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Phytolith and diatom evidence for rice exploitation and environmental changes during the early mid-Holocene in the Yangtze Delta

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ABSTRACT

Using phytolith analysis from a well-dated and high-resolution sediment sequence in the apex of northern Yangtze Delta, we investigate environmental changes, the rise and decline of rice exploitation and possible impacts of environment on rice exploitation during the early mid-Holocene. The phytolith sequence documents a relatively warm and dry interval during ca.9000 to 8200 cal yr BP, followed by climatic amelioration before 7200 cal yr BP. Phytolith evidence indicates that rice exploitation at the apex of northern Yangtze Delta began at 8200 cal yr BP, flourished by 7700 cal yr BP and ceased after 7400 cal yr BP. The first emergence of marine diatom species approximately 7300 cal yr BP likely indicates an accelerated sea-level rise. The apparent correlation of the initiation of rice exploitation with climatic amelioration during the early mid-Holocene suggests that climatic changes may have played an important role in facilitating rice exploitation. Both the ideal climatic conditions and stable sea level enabled flourishing rice exploitation during 8200 to 7400 cal yr BP. Although the climate remained warm and wet after 7400 cal yr BP, local sea-level rise possibly led to the termination of earlier rice exploitation at this site of the northern Yangtze Delta.

Introduction

The Yangtze Delta was a core area for the early development of rice agriculture (Zhao, 2010). The influences of early Holocene sea-level rise, delta evolution, and climatic warming on agricultural development have long been a focus of research (Stanley and Chen, 1996; Hori and Saito, 2007; Long et al., 2014). Variations in the rate of sea-level rise (Lambeck et al., 2014) may have threatened or destroyed agricultural development (Zong et al., 2007; Chen et al., 2008; Shu et al., 2010), while enabling formation of the Yangtze Delta (Bird et al., 2010), which facilitated the establishment and development of agriculture (Zong et al., 2012, 2013). Following the end of the last glacial, the period of climatic amelioration until the mid-Holocene provided ideal environmental conditions for the establishment of permanent settlements and the domestication of rice in the Yangtze Delta (Yi et al., 2003; Wang et al., 2010a). The archaeological record indicates that rice exploitation first emerged around the Majiabang Culture (7200–5200 cal yr BP) in the Yangtze Delta. This was followed by improved rice exploitation during the Songze (5700–5200 cal yr BP) and Liangzhu (5500–4000 cal yr BP) periods (Long and Taylor, 2015).

Rice exploitation appears to have commenced later in the Yangtze Delta region than elsewhere. Early exploitation of rice was discovered at Yuchanyan, in the middle reaches of the Yangtze River (Zhao and Piperno, 2000). Subsequently, rice was more extensively exploited at Pengtoushan and Bashidang sites (Fig. 1). Even in northern China, newly recovered records indicate that exploitation of rice occurred no later than 8000 cal yr BP (Jin et al.,

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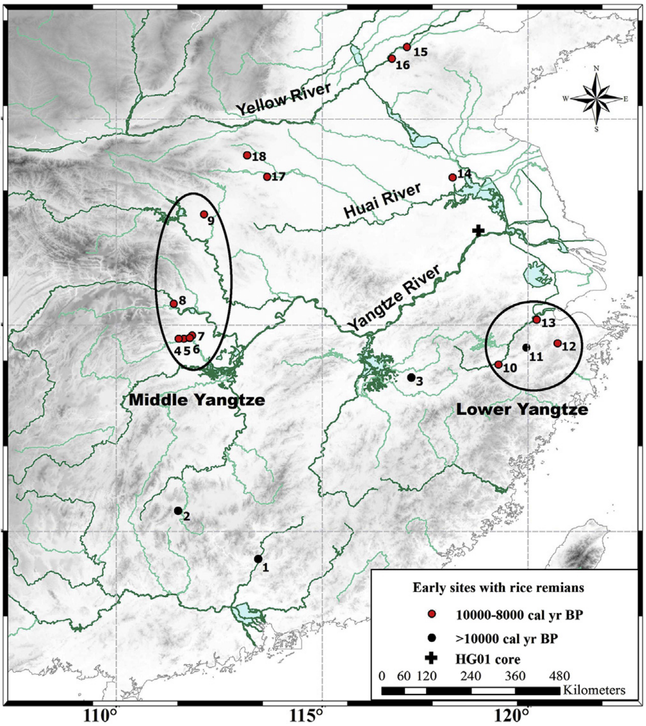

Figure 1. The main archaeological sites with rice remains in China cited in this study. 1 Niulandong. 2 Yuchanyan. 3 Diaotonghuan. 4 Shanlonggang. 5 Pengtoushan. 6 Shiligang. 7 Bashidang. 8 Chengbeixi. 9 Baligang. 10 Hehuashan. 11 Shangshan. 12 Xiaohuangshan. 13 Kuahuqiao. 14 Shunshanji. 15 Xihe. 16 Yuezhuang. 17 Jiahu. 18 Tanghu. The black cross represents our research area.

2014). The Ningshao Plain, south of the main Yangtze Delta, experienced similar sea-level rise and climate changes during the early to mid-Holocene, and rice in this area developed in the early stage of domestication before 8000 cal yr BP, during the Kuahuqiao Culture (Zheng et al., 2004).

The Yangtze Delta shares a similar environmental background with the Ningshao Plain. Its climate condition is more favorable for rice exploitation than that in northern China. Why did rice exploitation emerge here much later than that in the other regions mentioned above? Many studies have examined this issue (Stanley and Chen, 1996; Zhu et al., 2003; Atahan et al., 2007, 2008; Chen et al., 2008; Wang et al., 2012; Wu et al., 2014a), but the reasons remain unclear. Catastrophic events (flooding, marine transgression, or storm tides) (Zhu, 2005; Wu et al., 2012), development of sterile soil on stiff muds, low temperature (Chen et al., 2008), and brackish water (Wang et al., 2012) have been suggested as reasons for the non-favorable conditions for rice exploitation in the Yangtze Delta area during the early Holocene. The main questions are therefore as follows: (1) Did rice exploitation exist in the Yangtze Delta before 8000 cal yr BP? (2) If so, what reasons forced the emergence, development, and termination of rice exploitation at this site, climatic or hydrological background, or both? A more detailed insight into the environmental background is central to understanding the complexities of human occupation and agriculture in the Yangtze Delta area (Crawford, 2012).

Although many previous studies have reconstructed detailed environmental changes and climatic variability, especially in the southern parts of the delta (Liu et al., 1992; Zhang et al., 2004, 2005; Chen et al., 2005; Tao et al., 2006; Wang et al., 2010b; Wang et al., 2010c, 2012; Qin et al., 2011; Wang and Yang, 2013), reliable reconstruction is hampered by comparatively low temporal resolution in the middle and lower delta regions during the early mid-Holocene. Archaeological sites faithfully recorded the development of rice exploitation (Stanley and Chen, 1996; Atahan et al., 2007, 2008; Itzstein-Davey et al., 2007; Innes et al., 2009; Zong et al., 2011, 2012; Innes et al., 2014; Long et al., 2014; Patalano et al., 2015); however, these records may lack the details necessary for the reconstruction of climate changes due to low temporal resolution, sedimental hiatuses, and extensive human influences. Consequently, the use of high-resolution sedimentary records, which are free of the effects of accelerated sea-level rise, is key to resolving the above issues.

In this paper, we present detailed phytolith and diatom records from the apex region of the northern Yangtze Delta in order to constrain the initiation of rice exploitation and reconstruct environmental changes during the early mid-Holocene.

Regional setting

The Yangtze Delta lies on the east coast of China, which occupies an area of approximately 5.2×10^4 km^2. It is divided into three major sections: 1) the main delta body, 2) the southern flank, and 3) the northern flank (Li et al., 2002). It is located in a transitional zone between temperate and subtropical climates, with an annual mean temperature of ca.15.5 °C and a mean precipitation of ca. 1100 mm (Jiang, 1991). HG01 core was retrieved from the upper region of the Yangtze Delta in 2010 (at 32°17′21″ N, 118°48′09″ E, 7.5 m a.s.l.). It is located to the northeast of Nanjing, an apex area of the Yangtze Delta, between Nanjing and Yizheng (Fig. 2).

Several previous studies indicated that the formation of the Yangtze Delta plain was initiated at about 8000 cal yr BP (Stanley and Chen, 1996; Hori and Saito, 2007), and that it spread from the area between Nanjing and Yizheng (Song et al., 2013). Meanwhile, the depocenter moved landward as a result of sea-level rise during the early Holocene (Hori and Saito, 2007). The upper region of the present Yangtze Delta (the delta apex region) received large amounts of sediment materials and formed a relatively continuous sediment sequence during the early mid-Holocene (Song et al., 2013).

Materials and method

Sedimentary facies

The 23.2-m-long sediment core consists of two main sections (Fig. 3). The lower section (below 17.16 m depth) consists of late Pleistocene sediments in the Low Yangtze region, and it is categorized as “hard clay”. The section above 17.16 m depth is composed of Holocene sediments and comprises three divisions of facies: (1) flood plain facies (17.16–5.38 m depth), (2) channel fill facies (5.38–3.50 m depth), and (3) flood plain to surface soil facies (3.50–0 m depth).

The sediments of 17.16–5.38 m depth in the HG01 core consists of heavily bioturbated gray clay to silt, containing abundant plant fragments and gastropods. The mud content accounts for >87% of the sediments. The overall median grain size is about 7-6φ. There are some granules in the lower part. Freshwater gastropods of *Parafossarulus striatulus* and *Gyraulusalbus* are scattered in most sediments of this unit. The brackish water type, *Assiminea cf. sculpta*, can be observed only at 10.8 m depth. A 5-mm-diameter calcareous concretion occurs at 14.33 m. Partial silt–clay couplets are observed at depths of 12.70–12.40 m, 11.37–11.00 m, and 7.60–7.40 m. It should be noted that abundant plant fragments, freshwater gastropods, and other organic materials were found in the floodplain section, indicating terrestrial sediment source. The muddy sediments and weak couplets indicate weak flow conditions. The most floodplain sedimentation occurs during floods and that it is mostly due to suspension (Miall, 1992; Collinson, 1996).

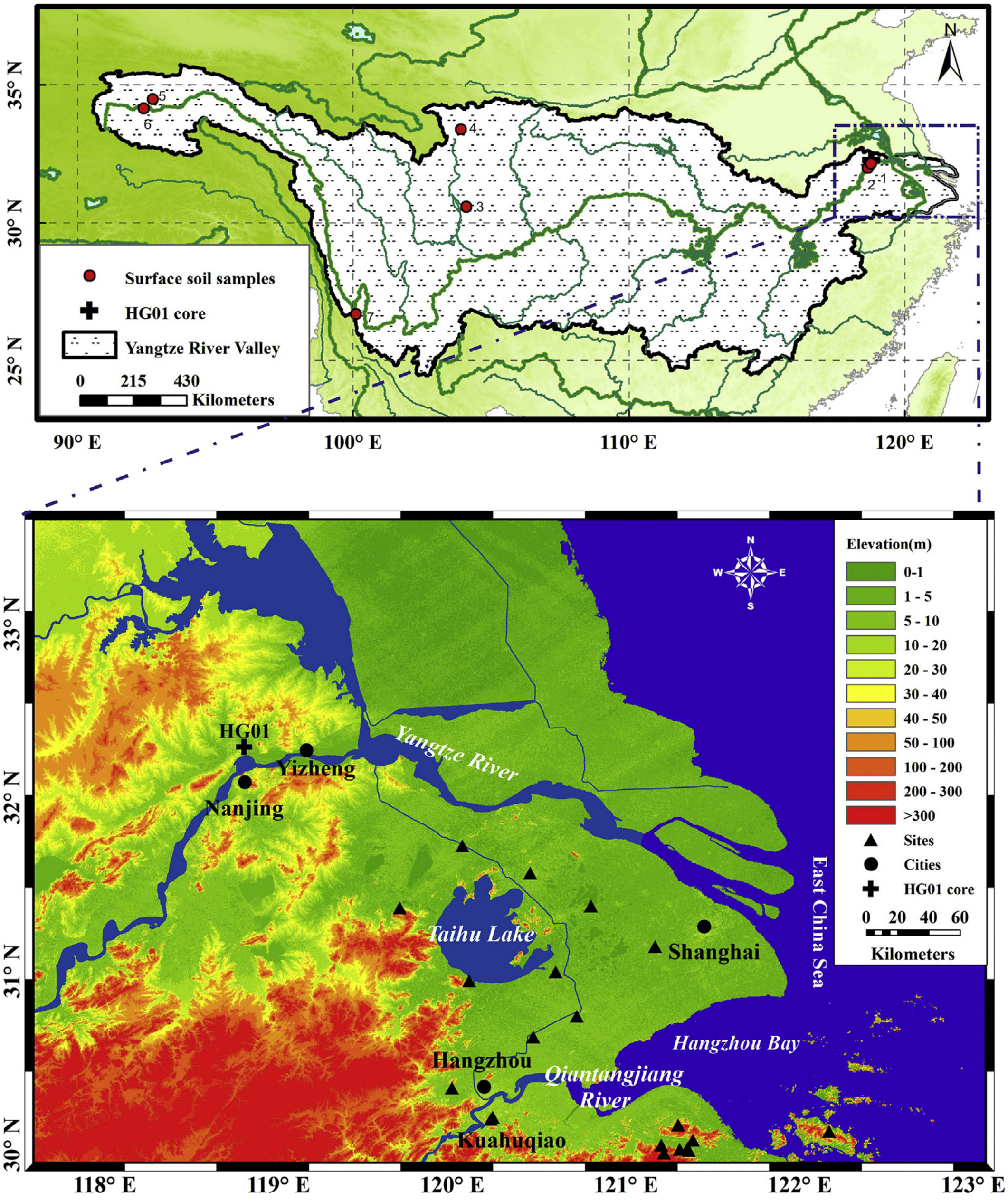

Figure 2. Locations of the surface soil samples, HG01 core, and main archaeological sites in the lower Yangtze River.

thus, it is probably of floodplain/lake environment, which remained a comparatively stable sedimentary environment (Song et al., 2013). In this study, we only analyzed the section of the relatively stable sediment so that dramatic changes in the sedimentary facies do not affect the climatic reconstruction.

Age model

AMS ^{14}C dates were used to construct the chronological model. Eleven plant residues or charcoal samples were selected for the dating analysis. All the dating samples were measured at Beta Analytic Lab. Conventional ages were calibrated to calendar years using Calib Rev 7.0.4 and the IntCal13 calibration curve (Reimer et al., 2013). Depth-to-age transformation was performed by liner interpolation between controls points of AMS ^{14}C dates (Fig. 4); detailed dating results are given in Table 1. The relative sediment section was dated from ca. 9000 to 7200 cal yr BP. During this period, all the dating results showed good chronological sequence, indicating that the sediment between 9000 and 7200 cal yr BP was stable and continuous.

Surface soil samples

Seven surface soil samples were collected from 0 to 2 cm depth along the Yangtze River Valley, from 10 to 4660 m a.s.l. Two of them are from the floodplain at the low Yangtze River near Nanjing area. The others were collected from the upper reaches of Yangtze River. The locations of the sample sites are shown in Figure 2. Two samples were collected from the origins of the Yangtze River.

Phytolith analysis

The sediment core between 9000 and 7200 cal yr BP was subsampled at 5-cm intervals for the phytolith analyses. Subsamples of

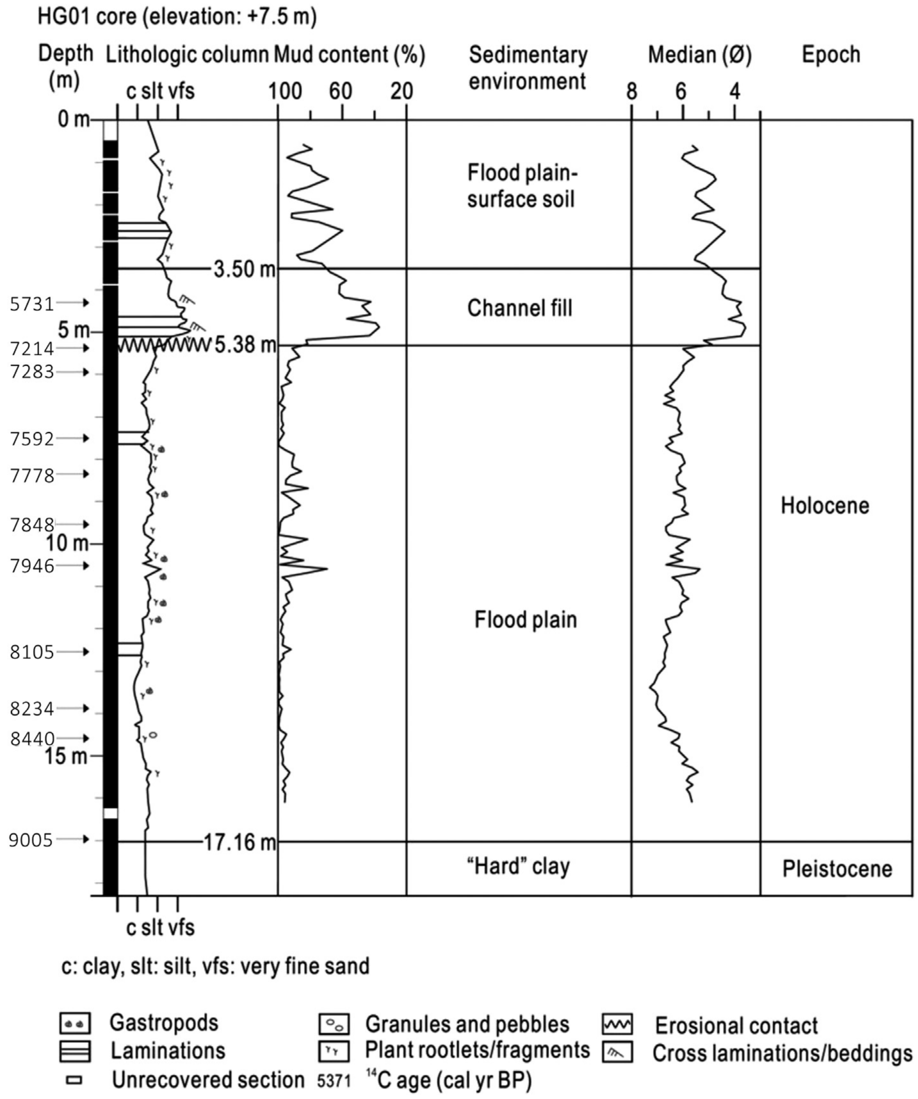

Figure 3. Lithological column and sedimentary environment recorded in the HG01 core (modified from Song et al., 2013).

core sediment and surface soil samples were freeze-dried and homogenized. Phytoliths were extracted by the conventional wet digestion method (Lu et al., 2009), as follows: (1) Approximately 1 g of dry sample was deflocculated with 5% sodium polyphosphate. (2) Organic matter was oxidized by H_2O_2 (30%). (3) Carbonates were removed by HCl (10%). (4) Phytoliths were extracted by heavy liquid ($ZnBr_2$, 2.35 g/cm^3). The final recovered phytoliths were permanently mounted on glass microscopic slides with Canada balsam. Identification and counting of phytoliths were carried out using a Leica DM 750 microscope at 400× magnification. At least 500 phytoliths were counted for each sample. Phytoliths were classified according to the system proposed by Lu et al. (2006) and described according to International Code for Phytolith Nomenclature (ICPN1.0) (Madella et al., 2005).

In this study, rice included three distinctive phytolith types: (1) Rice bulliform produced in the leaf bulliform cells; (2) Paralleled bilobates, produced in leaf cells; (3) Double-peaked glume phytoliths produced in the epidermis of the rice husk. Of these, rice bulliform (with fish-scale decorations on the edges) and double-peaked glume can be used to distinguish domesticated rice from wild varieties (Zhao et al., 1998; Lu et al., 2002; Fuller and Castillo, 2014). The bulliform phytoliths of domesticated rice usually have more than nine fish-scale decorations, whereas wild rice varieties have fewer than nine (Lu et al., 2002; Huan et al., 2015). Although wild rice also produces bulliform phytoliths with more than nine fish-scale decorations, this type accounted for less than 26% of wild rice soil samples, compared with more than 54% in domesticated rice soil samples (Huan et al., 2015). Bulliform phytoliths provide reliable discrimination between wild and domesticated species of rice, especially in the absence of macrofossil remains (Lu et al., 2002). This approach has therefore been widely used in the studies of rice origins and domestication (Saxena et al., 2006; Itzstein-Davey et al., 2007; Zhang et al., 2012; Jones et al., 2013; Qiu et al., 2014; Wu et al., 2014b).

Diatom analysis

Diatoms were extracted and identified simultaneously with phytoliths. No additional extraction processes were required. In this study, we did not calculate quantitative statistics on all of the diatoms recovered from the HG01 core sediment, but only qualitative descriptions of the frequency of common diatom species. We paid particular attention to marine diatoms, particularly to their earliest occurrence in the sequence.

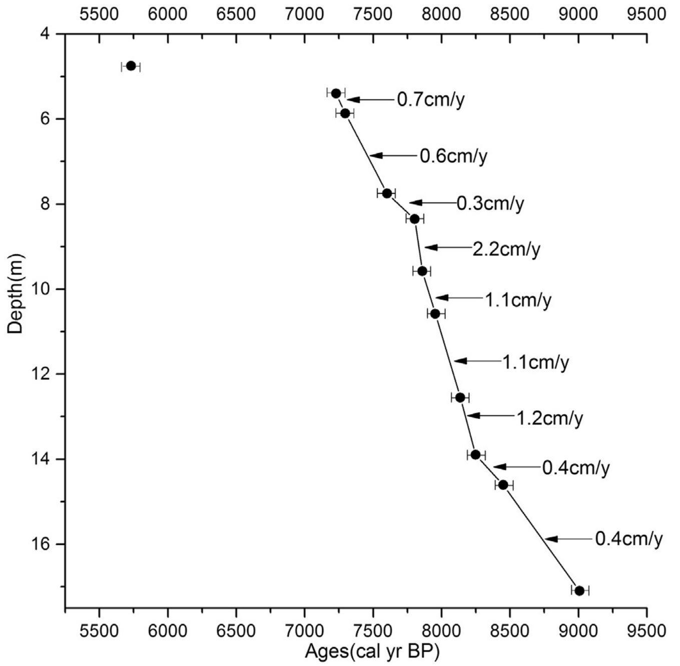

Figure 4. Age-depth relationship and sedimentation rates of the HG01 core. Black dots represent the median age. Age bars represent calibrated ages with 2σ error. Sedimentation rates (cm/y) were calculated based on the calibrated median ages.

Results

Phytolith assemblages in surface soil samples

As shown in Figure 5, the phytolith assemblages between the samples from upper reaches and those from the lower reaches showed significant differences. Two floodplain samples near Nanjing showed similar phytolith assemblages. They presented a high abundance of bilobate, bamboo phytoliths (long saddle and bamboo bulliform), and bulliform phytoliths (square and rectangle). The percentages of rondel and trapezoid phytoliths were moderate. Note that a few globular echinate and rice phytoliths were identified from the two floodplain samples. Other samples from the upper reaches of Yangtze River were characterized by the high abundance of gobbet, trapezoid, and rondel phytoliths. The percentages of bulliform phytoliths and bilobate were very low. Bamboo phytoliths, globular echinate, and rice phytoliths were absent in these samples.

Phytolith assemblages in the HG01 core

Thirty phytolith morphotypes were identified from the HG01 core, of which the major phytoliths are shown in Figure 6. The percentage phytolith diagram of HG01 sediment core during 9000 to 7200 cal yr BP can be divided into two main phytolith assemblage zones according to stratigraphically constrained cluster analysis (Fig. 7).

Zone A (16.93–13.33 m, 9000–8200 cal yr BP)

The assemblages of phytolith zone A are characterized by low proportions of bamboo phytoliths (long saddle and bamboo bulliform) (4.3%), fan (8.0%), broad-leaf (0.1%), and square (1.8%) forms. This homogeneous zone is dominated by rectangles (20.3%), bilobates (12.0%), points (10.7%), and rondels (10.3%) forms.

Zone B (13.33–5.43 m, 8200–7200 cal yr BP)

Phytolith zone B is characterized by a significant increase in the proportions of bamboo phytolith (12.2%), bulliform (18.0%), broad-leaf (1.8%), and square (3.7%) forms. The percentages of bilobate, point, and rondel types show a declining trend but these forms persist at relatively low abundances. The proportion of rectangle types remained unchanged from the oldest zone.

Rice phytoliths in the HG01 core

Rice phytoliths (mainly Rice bulliform) first appear at a depth of 13.43 m (8209 cal yr BP). The numbers of rice bulliform increased from 1 to 2 at depths of 13–11 m (8200–8000 cal yr BP) to a maximum of nine at a depth of 8.08 m (7710 cal yr BP). Their numbers then declined to two at a depth of 6.57 m (7410 cal yr BP); no rice phytoliths were found after this depth. It should be noted that one double-peaked glume cell and parallel bilobate were identified at a depth of 8.08 m (7710 cal yr BP).

A total of 582 rice bulliforms were identified in the HG01 core sediments after a further 4–5 slides were scanned for those samples in which rice phytoliths were found. However, only 48 with fish-scale decorations were counted; of these, 30 had more than nine fish scales, while 18 had less than eight fish scales (Fig. 8).

Marine diatom species in the HG01 core

Typical species of marine diatoms, such as *Coscinodiscus radiatus* and *Triceratium favus*, first occurred at a depth of 5.53 m (7246 cal yr BP) (Fig. 9). Subsequently, they were identified in every sample from 5.53 to 5.03 m. Prior to this time, the recovered diatoms were mainly identified as freshwater, brackish and salty lake species, such as *Neidium iridis, Stephanodiscus medius, Gyrosigma acuminatum, Eunotia implicata, Gomphonema clavatum, Gomphonema hebridense, Cymbella schimanski, Nitzschia sinuate, Stauroneis nobilis, Cymbella inaequalis, Epithemia adnata,* and *Surirella bohemica* Maly. No typical species of marine diatoms were found before 7246 cal yr BP.

Table 1
Radiocarbon ages from the core HG01.

Lab ID (Beta-)	Depth (m)	Dating materials	Conventional age (^{14}C yr BP)	2σ Calibration (cal yr BP)	Median age (cal yr BP)
291707	4.75	Plant fragments	5010 ± 40 BP	5713–5749	5731
287364	5.40	Plant fragments	6270 ± 40 BP	7154–7273	7214
270343	5.87	Plant fragments	6350 ± 50 BP	7258–7308	7283
270345	7.75	Plant fragments	6730 ± 40 BP	7575–7609	7592
270346	8.35	Plant fragments	6950 ± 50 BP	7728–7828	7778
270347	9.58	Plant fragments	7010 ± 50 BP	7826–7870	7848
270348	10.58	Plant fragments	7100 ± 50 BP	7931–7961	7946
270349	12.55	Plant fragments	7300 ± 50 BP	8042–8168	8105
270350	13.90	Plant fragments	7460 ± 50 BP	8206–8262	8234
270351	14.61	Plant fragments	7680 ± 50 BP	8418–8462	8440
287365	17.10	Charred plant	8070 ± 40 BP	8997–9013	9005

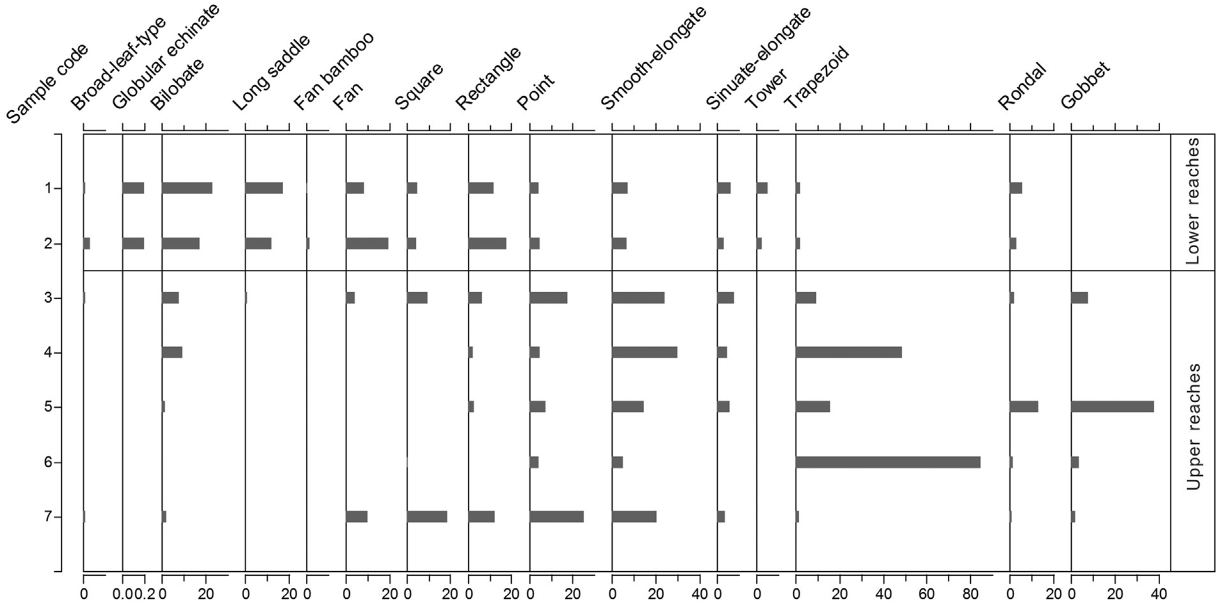

Figure 5. Phytolith assemblages of surface soil samples in the Yangtze River Valley.

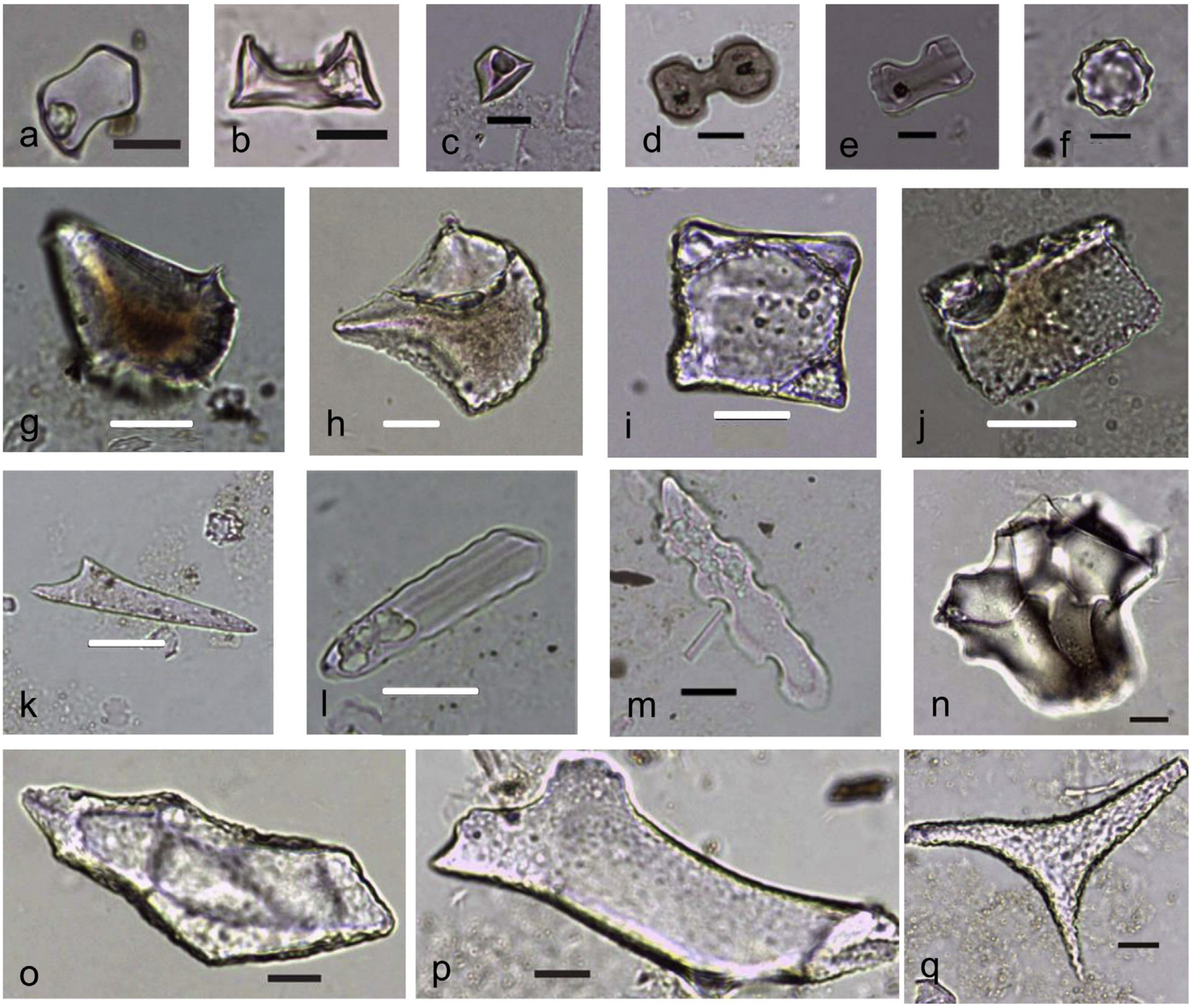

Figure 6. Images of typical phytolith morphotypes identified in HG01 core. **a, b** Long saddle. **c** Rondal. **d, e** Bilobate. **f** Globular echinate. **g** Bamboo bulliform. **h** Bulliform. **i** Square. **j** Rectangle. **k** Point. **l** Wavy-trapezoid. **m** Wavy-narrow-trapezoid. **n**–**q** Broad-leaf-type. Scale: black bar = 10 μm; white bar = 20 μm.

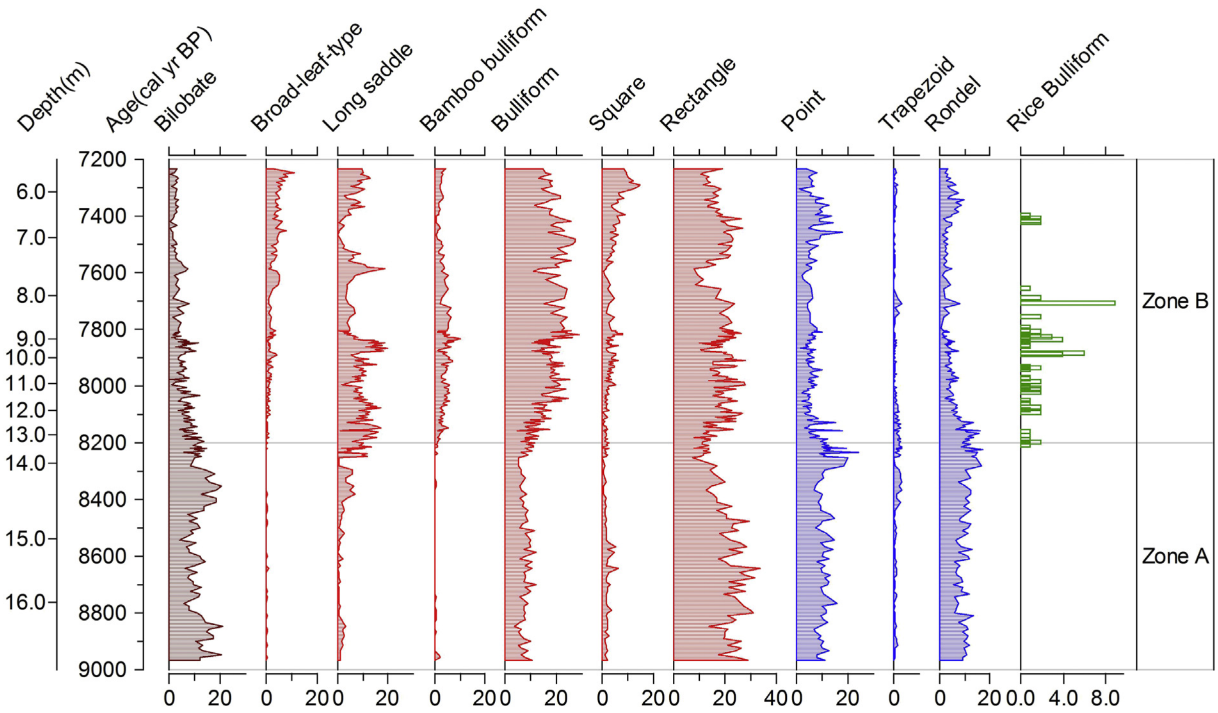

Figure 7. Selected phytolith assemblages from the HG01 core. The rice bulliform numbers were expressed as absolute numbers of all phytoliths counted; others were expressed as percentages of all phytoliths counted.

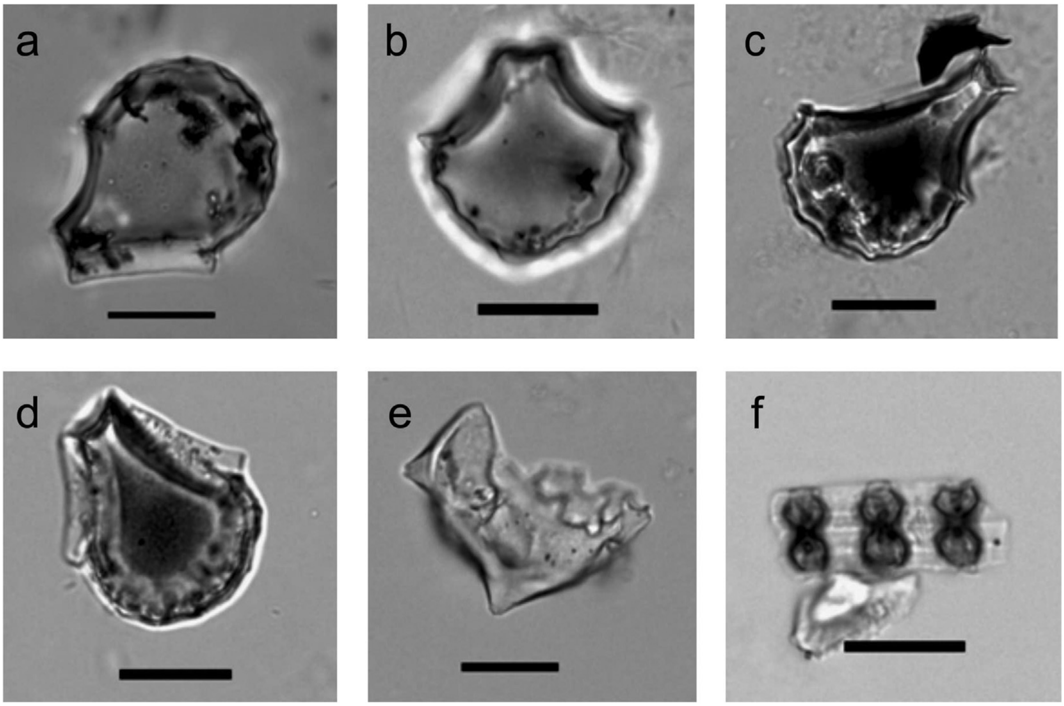

Figure 8. Images of rice phytoliths recovered from HG01 core. **a,b** Rice bulliform with >9 fish-scale decorations. **c** Rice bulliform with <9 fish-scale decorations. **d** Rice bulliform with indistinct decorations. **e** Double-peaked glume cells. **f** Bilobates parallel. Scale: black bar = 20 μm.

Discussion

Phytolith of HG 01 sediments sourced from the regional vegetation

Identifying the main phytolith source area is crucial for the interpretation of assemblages and proxies (Aleman et al., 2014). Phytoliths can be transported to long distances with wind and water (Lu et al., 2002; Latorre et al., 2012). It is a well-known fact that modern soils and profiles mainly received local depositions of phytoliths, and hence they can be taken as reliable proxies for reconstructing changes in palaeovegetation (Osterrieth et al., 2009). However, for the lacustrine and fluvial sediments, the

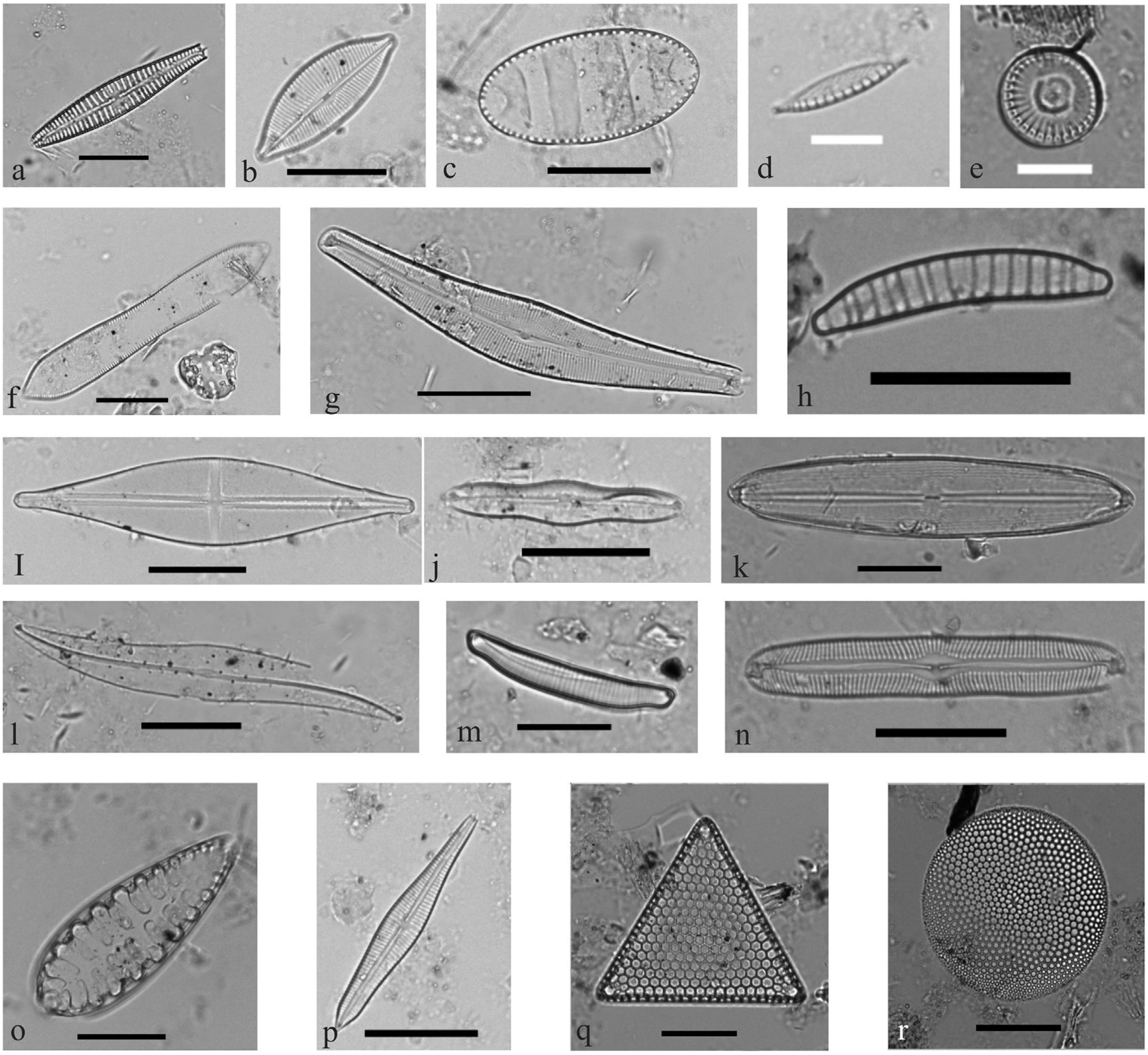

Figure 9. Images of freshwater and marine diatom species identified from the HG01 core. **a** *Gomphonema clavatum*. **b** *Cymbella inaequalis*. **c** *Cymatopleura elliptica*. **d** *Nitzschia sinuata* var. *delongnei*. **e** *Stephanodiscus medius*. **f** *Cymatopleura solea*. **g** *Cymbella schimanski*. **h** *Epithemia adnata*. **i** *Stauroneis nobilis*. **j** *Caloneis ventricosa*. **k** *Neidium iridis*. **l** *Gyrosigma acuminatum*. **m** *Eunotia implicata*. **n** *Pinnularia maior*. **o** *Surirella bohemica*. **p** *Gomphonema hebridense*. **q** *Triceratium favus*. **r** *Coscinodiscus radiatus*. Scale: black bar = 40 μm; white bar = 20 μm.

phytolith sources are more complex, depending on different modes of transport and deposition (Garnier et al., 2013). In this study, we considered the sediments in floodplain section to have been mainly sourced from the local surrounding regions on the basis of the following two aspects:

Firs, the new model, which consolidated all the available archaeological evidence, demonstrated that the Middle Yangtze is one of the origin centers for the domestication and dispersal of rice (Silva et al., 2015). Rice remains were found in many archaeological sites in the Middle Yangtze, such as Pengtoushan, Bashidang, and Baligang (Fig. 1). Therefore, the rice phytoliths deposited in the sediments of the HG01 core should have emerged before 9000 cal yr BP, but not after 8200 cal yr BP, in case they were all sourced from the middle reaches of the Yangtze River. This shows that the rice phytoliths in the sediments of the HG01 core were likely not influenced by long-distance transport. The rice phytoliths and phytolith assemblages may therefore represent regional vegetation of the Yangtze Delta.

Second, the results of seven surface soil samples showed that two floodplain samples near Nanjing were characterized by similar phytolith assemblages, but were in contrast with the assemblages of other samples from the upper reaches of Yangtze River. Some diagnostic phytoliths, such as Rice phytoliths and globular echinate, were identified from the two floodplain samples, but these were absent in the other samples form the upper reaches of Yangtze River. Gobbet phytolith was only presented in the samples from the upper reaches. The significant differences between the samples from the lower and upper reaches of Yangtze River indicated small phytolith contributions from the upper samples to the lower samples near Nanjing. Thus, phytoliths deposited in the floodplain sediments of the HG01 core can be treated as a reliable indicator of regional vegetation.

Early mid-Holocene environmental changes in the Yangtze Delta

Phytolith is a long-established climatic indicator. Different types of phytolith, as suggested by the study of phytolith assemblages in the Chinese surface soil, may represent different climatic conditions, which can be used in reconstructing the past climate. Broadleaf phytoliths are produced by many tropical or subtropical broad-leaf plants. Long saddle and bamboo bulliform, produced by the Bambusoideae subfamily, are good indicators of warm and wet climate. Bulliform, square, and rectangular forms were deposited in cells of the subfamilies Oryzoideae, Arundinoideae, and Panicoideae. Phytolith assemblages from Chinese surface soil samples indicate that the above mentioned six types of phytoliths increased steadily toward the warmer and wetter regions (Lu et al., 2006, 2007) (Fig. S1–S6). Thus, they can be regarded as general indicators of wet and warm climate. Rondel and trapezoid types were exclusively from the subfamily Pooideae. As shown in Figs. S8 and S9, these two types of phytoliths decreased toward the high temperature and precipitation regions. Thus, the high abundance of rondel and trapezoid in phytolith assemblage indicates cold and dry climate (Wang and Lu, 1992). Bilobate phytoliths were mainly produced by the subfamily Panicoideae. Most plant species of this subfamily do not favor the low temperature in northern China and high rainfall in southern China (Lu et al., 2000). Phytolith assemblages of Chinese surface soil also showed that the highest abundance of bilobate did not correspond to the warmest and wettest climate but to a moderate warm and wet condition (MAT = 16°C, MAP = 1000 mm; Fig. S10). Our research region, Yangtze Delta, is located in the warm and wet climate zone. We thus conclude that the increase in bilobate phytoliths (Panicoideae plants) is indicative of possible warm and dry climatic conditions in the Yangtze Delta.

From 9000 to 8200 cal yr BP, the samples contained 35% phytoliths that favor warm and wet conditions, and they contained 21% phytoliths associated with cold and dry conditions, indicating comparatively low proportions associated with warm and wet conditions. However, bilobate phytolith accounted for 12% of the total phytoliths, indicating that the climatic conditions were not especially wet. Overall, phytolith assemblages in Zone A indicate a warm and dry climate. A significant increase in the variety of warm and wet types (55%), including long saddle, bamboo bulliform, square, broad-leaf-type and rectangle types, indicates that during 8200 to 7200 cal yr BP, the climate became warm and wet. The significant decrease of bilobate phytoliths also indicates the development of comparatively wet conditions. Overall, the phytolith assemblages in Zone B indicate warm and wet climate, implying a mid-Holocene Climate Optimum (HCO) in the Yangtze Delta.

Our palaeoclimatic reconstruction is well supported by previous studies in the lower Yangtze. For example, Holocene lacustrine pollen record of Chaohu lake shows a fully developed evergreen and deciduous mixed broad-leaved forest during 8250 to 7550 cal yr BP, which was interpreted as the beginning of the HCO (Chen et al., 2009). Other pollen records from Taihu plain (southern Yangtze Delta) show a warm and wet climate during 8000 to 5000 cal yr BP indicated by an increase in the evergreen broad-leaved forests (Chen et al., 2005; Wang et al., 2010b).

Initiation of rice exploitation in the apex of the northern Yangtze Delta

The first occurrence of rice phytoliths in the HG01 sediment core at about 8200 cal yr BP is probably the earliest evidence of rice in the Yangtze Delta discovered to date, but they belong to either wild or domesticated species. Although neither marcofossil nor cultural remains were found, the phytolith analyses in this study provide some insights into the features of early rice exploitation in the Yangtze Delta. A total of 48 rice bulliform phytoliths clearly displayed fish-scale decorations and were thus counted, from which approximately 63% had more than nine fish scales. According to the newly established criterion for discriminating between wild and domesticated rice (Huan et al., 2015), the higher proportions of rice bulliforms with more than nine decorations suggest that the recovered rice from the HG01 core was already developed at the domestication stage in the Yangtze Delta, and earlier than that previously known.

The data indicate that 8200 cal yr BP is an important boundary for climate change and rice exploitation during the early to mid-Holocene. For climatic changes, our phytolith assemblages indicate that the climate became wet and warm after 8200 cal yr BP. Temperature and precipitation have increased in northern China since 8200 cal yr BP (Wen et al., 2010; Zhao and Yu, 2012). For rice exploitation, the number of rice relic sites not only increased significantly but were also distributed more broadly between 8000 and 6000 cal yr BP (Gong et al., 2007). Early evidence for the emergence of rice exploitation has been found at many archaeological sites across eastern China, such as Tanghu and Baligang in Henan Province (Zhang et al., 2012; Deng et al., 2015), Yuezhuang in Shandong Province (Jin et al., 2014), Kuahuqiao in Zhengjiang Province (Zheng et al., 2004) and Bashidang in Hubei Province. Between 8200 and 7700 cal yr BP, recovered rice phytoliths show a general increasing trend. There is also evidence of significantly warmer and wetter climatic conditions during the mid-Holocene in the Yangtze Delta. This coincides with the increases in rice phytoliths, once again indicating that the climatic changes at the local scales during the early mid-Holocene might have had a significant influence on rice development. We therefore suggest that a warmer and wetter mid-Holocene likely facilitated the emergence of rice exploitation in the Yangtze Delta and perhaps other regions of eastern China.

Sea-level rise and rice exploitation in the apex of the northern Yangtze Delta

The deglacial and Holocene global sea-level rise from −134 m at 21,000 cal yr BP to 0 m at ca. 4000 cal yr BP (Lambeck et al., 2014) exhibited a profound influence on the habitats of the continental shelf and coastal regions in East Asia (Stanley and Chen, 1996; Innes et al., 2009; d'Alpoim Guedes et al., 2016). The relationship between sea-level changes and rice exploitation is long and complex and has been the subject of considerable research and debates in the Yangtze Delta. However, previous studies mainly concentrated on the southern Yangtze Delta during the mid-Holocene (Itzstein-Davey et al., 2007; Zong et al., 2011; Innes et al., 2014). Few studies have paid attention to the northern Yangtze Delta during the early to mid-Holocene.

Diatom records in the HG01 core from the apex of the northern Yangtze Delta indicate that offshore and marine species, such as *C. radiatus* and *T. favus*, were first found in the HG01 core sediment at about 7300 cal yr BP. Prior to this, the recovered diatoms were freshwater, brackish, and salty lake species (Fig. 9 a–p). No marine diatom species were found before 7300 cal yr BP, indicating that the apex of Yangtze Delta was unaffected by the sea-level rise. A relative stable sea level between 8000 and 7400 cal yr BP probably caused cessation of the sea-level rise in the Yangtze Delta. The emergence of marine diatom assemblages at about 7300 cal yr BP probably implied that a rapid sea-level rise or storm surge tides after the cessation of the sea-level rise transported many marine diatoms to the apex of the Yangtze Delta. This rapid sea-level rise was also presented by Bird et al. in the Singapore region during the period 7400–7000 cal yr BP (Bird et al., 2007). While the sea levels showed an increase during 7900 to 7200 cal yr BP (Wang et al., 2013), a rapid rise at about 7300 cal yr BP would have led to the intrusion of sea water into the Nanjing area. Further, although an intrusion of sea water was recorded before 7300 cal yr BP (Song et al., 2013) as well, it may not have been as powerful as the later ones.

Rice exploitation was thus initiated at 8200 cal yr BP and flourished by 7710 cal yr BP; however, it ceased locally after

7400 cal yr BP in the apex of the northern Yangtze Delta. We conclude that this cessation of rice exploitation may be attributed to problems of frequent marine inundation resulting from the rising sea level (Fig. 10).

In other early archaeological sites, such as at Kuahuqiao in the Ningshao Plain, we found similar rise and decline of rice exploitation over time. Previous studies demonstrated that the Kuahuqiao site was first inhabited at 8000 cal yr BP (Innes et al., 2009). Subsequently, environmental changes resulting from human activities appeared. Micro-fossil records at the site indicate increasing levels of human settlements and rice exploitation (Shu et al., 2010). Rice exploitation, involving high-intensity clearance of vegetation by fire, was established at 7700 cal yr BP. After 7400 cal yr BP, rice exploitation at Kuahuqiao ceased because marine inundation resulted from sea-level rise (Zong et al., 2007).

The similar development time of rice exploitation between Kuahuqiao and our study area illustrates the complicated constraints introduced by environmental changes (climate changes and sea-level rise) on the initiation, establishment, and continuation of rice exploitation in the Yangtze Delta. Climatic amelioration during the early mid-Holocene favored the initiation of rice exploitation at about 8000 cal yr BP in these regions. However, for the establishment of rice exploitation, both climatic amelioration and comparatively stable sea level provided ideal environmental conditions. Although the climate did not change dramatically at about 7400 cal yr BP, sea-level rises led to an abrupt termination of rice exploitation in the north flank of the Yangtze Delta. We speculate that the habitat was forced to move into the southern flank of the Yangtze Delta, to escape the influence of the sea-level rice during the early mid-Holocene. A new period, the Majiabang culture, came into form in these habitats.

Conclusions

This study presents a new phytolith and diatom record of early mid-Holocene climate changes and evidence of early rice exploitation in the Yangtze Delta. Our results show that rice phytoliths first appeared at ca. 8200 cal yr BP in the apex of the northern Yangtze Delta. These rice relics probably developed at the stage of domestication, as proposed on the basis of diagnostic phytoliths of the domesticated rice. To the best of our knowledge, it is probably the earliest evidence of rice exploitation in the Yangtze Delta, which resulted a broad expansion from the surrounding regions after 8200 cal yr BP when the climate began to become warm and wet. A comparatively stable sea level and climate optimum during the 8200 to 7400 cal yr BP supported continuous rice exploitation in the Yangtze Delta at this site. The appearance of marine diatom taxa possibly indicated a local rapid sea-level rise at about 7300 cal yr BP, which likely resulted in the collapse of rice exploitation in this region. We speculated that habitats were probably forced to move to the regions of the southern Yangtze Delta, such as the Taihu area. Rice exploitation continued in that area during the

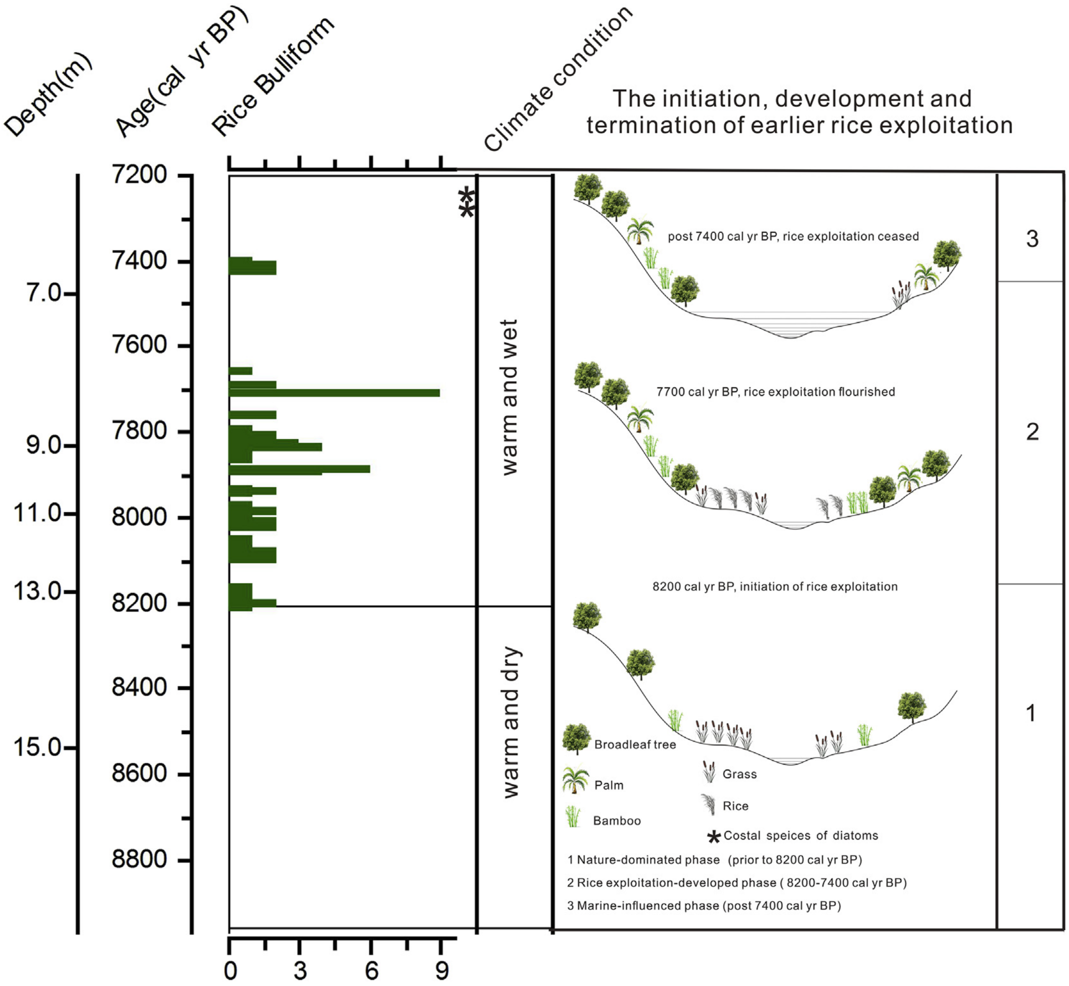

Figure 10. Early rice exploitation, climatic changes, and sea-level rise in the apex of the northern Yangtze Delta.

Majiabang culture. Thus, the environmental background of climate change and sea-level rise are crucial for understanding the rise and decline of rice exploitation during the early to mid-Holocene in the Yangtze Delta. Further studies are required on the environmental background to the rise and decline of rice exploitation, because such findings may help us understand the complexities of human adaptations in the Yangtze Delta.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.yqres.2016.08.001.

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