Quaternary International 519 (2019) 122–130

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Mid- to late Holocene vegetation change recorded at a Neolithic site in the Yangtze coastal plain, East China

Liang Tang[a,b], Junwu Shu[c], Jie Chen[d], Zhanghua Wang[a,b,*]

[a] State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai, 200062, China
[b] Institute of Urban Development, East China Normal University, Shanghai, 200062, China
[c] CAS Key Laboratory of Economic Stratigraphy and Palaeogeography, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing, 210008, China
[d] Shanghai Museum, Shanghai, 200003, China

ARTICLE INFO

Keywords:
Pollen
Rice cultivation
Agricultural activity
Aquatic plants
Hydrological environment
Sea-level rise

ABSTRACT

There has been an ongoing debate about human impacts on the evolution of the vegetation cover on the Yangtze delta plain dating back to the Neolithic period. In this study, we carried out pollen identification and grain size analysis on two sediment profiles obtained from the Neolithic Guangfulin site in the Yangtze delta. Together with published results of radiocarbon ages, organic elemental chemistry and archaeological findings, we reconstructed the palaeoecological evolution and human activities at the site during the mid- to late Holocene and distinguished between the impacts on vegetation induced by human and hydrological processes. The results show three events of significant reduction in the abundance of arboreal pollen, which occurred at *c.* 4635, 2000, and 800 cal yr BP, respectively. The first two events were accompanied by an obvious increase in Poaceae pollen, whereas the last one occurred with a sharp increase in the abundance of Brassicaceae pollen. These findings suggest that the reductions in arboreal pollen resulted from deforestation for the expansion of rice cultivation at *c.* 4635 and 2000 cal yr BP, and expansion of Brassicaceous oil crops *c.* 800 years ago. The change in cultivation pattern *c.* 800 years ago was consistent with the increase in population migration from northern China caused by war at that time. The pollen of aquatic plants increased sharply at *c.* 4500 cal yr BP, which reflected the change in hydrological environment related to sea-level rise at the Yangtze River mouth.

1. Introduction

Palynological studies show that vegetation change was affected by both climate change and human activities in the Holocene (Xiao et al., 2004; Chen et al., 2009; Innes et al., 2009, 2014; Shu et al., 2010). For example, Innes et al. (2014) reported the increase in abundance of *Pinus* in the Taihu plain, near the Yangtze coast at *c.* 4200 cal yr BP and linked it to the climatic cooling at that time. Other studies of the pollen records indicate that obvious human disturbance occurred, particularly at archaeological sites during the Neolithic time (Zong et al., 2007, 2012; Innes et al., 2009; Shu et al., 2010). At the Kuahuqiao site, south of Hangzhou Bay, deforestation for human settlement and rice farming was inferred from the significant decline in tree flora at 7700 cal yr BP (Zong et al., 2007; Innes et al., 2009). In the sedimentary record of Lake Chaohu in the lower Yangtze valley, Chen et al. (2009) reported a decline in the arboreal pollen at *c.* 5000 cal yr BP, which was suggested to be the result of deforestation by the Neolithic people. Further, Zong et al. (2012) suggested that human disturbance of the vegetation had increased significantly in the Yangtze delta plain during the late Neolithic period.

However, the nature of human disturbance of the vegetation during the late Neolithic period was debated for a long time because archaeological evidence showed that the prehistorical human population mainly utilized the swamp/marsh on the Yangtze coast that was easy to reclaim and manage (Zheng et al., 2009, 2012; Shu et al., 2010; Li et al., 2012; Wen et al., 2014; Wang et al., 2017). It was therefore proposed that deforestation by the prehistorical population should be limited to within a small area of the settlement sites even during the period of the highly developed Liangzhu culture (Shu et al., 2010; Li et al., 2012). Some other pollen studies in the Yangtze delta (Fig. 1a) also reported that human impacts on vegetation occurred mainly during the historical period of the late Holocene (Liu and Qiu, 1994; Yi et al., 2003, 2006).

The hydrological environment is also one of the critical factors controlling the vegetation in coastal plains (Hayden et al., 1995;

* Corresponding author. State Key Laboratory of Estuarine and Coastal Research, Institute of Urban Development, East China Normal University, Shanghai, 200062, China.
E-mail address: zhwang@geo.ecnu.edu.cn (Z. Wang).

https://doi.org/10.1016/j.quaint.2018.12.031
Received 27 March 2018; Received in revised form 17 August 2018; Accepted 31 December 2018
Available online 02 January 2019

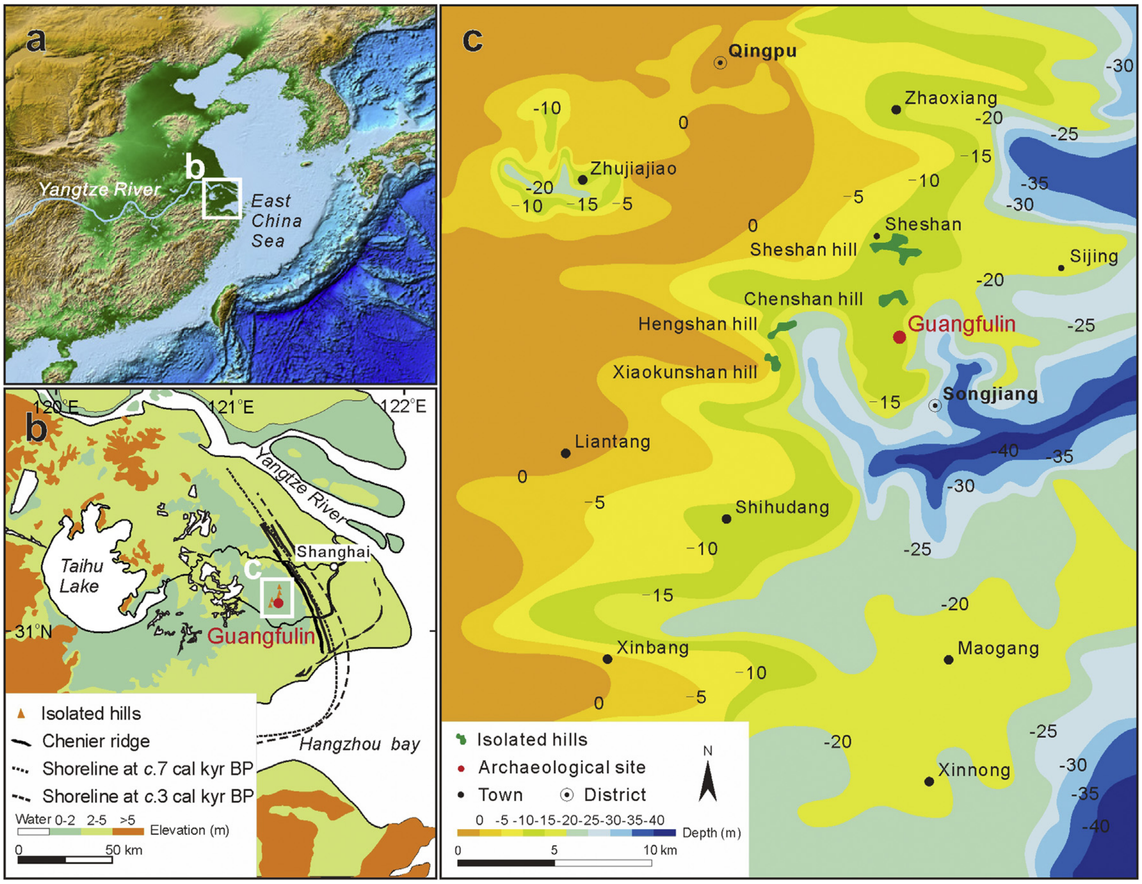

Fig. 1. (a) Location of the study area; (b) Geographical map showing the present topographic features and the positions of cheniers and palaeo-shorelines during the mid-Holocene; (c) Location of Guangfulin site and the palaeotopography of pre-Holocene base around (after Wang et al., 2014).

Röderstein et al., 2014) and it is directly affected by changes in sea level and freshwater supply (Chen et al., 2018). Previous studies of pollen indicate that the rising water table extensively occurred at the last stage of the Liangzhu culture in the Taihu plain (Zong et al., 2011, 2012). Our latest study on the coastal plain south of Hangzhou Bay revealed a rapid sea-level rise at *c.* 4510–4390 cal yr BP (Fig. 1b; Wang et al., 2018). It remains unclear whether the previously reported increase in water level inferred from the pollen records (Zong et al., 2011, 2012) is the response of vegetation linked to this sea-level rise on the Yangtze coast.

Furthermore, we examined those published profiles from the Yangtze coast and found limited age constraints from the late stage of the Neolithic culture. We suggest that the lack of chronology will restrict full understanding of the complicated processes of vegetation change resulting from both natural and human's impact. Hence, in this study we used two profiles obtained during the excavation of the Neolithic Guangfulin site on the east Taihu plain (Fig. 1) and analysed pollen records and grain size. Combined with published results of organic chemistry and AMS ^{14}C dating (Wang et al., 2014), we investigated the changes in vegetation at this site from the late Neolithic period and reconstructed human activities and hydrological environmental change influenced by sea level.

2. Study area and the Neolithic Guangfulin site

The Taihu plain on the south Yangtze coast is a low-lying area with mean ground elevation of 2–5 m (Fig. 1b). A series of chenier ridges occur in the eastern plain, which were inferred to be the coastlines during the mid- to late Holocene (Yan et al., 1989). The climate of the study area is subtropical monsoon with a mean annual temperature of 16–18 °C and mean annual precipitation of 1123 mm. The regional vegetation is characterised by subtropical mixed evergreen and deciduous broad-leaved forests. Major arboreal taxa are *Cyclobalanopsis*, *Castanopsis*, *Lithocarpus*, *Quercus*, *Castanea*, and *Liquidambar formosana*; aquatic taxa are dominated by *Nelumbo nucifera*, *Zizania caduciflora*, *Sagitaria*, *Trapa bispinosa*, *Lemna minor*, Potamogetonaceae, *Typha*, *Azolla imbricata*, and *Salvinia natans* (Wu, 1980). At the present time, natural vegetation is difficult to find because of the long history of human disturbance in this area.

The Neolithic Guangfulin site (31°3′51.05″N and 121°11′38.42″E; Fig. 1) is located southwest of Shanghai with ground elevation of 3–4 m (Yellow Sea datum; Song et al., 2003). There are several hills to the west and northwest of the site. The palaeotopography of the pre-Holocene base shows that this site was located on the terrace of an incised palaeo-valley (Fig. 1c; Wang et al., 2014). The archaeological findings of artefacts and AMS ^{14}C dating revealed that prehistorical humans started to settle at this site at *c.* 5500 cal yr BP (Chen et al., 2010). This site was occupied by the people of prehistorical late Songze (*c.* 5500–5300 cal yr BP), Liangzhu (*c.* 5300–4400 cal yr BP), and Guangfulin cultures (*c.* 4300–3900 cal yr BP), and those during the historical period (Chen et al., 2010). During an archaeological excavation in 2008, housing sites, graves, and rice paddy fields of the Guangfulin culture were uncovered (Huang et al., 2014). Archaeologists also found relics of marshes, lakes and river channels beside the settlement (Huang et al., 2014; Wang et al., 2014).

3. Materials and methods

3.1. Stratigraphy of profiles GFL-A and GFL-B

Two profiles, GFL-A and GFL-B, were obtained from buried marsh

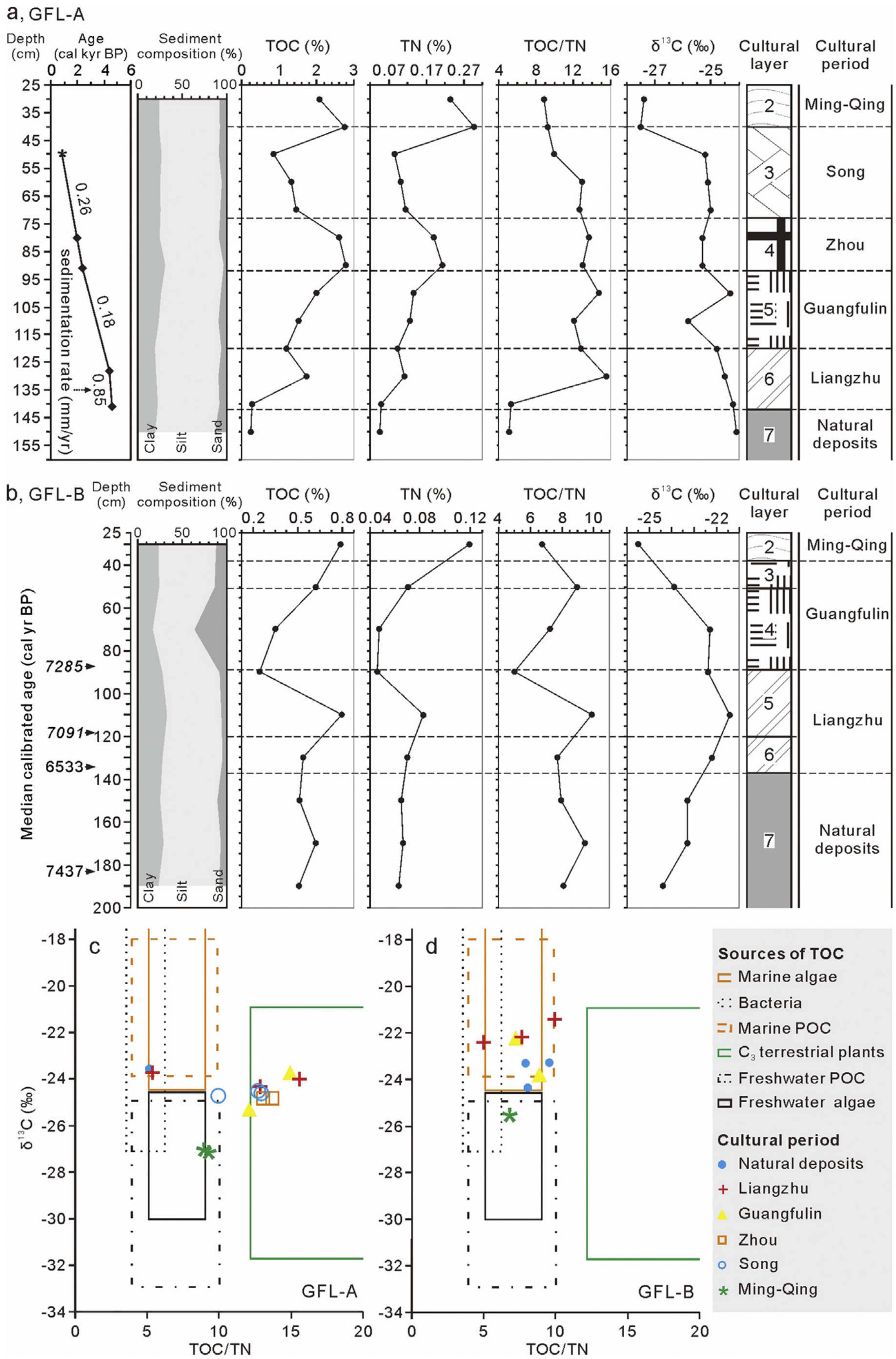

Fig. 2. (**a**), (**b**): Composite depth profiles of GFL-A and GFL-B showing radiocarbon ages, sediment composition, total organic carbon (TOC), total nitrogen (TN), TOC/TN ratio, stable isotope $\delta^{13}C$, cultural layer and period. (**c**)–(**d**): Plots of $\delta^{13}C$ versus TOC/TN to discriminate the organic carbon sources for profiles GFL-A and GFL-B (Lamb et al., 2006). The age with * was calculated according to the sedimentation rate. The ages in italic in profile GFL-B are supposed to be derived from old carbon (Wang et al., 2012).

and river channel environments, respectively, at the site in 2008 (Wang et al., 2014). Profile GFL-A was from the western wall of 08SG I T5422, and is 160 cm deep. Profile GFL-B was from the western wall of 08SG I T4819 and is 200 cm deep.

According to field observations, profile GFL-A can be divided into seven units (Fig. 2a). Unit 7 (160–142 cm) consists of light grey soft mud and contains no artefacts. It was inferred to be the natural deposits before human cultivation. Unit 6 (142–120 cm) is greenish grey mud with artefacts of the late Liangzhu culture. Unit 5 (120–92 cm) is greenish grey soft mud with artefacts of the Guangfulin culture. Unit 4 (92–73 cm) is grey soft mud with pottery of the Zhou dynasty. Unit 3 (73–40 cm) is black mud with artefacts of the Song dynasty. Unit 2 (40–25 cm) is brownish yellow hard mud with celadon and fragments of pottery of the Ming and Qing dynasties. Unit 1 (25–0 cm) is a modern rice paddy soil.

Profile GFL-B can also be divided into seven units (Fig. 2b). Unit 7 (200–137 cm) consists of grey mud without artefacts and was inferred to be the natural deposit before human settlement. Unit 6 (137–120 cm) is a light grey mud with Liangzhu artefacts. Unit 5 (120–89 cm), a greenish grey mud in the lower section and dark grey sticky mud in the

Table 1
AMS^{14}C ages at Neolithic Guangfulin site reported by Wang et al. (2014). All ages were recalibrated using the Calib. v. 7.1 program (Stuiver et al., 2017).

Profiles	Depth	Dating material	δ^{13}C	Conventional^{14}C age	Calibrated age (cal yr BP)			Laboratory
	(cm)		(‰ VPDB)	(yr BP, ± 1σ)	2 sigma	Probability	Median	number
GFL-A	80	Organic-rich mud	−33.8	2031 ± 28	1919–2061	0.954	1980	XA4800
	91	Organic-rich mud	−34.05	2376 ± 33	2338–2491	0.971	2404	XA4801
	128	Organic-rich mud	−26.52	4019 ± 29	4420–4534	0.970	4480	XA4802
	141	Organic-rich mud	−25.67	4111 ± 29	4525–4813	1	4633	XA4803
GFL-B	87	Organic-rich mud	−23.51	6350 ± 38	7174–7415	1	7285	XA4804
	118	Organic-rich mud	−19.47	6205 ± 29	7004–7179	0.941	7091	XA4805
	134	Organic-rich mud	−19.44	5737 ± 30	6451–6633	1	6533	XA4806
	183	Organic-rich mud	−21.56	6518 ± 35	7412–7500	0.846	7437	XA4807

upper section containing pottery of the Liangzhu culture. Unit 4 (89–51 cm) is greenish grey mud with grey pottery of the Guangfulin culture. Unit 3 (51–38 cm), a light yellowish brown mud, contains burnt earth and artefacts of the Guangfulin culture. Unit 2 (38–25 cm) is a brownish yellow hard mud dating from the Ming and Qing dynasties. Unit 1 (25–0 cm) is the modern rice paddy soil.

3.2. AMS ^{14}C ages and organic carbon sources in the two profiles

Eight samples of organic-rich mud were collected from two profiles and were dated by AMS ^{14}C method in the Xi'an Accelerator Mass Spectrometry Center, China (Wang et al., 2014). Here we recalibrated the ages using the Calib. v. 7.1 program (http://www.sciencedirect.com/science/article/pii/S104061821630074X?via=ihub; Stuiver et al., 2017, Table 1).

The published organic chemistry (Wang et al., 2014) was used in this study to help with interpretation of the sedimentary environment (Fig. 2). In the profile GFL-A, the level of TOC is generally low and the organic carbon is dominated by marine algae and particulate organic carbon (POC) at 160–140 cm (before *c.* 4600 cal yr BP; Fig. 2a, c). TOC rises obviously and terrestrial C_3 plants prevailed in the Liangzhu and Guangfulin cultural layers. TOC reaches the maximum concentration in the profile in the layer of the Zhou dynasty and then declines sharply in the layer of the Song dynasty. The organic carbon was contributed mainly by terrestrial C_3 plants in both these layers. TOC increases again in the layer of the Ming-Qing dynasties, and the organic carbon is contributed predominately by freshwater algae and POC (Fig. 2a, c). In the profile GFL-B, TOC is generally low, and the lowest value appears at the top of the Liangzhu layer (at *c.* 90 cm; Fig. 2b, d). The organic carbon is derived from marine algae and POC below 38 cm (layers of the Guangfulin, Liangzhu and natural deposits) and from freshwater algae in the layer of the Ming-Qing dynasties (Fig. 2d). Such organic chemistry indicates that marsh and lacustrine environments prevailed at GFL-A and a tidal channel occurred at GFL-B during the prehistorical period.

3.3. Grain size and pollen analyses

For grain size analysis, 13 samples *c.* 2.5 cm thick were taken at 10 cm intervals from profile GFL-A, and nine samples *c.* 5 cm thick were collected at 20 cm intervals from profile GFL-B. After mixing and drying, a *c.* 0.1 g specimen was taken from each sample and was pretreated with 10% H_2O_2 and 10% HCl to remove organic matter and carbonates respectively, and then washed in distilled water to remove residual HCl. Finally 5 ml of 5% $Na(PO_3)_6$ was added to each sample before shaking in an ultrasonic bath for 15 min to prevent flocculation of fine-grained particles. Measurements were performed with a Beckman Coulter Laser Diffraction Particle Size Analyzer (LS13320), at the State Key Laboratory of Estuarine and Coastal Research, East China Normal University.

At least two samples were taken from each cultural layer for pollen analysis. The thickness of each sample in profiles GFL-A and GFL-B is *c.* 2.5 cm and *c.* 5 cm, respectively. Altogether 26 samples were collected from the profiles. Preparation and identification of pollen, spores, and algae was carried out in the Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences (NIGPCAS). Preparation followed the standard procedure developed by Moore et al. (1991) including successive treatments with 10% HCl to dissolve calcareous minerals, 10% NaOH to remove humus acid, and 40% HF to digest silicates. Pollen identification was performed under a Leitz microscope, at × 400 magnification, with the help of references on modern pollen and spores (Beijing Institute of Botany, Academia Sinica, 1976; Institute of Botany and South China Institute of Botany, Academia Sinica, 1982; Wang et al., 1995) as well as modern pollen keys kept in NIGPCAS. Pollen counts were conducted until the total of terrestrial pollen including arboreal and terrestrial herbs exceeded 200 grains. The relative abundance of arboreal and terrestrial herbs was expressed as a percentage relative to the sum of the terrestrial taxa in a sample, while the relative abundance of aquatic herbs, ferns and algae was calculated based on the sum of all counted palynomorphs. Pollen diagrams were constructed using Tilia 2.0.41 and zones were determined based on cluster analysis using the CONISS function in the program (Grimm, 1987). According to the size, aperture and ornamentation, *Quercus* was assigned to evergreen (*Quercus*-E) and deciduous (*Quercus*-D) types; i.e., those of tricolporoidate or tricolporate with fine granular sculpture on pollen surface were assigned to *Quercus*-E, while those of tricolpate with coarsely granulated ornamentation were counted as *Quercus*-D (Zhang and Wang, 1986; Liu et al., 2007). In addition, based on morphological researches of modern Poaceae pollen, the pollen grains of most cultivated rice (*Oryza sativa*) especially after HF treatment is mostly ≥ 35 μm in diameter, so Poaceae (≥35 μm) was used as a criteria in this paper to indicate the probability of human rice farming (Shu et al., 2007; Wang et al., 2010a; Yang et al., 2012).

4. Results

4.1. Grain size and interpretation of the sedimentary environment

The sediment in GFL-A from the marsh environment is dominated by silt (68%) throughout the profile (Fig. 2a). The mean contents of clay and sand fractions are 24% and 8%, respectively. There is little change in the grain size distribution except a slight increase in clay content from the layer of the Guangfulin culture upwards (Fig. 2a). The frequency curves of grain size are characterised by a narrow and steep peak between 27.4 and 30.1 μm and a secondary peak at 194.2 μm for the sediments below 140 cm (the natural deposits and the lower part of Liangzhu layer; Fig. 3a and b). Frequency curves of the samples above 140 cm are slightly wider with gentle slope and peak values occurring at 14.3–27.4 μm (Fig. 3b–f). Therefore, no obvious change in the sedimentary environment occurred in profile GFL-A. The change in the shape of frequency curves above 140 cm reflects a slight increase in fine-grained sediments that were deposited in the still-water environment, which may indicate an increase in the local water table.

In GFL-B, located in the buried tidal channel environment, on

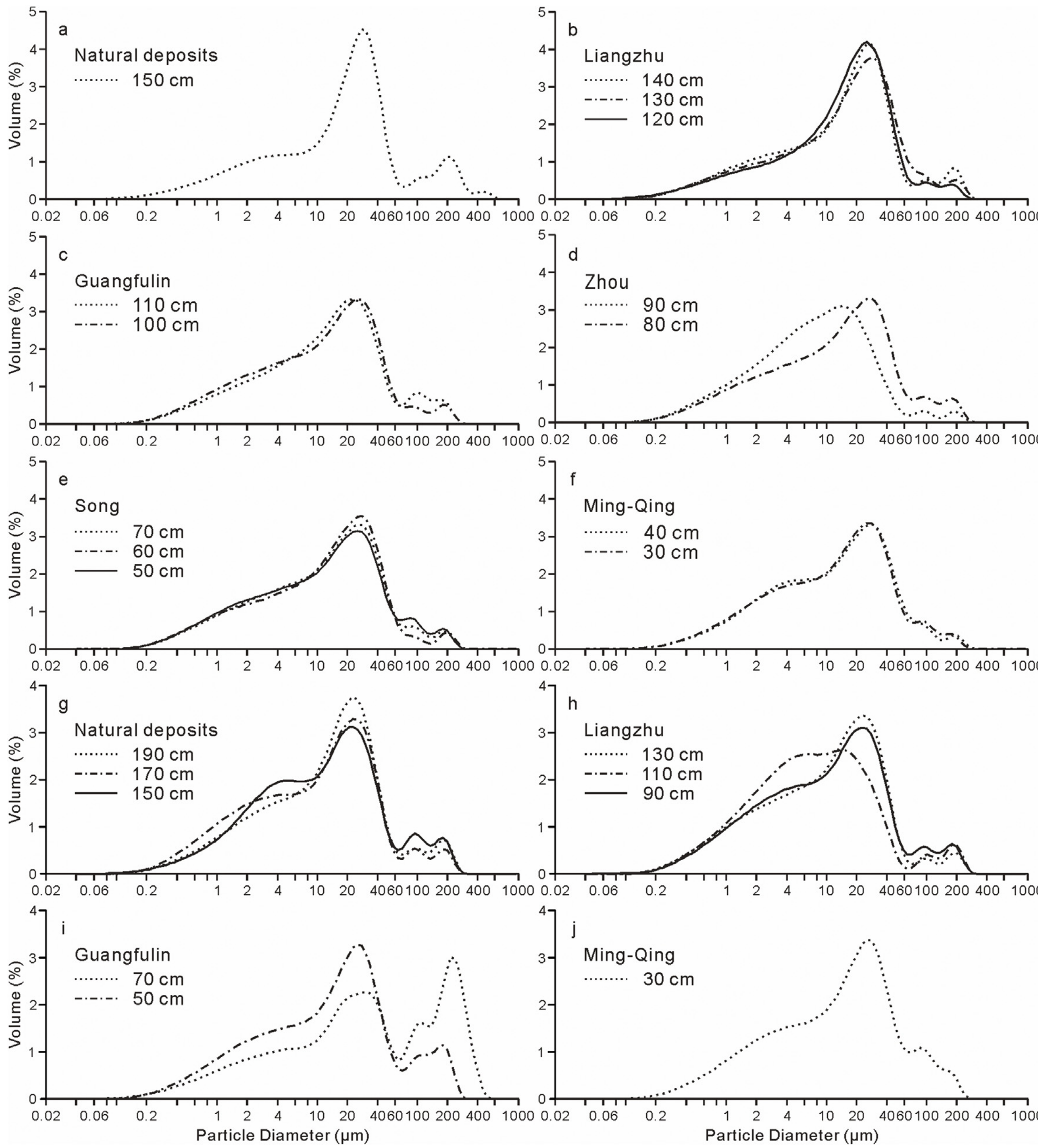

Fig. 3. Grain size frequency curves of representative samples from profiles GFL-A (a–f) and GFL-B (g–j) at Guangfulin site. Little change occurred in the peak size and shape of the curve for samples from GFL-A. In contrast, an obvious peak at *c.* 200 μm occurred for the samples of Guangfulin cultural layer in GFL-B, indicating strong water currents.

average the content of silt is around 62%, clay 26%, and sand 12% (Fig. 2b). Grain size is consistent from the natural deposit layer to the layer of the Liangzhu culture. The sand content increases sharply in the Guangfulin cultural layer, and then decreases in the layer of the Ming and Qing dynasties (Fig. 2b). The frequency curves of grain size are wide and gentle with a major peak at 14.3–27.4 μm and a secondary peak at *c.* 4 μm for sediments in layers of the natural deposit, Liangzhu culture and Ming-Qing dynasties (Fig. 3g, h, j), which possibly reflect water currents during the ebb and flood tides. In the layer of the Guangfulin culture, there are two obvious peaks. The one at *c.* 25 μm is consistent with samples in the other layers, but the other at *c.* 200 μm suggests this was a tidal channel possibly experiencing storm events (Fig. 3i).

4.2. Pollen assemblage

Four pollen zones were recognized for GFL-A and three for GFL-B based on the cluster analyses of the relative (percentage) abundance (Fig. 4). The absolute (concentration) abundance of GFL-A (Fig. 5) is also displayed to help interpret vegetation change.

4.2.1. Profile GFL-A

Zone 1 (before c. 4500 cal *yr BP; 160*–130 cm*; natural deposit and the bottom section of the Liangzhu layer)*. The lowest pollen concentration (1070–2882 grains/g) of the whole profile occurred in this zone. Arboreal taxa dominate the pollen assemblages with a mean percentage of 64% (Fig. 4). *Pinus* and evergreen *Quercus* are the most abundant taxa. Deciduous *Quercus* and *Ulmus* maintain moderate abundance. Pollen of *Betula*, *Corylus*, *Liquidambar* and *Juglans* occurred sporadically. The herbaceous pollen was mostly composed of Poaceae (< 35 μm)

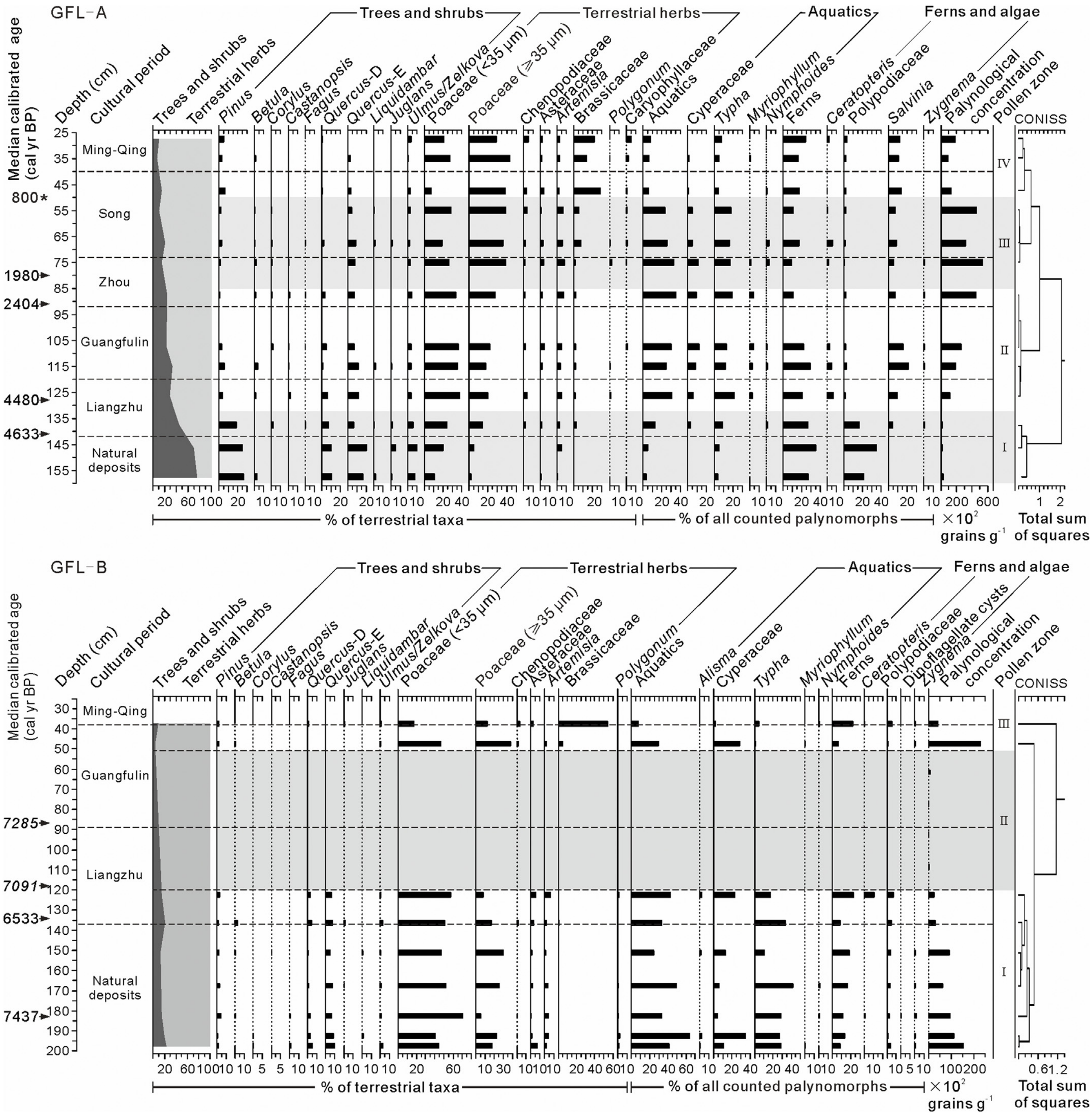

Fig. 4. Pollen percentage diagrams of selected taxa for profiles GFL-A and GFL-B at Guangfulin site. Grey brands represent pollen zones. Dashed lines are cultural layer boundaries. The age with * was calculated according to the sedimentation rate.

(11–24%), while the Poaceae (≥ 35 μm) has a low percentage (2–14%). *Artemisia* (1–5%) generally occurs. Aquatic pollen, mainly *Typha* (4–9%), appears with relatively low values. Fern spores that were contributed mostly by Polypodiaceae (16–35%) are abundant.

In addition, pollen assemblages changed apparently at *c.* 4600 cal yr BP. Before this both the percentage and concentration of arboreal pollen are higher, being > 73% and 1276 grains/g on average, respectively. After *c.* 4600 cal yr BP, the pollen was predominantly contributed by terrestrial herbs (54%), particularly the Poaceae (Fig. 4), of which the < 35 μm pollen increased to 24% and the ≥ 35 μm pollen increased obviously to 14%. The abundance of aquatic plant pollen such as *Typha* and Cyperaceae increased slightly, and *Nymphoides*, *Salvinia* and *Zygnema* appeared at low levels. Both the percentage and concentration of Polypodiaceae decreased substantially. Freshwater algae *Zygnema* appeared at relatively low levels.

*Zone II (c. 4500–*2000 *cal yr BP; 130–*85 cm*; the upper section of the Liangzhu layer to the lower section of the Zhou dynasty)*. Pollen concentrations increased obviously in this zone. The percentage of arboreal pollen decreased to 16–34%, while its concentration increased obviously upwards and reached a peak (2289–7568 grains/g) at the top of this zone (Fig. 5). By contrast, both the percentage and concentration of terrestrial herbs increased (66–76%, 5396–23460 grains/g) in this zone, among which the abundance of Poaceae (< 35 μm) increased significantly, while the ≥ 35 μm fraction changed slightly. The

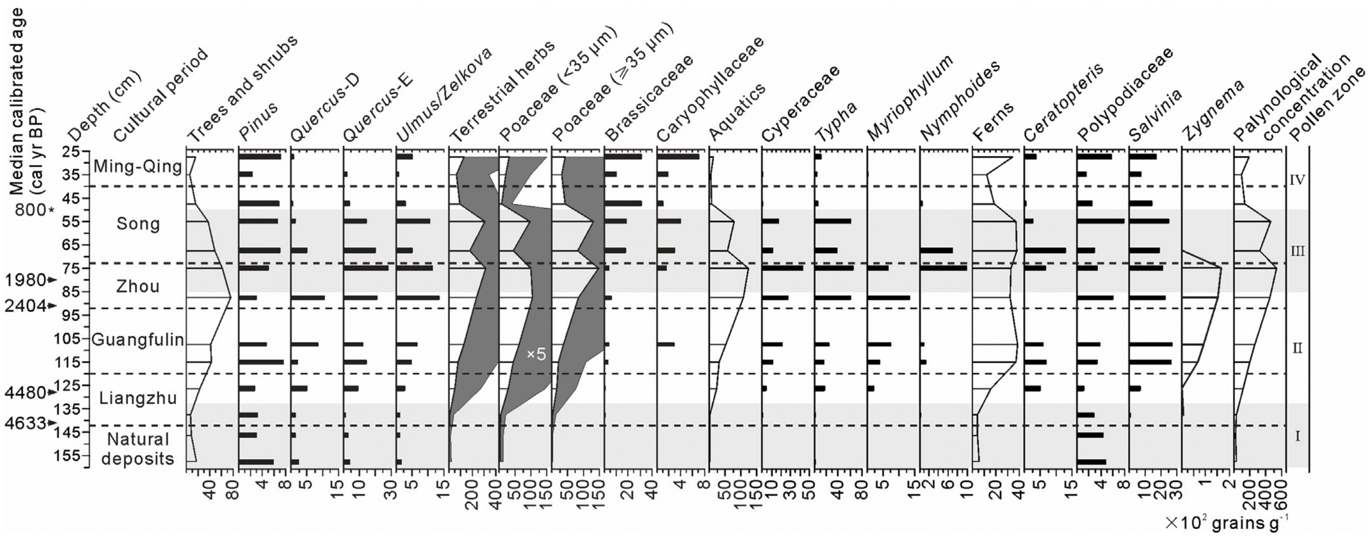

Fig. 5. Diagram showing pollen concentrations of selected taxa from profile GFL-A at the Guangfulin site. Grey brands represent pollen zones. Dark-grey silhouettes show values exaggerated × 5. Dashed lines are cultural layer boundaries. The age with * was calculated according to the sedimentation rate.

abundance of aquatic pollen also increased obviously (25–35%, 2344–10746 grains/g), consisting mostly of *Typha* and Cyperaceae. Other wetland plants such as *Myriophyllum* (3–4%) and *Ceratopteris* (3–6%) were present and the abundance of *Salvinia* increased obviously from 9 to 21% and 709–2708 grains/g. Freshwater algae *Zygnema* appeared sporadically.

Zone III (c. 2000–800 cal *yr BP; 85*–50 cm*; the upper section of the Zhou dynasty and the mid and lower section of the Song dynasty)*. The total pollen concentration in this zone increased to the highest values (32156–53320 grains/g) of the entire profile. However, the concentration of arboreal pollen dropped rapidly upward (Fig. 5), and its percentage was lower than in Zone II and kept decreasing upwards (Fig. 4). The percentage of Poaceae (< 35 μm) is also lower than that in the underlying zone with some fluctuation. In contrast, both the percentage and concentration of Poaceae (≥ 35 μm) increased obviously compared with Zone II. Aquatic pollen, in particular *Typha* and Cyperaceae, was still abundant (23–33%), but decreased slightly upward. *Myriophyllum* and *Nymphoides* disappeared in the upper part of this zone. Spores that were dominated by *Salvinia* and *Ceratopteris* decreased compared with those in Zone II.

Zone IV (from c. 800 cal *yr BP; 50*–25 cm*; the upper section of the Song dynasty and the layer of the Ming-Qing dynasties)*. In this zone the pollen concentration declined to 9139–18715 grains/g. Both the percentage and concentration of arboreal pollen further reduced (8–15%, 578–1665 grains/g). The concentration of terrestrial herbs, especially Poaceae (both ≥ 35 μm and < 35 μm), decreased significantly, but the percentage of Poaceae (≥ 35 μm) remained at high level. The abundance of Brassicaceae pollen increased sharply (21% and 2393 grains/g on average), while the abundance of aquatic pollen dropped considerably.

4.2.2. Profile GFL-B

In GFL-B, pollen concentrations were low (59–15325 grains/g and 5164 grains/g on average) except in the top section of the Guangfulin layer (22974 grains/g). Terrestrial herbs dominate throughout the profile (85% on average).

Zone I (200–120 cm*; natural deposit and the lower section of the Liangzhu layer)*. Pollen concentration was the highest in the profile (2411–15325 grains/g) and decreased upwards. Terrestrial herbs, mainly Poaceae (61–78%) dominated in all taxa. The average abundance of Poaceae (< 35 μm) was *c.* 52% and Poaceae (≥ 35 μm) *c.* 18%. Pollen of arboreal taxa was 14–24% and dominated by evergreen *Quercus* (6–14%). Other species such as deciduous *Quercus*, *Pinus* and *Ulmus* have low values (1–3%). Species of *Corylus*, *Fagus*, and *Liquidambar* appeared only sporadically. Ferns were dominated by Polypodiaceae and the content was stable at *c.* 14%. Marine species of dinoflagellate cysts appeared sporadically.

Zone II (120–51 cm*; upper section of the Liangzhu culture and the mid- and lower section of the Guangfulin culture)*. Pollen concentrations decreased significantly in this zone and it is not possible to calculate the relative abundance of each species owing to the very low concentrations (59–589 grains/g, 239 grains/g on average).

Zone III (51–25 cm*; upper section of the Guangfulin culture and the layer of the Ming-Qing dynasties)*. Terrestrial herbs still dominated with an average percentage of *c.* 93% in this zone. The most abundant plant was Poaceae (*c.* 84%) in the layer of the Guangfulin culture. In the layer of the Ming-Qing dynasties Brassicaceae (*c.* 54%) became dominant. The abundance of aquatic herbs remained high in the Guangfulin cultural layer, and dropped sharply in the layer of the Ming-Qing dynasties.

5. Discussion

5.1. Differences in the pollen records of the two profiles

There are significant differences between the GFL-A and GFL-B profiles in terms of pollen concentrations and assemblages. In GFL-A, pollen concentration is high and taxa are diverse, and characterised by obvious changes in abundance of arboreal and herbaceous pollens and fern spores (Figs. 4 and 5). In GFL-B, pollen concentration is much lower and taxa are dominated by herbs throughout the profile. We suggest that sedimentary environment plays a key role in the production and preservation of pollen in these two profiles. The high content of TOC and consistent grain size at GFL-A (Fig. 2a) reflects a stable closed marsh environment with high plant productivity and good conditions for pollen preservation in the sediments (Landman and Jones, 2007).

A river channel environment was identified at GFL-B during the archaeological excavation (Wang et al., 2014). The low content of TOC and its dominant contribution from marine algae/POC (Fig. 2b, d), together with the appearance of marine dinoflagellate cysts (Fig. 4b) indicate that this river channel was connected to the sea and influenced by tidal currents. Furthermore, the peaks around 200 μm in the frequency curve of grain size for the sediments in the Guangfulin cultural layer (Fig. 3i) are evidence of strong water currents which could be the records of a storm event because the organic chemistry change indicates an increase in organic carbon with a marine source at that time (Fig. 2b). Such an open and unstable hydrological environment significantly limited the contribution of local pollen (Xu et al., 2001; Li et al., 2004; Landman and Jones, 2007). Moreover, the pollen fossils preserved in sediments of such environments are always transported from other places by currents (Xu et al., 2001). We thus suggest that the pollen distribution in GFL-B is not suitable for reconstruction of the local vegetation. However, the useful information we can derive from this profile is that its relatively high abundance of Poaceae infers a rich resource of grass species including wild rice (*Oryza rufipogon*) at the site, which is advantageous for rice cultivation. The vegetation changes as discussed in Section 5.2 below are thus mainly derived from the pollen record at GFL-A, where the marshes persisted throughout the period covered by this study.

5.2. Vegetation change and its implications for agricultural activities during the mid to late Holocene

Pollen records from GFL-A show three major changes in vegetation, which we suggest were linked to agricultural activities (Fig. 4). The first change occurred at *c.* 4635 cal yr BP when the vegetation of mixed broadleaf and conifer woodland dominated by *Pinus* and *Quercus* changed abruptly into Poaceae-dominated grassland. This change occurred on the boundary between the undisturbed natural deposit and the Liangzhu cultural layer, and is characterised by an increase in abundance of Poaceae ($\geq 35\,\mu m$; Figs. 4 and 5). We suggest that this was mainly the result of rice cultivation through marsh reclamation by the Liangzhu people, which reflected an expansion/intensification of agricultural activity at the late stage of the Liangzhu period. The decline in abundance of Polypodiaceae also implies woodland clearance because this fern prefers living in the woods (Figs. 4 and 5; Jiang et al., 2008). Further, the increase in abundance of aquatic plants including *Typha*, *Nymphoides* and *Salvinia* and open shallow water algae *Zygnema* (Fig. 4) suggests the formation of a freshwater wetland at that time, and this is supported by the dominance of organic carbon sourced from terrestrial C_3 plants after 4635 cal yr BP (Fig. 2c). We suggest such changes in the hydrological and ecological environment provided the favorable precondition for rice cultivation by the Liangzhu people.

The second obvious increase in Poaceae ($\geq 35\,\mu m$) and decrease in arboreal taxa occurred at *c.* 2000 cal yr BP (Figs. 4 and 5). This change was accompanied by an increase in the pollen related to cultivation, mainly Brassicaceae and Caryophyllaceae (Li et al., 2008), which indicates that rice agriculture expanded once again with the deforestation. This deforestation was also shown in the Qingpu profile (Itzstein-Davey et al., 2007; Atahan et al., 2008), *c.* 30 km to the northwest of the Guangfulin site. We suggest that human activities intensified in the east Taihu plain at *c.* 2000 cal yr BP. Previous studies also reported the intensified human activities *c.* 2000 years ago in the Yangtze basin (Saito et al., 2001; Wang et al., 2011). Historical documents have shown that *c.* 2000 years ago with the establishment of the unified and prosperous Han dynasty, an increase in the human population was recorded (Sun, 1992; Shang, 2003; Yu, 2009). We thus suggest that this expansion of rice cultivation in the Taihu plain is a response to the increase in human population at that time.

The abundance of arboreal pollen fell again at *c.* 800 cal yr BP (upper part of the Song cultural layer; Figs. 4 and 5), indicating further deforestation. We infer that this intensified deforestation occurred following the defeat of the Northern Song dynasty by the Liao nomads leading to southward migration from the Yellow River basin at that time (Qu and Li, 1992; Ge et al., 1993). At this stage, Brassicaceae economic oil crops (most likely *Brasscia campestris* var. *purpuraria*), a group of cultivated plants that favor dry land (Shu et al., 2007; Li et al., 2008) increased sharply in abundance in both GFL-A and GFL-B (Fig. 4). Meanwhile, the abundance of Poaceae decreased. The increase in Brassicaceae *c.* 800 years ago was also recorded in the sediments of the subaqueous Yangtze delta (Wang et al., 2010b). We thus suggest that the population migration from the northern China led to a change in agricultural pattern and associated vegetation in the Taihu plain *c.* 800 years ago. This speculation is consistent with a previous report about increased soil and rock erosion in the upper Yangtze basin owing to this population movement (Wang et al., 2011).

5.3. Expansion of aquatic plants during the late stage of the Neolithic period

In the late stage of the Liangzhu culture, aquatic plants, particularly *Typha* and Cyperaceae increased significantly at *c.* 4480 cal yr BP (Fig. 4). The occurrence of *Myriophyllum* and *Ceratopteris* and the increase in *Salvinia* further indicates an expansion and deepening of the water bodies at the site (Shu et al., 2007). We suggest that this rise of local water level at the Guangfulin site, which is consistent with previous reports from other sites in the Taihu plain (Wang et al., 2010a; Zong et al., 2011, 2012; Innes et al., 2014), was induced by the abrupt sea-level rise during 4500–4400 cal yr BP (Wang et al., 2018). Little change occurred in the abundance of Poaceae ($\geq 35\,\mu m$; Fig. 4a), while the concentration of arboreal pollen clearly increased from *c.* 4480 cal yr BP (Fig. 5), indicating no expansion of agricultural activity in the late stage of the Liangzhu culture. Thus, we suggest the obvious increase in Poaceae ($< 35\,\mu m$) at that time (Fig. 4a) was the result of the expansion of the inundated area and possibly the increase in reed communities (*Phragmites communis*) that is a major species of Poaceae that favors coastal wetlands (Li et al., 2006; Shu et al., 2010).

Aquatic vegetation was dominant in the Neolithic Guangfulin cultural layer, induced by the high relative sea level at that time (Wang et al., 2018). In addition, the abrupt coarsening of the sediments and increase in marine contribution of organic carbon in the Guangfulin cultural layer in GFL-B (layer 4; Fig. 2b) indicate an increase in coastal flooding and possibly in extreme events. Archaeological excavation also produced evidence of flooding beside the abandoned houses at this site during the Guangfulin period (Huang et al., 2014). We speculate that the rising water level and increase in flooding restricted agricultural activity during the Guangfulin cultural period, and that this explains the recovery of woodlands as evidenced by the increase in the concentration of arboreal pollen in the Guangfulin cultural layer (Fig. 5).

6. Conclusions

We reconstructed the evolution of the vegetation cover and linked it to human activity and hydrological environmental change at the Neolithic Guangfulin site in the Yangtze delta plain, based on pollen and grain size analyses, together with published results of radiocarbon ages, organic carbon, and archaeological findings. We revealed four periods of change in vegetation during the mid- to late Holocene. We conclude that three of these changes at *c.* 4635, 2000 and 800 cal yr BP were mainly induced by human agricultural activities, while the other one at *c.* 4500 cal yr BP was the result of hydrological environmental change controlled by sea-level rise at that time.

(1) The abrupt decrease in arboreal pollen and the increase in Poaceae ($\geq 35\,\mu m$) at *c.* 4635 cal yr BP resulted from the clearing of arboreal plants by the Liangzhu people for rice cultivation following the freshening of the wetland.
(2) A significant increase in aquatic plants from *c.* 4500 cal yr BP indicated the expansion of wet areas, in response to relative sea-level rise in the Yangtze River mouth.
(3) Poaceae ($\geq 35\,\mu m$) further increased accompanied by a decline in arboreal pollen at *c.* 2000 cal yr BP, suggesting the expansion of rice cultivation related to an increase in the human population.
(4) Brassicaceae increased significantly from *c.* 800 cal yr BP, reflecting the change in agricultural pattern possibly oil crops cultivation mainly induced by the population migration from the northern China.

Acknowledgements

This study was supported by the National Natural Science Foundation of China (Grant No. 41576042 and 41877436) and National Social Science Key Foundation of China (Grant No. 16ZDA147). We are grateful to Dr. Brian Finlayson and an anonymous reviewer for their valuable suggestions for improving the manuscript.

References

Atahan, P., Itzstein-Davey, F., Taylor, D., Dodson, J., Qin, J., Zheng, H., Brooks, A., 2008. Holocene-aged sedimentary records of environmental changes and early agriculture in the lower Yangtze, China. Quat. Sci. Rev. 27 (5), 556–570.
Beijing Institute of Botany, Academia Sinica, 1976. Sporae Pteridophytorum Sinicorum. Science Press, Beijing, pp. 451 (in Chinese).
Chen, W., Wang, W.M., Dai, X.R., 2009. Holocene vegetation history with implications of human impact in the Lake Chaohu area, Anhui Province, East China. Veg. Hist. Archaeobotany 18 (2), 137–146.
Chen, J., Wang, Z.H., Li, C.H., 2010. Reanalysis of several points of environmental archaeology at the Guangfulin site. East Asia Archaeology 105–116 (in Chinese).
Chen, T., Ryves, D.B., Wang, Z., Lewis, J.P., Yu, X., 2018. Mid- to late Holocene morphological and hydrological changes in the south Taihu area of Yangtze delta plain, China. Palaeogeogr. Palaeoclimatol. Palaeoecol. 498, 127–142.
Ge, J., Cao, S., Wu, S., 1993. Migrations in Historic China. Fujian People's Publishing House, Fuzhou, pp. 691 (in Chinese).
Grimm, E.C., 1987. CONISS: a FORTRAN 77 program for statigraphically constrained cluster analysis by the method of increment sum of squares. Comput. Geosci. 13, 13–35.
Hayden, B.P., Santos, M.C.F.V., Shao, G., Kochel, R.C., 1995. Geomorphological controls on coastal vegetation at the Virginia Coast Reserve. Geomorphology 13 (1–4), 283–300.
Huang, X., Wang, J.W., Zhai, Y., Song, J., 2014. 2008 excavation on the Guangfulin site in songjiang district, Shanghai. In: Proceedings on the Excavation at Guangfulin. Shanghai Ancient Books Publishing House, Shanghai, pp. 64–97 (in Chinese).
Innes, J.B., Zong, Y., Chen, Z., Chen, C., Wang, Z., Wang, H., 2009. Environmental history, palaeoecology and human activities at the early Neolithic forager/cultivator site at Kuahuqiao, Hangzhou, eastern China. Quat. Sci. Rev. 28 (23–24), 2277–2294.
Innes, J.B., Zong, Y., Wang, Z., Chen, Z., 2014. Climatic and palaeoecological changes during the mid- to Late Holocene transition in eastern China: high-resolution pollen and non-pollen palynomorph analysis at Pingwang, Yangtze coastal lowlands. Quat. Sci. Rev. 99 (9), 164–175.
Institute of Botany and South China Institute of Botany, Academia Sinica, 1982. Angiosperm Pollen Flora of Tropic and Subtropic China. Science Press, Beijing, pp. 453 (in Chinese).
Itzstein-Davey, F., Atahan, P., Dodson, J., Taylor, D., Zheng, H., 2007. Environmental and cultural changes during the terminal Neolithic Qingpu, Yangtze delta eastern China. Holocene 17 (7), 875–887.
Jiang, W., Leroy, S.A.G., Ogle, N., Chu, G., Wang, L., Liu, J., 2008. Natural and anthropogenic forest fires recorded in the Holocene pollen record from a Jinchuan peat bog, northeastern China. Palaeogeogr. Palaeoclimatol. Palaeoecol. 261, 47–57.
Lamb, A.L., Wilson, G.P., Leng, M.J., 2006. A review of coastal palaeoclimate and relative sea-level reconstructions using $\delta^{13}C$ and C/N ratios in organic material. Earth Sci. Rev. 75, 29–57.
Landman, N.H., Jones, D.S., 2007. Paleopalynology, second ed. Springer, Dordrecht, pp. 813.
Li, Y.C., Xu, Q.H., Yang, X.L., Xiao, J.L., Liang, W.D., Peng, Y.J., 2004. Distribution and source of pollens and spores in surface sediments of Daihai Lake, Inner Mongolia. J. Palaeogeogr. 6 (3), 316–328 (in Chinese, with English Abstract).
Li, C.H., Chen, J., Wang, W.M., 2006. Pollen records from Guangfulin relics, songjiang district of Shanghai. Acta Micropalaeontol. Sin. 23 (2), 175–181 (in Chinese, with English Abstract).
Li, Y.Y., Zhou, L.P., Cui, H.T., 2008. Pollen indicators of human activities. Chin. Sci. Bull. 53 (9), 1281–1293.
Li, C., Zheng, Y., Yu, S., Li, Y., Shen, H., 2012. Understanding the ecological background of rice agriculture on the Ningshao plain during the Neolithic age: pollen evidence from a buried paddy field at the Tianluoshan cultural site. Quat. Sci. Rev. 35 (6), 131–138.
Liu, K.B., Qiu, H.L., 1994. Late-holocene pollen records of vegetational changes in China: climate or human disturbance? Terr. Atmos. Ocean Sci. 5 (3), 393–410.
Liu (Christopher), Y.S., Zetter, R., Ferguson, D.K., Mohr, B.A.R., 2007. Discriminating fossil evergreen and deciduous *Quercus*, pollen: a case study from the Miocene of eastern China. Rev. Palaeobot. Palynol. 145 (3), 289–303.
Moore, P.D., Webb, J.A., Collinson, M.E., 1991. Pollen Analysis. Blackwell Scientific Publications, Oxford, UK, pp. 216.
Qu, G., Li, J., 1992. Population and Environment of China. China Environmental Science Press, Beijing, pp. 237 (in Chinese).
Röderstein, M., Perdomo, L., Villamil, C., Hauffec, T., Schnetterd, M.L., 2014. Long-term vegetation changes in a tropical coastal lagoon system after interventions in the hydrological conditions. Aquat. Bot. 113 (2), 19–31.
Saito, Y., Yang, Z., Hori, K., 2001. The Huanghe (Yellow River) and Changjiang (Yangtze River) deltas: a review on their characteristics, evolution and sediment discharge during the Holocene. Geomorphology 41 (2), 219–231.
Shang, X.L., 2003. Investigation of the population quantity change of west han dynasty. J. Zhengzhou Univ. (Eng. Sci.) 36 (3), 19–22 (in Chinese, with English Abstract).
Shu, J.W., Wang, W.M., Chen, W., 2007. Holocene vegetation and environment changes the NW Taihu plain Jiangsu province east China. Acta Micropalaeontol. Sin. 24 (2), 210–221 (in Chinese, with English Abstract).
Shu, J., Wang, W., Jiang, L., Takahara, H., 2010. Early Neolithic vegetation history, fire regime and human activities at Kuahuqiao, Lower Yangtze River, East China: new and improved insight. Quat. Int. 227 (1), 10–21.
Song, J., Zhou, L., Chen, J., Jiao, T., 2003. The Guangfulin site in songjiang district, Shanghai in 1999-2000. Chin. Archaeol. 3 (1), 34–41.
Stuiver, M., Reimer, P.J., Reimer, R.W., 2017. CALIB 7.1. http://calib.org/calib/, Accessed date: October 2017.
Sun, X., 1992. Distribution and migration of population during Qin and Han dynasties. Chin. J. Popul. Sci. (4), 44–48 (in Chinese).
Wang, F., Chien, N., Zhang, Y., Yang, H., 1995. Pollen Flora of China, second ed. Science Press, Beijing, pp. 461 (in Chinese).
Wang, W.M., Shu, J.W., Chen, W., Ding, J.L., 2010a. Holocene environmental changes and human impact in the Yangtze river delta area, east China. Quat. Sci. 30 (2), 233–244 (in Chinese, with English Abstract).
Wang, Z., Xu, H., Zhan, Q., Saito, Y., He, Z., Xie, J., Li, X., Dong, Y., 2010b. Lithological and palynological evidence of late Quaternary depositional environments in the subaqueous Yangtze delta, China. Quat. Res. 73, 550–562.
Wang, Z., Li, M., Zhang, R., Zhuang, C., Liu, Y., Saito, Y., Xie, J., Zhao, B., 2011. Impacts of human activities on the late-Holocene development of the subaqueous Yangtze delta, China, as shown by magnetic properties and sediment accumulation rates. Holocene 21 (120), 393–407.
Wang, Z., Zhuang, C., Saito, Y., Chen, J., Zhan, Q., Wang, X., 2012. Early mid-Holocene sea-level change and coastal environmental response on the southern Yangtze Delta plain, China: implications for the rise of Neolithic culture. Quat. Sci. Rev. 35 (6), 51–62.
Wang, Z.H., Chen, J., Zhan, Q., Zhuang, C.C., Wu, X.X., Wang, X.D., 2014. The relationship between palaeogeographic environment and Neolithic culture during the Holocene at Guangfulin site. In: Proceedings on the Excavation at Guangfulin. Shanghai Ancient Books Publishing House, Shanghai, pp. 325–335 (in Chinese).
Wang, X., Mo, D., Li, C., Yu, S.Y., Xue, B., Liu, B., Wang, H., Shi, C., 2017. Environmental changes and human activities at a fortified site of the Liangzhu culture in eastern China: evidence from pollen and charcoal records. Quat. Int. 438, 189–197.
Wang, Z., Ryves, D., Lei, S., Nian, X., Lv, Y., Tang, L., Wang, L., Wang, J., Chen, J., 2018. Middle Holocene marine flooding and human response in the south Yangtze coastal plain, East China. Quat. Sci. Rev. 187, 80–93.
Wen, Z.C., Sun, G.P., Xie, L.J., Sun, Y.G., 2014. The geochemical characteristics and significance of soil organic matter in the Tianluoshan Site of Hemudu cultural. Geochimica 43 (2), 166–173 (in Chinese, with English Abstract).
Wu, Z.Y., 1980. The Vegetation of China. Science Press, Beijing, pp. 1382 (in Chinese).
Xiao, J., Xu, Q., Nakamura, T., Yang, X., Liang, W., Inouchi, Y., 2004. Holocene vegetation variation in the Daihai Lake region of north-central China: a direct indication of the Asian monsoon climatic history. Quat. Sci. Rev. 23 (14), 1669–1679.
Xu, Q.H., Li, R.L., Zhu, F., Yang, X.l., Liang, W.D., 2001. Pollen sedimentary facies of fluvial sediments on North China Plain. J. Palaeogeogr. 3 (2), 55–63 (in Chinese, with English Abstract).
Yan, Q., Xu, S., Shao, X., 1989. Holocene cheniers in the Yangtze delta, China. Mar. Geol. 90 (4), 337–343.
Yang, S., Zheng, Z., Huang, K., Zong, Y., Wang, J., Xu, Q., Rolett, B.V., Li, J., 2012. Modern pollen assemblages from cultivated rice fields and rice pollen morphology: application to a study of ancient land use and agriculture in the Pearl River Delta, China. Holocene 22 (12), 1393–1404.
Yi, S., Saito, Y., Zhao, Q., Wang, P., 2003. Vegetation and climate changes in the Changjiang (Yangtze River) Delta, China, during the past 13,000 years inferred from pollen records. Quat. Sci. Rev. 22 (14), 1501–1519.
Yi, S., Saito, Y., Yang, D.Y., 2006. Palynological evidence for Holocene environmental change in the changjiang (Yangtze River) delta, China. Palaeogeogr. Palaeoclimatol. Palaeoecol. 241, 103–117.
Yu, C.L., 2009. The contradiction between land resources and population during the Western Han Dynasty. Research for Qin and Han dynasties 182–188 (in Chinese).
Zhang, J.T., Wang, P.L., 1986. Pollen morphology of *Quercus* L. In China. Acta Pyhtotaxonomica Sinica 24 (5), 362–369 (in Chinese, with English Abstract).
Zheng, Y., Sun, G., Qin, L., Li, C., Wu, X., Chen, X., 2009. Rice fields and modes of rice cultivation between 5000 and 2500 BC in east China. J. Archaeol. Sci. 36 (12), 2609–2616.
Zheng, Y.F., Sun, G.P., Chen, X.G., 2012. Response of rice cultivation to fluctuating sea level during the Mid-Holocene. Chin. Sci. Bull. 57 (4), 370–378.
Zong, Y., Chen, Z., Innes, J.B., Chen, C., Wang, Z., Wang, H., 2007. Fire and flood management of coastal swamp enabled first rice paddy cultivation in east China. Nature 449 (7161), 459–462.
Zong, Y., Innes, J.B., Wang, Z., Chen, Z., 2011. Mid-Holocene coastal hydrology and salinity changes in the east Taihu area of the lower Yangtze wetlands, China. Quat. Res. 76 (1), 69–82.
Zong, Y., Innes, J.B., Wang, Z., Chen, Z., 2012. Environmental change and Neolithic settlement movement in the lower Yangtze wetlands of China. Holocene 22 (22), 659–673.