from the intensively utilized Zhaoshan (ZS) group, yet it was non-selected (Table S1).

The neglect of certain stone sources may have been due to cultural considerations, choices that we cannot identify based purely on our geoscience approach. For instance, stones from the Qianligang group (QLG) were excluded from usage in the walls, yet they provided the raw material for the stone tool production at Liangzhu sites.

Admittedly, our excavated areas account for a small segment of the entire wall bases and conceivably, continued excavations in more parts of the Liangzhu walls may yet reveal additional construction episodes with stones from existing or new lithological groups that otherwise have not yet been documented. Our suggestion for the stone collection activity just described, mainly based on the physical, availability, and accessibility of stones, cannot rule out entirely the possibility that stones from the lithological groups such as pingyao were actually used in the construction of the walls. However, our current evidence permits the tentative conclusion that the Liangzhu builders preferred to collect stones directly from the source areas rather than engaging in large-scale, formal mining and processing. Only a very few the thousands of construction stones had been broken, with or without the use of tools. In principle, the stones were selected according to size, shape, surface access, and availability. These considerations would maximize the time of individual laborers in the most time-consuming tasks of collection and other tasks such as transportation.

4.2 | Labor organization of stone collection and construction

The Liangzhu workers were armed with few tools but most importantly with an awareness of what kinds of stones they needed and where to collect them. With this knowledge, a small team did not need to devote much time to collect the stones. We conducted a preliminary assessment of possible transportation routes and transportation tools (e.g., bamboo rafts that have been found at Liangzhu sites, Figure S6) for the Liangzhu workers to transport the collected stones to the construction sites. However, as these results are preliminary and need to be supplemented by more evidence, we will report them separately.

After a unit of stones arrived at the designated construction area, we suggest that the collected stones were unloaded directly to build the stone bases. Each construction unit of stones would be enough to build around 4–5.2 m$^2$ of the stone bases, as seen in the excavations. These parameters furthermore accord with the petrological examination of the stones of individual construction areas, matched with their geological sources (e.g., Figure 8). Each workforce team could be composed of few individual laborers. Given the diverse lithological groups that supplied the construction stones (Table 5), probably many small teams worked simultaneously, collecting stones from diverse source areas and transporting them to the construction areas. The next stages of wall base construction may
| Sample no. | Rock type                | Sampling location                      | E-283  | 001-1  | W-376  | 001-7  | W-3119 | 095-1  | N-209  | 247-2  | N-591  | 079-1  |
|------------|--------------------------|----------------------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|            | Rhyolitic vitric tuff    | Eastern wall                           | 80.14  | 79.33  | 75.66  | 76.12  | 64.22  | 64.89  | 65.07  | 63.83  | 64.81  | 64.52  |
|            |                          | Yanshan lithological group             | 0.12   | 0.10   | 0.17   | 0.18   | 0.58   | 0.49   | 0.51   | 0.52   | 0.50   | 0.51   |
|            | Rhyolitic crystal ignimbrite | Western wall-1                       | 10.98  | 11.21  | 13.30  | 13.62  | 16.74  | 15.88  | 16.12  | 15.38  | 17.62  | 17.80  |
|            |                          | Shishanxia lithological group          | 0.31   | 0.11   | 1.48   | 1.08   | 4.45   | 3.36   | 4.65   | 4.37   | 3.80   | 3.88   |
|            | Trachyandisite crystal ignimbrite | Western wall-1               | 0.25   | 0.09   | 1.32   | 0.95   | 2.67   | 1.73   | 2.61   | 2.22   | 3.72   | 3.70   |
|            |                          | Yaobei lithological group             | 0.05   | 0.02   | 0.14   | 0.12   | 1.60   | 1.47   | 1.84   | 1.94   | 0.07   | 0.16   |
|            | Monzonite porphyry       | Northern wall                       | 0.00   | 0.00   | 0.04   | 0.01   | 0.09   | 0.08   | 0.07   | 0.09   | 0.11   | 0.06   |
|            |                          | Zhaoshan lithological group           | 0.05   | 0.05   | 0.24   | 0.15   | 1.19   | 0.90   | 0.87   | 1.12   | 0.80   | 0.48   |
|            | Quartz andesite          | Northern wall                       | 0.04   | 0.02   | 0.11   | 0.06   | 1.76   | 2.13   | 0.75   | 2.92   | 3.40   | 3.28   |
|            |                          | Zhishao lithological group            | 0.70   | 0.96   | 1.37   | 1.43   | 3.50   | 3.36   | 3.76   | 3.15   | 4.71   | 4.51   |
|            |                          | Northern wall                       | 5.43   | 6.81   | 6.15   | 5.87   | 5.19   | 5.66   | 5.47   | 5.20   | 3.20   | 3.34   |
|            |                          | Northern wall                       | 0.06   | 0.03   | 0.04   | 0.04   | 0.20   | 0.16   | 0.16   | 0.14   | 0.26   | 0.28   |
|            |                          | Northern wall                       | 2.42   | 1.88   | 2.21   | 2.41   | 1.60   | 2.88   | 1.88   | 3.04   | 0.56   | 0.94   |
| Total      |                          |                                      | 100.12 | 100.36 | 100.74 | 100.95 | 99.36  | 99.63  | 99.12  | 99.55  | 99.75  | 99.58  |

*TiFe₂O₃ refers to total Fe oxides, recalculated based on the contents of Fe₂O₃.*

**TABLE 6** Main oxide components of the construction and surveyed stones (wt%)
| Sampling no. | Rb (× 10^-6) | Sr (× 10^-6) | Zr (× 10^-6) | Nb (× 10^-6) | Ba (× 10^-6) | Th (× 10^-6) | Ta (× 10^-6) | Hf (× 10^-6) | La (× 10^-6) | Ce (× 10^-6) | Pr (× 10^-6) | Nd (× 10^-6) | Sm (× 10^-6) | Eu (× 10^-6) | Gd (× 10^-6) | Tb (× 10^-6) | Dy (× 10^-6) | Ho (× 10^-6) | Er (× 10^-6) | Tm (× 10^-6) | Yb (× 10^-6) | Lu (× 10^-6) | ΣREE (× 10^-6) | LREE (× 10^-6) | HREE (× 10^-6) | L/H | δEu |
|--------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| E-283        | 186         | 268         | 268         | 143         | 143         | 2.29        | 7.9         | 158         | 170         | 5.59        | 1006        | 1.53        | 9.67        | 2.15        | 6.45        | 0.94        | 1.00        | 369.3       | 331         | 38         | 8.7         | 0.05        |
| 001-1 Rhyolitic vitric tuff | 268         | 255         | 195         | 141         | 9.32        | 1.43        | 6.2         | 185         | 22.7        | 0.887       | 9.81        | 1.50        | 8.28        | 1.61        | 4.50        | 0.65        | 0.65        | 219.6       | 943         | 219         | 12.5        | 0.07        |
| 001-7 Rhyolitic crystal ignimbrite | 255         | 266         | 137         | 8.88        | 1.47        | 2.43        | 3.7         | 117         | 12.7        | 0.995       | 8.29        | 1.30        | 7.94        | 1.71        | 5.04        | 0.72        | 0.69        | 219.6       | 943         | 219         | 12.5        | 0.07        |
| W-376 Trachyandesitic crystal ignimbrite | 195         | 324         | 12.98       | 1.02        | 1.12        | 0.82        | 1.37        | 117         | 9.35        | 1.78        | 6.47        | 3.75        | 103         | 1.09        | 3.15        | 0.43        | 0.42        | 219.6       | 943         | 219         | 12.5        | 0.07        |
| W-3119 Monzonite | 141         | 317.27      | 1.500       | 11.96       | 1.22        | 1.09        | 0.88        | 117         | 3.6         | 0.88        | 5.46        | 9.60        | 1.30        | 1.03        | 4.56        | 0.72        | 0.69        | 219.6       | 943         | 219         | 12.5        | 0.07        |
| 095-1 Monzonite Porphry | 144         | 419.47      | 1.546       | 11.96       | 1.22        | 1.09        | 0.88        | 117         | 3.6         | 0.88        | 5.46        | 9.60        | 1.30        | 1.03        | 4.56        | 0.72        | 0.69        | 219.6       | 943         | 219         | 12.5        | 0.07        |
| N-209 Northern wall | 344         | 355         | 1.546       | 11.96       | 1.22        | 1.09        | 0.88        | 117         | 3.6         | 0.88        | 5.46        | 9.60        | 1.30        | 1.03        | 4.56        | 0.72        | 0.69        | 219.6       | 943         | 219         | 12.5        | 0.07        |
| 247-2 Northern wall | 192         | 192         | 1.546       | 11.96       | 1.22        | 1.09        | 0.88        | 117         | 3.6         | 0.88        | 5.46        | 9.60        | 1.30        | 1.03        | 4.56        | 0.72        | 0.69        | 219.6       | 943         | 219         | 12.5        | 0.07        |
| N-591 Northern wall | 212         | 825         | 1.546       | 11.96       | 1.22        | 1.09        | 0.88        | 117         | 3.6         | 0.88        | 5.46        | 9.60        | 1.30        | 1.03        | 4.56        | 0.72        | 0.69        | 219.6       | 943         | 219         | 12.5        | 0.07        |
| 079-1 Northern wall | 838         | 825         | 1.546       | 11.96       | 1.22        | 1.09        | 0.88        | 117         | 3.6         | 0.88        | 5.46        | 9.60        | 1.30        | 1.03        | 4.56        | 0.72        | 0.69        | 219.6       | 943         | 219         | 12.5        | 0.07        |

**Notes:**
- LREE: Light Rare Earth Elements, HREE: Heavy Rare Earth Elements, δEu = (Eu/Eu*) - 1.
- Rhyolitic vitric tuff, Rhyolitic crystal ignimbrite, Trachyandesitic crystal ignimbrite, Monzonite, Quartz andesite.
have involved more or different laborers to assist with unloading, sorting, and positioning the stones. Additional considerations may be applicable for other labor tasks, such as making and operating the bamboo rafts.

The estimated working time and investment in each component of a construction episode was manageable by small teams. The raw material stones were surface-accessible, hand-portable, and suitable for loading and unloading in shoulder-mounted supports and/or in bamboo rafts. The evident construction units in the walls revealed the products of these small working groups, applied repeatedly for the complete wall construction.

Our interdisciplinary research altogether provided a picture of the multiple steps in a massive construction undertaking. Our findings showed that people selected the construction stones from particular natural sources but not from others, in diverse and scattered zones. The episodes of stone collection and transportation could be completed by small teams with flexible arrangements to maximize efficiency. Transportation was the component that required specialized advance planning and coordination to ensure that transportation tools could be available and repaired when needed and other factors. Next, the stones were delivered to designated locations, definitely with preplanning and possibly complicated if multiple construction localities were operating simultaneously. For the final stage of arranging stones into base layers, this task actually was simple in itself, but it involved numerous repeated instances that must have been coordinated toward the overall goal (Figure 12).

A central organization must have been responsible for coordinating the multiple working groups, producing consistent construction results throughout the wall-building. The organizing efforts would have been necessary for assigning the specific tasks to individuals, creating a workforce schedule, ensuring that everyone followed the plans. Realistically, the project needed to cope with interruptions of severe weather events, floods, and other concerns compounded over time. These aspects about ancient Liangzhu society now can be explored more seriously, for example, following the detailed evidence here about the actual wall construction.

5 | CONCLUSIONS

The enormous scale of construction at Liangzhu City has prompted an assertion that the planning and logistics behind the construction was so sophisticated that it was critical to the rise of kingship and the emergence of early states (Liu et al., 2017; Liu et al., 2020; Renfrew & Liu, 2018). Our interdisciplinary project contributes new data for this study theme, particularly in terms of the organization and process of the stone collection and construction of the stone bases of the Liangzhu City walls.

For large-scale construction projects at Liangzhu and elsewhere, the full scope of labor activities and contexts cannot be known in their entirety, but the surviving stones hold significant value for revealing the physical outcomes and how those results were possible. The stone components have been well preserved, thus supporting our detailed examinations of their material characteristics, matching with geological sources, and implications of cultural use and labor based on their physical and petrological properties. The interdisciplinary studies described here supported a successful feedback system for a more holistic insight into the stone collection and construction procedures, and their roles in larger contexts of the Liangzhu cultural and natural landscape.

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