Intensification of rice farming and its environmental consequences recorded in a Liangzhu reservoir, China

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Abstract

The origin and subsequent development of rice agriculture enabled humans to transition from hunter-gatherers to farmers, thereby profoundly changing human society. However, less attention is focused on when and how rice cultivation practices began to alter the landscape. In this study, sediment from the reservoir inside the Mifenglong dam, Liangzhu hydraulic system was sampled. Accelerator mass spectrometry (AMS) radiocarbon dating and optically stimulated luminescence (OSL) dating results revealed that the duration of the Mifenglong reservoir ranged from 4,900 cal BP to 1,500 cal BP. The results showed that between 2,500 cal BP and 1,500 cal BP, intensive rice farming practices transformed the surrounding vegetation and landscapes through deforestation and changes in herbaceous plant structure. This study provides an insight into the impact of human activities and how they influenced the environment on a local scale, as well as contributing to a deeper understanding of the relationships between agricultural development and landscape changes.

Keywords

Anthropocene; Rice cultivation; Landscape; Phytolith; Vegetation; Human activity

1. Introduction

Human impact on the planet is becoming so profound that the current era is proposed to be termed the Anthropocene (Ruddiman 2013; Lewis and Maslin 2015; Waters et al. 2016). The transition and intensification of agriculture was accompanied by an increasingly extensive scale of landscape modification and environmental consequences (Ellis 2011; Gowdy and Krall 2014; Rosen et al. 2015; Zheng et al. 2021). Rice (*Oryza sativa* L.), one of the earliest domesticated crops (Yan 1982; 1989; Larson et al. 2014; Zuo et al. 2017; Wang et al. 2018), supported cultural and social transitions and eventually paved the way for the rise of ancient civilizations in Asia (Fuller 2011;

Guedes 2011; Rosen et al. 2017). Previous studies focused on greenhouse gas emissions from rice farming have shown that the expansion of irrigated rice paddies directly caused the anomalous increase in methane from 5,000 years BP (Ruddiman 2003; Ruddiman et al. 2008; Fuller et al. 2011); however, less scholarly attention has been paid to understanding when and how rice cultivation practices began to alter the landscape. Among the challenges facing scholars is understanding and quantifying the multi-faceted relationship between intensified rice farming and environmental changes to establish a more holistic, long-term perspective on Anthropocene and Holocene rice farming.

Recent studies have suggested that, on a local scale, when the ecological system surrounding the fields was relatively stable, the high frequency of in-field vegetation changes was closely related to intensive rice farming (Jin et al. 2019), and on a regional scale, the expansion of rice agriculture caused widespread deforestation and biodiversity changes in southern China and Southeast Asia approximately 2,000 years ago (Ma et al. 2020; Zheng et al. 2021). These significant findings have established the first step towards revealing the complex and multi-scalar interactions between rice farming and the environment. However, most of these studies solely applied environmental proxies, primarily pollen records, and it remains to be determined whether such records can be directly linked to the history of rice farming, as rice pollen cannot be distinguished from Poaceae pollen (Mao and Yang 2012).

Phytoliths are silica structures that accumulate in the cells and tissues of higher plants. They are abundant in plants and generally have good *in situ* preservation and can be used to identify individual genera or species (Wang and Lu 1993; Dolores 2006). Owing to these qualities, phytolith studies play a key role in the reconstruction of environmental and vegetation changes (Lu et al. 2006; Lu et al. 2007). Specifically, rice phytoliths can be distinguished from their wild relatives with great accuracy (Huan et al. 2015; Huan et al. 2020). Therefore, this method greatly contributes to the assessment of the processes and intensity of rice agriculture and synchronous local environmental changes. At present, most rice phytolith studies only focus on the process of rice domestication and spread of rice farming (Ma et al. 2016; Deng et al. 2018; Ma et al. 2018; Deng et al. 2020; Dai et al. 2021; Huan et al. 2021), with a pronounced lack of synchronous analysis of vegetation and landscape changes associated with the practice. Although some studies have analyzed environmental changes using diatoms or pollen records (He et al. 2018; He et al. 2020a; He et al. 2020b), much of the discussion thus far has only focused on how the environment might influence rice domestication (Lu et al. 2002; Zong et al. 2012; Zuo et al. 2016; Shao et al. 2021).

The Liangzhu culture (5,300–4,300 years BP) displayed a clear trend of intensified rice production and unprecedented, large-scale earthwork construction (Liu et al. 2017). The latter is represented by the Liangzhu City site and the Liangzhu site cluster surrounding it. The Liangzhu site cluster encompassed the inner city, outer city, a network of waterways, a hydraulic system with high and low dams, Tangshan levees, and numerous smaller mounds for residential and other purposes (Fig. 1) (Liu and Wang 2014; Wang 2016). The construction of the hydraulic system outside Liangzhu City began as early as 5,100 years BP and was completely established at 4,800 years BP. The low dams were built on swampy lands with an altitude of approximately 0 m, and the higher dams were distributed between isolated hilly formations at altitudes of 30–40 m (Liu et al. 2017). They formed large reservoirs spanning several dozen hectares (Liu et al. 2017) which could continue to receive sediments from the surrounding area; therefore, the rice utilization sequence and regional landscape change could be recorded by the sediment from the reservoir.

In this study, sediment from the reservoir inside the Mifenglong (MFL) dam was sampled. Based on analyses of phytoliths, charcoal, and geochemistry, together with accelerator mass spectrometry (AMS) radiocarbon dating and optically stimulated luminescence (OSL) dating, this study reconstructed the sedimentation history at the reservoir and the rice utilization history and corresponding vegetation and landscape changes represented by the reservoir during and after the Liangzhu period. This study provides new evidence for understanding the relationship between farming activities and the consequent landscape changes.

2. Materials and methods

2.1 Sediment and sampling

The MFL profile (119.983°E, 30.397°N) was located inside the MFL high dam (Fig. 1), which was located approximately 40–50 m from the main dam body. The profile had a subtropical monsoon climate with a mean annual temperature of ~16 °C and mean annual precipitation of ~1,100 mm, and the vegetation was characterized by subtropical mixed forests of evergreen trees. The excavated portion of the profile was 188 cm deep and was divided into seven main layers (Fig. 1C): Layer 1 (0–30 cm) was the yellowish modern topsoil with abundant plant roots; Layer 2 (30–42 cm) consisted of compact, grey-yellowish silt sediments with plant roots; Layer 3 (42–72 cm) was composed of light-greyish silty clay with the inclusion of some pottery shards; Layer 4 (72–130 cm) consisted of dark-grayish clayey silt; Layer 5 (130–164 cm) was mainly composed of grey-yellowish silt; Layer 6 (164–185 cm) and Layer 7 (185–188 cm) were both composed of yellowish-brown silt, with bedrock occurring below Layer 7.

A total of 85 sediment samples were collected for phytolith, charcoal, magnetic susceptibility (MS), grain size, and C/N ratio analyses, including six samples from the upper 30 cm of Layer 1, which were sampled at 5 cm intervals, and 76 samples from the 30–188 cm layers (Layer 2–Layer 7), which were sampled at 2 cm intervals. A total of 12 dating samples were collected (Fig. 1C), including three samples for OSL dating and nine samples (one plant remains, two charcoal, and six organic sediment) for AMS ^{14}C dating.

2.2 Phytolith extraction and identification

Phytoliths were extracted from soil samples following established protocols (Piperno 1988; Lu et al. 2002) with minor modifications. Approximately 2 g of each sample was weighed and dissolved in 30% H_2O_2 and 15% HCl to remove organic matter and carbonates, respectively. The samples were then subjected to heavy liquid flotation using $ZnBr_2$ (density, 2.35 g/cm^3) to separate the phytoliths, which were subsequently mounted on a slide using Canada balsam. After air drying, the phytoliths on the slide were counted and identified using a Leica DM750 microscope at 400X magnification. Diatoms and charcoal were extracted and identified simultaneously with the phytoliths.

More than 400 phytolith particles in each sample were identified and recorded according to published references and criteria (Wang and Lu 1993; Lu et al. 2006; Lu et al. 2007; Lu et al. 2009; Ge et al. 2018; Ge et al. 2020a; Ge et al. 2020b). In particular, for samples with rice phytoliths, the slides were scanned until 50 rice bulliform phytoliths with clear and countable scales were observed in order to calculate the proportion of rice bulliform phytoliths with ≥ 9 scales (Wang and Lu 2012; Huan et al. 2015; Tang et al. 2021).

2.3 Magnetic susceptibility, grain size, and C/N ratio analysis

The MS was measured in the Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics at the Chinese Academy of Sciences on air-dried samples using a Bartington Instruments MS2 susceptibility meter. The operation procedure began by grinding the soil sample and then weighing approximately 5 g of each sample into a transparent plastic box. When the instrument conditions were stable, a low frequency was measured as the MS of the sample. Finally, according to the weight and instrument readings, we calculated the mass MS (χ, $10^{-8}\cdot m^3/kg$).

The grain size was measured using an LS 13 320 laser particle size analyzer. All the samples were pre-treated with H_2O_2 to remove organic materials and HCl to remove carbonates, and sodium hexametaphosphate was added as a dispersing agent.

The total organic carbon (TOC) and total nitrogen (TN) were measured at the Physical and Chemical Analysis Center of the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences. First, approximately 1 g of the sample was ground and passed through an 80-mesh sieve, after which approximately 5 ml CH_3COOH (1 mol/L) was added to the sample. After 24 hours, the sample was bathed to neutrality (pH = 7) with deionized water, then dried and milled again, ground, and passed through a 150-mesh sieve. Thereafter, the sample was weighed and wrapped tightly in tinfoil, and subsequently placed in a Vario MACRO cube elemental analyzer.

3. Results

3.1 Radiocarbon and OSL dating results

Three OSL dating samples were submitted to the Fujian Normal University for OSL dating. The sample at the bottom of the profile was dated to 10,130±460 years BP, the sample at the bottom of Layer 5 was dated to 4,710±200 years BP, and the sample at the top of the profile was dated to 590±30 years BP.

Nine dating samples were sent to the Beta Analytic Laboratory and Center for Applied Isotope Studies of the University of Georgia for AMS ^{14}C dating. The radiocarbon ages were calibrated by OxCal 4.4 using the IntCal 20 atmospheric curve (Reimer et al. 2020).

Complete details of the 12 dates in this study are presented in Table 1. An age-depth model was constructed using the Bacon model (Blaauw 2010) (Fig. 2) and applied to the diagram of the phytolith in Figures 4&5.

3.2 Phytolith results

Abundant phytoliths were found in all 85 samples. 28 phytolith morphotypes were identified (Fig. 3). Typical rice phytoliths were found, including double-peaked, bulliform, and parallel-bilobate types. Other main phytolith types include square, rectangle, smooth elongate, acicular hair cell, rondel, reed bulliform, bilobate, trapeziform sinuate, and so forth.

The phytolith assemblage (Fig. 4) was characterized by a high proportion of elongate psilate (23.6%), followed by square (12.04%), rondel (11.93%), and bilobate (10.30%) types. Specifically, the percentages of long saddle, trapeziform sinuate, and rondel were low in Layers 6 and 7, then increased from Layer 5 upward, remaining high. The trend of change in the reedy bulliform was contrary to that of the long saddle. Bulliform, square, and rectangle showed the same trend of change: they accounted for a high proportion in Layers 5–7 and remained low in Layers 3 and 4, before returning to percentages similar to those observed in Layers 1 and 2. The abundance of woody type clearly decreased in the upper region of Layer 4, while the rice phytoliths showed a peak in terms of percentage. The proportion of rice bulliform phytoliths with $\geq$ 9 scales in Layer 6 was 38.78±7.71%, whereas those in Layers 5 and 4 were approximately 52.52±3.76%, and reached approximately 53.54±3.67% in Layers 1–3.

The concentration of charcoal in the studied profile ranged from 238,221 grains/g to 344 grains/g. The concentration of charcoal displayed three peaks in Layers 6, 4, and both 3 and 2 (Fig. 4). In particular, the average concentration of charcoal in the peak of Layer 6 was 38,266±35,560 grains/g, in the peak of upper Layer 4 was 38,811±16,059 grains/g, and the peak of Layers 3 and 2 was 80,898±88,066 grains/g.

3.3 MS, grain size, and C/N ratio results

The MS ranged from 19.82 to 3.17 in the samples. The average MS in Layer 7 was 10.26±0.37, 7.57±1.66 in Layer 6, 7.74±3.25 in Layer 5, 8.53±3.12 in Layer 4, 5.29±1.21 in Layer 3, 7.14±1.52 in Layer 2, and 8.04±1.74 in Layer 1. MS showed two peaks in middle Layer 5 and upper Layer 4 (Fig. 4).

The mean grain size ranged from 10.7–3.53 μm in the profile and was steady from Layer 6 to Layer 4, then increased in Layer 3 (Fig. 4). The average mean grain size in Layer 7 was 8.45±1.97 μm, 4.07±0.43 μm in Layer 6, 4.08±0.18 μm in Layer 5, 4.58±0.61 μm in Layer 4, 8.27±0.67 μm in Layer 3, 9.39±0.42 μm in Layer 2, and 9.44±0.85 μm in Layer 1.

The C/N ratio showed an increasing trend from Layer 7 (3.91±0.37) and Layer 6 (6.47±0.66) to Layer 5 (9.19±1.38), and remained high in Layer 4 (11.31±1.53), thereafter dropping in Layer 3 (7.24±1.10) and Layer 2 (7.58±0.96), and remained low in Layer 1 (8.67±0.31) (Fig. 4).

4. Discussion

4.1 The duration time of the Liangzhu reservoir

In our study, we observed that the depositional facies of Layers 5 and 4 differed from those of the other layers (Fig. 1); the color of the sediment in these two layers was greyish whereas that of other layers were yellowish; the grain size of both layers remained low and stabilized around 4 μm. The C/N ratio was high in Layers 5 and 4 (Fig. 4), indicating that the deposition during this period was mainly from external sources. C/N ratio could provide information on the source of organic matters. In general, the C/N ration in terrestrial plants and humus was higher than 12, and that of aquatic plants in freshwater lakes was lower than 10 (Wang and Wang 1992), hence, the high C/N value indicates that great contribution of terrigenous organic matter (Dean 1999). Therefore, Layers 4 and 5 in the studied profile would have been deposited when the reservoir was still functioning.

At the bottom of Layer 5, the OSL dating result was 4,710±200 cal BP (Table 1). Although there are no more precise dates in the key location of this profile, the dates of the dams could help to cross-validate it. There were "sand bags" resembled by grayish clay wrapped by grass leaves in the dam bodies. The annual grassy plants found inside the sand bags provide ideal materials for dating the age of dams (Liu et al. 2017). The AMS dating results of grasses at Mifenglong dam body is 5,000–4,900 cal BP. The nearby high dam bodies of Qiuwu and Shiwu also dated to 5,000–4,900 cal BP and the Ganggongling dated to 5,100–4,900 cal BP (Liu et al. 2017; Zhejiang Provincial Institute of Relics and Archaeology 2019). So, the dating results of high dam bodies consistently around 4,900 cal BP. Combined with the AMS ^{14}C dating results of the dam bodies and OSL result from the boundary between Layers 5 and 6, we estimate that the MFL reservoir began to store water at 4,900 cal BP.

At the top of Layer 4, the sediment color changed from greyish to yellowish, and the grain size increased (Fig. 5). This suggests that the MFL reservoir became much less, if at all, influenced by alluvial or colluvial processes. In other words, the sediments might be considered evidence that the reservoir was no longer in use. This drastic change in the reservoir function occurred around 1,500 cal BP, and was evidenced by the AMS ^{14}C dating results at the boundary of Layers 4 and 3 (Table 1). Considering there were no related archaeological culture occupations to verify the abandon time of the reservoir so far (Zhejiang Provincial Institute of Relics and Archaeology 2019), the dating results of MFL profile offer a reference to the abandon time.In summary, our OSL and ^{14}C dates and sedimentological results show that the MFL reservoir was used continuously between 4,900 cal BP and 1,500 cal BP. In the following section (section 4.2), we further discuss how these sediment and microfossil records provide first-hand evidence of the history of rice farming and related environmental changes in the region.

4.2 Intensive rice farming and its environmental consequence

The rice domestication traits reflected by the rice bulliform phytolith (Huan et al. 2015; Huan et al. 2020) suggest that all the rice was fully domesticated during and after the Liangzhu period. The deposition process in Layers 1-3 might been disturbed because plenty of modern plant roots were found when sampling, hence the results here might not reflect accurate pattern of human activities and landscape change. Although double-peaked rice phytoliths appeared in Layers 6 and 7, we focused on the phytolith remains from Layer 5 and the overlying layers at the MFL reservoir in this study, as the aforementioned phytoliths had a low percentage and other rice phytolith types were absent in Layers 6 and 7. These records mainly present the regional rice farming history after the initial construction of the dam.

After the Liangzhu hydraulic system was constructed in the Liangzhu period (Zhejiang Provincial Institute of Relics and Archaeology 2019), the rice traits reflected by rice bulliform phytolith suggests they were fully domesticated during Liangzhu period since 4,900 cal BP. Archaeological discoveries in this region showed that rice farming witness a sound development with the emergence of different type of stone tools include ploughing tools and tools for cutting the whole rice plants (Zhuang et al. 2014). The technological innovations on agricultural tools along with irrigated rice paddy fields further promoted the rice faming development (Zhuang et al. 2014). However, rice phytoliths comprised a low percentage in the phytolith assemblage. One possible explanation is that the deposition of sediments in the reservoir through surface sheetwash and other alluvial and colluvial processes had just begun. Another is that human activities during the Liangzhu period were not impactful enough to affect the environment around the high dams which was at higher altitude and surrounded by hills. As for the environment around low dams, whether they were affected needs to be confirmed by future studies in the low dam sedimentary area. From the Qianshanyang-Guangfulin period (4,300–3,800 years BP) to the Maqiao period (3,800–3,200 years BP), rice phytoliths remained low, and were interrupted in 4,000–3,700 years BP, which coincided with a decline in archaeological culture in this area (Zhang 2017; He et al. 2021).

During historical period, the charcoal concentration and MS remained high during 2,500–1,500 cal BP, implying intensive human activity. Rice farming practices, reflected by the percentage of rice phytoliths (rice bulliform, rice double-peaked, and rice parallel-bilobate phytoliths) suggested that rice farming was culminating, accompanied by dramatic vegetation changes in the high dam area. These changes include a notable decrease in woody type phytoliths and Pooideae phytoliths (rondel and trapeziform sinuate), and a slight increase in Bambusoideae phytoliths (long saddle) and Panicoideae phytoliths (bilobate, multilobate, and cross).

The decrease in woody type phytoliths during this historical period might be associated with human-induced deforestation in this region. Pollen analysis suggests that intensive rice agriculture could lead to extensive deforestation (Zong et al. 2007). Our phytolith data further demonstrates changes in the Poaceae species assemblage due to intensified rice farming and/or similar activities. The expansion of rice paddies led to a decrease in Pooideae grass and an increase in Bambusoideae, which prefer a similar environment to rice. Specifically, the increase in Panicoideae plants is very likely to be an indicator of weeds in rice paddies. Most of the common weeds in rice paddies belong to Panicoideae, such as barnyard grass (*Echinochloa* sp.), and have been processed with rice since the beginning of rice domestication and cultivation in prehistoric China (Yang et al. 2015). The phytolith record presented in this study, provide important microfossil plant evidence that intensive rice farming might alter the surrounding vegetation landscape due to deforestation and reduction in woody plants and altered floral structure in herbaceous plants.

5. Conclusion

Based on analyses of phytolith, charcoal, and sediment geochemistry, together with AMS ^{14}C

and OSL dating from the reservoir sediment inside the MFL dam of the Liangzhu hydraulic system, our study revealed the duration of the use of the reservoir and reconstructed historical rice utilization and corresponding vegetation and landscape changes during and after the Liangzhu period. The dating results and changes in sedimentary facies indicated that the MFL reservoir was in use from 4,900 cal BP to 1,500 cal BP, lasting 3,200 years. The phytolith remains indicated that the rice had been fully domesticated since the Liangzhu cultural period, and intensive rice farming during 2,500–1,500 cal BP might transform the surrounding landscape through forest clearance and structural changes in grass plants. These findings provide new insights into understanding how rice cultivation practices impacted the environment in the Lower Yangtze River, as well as understanding the relationship between agricultural development and landscape changes.

Author contributions

Xiujia Huan: Conceptualization, Formal analysis, Investigation, Visualization, Writing - Original Draft, Writing - Review & Editing. **Jianping Zhang:** Conceptualization, Resources, Writing - Review & Editing. **Yijie Zhuang:** Writing - Review & Editing. **Chou Fan:** Resources. **Ningyuan Wang:** Resources. **Xiang Ji:** Resources. **Konglan Shao:** Investigation. **Keyang He:** Resources. **Jianhui Jin:** Investigation. **Xinxin Zuo:** Investigation. **Houyuan Lu:** Conceptualization, Writing - Review & Editing.

Data availability

The data used to support the findings of this study are included within the article and the raw data of this study are available from the corresponding author upon request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures and Tables

Figure 1 (A) Geographic location of the Liangzhu Site Cluster, (B) the structure of the Liangzhu hydraulic system (after Wang 2016), and (C) sampling of the MFL profile

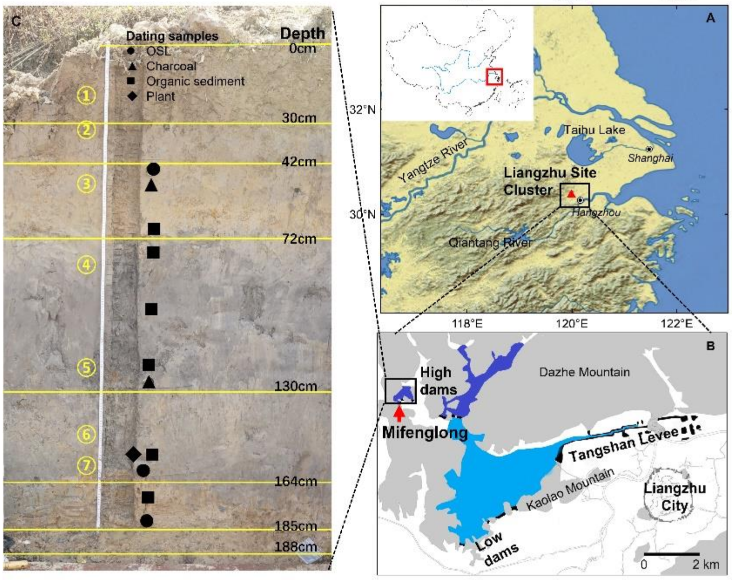

Figure 2 Age-depth model of MFL profile based on Bacon

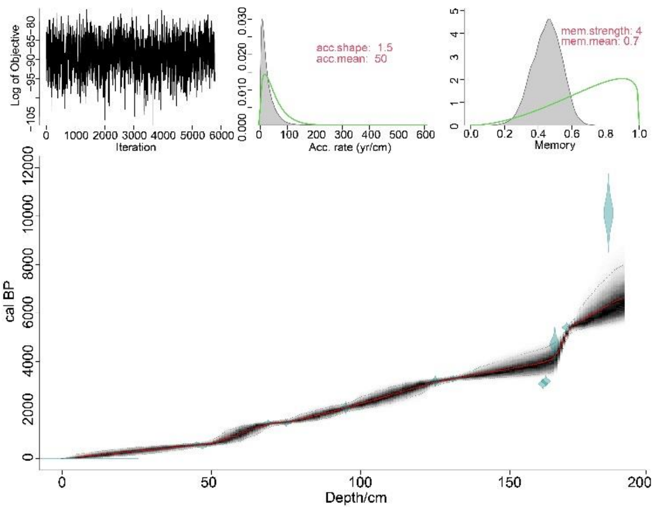

Figure 3 Phytoliths obtained from the studied profile

(a,b) Long saddle; (c) rondel; (d) bilobate; (e) multilobate; (f,g) trapeziform sinuate; (h) acicular hair cell; (i) sinuate elongate; (j) woody type; (k) reed bulliform; (l) square; (m) rectangle; (n) sedge type; (o) spherical crenate; (p,q) rice parallel-bilobate; (r–t) rice double-peaked; (u,v) rice bulliform with < 9 fish-scale decorations; (w–y) rice bulliform with ≥ 9 fish-scale decorations (scale bar 20 μm).

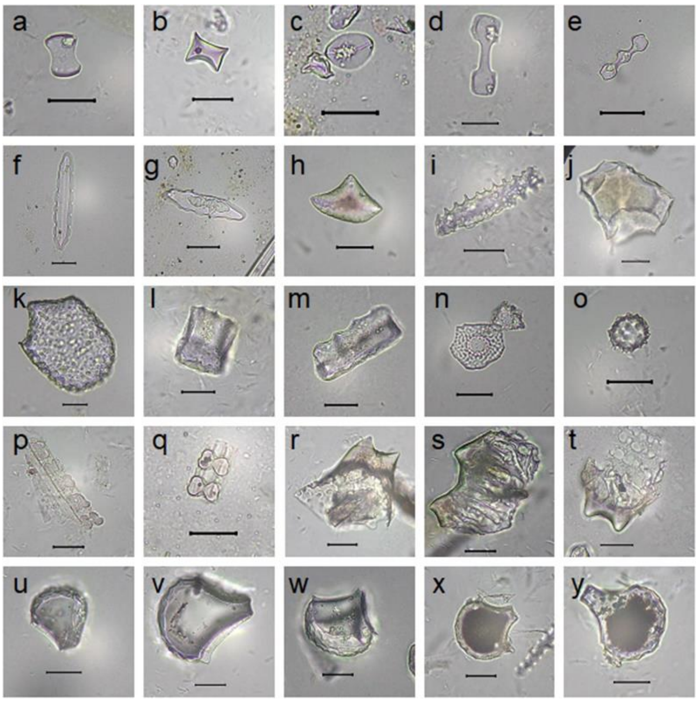

Figure 4 Percentage diagram of major phytolith types and geochemical results

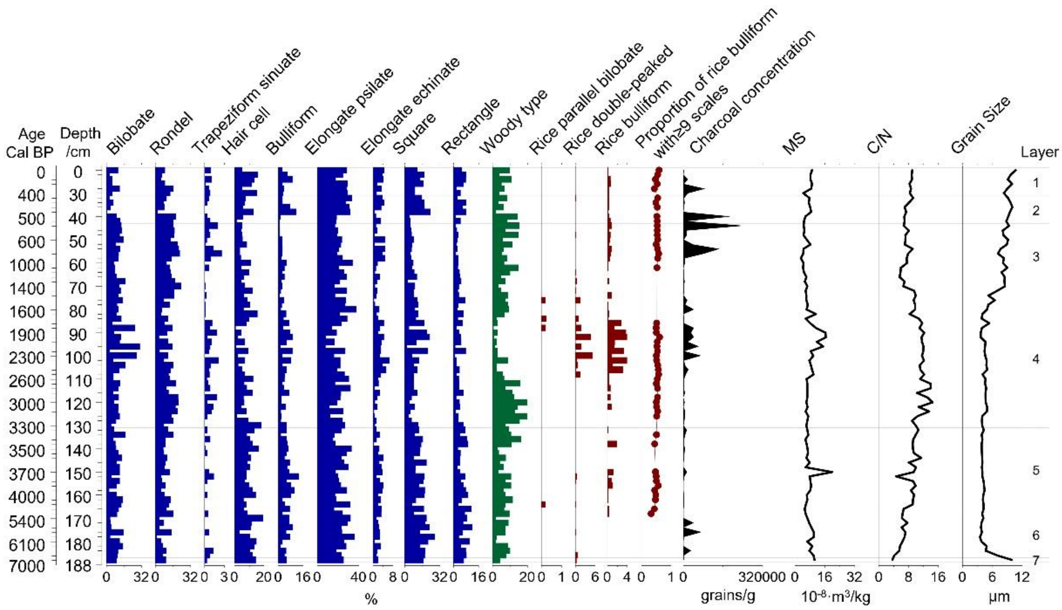

Figure 5 Percentage of phytolith taxa and corresponding cultural periods

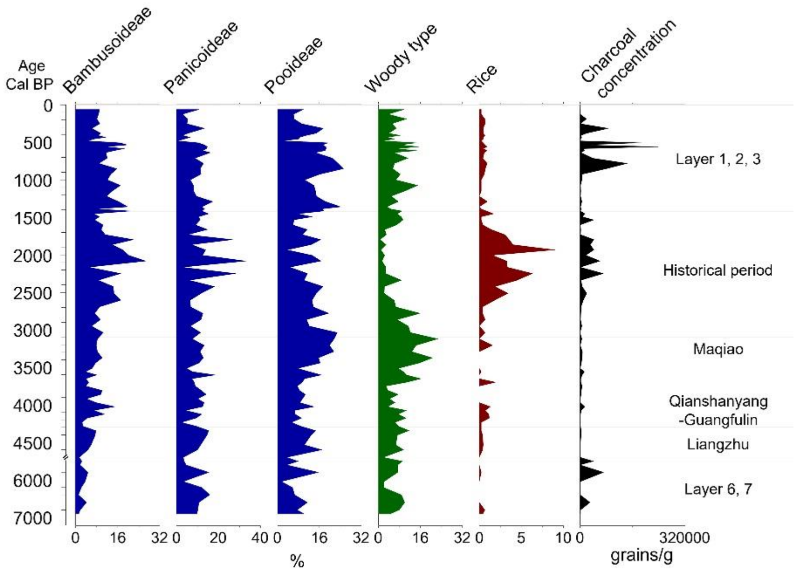

Table 1 AMS ^{14}C and OSL dating results

Lab code	Method	Material	Depth (cm)	Uncalibrated ^{14}C date (BP)	Calibrated dates (95% range, cal BP)	Mean & sigma (cal BP)
2018089	OSL	blocky sample	45–42	N/A	N/A	590±30
32522	AMS ^{14}C	charcoal	48–46	430±25	459–524	491±28
Beta-600921	AMS ^{14}C	organic sediment	70–68	1600±30	1405–1535	1469±38
Beta-598669	AMS ^{14}C	organic sediment	76–74	1600±30	1405–1535	1469±38
Beta-598668	AMS ^{14}C	organic sediment	96–94	2120±30	1998–2150	2092±69
Beta-600920	AMS ^{14}C	organic sediment	126–124	3000±30	3073–3225	3189±63
32523	AMS ^{14}C	charcoal	132–130	3080±25	3220–3365	3293±41
Beta-598667	AMS ^{14}C	organic sediment	162–160	3000±30	3073–3255	3189±63
Beta-599578	AMS ^{14}C	plant	162–160	2930±30	2965–3171	3080±56
2018086	OSL	blocky sample	165–162	N/A	N/A	4710±200
Beta-600919	AMS ^{14}C	organic sediment	170–168	4690±30	5319–5479	5403±58
2018085	OSL	blocky sample	183–180	N/A	N/A	10130±460