

Durham Research Online

Deposited in DRO:

07 September 2010

Version of attached file:

Accepted Version

Peer-review status of attached file:

Peer-reviewed

Citation for published item:

Innes, J. B. and Zong, Y. and Chen, Z. and Chen, C. and Wang, Z. and Wang, H. (2009) 'Environmental history, palaeoecology and human activity at the early Neolithic forager/cultivator site at Kuahuqiao, Hangzhou, eastern China.', *Quaternary science reviews.*, 28 (23-24). pp. 2277-2294.

Further information on publisher's website:

<http://dx.doi.org/10.1016/j.quascirev.2009.04.010>

Publisher's copyright statement:

NOTICE: this is the author's version of a work that was accepted for publication in *Quaternary science reviews*.

Additional information:

Use policy

The full-text may be used and/or reproduced, and given to third parties in any format or medium, without prior permission or charge, for personal research or study, educational, or not-for-profit purposes provided that:

- a full bibliographic reference is made to the original source
- a [link](#) is made to the metadata record in DRO
- the full-text is not changed in any way

The full-text must not be sold in any format or medium without the formal permission of the copyright holders.

Please consult the [full DRO policy](#) for further details.

Environmental history, palaeoecology and human activity at the early Neolithic forager/cultivator site at Kuahuqiao, Hangzhou, eastern China

James B. Innes^a, Yongqiang Zong^b, Zhongyuan Chen^c, Chun Chen^d, Zhanghua Wang^c, Hui Wang^c

^a Geography Department, Durham University, Durham, DH1 3LE, U.K.

^b Department of Earth Sciences, The University of Hong Kong, Hong Kong, SAR China

^c Department of Geography, East China Normal University, Shanghai 200062, China

^d Department of Cultural Heritage, Fudan University, Shanghai 200433, China

Abstract

The date and location of the adoption of rice cultivation by foraging cultures in China is of considerable current interest but its understanding is hampered by a lack of information regarding its palaeoenvironmental context. We present detailed multi-proxy palaeoecological research at the earliest-dated site of rice cultivation in the coastal littoral of east China which has revealed the precise environmental setting of this early Neolithic settlement and its incipient cultivation at c. 7750 cal BP. Regional and local environmental changes governed the character of the site and the duration of human activity. After an episode of marine conditions, natural hydrological succession and terrestriation of the site preceded fire clearance of marsh fen-carr alder scrub that prepared the ground for cultivation and then maintained a reedswamp-type wet grassland in which rice was grown. Cropping of *Typha* stands may have formed part of the subsistence base before the site was overwhelmed by marine inundation c. 7200 cal BP, after which rice cultivation spread to Neolithic sites of Hemudu type elsewhere in the coastal lowlands. We suggest that integrated multi-proxy palaeoecological studies are vitally important for the full understanding of such key wetland archaeological sites.

Corresponding author. Tel.: +44 191 334 1831; fax: +44 191 334 1801.

E-mail address: J.B.Innes@Durham.ac.uk (James Innes).

1. Introduction

The invention and development of agriculture by human communities in the Holocene, based upon the domestication and controlled breeding of plants and animals (Mannion, 1999), is the single most important factor in the transformation of the world's biophysical systems from entirely natural to the situation existing today, when much of the world's surface is turned over to farming of a few selected food crops at varying degrees of intensity (Diamond, 2002). Despite its importance, however, our understanding of agriculture's origins and the details (the stimuli, mechanisms, environmental context, even dates and locations) of the transition from reliance on foraging (culturally Palaeo/Mesolithic) to reliance on farming (culturally Neolithic) economies remains uncertain, particularly for its earlier stages. It is now clear, however, that even in its global core areas where agriculture was conceived, domestication and the switch to Neolithic farming was a gradual, prolonged process rather than a swift, revolutionary event (Pringle, 1988). In the case of cereals, there was a long period of increasingly intensive exploitation before domestication was achieved, starting with the collection and processing of wild cereal grains by foragers (Kislev et al., 2004; Piperno et al., 2004), then the sowing of the surplus seeds in more convenient locations near settlements and passing into the intentional and increasingly intensive cultivation of these wild cereal forms (Weiss et al., 2006; Willcox et al., 2008) before eventual domestication. In a few locations the change to cereal cultivation may even have occurred some millennia before the start of the Holocene, perhaps encouraged by Late Glacial environmental change (Hillman et al., 2001). In all locations the eventual creation of truly domesticated cereal varieties was almost certainly accidental, requiring evolutionary changes in plant genotype and morphology, and arose from the concentration of wild forms during their cultivation and from the selection of more productive and desirable plants by the cultivators. It follows that dedicated cultivation of wild cereals over a long period of time, at least several centuries and probably millennia, was a prerequisite for the gradual emergence of domesticated cereals.

1.1 Neolithic rice cultivation in China

In the case of rice, the history of its use, cultivation and domestication is long and complex (Underhill, 1997; Lu, 1999; Sweeney and McCouch, 2007) and has been the subject of considerable research and debate. The proposal that China was one of the core areas where rice

agriculture originated (Chang, 1989; Glover and Higham, 1996; Wang and Sun, 1996; Crawford and Shen, 1998; Higham and Lu, 1998; Lu, 2006) has been confirmed by modern genetic research (Khush, 1997; Londo et al., 2006) that indicates domestication occurred in the south central China region more than once, with the domesticate *Oryza sativa (japonica)* arising from its wild perennial progenitor *O. rufipogon*. While the timing of these events and specific locations of the domestication centres remain uncertain, there is now strong evidence that the earliest rice cultivation and domestication may have occurred in areas of the Yangtze valley (Normile, 1997), particularly its middle basin (Pei, 1998; Zhao, 1998; Zhao and Piperno, 2000; Sato, 2002) but also its lower reaches (Yan, 1992; Jiang and Liu, 2006; Fuller et al., 2007). Certainly the collection and use of wild rice by foragers occurred over a very long period in the Yangtze region, at least since the start of the Holocene (Zhao et al., 1995; Higham and Lu, 1998; Yuan, 2002), and probably significantly before (Zhao et al., 1995). Environmental factors, especially climate, would have been very influential regarding the availability of thermophilous wild rice to foragers in the Yangtze valley. It would certainly have been present there in abundance after the Pleistocene/Holocene transition, although near the northern limit of its natural range, because of the switch at that time to the favourable environmental conditions of a warm, humid monsoonal climate (Jarvis, 1993; Wang et al., 2005), so favourable that archaeological rice remains from the start of the Holocene have even been recorded in Henan Province well to the north of the Yangtze (Chen et al., 1995; Chen and Jiang, 1997; Zhang and Wang, 1998; Hu et al., 2006), in an area where dryland agriculture is practised today. There are also, however, several pre-Holocene records of rice remains from archaeological sites, often caves and rock shelters, in the Yangtze area (Zhao, 1998) and wild rice must have been present there, although perhaps not in its aquatic form, during the Late Pleistocene except for its coldest and driest periods (Lu et al., 2002). The gathering of wild rice in quantity, for food and husks for tempering pottery fabric, seems proven at these Lateglacial sites, but claims have also been made that archaic cultivated forms occur even in these very early assemblages (Zhao et al., 1995; Chen, 1998; Zhang, 1999), so that the date and environmental context of first rice cultivation have been contentious and difficult to establish, as remains of wild and cultivated rice are difficult to distinguish. Most Neolithic and even later (Itzstein-Davey et al., 2007a) site assemblages include both, as well as transitional forms. Once systematic rice cultivation did begin in the Yangtze valley, as elsewhere, there must have been an extended period of cultivation before the morphological changes that signify domesticated rice

occurred. Although there is still strong debate on when this happened (Liu et al., 2007a, b; Fuller et al., 2008a), recent examination of rice grains in the lower Yangtze region support a protracted cultivation phase of well over a millennium before true domestication occurred as late as 6000 years ago in the middle Neolithic (Fuller et al., 2007, 2008b, 2009). Cultivation of morphologically wild varieties was evidently a necessary and lengthy episode in the cultural trajectory towards full domestication and intensive rice farming. Establishing the timing and circumstances of this adoption of systematic rice cultivation is therefore of the highest importance. The eastern coastal lowlands that include the area of the Yangtze delta (Fig. 1a) are ideal for pursuing this research aim, containing several very early Neolithic sites (Fig. 1b). These early Neolithic sites range in time from the start of the Holocene c. 10 000 years ago, as at Shangshan where putative cultivation has been recorded (Jiang and Liu, 2006; Liu et al., 2007a), to around 6000 years ago, as at Hemudu (Zhao and Wu, 1988; Jiang, 2003; Fuller et al., 2007) where unequivocal domesticated rice occurred as part of an assemblage that still included wild and cultivated forms (Tang et al., 1994). Farming at Hemudu is suggested by many specialised agricultural implements but significantly even at Hemudu rice of all types still remained a minority component of a diverse wild plant food resource base (Qin et al., 2006) dominated by acorns and other nuts (Fuller, 2006; Fuller et al., 2007). Even in the later Neolithic, wild foods remained an important part of rice farmers' diet along the Yangtze (Zhao, 2005). Certainly, throughout the first half of the Holocene Chinese early Neolithic groups of the lower Yangtze appear to have been foragers first and cultivators second.

1.2 *Palaeoecology and rice cultivation*

We agree with Fuller et al. (2008a) that multiple lines of evidence will be required to achieve a good understanding of the history of rice agriculture as *Oryza* archaeobotanical data remain ambiguous, particularly for the key early stage when systematic rice cultivation was added to rice gathering. As well as rice macrofossils, on archaeological sites these data are mainly represented by rice phytolith studies (Jiang and Piperno, 1994; Jiang, 1995; Pearsall et al., 1995; Zhao et al., 1995; Zhao et al., 1998; Wang and Ding, 1999; Zhao and Piperno, 2000) that have become increasingly sophisticated (Zheng et al., 2003; Lu et al., 2006; Itzstein-Davey et al., 2007a). Understanding of the start of rice cultivation is still hampered, however, by ignorance of the ecological conditions that accompanied it. A few recent studies have added palynology to phytolith

analysis, to reconstruct the local vegetation in which cultivation took place (Huang and Zhang, 2000; Yasuda et al., 2004; Itzstein-Davey et al., 2007b), adding an environmental context to human activity. In this paper we take this further, supplementing pollen and phytolith data with several other biological proxies, including fungal spores, algae, microcharcoal, diatoms and foraminifera, to reconstruct detailed wetland successions, define the precise natural palaeoecological context in which rice cultivation began and clarify the environmental changes the human activity caused. We have chosen Kuahuqiao, a site in the Hangzhou lowlands in the lower Yangtze region of east China, for the detailed analyses as it contains excavated waterlogged cultural sediments with good organic preservation and archaeological context, and clear evidence of the earliest rice cultivation in a region where wild rice naturally occurred. Also, the site lies in an area that would have been coastal swamp in the earlier Holocene, an ecological zone that has been proposed (Higham, 1995) as the most likely habitat where earliest rice cultivation took place, and an environment that offers the opportunity to integrate a wide range of palaeoecological proxies effectively, as shown by Zheng and Li (2000) elsewhere in coastal southeast China. A brief report on our research at Kuahuqiao has been published previously (Zong et al., 2007).

2. The study site

Kuahuqiao (30°08'42"N and 120°13'02"E) is located c. 5 km south of Hangzhou City in Zhejiang Province (Fig. 1b), and lies at the boundary between the upland region to the south and west and the flat coastal plain around Hangzhou Bay to the east and north. It is situated in a natural zone of transition between the fluvial and terrestrial environments upstream of the Qiantang river mouth above Hangzhou City and the wetland environments of the coastal lowlands that are today largely given over to intensive paddy rice production. The archaeological site lies in a shallow depression, with ground altitudes around 3.8 m above local mean sea level (the Yellow Sea datum), between two lines of hills (Fig. 1c). Within this basin, the unconsolidated sediment sequence comprises a 2-3 m thick grey clay layer at the base, coarsening downwards to incorporate sands and gravels, overlain by a layer of brown organic-rich silty clay (Table 1). This is overlain by 'cultural' levels comprising highly organic clays that were deposited naturally but which include abundant plant remains, organic detritus and archaeological material. These are sealed by a

layer of grey clay up to a metre thick that becomes laminated in its upper part and forms the disturbed topsoil at the surface.

Much of the site was destroyed in the 1970s when the basal clays were dug out and used for brick-making. Parts of the remaining deposits were excavated for the first time in 1990, and again in 2001 and 2002 (Fig. 1d), by the Zhejiang Provincial Institute of Cultural Relics and Archaeology, with a total area of 1080 m² investigated (Jiang, 2004). At the centre of the surviving site the cultural layers are at their thickest, about 3 m, where a domestic settlement area was located, inferred from the distribution of the archaeological finds and primarily by the discovery of at least four wooden pile-dwellings during the 1990 excavation (Fig. 1d). These show that the settlement was situated within wet coastal marshland during its period of occupation, confirming the interpretation implied by the character of the cultural sediments themselves, organic clays and mud that would have been laid down within sub-aquatic environments, and explaining the survival of the cultural layers as waterlogged organic soils as well as the wealth of cultural and organic material they contain, well preserved by their waterlogged nature. The cultural layers at Kuahuqiao lie more than a metre below present day mean sea level. One of the most important preserved organic artefacts that testifies to the aquatic nature of the site is a wooden dugout canoe (Jiang and Liu, 2005) made of pine and over 5.5 m long that was recovered from near the northwest edge of the area that was excavated in 2001-02. Other well-preserved organic materials include wooden paddles and spades, ladders, worked timbers and adze handles, bamboo and bone implements, and fabric matting. The function of the tools made from organic material is not easy to deduce, but some at least appear to be digging implements. These could have been used in constructing the earthen walls that were found supporting the pile-dwellings, but could also have had a role in food production.

Other archaeological finds from Kuahuqiao (Jiang, 2004) include storage pits and a large number and range of pottery types that form a previously unrecorded class of ceramic assemblage, mostly tempered with charred plants fragments and rice husks. Most significantly, the cultural organic soils preserved abundant biological remains. There were a large number of bones from a variety of animals, birds and fish that included some domestic pig and dog but mainly comprised wild species (Yuan et al., 2008), suggesting that hunting formed the major faunal element of the economy. Oyster shells were common as were a wide variety of plant remains, particularly nuts, fruits and seeds, and in particular acorns that were often found in large numbers in the storage pits.

Wild plant species predominated, indicating that gathering, added to fishing and the hunting of wild game, formed the staple of a mainly foraging economy with a wide resource base. Significantly, however, more than a thousand rice grains and many rice phytoliths were recovered, mostly wild varieties but including large numbers of morphologically advanced but not yet domesticated forms (Zheng et al., 2004). The character of the wild rice harvested at Kuahuqiao remains the subject of debate (Pan, 2008; Fuller and Qin, 2008). While primarily a forager settlement exploiting the rich natural resources of the coastal marshes and hinterland, Kuahuqiao has an element of incipient rice cultivation within the resource base which, allied to the limited presence of domesticated pigs, the earliest food animal domesticated in China (Yuan and Flad, 2002), classifies it as very early Neolithic, supported by calibrated radiocarbon dates on the canoe of c. 8000 years ago (Jiang and Liu, 2005). Analysis of all the radiocarbon dating results (Jiang, 2004) for the Neolithic material at Kuahuqiao suggests clearly that occupation of the site began at or shortly before 8000 cal BP, although it should be remembered that the studied area is only a proportion of the original extent of the site.

The new research data presented in the present paper are from a sediment profile recovered in 2005 from an exposed section at the eastern edge of the site, where the cultural layer is about 0.5 m thick, that had been opened during the 2001-02 excavations (Fig. 1e). The eastern face of trench T0512 was sampled at a point about 8 m from where the dugout canoe was found (Fig. 1e). Sub-samples were taken for analysis through the full sediment sequence at no more than 5 cm vertical increments, closing to 1 cm intervals through most of the cultural layers. Although much archaeological material was recovered, no pile-dwellings or other evidence of domestic activity and settlement were found during the 2001-02 excavation. This location on the periphery of the site was chosen for the present study in order to make palaeoecological reconstruction more reliable, as the sediments there, being about 100 m away from the domestic settlement area in the central part of the site, would be much less likely to have been disturbed during the occupation.

The absence of any sediment mixing and stratigraphic disturbance at the sampled section is confirmed by the very good chronological series formed by the radiocarbon dates through the sequence. The stratigraphic integrity of the cultural deposits will have been protected from subsequent disturbance by the sealing layer of clay that extends to the current surface. The sampled section would still have been close enough to the locations of human activity to record its environmental effects clearly, however. A multi-core study (Waller, 1998) would have been

necessary to reconstruct fully the vegetational and palaeoenvironmental history of the marshland landscape around Kuahuqiao but this is not the purpose of this research and so such a study has not been undertaken. Single-core studies elsewhere in the Taihu region (Okuda et al., 2003; Atahan et al., 2008) have provided high-quality information regarding geographical changes and human activity.

The single core that is presented in this paper, its location carefully selected to maximise recovery of evidence for both human activity and natural processes, is sufficient to answer the research question: the timing and nature of the start of rice cultivation. This began at our studied profile at c. 7750 cal BP (Table 2). Several of the previously published (Jiang, 2004) radiocarbon dates from Kuahuqiao, however, show that people were present at the site for a few centuries before that time, from c. 8000 cal BP, as exemplified by the dugout canoe dates already mentioned above. While rice cultivation in the wider Taihu region at this earlier date is considered possible by other authors (Zhang et al., 2004), none of the several other radiocarbon dates on cultural contexts from the Kuahuqiao excavations may be interpreted as indicating rice cultivation elsewhere on the site before the starting date in our profile of c. 7750 cal BP. As the available chronological and archaeological evidence stands, therefore, it seems that the earlier cultural phases at Kuahuqiao record settlement and foraging activities only, and that the profile presented in this paper represents the earliest known Neolithic rice cultivation at the site.

3. Materials and methods

Samples were prepared for palynological analysis using standard laboratory techniques, including alkali digestion, sieving at 180 μm , hydrofluoric acid digestion and acetolysis (Moore et al., 1991), and were stained before mounting on microscope slides. These techniques have been shown not to affect the preservation of other microfossil types adversely, such as fungal spores (Clarke, 1994). Microfossils (i.e. all palynomorphs <180 μm in size) were identified using standard reference keys and type slides and were counted using a Nikon stereomicroscope at magnifications of x400, using x600 oil immersion lenses for identification of critical features. Exotic *Lycopodium* spores were added in known volume as a marker before processing, allowing the calculation of palynomorph concentrations and influx rates. Standard reference sources were used for identification of pollen grains (Wang et al., 1995) and pteridophyte spores (Zhang et al., 1990). A minimum sum of 200

land pollen grains was counted at each sampled level, as well as all the aquatic pollen, pteridophyte and bryophyte spores observed while attaining that sum, after which slide scanning continued for rare or indicator types and to confirm the presence or absence of cultigen pollen. Oak pollen grains have been differentiated into *Quercus* (deciduous, including *Lepidobalanus*) and *Cyclobalanopsis* (evergreen) forms using published keys and photographs (Chang and Wang, 1986; Jarvis et al., 1992). Gramineae (grass) pollen has been divided into two size classes in order to differentiate grains likely to be of cereal (*Oryza*) type (40 μm and above) from other wild grasses (<40 μm), following Wang et al. (1995) and Chaturvedi et al. (1998), and as adopted by previous investigators, e.g. Atahan et al. (2008). Microscopic charcoal particles (microcharcoal) were counted upon the microscope slides relative to the standard pollen sum, providing a pollen/microcharcoal ratio. Microcharcoal particles of about 30 μm in diameter comprised the basic measurement unit, which is similar to the spores of the introduced marker exotic *Lycopodium clavatum* (Stockmarr, 1971). Microcharcoal particles were numbered by size relative to this basic 30 μm unit, as described by Innes and Simmons (2000). Unless very tiny, particles less than 30 μm in size could be aggregated to form the basic unit. Separate curves for the different microscopic size ranges are not presented, as fragmentation of particles must have occurred in the pollen preparation process. Most particles counted were of the smaller size ranges.

Diatom counts were also made throughout the profile. The technical procedures for diatom analysis follow those described by Palmer and Abbott (1986). A minimum count of 300 diatom valves was reached for the majority of samples, and all diatoms are identified to species level (e.g. van der Werff and Huls, 1958-1966; Jin et al., 1982). Taxa are classified according to an halobian system based on salinity tolerances (Vos and de Wolf, 1993). Rice phytolith counts were made from the diatom slides and are shown as numbers counted, but are not separated into likely wild and likely domestic varieties. Full phytolith analyses have been completed and published elsewhere (Jiang, 2004; Zheng et al., 2004, 2007) and are not repeated here. Other non-pollen palynomorphs (NPPs), mainly comprising fungal spores and remains of algae and invertebrates, were also recorded with at least 100 identified on the pollen slides at each counted level. Taxonomic identification of NPPs was achieved where possible, but otherwise they were identified to van Geel's catalogue of provisional type numbers, using the illustrations and descriptions published in several papers (e.g. van Geel, 1978, 1986, 2001; van Geel and Aptroot, 2006; van Geel et al., 2003). The corresponding fungal catalogue type number is shown after the first

mention of a taxon in the text and on the figures in all cases. NPP frequencies are shown as percentages of the total land pollen sum. Radiocarbon dates are AMS determinations on small organic fragments or charcoal, except for the two radiometric dates on bulk organic sediment that were published by Jiang (2004) and are relevant to the studied profile. Dates were calibrated using program Calib5.1 (Stuiver et al., 1998). Microfossil diagrams have been constructed using the TILIA programme (Grimm, 1993).

4. Results and interpretation

Full details of the nine AMS ^{14}C dates obtained for this study are shown in Table 2. Two radiometric dates are also shown which were published as part of the original excavation of the site (Jiang, 2004) and which dated respectively the end the deposition of the lower clay and the onset of that of the upper clay at the site, so bracketing the more organic sequence. The calibrated age ranges of all the AMS dates are narrow and the central calibrated age of all the dates is shown on the microfossil diagrams. Most dates are clustered within the half metre of the profile that includes the cultural soil layers and show that these cultural units accumulated very quickly. They form a very good consistent series that provides a precise chronological framework for the period of human activity at the site. This is despite the propensity for dates on alluvial sediment to yield anomalous results because of the incorporation of material reworked and transported by fluvial action from areas away from the site of deposition. Such dating effects have been reported from the Yangtze system (Stanley and Chen, 2000; Stanley and Hait, 2000) and from the Hangzhou lowlands (Atahan et al., 2008). But the Kuahuqiao site, despite its closeness to the head of a significant river estuary, appears to have escaped such adulteration, because its sheltered location and its deposition as an organic marsh soil rather than as natural alluvial accumulation comprising material eroded from higher in the catchment. Major soil destabilisation and erosion after intensive catchment deforestation, necessary for the creation of large reservoirs of stored alluvial sediment in the river valleys of the Yangtze delta region, did not occur until much later, in the Iron Age (Atahan et al., 2007). The consistency of the dating series, allowing for age range overlaps, supports the reliability not only of the chronology but also therefore of the biostratigraphy, an important requirement for high-resolution palaeoecological studies.

The full microfossil data from Kuahuqiao are presented in a series of diagrams, all of which show the seven main sedimentary units that have been identified at the site as reflecting major

changes in depositional environment or archaeological context (Jiang, 2004; Zong et al., 2007), assisting inter-diagram correlation. The sequence of sedimentary units is: basal grey clay (up to 157.5 cm), organic brown-grey clay (157.5-113 cm), highly organic brown clay which is equivalent to the lower cultural layer (113-90.5 cm), slightly organic grey clay (90.5-88 cm), highly organic brown clay which is separated into the middle cultural layer (88-80.5 cm) and the upper cultural layer (80.5-71.5 cm) and upper grey clay (above 71.5 cm). Of these, the slightly organic grey clay in mid-profile is the only one not to extend across the entire site, being confined to the area around the sampled profile. The tree, shrub and herb pollen frequencies are shown on Fig. 2, as well as aquatic pollen, pteridophyte and bryophyte spores and microcharcoal, all calculated as percentages of the total land pollen sum. The non-pollen palynomorph frequencies are shown on Fig. 3, with the microcharcoal curve as percentages of total NPPs included. Full diatom frequencies are presented on Fig. 4, with diatom summary curves and foraminiferal data on Fig. 5. *Oryza* phytolith counts are shown on Fig. 6, which is a conspectus diagram that includes the most diagnostic microfossil curves, some of which are composite and combine ecologically similar taxa, and upon which is also described the sequence of palaeoenvironmental conditions at the site. Based primarily upon the pollen data, but informed by the other proxy data records, eleven microfossil assemblage zones (Kua-1 to Kua-11) are recognised and applied to all the diagrams. Zone boundaries do not always correspond with the sedimentary unit boundaries. The dates of zone boundaries are interpolated between the radiocarbon dated horizons' central calibrated ages.

The interpretation of the Kuahuqiao palaeoecological data that are described below requires some consideration of the taphonomy of the microfossil assemblages and their environment of deposition, as these will have varied during the accumulation of the sediment profile. That all the sedimentary units described in Table 1 comprise silts and clays, of varying organic content, shows that deposition took place in aquatic environments throughout the Holocene history of the site, with varying water depth and quality, and differing vegetation communities, at different times. The analysed profile, apart from estuarine clays at its lower and upper limits, comprises sediments laid down within perimarine freshwater coastal marshes, a complex wetland ecotype that can include a wide variety of habitats and environments within a small spatial area (van der Woude, 1983), all of which contain biological communities constantly changing under the influences of autogenic hydroseral successions and external factors (Waller et al., 1999). Such marshes predominantly comprise fen systems, with a mosaic of pool, reedswamp, sedge fen and fen-carr vegetation, all of

which provide differing source areas (Waller, 1998) for the local components of the pollen assemblage preserved in each horizon in a marsh profile like Kuahuqiao. Changes in the size of the wetland and in plant community structure will have changed local source areas and caused changes in the proportions of pollen derived from the various elements of the wetland vegetation (Waller et al., 2005). In the case of Kuahuqiao, the site also would have had a considerable input of extra-local pollen derived from vegetation, mainly trees and shrubs, growing on the substantial areas of higher, dry ground around the wetland (Fig. 1c), as well as a more regional tree component from further away. It is such extra-local and regional dry ground components (Binney et al., 2005) that provide information regarding woodland changes governed by climate, whereas the local wetland element provides data on any hydroseral and sea-level changes. Human impacts are likely to be recorded in both the local and extra-local components of the pollen record, depending on their scale and location. The sources of the microfossil data recorded at Kuahuqiao have been taken into account in the interpretation and discussion of environmental changes at the site.

4.1 *Microfossil data*

Zone Kua-1 (below 157.5 cm; before c. 9021 cal BP) is characterised by arboreal pollen, primarily deciduous *Quercus*, the evergreen taxa *Cyclobalanopsis* and *Castanopsis/Lithocarpus*, and *Pinus*. Also present but in lower values are *Ulmus/Zelkova*, *Liquidambar*, *Castanea*, *Carpinus*, Cupressaceae and *Pterocarya*. Prominent among the non-tree pollen types are Cyperaceae and the smaller size division of the Gramineae. *Artemisia* and Chenopodiaceae (which includes *Amaranthus*-type) are the only other significant herb taxa, the latter in particular likely to be of saltmarsh origin. Most abundant among the non-pollen palynomorphs are fungal spores of the Sordariaceae (55A) and *Coniochaeta* cf. *ligniaria* (172), both general decomposers and not specifically diagnostic. Several NPPs indicative of shallow water conditions occur, including Type 128, the alga *Spirogyra* (130) and the cyanobacterium *Gloeotrichia* (146). Most important are high frequencies of Type 705 (Bakker and van Smeerdijk, 1982), the presence of the acritarchs *Michrystidium* (115) and *Cymatiosphaera* (116) and *Operculodinium* dinoflagellate cysts (704A), all of which indicate intertidal sedimentation. This is supported by the diatom data from this zone, dominated by a wide range of salt-tolerant marine (polyhalobous) and estuarine (mesohalobous)

forms of which *Nitzschia granulata* and *N. hungarica* are the most abundant. A tidal flat or lower saltmarsh depositional environment is indicated for the clay of Kua-1.

Zone Kua-2 (157.5-142 cm; c. 9021 - c. 8690 cal BP) is characterised by an arboreal pollen assemblage very similar to that of the previous zone, although frequencies of the main taxa are reduced. Differences include the presence of a much wider range of tree and shrub types, with the appearance of several taxa like *Betula*, *Salix* and Moraceae in low values. Herb pollen taxa remain dominated by Cyperaceae and small Gramineae, the latter rising gradually through the sub-zone. *Artemisia* values are consistent but Chenopodiaceae frequencies are much reduced from those of Kua-1. Freshwater aquatic pollen increase in diversity with *Myriophyllum*, *Potamogeton* and especially *Typha* prominent. Pteridophyte spores of freshwater wetland like *Equisetum* and *Osmunda* also rise. A switch from an intertidal to a shallow freshwater depositional environment is indicated. This is clearly shown in the diatom flora, with halophyte taxa removed from the record and replaced by a high diversity of freshwater forms. Non-pollen palynomorphs agree with this interpretation and add ecological precision. Algal taxa are particularly sensitive to changes in water conditions (Chmura et al., 2006). *Gloeotrichia* and *Spirogyra* are consistently important, indicating shallow open water, as do peaks for the fungal spore Type 121 and the alga *Botryococcus* (766), but other taxa suggest it was warm, eutrophic and also vegetated, shown (Haas, 1996) by peak values for oocytes of the Neorhabdocoela flatworm *Gyratrix hermaphroditus* (353A). Fungal type 11, recorded as specific to cyperaceous plants (van Geel, 1978) also occurs, suggesting the presence of sedges *in situ* around the sampling point, and this is supported by peaks in fungal spores which are associated (van Geel et al., 1981) with sedge fen environments (Type 306) or fen-reedswamp (Type 708). Increasing spore frequencies of the ascomycete fungi *Cercophora* (112) and *Chaetomium* (7A), decomposers of plant cellulose (van Geel, 2001; van Geel and Aptroot, 2006), also point to increasing levels of vegetation in the local aquatic system. *Oryza* phytoliths occur in very low numbers throughout this sub-zone (Fig. 6).

Zone Kua-3 (142-122 cm; c. 8690 - c. 8120 cal BP) is characterised by the same major taxa as the lower zones, *Quercus*, *Cyclobalanopsis* and *Castanopsis/Lithocarpus*, and by a similar range of less prominent tree and shrub types. *Carpinus* and Hamamelidaceae become significant. Small Gramineae pollen dominate the herb assemblage with subsidiary curves for Cyperaceae, *Artemisia* and *Typha*. Many semi-aquatic wetland herb types occur in low values, including aquatics *Potamogeton*, *Nuphar*, *Nelumbo*, *Iris* and *Typha latifolia*, and likely marsh herbs like

Labiatae and Liliaceae. A denser, shallower-water form of reedswamp and succession to marsh/fen plant communities is recorded. The diatom flora is almost entirely freshwater, and similar to that of the previous sub-zone, with a few taxa, particularly *Navicula lacustris*, *Gomphonema acuminatum*, *Eunotia tenella* and *Pinnularia microstauron*, most abundant. Interestingly, the halophobous form *Frustulia rhomboides* is common only in this sub-zone, highlighting the very low salinity levels during this period. The NPPs support the interpretation of shallow water, shown by increases in spores of the green algae Zygnemataceae (van Geel, 2001; van Geel and Grenfell, 1996) which inhabit shallow standing water and waterlogged soils. Frequencies for *Zygnema* (58) and *Mougeotia* (313) from this family are highest in this sub-zone, while *Botryococcus* remains important. NPPs that indicate standing water and eu- to mesotrophic helophyte marsh habitats, Types 123, 404, 715 and *Persiciospora* (124), occur in this sub-zone, while taxa that prefer more open water, like *Gloeotrichia* and Type 128, decline. Gradual increases in *Coniochaeta* cf. *ligniaria*, Sordariaceae spores and *Chaetomium*, and the appearance of *Gelasinospora* cf. *retispora* (2), imply dense marsh/fen vegetation and terrestrialisation. *Oryza* phytoliths are still recorded in very low numbers throughout this sub-zone.

Zone Kua-4 (122-115.5 cm; c. 8120 - c. 7828 cal BP) is characterised by small but significant increases in pollen frequency of several woody taxa, or their first appearance. *Salix* is most increased, but many other shrub types including Rutaceae, Myrsinaceae, *Celtis*, Hamamelidaceae, Moraceae, *Acer* and *Nyssa* increase, as well as several tree taxa including *Castanea*, *Cyclobalanopsis* and *Liquidambar*. A slight increase in *Typha* percentages occurs but small Gramineae remains the only well represented herb pollen type. Wet fen-carr seems to be the habitat represented in this sub-zone, for NPPs indicative of wet conditions are still dominant, with a peak in Type 708 for example, but fungal taxa like *Coniochaeta xylariispora* (6), *Chaetomium*, *Podospora* (368) and Types 12 and 324 suggest an increase in drier habitats. The diatom flora is still heavily dominated by freshwater forms, but the start of slight but continuous curves for a few mesohalobous taxa, for example *Amphora coffeaeformis* and *Cyclotella striata*, and the decline of the halophobe form *Frustulia rhomboides*, make a slight brackish water influence feasible. *Oryza* phytoliths are still recorded in very low numbers throughout this sub-zone.

Zone Kua-5 (115.5-113 cm; c. 7828 – c. 7752 cal BP) is defined by the sharp rise in *Alnus* pollen frequencies to almost 50% of total land pollen, causing relative falls in the percentages of almost all other pollen taxa. Exceptions are the occurrence of Araliaceae and the start of a

consistent curve for *Corylus/Ostrya*. The development of a local dense alder carr vegetation seems necessary to account for such high frequencies, and fungal spores that indicate woody, carr-type vegetation are also well represented at this horizon, primarily *Coniochaeta* cf. *retispora* and *Chaetomium* but also the appearance of *Hypoxylon argillaceum* (327) and *Spadicoides bina* (98), obligate wood decomposers. Little change occurs in the ecological signal of the diatom flora, although a clear change in the assemblage occurs with the rise to high values of *Cyclotella glomerata* coinciding with a major decline in *Eunotia tenella* across this sub-zone. The number of *Oryza* phytoliths recorded increases and, as other indicators of human presence such as Gramineae pollen grains >40 µm (likely to be *Oryza*) and ova of the parasitic worm *Trichuris* (531) are recorded, some low level human activity may be represented here.

Zone Kua-6 (113-94 cm; c. 7752 - c. 7607 cal BP) is characterised by the fall to very low frequencies of *Alnus* pollen and the rise to almost 60% of total land pollen of small Gramineae. Most other tree taxa percentages also fall, including *Quercus*, *Cyclobalanopsis*, *Castanopsis/Lithocarpus*, *Liquidambar*, *Ulmus/Zelkova* and Hamamelidaceae, while *Carpinus*, previously significant, ceases to be recorded. Gramineae >40 µm percentages increase markedly and a consistent curve for the disturbance indicator *Plantago* begins. Other herb pollen likely to represent weeds of open or disturbed ground include Compositae, *Polygonum* and Cruciferae. Microcharcoal frequencies, previously very low, rise sharply to very high values. *Trichuris* forms a consistently high curve and other NPPs indicative of disturbance or cultural activity increase, including *Podospora*, Type 574 and *Glomus* (207) a fungal indicator of disturbed soils. These data are in accord with the archaeological designation of this unit as of cultural origin, and the number of *Oryza* phytoliths counted in this zone is substantial (Fig. 6). Reedswamp NPP frequencies, particularly of fungal Types 306 and 708, increase sharply, matching the rise in small Gramineae. The diatom flora is still dominated by freshwater forms, with *Cyclotella glomerata*, *Synedra acus* and *Navicula lanceolata* prominent. A few valves of salt-tolerant taxa are recorded consistently, however, particularly *Cyclotella striata*, *Amphora coffeaeformis*, *Achnanthes brevipes* and *Nitzschia granulata*, and there must have been some slight brackish-water influence to allow these estuarine or saltmarsh forms to join the assemblage. There are no marine taxa except for a very low but regular presence of *Paralia sulcata*, which is often the only polyhalobous marine planktonic form found within such dominantly freshwater environments in coastal-fringe locations (Zong, 1997).

Zone Kua-7 (94-90.5 cm; c. 7607 - c. 7602 cal BP) is characterized by a rise in the frequencies of arboreal pollen, with *Quercus*, *Cyclobalanopsis*, *Liquidambar*, *Castanopsis/Lithocarpus* and *Ulmus/Zelkova* all increased. Several shrub taxa, including *Acer*, *Alnus*, Oleaceae and *Celtis*, also rejoin the assemblage. Microcharcoal values fall sharply, both Gramineae size classes are significantly reduced and disturbed ground weed pollen and cultural NPPs also cease to be recorded. A decline in disturbance activity occurred, resulting in some limited woodland regeneration. Some increased wetness is recorded, with small peaks in NPP algae Types 128 and *Spirogyra*, and the rise in Chenopodiaceae pollen supports the diatom data in suggesting a brackish element to the wetland. Unlike most probable indicators of activity, *Oryza* phytolith numbers do not decline, so perhaps are referable to wild rice in this zone.

Zone Kua-8 (90.5-81 cm; c. 7602 - c. 7592 cal BP) includes the thin clay unit in the stratigraphy that separates the lower and middle cultural layers. Tree pollen values fall through the first half of this zone, particularly *Cyclobalanopsis* and *Castanopsis/Lithocarpus*, although *Quercus* frequencies are maintained until late in the zone when signs of intense human activity are present and they fall sharply. At that point *Oryza*-type Gramineae pollen reaches a peak with weeds of disturbed ground including Ranunculaceae, *Rumex*, *Plantago*, *Polygonum*, Apiaceae and Cruciferae. Secondary shrubs like *Acer*, *Betula* and *Corylus/Ostrya* increase after disturbance. Percentages of small Gramineae pollen and microcharcoal peak, while *Typha* frequencies rise through the zone to abundance near its end. Cultural NPPs mirror the pollen data, with *Trichuris* worm ova, *Chaetomium*, Type 406 and Sordariaceae (55B) all greatly enhanced. The curves for possible halophyte pollen *Artemisia* and Chenopodiaceae remain low but steady. Figs. 4 and 5 show that the low but consistent influence of salt-tolerant diatoms is maintained in this zone, with true polyhalobous forms *Biddulphia rhombus* and *Paralia sulcata* present with several estuarine types. Freshwater forms still account for over 80% of the assemblage, however.

Zone Kua-9 (81-79 cm; c. 7600 cal BP) is a very brief period of limited regeneration when indicators of disturbance and activity fall and tree pollen frequencies rise slightly. Pollen percentages of both Gramineae size classes, disturbed ground weeds and *Typha* fall, and microcharcoal frequencies are much reduced. The fall in *Trichuris* values is pronounced. *Quercus*, *Betula*, *Carpinus*, *Castanopsis/Lithocarpus*, *Acer*, Cupressaceae, *Salix* and Taxodiaceae all increase, as do NPPs associated with woody vegetation, including Type 122 and *Coniochaeta*

xylariispora. Fig. 5 suggests a slight replacement of freshwater diatoms by mildly salt-tolerant forms, but the fluctuations are too small to be reliable.

Zone Kua-10 (79-71.5 cm; c. 7600 - c. 7500 cal BP) is characterised by the return to higher frequencies of both small Gramineae and *Oryza*-type Gramineae grains, along with *Typha* and the full range of disturbed ground weeds *Plantago*, *Polygonum*, Cruciferae Ranunculaceae and *Rumex*. *Pteridium* also increases, as does microcharcoal initially. *Oryza* phytolith numbers are the highest of the diagram. A return to significant levels of activity is recorded, although reductions in frequencies of tree and shrub taxa are slight, with some, like Cupressaceae, *Acer*, *Alnus* and *Pterocarya*, increasing. NPPs signifying disturbance and human activity, *Trichuris*, *Chaetomium*, Sordariaceae Type 55B, *Podospora* and *Glomus*, all increase. Notable are peaks for Types 159 and 406, with uncertain ecological affinities. The waterlogged nature of the surface is shown by consistent curves for *Potamogeton* pollen, *Zygnema* algae and fungal spore Types 12, 90 and 159. The diatom flora is characterized by the gradual replacement of freshwater taxa by mesohalobous and polyhalobous estuarine forms, as marine influence steadily increased.

Zone Kua-11 (71.5-64 cm; c. 7500 - c. 7000 cal BP) records increases in many tree and shrub pollen types. Indicators of human activity are no longer recorded, with *Oryza* phytoliths entirely absent. Small Gramineae and *Typha* frequencies remain substantial, and pollen percentages of probable halophytes *Artemisia* and Chenopodiaceae rise. The presence of Compositae pollen grains of *Youngia* type may also signify saltmarsh environments. Marine indicators among the NPPs include acritarchs *Micrhystridium* and *Cymatiosphaera*, dinocyst *Operculodinium* and Type 705. These records agree well with the main microfossil change of this zone, the major switch from a dominantly freshwater diatom assemblage to one restricted to halophyte forms, with a wide range of mesohalobous estuarine and polyhalobous marine types. Common taxa include *Nitzschia granulata*, *Achnanthes brevipes*, *Actinoptychus senarius* and *Coscinodiscus obscurus*. This continues the trend from the previous zone. Above the zone boundary, estuarine foraminifera occur (Fig. 5), mainly *Ammonia beccarii* and *Elphidium advenum* suggesting increasing salinity.

5. Discussion

Culturally, the Kuahuqiao site lies in the early stages of the transition between the hunting and gathering strategy of Mesolithic foragers and the food-production economy of Neolithic farmers. It is therefore vital for understanding the change from sedentary foraging, as at Shangshan, c. 100 km south of Kuahuqiao, where pottery pastes are found tempered with charred plants including rice husks and dated to c. 10,000 to 8000 cal BP (Jiang and Liu, 2006), to full domestication as at Hemudu, c. 200 km east of Kuahuqiao, where a large quantity of rice grains and husks have been found and dated to between c. 7000 and 6000 cal BP (Crawford and Shen, 1998; Jiang, 2003). Kuahuqiao is a classic site for studying the adoption of pre-domestication rice cultivation in east China. The several forms of independent but complementary proxy data described above allow a detailed reconstruction of palaeoecological change at the site and the placement of the early Neolithic settlement and land-use there into a secure palaeoenvironmental context.

5.1 Vegetation history and climate

The pollen diagram from Kuahuqiao records almost two thousand years of vegetation history of which the first half, zones Kua-1 to Kua-4, corresponds to the natural local and regional vegetation successions before human interference began at the site. There are several published pollen profiles from the lower Yangtze region with which it can be compared (Liu et al., 1992; Wang et al., 1995; Xu et al., 1996; Tao et al., 2005; Chen et al., 2005; Yi et al., 2006; Shu et al., 2007) as well as more general regional syntheses for east China (Liu, 1988; Sun and Chen, 1991; Ren and Beug, 2002; Zhang et al., 2005; Ren, 2007) and national climate records (Shi et al., 1993; Zheng et al., 2004; Feng et al., 2006). The Hangzhou/lower Yangtze area lies near the boundary between the temperate broadleaf forest biome of northeast China and the sub-tropical evergreen forest biome of the southeast, and so the mixed deciduous/evergreen forests there are very sensitive to climate change due to shifts in the strength and influence of the summer monsoon (Yu et al., 2002; Morrill et al., 2003; Wang et al., 2005). The pollen data from this area show that at the start of the Holocene the monsoon strengthened and dominated climate in east China, producing warm, wet conditions which continued until about 9000 cal BP, when weakening of the monsoon brought cooler and drier weather to the region. This persisted until about 7600 cal BP (Chen et al., 2005; Yi et al., 2003, 2006), when the re-establishment of strong monsoonal dominance initiated very warm and wet 'mid-Holocene optimum' or 'megathermal' climate that lasted for the next few

millennia until about 6000 cal BP (An et al., 2000; Yasuda et al., 2004). These dates and climate fluctuations in the study area agree well with environmental data from other regions of southeast China (Zheng and Li, 2000). The two warm and humid phases were characterised by sub-tropical evergreen trees, particularly *Cyclobalanopsis* and *Castanopsis/Lithocarpus*, whereas during the early Holocene cooling phase after c. 9000 cal BP these decline and temperate deciduous trees, particularly *Quercus* (*Lepidobalanus*), become dominant and other cool climate trees like *Pinus* become significant. At Kuahuqiao, pollen zones Kua-1 to Kua-4 fall exactly within the time-frame of this regional cooler, less humid period before 7600 cal BP. Although *Cyclobalanopsis* pollen frequencies probably underestimate actual tree representation (Yu et al., 2004), as deciduous *Quercus* is more abundant than the evergreen trees in these zones, with a consistent *Pinus* curve also present, the Kuahuqiao data agree well with the regional climatic and vegetational evidence for this period. The fact that the Kuahuqiao canoe and several other wooden artifacts recovered during the archaeological excavation (Jiang, 2004) were made from pine wood strongly suggests local growth of *Pinus* in the early phases of the occupation. The coldest part of this cool phase is likely to correspond to the global 8200 cal BP climatic deterioration event that has been recognised in China (Wang et al., 2005). This would correspond to the end of zone Kua-3 at Kuahuqiao but, although it is noteworthy that *Closterium* algae, which prefer colder waters, are only present just above this level, there is no real evidence for cooling at this point in the profile.

While regionally the period after c. 7600 cal BP saw a return to warm, wet climate that favoured the expansion of sub-tropical evergreen trees, climatic effects on forest history at Kuahuqiao are obscured by the impact of human activity on the vegetation, which may have included some limited forest disturbance at least in zone Kua-6, and by greatly increased pollen production by local wetland herb communities. The evergreen trees do increase in frequency at the expense of deciduous *Quercus*, however, and so Kuahuqiao conforms to the regional megathermal pattern. Throughout the profile the locality remained well wooded, as tree and shrub pollen is continually around 70% of total land pollen except in zone Kua-6 where the expansion of local grassland communities reduces it to about 40%.

5.2 Site hydrology

The use of several types of biological proxy data at Kuahuqiao has meant that a detailed appraisal of hydrological changes there has been possible, and this has proved critical to understanding of the site's sedimentary and palaeoecological history, and so also its human exploitation. Sea-level change was clearly a defining factor in the site's hydrological history, as its natural and cultural organic sediments are intercalated within thick deposits of marine clay. Sea level rose rapidly on the eastern China coast in the first Holocene millennium (Zhang and Zhao, 1990; Chen and Stanley, 1998; Zong, 2004) until the present Yangtze Delta/ Hangzhou Bay area was inundated and the Yangtze delta began to form, demonstrated by shallow marine and intertidal facies there of early Holocene age (Wu, 1983; Yan and Hong, 1987; Chen et al., 2000; Li et al., 2000; Wang et al., 2006). In places marine environments penetrated landward of the present coast along inlets and incised valleys (Yan and Huang, 1987; Hori et al., 2001, 2002), as at Kuahuqiao. Recent research (Bird et al., 2007) has shown that the rate of eustatic sea-level rise slowed considerably in the period between c. 8000 and c. 7500 cal BP allowing vegetation colonising the newly stabilised coastal fringes due to high rates of sedimentation. At Kuahuqiao and similar sites on the eastern China coast (Zheng and Li, 2000), estuarine depositional environments were replaced by freshwater marshes and lagoons within which more organic sediments accumulated. The switch at Kuahuqiao from intertidal sedimentation to open freshwater suggests that the site became isolated from marine influence rapidly (Fig. 5). There followed several centuries of organic clay deposition and shallowing of freshwater levels within the reedswamp and marsh environments at Kuahuqiao, as hydrosereal vegetation succession progressed. Eventually water levels fell sufficiently to allow the establishment of riparian carr woodland on the organic marsh soils by c. 7800 cal BP. Removal of this woodland by human activity deflected this succession back to shallow reedswamp communities, but natural hydrological changes also occurred from this time onwards. The Kuahuqiao diatom data indicate the return of brackish water influence which persists at a consistently low level until c. 7500 cal BP when the site was overwhelmed by marine transgression. This fits well with the sea-level curve of Bird et al. (2007), which records a return to rapid sea-level rise at about this time, and with the other sea-level histories for the region, which record sea level rising from this time until reaching its regional maximum between 7000 and 6000 cal BP during the peak of the mid-Holocene climatic megathermal (Liu et al., 1992; Zhu et al., 1996; Chen et al., 2000; Wang et al., 2001). The constant but faint marine influence for three hundred years after c. 7800 cal BP suggests either a very slowly rising sea level for that period that

did not outpace sedimentation, with a sudden acceleration at c.7500 cal BP, or the protection of the site from marine transgression by a barrier system, either natural or artificial. Any artificial barrier, or 'bundling' would presumably have been rather rudimentary at this early date, although the presence on the site of wooden digging implements and of clay walls reinforcing the dwellings (Jiang, 2004) suggests that the capability for barrier construction was present. If any barrier system existed, it failed around 7500 cal BP when the site was overwhelmed by fully marine environments, as shown by the foraminiferal record (Fig. 5).

5.3 *Human activity*

Rice is a wetland grass and requires relatively specific and stable water depths and quality for its successful cultivation, so factors affecting site hydrological conditions were clearly of critical importance regarding its cultivation by Neolithic communities, especially in such a low-lying coastal area as the Hangzhou/Yangtze delta plain, much of which is 2 m above YSD and so vulnerable to even small changes in sea level and ground water. Climatic and sea-level fluctuations in the first half of the Holocene must have had major implications for the location of Neolithic settlements, their success and even survival in this area (Stanley and Chen, 1996; Chen et al., 2005, 2008; Yu et al., 2000) as elsewhere in coastal eastern China (Jiao, 2006). With rising water tables and frequent flooding (Zhu et al., 2003) local topographic variability must have caused major differences in settlement potential over small spatial areas (Stanley and Chen, 1996; Zhang et al., 2004; Xin and Xie, 2006). A key finding at Kuahuqiao is that foragers chose a coastal marsh location for wet rice cultivation that by natural hydrological succession had reached an optimum water depth, during a period of stable sea level, which they then maintained by very high intensity clearance and management of the coastal marsh vegetation by fire. Not necessary for low-scale pioneer rice cultivation (White, 1995), such significant clearance suggests site selection for higher intensity land-use. Moderate microcharcoal increases have been linked with rice cultivation in the mid-Holocene elsewhere in the area, as at Guangfulin in the Yangtze delta (Itzstein-Davey et al., 2007c), where later Neolithic cultivators used burning as an integral part of the planting process, as at Chuodun (Cao, 2006). Kuahuqiao, however, is the earliest and most intensive example of Chinese foragers' fire-clearance of carr woodland to prepare ground for rice cultivation and associated settlement. The fall of tree and shrub pollen frequencies from 60% to 30% of total land pollen during the first cultivation phase Kua-6 suggests complete removal of local wetland shrubs,

but no diminution of forest on drier ground to landward. There is no evidence that fire was used to manipulate the forest beyond the wetland to improve hunting in the way attributed to mid-Holocene foragers in Europe (Simmons, 1996) or near-recent foragers in North America (Delcourt et al., 1998), but separating a microcharcoal component that was derived from higher, dry ground from the total microcharcoal curve is impractical, unless the low but consistent microcharcoal levels in the pre-cultural sediments of Kua-1 to Kua-5 (Fig. 2) represents a regional signal.

A further interesting aspect of the rice cultivation system at this very early date is that of grazing (Mesléard et al., 1999) and manuring (perhaps artificially) of the cultivation site by domesticated animals. These would have been pigs, the only animal certainly domesticated in China at this early date, and there is morphological skeletal evidence at the site for the presence of domesticated pigs (Jiang, 2004), although most *Sus* bones at Kuahuqiao are of wild boar type. Manuring perhaps occurred consistently, judging by the high values of spores of coprophilous fungi (Graf and Chmura, 2006) and *Trichuris* parasitic worm ova (Pike, 1968), the latter infecting both pigs and people. *Trichuris* ova have been recorded in quantity at later Neolithic settlement/cultivation sites, as at Chengtoushan in the middle Yangtze (Yasuda et al., 2004). At Kuahuqiao pig-keeping at this early date was probably small scale (as the bone assemblage is heavily dominated by wild animals, particularly deer) but concentrated in the small area selected for cultivation, hence magnifying its effects, such as the high *Trichuris* levels. The use of pigs to prepare swampy ground for cultivation was a common practice in other subsistence farming cultures (Takács, 1982). The ‘on site’ environmental evidence from Kuahuqiao not only establishes the presence of extremely early dedicated rice cultivation but is important (Underhill, 1997) in that it allows for the first time an assessment of the earliest Neolithic rice cultivation system itself. As the proportion of tidal brackish influence is maintained at a consistent low level throughout the c. 300 years of cultural activity at Kuahuqiao, despite a slowly rising sea level, it is likely that the input of floodwater to the cultivated areas may well also have been controlled by the cultivators. The earliest system of rice cultivation in China may well have been a form of ‘receding-flood’ water regulation (Glover and Higham, 1996), with artificial earth barriers to retain some nutrient-rich, silt-bearing seasonal floodwater (Mesléard et al., 1999) and provide rice with the consistent water regime it requires. Water-management systems were probably part of rice cultivation practices from the beginning (Ling et al., 2005; Udatsu et al., 1998; Ruddiman et al., 2008) and the degree of control thus exercised by the Kuahuqiao occupants supports hypotheses

that low intensity ‘paddy’ style wet rice production (Barnes, 1990; Pei, 1998, 2002; Zhao and Wu, 1988; Wang and Ding, 1999; Cao et al., 2006) occurred during the very early Neolithic in the eastern Chinese lowlands, as early as 7000 cal BP (Wang and Zhang, 1998), although in some cases actual ‘paddy’ plots are presumed rather than demonstrated. The partly organic alluvial sediments containing cultural material at Kuahuqiao may well effectively be the earliest ‘paddy soils’ yet discovered. It is likely that the wild rice strains cultivated there could withstand the low salinity levels suggested by the diatom evidence (Zeng and Shannon, 2000) but rudimentary ‘bundling’ was necessary to protect the crop from major marine inundation, achieved until the system failed at the start of zone Kua-11 through enhanced sea-level rise or storm surge penetration. There are other examples of foragers protecting ‘speciality’ crops around their settlements through the use of artificial barriers (Hynes and Chase, 1982).

As stressed by Fuller (2006), Fuller et al. (2007) and Atahan et al. (2008), rice cultivation would have been only one aspect of the exploitation of coastal littoral resources at forager/cultivator sites like Kuahuqiao. In addition to the collection of wild foods, other measures may have been taken to increase the productivity of the wetland environment. The low-intensity controlled burning of the reedswamp promoted the growth of cattail (*Typha*) which was perhaps deliberate as *Typha* is itself an important crop for food and materials (Morton, 1975; Zhao et al., 1999), exploited and processed by hunter-gatherers since long before the Holocene (Aranguren et al., 2007). High levels of burning within lakeside *Typha* stands recorded at the forager site of Star Carr in northern England (Law, 1998) may well reflect similar promotion of a valuable plant resource.

6. Conclusion

Kuahuqiao was occupied by sedentary foragers who pioneered rice cultivation in the lower Yangtze area and who transformed the site’s local vegetation and exercised almost complete control over their cultivation environment. Their occupation lasted only about three hundred years and it is tempting to attribute that short period to the constraints of major environmental factors. Settlement of the Kuahuqiao marshlands required a phase of relative stasis in Holocene sea-level rise, and had to wait until natural plant succession and sedimentation reduced the water regime to a depth and quality favourable for wet rice cultivation. It probably also had to wait, however, for the warmer, wetter climate phase that started about 7750 cal BP before substantial rice cultivation

would be successful at this northerly latitude (Lu et al., 2002). Settlement and cultivation was brought to an end by the renewed rapid sea-level rise that began at about 7400 cal BP and inundated the site despite the inhabitants' efforts at flood control, forcing them to move. The short duration of Kuahuqiao highlights the vulnerability of early rice cultivation in this productive but environmentally vulnerable coastal fringe ecosystem. That Kuahuqiao is one of very few incipient cultivator sites yet found of this age shows that it was at or near the start of this innovation in rice production, but the greater number of Neolithic forager/cultivator sites of Hemudu-type (Jiang, 2003) that date to the following millennium, such as Tian Luo Shan (Fuller, 2006) show that cultivation techniques were continued and developed by people who spread across the lower Yangtze/Hangzhou area, under still favourable mid-Holocene megathermal climate (Sun et al., 1981), to locations of higher topography beyond the reach of the rising sea level. Extending this paper's multi-proxy palaeoecological research methodology to these sites, and to possible forager/cultivator correlatives of Kuahuqiao such as key sites like Pengtoushan around the lakes of the central Yangtze valley (Pei, 1998), and to the north in Henan Province (Chen and Jiang, 1997), would help to broaden understanding of the development of rice cultivation in China.

Acknowledgements

This research is supported by the Leverhulme Trust, U.K under project number F/000128/AL. We thank Baocheng Zhao, Fengling Yu, and members of the Xiaoshan Museum for their assistance in fieldwork.

References

- An, Z., Porter, S.C., Kutzbach, J.E., Wu, X., Wang, S., Liu, X., Li, X., Zhou, W., 2000. Asynchronous Holocene optimum of the East Asian monsoon. *Quaternary Science Reviews* 19, 743-762.
- Aranguren, B., Becattini, R., Mariotti Lippi, M., Revedin, A., 2007. Grinding flour in Upper Palaeolithic Europe (25 000 years bp). *Antiquity* 81, 845-855.
- Atahan, P., Grice, K., Dodson, J., 2007. Agriculture and environmental change at Qingpu, Yangtze Delta region, China: a biomarker, stable isotope and palynological approach. *The Holocene* 17, 507-515.
- 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. *Quaternary Science Reviews* 27, 556-570.
- Barnes, G. L., 1990. Paddy soils now and then. *World Archaeology* 22, 1-17.
- Bakker, M., van Smeerdijk, D.G., 1982. A palaeoecological study of a late Holocene section from "Het Ilperveld", Western Netherlands. *Review of Palaeobotany and Palynology* 36, 95-163.
- Binney, H.A., Waller, M.P., Bunting, M.J., Armitage, R.A., 2005. The interpretation of fen carr pollen diagrams: the representation of the dry land vegetation. *Review of Palaeobotany and Palynology* 134, 197-218.
- Bird, M.I., Fifield, L.K., Teh, T.S., Chang, C.H., Shirlaw, N., Lambeck, K., 2007. An inflection in the rate of early mid-Holocene eustatic sea-level rise: a new sea-level curve from Singapore. *Estuarine, Coast and Shelf Science* 71, 523-536.

- Cao, Z., Ding, J., Hu., Z., Knicker, H., Kogel-Knabner, I., Yang, L., Yin, R., Lin, X., Dong, Y., 2006. Ancient paddy soils from the Neolithic age in China's Yangtze River Delta. *Naturwissenschaften* 93, 232-236.
- Chang, K-T., Wang, P-L., 1986. Pollen morphology of *Quercus* L. in China. *Acta Phytotaxonomica Sinica* 24, 362-369.
- Chang, T.T., 1989. Domestication and spread of cultivated rices. In: Harris, D.R., Hillman, G.C. (Eds.), *Foraging and Farming: the Evolution of Plant Exploitation*. Unwin Hyman, London, pp. 408-417.
- Chatuvedi, M., Datta, K., Nair, P.K.K., 1998. Pollen morphology of *Oryza* (Poaceae). *Grana* 37, 79-86.
- Chen, B.Z., Jiang, Q., 1997. Antiquity of the earliest cultivated rice in central China, and its implications. *Economic Botany* 51, 307-310.
- Chen, B.Z., Wang, X.K., Zhang, J.H., 1995. The discovery and significance of *Oryza* phytoliths in the Neolithic site at Jiahu, Ouyang County, Henan Province. *Chinese Science Bulletin* 40, 339-342 (in Chinese).
- Chen, X., 1998. Searching for the early Neolithic in China. *Documenta Praehistorica* 25, 17-26.
- Chen, Z., Stanley, D.J., 1998. Sea-level rise on eastern China's Yangtze delta. *Journal of Coastal Research* 14, 360-366.
- Chen, Z., Song, B., Wang, Z., Cai, Y., 2000. Late Quaternary evolution of the sub-aqueous Yangtze delta, China: sedimentation, stratigraphy, palynology and deformation. *Marine Geology* 162, 423-441.

- Chen, Z., Wang, Z., Schneiderman, J., Tao, J., Cai, Y., 2005. Holocene climate fluctuations in the Yangtze delta of eastern China and the Neolithic response. *The Holocene* 15, 917-926.
- Chen, Z., Zong, Y., Wang, Z., Wang, H., Chen, J., 2008. Migration patterns of Neolithic settlements on the abandoned Yellow and Yangtze River deltas of China. *Quaternary Research* 70, 301-314.
- Chmura, G.L., Stone, P.A., Ross, M.S., 2006. Non-pollen microfossils in Everglades sediments. *Review of Palaeobotany and Palynology* 141, 103-119.
- Clarke, C., 1994. Differential recovery of fungal and algal palynomorphs versus embryophyte pollen and spores by three processing techniques. In: Davis O.K. (Ed.), *Aspects of Archaeological Palynology: Methodology and Applications*. AASP Contributions Series 29, 53-62.
- Crawford, G.W., Shen, C., 1998. The origins of rice agriculture: recent progress in East Asia. *Antiquity* 72, 858-866.
- Delcourt, P.A., Delcourt, H.R., Ison, C.R., Sharp, W.E., Gremillion, K.J., 1998. Prehistoric human use of fire, the eastern agricultural complex, and Appalachian oak-chestnut forests: palaeoecology of Cliff Palace Pond, Kentucky. *American Antiquity* 63, 263-278.
- Diamond, J., 2002. Evolution, consequences and future of plant and animal domestication. *Nature* 418, 700-707.
- Feng, Z., Thompson, L.G., Mosley-Thompson, E., Yao, T., 1993. Temporal and spatial variations of climate in China during the last 10,000 years. *The Holocene* 3, 174-180.
- Fuller, D.Q., 2006. The archaeobotany of Tian Luo Shan: an investigation of foraging and rice cultivation in the Hemudu Neolithic culture (Yangzi Delta, China).

<http://www.ucl.ac.uk/archaeology/staff/profiles/fuller/tian-luo-shan/index.html> (accessed 11.12.06)

Fuller, D.Q., 2007. Contrasting patterns in crop domestication and domestication rates: recent archaeobotanical insights from the Old World. *Annals of Botany* 100, 903-924.

Fuller, D.Q., Harvey, E., Qin, L., 2007. Presumed domestication? Evidence for wild rice cultivation and domestication in the fifth millennium BC of the Lower Yangtze region. *Antiquity* 81, 316-331.

Fuller, D.Q., Lin, Q., Harvey E., 2008a. Rice archaeobotany revisited: comments on Liu et al. 2007. <http://www.antiquity.ac.uk/ProjGall/fuller1/index.html> (accessed 4.5.08).

Fuller, D.Q., Qin, L., Harvey, E., 2008b. Evidence for a late onset of agriculture in the lower Yangtze region and challenges for an archaeobotany of rice. In Sanchez-Mazas, A., Blench, R., Ross, M.D., Peiros, I., Lin, M., (Eds.), *Past Human Migrations in East Asia. Matching Archaeology, Linguistics and Genetics*. Routledge, London, pp. 40-83.

Fuller D.Q., Qin, L., 2008. Immature rice and its archaeobotanical recognition: a reply to Pan. *Antiquity* 82, <http://www.antiquity.ac.uk/ProjGall/fuller/index.html> (accessed 7.10.08).

Fuller, D.Q., Qin, L., Zheng, Y., Zhao, Z., Chen, X., Hosoya, L-A., Sun, G-P., 2009. The domestication process and domestication rate in rice: spikelet bases from the lower Yangtze. *Science* 323, 1607-1610.

Glover, I.C., Higham, C.F.W., 1996. New evidence for early rice cultivation in South, Southeast and East Asia. In: Harris R.D. (Ed.), *The Origin and Spread of Agriculture and Pastoralism in Eurasia*. UCL Press, London, pp. 413-441.

- Graf, M-T., Chmura, G.L., 2006. Development of modern analogues for natural, mowed and grazed grasslands using pollen assemblages and coprophilous fungi. *Review of Palaeobotany and Palynology* 141, 139-149.
- Grimm, E.C., 1993. TILIA Software. Illinois State Museum, Chicago.
- Haas, J.N., 1996. Neorhabdocoela oocytes – palaeoecological indicators found in pollen preparations from Holocene freshwater lake sediments. *Review of Palaeobotany and Palynology* 91, 371-382.
- Higham, C.F.W., 1995. The transition to rice cultivation in south-east Asia. In: Price, TD, Gebauer, A.B. (Eds.), *Last Hunters, First Farmers. New Perspectives on the Transition to Agriculture*. School of American Research, Santa Fe, pp. 127-156.
- Higham, C., Lu, T.L-D., 1998. The origins and dispersal of rice cultivation. *Antiquity* 72, 867-877.
- Hillman, G., Hedges, R., Moore, A., Colledge, S., Pettitt, P., 2001. New evidence of Lateglacial cereal cultivation at Abu Hureyra on the Euphrates. *The Holocene* 11, 383-393.
- Hori, K., Saito, Y., Zhao, Q., Cheng, X., Wang, P, Sato, Y., Li, C., 2001. Sedimentary facies and Holocene progradation rates of the Changjiang (Yangtze) delta, China. *Geomorphology* 41, 233-248.
- Hori, K., Saito, Y, Zhao, Q., Wang, P., 2002. Evolution of the coastal depositional systems of the Changjiang (Yangtze) River in response to late Pleistocene-Holocene sea-level changes. *Journal of Sedimentary Research* 72, 884-897.
- Hu, Y., Ambrose, S.H., Wang, C., 2006. Stable isotopic analysis of human bones from Jiahu site, Henan, China: implications for the transition to agriculture. *Journal of Archaeological Science* 33, 1319-1330.

- Hynes, R.A., Chase, A.K., 1982. Plants, sites and domiculture: Aboriginal influence upon plant communities in the Cape York Peninsula. *Archaeology in Oceania* 17, 38-50.
- Huang, F., Zhang, M., 2000. Pollen and phytolith evidence for rice cultivation during the neolithic at Longqiuzhuang, eastern Jianghuai, China. *Vegetation History and Archaeobotany* 9, 161-168
- Innes, J.B., Simmons, I.G., 2000. Mid Holocene charcoal stratigraphy, fire history and palaeoecology at North Gill, North York Moors, UK. *Palaeogeography, Palaeoclimatology, Palaeoecology* 164, 151-161.
- Itzstein-Davey, F., Taylor, D., Dodson, J., Atahan, P., Zheng, H., 2007a. Wild and domesticated forms of rice (*Oryza* sp.) in early agriculture at Qingpu, lower Yangtze, China: evidence from phytoliths. *Journal of Archaeological Science* 34, 2101-2108.
- Itzstein-Davey, F., Atahan, P., Dodson, J., Taylor, D., Zheng, H., 2007b. Environmental and cultural changes during the terminal Neolithic: Qingpu, Yangtze delta, eastern China. *The Holocene* 17, 875-887.
- Itzstein-Davey, F., Atahan, P., Dodson, J., Taylor, D., Zheng, H., 2007c. A sediment-based record of Lateglacial and Holocene environmental changes from Guangfulin, Yangtze delta, eastern China. *The Holocene* 17, 1221-1231.
- Jarvis, D. I., 1993. Pollen evidence of changing Holocene monsoon climate in Sichuan province, China. *Quaternary Research* 39, 325-337.
- Jarvis, D.I., Leopold E.B., Liu, Y., 1992. Distinguishing the pollen of deciduous oaks, evergreen oaks and certain rosaceous species of southwestern Sichuan Province, China. *Review of Palaeobotany and Palynology* 75, 259-271.

- Jiang, L., (Ed.) 2003. Hemudu: A Neolithic site and its Archaeological Excavations. Wenwu Press, Beijing (in Chinese).
- Jiang, L., (Ed.) 2004. Kuahuqiao. Wenwu Press, Beijing (in Chinese).
- Jiang, L., Liu, L., 2005. The discovery of an 8000-year-old dugout canoe at Kuahuqiao in the Lower Yangzi River, China. *Antiquity* 79, 305. <http://antiquity.ac.uk/ProjGall/liu/index.html> (accessed 10.12.05)
- Jiang, L., Liu, L., 2006. New evidence for the origins of sedentism and rice domestication in the Lower Yangtze River, China. *Antiquity* 80, 355-361.
- Jiang, Q., 1995. Searching for evidence of early rice agriculture at prehistoric sites in China through phytolith analysis: an example from central China. *Review of Palaeobotany and Palynology* 89, 481-485.
- Jiang, Q., Piperno, D.R., 1994. Phytolith analysis of an archaeological site (Longshan period) in Zhumadian City, Henan Province, China: Paleoenvironmental and cultural implications. *Geoarchaeology* 9, 409-417.
- Jiao, T., 2006. Environment and culture change in Neolithic Southeast China. *Antiquity* 80, 615-621.
- Jin, D., Cheng, X., Lin, Z., Liu, X., 1982. Marine diatoms in China (in Chinese). China Ocean Press, Beijing.
- Kislev, M.E., Weiss, E., Hartmann, A., 2004. Impetus for sowing and the beginning of agriculture: ground collecting of wild cereals. *Proceedings of the National Academy of Sciences* 101, 2692-2695.
- Khush, G.S., 1997. Origin, dispersal, cultivation and variation of rice. *Plant Molecular Biology* 35, 25-34.

- Law, C., 1998. The uses and fire-ecology of reedswamp vegetation. In: Mellars, P., Dark, P. (Eds.), *Star Carr in Context*. McDonald Institute Monographs, Cambridge, pp. 197-206.
- Li, C.X., Chen, Q.Q., Zhang, J.Q., Yang, S.Y., Fan, D.D., 2000. Stratigraphy and palaeoenvironmental changes in the Yangtze Delta during the Late Quaternary. *Journal of Asian Earth Sciences* 18, 453-469.
- Ling, Q., Ding, Y., Zhang, H. 2005. The origin of Chinese ancient cultivated rice production and lowland rice. *Southeast Culture* 5, 6-11 (in Chinese).
- Liu, K-B., 1988. Quaternary history of the temperate forests of China. *Quaternary Science Reviews* 7, 1-20.
- Liu, K-B., Sun, S., Jiang, X., 1992. Environmental change in the Yangtze River Delta since 12,000 years BP. *Quaternary Research* 38, 32-45.
- Liu, L., Lee, G-A., Jiang, L., Zhang, J., 2007a. The earliest rice domestication in China. <http://www.antiquity.ac.uk/ProjGall/liy1/index.html> (accessed 11.10.07).
- Liu, L., Lee, G-A., Jiang, L., Zhang, J., 2007b. Evidence for the early beginning (c. 9000 cal. BP) of rice domestication in China: a response. *The Holocene* 17, 1059-1068.
- Londo, J.P., Chiang, Y-C., Hung, K-H., Chiang, T-H., Schaal, B.A., 2006. Phylogeography of Asian wild rice, *Oryza rufipogon*, reveals multiple independent domestications of cultivated rice, *Oryza sativa*. *Proceedings of the National Academy of Sciences* 103, 9578-9583.
- Lu, H.Y., Liu, Z.X., Wu, N.Q., Berné, S., Saito, Y., Liu, B.Z., Wang, L., 2002. Rice domestication and climate change: phytolith evidence from east China. *Boreas* 31, 378-385.
- Lu, H.Y., Wu, N.Q., Yang, X.D., Jiang, H., Liu, K.B., Liu, T.S., 2006. Phytoliths as quantitative indicators for the reconstruction of past environmental conditions in China I: phytolith-based transfer functions. *Quaternary Science Reviews* 25, 945-959.

- Lu, T., 1999. Transition to Foraging and Farming and the Origin of Agriculture in China. British Archaeological Reports International Series 774. Oxford.
- Lu, T., 2006. The occurrence of cereal cultivation in China. *Asian Perspectives* 45, 129-158.
- Mannion, A., 1999. Domestication and the origin of agriculture: an appraisal. *Progress in Physical Geography* 23, 37-56.
- Mesléard, F., Lepart, J., Grillas, P., Mauchamp, A., 1999. Effects of seasonal flooding and grazing on the vegetation of former ricefields in the Rhone delta (Southern France). *Plant Ecology* 145, 101-114.
- Moore, P.D., Webb, J.A., Collinson, M.E., 1991. *Pollen Analysis*. Blackwell Scientific Publications, Oxford, UK.
- Morton, J. F., 1975. Cattails (*Typha* spp.) - Weed problem or potential crop? *Economic Botany* 29, 7-29.
- Morrill, C., Overpeck, J. T., Cole, J. E., 2003. A synthesis of abrupt changes in the Asian summer monsoon since the last deglaciation. *The Holocene* 13, 465-476.
- Normile, D., 1997. Yangtze seen as earliest rice site. *Science* 275, 309-310.
- Okuda, M., Sato, Y., Tang, L.H., Takahashi, M., Toyama, S., Yano, A., Kitagawa, H., Yasuda, Y., 2003. Late Holocene vegetation and environment at Cauduntou, west of Yangtze Delta, SW Jiangsu Province, East China. *Quaternary International* 105, 39-47.
- Palmer, A.J.M., Abbott, W.H., 1986. Diatoms as indicators of sea-level change. In: O. van de Plassche (Ed.), *Sea-level Research: a Manual for the Collection and Evaluation of Data*. Geo Books, Norwich, pp. 457-488.
- Pan, Y., 2008. Immature wild rice harvesting at Kuahuqiao, China? *Antiquity* 82, <http://www.antiquity.ac.uk/ProjGall/pan/index.html> (accessed 7.10.08).

- Pearsall, D.M., Piperno, D.R., Dinan, E.H., Umlauf, R., Zhao, Z.J., Benfer, R.A., 1995. Distinguishing rice (*Oryza sativa* poaceae) from wild *Oryza* species through phytolith analysis: results of preliminary research. *Economic Botany* 49, 183-196.
- Pei, A., 1998. Notes on new advancements and revelations in the agricultural archaeology of early rice domestication in the Dongting Lake region. *Antiquity* 72, 878-885.
- Pei, A., 2002. Rice Paddy agriculture and pottery from the middle reaches of the Yangtze river. In: Yasuda Y. (Ed.), *The Origins of Pottery and Agriculture*. Roli Books Pvt. Ltd, New Delhi, pp. 167-181.
- Pike, A.W., 1968. Recovery of helminth eggs from archaeological excavations, and their possible usefulness in providing evidence for the purpose of an occupation. *Nature* 219, 303-304.
- Piperno, D.R., Weiss, E., Holst, I., Nadel, D., 2004. Processing of wild cereal grains in the Upper Palaeolithic revealed by starch grain analysis. *Nature* 430, 670-673.
- Pringle, H., 1998. The slow birth of agriculture. *Science* 282, 1446.
- Qin, L., Fuller, D.Q., Harvey, E., 2006. Subsistence of Hemudu Site, and reconsideration of issues in the study of early rice from Lower Yangtze. *Dongfang Kaogu [Oriental Archaeology]* 3, 307-350 [in Chinese].
- Ren, G., 2007. Changes in forest cover in China during the Holocene. *Vegetation History and Archaeobotany* 16, 119-126.
- Ren, G., Beug, H-J., 2002. Mapping Holocene pollen data and vegetation of China. *Quaternary Science Reviews* 21, 1395-1422.

- Ruddiman, W.F., Guo, Z., Zhou, X., Wu, H., Yu, Y., 2008. Early rice farming and anomalous methane trends. *Quaternary Science Reviews* 27, 1291-1295.
- Sato, Y-I., 2002. Origin of rice cultivation in the Yangtze River Basin. In: Yasuda Y. (Ed.), *The Origins of Pottery and Agriculture*. Roli Books Pvt. Ltd, New Delhi, pp. 143-150.
- Shi, Y., Kong, Z., Wang, S., Tang, L., Wang, F., Yao, T., Zhao, X., Zhang, P., Shi, S., 1993. Mid-Holocene climates and environments in China. *Global and Planetary Change* 7, 219–233.
- Simmons, I.G., 1996. *The Environmental Impact of Later Mesolithic Cultures*. Edinburgh University Press, Edinburgh.
- Shu, J-W., Wang, W-M., Chen, W., 2007. Holocene vegetation and environment changes in the NW Taihu plain, Jiangsu Province, East China. *Acta Micropalaeontologica Sinica* 24, 210-221.
- Stanley, S.J., Chen, Y., 1996. Neolithic settlement distributions as a function of sea level-controlled topography in the Yangtze delta, China. *Geology* 24, 1083-1086.
- Stanley, S.J., Chen, Z., 2000. Radiocarbon dates in China's Holocene Yangtze delta: record of sediment storage and reworking, not time of deposition. *Journal of Coastal Research* 16, 1126-1132.
- Stanley, S.J., Hait, A.K., 2000. Deltas, radiocarbon dating and measurements of sediment storage and subsidence. *Geology* 28, 295-298.
- Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. *Pollen et Spores* 13, 615-621.
- Stuiver, M., Reimer, P.J., Braziunas, T.F., 1998. High-resolution radiocarbon age calibration for terrestrial and marine samples. *Radiocarbon* 40, 215-230.

- Sun, X., Chen, Y., 1991. Palynological records of the last 11,000 years in China. *Quaternary Science Reviews* 10, 537-544.
- Sun, X., Du, N., Chen, M., 1981. Palaeovegetation and palaeoclimate during the time of the Hemudu people. *Acta Botanica Sinica* 23, 147-151. (in Chinese).
- Sweeney, M., McCouch, S., 2007. The complex history of the domestication of rice. *Annals of Botany* 100, 951-957.
- Takács, L., 1982. Grubbing by swine as a means of preparing the soil on swampy ground. *Tools and Tillage* 4, 155-157.
- Tang, S., Sato, Y.I., Yu, W., 1994. Discovery of wild grass grains (*O. rufipogon*) in the Hemudu ancient carbonized rice. *Agricultural Archaeology (Nongye Kaogu)* 3, 88-122 (in Chinese).
- Tao, J., Chen, M-T., Xu, S., 2005. A Holocene environmental record from the southern Yangtze River delta, eastern China. *Palaeogeography, Palaeoclimatology, Palaeoecology* 230, 204-229.
- Udatsu, T., Tang, L.H., Wang, C.L., Zheng, Y.F., Yanagisawa, K., Sasaki, A., Fujiwara, H., 1998. Investigation of paddy relics in China. *Agricultural Archaeology* 1, 138-152 (in Chinese).
- Underhill, A.P., 1997. Current issues in Chinese Neolithic archaeology. *Journal of World Prehistory* 11, 103-160.
- van der Werff, A., Huls, H., 1958-1966. *Diatomeeënflora van Nederland*, 8 parts, published privately by van der Werff, A., Westzijde, 13a, De Hoef (U), The Netherlands.
- van der Woude, J.D., 1983. Holocene palaeoenvironmental evolution of a perimarine fluvial area. *Geology and palaeobotany of the area surrounding the archaeological excavation at*

- the Hazendonk river dune (Western Netherlands). *Analecta Praehistorica Leidensia* 16, 1-124.
- van Geel, B., 1978. A palaeoecological study of Holocene peat bog sections in Germany and the Netherlands. *Review of Palaeobotany and Palynology* 25, 1-120.
- van Geel, B., 1986. Application of fungal and algal remains and other microfossils in palynological analyses. In: Berglund, B.E., (Ed.), *Handbook of Palaeoecology and Palynology*. John Wiley, New York, pp. 497-505.
- van Geel, B., 2001. Non-pollen palynomorphs. In: Smol, J.P., Birks H.J.B., Last, W.M. (Eds.), *Tracking Environmental Change using Lake Sediments. Volume 3: Terrestrial, Algal and Siliceous Indicators*. Kluwer, Dordrecht, pp. 99-119.
- van Geel, B., Aptroot, A., 2006. Fossil ascomycetes in Quaternary deposits. *Nova Hedwigia* 82, 313-329.
- van Geel, B., Grenfell, H.R., 1996. Green and blue-green algae. 7A – Spores of Zygnemataceae. In: Jansonius, J., McGregor, D.C. (Eds.), *Palynology: principles and applications*. American Association of Stratigraphic Palynologists Foundation 1, 173-179.
- van Geel, B., Bohncke, S.J.P., Dee, H., 1981. A palaeoecological study of an upper Late Glacial and Holocene sequence from “De Bochert”, The Netherlands. *Review of Palaeobotany and Palynology* 31, 367-448.
- van Geel, B., Buurman, J., Brinkkemper, O., Schelvis, J., Aptroot, A., van Reenen, G., Hakbijl, T., 2003. Environmental reconstruction of a Roman period settlement site in Uitgeest (The Netherlands), with special reference to coprophilous fungi. *Journal of Archaeological Science* 30, 873-883

- Vos, P.C., de Wolf, H., 1993. Diatoms as a tool for reconstructing sedimentary environments in coastal wetlands: methodological aspects. *Hydrobiologia* 269/270, 285-296.
- Waller, M.P., 1998. An investigation into the palynological properties of fen peat through multiple pollen profiles from south-eastern England. *Journal of Archaeological Science* 25, 631-642.
- Waller, M.P., Binney, H.A., Bunting, M.J., Armitage, R.A., 2005. The interpretation of fen carr pollen diagrams: pollen-vegetation relationships within the fen carr. *Review of Palaeobotany and Palynology* 133, 179-202.
- Waller, M.P., Long, A.J., Long, D., Innes, J.B., 1999. Patterns and processes in the development of coastal mire vegetation: multi-site investigations from Walland Marsh, southeast England. *Quaternary Science Reviews* 18, 1419-1444.
- Wang, C., Ding, J., 1999. Research on ancient rice cultivation in Dongshan village near Zhangjiagang City, Jiangsu Province, PR China. *Agricultural Archaeology* 3, 88-97.
<http://http-server.carleton.ca/~bgordon/Rice/paper_database.htm> (accessed 01/06/07).
- Wang, F., Chien, N., Zhang, Y., Yang, H., 1995. *Pollen Flora of China* (second edition). Science Press, Beijing (in Chinese).
- Wang, J., Chen, X., Zhu, X., Liu, J., Chang, W., 2001. Taihu Lake, lower Yangtze drainage basin: evolution, sedimentation rate and the sea level. *Geomorphology* 41, 183-193.
- Wang, C., Ding, J., 1999. Research on ancient rice cultivation in Dongshan village, near Zhangjiagang City, Jiangsu Province, PR China. *Agricultural Archaeology* 3, 88-97. (in Chinese) Scanned by Wu, Y.; translated and edited by Gordon, B. Available from: http://http-server.carleton.ca/bgordon/Rice/paper_database.htm (accessed 01/06/07).

- Wang, C., Zhang, M., 1998. Primitive paddy rice in Gaoyoulong Village sites. *Agricultural Archaeology* 1, 172-181.
- Wang, J., Yang, Z., Zhuo, Z., Qiu, Y., Zhang, K., Yun, D., Liang, Z., Yang, X., 2006. Late Quaternary sediments and palaeoenvironmental evolution in Hangzhou Bay. *Journal of Palaeogeography* 8, 551-558 (in Chinese).
- Wang, X.Z., Jiang, Q.H., MacNeish, R.S., 1995. Palynology and palaeoclimate in the Dayuan Basin. In: MacNeish, R.S., Libby, J.G. (Eds.), *Origins of Rice Agriculture*. The University of Texas, El Paso, pp. 59-68.
- Wang, X.K., Sun, C.Q., 1996. *Origin and differentiation of Chinese cultivated rice*. China Agricultural University, Beijing (in Chinese).
- Wang, Y., Cheng, H., Edwards, R.L., He, Y., Kong, X., An, Z., Wu, J., Kelly, M., Dykoski, C., Li, X., 2005. The Holocene Asian monsoon: links to solar changes and North Atlantic climate. *Science* 308, 854-857.
- Weiss, E., Kislev, M.E., Hartmann, A., 2006. Autonomous cultivation before domestication. *Science* 312, 1608-1610.
- White, J.C., 1995. Modeling the development of early rice agriculture: ethnoecological perspectives from Northeast Thailand. *Asian Perspectives* 34, 37-68.
- Willcox, G., Fornite, S., Herveux, L., 2008. Early Holocene cultivation before domestication in northern Syria. *Vegetation History and Archaeobotany* 17, 313-325.
- Wu, W., 1983. Holocene palaeogeography of the Hangzhou Bay. *Acta Geographica Sinica* 38, 113-126 (in Chinese).

- Xin, Z., Xie, Z., 2006. Construction of the simulating model for geomorphic evolution on the Yangtze delta, China. *Acta Geographica Sinica* 61, 549-560 (in Chinese).
- Xu, X., Chang, W.Y.B., Liu, J., 1996. Changes in vegetation and climate in the Taihu Lake during the last 11,000 years. *Acta Palaeontologica Sinica* 35, 175-186.
- Yan, W., 1992. Origins of agriculture and animal husbandry in China. In: Aikens C.M., Song N. (Eds.), *Pacific Northeast Asia in Prehistory: Hunter-fisher-gatherers-farmers and Sociopolitical Elites*. Washington State University Press, Pullman. pp.113-123.
- Yan, Q.S., Hong, X.Q., 1987. Holocene transgression on the southern Yangtze plain. *Acta Geographica Sinica* 9, 744-752 (in Chinese).
- Yan, Q.S., Huang, S., 1987. Evolution of Holocene sedimentary environment in the Hangzhou-Jiaxing-Huzhou plain. *Acta Geographica Sinica* 42, 1-15 (in Chinese).
- Yasuda, Y., Fujiki, T., Nasu, H., Kato, M., Morita, Y., Mori, Y., Kanehara, M., Toyama, S., Yano, A., Okuno, M., Jiejum, H., Ishihara, S., Kitagawa, H., Fukusawa, H., Naruse, T., 2004. Environmental archaeology at the Chengtoushan site, Hunan Province, China, and implications for environmental change and the rise and fall of the Yangtze river civilization. *Quaternary International* 123-125, 149-158.
- 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. *Quaternary Science Reviews* 22, 1501-1519.
- Yi, S., Saito Y., Yang, D-Y., 2006. Palynological evidence for Holocene environmental change in the Changjiang (Yangtze River) Delta, China. *Palaeogeography, Palaeoclimatology, Palaeoecology* 241, 103-117.

- Yu, G., Ke, X., Xue, B., Ni, J., 2004. The relationships between the surface arboreal pollen and the plants of the vegetation of China. *Review of Palaeobotany and Palynology* 129, 187-198.
- Yu, S., Zhu, C., Song, H., Qu, W., 2000. Role of climate in the rise and fall of Neolithic cultures on the Yangtze Delta. *Boreas* 29, 157-165.
- Yu, G., Xue, B., Sun, X., 2002. Reconstruction of Asian palaeomonsoon patterns in China over the last 40 kyrs: a synthesis. *Quaternary Research (Daiyongki Kenkyuu)* 41, 23-33.
- Yuan, J., 2002. Rice and pottery 10,000 yrs BP at Yuchanyan, Dao county, Hunan province. In: Yasuda, Y. (Ed.), *The Origins of Pottery and Agriculture*. Roli Books Pvt. Ltd, New Delhi, pp. 157-166.
- Yuan, J., Flad, R.K., 2002. Pig domestication in ancient China. *Antiquity* 76, 724-732.
- Yuan, J., Flad, R.K., Lou, Y., 2008. Meat-acquisition patterns in the Neolithic Yangzi river valley, China. *Antiquity* 82, 351-366.
- Zeng, L., Shannon, M.C., 2000. Salinity effects on seedling growth and yield components of rice. *Crop Science* 40, 996-1003.
- Zhang, C., 1999. The Mesolithic and the Neolithic in China. *Documenta Praehistorica* 26, 1-13.
- Zhang, H.N., Zhao, H.M., 1990. Preliminary study on sea-level changes during Late Pleistocene-Holocene in the southeast coastal areas. *Acta Oceanologica Sinica* 12, 620-631.
- Zhang, J., Wang, X., 1998. Notes on the recent discovery of ancient cultivated rice at Jiahu, Henan Province: a new theory concerning the origin of *Oryza japonica* in China. *Antiquity* 72, 897-901

- Zhang, Q., Liu, C., Zhu, C., Jiang, T., 2004. Environmental change and its impacts on human settlement in the Changjiang river delta in Neolithic age. *Chinese Geographical Science* 14, 239-244.
- Zhang, Q., Hartmann, H., Becker, S., Zhu, C., 2005. Palaeoclimate of the Yangtze River's lower reaches for the past 14,000 years. *Asian Journal of Water, Environment and Pollution* 2, 31-38.
- Zhang, Y., Xi, Y., Zhang, J., Gao, G., Du, N., Sun, X., Kong, Z., 1990. Spore Morphology of Chinese Pteridophytes. Science Press, Beijing.
- Zhao, H., Xie, H., Zhao, Y., 1999. The nutrient value and exploitation potentials of *Typha* pollen in northeastern China. *Acta Hydrobiologica Sinica*. 23, 279-282.
- Zhao, S., Wu, W-T., 1988. Early Neolithic Hemudu culture along the Hangzhou estuary and the origin of domestic paddy rice in China. *Asian Perspectives* 27, 29-34.
- Zhao, Z., 2005. New data for study on the origins of agriculture in China. In: Institute of Archaeology, Chinese Academy of Social Sciences (Ed.), *Chinese Archaeology in the New Century*. Kexue Press, Beijing, pp. 86-110. (in Chinese).
- Zhao, Z., Pearsall, D.M., Jiang, Q.H., 1995. Analysis of phytoliths from Xianrendong and Wangdong. In: MacNeish R.S., Libby J.G. (Eds.), *Origins of Rice Agriculture*. University of Texas Press, El Paso, pp. 47-52.
- Zhao, Z., 1998. The middle Yangtze region in China is one place where rice was domesticated: phytolith evidence from the Diaotonghuan cave, northern Jiangxi. *Antiquity* 72, 885-897.
- Zhao, Z., Pearsall, D.M., Benfer, R.A. Jr., Piperno, D.R., 1998. Distinguishing rice (*Oryza sativa*, Poaceae) from wild rice *Oryza* species through phytolith analysis 2: Finalized method. *Economic Botany* 52, 134-145.

- Zhao, Z., Piperno, D.R., 2000. Late Pleistocene/Holocene environments in the middle Yangtze River valley, China and rice (*Oryza sativa* L.) domestication: the phytolith evidence. *Geoarchaeology* 15, 203-222.
- Zheng, Y., Matsui, A., Fujiwara, H., 2003. Phytoliths in rice detected in the Neolithic sites in the valley of the Taihu lake in China. *Environmental Archaeology* 8, 177-183.
- Zheng, Z., Li, Q., 2000. Vegetation, climate and sea level in the past 55,000 years, Hanjiang Delta, southeastern China. *Quaternary Research* 53, 330-340.
- Zheng, Y., Jiang, L-P, Zheng, J-M., 2004. Study on the remains of ancient rice from Kuahuqiao site in Zhejiang Province. *Chinese Journal of Rice Science* 18, 119-125 (in Chinese).
- Zheng, Y., Sun, G., Chen, X., 2007. Characteristics of the short rachillae of rice from archaeological sites dating to 7000 years ago. *Chinese Science Bulletin* 52, 1654-1660.
- Zheng, Y.Q., Yu, G., Wang, S.M., Xue, B., Zhuo, D.Q., Zeng, X.M., Liu., H.Q., 2004. Simulation of paleoclimate over East Asia at 6 ka BP and 21 ka BP by a regional climate model. *Climate Dynamics* 23, 513-529.
- Zhu, C., Cheng, P., Lu, C., Wang, W., 1996. Shoreline movements in the Yangtze delta and Su-bei coastal areas over the last 7000 years. *Scientia Geographica Sinica* 16, 207-213 (in Chinese).
- Zhu, C., Zheng, C.G., Ma, C.M., Yang, X.X., Gao, X.Z., Wang, H.M., Shao, J.H., 2003. On the Holocene high-level highstand along the Yangtze delta and Ningshao plain, east China. *Chinese Science Bulletin* 48, 2672-2683.
- Zong, Y., 1997. Implications of *Paralia sulcata* abundance in Scottish isolation basins. *Diatom Research* 12, 125-150.

Zong, Y., 2004. Mid-Holocene sea-level highstand along the southeast coast of China. *Quaternary International* 117, 55-67.

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, 459-462.

Table 1. Lithostratigraphy of the sampled profile at Kuahuqiao

Depth (cm) below field datum	Depth (cm) relative to sea level (YSD)	Lithology
0 to 34	-127 to -161	Grey laminated silt and clay
34 to 68	-161 to -195	Grey clay
68 to 71.5	-195 to -198.5	Grey clay with organic matter
71.5 to 88	-198.5 to -215	Brown to light brown organic clay, rich in organic detritus and plant fragments ¹
88 to 90.5	-215 to -217.5	Slightly organic grey clay
90.5 to 113	-217.5 to -240	Brown to light brown organic clay, rich in organic detritus and plant fragments ²
113 to 157.5	-240 to -284.5	Brown-grey highly organic clay
157.5 to 170	-284.5 to -297	Grey clay
170 →	-297 →	Grey clay grading into yellowish silt-clay with sand and gravel

¹ Corresponds to both the middle and upper cultural layers, which are separated at 80.5 cm depth.

² Corresponds to the lower cultural layer.

Table 2. Details of radiocarbon dates from the Kuahuqiao section, showing calibrations, the material dated, laboratory codes and the stratigraphic events to which the dates relate.

Depth below surface (cm)	Depth below sea level (cm)	Lab code	Methods	Conventional ¹⁴ C date: yr BP	Material	Calibrated date: years BP (1σ)	Central calibrated age: years BP (1σ)	Events
68.0	195.0	*	Radiometric	6330±190	Bulk organic	7144-7428	7286±142	Brackish water conditions
73.0	200.0	BA05766	AMS	6710±40	Organic fragments	7564-7612	7588±24	End of human activities
81.0	208.0	BA05767	AMS	6805±35	Organic fragments	7616-7670	7643±27	Rise in cultural NPPs
83.5	210.5	GZ1311	AMS	6743±36	Organic fragments	7574-7622	7598±24	Decline in reedswamp NPPs
86.5	213.5	GZ1312	AMS	6710±31	Organic fragments	7566-7608	7587±21	Rise in <i>Typha</i>
97.5	224.5	GZ1314	AMS	6752±33	Charcoal	7579-7622	7601±22	End of large-scale burning
102.5	229.5	GZ1315	AMS	6783±32	Leaf	7607-7662	7632±30	Increase in reedswamp NPPs
111.0	238.0	GZ1316	AMS	6851±33	Organic fragments	7653-7709	7681±28	Start of human activity. Burning and end of alder carr
111.0	238.0	BA05768	AMS	6870±40	Organic fragments	7663-7749	7706±43	
115.5	242.5	GZ1317	AMS	6996±33	Organic fragments	7792-7863	7828±36	Rise of alder carr
155.0	282.0	*	Radiometric	8125±250	Bulk organic	8722-9319	9021±299	Changing to freshwater conditions

AMS stands for Accelerator Mass Spectrometry. * reproduced from Jiang (2004). These two radiometric dates were from The Institute of Crustal Dynamics, China Earthquake Administration; the AMS dates with a BA code were from the School of Archaeology, Beijing University, China; those with a GZ code were from the Guangzhou Institute of Geochemistry, China.

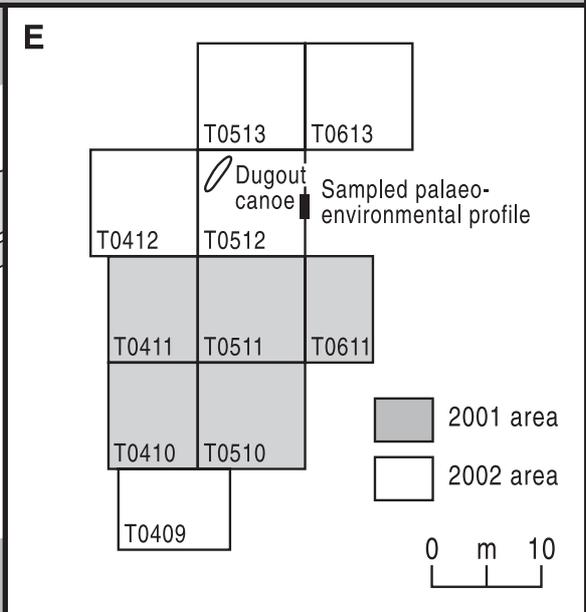
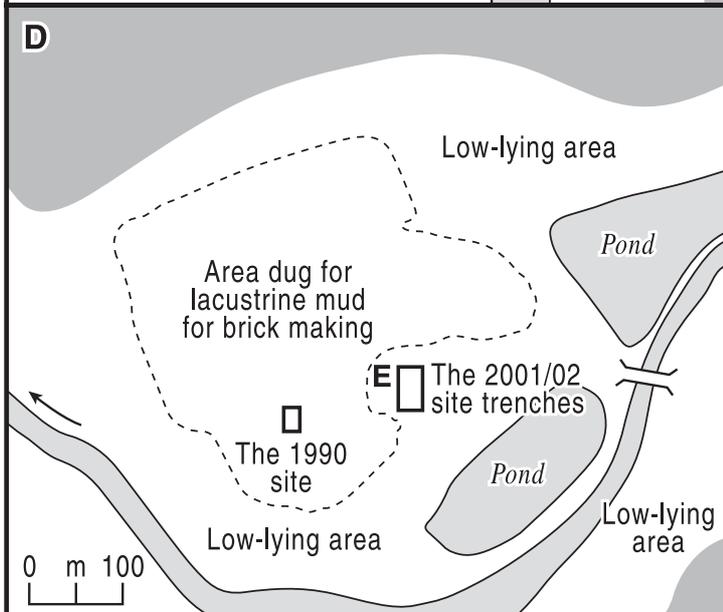
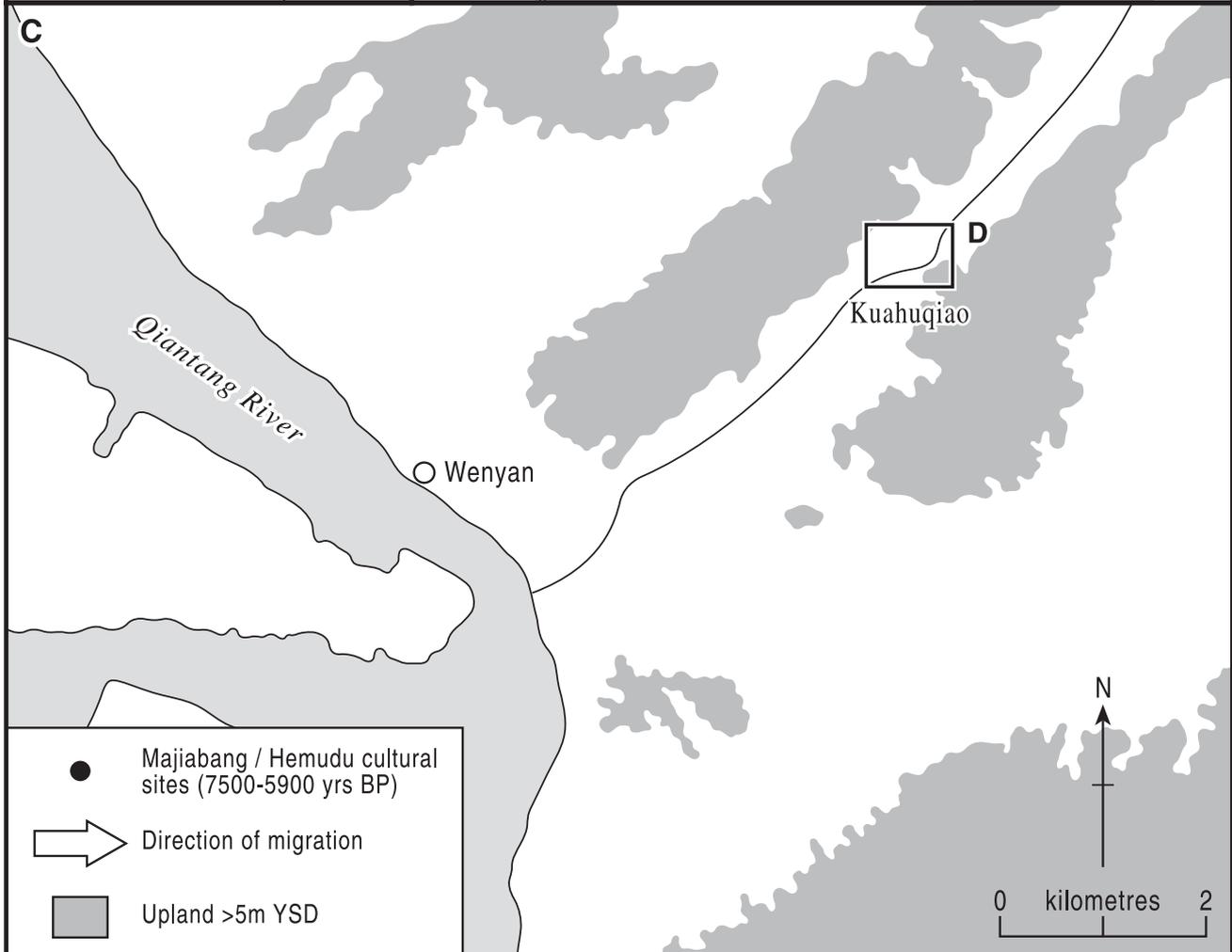
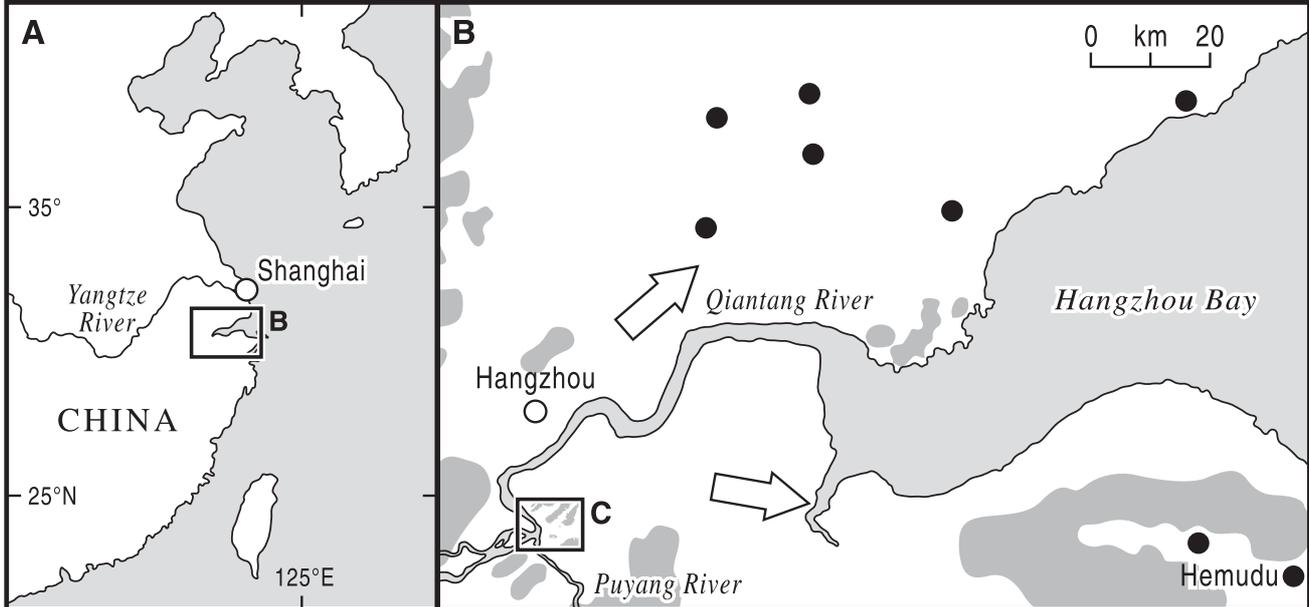


Fig. 1. Location of Kuahuqiao, in the Hangzhou lowlands of eastern China, to the south of Shanghai and the Yangtze delta (A), and of earlier Neolithic sites in the area (B). Kuahuqiao lies between the higher ground of the uplands to the south and west, occupied by late Mesolithic and early Neolithic hunters and foragers at sites such as Shangshan, and sites on the coastal wetlands of Hangzhou Bay to the east and north, occupied by early Neolithic farmers of the Majiabang culture at classic archaeological sites such as Hemudu. The site lies between two ridges in a valley that is open to the tidal rivers to the west (C). Much of the site was removed for brick-making but two phases of archaeological excavation have been undertaken since then (D). The location of the profile sampled for palaeoenvironmental analyses in this paper is shown in relation to the most recently excavated area and to major archaeological discoveries at the site (E).

Fig. 2. Percentage pollen diagram from Kuahuqiao. Pollen and microscopic charcoal fragment (microcharcoal) frequencies are calculated as percentages of a total land pollen sum that includes all trees, shrubs and terrestrial herbs, but not aquatic herbs or pteridophyte and bryophyte spores. Calibrated radiocarbon age ranges before present (cal BP) are shown on the left of the diagram. The seven stratigraphic units in the analysed section are shown on the right of the diagram and form the basis for pollen zone boundaries. Depths are in centimetres below present ground surface.

Kuahuqiao

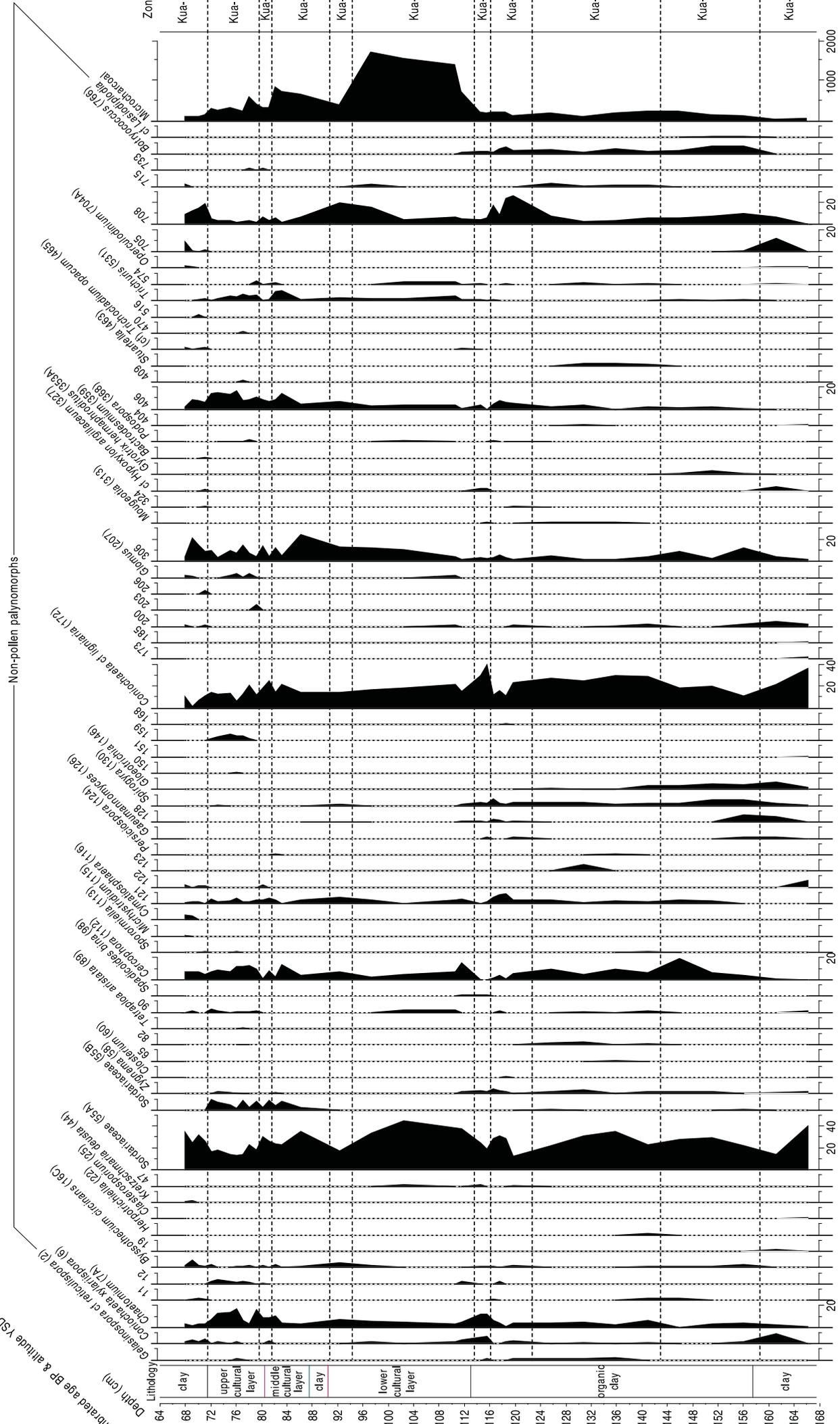


Fig. 3. Percentage non-pollen palynomorph (NPP) diagram from Kuahuqiao. NPPs and microscopic charcoal fragment (microcharcoal) frequencies are shown as percentages of the total NPP sum. Diagram zonation and radiocarbon dates follow figure 2.

Fig. 4. Percentage diatom diagram from Kuahuqiao. Diatom frequencies are calculated as percentages of total diatom valves counted.

Kuahuqiao

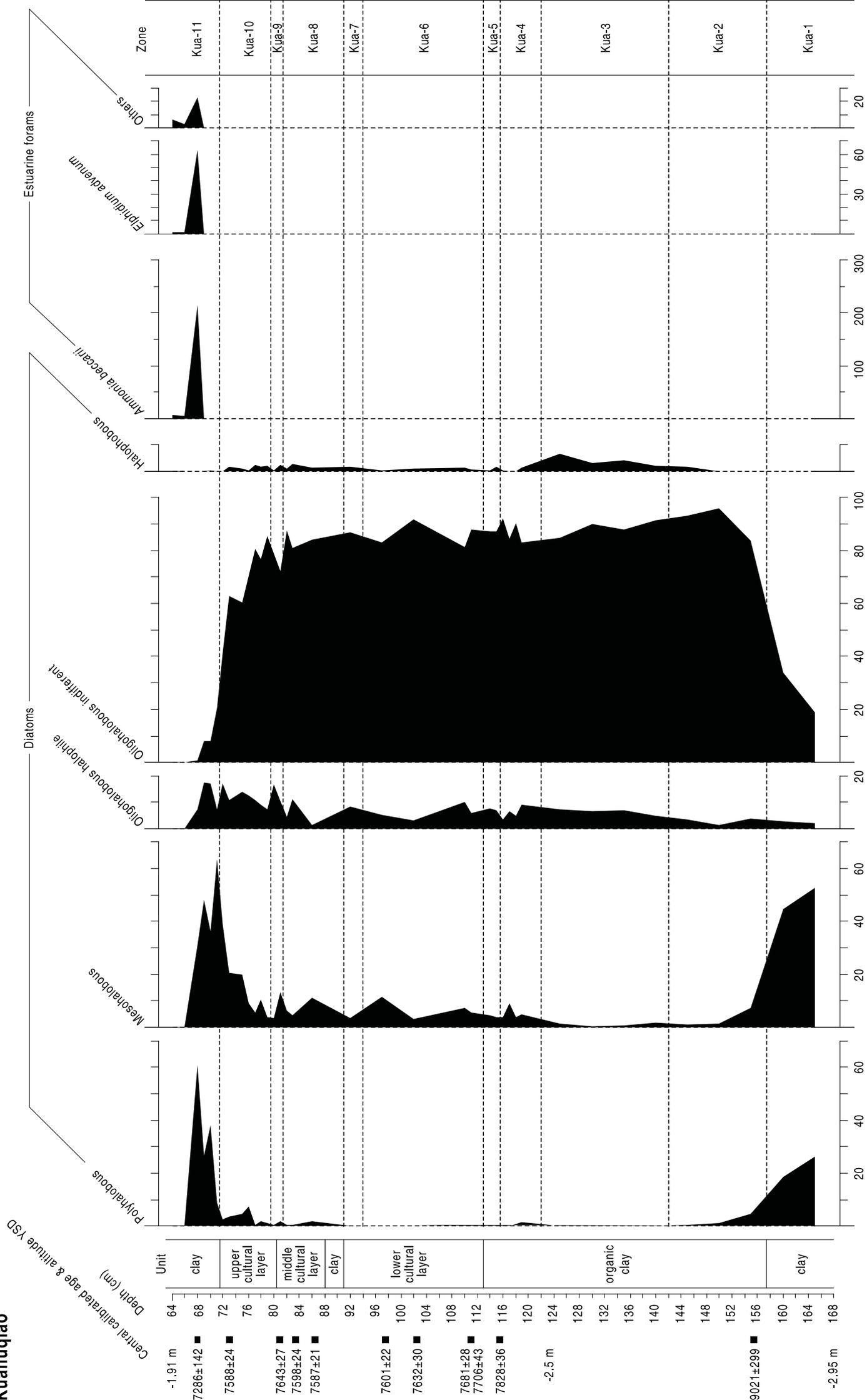


Fig. 5. Summary of diatom groups on salinity requirements, with foraminifera data included.

Kuahuqiao

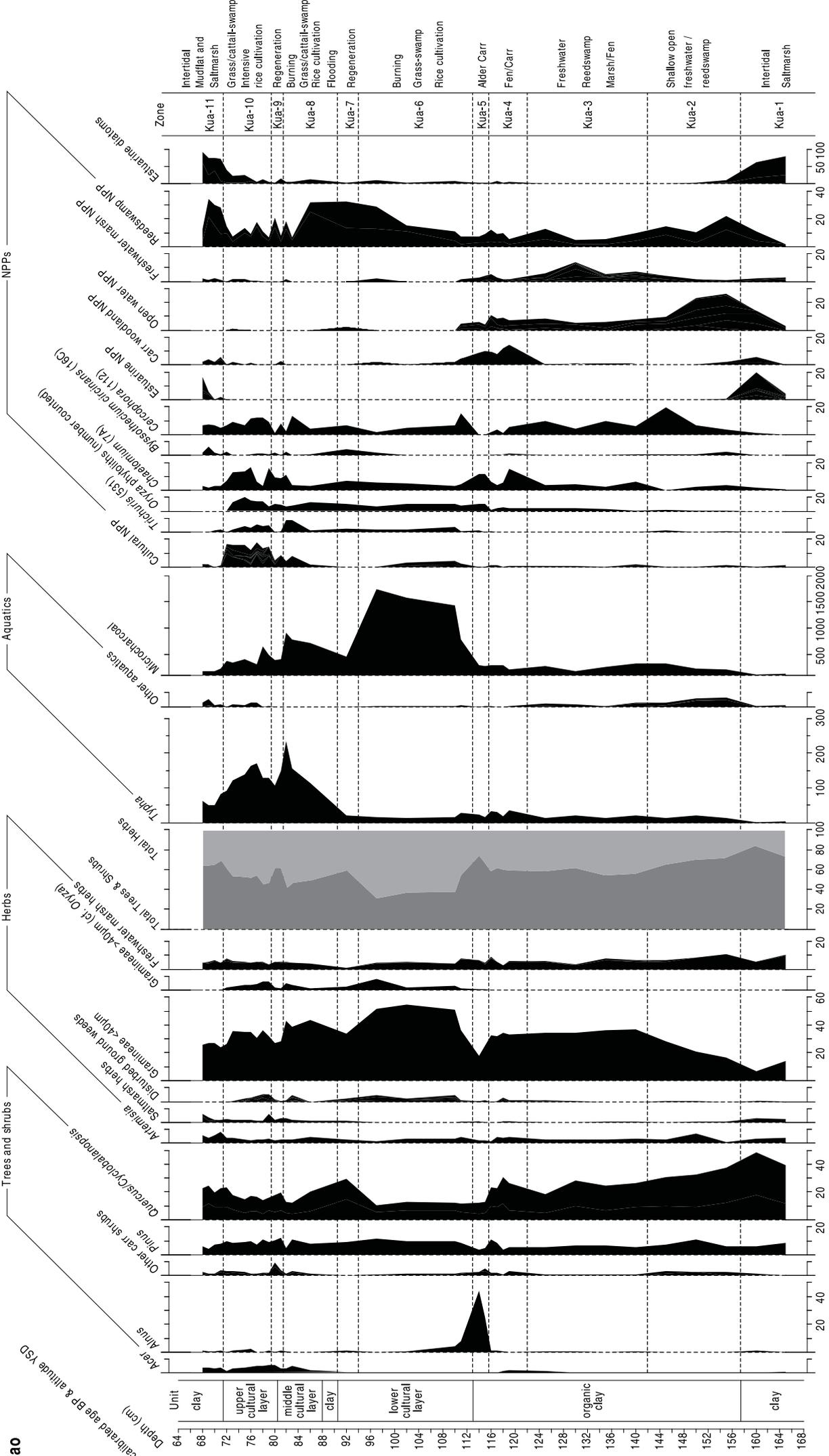


Fig. 6. Summary diagram showing selected palaeoenvironmental proxies and interpretation of the main environmental factors for each zone.