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RESEARCH ARTICLE

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A 7000-year record of environmental change: Evolution of Holocene environment and human activities in the Hangjiahu Plain, the lower Yangtze, China

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Abstract

The Hangjiahu Plain in the lower Yangtze is one of the core areas that sustained the flourishment of the Liangzhu Civilization. This study reconstructed Holocene environmental change on the Hangjiahu Plain based on a sediment core collected from the Tangqi ZK-3 location situated on the low-lying Hangzhou-Taihu region of the Yangtze Delta. We applied OSL dating, grain size analysis, pollen analysis, and magnetic susceptibility to reconstruct Holocene environmental change and compared our data with other published results. Our results showed that (i) before ~7.0 ka B.P., the ZK-3 core recorded a strong hydrodynamic force, resulting in the widespread deposition of light grayish silt clay or clayey silt in the region. The climate was warm and humid, and the vegetation was mixed evergreen deciduous coniferous forest. (ii) Between 7.0 and 6.0 ka B.P., the hydrodynamic condition in ZK-3 core became weaker, and the climate remained warm and humid. Although most of the Hangjiahu Plain were still covered by the light grayish silt clay or clayey silt, some higher grounds began to emerge as sea-level rise slowed, which coincided with the development of the Majiabang culture. (iii) Between 6.0 and 4.5 ka B.P., the deposition of yellowish silty clay indicates a shallow-water hydrological environment at ZK-3, as the regional water level was dropping while more land was emerging, which provided a favorable physical environment for the prosperity of the Songze and Liangzhu cultures. The period experienced a drier and cooler climate, with evidence of deforestation. (iv) Between 4.5 and 3.0 ka B.P., the sediments in the ZK-3 core were dominated by light grayish clay, indicative of a return to a deep-water environment with a prolonged waterlogging condition. The climate remained dry and cool with further deforestation. However, the widely distributed yellowish silt clay suggests frequent floods in the region, resulting in a sharp reduction of settlement sites and the eventual decline of the Liangzhu Civilization.

KEYWORDS
geoarchaeology, geomorphic evolution, Holocene, human activities, lower Yangtze River

1 | INTRODUCTION

The Liangzhu Civilization (5300–4300 B.P.) is now being considered one of the earliest urban centers in prehistoric East Asia. It enjoyed an unprecedented level of agricultural intensification and craft development, which sustained the construction and operation of its enormous urban center and hydraulic system (Liu et al., 2014; Z. H. Zhang, 2004). As one of the core distribution areas of the Liangzhu culture, the southern Taihu Lake plain, or to be more specifically, the Hangjiahu ("Hang" refers to "Hangzhou City," "Jia" refers to "Jiaxing City," and "Hu" refers to "Huzhou City") Plain in the lower reaches of the Yangtze River is highly susceptible to Holocene climate and environmental vagaries caused by changes in East Asian monsoon intensity (An, 2000; Sun & Chen, 1991; Wenxiang & Tungsheng, 2004) and sea level fluctuations (Z. Y. Chen & Stanley, 1998; Song et al., 2013; Xie & Yun, 2012; Zhao et al., 1979; Zong, 2004). Recently, there has been a growing interest in the scientific quest for the environmental factors that might be linked to the rise and fall of the Liangzhu Civilization. Previous research has demonstrated the close interaction between cultural evolution and environmental change in the lower Yangtze. Some scholars have started to elaborate how humans responded to Holocene relative sea-level change and environment fluctuations (Bird et al., 2010; Innes et al., 2014; Z. Wang et al., 2012, 2013; Wu, 1988; Zhuang & Du, 2021). Several studies have found that human activities increased when the relative sea level was stable or dropping (He et al., 2018; Shi et al., 2011; Z. Wang et al., 2013), while such activities became weaker when the relative sea level was rising in the Yangtze Delta region (Z. Chen et al., 2008; Shi et al., 2011; Stanley & Chen, 1996; Wu et al., 2014; Q. Zhang, Jiang, et al., 2004; Q. Zhang, Liu, et al., 2004; Zong et al., 2011a). Since rice farming played a predominant role in the subsistence economies of societies in the lower reaches of the Yangtze River, it has been suggested that changes in the hydrological environment would affect productivity of rice farming and thus have a profound impact on cultural development and succession in the region (He et al., 2018; Innes et al., 2014; Jin et al., 2018; Patalano et al., 2015; Zheng et al., 2011; Zong et al., 2007, 2011b). Although the causes of the rise and fall of the Liangzhu culture are still under heated scholarly debate (Shi, 1993; Shi et al., 2011; Yu et al., 2000; Z. K. Zhang et al., 1998, 2005; Zhu et al., 1996), there is a growing consensus that hydrology and geomorphology are some of the key factors that were directly related to the developmental discourse of the culture (He et al., 2021; Ling et al., 2021; Shi et al., 2011; Stanley et al., 1999; Wu et al., 2014; Q. Zhang, Liu, et al., 2004) and thus merit more research attention.

As the heartland of the Liangzhu Civilization, the Hangjiahu Plain underwent dramatic geomorphological and hydrological changes during the middle to late Holocene. However, the temporal and spatial variations of the geomorphological and hydrological conditions in the region and how the environmental change affected human activities remain significantly understudied. Based on OSL dating, grain size analysis, pollen analysis, and magnetic susceptibility of the Tangqi ZK-3 sediment core and a comparison of our first-hand data with other published results, this paper aims at (i) reconstructing Holocene climate and vegetation changes; (ii) reconstructing hydrological conditions and sedimentation processes; and (iii) investigating the relationship between the cultural development and environmental vagaries in the Hangjiahu Plain.

2 | REGIONAL SETTING

2.1 | Environmental and geomorphological settings

The Hangjiahu Plain in the northern part of Zhejiang Province is located on the southern edge of the Yangtze River Delta, south of Taihu Lake, and north of the Qiantang River in the Hangzhou Bay, with an area of about 6400 km^2 and abundant water resources (Figure 1).

The regional terrain is generally low and flat, between 2 and 4 m (above the sea level, same below), with a dense network of rivers and lakes on the alluvial plain. The lowest region in the plain is the northeast, 2–3 m. The Qiantang River and Hangzhou Bay in the southwest are on higher positions, 3.5–5.5 m. The landform types mainly include low hills, mounds, and plains. As the outliers of the Tianmu Mountains, the low hills (100–200 m) are distributed in the eastern part of the Hangjiahu Plain. Mounds with an elevation of 10–100 m are scattered in the southwestern part of the plain. Low-lying plains, less than 10 m, are, however, the predominant landform of the region (Figure 1).

The dense water network in the region includes a complex canal system, the East Tiaoxi River and the West Tiaoxi River, and other natural and artificial waterbodies. The canal system generally flows from southwest to northeast. The East Tiaoxi River originates from the southern piedmont of the Tianmu Mountain and flows east from Lin'an County to merge with the South Tiaoxi River, the North Tiaoxi River,

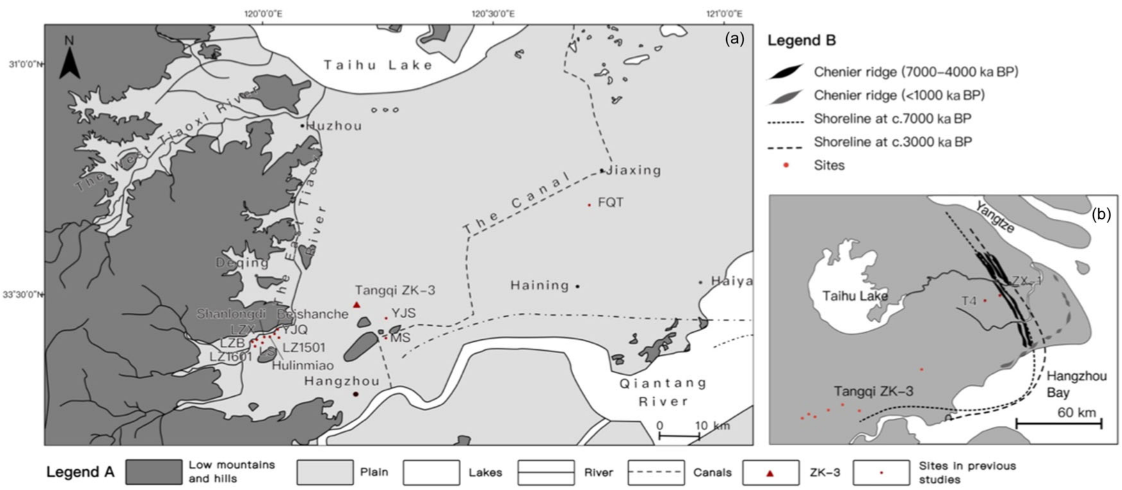

FIGURE 1 Location of the Tangqi ZK-3 core. (a) Tangqi ZK-3 core and sites in previous studies. (b) Geographic location of the study area. LZB, LZX, Shanlongdi, Hulinmiao, Beishanche, and YJQ are profiles studied by Shi et al. (2011); MS and LS are profiles studied by Jin et al. (2018); LZ1501 and LZ1601 by Ling et al. (2021); T4 and ZX-1 by Zong et al. (2011b).

and the Middle Tiaoxi River before flowing east to join the East Tiaoxi River at Pingyao, which then enters Taihu Lake via Deqing and Wuxing to the north. The West Tiaoxi River joins the waters in the northern part of the Tianmu Mountain and meets the East Tiaoxi River via Xiaofeng, Anji, and Huzhou (Xu, 2012; C. M. Yan et al., 1959).

The Hangjiahu Plain traditionally belonged to the so-called Jiangnan (South of the Yangtze River) region, which has experienced several marine transgression and regression since the Pleistocene. The sediments in the region are dominated by alluvium, mainly of silty clay, clayey silt, and silt, from the Yangtze River, Qiantang River, and lacustrine deposits. Below the Holocene strata are the Pleistocene hard and dense yellowish brown and brownish yellow clay layers rich in ferromanganese nodule and grayish iron-depletion white bands. There is an evident sedimentation gap between the two layers at the interface between Pleistocene and Holocene (X. L. Chen, 1991; Q. S. Yan & Huang, 1987).

The Holocene climate change in the lower Yangtze River region has been well studied, synchronous with major global climate events. The mid-Holocene climate was humid and wet as consistently shown by pollen and geochemical studies (Atahan et al., 2008; Yi et al., 2003; Yu et al., 2000). These records also show evidence of possible drier-and-cooler climate events at 5.5 and 4.0 ka B.P., respectively (Y. Li et al., 2010; Yu et al., 2000).

The environment of the Hangjiahu Plain is profoundly influenced by sea-level changes. Despite the persisting scholarly disagreement on Holocene sea-level fluctuations, especially on if there was a mid-Holocene sea-level highstand in current studies (Bird et al., 2007, 2010; Z. Y. Chen et al., 1997; Y. Wang, 1989; Zhu et al., 2003), it is generally agreed that the early-Holocene sea level rose rapidly after the last glacial period, and the rate of sea-level rise slowed down until about 7.5–7.0 ka B.P., with the sea level close to the present level (Figure 2) (Z. Y. Chen & Stanley, 1998; Lambeck et al., 2014; Song et al., 2013; Xie & Yun, 2012; J. Zhang et al., 1982; Zhao et al., 1979; Zong, 2004). This marked a large-scale transition from the marine to terrestrial sedimentation environment. After 7.0 ka B.P., the sea level continued to fluctuate, but with a smaller magnitude. There is no a universally agreed sea-level fluctuation curve for the late Holocene, but according to some studies, the sea level dropped around 6–4.5 ka B.P. (He et al., 2018; Z. Wang et al., 2012, 2013) before rising again around 4.5 ka B.P. (Stanley et al., 1999; Wang et al., 2018; Xie & Yun, 2012; H. R. Yang & Xie, 1984; Zheng et al., 2011). The establishment of coastal barrier ridges (Z. Y. Chen & Stanley, 1998; Q. S. Yan & Huang, 1987) and a rapid sedimentation rate (Q. S. Yan & Huang, 1987) suggest that during the late Holocene, the region was affected by rising groundwater as a result of sea level rise (Zong et al., 2011b) (Figure 2).

2.2 | Archaeological background

The earliest Neolithic culture in the Hangjiahu Plain is the Majiabang Culture (7.0–6.0 ka B.P.), after which the Songze Culture (6.0–5.3 ka B.P.), Liangzhu Culture (5.3–4.3 ka B.P.), and Qianshanyang-Guangfulin Culture (4.3–4.0 ka B.P.) developed, before being succeeded by the Maqiao Culture (3.9–3.2 ka B.P.).

The Majiabang culture (7.0–6.0 ka B.P.) was mainly distributed in the area around Taihu Lake, but its influential zone reached as far south as the Hangzhou Bay, as far north as the Jianghuai region, and as far west as the Ningzhen region. Rice farming was already an important economic strategy, with the cultivated rice remains being found at sites such as Caoxieshan, Songze, and Luojiajiao (Z. H. Zhang, 2004).

The distribution of the Songze culture (6.0–5.3 ka B.P.) sites overlaps with that of the Majiabang culture, but the influence of the Songze culture expanded considerably, reaching the Jianghuai region in the north, the Hangzhou Bay in the south, and Anhui Province in the northwest. While rice farming continued to dominate subsistence economy, hunting and gathering remained important supplements to food production (Z. H. Zhang, 2004).

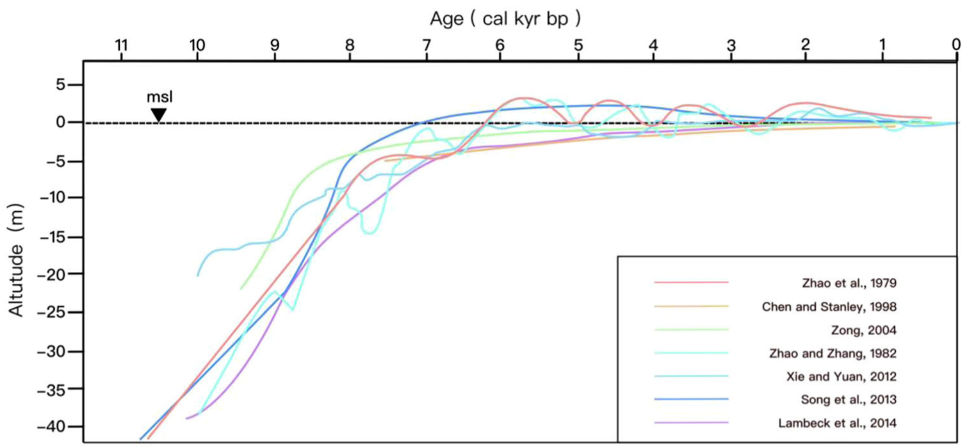

FIGURE 2 Reconstructed sea-level curves in the East China Sea in the Holocene [Color figure can be viewed at wileyonlinelibrary.com]

The Liangzhu culture (5.3–4.3 ka B.P.) spreads around the Taihu Lake with the Hangjiahu Plain emerging as one of the main regions of the distribution of Liangzhu culture sites. The influence of the Liangzhu culture reached an even wider area, as far as Jiangsu and Shandong in the north, the Ningzhen area, Anhui Province and Hubei Province in the west, and north of Jiangxi Province and Guangdong Province in the south. Agriculture, livestock breeding, pottery industry, manufacturing of stone and jade tools, and textile production were all developed to a high degree in the Liangzhu culture. Rice farming became overwhelmingly predominant in the subsistence economy as rice remains have been found at many sites (Zheng et al., 2014). The rice grains were very close to the present-day japonica rice with stable morphological characteristics (Zheng et al., 2014). The late Liangzhu period rice paddies were found at the Maoshan site in Yuhang, with irrigation canals, river channels, roads, water outlets, and an east-west ditch separating the paddies from the settlement (Zhuang et al., 2014). These findings suggest that rice production was significantly intensified at this time. Stone plows were also commonly found at Liangzhu culture sites. Although their exact functions remains to be further investigated, their popularity points to the establishment of a more efficient farming method across the Liangzhu region. During the Liangzhu period, the Liangzhu Ancient City was the largest walled town found in contemporary China, covering an area of about 300 ha. The large earthen walls are 20–145 m wide and about 4 m high, surrounded by moats about 100 m wide. Eight water gates and waterways were the main means of transportation inside and the surrounding the city. The center of the city was the palace site of Mojiaoshan (ca. 30 ha in size), while in the northwestern corner was the elite cemetery site of Fanshan. The outer part of the city is an area (about 8 km^2) with a dense distribution of Liangzhu culture sites, outside of which was an enormous hydraulic system (Liu et al., 2014).

There were few remains excavated from the early Qianshanyang culture. The characteristics of these remains still showed a continuation of the late Liangzhu culture, but some distinctive features of the Qianshanyang culture had already appeared. However, while the late Qianshanyang culture pottery was rich in variety and significantly influenced by cultures from other regions, the main features remain the same (Guo, 2018).

The Guangfulin culture (4.2–4.0 ka B.P.) was distributed in the area around Taihu Lake. Archaeological studies show that the Guangfulin culture was distinctively different from the Liangzhu culture and was instead strongly influenced by cultures outside the Taihu Lake region. This phenomenon is described by some scholars a “cultural replacement” (J. Chen, 2006; Song et al., 2008).

Contrary to this, the Maqiao culture (3.9–3.2 ka B.P., contemporary with the Xia-Shang period in the Central Plains) displayed both the Liangzhu culture elements and influences from the Yellow River basin cultures far in the north (Gao, 2005; Song, 1999; Song et al., 2002). The Maqiao culture sites are mainly distributed in the area surrounding Taihu Lake and in the northeastern of Zhejiang Province, south of the Hangzhou Bay.

3 | MATERIALS AND METHODS

3.1 | Materials

To obtain continuous Holocene sedimentary sequences in the west central Hangjiahu Plain for the reconstruction of regional environment, we conducted a drilling survey in Tangqi Town where thick Holocene deposits are preserved. A long sediment core of about 10 m was collected from a lowland location between two rivers, being labeled as the Tangqi ZK-3 borehole (N30°28′28″, E120°12′13″) (Figure 1).

According to the sedimentary characteristics of the Tangqi ZK-3 borehole, there are 13 strata in the borehole (Figure 3).

3.2 | Methods

In total, 10 samples were collected from different layers of the ZK-3 borehole for OSL dating. The OSL dating was measured in the OSL

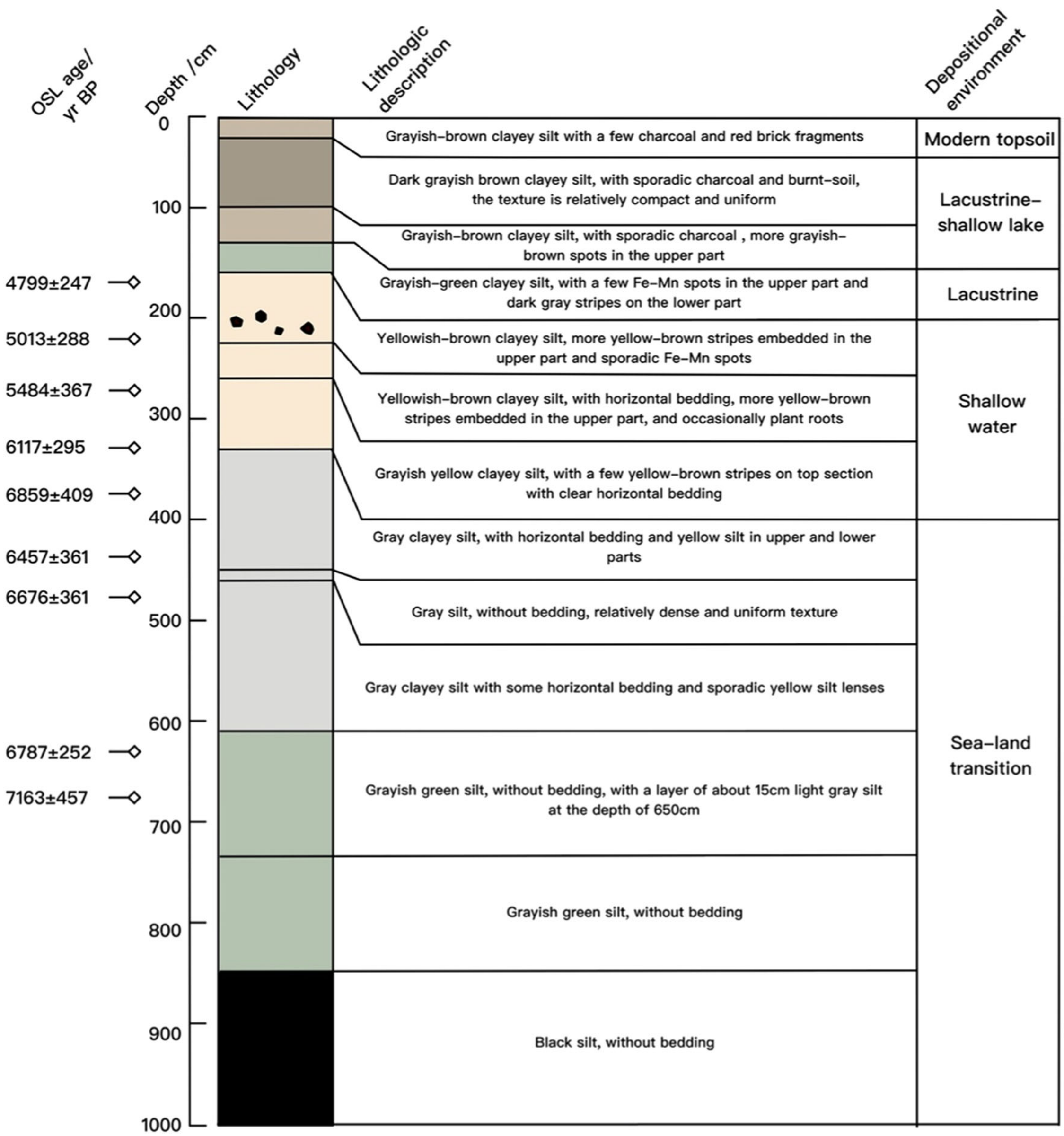

FIGURE 3 Litho-sedimentary description of the Tangqi ZK-3 borehole [Color figure can be viewed at wileyonlinelibrary.com]

Laboratory of Environmental Archaeology, Institute of Geography, Henan Provincial Academy of Sciences. Quartz particles (4–11 um) were obtained from all the samples following the conventional pretreatment method (Murray & Olley, 2002). The equivalent dose (De) was measured by the single-aliquot regenerative-dose method (SAR) (Murray & Olley, 2002). The contents of U, Th, and K were measured by the neutron activation method (NAA) in the Analysis and Testing Research Center of Beijing Institute of Nuclear Industry and Geology. The water content was with a standard deviation of 5%. The age-depth model for the cores was created using the Bacon age-depth model.

Grain size composition and distribution can directly reflect sedimentation environments. The particle size analysis was performed at the Laboratory of Surface Process Analysis and Simulation, College of Urban and Environmental Sciences, Peking University. The instrument used to measure grain size was a Mastersizer-2000 laser particle size meter manufactured by Malver, UK, with a resolution of 0.15φ and a measurement range of 0.02–2000 μm and a relative error of <3%. Particle size analysis was calculated by the Folk and Ward formula (Shepard, 1954).

Sixty-five samples were processed for pollen identification at the Laboratory of Environmental Evolution and Ecological Construction, Hebei Normal University. Pollen was extracted by adopting the conventional method using HCl–NaOH–HF treatment (Faegri et al., 1989). Pollen was counted under a Carl Zeiss AX10 optical biological microscope at 400 times magnification. The number of pollen counted for each sample reached more than 300. For a few samples with lower pollen content, at least 150 pollen grains were counted. The species were identified based on Vos and de Wolf (1993) and Zong and Sawai (2015).

The magnetic susceptibility indexes chosen for the analysis include low-frequency magnetic susceptibility (χ_{lf}), high-frequency magnetic susceptibility (χ_{hf}), and frequency-dependent magnetic susceptibility ($\chi_{fd\%}$). Low-frequency magnetic susceptibility (χ_{lf}) and high-frequency magnetic susceptibility (χ_{hf}) were determined by subtracting the average of the pre and post background values from the magnetic susceptibility measured by the Laboratory for Earth Surface Processes of Peking University. To reduce the effect of measurement errors, each sample was tested six times for high-frequency magnetic susceptibility and low-frequency magnetic susceptibility, and the average value was taken as the final measurement value. The value of the frequency-dependent magnetic susceptibility ($\chi_{fd\%}$) is calculated as follows:

$$\chi_{fd\%} = \frac{(\chi_{lf} - \chi_{hf})}{\chi_{lf}} \times 100\%.$$

4 | RESULTS

4.1 | OSL dating

Ten OSL dates from the ZK-3 borehole profile are shown in Table 1. The age-depth model for the cores corrected by the Bacon age-depth model is shown in Figure 4.

Combined with the description of the litho-sedimentary sequence and the OSL dates, the 13 sublayers represent four stages of sedimentation environment during the Holocene: (i) 1000–300 cm, between 8.0 and 5.7 ka B.P., light grayish clayey silt or silt, suggestive of an sedimentation environment in the marine–terrestrial transitional zone; (ii) 330–155 cm, about 5.7–4.7 ka B.P., yellowish brown clayey silt with horizontal sediment beddings indicating a shallow water condition on a floodplain environment; (iii) 155–125 cm, about 4.7–3.0 ka B.P., grayish clayey silt with a few ferromanganese nodules in the upper part and dark grayish stripes in the lower part, representative of typical lacustrine sediments; and (iv) 125–0 cm, about 3.0 ka B.P. to the present, grayish brown clayey silt indicative of a lacustrine shallow-lake environment and modern topsoil on the top 20 cm.

4.2 | Grain size analysis

The particle size results of the 66 sediment samples provide further evidence of the sedimentation process and hydrological environment during these four stages (Figure 5).

Stage I (1000–330 cm, about 8.0–5.7 ka B.P.): clayey silt layer or silt layer, the median grain size is between 23.10 and 62.10 µm, fluctuating greatly below 800 cm depth, with the content of coarse silt and sand decreasing upward. The sorting coefficient is 1.45φ < So < 2.17φ, which is the best in the whole core, and the skewness index is −0.44φ < Sk < −0.01φ, with an extremely negative skewness to near symmetry. This stage corresponds to a process of continuous hydrodynamic weakening in the sedimentation environment.

Stage II (330–155 cm, about 5.7–4.7 ka B.P.): clayey silt with a median grain size of 15.00–26.20 µm. This is significantly reduced compared to the previous stage. In particular, the percentage of sand decreases sharply, while that of clay increases. The average particle size (Mz) also shows a decreasing size trend. The sorting coefficient (2.08φ < So < 2.44φ) becomes poor. The skewness index (−0.39φ < Sk < −0.25φ) shows a very negative deviation, which is slightly closer to 0 than the previous stage. Overall, these results suggest significantly weakened hydrological conditions.

Stage III (155–125 cm, about 4.7–3.0 ka B.P.): clayey silty sand, the median grain size is 15.4–22.10 µm with the increasing content of clay and fine silt and decreasing content of sand. The sorting coefficient (2.27φ < So < 2.46φ) becomes poorer, while the skewness index (−0.39φ < Sk < −0.25φ) shows an extremely negative deviation. The hydrodynamic of the sedimentation environment becomes more weakened.

Stage IV (125–0 cm, about 3.0 ka B.P.): grayish-brown clayey silt with median grain size of 11.10–28.30 µm, a sorting coefficient of

TABLE 1 Results of OSL dating of the Tangqi ZK-3 borehole

Sample number	Depth (cm)	U (ppm)	Th (ppm)	K (%)	Equralent dose (Gy)	Annual effective dose (Gy/ka)	OSL age (a)
ZK3-2-2	170–180	1.816	9.062	1.873	18.25 ± 0.28	3.803 ± 0.187	4799 ± 247
ZK3-3-1	215–225	2.178	13.186	2.140	23.59 ± 0.45	4.706 ± 0.255	5013 ± 288
ZK3-3-2	270–280	2.284	12.641	2.006	24.91 ± 0.92	4.542 ± 0.254	5484 ± 367
ZK3-4-1	330–340	2.153	12.883	2.149	22.70 ± 0.30	3.711 ± 0.172	6117 ± 295
ZK3-4-2	375–385	1.839	10.649	1.912	22.04 ± 0.86	3.214 ± 0.145	6859 ± 409
ZK3-5-1	440–450	1.966	11.146	1.890	21.10 ± 0.66	3.268 ± 0.152	6457 ± 361
ZK3-5-2	475–485	1.754	9.484	1.925	20.60 ± 0.67	3.085 ± 0.134	6676 ± 361
ZK3-7-1	625–635	1.894	9.822	1.927	18.67 ± 0.17	2.751 ± 0.099	6787 ± 252
ZK3-7-2	670–680	2.083	11.467	2.069	21.64 ± 1.14	3.021 ± 0.109	7163 ± 457
ZK3-8	770–780	2.112	11.542	2.025	20.13 ± 0.32	2.991 ± 0.108	6729 ± 265

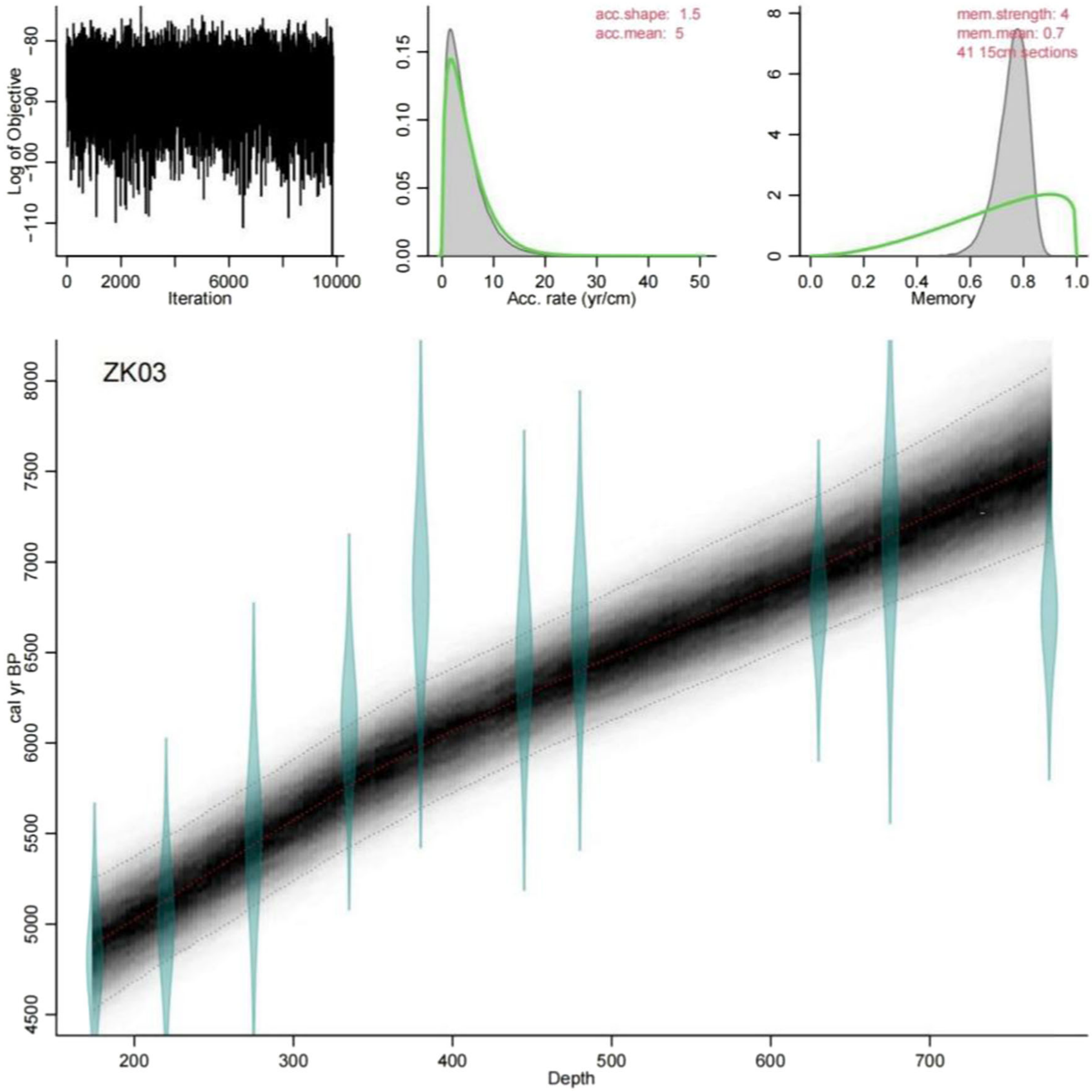

FIGURE 4 Bacon age-depth model for the ZK-3 core [Color figure can be viewed at wileyonlinelibrary.com]

$1.87\varphi < So < 2.57\varphi$, and a skewness index of $-0.32\varphi < Sk < -0.11\varphi$. An obvious fluctuation occurs at the depth of about 100 cm (~3 ka B.P.) suggesting a more obvious influence by human activities and a lacustrine shallow-lake environment.

4.3 | Magnetic susceptibility analysis

The magnetic susceptibility can reflect the variation of the relative content of magnetic minerals in sediments, especially ferromagnetic minerals (Thompson et al., 1980; Zhisheng et al., 1993). The magnetic susceptibility is widely used in the study of Quaternary loess, palaeosols (Lv et al., 1994; Wang & Dong, 1996), and lake sediments (Hu et al., 2001; Y. F. Zhang et al., 2005; Z. K. Zhang et al., 1998). For lake sediments, it is generally considered that high magnetic susceptibility indicates a wet climate and a higher lake surface, vice versa (Hu et al., 2001; Z. K. Zhang et al., 1998), but the magnetic susceptibility should be compared with other sedimentological and biochemical indicators for a more robust interpretation of environmental change in any study region (Wu, 1993). The intensity of human activities can also have a significant impact on the magnetic susceptibility values and sometimes even mask the effects of environmental changes (Shi et al., 2007; Q. Zhang et al., 2001).

The magnetic susceptibility values of samples collected from the ZK-3 borehole are shown in Figure 5. They reflect several stages of change.

Stage I (1000–330 cm, about 8.0–5.7 ka B.P.): the high-frequency (χ_{hf}) and low-frequency (χ_{lf}) magnetic susceptibility changes are almost synchronized. The X_{lf} value is between $11.37 \sim 36.49 \times 10^{-8}$ m^3/kg (20.58×10^{-8} m^3/kg on average), while the X_{hf} value is between $11.25 \sim 35.91 \times 10^{-8}$ m^3/kg (20.23×10^{-8} m^3/kg on average). Both X_{lf} and X_{hf} values remain relatively large with a gradually decreasing trend: the fluctuation of the curve is sharp before ~7.0 ka B.P. but tends to become smoother after 7.0 ka B.P. The frequency-dependent magnetic

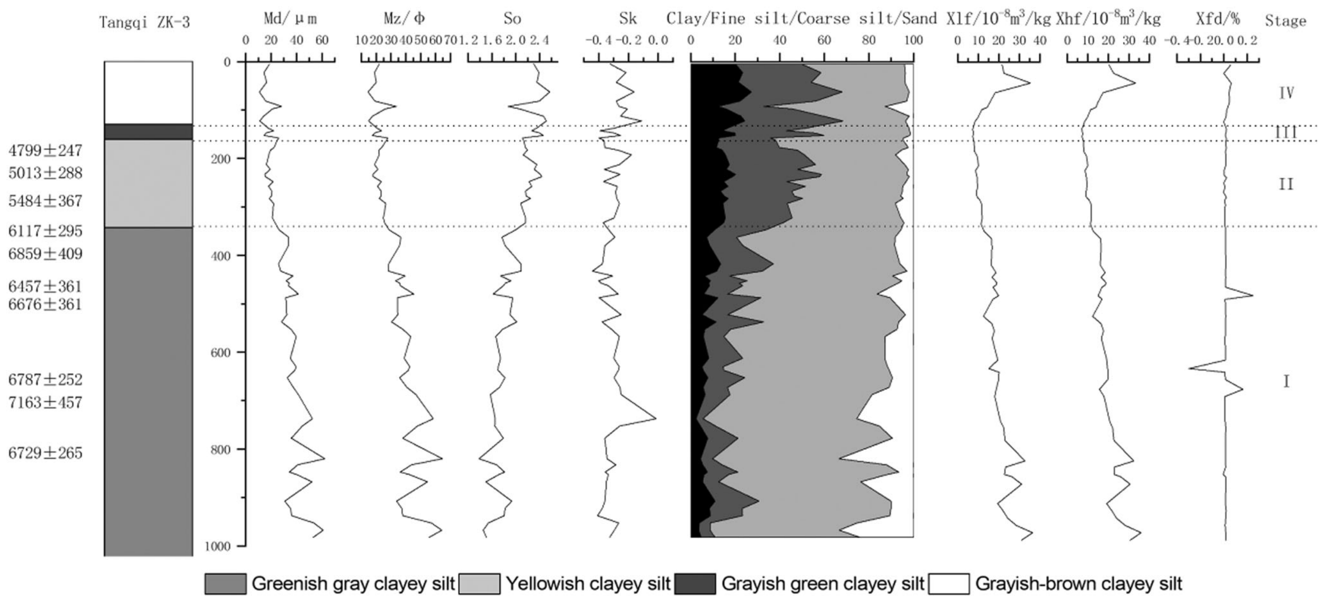

FIGURE 5 Grain size analysis and magnetic susceptibility results of the Tangqi ZK-3 core

susceptibility ($\chi_{fd\%}$) is between −29.93%~24.89% (1.52% on average) with three significant fluctuations at 475–480 cm, 625–635 cm, and 670–675 cm, respectively.

Stage II (330–155 cm, about 5.7–4.7 ka B.P.): both X_{hf} (7.466 ~ 11.76 × 10^{-8} m^3/kg, 9.29 × 10^{-8} m^3/kg on average) and Xlf (7.645 ~ 11.87 × 10^{-8} m^3/kg, 9.40 × 10^{-8} m^3/kg on average) are smaller than the previous stage, with occasional minor fluctuations. The value of $X_{fd\%}$ is 0.37%~2.34% (1.22% on average) and the curve is smooth.

Stage III (155–125 cm, about 4.7–3.0 ka B.P.): the value of X_{hf} (7.125 ~ 7.422 × 10^{-8} m^3/kg, 7.26 × 10^{-8} m^3/kg on average) and X_{lf} (7.291 ~ 7.527 × 10^{-8} m^3/kg, 7.40 × 10^{-8} m^3/kg on average) does not change significantly. The value of $X_{fd\%}$ is 1.39% ~ 2.28% (1.79% on average), which changes slightly from the previous.

Stage IV (125–0 cm, about 3.0 ka B.P.): both Xhf (8.319 ~ 33.24 × 10^{-8} m^3/kg, 16.88 × 10^{-8} m^3/kg on average) and X_{lf} (8.313 ~ 35.46 × 10^{-8} m^3/kg, 17.55 × 10^{-8} m^3/kg on average) show a large increase, and the curve fluctuates sharply. The value of $X_{fd\%}$ is −0.07% ~ 5.88% (3.23% on average).

4.4 | Pollen analysis

Of the 65 pollen samples from the ZK-3 borehole profile, 71 pollen species were identified, including 24 arboreal types, 10 shrub types, and 37 herbaceous types. Abundant fern spores were also identified.

The main arboreal species in ZK-3 include *Pinus*, *Quercus*, *Betula*, *Ulmus*, *Tsug Chinensis*, *Picea*, *Juglans*, *Castanea*, and so forth. The pollen of shrub species mainly includes *Apocynaceae*, *Rosaceae*, *Corylus/Ostryopsis*, and so on. Herbaceous species are mainly Gramineae, Asteraceae, Artemisia, Quinoa, Buttercup, Labiatae, and so on, but also including some aquatic herbs, such as Salviaceae, Fragaria, and so forth. The spores of ferns are *Pteris cretica* L. var. nervosa, *Pteris cretica* L. var. nervosa, *Ceratopteris*, *Polypodium*, and so forth.

Since the ZK-3 was located in the transitional zone between tidal and terrestrial environments, the sedimentary environment was volatile. For a more accurate analysis of vegetation changes, we used the percentages of trees, shrubs, and terrestrial herbs based on the abundance of terrestrial taxa, excluding the aquatic herbs, ferns, and algae. The percentage of aquatic herbs, ferns, and algae to all counted pollen grains was used as an indicator for the local ecological environment.

Based on the results of the cluster analysis, the pollen of the ZK-3 borehole could be divided into five zones with significant variations in the concentration and percentages of pollen between these zones (Figures 6 and 7). Corresponding to the sedimentation stages, Zones 1, 2, and 3 belong to Stage I, Zone 4 to Stage II, the bottom of Zone 5 to Stage III, and the rest of Zone 5 to Stage IV.

Zone 1 (833–1000 cm, 8–7.5 ka B.P.): the percentage of trees in terrestrial species is 73.32%, among which *Genus Pinus* (30.5%–72.4%, average 51.5%) and *Quercus spp*. (0.3%–17.7%, average 8.2%) are dominant, while *Spruce* (0–5.5%, average 2.2%) is of a low percentage. The average percentage of shrubs is 2.49%. The most common species is *Rosaceae*. The percentage of terrestrial herbs is very low (6.86%). Similarly, the percentage of aquatic herbs, mainly ferns and algae, is 8.31%, which is the lowest value compared to other zones in the profile.

Zone 2 (833–480 cm, 7.5–6.4 ka B.P.): the total quantity of pollen is more than that in Zone 1. The percentage of trees is 73.63%, dominated by *Pinus* spp. (20.0%–78.0%, average 47.8%) and *Quercus* spp. (0.9%–17.9%, average 9.9%). The percentage of shrubs increases slightly (3.71%), while that of terrestrial herbs (5.01%) is slightly reduced. The percentage of aquatic herbs, mainly ferns and algae (11.35%), also increases.

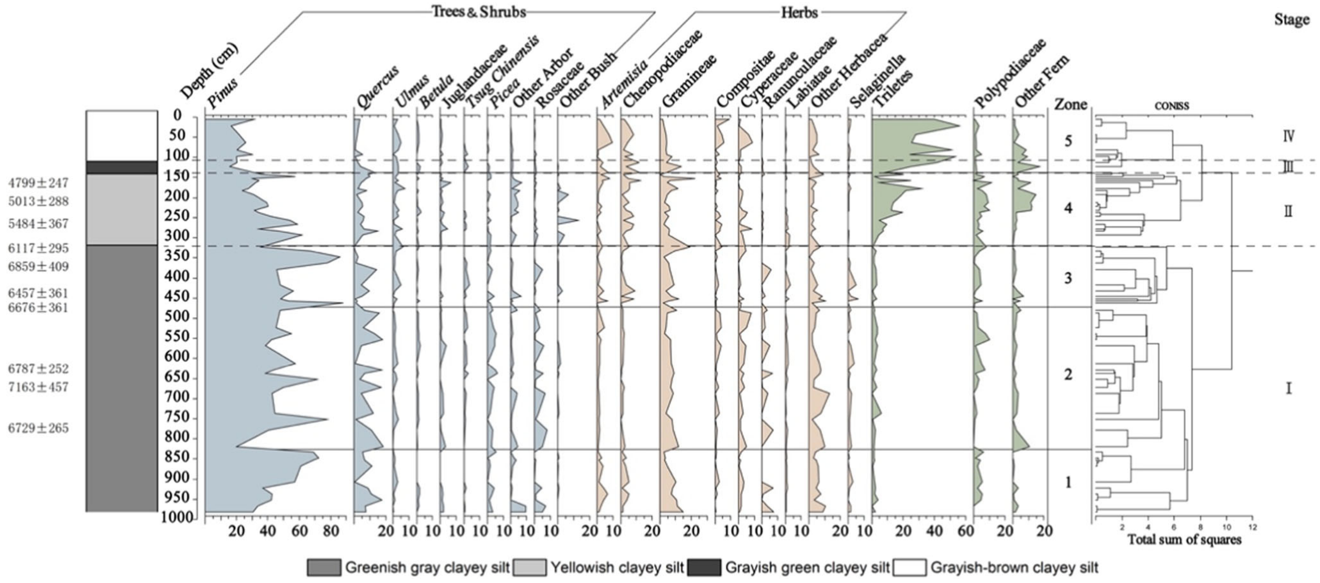

FIGURE 6 Pollen percentage chart of the Tangqi ZK-3 core [Color figure can be viewed at wileyonlinelibrary.com]

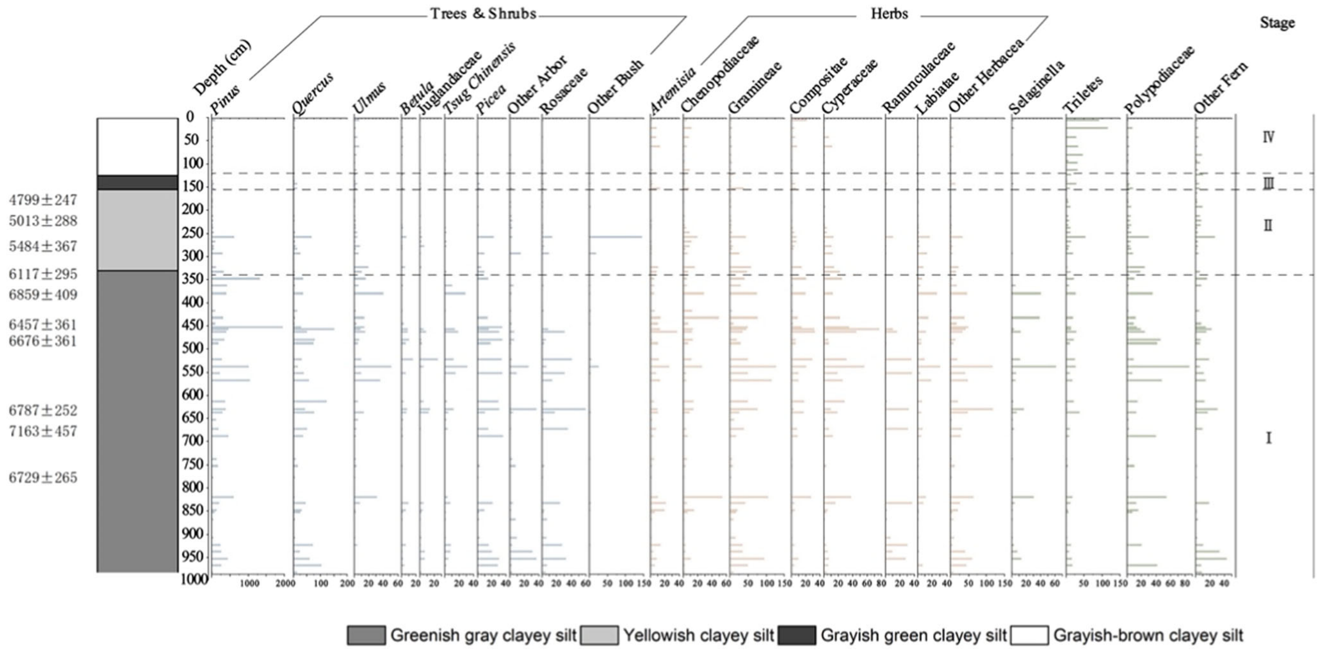

FIGURE 7 Pollen concentration chart of the Tangqi ZK-3 core [Color figure can be viewed at wileyonlinelibrary.com]

Zone 3 (480–323 cm, 6.4–5.7 ka B.P.): the total quantity of pollen is less than that Zone 2. The percentage of trees (77.50%) reaches the maximum of the entire profile, with *Pine* (35.7%–88.2%, mean 60.7%) being predominant and an increasing percentage of *Elm* (0.6%–5%, mean 2.1%). The percentage of shrubs is 1.25%, lower than that in Zone 2. The percentage of terrestrial herbs is 7.05%. The percentage of aquatic herbs of ferns and algae (9.00%) decreases.

Zone 4 (323–137 cm, 5.7–4.5 ka B.P.): the quantity of pollen is less than that Zone 3. The percentage of trees (73.45%) decreases, while that of shrubs (3.46%) increases slightly. In particular, the percentage of terrestrial herbs (10.56%) rises. The percentage of aquatic herbs of ferns and algae (25.20%) increase significantly.

Zone 5 (137–0 cm, 4.5 ka B.P.): total pollen quantity increases markedly. This zone saw a sharp reduction of trees (59.97%). Percentage of shrubs (0.86%) is slightly higher than the previous stage. The percentage of terrestrial herbs (21.34%) is up to the maximum of the entire profile. The percentage of aquatic herbs of ferns and algae (49.46%%) also increases to a maximum level.

5 | DISCUSSION

5.1 | Evolution of Holocene environment in the Hangjiahu Plain

5.1.1 | Climate and vegetation environment

Combining the stratigraphic examination, OSL dates, and the results of the palynological and magnetic susceptibility analyses, the ZK-3 borehole provides the us most detailed evidence of Holocene climate and vegetation changes of the region. Between 8.0 and 5.7 ka B.P., the pollen assemblage shows that the vegetation is dominated by a mixed coniferous and broad-leaved forest. Pollen concentration fluctuates (first increases but followed by a decrease), indicating a generally warm and humid climate that was gradually giving way to a dry and cool condition. This coincides with the change of magnetic susceptibility values. Between 5.7 and 4.7 ka B.P., the pollen concentration decreases with a noticeable reduction of the tree species. Together with the decline of both low-frequency magnetic susceptibility and high-frequency magnetic susceptibility, these results point to a drier and cooler climate during this period. The reduction of tree pollen might also imply the onset of intensified human activities. Between 4.7 and 3.0 ka B.P., while the increase of terrestrial herbs and decrease of trees in the pollen assemblage indicate a continued dry and cool climate, they might be also associated with deforestation caused by human activities. From ~3.0 ka B.P. to present, the sharp reduction in trees and the evident increase of terrestrial herbs in the pollen assemblage indicate a further climate deterioration. Meanwhile, the increased high- and low-frequency magnetic susceptibility might point to intense human activities during this period.

These results described above are generally consistent with previous studies on Holocene climate and vegetation in the area. Further synthesizing these results with published data allows us to refine the resolution of our reconstruction of the Holocene climate in the region. The climate between 8.0 and 7.0 ka B.P. was warm and humid (Yi et al., 2003), and the vegetation was mixed evergreen deciduous coniferous forest (Yi et al., 2003). Between 7.0 and 4.5 ka B.P., while the climate enjoyed a warmest and most humid period during the Holocene (Ma & Tian, 2010; Qu et al., 2000; Q. Zhang, Liu, et al., 2004), it was also punctuated by a dry and cool event around 5.5 ka B.P. But it should be noted that, despite this climate event, the mixed evergreen deciduous broad-leaf forest was maintained due to the overall optimal water and heat conditions in the region (Shi et al., 2011). During 4.5–3.0 ka B.P., the vegetation was dominated by a mixed evergreen deciduous broadleaf forest. The trend of a dry and cool climate was obvious, and the forest vegetation was disturbed to a large extent by human activities (Ma & Tian, 2010; Shi et al., 2011). From 3.0 ka B.P., the climate saw some evident short-term fluctuations (G. F. Yang et al., 2008). The pollen records from the profile at the Guangfulin site showed a significant decrease in arboreal species and a prominent increase in Chenopodiaceae and *Artemisia* postdating the late Liangzhu culture, which must have been associated with a gradual deterioration of the regional climate while the intensity of human activities was significantly reduced during this time (C. H. Li et al., 2009).

5.1.2 | Evolution of geomorphology and hydrology in the Hangjiahu Plain

The sedimentary sequence from the ZK-3 borehole also offers direct evidence for the changing hydrologic and geomorphic environments in the region. Comparing our results with the lithological characteristics and dating results of other published profiles in the region (Figures 1 and 8), we can reconstruct the evolution of the hydrological and geomorphological environment in the Hangjiahu Plain since 8.0 ka B.P. as follows.

Before ~7.0 ka B.P.

The sediments at ZK-3 were light grayish clayey silt or silt with large-sized grains and of fluctuating magnetic susceptibility values, which suggest a typical tidal-terrestrial environment with strong hydrological conditions in deep water and a rapid sedimentation rate. Sediments with such characteristics are widely distributed in the Hangjiahu Plain (Ling et al., 2021; Shi et al., 2011; Zong et al., 2011b) (Figure 8), representative of a similar tidal-terrestrial environment across the region. With a rapid relative sea-level rise before 7.0 ka B.P. (Z. Y. Chen & Stanley, 1998; Lambeck et al., 2014; Zhao et al., 1979; Zong, 2004) (Figure 2), the Hangjiahu Plain experienced a rapid accretion of the delta.

7.0–6.0 ka B.P.

The sediments in this period were similarly dominated by light grayish clayey silt or silt with smaller grain size. The low- and high-frequency magnetic susceptibilities showed a steadily decreasing trend, indicating that the water-level became deeper, and the hydrological conditions were weaker than the previous stage. It marked remarkable changes in the sedimentation environment of the Hangjiahu Plain beginning from around 7.0 ka B.P. Some areas on higher terrains began to emerge as the sedimentation process stopped, such as at the Liangzhu West section (Shi et al., 2011), the E2 and T1 sections (Zong et al., 2011b), and the LZ1501 section (Ling et al., 2021). Although most of the area was still in the tidal-terrestrial environment, such as FQT and ZK-3, the depositional characteristics, smaller grain size, and decreasing magnetic susceptibility also indicate further deepening of the lakes and weaker hydrological conditions than the previous phase. This might be caused by the slow rise of the relative sea level from about 7.0 ka B.P. (Z. Y. Chen & Stanley, 1998; Lambeck et al., 2014; Song et al., 2013; Xie & Yun, 2012; J. Zhang et al., 1982; Zhao et al., 1979; Zong, 2004), which also led to a slower sedimentation rate.

6.0–4.5 ka B.P.

The sedimentation environment changed during this stage. The sediments were dominated by yellowish brown clayey silt with

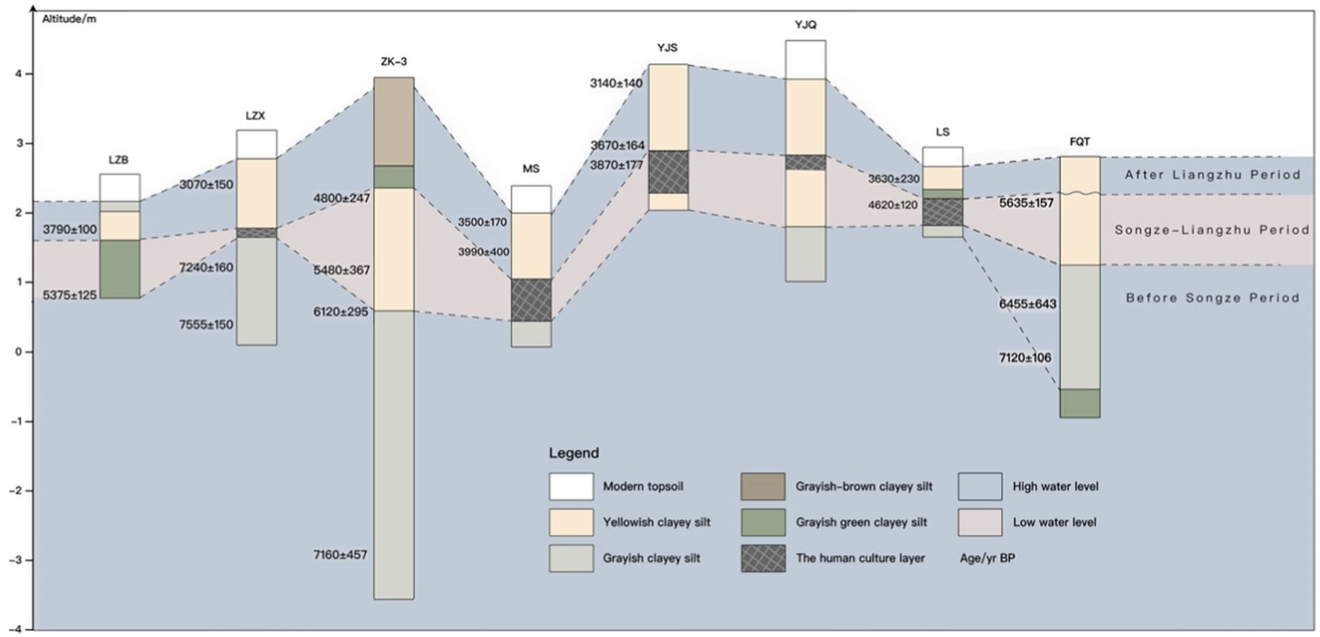

FIGURE 8 Comparison of Holocene sedimentary profiles in the Hangjiahu Plain (LZB, LZX, and YJQ, according to Shi et al. (2011); MS and LS recording to Jin et al. (2018) [Color figure can be viewed at wileyonlinelibrary.com]

horizontal beddings, which indicated a weak hydrological condition and a shallow-water environment as an even larger area emerged (Wang & Liu, 1996). At the Yujiashan site, for instance, the Liangzhu cultural layer (5.3–4.3 ka B.P.) overlaid on the yellow silt, and at the Liangzhu West, Shanlongdi, Hulinmiao, and Maocaodi locations too, the Liangzhu cultural layer sat directly on top of the light grayish silt (Shi et al., 2011). This is also consistent with previous studies that most of the Hangjiahu Plain was above the sea level by this stage (Yu et al., 2000). It seems that the backwater effect of regional rivers was weakened by the slight decrease in the sea level around 6.0–4.5 ka B.P. (Figure 2) (Xie & Yun, 2012; H. R. Yang & Xie, 1984; J. Zhang et al., 1982; Zhao et al., 1979), leading to the drop of the water level of regional rivers and a reduction of waterbodies.

4.5–3.0 ka B.P.

The sediments at the ZK-3 core being deposited during 4.5–3.0 ka B.P. were of light grayish clayey silt, with a few ferromanganese nodules in the upper part and iron-depleted blackish gray stripes in the lower part, pointing to a lacustrine sedimentation environment. Yellowish clayey silt is commonly found in the Hangjiahu Plain during this period (Figure 8), such as in the LZ1501 and LZ1601 profiles (Ling et al., 2021) and the T4 and ZX-1 sites (Zong et al., 2011b). At some locations, the yellowish clayey silt directly covered the Liangzhu cultural layer, such as at the Yujiashan profile, but also at the Maoshan profile (Jin et al., 2018), the Liangzhu West, Shanlongdi, Hulinmiao, Beishanche, and Yanjiaqiao profiles (Shi et al., 2011). This stratigraphic order is widely considered evidence of a direct relationship between the region-wide floods, possibly related to another episode of sea-level rise and the decline of the Liangzhu culture (Figure 2) (He et al., 2021; Wang et al., 2018; Xie & Yun, 2012; H. R. Yang & Xie, 1984), which is further discussed below.

5.2 | Environment and the rise and fall of prehistoric cultures in the Hangjiahu region

The rise and fall of the Neolithic cultures in the region were intricately intertwined with the fluctuating hydrological and geomorphological conditions of the Hangjiahu Plain. Below we further discuss the evolution of such close environmental–societal dynamics from 7.0 to 6.0 ka B.P., 6.0–4.5 ka B.P., and 4.5–3.0 ka B.P. periods, corresponding to the Majiabang culture period, the Songze-Liangzhu culture period, and the Guangfulin-Qianshanyang to Maqiao culture period, respectively.

5.2.1 | 7.0–6.0 ka B.P.

Before ~7.0 ka B.P., much of the Hangjiahu Plain was still inundated in water and was not suitable for human occupation. Around 7.0 ka B.P., continued land aggradation due to the rapid sedimentation rate and the shallowing water depth turned some higher-altitude locations, with intermittent sedimentation, into inhabitable places. This improved hydrological and geomorphological environment fostered the emergence of earliest Neolithic culture in the Hangjiahu Plain. The Majiabang culture sites (7.0–6.0 k B.P.) were located on such emerged land, where some cultural layers directly overlying the late Pleistocene layers (Shen et al., 2004) (Figures 8 and 10a). The number of Majiabang culture sites reached 85 in total, including 40 in the Hangjiahu area (Figure 9). The condition of the Hangjiahu Plain became suitable for rice farming, and some sites even saw the construction of ditches and wells, which are recognized as the earliest irrigation systems (Ding, 2010). However, as the range of waters was still large, fishing, hunting, and gathering continued to be important sources of food production in this period (Z. H. Zhang, 2004).

6.0–4.5 ka B.P.

Between the Songze culture (6.0–5.3 ka B.P.) and the Liangzhu culture (5.3–4.3 ka B.P.) period, the water level of rivers and lakes in the

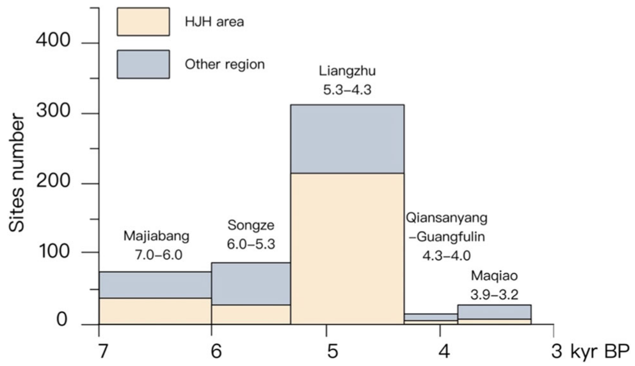

FIGURE 9 Number of settlements in each cultural period of the Holocene [Color figure can be viewed at wileyonlinelibrary.com]

Hangjiahu Plain dropped substantially. The sedimentation environment in low-lying areas became a shallow water condition, while a much larger area emerged, which created an unprecedentedly conducive environment for the development of the Songze and Liangzhu cultures. The number of Songze culture sites increased to 91 (Figure 9). The growth was most notable in the northeastern part of Taihu Lake, and interestingly, the number of settlements in the Songze culture period on the Hangjiahu Plain was even less than the previous period, with only 31 sites (Figures 9 and 10b). In the Liangzhu culture period, however, the number of settlements increased dramatically to 312 (Figures 9 and 10c), and they were concentrated in the Hangjiahu Plain, with almost 220 sites being found here. In particular, there was only one settlement in the piedmont area of the western mountains during the Songze culture period. This changed dramatically during the Liangzhu period. There were not only a large number of settlements, but also the establishment of the ancient city of Liangzhu, as the sole center of the region and probably represented the earliest state-level society in prehistoric East China.

There were two possible reasons for the spatial and temporal changes of settlements from the Songze to Liangzhu culture period. On the one hand, according to sedimentary records such as the ZK-3 borehole, a dry and cool climate prevailed during this period, with a significant decrease in precipitation at about 5.5 ka B.P., resulting in a weak alluvial and flooding effect in the piedmont area of the western mountains. On the other hand, sea level also dropped slightly during

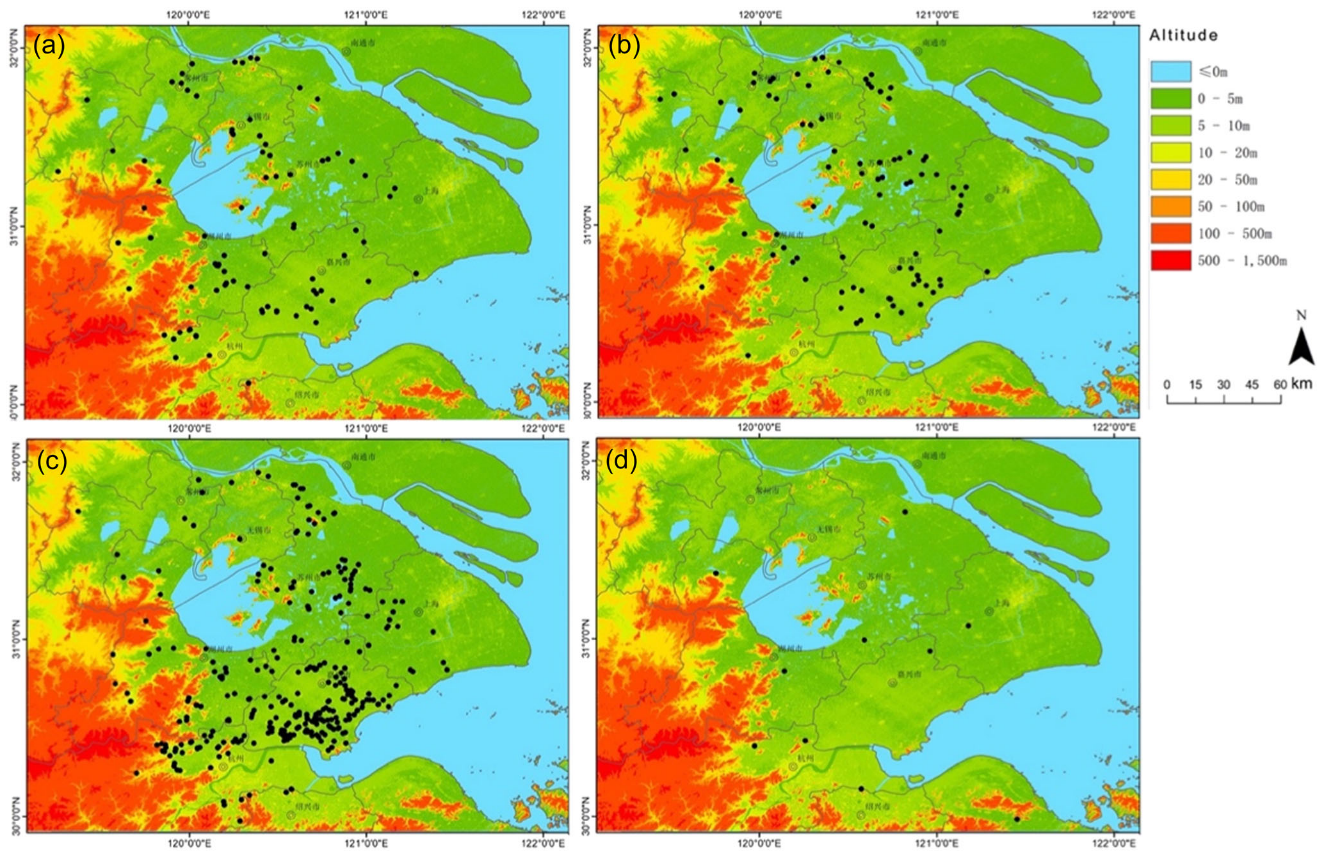

FIGURE 10 Distributions of sites in the Hangjiahu Plain. (a) Majiabang period, (b) Songze period, (c) Liangzhu period, and (d) Guangfulin-Qiansanyang period. [Color figure can be viewed at wileyonlinelibrary.com]

the period (Figure 2), and the water level of the region was further reduced. These processes resulted in expanding land formation and the region became more suitable for human activities as an increasing number of settlements started to appear on low-lying terrains. The Hangjiahu Plain as a whole provided a safe and stable hydrological environment for human settlements in this period. Under such suitable hydrological conditions, rice farming developed rapidly during the Songze-Liangzhu period. The excavation of the rice fields at the Maoshan site demonstrates the sophisticated level of irrigation and water management (Jin et al., 2018; Zhuang et al., 2014). Rice agriculture as the main form of subsistence economy supported the increase in population and cultural development, which contributed to the flourishing of the Liangzhu culture.

4.5–3.0 ka B.P.

The Liangzhu culture saw a dramatic decline from 4.3 ka B.P., as the number of settlements dropped sharply. In the succeeding Qianshanyang-Guangfulin (4.3-4.0 ka B.P.) culture period (Figures 9 and 10d) and the Maqiao (3.9–3.2 ka B.P.) culture period, only 13 and 30 (Figure 9) sites were found, respectively, and the culture characteristics also changed drastically, with strong external influences from to the Longshan culture in the Yellow River. The reasons for the decline of the Liangzhu culture are widely discussed (Shi et al., 2011; Shi, 1993; Yu et al., 2000; Y. F. Zhang et al., 2005; Z. K. Zhang et al., 1998; Zhu et al., 1996). Many studies support the viewpoint that the decline of the Liangzhu culture was at least partly related to sea level change (Bird et al., 2010; He et al., 2018; Innes et al., 2014; Z. Wang et al., 2012, 2013; Wu, 1988), but evidence to critically evaluate such claims has not been available.

As shown by Figure 8, the yellow clayey silt deposits are commonly found in the region, representing widespread flooding events which were probably caused by a rising sea level again (Figure 2) (He et al., 2021; Z. Wang et al., 2018; Xie & Yun, 2012; H. R. Yang & Xie, 1984). In the low-lying deltaic plains like the Hangjiahu Plain, the impact of the persistent and widespread flood on the Neolithic culture was catastrophic (Stanley & Chen, 1996; Q. Zhang, Jiang, et al., 2004). The frequent floods made most of the settlements of the Liangzhu culture no longer suitable for human occupation. Moreover, such large-scale floods also severely affected rice cultivation, without which it was impossible to support the subsistence needs of a large population in large ancient cities as well as normal settlement sites. These eventually led to the decline of Liangzhu culture.

6 | CONCLUSION

The climate and vegetation history in the Hangjiahu Plain was reconstructed by pollen and magnetic susceptibility results of this study. Between 8.0 and 4.5 ka B.P., the climate was warm and humid, and the vegetation was mixed evergreen deciduous coniferous forest, and the ~5.5 ka B.P. event was shown during this period. 4.5-3.0 ka B.P., the trend of climate drying and cooling was obvious, and the forest vegetation was significantly disturbed by human activities. From 3.0 ka B.P., the climate further deteriorated.

Based on the sedimentary records at the ZK-3 and evidence from other studies in the Hangjiahu Plain, we established the regional environmental process. Before ~7.0 ka B.P., the Hangjiahu Plain was a sea-land transition environment. Between 7.0 and 6.0 ka B.P., the hydrodynamic condition became weaker, and some higher grounds in the Hangjiahu Plain began to emerge. Between 6.0 and 4.5 ka B.P., the regional water level was dropping, and more lands were emerging. Between 4.5 and 3.0 ka B.P., the ZK-3 core returned to a deep-water environment, and floods occurred frequently in the Hangjiahu Plain.

Combined with the human activities in the Hangjiahu Plain, the onset of the land-forming process between 7.0 and 6.0 ka B.P. coincided with the development of Majiabang culture; between 6.0 and 4.5 ka B.P., the accelerating land-forming process and shrinking water areas in the region provided a favorable physical environment for the prosperity of Songze-Liangzhu cultures; in contrast, as the water level rose again between 4.5 and 3.0 ka B.P., large-scale floods also occurred frequently, which resulted in a sharp reduction of settlement sites and the eventual decline of the Liangzhu Civilization.

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