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Climatic and palaeoecological changes during the mid- to Late Holocene transition in eastern China: high-resolution pollen and non-pollen palynomorph analysis at Pingwang, Yangtze coastal lowlands.

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Abstract:

The transition to the Late Holocene/Neoglacial occurred as a worldwide process of climatic deterioration from the optimum thermal conditions of the mid-Holocene, culminating in an abrupt decline around 4200 cal yr ago, in a period of severe climatic deterioration that lasted for two or three centuries. This sudden climatic event has been recorded in many proxy data archives from around the world, and its effects were manifest in different ways depending on the reaction of regional weather systems and conditions, but often as greatly increased aridity and/or cold temperatures. It has been regarded as causing or contributing to the sudden collapse of several well-established human societies at that time, including advanced agricultural Late Neolithic cultures in eastern China. We have used high-resolution pollen and non-pollen palynomorph analysis to examine the nature of this climatic transition through its impacts on the vegetation and hydrology at Pingwang, a site in the Yangtze coastal lowlands which has no evidence of complicating environmental influences such as sea-level rise or significant human land-use activity, factors previously suggested as alternative reasons for changes in forest composition. Our results show two phases of forest alteration, one gradual from about 5500 cal BP and one sudden at about 4200 cal BP., in which the frequencies of subtropical forest elements fall and are replaced by those of conifers and cold-tolerant trees. Total arboreal pollen frequencies do not decline and the proportion of temperate forest trees, tolerant of a wide range of temperatures, remains unchanged throughout, both ruling out human land clearance as a cause of the change in forest composition. As these dates accord very well with the known timings of climate deterioration established from other proxy archives in the region, we conclude that climate was the main driver of vegetation change in eastern China at the mid- to Late Holocene transition. Our hydrological results support the view that a combination of rising local water level and climatic cooling during the 4200 cal BP event was the probable cause of societal collapse in the lower Yangtze valley.

KEYWORDS: Neolithic; coastal east China; palynology; climate change; Neoglacial; vegetation history

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1. Introduction

Holocene climate history is now relatively well understood at the global scale, with the recognition of a series of significant temperature events that occurred within the longer-term evolution of the present interglacial's temperate climate, some of which represent tipping points, major shifts that mark phase transitions between longer periods of more stable thermal conditions. One of the most important of these climatic shifts is Holocene event 3 (Bond et al., 2001), occurring relatively abruptly around 4200 years ago (hereafter cal BP) and having major environmental impacts worldwide, recognised (Walker et al., 2012) as the global transition from early and mid-Holocene thermal maxima (Renssen et al., 2012) to the Late Holocene (Neoglacial), with its colder, more extreme and more variable climatic regimes (Jessen et al., 2005; Marchant and Hoogiemstra, 2004; Wanner et al., 2011). This major climatic shift to unstable Neoglacial conditions in the centuries preceding 4000 cal BP has been recorded across the globe in a range of proxy climate data archives (Gear and Huntley, 1991; Jian et al., 1996; Phadtare, 2000; Stott et al., 2004; Booth et al., 2005; Magny et al, 2009; Geirsdóttir et al., 2013), affecting major atmospheric systems such as the North Atlantic Oscillation (Olsen et al. 2012), ENSO (Schulmeister and Lees, 1995), the Indian Monsoon (Overpeck et al., 1996; Gupta et al., 2003; Staubwasser et al. 2003) and the East Asian Monsoon (EAM) through global climatic teleconnections (Wang et al., 2000; Liu et al., 2004; Hong et al., 2005; Tan et al., 2008). A gradual onset of globally cooler conditions can be noted at around 5500 cal BP, with the major Neoglacial intensification at ca 4200 cal BP (Geirsdóttir et al., 2013). The EAM, which forms the focus of this paper, accords very well with the global data, with ample evidence of its progressive weakening after the mid-Holocene at ca 5500 cal BP, culminating in an abrupt decrease in its strength in the centuries before 4000 cal BP (An, 2000; An et al., 2000; Morrill et al., 2003; He et al., 2004; Yuan et al, 2004; Wang et al., 2005; Selveraj et al., 2007; Cosford et al., 2008; Cai *et al*., 2010).

1.1. Neoglacial climatic deterioration and human societies

The link between climatic and societal change can be very strong (Perry and Hsu, 2000; Caseldine and Turney, 2010; Zhang et al., 2011). It is not deterministic (Coombes and Barber, 2005) to assume that the change from the mid-Holocene climatic optimum to the much less congenial Neoglacial climate would have had significant effects upon human societies, particularly those that had developed intensive agricultural systems that supported high, sedentary populations, but which had become dependent upon stable, favourable and reliable climatic conditions. The more economically and socially specialized such societies became, the more vulnerable they would have been to any rapid environmental change (O'Sullivan, 2008). Human communities are resilient and adaptable (Anderson et al., 2007; Lu, 2007) and were able to cope and even flourish during the gradual climatic decline from the mid-Holocene thermal maximum around the world, the development of advanced agrarian societies based on the control of water resources in the major river valleys of the Middle East and China being good examples. In China such advanced, highly productive farming systems sustained the dense Neolithic populations of the Longshan, Shijiahe, Qijia and Liangzhu cultures in the Yellow River and Yangtze valleys during the millennium after 5000 cal BP (Liu and Feng, 2012; Zhuang et al., 2014). Abrupt climatic deterioration would have been difficult for such complex agrarian societies to cope with, however (Mo et al., 2011), and there is abundant archaeological and palaeoecological evidence that the rapid climate changes around 4200 cal BP caused severe economic and political dislocation, and even societal collapse, in many regions of the world (Dalfes et al., 1997; Sandweiss et al., 1999; Peiser, 1998; deMenocal, 2001). Major civilizations disintegrated at this time in India and the Middle East and the coincidence of societal failure and settlement abandonment with the rapid change to Neoglacial cold and arid conditions in these areas implies an environmental cause and a cultural effect, with climate as the driving force (Weiss et al., 1993; Cullen et al., 2000; Staubwasser et al., 2003; Drysdale et al., 2006; Staubwasser and Weiss, 2006; Riehl, 2012), although of course such a direct relationship can never be proven conclusively.

1.2. The East China example

One of the world's regions that has a clear correlation between cultural 'collapse' and the 4200 cal BP climate event is eastern China, and in particular the lower Yangtze valley, one of the historic heartlands of Chinese society and agricultural development. Liu and Feng (2012) and Wu et al. (2012) have evaluated the evidence for the development in the fifth millennium cal BP of the advanced agrarian cultures of central and eastern China mentioned above, and their sudden, almost synchronous demise around 4200 cal BP, when severe climate deterioration occurred. Many major Neolithic archaeological sites have culturally sterile sediments of this age that seal the rich cultural layers and are interpreted as flood deposits. Many authors (e.g. Yu et al., 2000, 2003; Jin and Liu, 2002; Wu and Liu, 2004; Zhang et al., 2005; Gao et al., 2007; Chen et al., 2008) are convinced that the 4200 cal BP event must have been responsible for site abandonment and for the culturally impoverished interlude of a few centuries recorded almost everywhere in north and east China around 4200 cal BP. Clear, independent evidence that the severe climatic deterioration of Holocene Event 3 had an impact on the east Asia region at this time may be seen in marine sediment records from the South China Sea, the East China Sea and the North-west Pacific generally. Jian et al. (1996) used oxygen isotope analysis on planktonic foraminifera from deep water marine sediments in the East China Sea to reconstruct sea-surface temperatures during the transition to the late Holocene, observing major cooling at the start of the Neoglacial around 4200 cal BP. Sun et al. (2005)'s oxygen isotope analyses from corals in the South China Sea show a major weakening of the monsoon and increase in its variability during the same period. Wang et al. (1999a, b), also using oxygen isotope data, identified a very clear abrupt cooling, the most severe in the Holocene apart from the 8200 cal BP event, at 4200-4000 cal BP in the northern South China Sea, a feature also observed by Wei et al. (1998) and by Chinzei et al. (1987) in the Sea of Japan. The ca. 4200 cal BP major cooling event is well attested in proxy climate records from the east Asia region, and it coincides with the apparent collapse of the late Neolithic cultures of the lower Yangtze area.

Although the circumstantial evidence that environmental pressures of varying kinds led to the collapse of the Liangzhu culture of the lower Yangtze around 4200 cal BP is very persuasive, we still do not know in detail the vegetation changes that preceded and accompanied the 4200 cal BP event there. New, high resolution palaeoecological data are required from within the Liangzhu's core settlement and agricultural area with which to establish these environmental preconditions. Most previous palynological research has been of low resolution, or situated too close to archaeological sites to be able to separate clearly any cultural impacts from the background vegetation history, or too far away to provide evidence of conditions within the cultural heartland itself. Also, not every pollen record agrees with the hypothesis that agricultural production almost ceased in the Taihu lowlands at this time (Itzstein-Davey et al., 2007b). In this paper we use high resolution palynology (both pollen and non-pollen palynomorphs) to investigate the nature and severity of the environmental changes during the transition to the Neoglacial in the Yangtze coastal lowlands of eastern China, as expressed in vegetation patterns and hydrology. A site at Pingwang has been selected where a more regional pollen signal might be expected, minimizing the influence of local human land-use in this intensively settled area, so that natural factors rather than agricultural impacts will have been the main driving force behind the vegetation history and environmental change. Zong et al. (2011) have shown that direct inundation by marine transgression could not have been the reason for the abandonment of the Taihu lowlands by Neolithic people at this time, and this paper will explore in detail whether climate deterioration and its consequences was the environmental driving force, if one existed.

2. The study area and site

The study area chosen is the coastal lowland around the Taihu lake west of Shanghai (Fig.1). Between the valley of the Yangtze river and Hangzhou Bay, throughout the mid- and Late Holocene this flat plain, mostly less than 5 m above sea level, was naturally occupied by woodland and by wetland ecosystems which had developed during and after the main postglacial sea-level rise on this coast (Tao et al. 2006; Zong et al., 2011, 2012a, b; Wang et al., 2012). Higher ground to the west and north (Fig. 1a) and low hills within the wetland would have naturally carried forest. As well as the main Lake Tai (Qu, 2000; Wang et al., 2001) these wetlands included many other lakes and smaller water bodies and a wide expanse of peat-forming bogs, swamps and marshes. Although sheltered from direct marine inundation after the mid-Holocene by a system of coastal barrier ridges (Yan et al., 1989), these wetland systems remained affected by the groundwater influence of sea-level fluctuation (Zong et al., 2011). While their fertile marsh soils made them highly attractive for Neolithic settlement and intensive wet rice agriculture under the warm and wet climate of the mid-Holocene Megathermal phase (Cao et al., 2006; Lu, 2007; Atahan et al., 2008; Qin et al., 2011), the Taihu lowlands would have been highly vulnerable to any changes to their hydrology, sedimentation regime and natural vegetation cover caused by even small-scale fluctuations in sea level or climate, or by fluvial input from the nearby Yangtze river. Lying at the biogeographical boundary between northeastern China's warm temperate broadleaf forests and southeastern China's sub-tropical evergreen forests (Box, 1995; Li et al., 1995; Ren and Beug, 2002; Ren, 2007; Cao et al., 2013), the natural vegetation of the lower Yangtze region would have been sensitive (Guiot et al., 2008) to climatic deterioration caused by the proposed reduction of the strength of the EAM during the transition to the Late Holocene (Morrill et al., 2003; Wang et al., 2005). It is an ideal location to test the environmental consequences of climate change during the transition to the Late Holocene Neoglacial in east China, and provide firmer evidence to assist interpretation of the archaeological record and evaluate the putative cultural responses (Chen et al., 2005, 2008). It can be difficult to distinguish vegetation changes caused by major climatic change from those set in train by human land-use (Liu and Qiu, 1994), particularly if both may be occurring at the same time and place, as both involve disturbance of established plant communities and the regeneration of changed vegetation units through seral pathways. This is particularly so in the Taihu lowlands, where usually population levels were high and agricultural activities were intensive during the mid- to late Holocene (Wu et al., 2012). For the purposes of this study a site was required that was at a significant distance from known Neolithic centres of agricultural activity, identified by archaeological sites and their concentrations of cultural material that are usually situated upon slightly higher land in the wetland. This should therefore contain a more 'natural' environmental signal with the influence of anthropogenic impacts on the vegetation reduced as much as possible, although there would still be a regional cultural signature in the pollen rain. It is not easy to get far away from known Neolithic cultural sites in this area, as there are so many. Nevertheless such locations do exist, mainly in areas that were very wet and perhaps agriculturally marginal, and one was selected at Pingwang to the south-east of Lake Taihu (Fig. 1) which lay more than 10 km from the nearest known archaeological site, and even further from any significant Neolithic settlement. The local hydrological history at Pingwang (30^{o} 57' 30"N; 120^{o} 38' 25"E; altitude 1.6 m Yellow Sea Datum) was summarised by Zong et al. (2011, 2012b). The sediments (Table 1) cover the whole of the mid- and late Holocene and record the development of various freshwater habitats above estuarine sediments after the postglacial rise of sea level was complete (Zheng and Li, 2000; Wang et al., 2012) and the final withdrawal of estuarine conditions from the area by 7000 cal BP after the establishment of coastal barrier ridges. Radiocarbon dating showed that the profile included the period of Liangzhu settlement and the Neoglacial cultural hiatus.

3. Material and methods

Samples were prepared for palynological analysis at 5 cm intervals using standard laboratory techniques, including alkali digestion, sieving at 180 μm, hydrofluoric acid digestion and acetolysis (Moore et al., 1991). Microfossils (all palynomorphs <180 μm in size) were identified using reference keys and type slides and counted using a stereomicroscope at magnification of ×400, using ×600 oil immersion lenses for critical features. Identification of pollen grains followed Wang et al. (1995) and pteridophyte spores Zhang et al. (1990). Where very similar pollen taxa cannot be differentiated with certainty, they are shown as a composite genus, i.e. *Ulmus*/*Zelkova*, *Corylus*/*Ostrya* and *Castanopsis*/*Lithocarpus*. *Quercus* includes *Lepidobalanus*. *Typha angustifolia* includes *Sparganium*. A minimum of 200 land pollen grains was counted at each sampled level, plus all aquatic pollen and pteridophyte and bryophyte spores observed while attaining that sum. Non-pollen palynomorphs (NPPs), mainly comprising fungal spores and algae, were also recorded with at least 200 identified on the pollen slides at each level. Taxonomic identification of NPPs was achieved where possible, otherwise they were identified using the catalogue of Type (HdV) numbers at the Hugo de Vries laboratory, Amsterdam, using illustrations and descriptions published in several papers (e.g. van Geel, 1986, 2001; van Geel and Aptroot, 2006). Microscopic charcoal particles (microcharcoal) were counted upon the microscope slides relative to the pollen sum, providing a pollen/microcharcoal ratio.

Our dates on the Pingwang profile comprise AMS radiocarbon results and in this study, as in most other recent research in this area, only fragile terrestrial plant macrofossils, pollen residues or basal peat that has accumulated in situ have been dated, bulk alluvial sediment being avoided. Pollen residues have been shown in recent published studies from the area (Itzstein-Davey et al., 2007a; Atahan et al., 2008; Qin et al., 2011) to provide reliable age curves. A statistically significant inversion occurs low in the profile in Table 2, but these dates refer to the early Holocene Megathermal which is not the main focus of this study. It is considered that the pollen residue date at 321 cm depth is more likely to be correct, based on existing regional pollen and radiocarbon evidence. The upper dates, bracketing the age period of interest in this study, are consistent and are accepted as accurate. Dates were calibrated according to Calib6.1 (Reimer et al., 2009) using the IntCal09 programme. Microfossil diagrams were constructed using the TILIA program TGView (Grimm, 2004).

4. Results and interpretation

While Zong et al. (2012a) showed only selected summary curves from Pingwang, here we present full microfossil data. Tree and shrub pollen percentages are shown on Fig. 2, herb pollen and pteridophyte spores on Fig. 3 and NPPs on Fig. 4, all with frequencies calculated as percentages of the total arboreal (tree + shrub) sum that reflects the more regional pollen rain. Fig. 2 includes summary curves for trees and shrubs based upon their life-form and temperature tolerances, although warm temperate and cool temperate are not separated. The CONISS (constrained incremental sum of squares) cluster analysis function (Grimm, 1987) within TGView has been used to zone the diagram based on the total land pollen percentages, and has recognised four pollen assemblage zones (PW-a to d) which are applied to all of the diagrams. The CONISS dendrogram is shown on Fig. 2.

Zone PW-a (380-362.5 cm). This zone is dominated by the subtropical tree *Cyclobalanopsis* and the warm temperate trees *Quercus* and *Salix*, the latter perhaps abundant in local carr habitat with its locally sourced pollen frequencies depressing *Cyclobalanopsis* percentages. There are background levels of temperate taxa such as *Ulmus*/*Zelkova*, *Castanea* and *Liquidambar*. Cooler climate taxa are poorly represented, with only *Pinus* pollen significant, probably not locally sourced. Poaceae, Cyperaceae and *Typha angustifolia* dominate the herb assemblage. Prominent NPP types include Sordariaceae (55A), *Coniochaeta* cf. *ligniaria* and HdV-11, as well as marsh/reedswamp taxa HdV-306 and 708. This zone corresponds to the basal peat layer at the site (Table 1) and includes evidence of carr and shallow water marsh environments. Zong et al. (2011) recorded a mixed diatom assemblage in this lower part of the profile, with evidence of saltmarsh or estuarine influence. The non-wetland vegetation was a subtropical forest with temperate elements which the date suggests existed not long after the start of the Megathermal mid-Holocene climate optimum.

Zone PW-b (362.5-232.5 cm). This zone is dominated by the subtropical genera *Cyclobalanopsis* and *Castanopsis*/*Lithocarpus* which consistently provide 50% of arboreal pollen, with temperate deciduous *Quercus* accounting for most of the rest. Other temperate trees are also significant, inluding *Ulmus*/*Zelkova*, *Castanea*, *Pterocarya* and *Liquidambar*. Conifers and cold tolerant trees are poorly represented, with a low background curve for *Pinus*. Non-arboreal pollen and spores are low, supplied mainly by Poaceae and Cyperaceae. Aquatic taxa are important, and *Potamogeton* and *Ceratopteris* increase later in the zone and there is a peak of the aquatic *Salvinia*. NPPs become increasingly dominated by aquatic types, with shallow water marsh taxa like *Zygnema*, *Mougeotia*, HdV-306 and HdV-708 being replaced in the upper part of the zone by more open water algal types, especially *Pediastrum*, HdV-128 and the cyanobacterium *Gloeotrichia*. The regional forest comprised a typical Megathermal optimum assemblage with evergreen subtropical trees dominant but with a significant temperate component. The local environment changed from shallow water marsh to aquatic and eutrophic, biologically productive habitats with deeper standing water, as shown by *Pediastrum* abundance, nearer to 5000 cal BP. Such *Pediastrum* frequencies are typical of limnic environments with emergent aquatic vegetation under warm, mid-Holocene climates (Jankovská and Komárek, 2000).

Zone PW-c (232.5-177.5 cm). At the start of this zone subtropical tree frequencies, *Cyclobalanopsis* and *Castanopsis*/*Lithocarpus*, fall from 50% to 25% of arboreal pollen. Of the warm temperate trees, the more cool-tolerant *Betula*, *Fagus* and *Alnus* increase but the more thermophilous, including *Pterocarya* and *Castanea*, decline markedly. Against this trend pollen of Moraceae, usually subtropical trees in east China (Sun et al., 2003), appears and rises in frequency in mid-zone. Distinct increases occur in the cold-tolerant trees Cupressaceae (which includes *Juniperus*), *Picea* and *Pinus*. Frequencies of the main warm temperate forest trees *Quercus*, *Liquidambar* and *Ulmus*/*Zelkova* are unaffected. The summary cuves on Fig.1 show an almost direct replacement of the subtropical genera by the cold-tolerant taxa. There is little change in the non-arboreal pollen and spores except for peaks in *Potamogeton, Myriophyllum* and Adiantaceae, all floating aquatics. The NPP assemblage shows major changes with *Gloeotrichia* rising to dominance and *Pediastrum* reduced, although still important. Peaks of the cyanobacterium *Anabaena*, intolerant of high temperatures, accompany *Gloeotrichia*'s rise. The local aquatic habitat seems to have become colder, deeper and less eutrophic, while the regional forest also adapted to colder temperatures during this zone.

Zone PW-d (177.5-130 cm). At the start of this zone, which has an interpolated date of 4200 cal BP, the frequencies for the subtropical trees *Cyclobalanopsis* and *Castanopsis*/*Lithocarpus* continue to fall, dropping to 15% of arboreal pollen. Moraceae, however, maintains values of almost 10% of total tree and shrub pollen. Warm temperate trees are little changed, but the cold-tolerant and coniferous taxa rise to 35% of the total. *Pinus* and Cupressaceae are particularly increased, and Taxodiaceae is consistently recorded. Aquatic pollen is still important although the rise of *Typha* and *Ceratopteris* late in the zone implies falling water levels. Present in low frequencies throughout, *Artemisia* increases late in the zone. *Gloeotrichia* is still abundant early in the zone, but decreases as marsh herbs, ferns and NPPs increase after ca 2800 cal BP. This zone sees a continued expansion of conifers in the forest at the expense of the subtropical genera.

5. Discussion

5.1. Yangtze region vegetation history

The biogeographical location of the lower Yangtze region means that its natural vegetation contains elements of both subtropical and temperate forests, and during the mid-Holocene

Megathermal optimum phase, subtropical forest trees were common there as the monsoon front lay to the north and the Yangtze had a very warm, humid and wet climate (Shi et al., 1993; Zheng et al., 2004; Zong et al., 2007; Innes et al., 2009; Li et al., 2010a; Cao et al., 2013). *Castanopsis* and *Cyclobalanopsis* were the dominant taxa, associated with thermophilous deciduous trees *Quercus*, *Liquidambar* and *Ulmus*/*Zelkova*. There are several published pollen profiles from the lower Yangtze region with which the Pingwang Megathermal record can be compared (Liu et al., 1992; Xu et al., 1996; Chen et al., 2005; Tao et al., 2006; Yi et al., 2006; Shu et al., 2007; Innes et al., 2009; Li et al., 2010b) 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 all show this general forest history. Zhao et al. (2009) have analysed the data from many pollen records across all of EAM China and conclude that whatever the Megathermal forest type, there was a shift to a more cold-tolerant forest community, in many regions with major expansion of conifers in particular, after about 4200 cal BP, and it may well have been responsible for the major forest decline that occurred in more arid regions (Zhao et al., 2009; Herzschuh et al., 2010), instead of the human impact explanation favoured by earlier workers (Liu and Qiu, 1994; Ren, 2000). This climate shift is well represented in the lower Yangtze (Wu et al., 2012), with a broadleaf temperate and conifer woodland established. As most rice agriculture occurred here on sites reclaimed from wetlands (Li et al., 2012), human impacts on the forest were probably not great except close to settlement sites (Atahan et al., 2008). This remained the case until major human forest clearance occurred after ca 2500 cal BP. (Atahan et al., 2007; Wang et al., 2011).

5.2. The 4200 cal BP climatic deterioration in China

While reservations exist (Maher, 2008; Maher and Thompson, 2012), the severe climatic deterioration at ca 4200 cal BP appears to be well attested in speleothem records from caves in several areas of China (Wang et al., 2001; Dykoski et al., 2005; Shao et al., 2006; Cosford et al., 2008; Hu et al., 2008; Dong et al., 2010). This widespread switch to cold conditions (Shi et al., 1993) is substantiated by many other forms of proxy data (Hong et al., 2000; Li et al., 2010b), including pollen records (Xiao et al., 2004; Lim and Fujiki, 2011; Chen et al., 2012). In more northerly and westerly areas of China towards the EAM margins the 4200 cal BP climatic deterioration and instability was expressed by a rapid switch to much more arid conditions (Hong et al., 2001; Schettler et al., 2006; Jiang and Liu, 2007; Mischke and Zhang, 2010; Wang et al., 2010; Wen et al., 2010), as the summer monsoon weakened and the winter monsoon strengthened (Yu et al., 2006; Jiang and Liu, 2007; Yancheva et al., 2007; Yang and Scuderi, 2010). Precipitation would have been the dominant factor controlling vegetation distributions (Wen et al., 2013). In the western part of the Chinese Loess Plateau, the climate until 4200 cal BP was humid (An et al., 2003; 2004; Gao et al., 2007), with organic palaeosol development. Southeast of Lanzhou, for example, wetlands seem to have existed in several river valleys, adjacent to Neolithic settlements (Feng et al., 2004, 2006). At about 4200 cal yr BP, the climate suddenly became drier in this region and from the reduction in the number of archaeological sites from this time, An et al. (2004, 2005) concluded that this period of intense aridity, which lasted for some centuries, had a major effect on the Neolithic Qijia people who lived in these river valleys, causing the collapse of their farming culture (Mo et al., 1996; Liu et al., 2010a). Previously distinct pollen and charcoal records of major human land-use impacts in this area also terminate at this time (Li et al., 2012). At the western and northern margins of the area of monsoonal influence, this period of maximum aridity (Wei and Gasse, 1999) caused lakes to dessicate almost completely (Chen et al., 1991; Morrill et al., 2006; Zhai et al., 2011). This drying tendency since about 4900 cal BP extended even to eastern coastal China, where some lake levels started to fall (Wu et al., 2010).

One of the clearest expressions of the climatic deterioration is in vegetation records (Zhao et al., 2009), many of which show major changes in the centuries leading up to 4000 cal BP. On the Western Loess Plateau and in the uplands of central China there was an abrupt change from forest to steppe as a response to the greatly increased aridity (Feng et al., 2006; Zou et al., 2009; Herzschuh et al., 2010; Zhou and Li., 2012). Elsewhere in north and west China at this time this much colder and arid phase changed mixed forest to domination by conifers (Sun and Weng, 1992; Jarvis, 1993; Ren, 2000; Makohonienko et al. 2004; Xiao et al., 2004; Jiang and Liu, 2007; Liu et al., 2010b; Xu et al., 2010; An et al., 2012), as pine was particularly favoured over oaks under the more arid and cold conditions (Ren and Zhang, 1998; Yi et al., 2003). Although there has been discussion as to whether human activity or climate change was responsible for the spread of *Pinus* in northeast China around 4200 cal BP (Ren, 2000; Xu et al., 2010), there is little evidence for human interference with the woodland during that period and climate change seems to be the most likely cause. In central eastern China the evergreen trees common during the Megathermal (Shi et al., 1994) were everywhere displaced by conifers within mixed, cool temperate woodland (Ren and Beug, 2002; Zhu et al., 2010), a change to a cooler forest biome recorded even in south China and Taiwan (Liew et al., 2006; Wang et al., 2007; Lee et al., 2010; Wu et al., 2012). There is more persuasive evidence for human activity having had an influence on the forest in the Yangtze region (Chen et al., 2009; Li et al., 2010b; Wu et al., 2012), but it declines and then stops almost everywhere in the centuries leading up to the 4200 cal BP event.

In contrast to the aridity phase in north and west China, in many places at this time in eastern and southern China peat deposits begin to form or expand markedly (Zhao et al., 2007; Zhang et al., 2011), including in the Taihu lowlands (Zhu et al., 2006), under greatly wetter conditions, providing pollen and other proxy records that confirm the abrupt and major climatic cooling at ca 4200 BP (Hong et al., 2000; Yu et al., 2006; Zhao et al., 2007; Ma et al. 2008, 2009) following the southerly withdrawal and weakening of the EAM (Wang et al., 2005; Liu et al., 2010c) which coincided with stronger winter monsoons (Yancheva et al., 2007). An important consequence of the 4200 cal BP climatic decline in eastern China seems to have been a dramatic increase in the incidence and severity of flooding in river valleys (Tan et al., 2008; Wu et al. 2012), where much of Late Neolithic settlement and agriculture was concentrated. Fields and settlements were often located close to water sources, lakes and river channels, making them highly vulnerable to rapid fluctuations in water levels (Wu et al., 2010). Often cultural deposits are terminated by major flood sediment layers that date to this event (Huang and Zhang, 2000; Bai et al., 2008; Yao et al., 2008; Huang et al., 2010, 2011, 2012a, b; Zhang et al., 2010) and represent disasters that must have buried fields and forced settlement evacuation (Xia et al., 2003; Liu et al., 2012), including some in the Yangtze Delta itself (Zhang, 2007; Zhang et al., 2004a) and at the termination of the Liangzhu (Zhu et al., 1996; Zhang et al. 2004b; Shi et al., 2008). Huang et al. (2011) record repeated floods which must have made cultural recovery in these locations very difficult.

5.3. Environmental evidence at Pingwang

5.3.1. Hydrological evidence

After the withdrawal of brackish marsh conditions from Pingwang, the site became dominated throughout its history by freshwater wetland environments, and increasingly by fully aquatic conditions, which probably explains the absence of archaeological material nearby and the lack of palynological evidence for agriculture throughout the profile (Figs. 3 and 4). The NPP record is particularly informative regarding the local hydrology, with HdV-128, *Spirogyra*, *Gloeotrichia*, *Zygnema* and *Pediastrum* all abundant and reflecting open water of various depths and trophic status, and the aquatic herb taxa *Potamogeton*, *Typha* and *Salvinia* support this. The significance of HdV-128, *Zygnema* and HdV-708 in zone PW-b suggests mesotrophic open water of relatively shallow depth (Bakker & van Smeerdijk, 1982; Pals et al., 1980). The microcharcoal curve is not high and probably represents a background regional signal of human activity, presumably on drier land but perhaps also burning of carr scrub within the wetland to establish paddy fields (Innes et al. 2009) and of dead plant stubble material to maintain them (Cao et al. 2006; Dodson et al., 2006; Zheng et al., 2009; Li et al., 2012; Hu et al., 2013; Zhuang et al., 2014). Although moderate throughout, the increased values at the top and base of the profile correlate with periods of shallower-water marsh conditions, when some increase in local human presence might be expected. It is interesting that microcharcoal frequencies fall sharply during the episode at the end of zone PW-c correlated with the 4200 cal BP event, supporting theories of greatly reduced human activity throughout the Taihu plain. The non-arboreal pollen and the NPPs indicate deeper water at this time, with *Gloeotrichia* abundant and replacing *Pediastrum* as a deeper and cooler but perhaps more eutrophic (van Geel et al., 1996) aquatic environment developed. Some eutrophication due to drainage from agricultural land during the Liangzhu period in zone PW-c might be expected, and low peaks of *Anabaena* would support this (van Geel et al., 1994; Hillbrand et al., 2014), although the major bloom in *Gloeotrichia* would supress the abundance of the light-demanding *Anabaena*. *Gloeotrichia* might also have been favoured by rising water levels and thus clearer water at this time, being favoured by increased light levels (Chmura et al., 2006). Presumably Pingwang was subsumed within the expanded water bodies of Taihu and the other lakes in the area which came into being after 4600 cal BP (Wang et al., 2001; Zong et al., 2012a, b), following significantly increased rainfall and drainage discharge from the Yangtze valley (Long et al., 2014; Wu et al., 2014).

5.3.2. Climatic or human influence

The arboreal pollen curves at Pingwang record woodland history all through the mid-Holocene Megathermal, across the Late Holocene transition and into recent times, and providing evidence from beyond the local aquatic environments at Pingwang. The expansion of conifers, mainly *Pinus*, and the decline of subtropical evergreens after ca 5400 cal BP is very clear and is the important feature of the vegetation history. In this respect it records the gradual onset of the Neoglacial in eastern China at this time as recorded in other sites (Zhong et al., 2010). The choice of the Pingwang site was designed to reduce the human element in woodland history as far as possible, as there are no records of significant Neolithic settlement near the site, even at the time of the greatest Liangzhu expansion. A complete absence of human influence on the site cannot be assumed, however, as there would be few areas beyond all human activity in the intensively settled Taihu lowland, if any, even the constantly flooded Pingwang locality. The complete absence of any big grass pollen grains that could be attributed to rice in the Pingwang pollen record, however, suggests that the site was well away from any cultivation throughout the Neolithic period. There are also no NPP indicators of pastoral farming and concentrations of livestock such as the dung fungi *Sporormiella* or *Podospora*, as were found near the early Neolithic agricultural settlement at Kuahuqiao (Zong et al., 2007; Innes et al., 2009). All are absent from Pingwang, and virtually all NPPs reflect wetland environments. It is possible that the rise in *Pinus* and Moraceae frequencies during zone PW-c might have been caused by regeneration of secondary woodland after forest clearance in this lower Yangtze region (Huang and Zhang, 2000; Chen et al., 2009; Li et al., 2010b), as this is the main Liangzhu settlement and farming period and area, and some authors have reported extensive forest clearance and agricultural intensification in the Late Neolithic in the lower Yangtze catchment between 5000 and 4200 cal BP, when it abruptly stopped (Yasuda et al., 2004; Zhuang et al., 2014). Liu (1988), Liu et al. (1992), Liu and Qiu (1994) and Okuda et al. (2003) have suggested that both climatic cooling and human disturbance may have contributed to the late Holocene *Pinus* rise in the lower Yangtze. This cannot be the case at Pingwang, however, where effects of significant forest clearance would be visible in the pollen record, even if none took place near to the site. During zone PW-c, when the Liangzhu culture was flourishing, tree pollen values generally remain high, with no increase in non-tree pollen that might indicate deforestation. The rise of Moraceae in zone PW-c is strange, however, if subtropical tree genera were in progressive decline. It is possible that Moraceae genera, mainly secondary trees, were increasing locally in successional woodlands as populations of *Cyclobalanopsis* and *Castanopsis*/*Lithocarpus* declined. An alternative, however, is that the Moraceae curve reflects human activity of a particular kind, taking advantage of the extensive water body at Pingwang. Retting of cannabis for fibres (e.g. Schofield and Waller, 2005) in the shallow lake edges could account for the increase in Moraceae pollen when subtropical genera are otherwise in decline. Moraceae frequencies are also high in zone PW-d, in later prehistory, when human activity might also be expected, although there remains no sign of rice agriculture. Similar high Moraceae frequencies attributed to human activity have been recorded elsewhere in the Taihu region (Itzstein-Davey et al., 2007b). It is interesting that Moraceae percentages fall abruptly at the end of zone PW-c, during the end-Neolithic cold phase and cultural hiatus, before recovering later. This would support both the origin of the Moraceae pollen in a human activity and the effectiveness of the ca. 4200 cal BP cold phase in temporarily stopping it, along with all other human activity and settlement in the Taihu plain.

The percentage representation of temperate trees, including the forest co-dominant *Quercus*, is almost unchanged throughout the Pingwang pollen profile, and forest composition changes are caused dominantly by the replacement of sub-tropical genera by cold-tolerant trees, mainly conifers. It is unreasonable to suggest that human land clearance for farming would have affected only sub-tropical trees and leave unscathed the deciduous temperate trees, especially the abundant oaks, that grew alongside them in the mixed forest. Only climate change and colder conditions can account for the direct replacement of the sub-tropical component of the forest by pine and other conifers. Although closer to the lower end of their temperature tolerance ranges, the deciduous temperate trees like *Quercus* could withstand the new colder environment and survive, whereas the sub-tropical genera could not. Given a competitive advantage by the colder climate, conifers moved in to occupy the place in the forest community vacated by the subtropical evergreens, particularly after the abrupt shift to the Neoglacial at ca 4200 cal BP, while the proportion of temperate deciduous trees remained unchanged.

6. Conclusions

The profile from Pingwang in the centre of the Taihu coastal plain contains no pollen evidence of cultivation, other forms of human land-use or clearance of woodland, except perhaps for the equivocal evidence of a slight increase in open ground weeds after ca 2500 cal BP. Certainly there is no indication of agricultural activity there throughout the Late Neolithic, despite the intensive settlement and agricultural use of the Taihu lowlands by the Liangzhu culture. Because of its palaeogeography, Pingwang therefore provides a record of sub-regional forest history, uncomplicated by local human activity, unless the Moraceae pollen curve indicates fibre processing in the lake. It shows very clearly the rise of *Pinus* and other conifers after ca 5400 cal BP, and the rapid acceleration of that rise at ca 4200 cal BP. These two dates agree very well with the timings of the onset of climatic deterioration and its severe intensification noted around the globe (e.g. Geirsdóttir et al., 2013). It also clarifies the reasons for that radical transformation of the forests of the lower Yangtze region, and by extension for the same changes in forest composition that can be seen throughout eastern China at this time, with change beginning at ca 5400 cal BP. Although it has been suggested previously that the rise of pine and other successional tree taxa in the Late Neolithic might have resulted from regeneration after major deforestation for agriculture, the Pingwang data make clear that the gradual and then sudden switch to a cold Neoglacial climate can account for the forest changes observed in regional vegetation history. The increased dominance of fully aquatic conditions across the Late Holocene transition at Pingwang is shown particularly clearly by the NPP results and accords with the evidence from several other Yangtze valley sites for severe flooding events at this time. It supports the hypothesis that severe and regular freshwater flooding or rising local water level (Stanley et al., 1999; Zong et al., 2012a; Long et al., 2014) on the Taihu plain, allied to significantly lower temperatures, is the explanation for the collapse of the Liangzhu culture, as well as other Late Neolithic cultures of the Yangtze valley, at ca 4200 cal BP. The abrupt switch to such adverse conditions would have made organised rice farming and complex settlement virtually impossible until a measure of climatic amelioration occurred some centuries later.

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Table 1. Lithostratigraphy at Pingwang (30^{o} 57’ 30”N; 120^{o} 38’ 25”E; altitude 1.6 m YSD)

Depth (m)	Descriptions
0.00 – 0.45	Paddy field soils
0.45 – 1.10	Brown to yellowish grey, hard to firm, clay
1.10 – 1.25	Blackish grey, soft, clay
1.25 – 1.80	Greenish grey, soft, clay
1.80 – 2.10	Brownish grey, soft, organic rich clay
2.10 – 3.10	Dark grey, soft, organic rich clay with small shells found in upper part
3.10 – 3.70	Greenish grey, soft, silt and clay
3.70 – 3.80	Blackish brown peat
3.80 – 4.00	Sticky hard clay (pre-Holocene)

Table 2. AMS Radiocarbon dates at Pingwang. Calibrated results are shown, using the Calib6.1 and IntCal09 programmes (Reimer et al., 2009). There is an inversion in the bottom two dates, but based on regional pollen and radiocarbon data Beta-253340 is more likely to be correct.

Depth (m)	Dated material	^{14}C date (a BP)	Calibrated age range (cal BP) (2σ)	Mid-point age (cal BP)	Laboratory code
1.59-1.61	pollen residue	2700±40	2750-2869	2810±60	Beta-255432
1.85-1.87	pollen residue	4430±40	4872-5280	5076±204	Beta-266433
2.25-2.27	plant macrofossil	4720±40	5324-5584	5454±130	Beta-243208
3.20-3.22	pollen residue	6800±50	7573-7724	7649.5±75.5	Beta-253340
3.75-3.77	peat	6290±50	7026-7322	7174±148	Beta-228442

Captions to figures

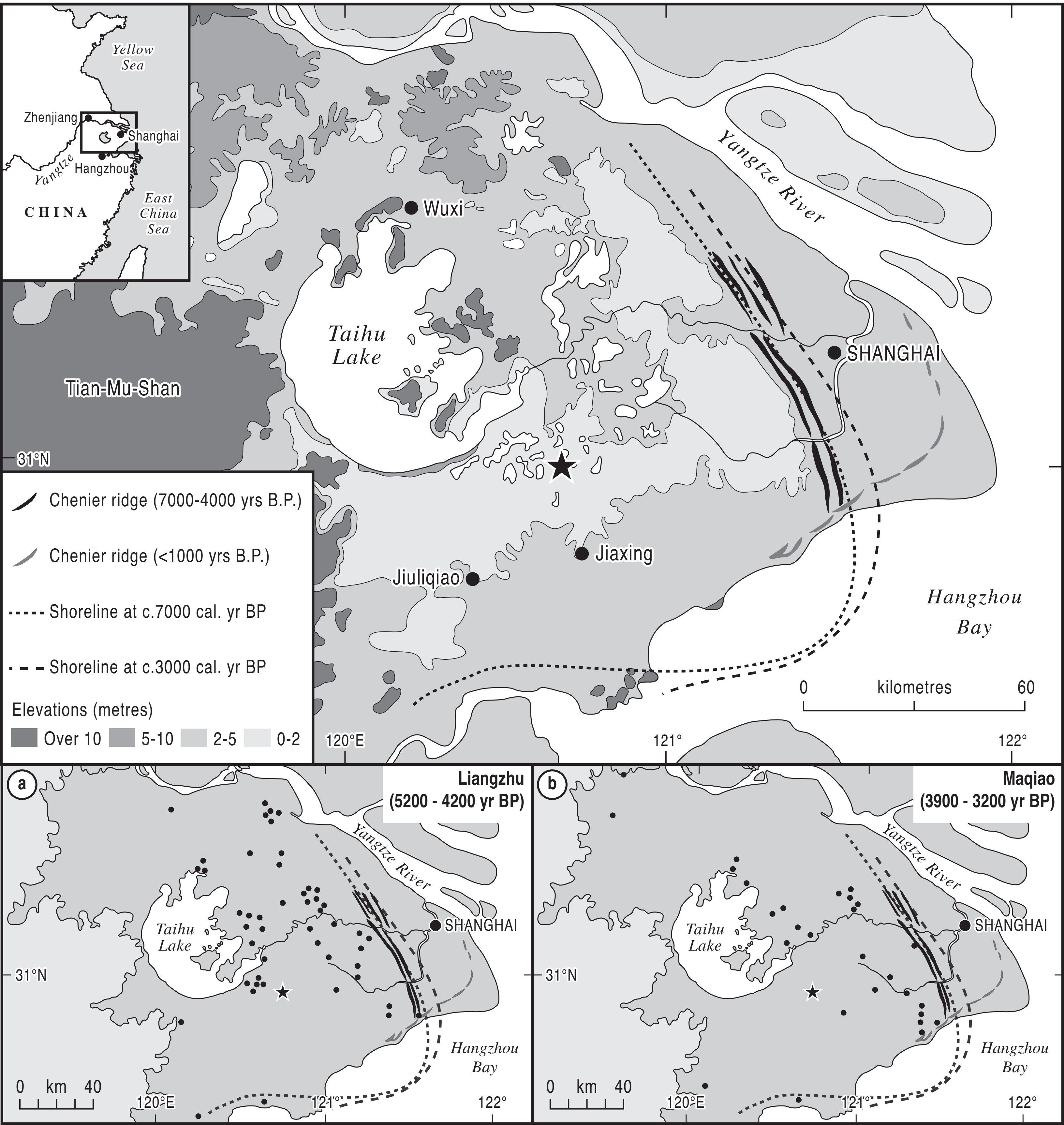
Fig. 1. Location of the study area, around Taihu lake in the Yangtze coastal plain, showing the topography and the position of other, smaller lakes, the barrier ridges to the east that protect the plain from the sea, and the location of the coring site at Pingwang. Figures 1a and 1b show the distribution of the main Late Neolithic archaeological sites of the Liangzhu and Maqiao cultures.

Fig. 2. Percentage tree and shrub pollen diagram from Pingwang. Frequencies are calculated as percentages of the total tree and shrub sum, with major stages in vegetation history and summary curves for ecological groupings also shown. Calibrated radiocarbon age ranges before present (cal BP) are shown on the left of the diagram, which is zoned at major changes in the tree and shrub pollen curves using the CONISS program. The timings of the following major environmental events are shown on the diagram. 1: Early in the mid-Holocene Megathermal 2: The end of major saline estuarine influence at the site (after Zong et al., 2011) 3: The maximum of the Megathermal optimum 4: The start of the climatic decline towards the Late Holocene 5: Abrupt climate deterioration ca 4200 cal BP. Depths are in centimetres below present ground surface.

Fig. 3. Percentage herb pollen and pteridophyte spore diagram from Pingwang, frequencies calculated as percentages of the total tree and shrub pollen sum. Diagram zonation, calibrated radiocarbon dates and environmental events follow Fig. 2. Depths are in centimetres below present ground surface.

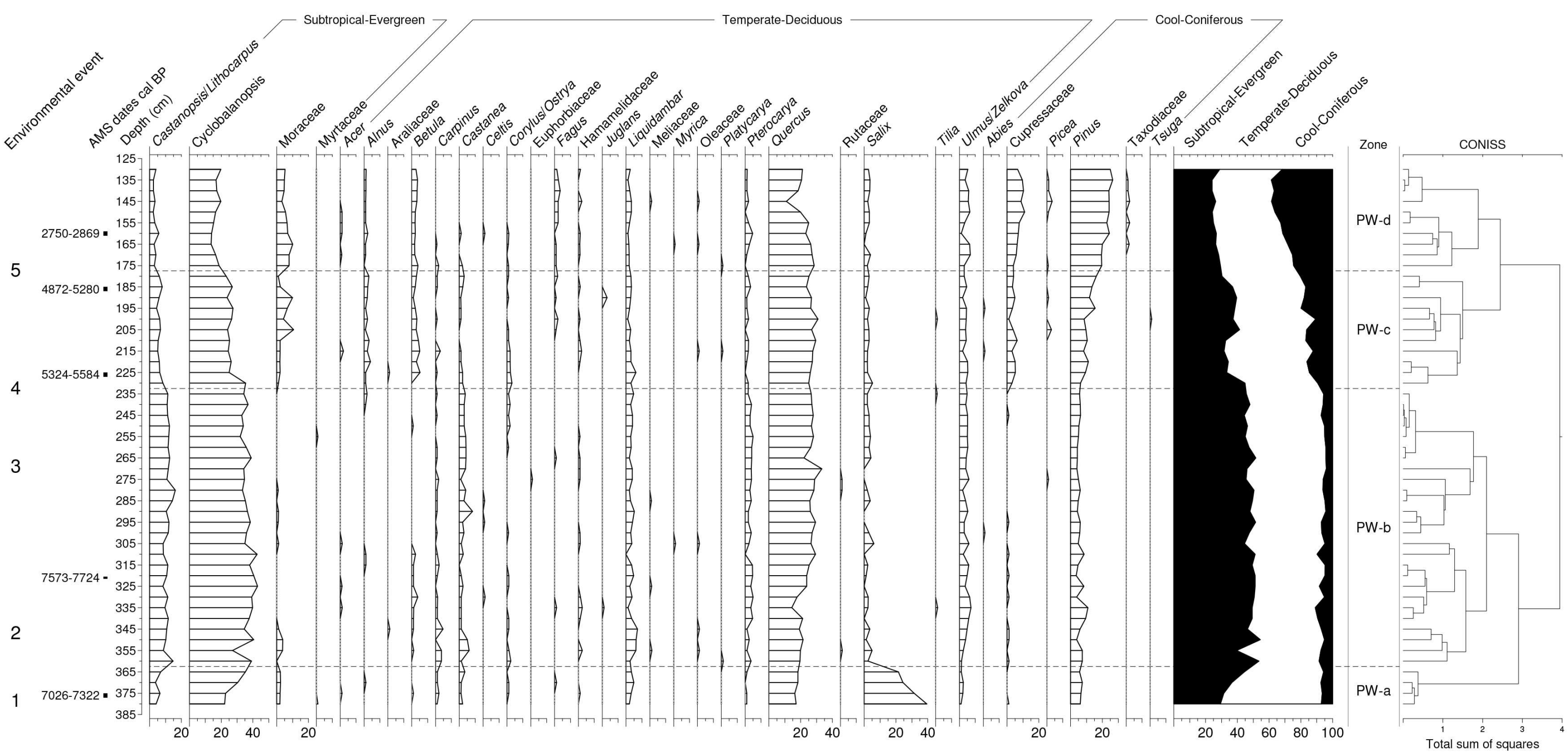
Fig. 4 Percentage non-pollen palynomorph (NPP) diagram from Pingwang. NPPs and microscopic charcoal fragment (microcharcoal) frequencies are shown as percentages of the tree and shrub pollen sum. X axis NPP type numbers refer to the catalogue of the Hugo de Vries laboratory, Amsterdam, and where taxon names are unknown they are assigned the prefix HdV. Diagram zonation, radiocarbon dates and environmental events follow Fig. 2. Depths are in centimetres below present ground surface.

*Figure



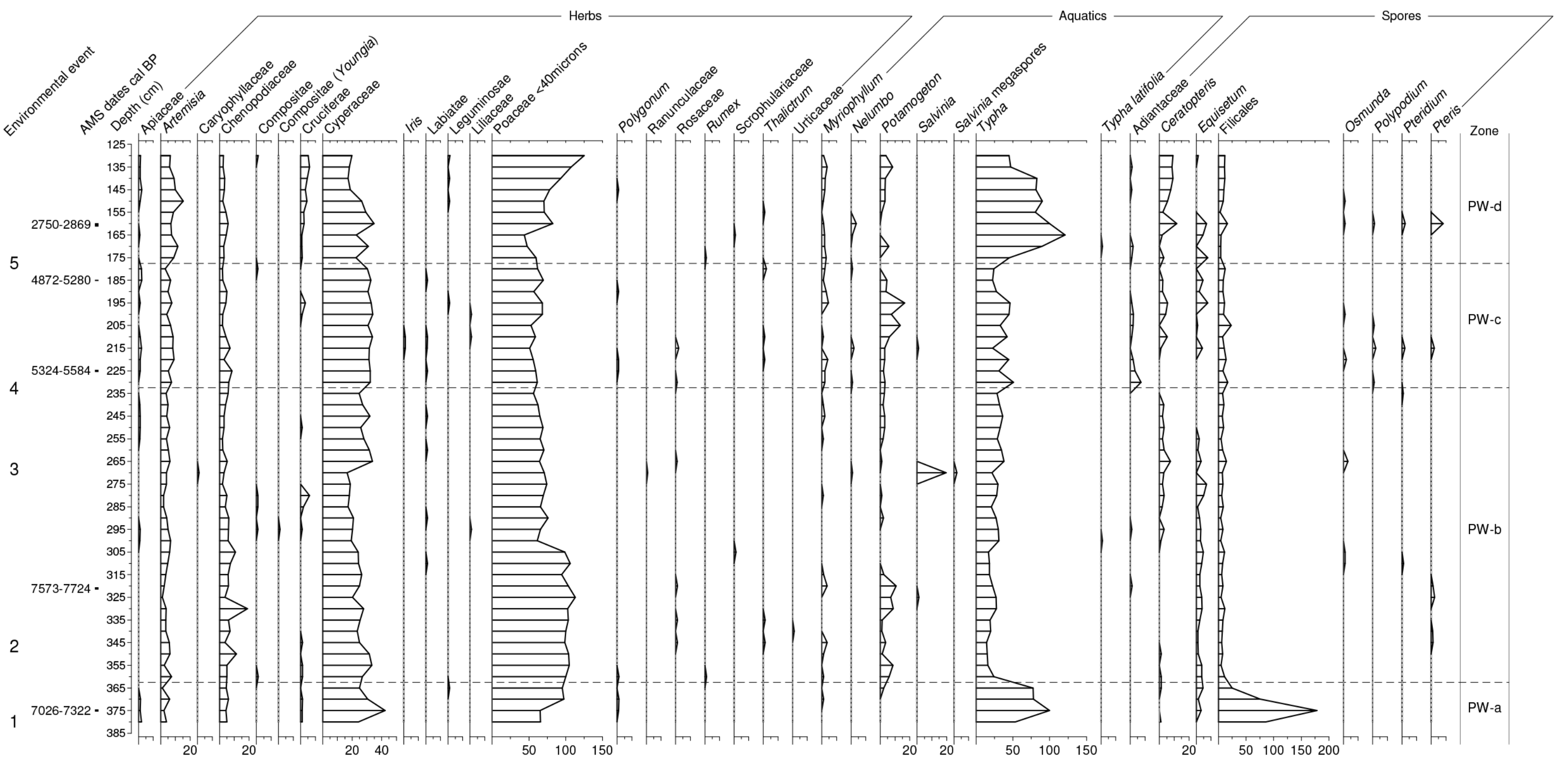
Yellow Sea
Zhenjiang
Shanghai
Hangzhou
Yangtze
CHINA
East China Sea
Tian-Mu-Shan
Taihu Lake
Wuxi
Yangtze River
SHANGHAI
Jiaxing
Jiuliqiao
Hangzhou Bay
31°N
Chenier ridge (7000-4000 yrs B.P.)
Chenier ridge (<1000 yrs B.P.)
Shoreline at c.7000 cal. yr BP
Shoreline at c.3000 cal. yr BP
Elevations (metres)
Over 10
5-10
2-5
0-2
120°E
121°
122°
0
kilometres
60
a
Liangzhu
(5200 - 4200 yr BP)
b
Maqiao
(3900 - 3200 yr BP)
0 km 40

*Figure



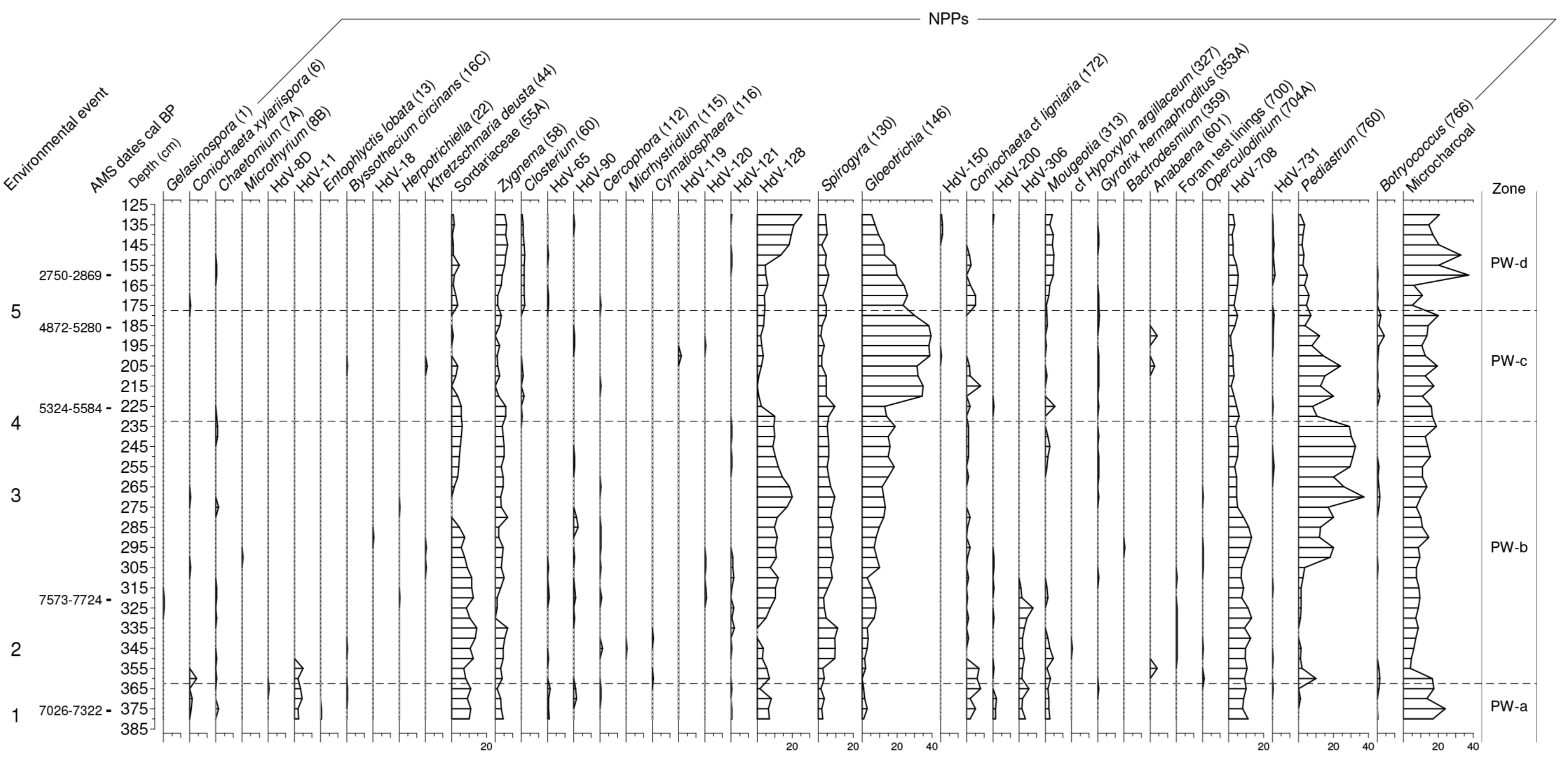
Subtropical-Evergreen
Temperate-Deciduous
Cool-Coniferous
Environmental event
AMS dates cal BP
Depth (cm)
Castanopsis/Lithocarpus
Cyclobalanopsis
Moraceae
Myrtaceae
Acer
Alnus
Araliaceae
Betula
Carpinus
Castanea
Celtis
Corylus/Ostrya
Euphorbiaceae
Fagus
Hamamelidaceae
Juglans
Liquidambar
Meliaceae
Myrica
Oleaceae
Platycarya
Pterocarya
Quercus
Rutaceae
Salix
Tilia
Ulmus/Zelkova
Abies
Cupressaceae
Picea
Pinus
Taxodiaceae
Tsuga
Subtropical-Evergreen
Temperate-Deciduous
Cool-Coniferous
Zone
CONISS
5
4
3
2
1
2750-2869
4872-5280
5324-5584
7573-7724
7026-7322
PW-d
PW-c
PW-b
PW-a
Total sum of squares

*Figure



Herbs
Aquatics
Spores
Environmental event
AMS dates cal BP
Depth (cm)
Apiaceae
Artemisia
Caryophyllaceae
Chenopodiaceae
Compositae
Compositae (Youngia)
Cruciferae
Cyperaceae
Iris
Labiatae
Leguminosae
Liliaceae
Poaceae <40microns
Polygonum
Ranunculaceae
Rosaceae
Rumex
Scrophulariaceae
Thalictrum
Urticaceae
Myriophyllum
Nelumbo
Potamogeton
Salvinia
Salvinia megaspores
Typha
Typha latifolia
Adiantaceae
Ceratopteris
Equisetum
Filicales
Osmunda
Polypodium
Pteridium
Pteris
Zone
PW-d
PW-c
PW-b
PW-a
5
4
3
2
1
2750-2869
4872-5280
5324-5584
7573-7724
7026-7322

*Figure


NPPs
Environmental event
AMS dates cal BP
Depth (cm)
Gelasinospora (1)
Coniochaeta xylariispora (6)
Chaetomium (7A)
Microthyrium (8B)
HdV-8D
HdV-11
Entophlyctis lobata (13)
Byssothecium circinans (16C)
HdV-18
Herpotrichiella (22)
Ktretzschmaria deusta (44)
Sordariaceae (55A)
Zygnema (58)
Closterium (60)
HdV-65
HdV-90
Cercophora (112)
Michrystridium (115)
Cymatiosphaera (116)
HdV-119
HdV-120
HdV-121
HdV-128
Spirogyra (130)
Gloeotrichia (146)
HdV-150
Coniochaeta cf ligniaria (172)
HdV-200
HdV-306
Mougeotia (313)
cf Hypoxylon argillaceum (327)
Gyrotrix hermaphroditus (353A)
Bactrodesmium (359)
Anabaena (601)
Foram test linings (700)
Operculodinium (704A)
HdV-708
HdV-731
Pediastrum (760)
Botryococcus (766)
Microcharcoal
Zone
PW-d
PW-c
PW-b
PW-a
5
4
3
2
1
2750-2869
4872-5280
5324-5584
7573-7724
7026-7322
125
135
145
155
165
175
185
195
205
215
225
235
245
255
265
275
285
295
305
315
325
335
345
355
365
375
385
20
20
20
20
40
20
20
40
20
40