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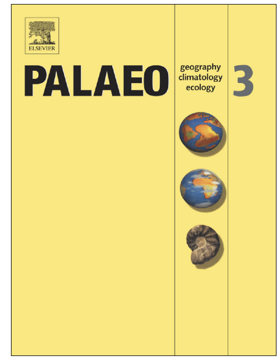

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Pollen and non-pollen palynomorph analyses of Upper Holocene sediments from Dianshan, Yangtze coastal lowlands, China: hydrology, vegetation history and human activity.

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Abstract

The coastal deltaic plain of the Yangtze River between Taihu (Lake Tai) and Shanghai in eastern China has been the scene of human settlement and agriculture since the early Neolithic, becoming increasingly intensive in the Upper Holocene when delta accretion and the establishment of a stable hydrological regime of freshwater lakes and wetlands allowed the development of extensive agriculture and complex society in late prehistoric and dynastic times. During this period the area was significantly affected by changes in sea level, climate and vegetation, resulting in a dynamic and complex environmental history, however little research has concentrated on environmental change and human impacts during the last few millennia. This study focuses on this late period, presenting the results of integrated sedimentary, microfossil and radiocarbon analyses from a core near the eastern margin of Lake Dianshan, to the east of Taihu. After the withdrawal of intertidal conditions and the conversion to freshwater lake at the core site about 2600 cal. yr BP, pollen and algal spore data show that increased sedimentation gradually reduced freshwater depth until a surface peat formed ca. 1500 cal yr BP. This also dates the start of a switch in woodlands from sub-tropical and warm temperate trees to a mainly cool temperate and coniferous tree flora, under climatic cooling and human impact. After this time water depths at the site increased greatly, partly due to climate change and flooding, but also because of the establishment of deepwater 'paddy' agriculture. Microcharcoal and pollen data show that a major episode of human impact using fire, with deforestation and rice cultivation, occurred between ca. 1500 and 1200 cal yr BP. These dates suggest it is one of the latest examples of ‘floodedfield’ ‘paddy’ cultivation before more intensive agricultural techniques were adopted in the area after ca. 800 cal. yr BP.

KEYWORDS: Yangtze coastal lowlands; palynology, climate change; human activity; vegetation history

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1. Introduction

The lower Yangtze River has been a highly important region in the initiation and development of Chinese agriculture, settlement, culture and society (Liu, 2004; Liu and Chen, 2012), with the highly fertile delta lowlands around Lake Taihu (Fig. 1). This region was the scene of agriculture and occupation since the early Neolithic period (Underhill, 1997; Fuller et al., 2007, 2009), when episodes of Middle Holocene drought, driving the migration of people from inland (Chen et al., 2008), combined with relative sea-level regression (Zong, 2004) to provide new areas of marshland along the coastal margins (Patalano et al., 2015). Based on ‘paddy’ farming systems in these lowland wetlands, the area supported intensive rice production and high population levels in the later Neolithic (Huang, 2003; Cao et al., 2006; Zong et al., 2007; Zheng et al., 2009; Qiu et al., 2014; Weisskopf et al., 2015; Zhang et al. 2017; Chen et al., 2018).

The Yangtze coastal plain around Lake Taihu is an area that was highly susceptible to the adverse effects of changing climate and sea level, or the consequences of intensive agriculture. Fluctuations in climate caused by changes in the strength of the East Asian Monsoon (Sun and Chen, 1991; An et al., 2000; Morrill et al., 2003; Wu and Liu, 2004; Dykoski et al., 2005; Wang et al., 2005), and hydrological changes caused by rise and fall in sea level or by Yangtze river floods, exerted major impacts on agrarian communities made vulnerable by their reliance on intensive rice farming (Zhang et al., 2005a, 2008b; Mo et al., 2011; Zheng et al., 2012; Long et al., 2016; He et al., 2018; Liu et al., 2018; Wang et al., 2018). The Neolithic Liangzhu culture (Lu, 2007; Li et al., 2010b; Liu et al., 2015; Wang et al., 2017; Renfrew and Liu, 2018) collapsed around 4200 cal. yr BP (Yu et al., 2000; Liu and Feng, 2012; Wu et al., 2012a) at a time when major deterioration of climate was well underway (Ma et al., 2009; Wu et al., 2014a; Bai et al., 2017; Yao et al., 2017), with some extreme cold periods between 4200 and

3800 cal. yr BP (Kajita et al. 2018). This major climate event, known as Holocene Event 3 (Bond et al., 2001), forms the abrupt culmination of the climate transition from the Middle Holocene thermal optimum to unstable, colder, Neoglacial conditions (Wanner et al., 2011). This major global climatic shift is now recognized (Walker et al., 2012, 2018) as defining the start of the Upper Holocene (Meghalayan) sub-epoch.

Human settlement and agriculture in the Yangtze Delta area continued to be influenced by environmental change and the effects of human land use for the rest of the Upper Holocene, as climate, sea level and sedimentation regimes in the deltaic wetlands changed through time and affected post-Neolithic cultures. While much palaeoecological research in the lower Yangtze has focused on the Neolithic, there has also been considerable work on later prehistoric and historic cultures and environments (Itzstein-Davey et al., 2007a, b; Atahan et al., 2007, 2008; Long et al., 2014). In particular, previous research indicates that urbanism and technological advances such as the introduction of iron tools (Rostoker et al., 1983; Shen, 1994) during a period of relative environmental stability after about 2400 cal. yr BP, around the time of the late Eastern Zhou and Qin dynasties, coincided with an expansion of rice cultivation and deforestation, as the intensity of agricultural land use increased, with improved water management and 'paddy' wet rice systems (Ikehashi, 2007).

This intensified human activity increased sedimentation in the Taihu coastal plain and increased sediment transport to the delta front, contributing to progradation of the delta and reduced coastal flooding (Liu et al., 1992; Li et al., 2000; Hori et al., 2001; Wang et al., 2001, 2011; Zhao et al., 2018), particularly after ca. 2000 cal. yr BP, although natural factors also caused progradation at this time (Chen, 1996). The establishment of chenier ridges around 1000 years ago gave further protection from marine inundation (Yan et al., 1989; Zhao, 1989; Zong et al., 2012; Long et al., 2014), as did the building of coastal embankments during this technologically advanced period (Tan, 1973; Chen and Zong, 1998; Yoshinobu, 1998; Song, 2002), while field and lake-edge embankments protected crops from freshwater flooding. This stable, protected hydrological environment allowed greater settlement and agriculture in the Taihu deltaic plain during a time of greater political stability and economic prosperity (Atahan et al., 2008) from the Iron Age Late Eastern Zhou cultural period onwards (Lu, 2005), but particularly in the Tang Dynasty.

In this paper, we analyse palynological data to infer the history of environmental change and human land use during the last three millennia in the area of lakes and freshwater wetlands that developed between Lake Taihu and the coast (Hong, 1991; Fang, 1993; Chen et al., 2005; Tao et al., 2006; Zhao et al., 2007; Atahan et al., 2008) after the decline of marine influence and the subsequent expansion of the Yangtze Delta (Hori et al., 2002a, b; Zong, 2004; Zong et al., 2011; Zhao et al., 2018). Results record natural palaeoenvironmental changes, as well as human land use and its impact upon the local and regional vegetation.

2. Study area

The site chosen for palynological analysis is at Dianshan (31º 5' 35" N; 120º 59' 0"E, altitude 2m Yellow Sea Datum), which lies on the eastern shore of Dianshan Lake, one of the larger of the small lakes to the east of Lake Taihu (Kung and Ying, 1991). The core was taken with a hand corer within a fruit garden near Dianfeng village, 600 m from the present shore of the lake, and it ended at 3.5 m depth in very hard clay. The samples were archived at the Geography Department, Durham University, UK. The core location, and those of several of the more important palynological sites in the area, is shown in Figure 1.

2.1. Palaeogeography

The study area comprises the coastal plain of the southern Yangtze Delta to the east of Lake Taihu, from the Yangtze river to Hangzhou Bay, eastern China (Fig. 1), an area which is mostly only a few metres above present sea level and has been so throughout the later Holocene. The establishment of coastal barrier ridges (Liu and Walker, 1989; Yan et al., 1989; Chen and Stanley, 1998) and rapid sedimentation (Sun et al., 1987: Yan and Huang, 1987) meant that in the later Holocene this coastal plain was usually only affected indirectly through elevated groundwater which followed any rise in sea level (Zong et al., 2011). Sea level has fluctuated around its present level for the last three millennia (Fig. 7G), and high water-tables, supplemented by periodic flooding from the Yangtze, which is still a problem (Yi et al., 2004), caused this lowland to become dominated by freshwater wetlands, from ca. 3000 cal. yr BP (Chen et al., 2005), when climate became wetter until about 1000 cal. yr BP (Xue et al., 2017). These were mainly marshland but including many shallow lakes, of which Taihu is by far the largest, occupying a depression in the western end of the plain (Sun and Mao, 2008). While the western part of Taihu is in a deeper basin and may have been a lake throughout the Holocene (Hong, 1991: Qu et al., 2000: Wang et al., 2001), its eastern part and the smaller water bodies to the east of it, including Lake Dianshan, are later Holocene creations, prompted by wetter climate, higher water-tables and by regular flooding from the Yangtze river after the climatic transition to the Upper Holocene (Innes et al., 2014). Numerous Neolithic sites occur at the bottom of Lake Dianshan (Wu et al., 2012a), proving its more recent origin. Areas of higher ground (Fig. 1) lay to the north and west of the Taihu plain, and also formed low islands of dry ground within the wetland. These higher areas would naturally have been occupied by woodland, and the wetland would have comprised a wide range of hydroseral habitats, from open water through reedswamp, marsh and fen to swamp and bog. These wetlands would have provided productive ecosystems for human exploitation (Zheng, 2013), and their fertile marsh soils supported wet rice cultivation (Cao et al., 2006: Atahan et al., 2008; Zhuang et al., 2014) which became intensive in the later Holocene and supported high human populations and cultural development (Liu, 2004).

2.2 Upper Holocene archaeology and cultural history

The Yangtze Delta has been a focus for human settlement at intervals during the Holocene at those times when stable environmental conditions allowed the exploitation of natural resources (Yuan et al., 2008; Fuller et al., 2009; Fuller and Qin, 2010; Qin et al., 2010; Liu et al., 2010; Qiu et al., 2016) and the establishment of rice farming (Fuller et al., 2007; Zheng et al., 2009; Nakamura, 2010; Wang et al., 2010; Zhuang et al., 2014).The Neolithic was one such major period of high population, reflected in the large numbers of archaeological sites of that period in the area (Zhang et al., 2005a; Hosner et al., 2016). After a period of greatly reduced population after the 4200 cal. yr BP climatic deterioration (Chen et al., 2005; Zhang et al., 2005a; Wu et al., 2014b; Chen et al., 2018), high populations became re-established at the end of the Shang Dynasty and thereafter due to continued southward migration (Duan et al., 1998), as shown by very high densities of archaeological sites dating to the last three millennia from the time of the Eastern Zhou (Hosner et al., 2016; Lu, 2005; Lu and Yan, 2005) onwards, far too many to be plotted on Figure 1, with site location constrained largely by water distribution in the Taihu lowland (Yu et al., 2012). The Dianshan sequence presented in this paper begins around the time of the demise of the Bronze Age Maqiao culture (Long and Taylor, 2015), and corresponds to the Lower Yangtze cultural periods of the Eastern Zhou (from 771 BC), the dynasties of Qin (221–206 BC), and Han (206 BC–AD 220), the Eastern Wu Kingdom (AD 200–280), the Jin Dynasty (AD 280–420), the 'Southern Dynasties' (AD 420–581), the dynasties of Sui (AD 581–618) and Tang (AD 618–906), the Wuyue kingdom (AD 906–978) and the Song Dynasty (AD 978–1279). Although cultural and social factors were very important (Lu, 2007), the collapse of dynasties, including the Han, Tang and Song, are associated with periods of low temperature and drought (Gao, 1997), which may well have caused crop failures and social conflict, and prompted migration (Ge et al., 1997; Zhang et al., 2005b; 2010; 2015; Pei et al., 2014, 2018).

3. Material and methods

3.1 Palynological analysis

48 sub-samples of 5 mm thickness from the Dianshan core were prepared for palynological analysis at 5 cm intervals, using standard laboratory techniques (Moore et al., 1991). Alkali digestion with NaOH was followed by sieving at 180 μm, removal of silicate mineral material with hydrofluoric acid, and acetolysis. Exotic *Lycopodium* spores (Stockmarr, 1971) were added to enable the calculation of microfossil concentrations. The residue was stained before mounting on microscope slides. The work of Clarke (1994) has shown that these procedures do little to affect the preservation of other microfossils, such as algae or fungal spores. Microfossils are defined as palynomorphs, which passed through the 180 μm sieve. The four highest levels did not contain countable pollen, but in the remaining 44 at least 200 terrestrial pollen grains were counted at each level, in most cases 250, as well as all aquatic pollen, pteridophyte and bryophyte spores that were encountered during that process.

Reference keys were used to aid identification of pollen and spores, primarily Wang et al. (1995) for pollen and Zhang et al. (1990) for pteridophyte spores. Sub-samples above 125 cm depth contained very few, poorly preserved pollen grains. Poaceae (grass) pollen grains have been divided into two size classes: those of 40 μm and above, which are almost certainly of cereal (*Oryza*) type, and those below 40 μm, which are more likely to originate from wild grasses (Wang et al., 1995; Chatuvedi et al., 1998), although could also include *Oryza* pollen (Maloney et al., 1989; Shu et al., 2007). This conforms to previous work in the study area (Atahan et al., 2008; Qin et al., 2011). Liu et al. (2016), following modern pollen studies of ‘paddy’ field Poaceae pollen (Yang et al., 2012), suggest that grass grains above 40 μm may indicate well-managed rice cultivation. *Quercus* pollen grains have been separated into those of evergreen oaks (*Cyclobalanopsis*) and of deciduous oaks, (including genera with very similar pollen grains and so combined into a composite curve *Quercus*/*Lepidobalanus*), using published keys and photographs (Chang and Wang, 1986; Jarvis et al., 1992). Composite curves are also employed for other genera with pollen that is very difficult to separate with certainty: *Ulmus*/*Zelkova*, *Corylus*/*Ostrya*, *Castanopsis*/*Lithocarpus* and *Typha*/*Sparganium*, where *Typha* is *T. angustifolia*.

Non-pollen palynomorphs (NPPs) were also recorded, with at least 100 counted at each level, and mainly comprised algal and fungal spores. Identification of NPPs was achieved by reference to the illustrations and descriptions in several published papers (e.g. van Geel, 1986, 2001; van Geel et al., 2003; van Geel and Aptroot, 2006) although, as many NPPs have not yet been identified and remain known only by their Type (HdV) number in the Hugo de Vries Laboratory catalogue in the University of Amsterdam (van Hoeve and Hendrikse, 1998), taxonomic identification was not always possible. HdV numbers are shown on the NPP diagram and with the first mention of an NPP type in the text. Microscopic charcoal particles (microcharcoal) that passed through the 180 μm sieve have been counted on the microscope slides relative to the pollen sum, providing a pollen/microcharcoal ratio. Particles of about 30 μm diameter formed the basic microcharcoal unit, as described in previous papers (Innes et al., 2009), and counts comprise multiples of that basic unit. Smaller fragments could be aggregated to form a single unit. Microfossil diagrams were constructed using the TILIA program of Grimm (2004). All microfossil counts are presented in Supplementary Tables S1 and S2.

3.2. Radiocarbon dating

Radiocarbon dates are AMS dates from Beta-Analytic, Miami, on the humin fraction of pollen (organic) residues or peat, the humin fraction being considered the most reliable as it is insoluble and cannot be vertically transported by water, and so remains preserved in the sediment in which it was deposited (Xu and Zheng, 2003). Bulk alluvial sediment samples were avoided as these have been shown to be likely to produce anomalous or at least unreliable dates (Stanley and Chen, 2000). Organic pollen residue concentrates, however, have been used in many published studies in this area (Itztein-Davey et al., 2007a; Atahan et al., 2008; Qin et al., 2010) and, although must be used with caution, produce consistent and reliable date series (Li et al., 2014). Five pollen residue dates are available for the Dianshan core. One of these was from the top of a Middle Holocene profile *in situ* peat layer, which did not contain terrestrial macrofossils, and two other dates on bulk peat were taken from the same level to check the age of this important stratigraphic horizon. Dates were calibrated using Calib 7.1 and IntCal13 (Reimer et al., 2013).

4. Results

4.1 Lithostratigraphy

The lithostratigraphy of the Dianshan core is shown in Figure 2 and Table 1. The hard clay at the base of the profile, which could not be penetrated, is probably the pre-Holocene layer that occurs beneath Holocene deposits throughout the area to the east of Lake Taihu (Li et al., 2000; Qin et al., 2008). It is thought to be a marine high-stand deposit from the last interglacial, in places capped by late Pleistocene fluvial material (Wang et al., 2006). The soft muds resting upon it are likely to be Holocene lagoonal deposits (Li et al., 2000), possibly intertidal at the base, which grade upwards into more organic freshwater limnic sediments and culminate in a thin peat layer. Above the peat are decreasingly organic limnic deposits, capped by silt, the upper meter of which has been disturbed by human activity and represents recent ploughsoil. Such a surface layer of brown agricultural ‘paddy’ soil (Barnes, 1990) is ubiquitous to sites dating to the last millennium in eastern China, for example at Qujialing in the middle Yangtze valley (Li et al., 2010b) or many sites in the Taihu plain (Zhang et al., 2017) as at Liangzhu (Li et al., 2010b), Chuodun (Li et al., 2007) and Kunshan (Gong et al., 2007), or several to the east of Lake Tai examined by Zong et al. (2011).

4.2 AMS ^{14}C dating

The AMS radiocarbon dating results are shown in detail in Table 2, including measured radiocarbon age, calibrated age ranges and mean calibrated age. Four of the pollen residue dates form a good series and are accepted as reliable, and are used to create the age-depth model curve (Fig. 3). Of the three dates that were taken from the top of the peat bed at 245 cm, all have similar results, their age calibrations being indistinguishable, and are therefore considered reliable. The residue date from this level was used in the age-depth model, for consistency with the other residue dates from the profile. The residue date of 1710 ± 40 ^{14}C yr BP from 330 cm depth (see Fig. 2 and Table 1) is considered erroneous, being out of series and much too young, and is the same as the dates on the peat bed almost a meter higher in the profile. It is not included in the creation of the age-depth model, and is not used in environmental reconstruction, although it is shown in parentheses on some diagrams and its age range is shown on Figure 3. The environmental data presented in this paper span the period from ca. 2650 cal. yr BP (700 BC) to ca. 700 cal. yr BP (AD 1250).

4.3 Palynology

The results of palynological analyses at Dianshan are presented in a series of microfossil diagrams. Tree and shrub (arboreal) percentages are shown on Figure 4, herb pollen and pteridophyte spores on Figure 5 and NPPs on Figure 6. NPP taxa are grouped according to their habitat and ecology, based upon published NPP literature (Miola, 2012). In each case frequencies are calculated as percentages of the total arboreal (AP) pollen sum. The CONISS (constrained incremental sum of squares) cluster analysis function (Grimm, 1987) within TGView has been used to subdivide the diagrams based on the total terrestrial pollen sum (trees, shrubs and herbs), and it has recognized six main local pollen assemblage zones (DS-a to f). These are described in Table 3 and have been applied to all of the diagrams, although the dendrogram is shown only on Figures 4 and 5. AMS dates are shown on the diagrams as calibrated age ranges BP. An environmental summary diagram is shown as Figure 7, in which section A shows tree and shrub taxa grouped according to their temperature tolerances (Subtropical/Evergreen, Warm Temperate and Cool/Coniferous), calculated as percentages of the total arboreal sum, section B shows total trees and shrubs versus total herbs as percentages of total terrestrial pollen, section C shows three curves reflecting vegetation disturbance and human activity, and section D shows total terrestrial pollen concentration per cc. Two curves show inferred temperature history (section E) and rainfall history (section F) for the region, both created by Li et al. (2018) using pollen-based numerical calibration models established using the Chinese surface pollen–climate database. Section G shows a regional sea-level history curve, after Yu et al. (2012).

5. Discussion

The radiocarbon dates from Dianshan make it clear that the site's palaeoenvironmental record represents a substantial part of the Upper Holocene. Comparison with other published diagrams from the Taihu area suggests that the base of the profile should be around 2500 years ago or a little earlier, based on regional vegetation and sea-level history (Zong, 2004; Itzstein-Davey et al., 2007a; Yu et al., 2012). The good series of dates and age-depth model confirm this, indicating that 340 cm depth dates to ca. 2650 cal. yr BP. The site therefore provides a reliable chronology for about two millennia from that time onwards, and an important Upper Holocene record. It allows the reconstruction of local and regional environments and human-induced environmental change in this heavily populated part of the Yangtze coastal lowlands.

5.1 Hydrology and depositional environments at the Dianshan site

Hydrology was a very important factor in the distribution and intensity of human settlement in the southern Yangtze Delta in the past (Li et al., 2010a; Qin et al., 2011; Long et al., 2014; Chen et al., 2018; Liu et al., 2018), and the data from Dianshan allows its reconstruction in that area. The lithostratigraphic record at Dianshan shows that the site has been dominated by aquatic depositional regimes, both fluvial and lacustrine, during the Upper Holocene, with changing facies denoting different water depths. Most sediments are lacustrine, some perhaps lagoonal, but the presence of a thin peat in mid-profile shows that some terrestrialisation occurred, before returning to deeper water deposition. This terrestrialisation was not confined to Dianshan, and peats of a similar age, about 1500 cal. yr BP, have been found in the Taihu lowlands at several locations (Chen and Stanley, 1998). The coring site is adjacent to the current Lake Dianshan which, as shown for Taihu lake by sedimentary and historical records (Hong, 1991; Shi and Zhu, 2004), would have been considerably larger after about 2500 cal yr BP, with episodes of higher rainfall (Gu et al., 2018; Li et al. 2018; Fig. 7F). The coring site would probably have been part of the shallow lake during such periods of higher rainfall, which Xue et al. (2017) report lasted from ca. 2500 to ca. 1200 cal. yr BP and coincided with much of the Dianshan profile, probably magnified by river floods (Huang et al., 2013). A similar period of higher rainfall has been recorded in the central Yangtze valley (Gu et al., 2018). Until drainage and reclamation in the last millennium (Yoshinobu, 1998), the Taihu plain would have generally supported aquatic environments. Increased flooding, rising water tables and the establishment of freshwater lacustrine conditions (Chen et al., 1997; Shi and Zhu, 1997) have been recorded at several sites on the Taihu plain and around Hangzhou Bay after about 2500 cal. yr BP, as at Guangfulin (Zhang et al., 2003a; Itzstein-Davey et al., 2007b; Atahan et al., 2008), Hemudu (Liu et al., 2016), Pingwang (Innes et al., 2014) and Chuodun (Zong et al., 2012; Long et al., 2014), indicated by microfossils of aquatic plants and algae as well as detrital and limnic sedimentation, as at Dianshan. The basal pollen assemblage, at the start of zone DS-a, has a high peak of Chenopodiaceae pollen which will represent saltmarsh taxa, before the withdrawal of marine influence, the rest of the zone having very low Chenopodiaceae frequencies that indicate slightly saline conditions within mostly freshwater environments, perhaps due to occasional tidal penetration along creeks in the delta (Yan and Huang, 1987). A similar removal of saltmarsh conditions occurred not far away at Qingpu before 2000 cal. yr BP (Itzstein-Davey et al., 2007a). Yue et al. (2015) and Rolett et al. (2011) recorded a similar withdrawal of marine influence at about the same time in the Fuzhou Basin, on the coast to the south of the Yangtze Delta, and it is probable that the base of the Dianshan profile formed during this period of marine regression.

At Dianshan freshwater aquatic genera *Myriophyllum*, *Potamogeton*, *Nelumbo* and *Nuphar* occur consistently and taxa that are at least semi-aquatic, Cyperaceae and *Typha*, occur throughout in high frequencies. The NPP record (Fig. 6) is particularly informative, with a wide range of aquatic and marsh taxa, such as types HdV-306 and HdV-708 in the lower two pollen zones, indicating reedswamp conditions with standing water, supported by the higher Poaceae frequencies and substantial *Typha* values. However, during the earliest phase, zone Ds-a, the presence of shallow, mesotrophic, rather than deeper open water is shown by high frequencies of algae HdV-128, *Zygnema* (HdV-58, van Geel et al., 1976) and *Pediastrum* (HdV-760, Jankovská and Komárek, 2000), and the cyanobacterial *Gloeotrichia* (HdV-146, Pals et al., 1980). *Gloeotrichia* suggests shallow and clear water (Chmura et al., 2006), and is common in supratidal freshwater swamps. In the lower Yangtze it has also been recorded as important at Pingwang (Innes et al., 2014). Up-profile changes in the NPP assemblage indicate succession towards shallower water reedswamp and fen environments, presumably caused by high sedimentation rates, supported by the stratigraphic transition from lake mud to a thin peat near the top of zone DS-b. The change from peat to organic lacustrine gyttja above 245 cm reflects significantly increased water depth, and records for the aquatic plant *Myriophyllum* in this phase indicate standing water of at least a metre depth (Aiken et al., 1979; Hannon and

Gaillard, 1997). This deeper water could have been caused by natural flooding from the Yangtze in this period (Chen, 1996; Shi and Zhu, 2004; Huang et al., 2013) or by local human hydrological management. Despite changes in depositional regime, pollen concentration values (Fig. 7D) do not fluctuate markedly throughout the profile, suggesting a relatively consistent rate of sediment deposition, other than for a brief fall during pollen zone DS-d.

Two levels with high percentages of the akinetes of blue-green alga *Aphanizomenon* (HdV-600) may indicate its temporary 'blooms', prompted by eutrophication of the lake water. Increased *Pediastrum* and *Botryococcus* are also likely to reflect increased trophic levels (Miras et al., 2015). Cyanobacterial blooms due to rapid eutrophication are common in recent lake sediment records (van Geel et al., 1994, 1996) and are a major modern problem in Taihu Lake (Guo, 2007), in Lake Dianshan (Cheng and Li, 2010), and in all the shallow lakes of the southern Yangtze Delta (Yang et al., 2008). The data from the Dianshan core, with high algal frequencies, indicates that eutrophication of lakes in the Taihu plain is not just a modern occurrence, but has been an important process since soon after their creation after 3000 cal. yr BP (Tao et al., 2006), prompted by high levels of agricultural activity and the erosion of nutrient-laden soils into the lakes in the last two and a half millennia, from the time of the Eastern Zhou culture onwards (Hori et al., 2001; Hosner et al., 2016; Long et al., 2016).

5.2 Upper Holocene climate and vegetation history

The lower Yangtze coastal lowland has been heavily affected by human activity at least since about 2100 cal. yr BP (Atahan et al., 2007, 2008; Li et al., 2010b; Wang et al., 2011), and the time of the Qin and Han Dynasties in the area, and agricultural paddy soils of Qin and Han age occur in the Taihu plain (Gong et al., 2007; Wissing et al., 2011; Lehndorff et al., 2014). It is also important, however, to examine the natural vegetation patterns during this period, particularly the type of woodland that would have been in existence under the climatic and other natural factors of the last few millennia. There are several pollen diagrams available from the lower Yangtze from which to reconstruct vegetation history (Wang et al., 1984; Sun and Chen, 1991; Liu et al., 1992, 2016; Yi et al., 2006; Shu et al., 2007; Chen et al., 2009; Li et al., 2010b; Wang et al., 2010; Long et al., 2014), the most important of which are shown on Figure 1. The location of the lower Yangtze valley near the transition point between two major forest biomes, those of the warm temperate to sub-tropical evergreen broadleaf and mixed forest to the south, and the temperate deciduous broadleaf forest to the north (Wu, 1980; Yu et al., 1998; Ren and Beug, 2002; Ren, 2007; Guiot et al., 2008), has meant that the area has always been very sensitive to climate change, primarily responding to fluctuations in the strength of the East Asian Monsoon (An, 2000; Zhao et al., 2009; Yao et al., 2017). This was very clear during the transition from the Middle Holocene to the Upper Holocene (Innes et al., 2014), with the change to a still humid, but colder and wetter climate (Yao et al., 2017), which also had very serious impacts on Neolithic cultures in the region, causing the replacement of thermophilous subtropical trees by cold-tolerant deciduous and coniferous trees. There have also been significant climatic fluctuations in the last few millennia, however, of both temperature (Yang et al., 2002; Ge et al., 2003, 2013; Li et al., 2018) and rainfall (Zheng et al., 2006; Li et al., 2018; Lu et al., 2015, 2018) including extreme events. Temperature fluctuations were probably due to changes in solar activity (Park, 2017), within a general cooling trend (Winkler and Wang, 1993; Jian et al., 1996; Ge et al., 2003). These climatic changes are reflected in the arboreal pollen record at Dianshan (Figs. 4 and 7A), and will have impacted human settlement in the area.

The Dianshan record indicates a mixed sub-tropical evergreen and warm temperate deciduous forest with *Quercus*, *Cyclobalanopsis*, *Castanopsis* and *Ulmus*/*Zelkova* before about 2000 cal. yr BP, with the thermophilous *Liquidambar* important in the earlier phases. A decline of the sub-tropical elements and their replacement by cool temperate and coniferous trees, *Pinus* and Cupressaceae, occurs after about 1500 cal. yr BP, and particularly after ca. 1350 cal. yr BP, with Taxodiaceae important later in the sequence. Collating several proxy data sources, Yang et al. (2002) have reconstructed temperature fluctuations for eastern China over the last two millennia, identifying warm and cool periods. They note warm but fluctuating conditions until ca. 1700 cal. yr BP, a colder phase until about 1400 cal. yr BP, a warm period from ca. 1400 to ca. 1200 cal. yr BP, a cooling period from ca. 1200 to ca. 600 cal. yr BP but with warmer phases, and cooler conditions after ca. 600 cal. yr BP until modern warming. This broadly agrees with the results of Ge et al. (2003, 2010) and Chen et al. (2005), and with recent modelling based on pollen records (Li et al., 2018), although exact matches are not to be expected. The warm and cold phases of the last millennium have been confirmed from historical records (Ge et al., 2003; Zhang et al., 2008b), and speleothem analysis (Chu et al., 2012) links these historical changes to monsoon variability (Zhang et al., 2008a). This variation in the summer monsoon (Zhang et al., 2007b) accounts for the wetter climate between ca. 3000 and 1000 cal. yr BP (Gu et al., 2018; Li et al., 2018; Xie et al., 2013; Xue et al., 2017) and the expansion of wetlands in the Yangtze coastal lowlands. The start of colder phases at ca. 1500 and ca. 600 cal. yr BP might fit with the Dianshan arboreal record, as at broadly those times coniferous and cold-tolerant trees increase while evergreen and warm temperate trees decline (Figs. 4 and 7). This change in forest composition from warm temperate oakwoods to cold-tolerant conifers, mainly *Pinus*, has been recorded in many places in the Taihu lowlands and nearby areas at this time (Liu et al., 1992; Feng et al., 1993; Xu et al., 1996; Okuda et al., 2003; Yi et al., 2003; Wang et al., 2008; Chen et al., 2009; Li et al., 2010b; Wang et al., 2010; Innes et al., 2014; Ma et al., 2016; Yao et al., 2017; Zhao et al., 2017). Surprisingly, however, *Pinus* pollen frequencies remained very low throughout this period at the nearby sites of Qingpu and Guangfulin (Itzstein-Davey et al., 2007a; Atahan et al., 2008), which suggests that the origin of pine pollen at sites in the Taihu plain may have been very local. The arboreal vegetation changes at Dianshan therefore fit with the regional climate evidence, and with the tree pollen records from most other pollen diagrams from the lower Yangtze area, in recording this trend over the last two millennia away from thermophilous evergreen and warm temperate trees towards conifers, but show distinct differences to some pollen profiles from east of Lake Taihu. It has been noted (Yang et al., 1996; Yin et al., 2016; Yao et al., 2017), that similar changes in the woodland composition might be attributable to human impacts, which occurred at this time in the lower Yangtze, and the rise of *Pinus* might be a response to forest clearance, although the simultaneous rise of other conifers at Dianshan favours climate change. Some of the trees which replace deciduous *Quercus* in the agricultural phase, such as *Alnus*, *Betula* and *Salix*, will be members of the post-clearance regeneration community, while the rise of *Fagus* after the main agricultural phase indicates long-term change in woodland composition, probably as a response to forest disturbance, but also encouraged by higher temperatures at times, as *Fagus* is one of the main warm-temperate deciduous trees in later Holocene eastern China (Hou, 2001). Human activity may also account for the increase in the thermophilous Moraceae after the end of the main farming phase, against the trend towards cooler climate trees, and may indicate its place in secondary woodland but perhaps also its cultivation (Itzstein-Davey et al., 2007b).

5.3 Human impact on the vegetation

Human agricultural activities have been a very important factor affecting vegetation in the lower Yangtze in the last two and a half millennia (Okuda et al., 2003; Itzstein-Davey et al., 2007a, b; Atahan et al., 2007, 2008; Li et al., 2010b; Zong et al., 2012; Yao et al., 2017), and the modern vegetation of the Delta is almost entirely anthropogenic (Yi et al., 2003). It can be difficult to distinguish the effects of climate change and human impacts on the vegetation (Liu and Qiu, 1994; Ren, 2000) from tree frequencies alone, particularly when both influences coincided. There is a range of disturbance and cultural indicator pollen and NPPs, however, that allows recognition of human activity, and agriculture is clear in the Dianshan record in Zone DS-c, when high frequencies of Poaceae greater than 40 μm, considered to represent *Oryza* pollen, occur for a period of about three hundred years. Peaks of *Ceratopteris* during this phase support the identification of rice agriculture (Maloney et al., 1989), as it was a common weed of rice paddies, strongly associated with that habitat, although recently greatly reduced due to habitat loss and declines in water quality (Dong et al., 2005). The high *Typha* percentages during this phase also support the presence of agriculture, as *Typha* is favoured by nutrient-rich environments such as are provided by cultivated and probably fertilised (Mesléard et al., 1999; Zhuang et al., 2014) rice fields. *Typha* is prominent in other examples of ancient rice cultivation in eastern China, as at Kuahuqiao in the early Neolithic (Zong et al., 2007; Innes et al., 2009), and at Jiangli in the late Neolithic (Qiu et al., 2014) not far from Dianshan. Both *Ceratopteris* and *Typha* may be used as an alternative food source, grown with rice. *Oryza* pollen and phytoliths are diagnostic of human agriculture after ca. 2400 cal. yr BP at several Yangtze Delta sites (Atahan et al., 2007a, b; 2008; Itzstein-Davey et al., 2007c), and adjacent higher areas (Ma et al., 2016), and are a reliable cultural marker, often coupled with the inwash of clastic material from eroded soils (Long et al., 2016). Itzstein-Davey et al. (2007c) did find that wild rice continued to be grown alongside domesticated rice during this period at Qingpu, at least until ca. 1800 cal. yr BP, so it is possible that this also occurred at Dianshan, although the DS-c cultivation phase started rather later than that date. Figure 7 (sections B and C) shows a decline in tree and shrub percentages during zone DS-c at Dianshan, and an expansion of herb pollen, presumably following woodland clearance which the consistently high microcharcoal curve (Fig. 6) indicates was caused by fire. This may well have been on the nearby slightly higher ground to the east of Lake Dianshan within the Taihu plain (Fig. 1), as well as local wetland carr and scrub (Zong et al., 2007) at this time of major expansion of rice cultivation (Itzstein-Davey et al., 2007c; Yin et al., 2016). Collation of microcharcoal records by Xue et al. (2018) shows that fire activity in eastern monsoonal China reached a peak around 2000 cal. yr BP, and was maintained at a high level thereafter. Continued high frequencies of microcharcoal, combined with evidence of deeper water at the site, may reflect the long-term use of a fire and irrigation system (Hu et al., 2013) of intensified deepwater flooded-field paddy agriculture (Ikehashi, 2007; Zhuang et al., 2014), with in-situ burning of rice straw after harvesting (Cao et al., 2006) to manage field ecology. Figure 7C combines pollen and NPP taxa into summary groups, and it is clear that major environmental disturbance was maintained for centuries, with disturbed-ground weeds and disturbance NPPs consistently in peak frequencies. The latter include types which may well be dung fungi (van Geel et al., 2003), such as *Podospora* and *Cercophora*, suggesting manuring of fields, for which there is evidence from the late Neolithic onwards (Zhuang et al., 2014) or at least the presence of animals, typically pigs (Yuan and Flad, 2002), in a mixed economy. Although the obligate dung fungus *Sporormiella* (HdV-113) has been prominent in some other published human impact phases in this area (Zong et al., 2007; Innes et al., 2009), it is absent at Dianshan. Although it is not always present in disturbance fungal assemblages (Blackford et al., 2006), this may suggest that any dung presence at Dianshan was limited, but *Sporormiella* is not favoured by very wet conditions (Wood and Wilmshurst, 2012), which may explain its absence. Also present in this limnic sediment of zone DS-c is the soil fungus *Glomus* (HdV-207), which suggests at least periodic erosion of destabilised soils into the water (van Geel, 1986; Marinova and Atanassova, 2006). High frequencies of *Gloeotrichia* may also be significant, as it is common in deepwater rice fields (Rother et al., 1988). Weeds of disturbance and cultivation present during this long period of agriculture include *Artemisia*, Chenopodiaceae, *Plantago* and Cruciferae (Brassicaceae), a typical weed assemblage during cultivation in this period, and also *Pteridium*. The high Cruciferae values after the end of the main agricultural phase could represent a wetland fringe plant such as *Cardamine*, although in this area high Cruciferae values are usually held to indicate intensive human agriculture, probably rape cultivation (Okuda et al., 2003; Yi et al., 2003, 2006; Shu et al., 2007; Wang et al., 2010, 2011; Lu et al., 2015; Jin et al., 2018; Zhao et al., 2018). The date of the Cruciferae peaks at Dianshan coincides with a major immigration of people from northern China to the

Yangtze valley (Qu and Li, 1992; Wang et al., 2010) and could represent their subsistence activities during periods when rice cultivation was not climatically favoured. The low levels of microcharcoal, however, suggest little woodland clearance, and land use that did not require fire. The microcharcoal present probably derives from domestic fires. The presence of *Polygonum* and *Fagopyrum* in the farming phase at Dianshan suggests cultivation of rapeseed and buckwheat, as at Cauduntou to the west of Lake Taihu (Okuda et al., 2003) and at CM97 to the north-east (Yi et al., 2003), as well as wild and domesticated rice (Itzstein-Davey et al., 2007c).

While the disturbance/agriculture phase at Dianshan is similar in form to analogous events at several sites in the lower Yangtze area (Okuda et al., 2003; Yi et al., 2003; Chen et al., 2009; Atahan et al., 2007, 2008; Li et al., 2010b; Liu et al., 2016) there are differences in detail which must be site specific. A feature of Atahan et al. (2008)'s work at nearby Qingpu was high *Osmanthus* frequencies for the post-2100 cal. yr BP period, interpreted as local cultivation of this tree. While small peaks of Oleaceae pollen occur at the end of the Dianshan phase, which could be *Osmanthus*, there is no evidence at Dianshan for such silviculture, which might have been very localised. Itzstein-Davey et al. (2007b) and Atahan et al. (2008) recorded a significant Moraceae presence at Guangfulin, similar to that late in the sequence at Dianshan and probably cultivated, but they did not record the taxon at Qingpu or Luojiang. There will have been considerable spatial differences in land use across the Taihu lowlands during the last two millennia, based on hydrology and also on local population levels, as the area saw natural population rise and considerable immigration from northern China at intervals during this period (Qu and Li, 1992; Duan et al., 1998; Pei et al., 2018), prompted by climatic deterioration and drought (Zhang, 2005; Zhang et al., 2015; Yin et al., 2016). Populations did not start to rise to very high levels, however, until about 350 cal. yr BP when policies of the new Qing Dynasty (Li, 1998) encouraged larger families, with land distribution linked to family size (China Statistical Yearbook, 1994). The Dianshan pollen diagram does not extend far enough towards the present for any consequences of that population expansion to be registered. Before that, Chinese population levels had remained high but fluctuated throughout the last two millennia, as phases of immigration occurred (Fang and Liu, 1992; Ge et al., 1997; Fan, 2010; Lee and Zhang, 2010). The start of the agricultural phase at Dianshan at ca. 1500 cal. yr BP is similar to that at some other sites in the area (Itzstein-Davey et al., 2007a, b;

Atahan et al., 2008; Wang et al., 2011). It dates to the period of the 'Southern Dynasties', with political instability in eastern China and large scale immigration of Han people from the Yellow River area (Duan et al., 1998; Fan, 2010). It was a time of higher rainfall (Gu et al., 2018; Li et al., 2018) and agricultural improvement and that, combined with population rise (Hosner et al., 2016), may account for increased cultivation intensity. The duration of this farming phase (ca. 1500 to 1200 cal. yr BP) continued into the Sui and Tang dynasties, during which the lower Yangtze had increased greatly in population and had become prosperous (Yin et al., 2016) and the food production and economic centre of China (Duan et al., 1998). Historical records (Yoshinobu, 1998) show major wetland reclamation, deforestation, over-exploitation of farmland and erosion during the mid to late Tang, mainly due to population pressure, which agrees well with the palynological data recorded at Dianshan and with environmental records from elsewhere in the lower Yangtze basin (Tan et al., 2018).

The end of rice cultivation at Dianshan was broadly contemporaneous with the end of the Tang. The decline is attributed at nearby Lake Chaohu by Wu et al. (2012b) to environmental factors, mainly flooding. Atmospheric temperature was the controlling factor (Sugihara, 1991) for rice cultivation in coastal eastern China in recent millennia (Zhang et al., 2007a), however, and while the higher temperatures in the first half of phase DS-c would have encouraged the expansion of rice agriculture, the subsequent reduction in temperature in the lower Yangtze (Li et al., 2018), starting from mid DS-c in Fig. 7E, might well have caused the decline of rice farming and prompted societal change and the end of the Tang (Fan, 2010; Zhang et al., 2010). In other places, major forest clearance and farming phases appear to have begun rather later than at Dianshan, commencing at about 1400 cal. yr BP, but then also reduced in intensity by ca. 1200 cal. yr BP (Long et al., 2016). A renewed intensification of farming occurred after about 800 cal. yr BP during the Song Dynasty, as at Taibai Lake in the Yangtze valley (Xiao et al., 2013), at site CM97 in the northeast Yangtze delta (Yi et al., 2003), at Luojiang on the southern coast of Hangzhou Bay (Atahan et al., 2008), at Chaohu Lake to the north of the Delta (Wang et al., 2008) and to the south along the coast at Fujian (Xu et al., 2013). The major increase in forest clearance for agriculture at around 800–600 cal. yr BP has been recorded at Gaochun, at the western edge of the Taihu plain (Yao et al., 2017), with greatly increased cereal cultivation, and this date for the final expansion of intensive farming is likely to have been similar across the Yangtze coastal lowlands. It may have been prompted by a return to higher temperatures correlated broadly with the Medieval Warm Period of this time (Cook et al., 2013; Li et al., 2018), the start of which can be seen in zone DS-f at Dianshan (Fig. 7E). This later agricultural phase is not registered at Dianshan, but its date is similar to that of the top of the Dianshan pollen profile, and so might be too late to be recorded, or else local factors such as lake expansion might have prevented major farming activity in the Dianshan locality. Proximity to the lake and its fluctuation water levels might always have made the Dianshan pollen site marginal except during periods of major population pressure and benign climate. The rise in Cruciferae and *Artemisia* pollen at Dianshan in zone DS-e and DS-f might reflect a switch to crops other than rice in this marginal area during a period of particularly cooler temperatures.

The Dianshan farming phase is of considerable interest as it seems to be the last of the kind of shifting agriculture used in the Yangtze lowlands since the Neolithic, as its structure is similar to that of earlier agricultural episodes (Okuda et al., 2003; Zong et al., 2007; Innes et al., 2009). It therefore agrees with Long et al. (2016)'s view that agricultural intensification was late coming to parts of the lower Yangtze lowlands. Its marginal wetland location might have limited the possible intensity of rice farming. Dianshan conforms with most sites in the lower Yangtze in recording some increased disturbance after ca. 2500 cal. yr BP, as with most areas of east and south-east China (Zhao et al., 2017), and on the south coast in the Pearl River delta (Zong et al., 2013), but with a period of negligible disturbance thereafter, until the rice agriculture phase started ca. 1500 cal. yr BP. The timing of the maximum agricultural impact seems to have varied considerably within the wider region of coastal eastern China, with the greatest expansion and impacts occurring within the last millennium, when the construction of sea walls and sluices, as in the Tang Dynasty (Yoshinobu, 1998) and the Yuan Dynasty (Zhang et al., 2003b), in particular a very strong wall in AD1172 (Zong et al., 2012b), allowed fully sedentary and more extensive agriculture in the Yangtze coastal lowlands (Yi et al., 2003).

6. Conclusions

(1) The core site has provided fine-resolution sedimentary and microfossil data regarding changes in hydrology and depositional environments in the deltaic plain to the east of Lake Taihu. It records the withdrawal of intertidal conditions about 2650 cal. yr BP, followed by progressive terrestrialization through freshwater aquatic and marsh systems due to high

sedimentation rates, culminating in the establishment of a surface peat about 1500 cal. yr BP. A return of deep water limnic sedimentation occurred between ca. 1500 and ca. 600 cal. yr BP, with phases of rapid eutrophication, and could reflect lake expansion in the deltaic plain or, more likely, resulted from human land use and water management. The site's hydroseral succession and depositional history is probably typical of that in the eastern deltaic plain.

(2) The core's pollen data indicates a mixed sub-tropical evergreen and warm temperate deciduous forest before ca. 2000 cal. yr BP, after which a fluctuating but long-term natural climatic cooling trend caused the gradual replacement of evergreen and warm temperate trees by cool temperate trees and conifers, increasingly after ca. 1300 cal. yr BP, and particularly after ca. 800 cal. yr BP. This fits well with the regional palaeoclimate data and the history of the East Asian Monsoon in the last three millennia.

(3) Little evidence of human activity occurs in the first millennium of the core's record. A major phase of woodland clearance by fire lasting about three hundred years after ca. 1500 cal. yr BP is recorded at the site, and the presence of high pollen frequencies of *Oryza*-type and other cultivation indicators shows that this phase resulted from human activity and wet rice, flooded-field 'paddy' agriculture, and correlates mainly with the Tang Dynasty period. It accords with historical records and palaeoecological data from other sites in the Taihu lowlands for increased agriculture at this time, and its end correlates with climatic deterioration and with the end of the Tang. The date and structure of the agricultural phase suggests it is one of the last examples of traditional clearance and 'paddy' rice cultivation, unlike the high intensity agricultural systems adopted in the area after ca. 800 cal. BP, the effects of which are not represented in the Dianshan core, probably because the extremely wet conditions of the Dianshan lake edge prohibited such agriculture.

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Captions to figures.

Fig. 1. Location of the study area to the east of Taihu Lake in the Yangtze coastal plain, showing the topography, location of smaller lakes and the position of the coring site at Dianshan, marked by a black star. The locations of some other palaeoenvironmental sites cited in the text are shown as numbers. 1. Chuodun (Zong et al., 2012; Long et al., 2014), 2. Dashi, Kunshan (Gong et al., 2007), 3. Qingpu (Atahan et al., 2007), 4. Pingwang (Innes et al., 2014), 5. Guangfulin (Atahan et al., 2008), 6. Zk01 (Shu et al., 2007), 7. LTD-12 (Lu et al., 2015), 8. Qidong (Liu et al., 1992), 9. CM97 (Hori et al., 2001; Yi et al., 2003, 2006), 10. Hu05 (Zhao et al., 2018), 11. Maoshan (Jin et al., 2018), 12. Liangzhu (Li et al., 2010; Wang et al., 2017), 13. Luojiang (Atahan et al., 2008), 14. Hemudu (Liu et al., 2016). Of these fourteen palaeoenvironmental sites shown on Figure 1, Chuodun, Qingpu, Guangfulin, Lianzhu and Hemudu are also important archaeological sites.

Fig. 2 Lithological column from the Dianshan core, showing depths (cm), sediment descriptions, depositional environments and AMS age ranges in calibrated years BP. Sub-samples for palynology were taken in the undisturbed sediment at 5 cm intervals, but only those from 125 to 340 cm contained countable pollen.

Fig. 3 Bayesian age-depth model from Dianshan using the P_sequence depositional model (Bronk Ramsey 2008). AMS ^{14}C dates are shown. The age ranges of the four dates used in the model are shown in blue and the anomalous date, not used in the model, is shown in yellow. Calibrations are derived from Calib 7.1 and IntCal13 (Reimer et al., 2013), and are shown on Table 2. The envelope represents the 95 % probability range confidence interval.

Fig. 4 Percentage tree and shrub pollen diagram from Dianshan. Frequencies are calculated as percentages of total trees and shrubs. Taxa are grouped by ecological tolerances. Pollen zones are labelled DS and are derived from the terrestrial pollen data using CONISS (Grimm, 1987). Calibrated radiocarbon date ranges are derived from Calib 7.1 and IntCal13 (Reimer et al., 2013).

Fig. 5 Percentage herb pollen and spore diagram from Dianshan. Frequencies are calculated as percentages of total trees and shrubs. Taxa are grouped by ecological tolerances. Pollen zones are labelled DS and are derived from the terrestrial pollen data using CONISS (Grimm, 1987). Calibrated radiocarbon date ranges are derived from Calib 7.1 and IntCal13 (Reimer et al., 2013).

Fig. 6 Percentage non-pollen palynomorph (NPP) diagram from Dianshan. Frequencies are calculated as percentages of total trees and shrubs. Taxa are grouped according to their habitat and ecology, based upon published NPP literature (Miola, 2012). The prefix 'HdV' refers to that taxon's number in the Hugo de Vries Laboratory catalogue in the University of Amsterdam. Pollen zones are labelled DS and are derived from the terrestrial pollen data using CONISS (Grimm, 1987). Calibrated radiocarbon date ranges are derived from Calib 7.1 and IntCal13 (Reimer et al., 2013).

Fig. 7 Selected environmental records from Dianshan and the Lower Yangtze Taihu region. A) Dianshan tree and shrub pollen grouped by climatic tolerance, percentages are of total tree and shrub pollen, B) Dianshan summary pollen percentages of trees and shrubs *versus* herb pollen, calculated as percentages of total terrestrial pollen, C) groupings of Dianshan pollen and non-pollen palynomorph (NPP) indicators of human activity and disturbance, D) concentration of Dianshan total terrestrial pollen as thousands of grains per cubic centimetre (k per cc), E) regional temperature relative to the Holocene mean (after Li et al. 2018), F) regional rainfall relative to the Holocene mean (after Li et al. 2018), G) regional sea-level change since ca. 3000 cal. BP (Yu et al. 2012). Calibrated radiocarbon date ranges are derived from Calib 7.1 and IntCal13 (Reimer et al., 2013).

Table 1.

Lithostratigraphy at Dianshan (31º 5’ 35” N; 120º 59’ 0”E, altitude 2m, Yellow Sea Datum)

Depth (m)	Descriptions
0.00 – 1.00	Disturbed topsoil
1.05 – 1.15	Brown-yellow silt
1.15 – 1.90	Green-grey mud
1.90 – 2.20	Dark grey mud
2.20 – 2.45	Green-grey highly organic mud
2.45 – 2.60	Black peat
2.60 – 2.65	Brown-black peaty mud
2.65 – 3.05	Green-grey mud
3.05 – 3.45	Grey mud with calcium carbonate patches
3.45 – 3.50	Hard clay

Table 2.

Results of AMS ^{14}C dating at Dianshan[a]

Depth cm.	Lab code	Material	^{14}C date (yr BP)	Age range (cal. yr BP)	Mean age (cal. yr BP)	Age range (cal. BC/AD)
145	Beta-443478	residue	890 ± 30	733 – 909	810	1041 – 1217 AD
185	Beta-443477	residue	1260 ± 30	1087 – 1281	1218	668 – 863 AD
245	Beta-504810	residue	1640 ± 30	1416 – 1613	1515	336 – 534 AD
245	Beta-228441	peat	1680 ± 40	1522 – 1704	1588	245 – 504 AD
245	Beta-241863	peat	1730 ± 40	1538 – 1726	1632	224 – 412 AD
300	Beta-504811	residue	2170 ± 30	2066 – 2309	2187	116 – 360 BC
330	Beta-24532	residue	1710 ± 40*	1536 – 1708	1622	242 – 414 AD

[a]Age range (2δ) and mean derived from calibration results using Calib 7.1 and IntCal13 (Reimer et al., 2013).
* considered to be anomalous and disregarded

Table 3.

Descriptions of pollen assemblage zones at Dianshan, including NPP content.

Zone DS-a (340-282.5 cm).

This lowermost zone has a diverse microfossil assemblage. Subtropical evergreen arboreal trees are well represented at around 40% of total tree and shrub pollen, contributed equally by *Cyclobalanopsis* and *Castanopsis/Lithocarpus*. Warm temperate trees comprise a similar component of the AP sum, and are heavily dominated by *Quercus*/*Lepidobalanus* with significant curves for *Liquidambar*, *Pterocarya*, *Carpinus*, *Ulmus*/*Zelkova* and *Fagus*. Coniferous trees are present in relatively low but significant frequencies, at a little over 20% of the AP sum. Tree and shrub frequencies as a whole comprise about 40% of total terrestrial pollen. Herb pollen is contributed mainly by Poaceae (<40 μm) and Cyperaceae, with a low but consistent curve for *Artemisia* (10% total AP). Apart from an initial high peak of Chenopodiaceae, other herb taxa are rare and are of wetland type. Spore and NPP taxa confirm the wetland nature of the non-arboreal (NAP) assemblage, with substantial *Typha*/*Sparganium* percentages and other aquatic herbs, and a wide variety of wetland/aquatic NPPs, notably *Zygnema* (HdV-58), *Gloeotrichia* (HdV-146), *Pediastrum* (HdV-760), HdV-128, HdV-306 and HdV-708. A low but consistent microcharcoal curve occurs.

Zone DS-b (282.5–242.5 cm).

Arboreal taxa, which contribute only 30% of the total terrestrial pollen sum, are dominated by the warm temperate *Quercus*/*Lepidobalanus*, which reaches 50% of AP. *Pterocarya* is the only other temperate tree to maintain a consistent pollen curve. *Cyclobalanopsis* frequencies are unchanged from the previous zone but *Castanopsis*/*Lithocarpus* percentages fall sharply, so that the subtropical component of AP is much reduced. Coniferous tree values are little changed from zone DS-a. NAP percentages dominate the total terrestrial pollen sum, with Poaceae (<40 μm) and Cyperaceae contributing almost all, only *Artemisia* being significant among the other herb types. Spore and NPP taxa are little changed from zone DS-a, the same wetland types present in the same proportions, although *Mougeotia* (HdV-313), *Gyrotrix hermaphroditus* (HdV-353A) and HdV-123, all wetland types, increasing in importance. Microcharcoal percentages are hardly increased from the previous zone.

Zone DS-c (242.5–187.5 cm).

In this zone, the start of which has a mean calibrated date of 1575 ± 129 ^{14}C yr BP, total AP frequencies fall initially to about 20% of total terrestrial pollen, before recovering slightly. *Cyclobalanopsis* frequencies are reduced, and subtropical tree abundance falls towards the end of the zone, although substantial peaks of Moraceae pollen occur. The greatest decline is shown by *Quercus*/*Lepidobalanus*, as its percentages are halved, being replaced mainly by other warm temperate trees and shrubs, primarily *Ulmus*/*Zelkova*, *Alnus*, *Betula* and *Salix*. Coniferous trees, Cupressaceae, *Pinus* and Taxodiaceae, increase from 20% to 40% of total AP as the zone progresses. NAP pollen rises to as much as 80% of total terrestrial pollen with Poaceae (<40 μm) and Cyperaceae still major contributors. They are joined, however, by greatly increased values for *Artemisia* and Poaceae (>40 μm), with Chenopodiaceae, Cruciferae (Brassicaceae), Compositae, Apiaceae and *Plantago* becoming important. Some of these herbs are likely to be non-wetland types, while *Pteridium* appears and maintains high values throughout the zone. Aquatic herbs *Typha*/*Sparganium*, *Potamogeton* and *Myriophyllum* all show much increased percentages, and a peak of *Ceratopteris* occurs. Wetland NPPs remain important, particularly *Gloeotrichia*, *Spirogyra* (HdV-130), *Mougeotia* and HdV-128, with *Zygnema* returning to the assemblage in high values. Peaks of new types *Aphanizomenon* cf. *gracile* (HdV-600) and *Botryococcus* (HdV-766) occur in mid-zone. Several non-wetland types appear or increase, notably *Chaetomium* (HdV-7A), Sordariaceae (HdV-55A), *Cercophora* (HdV-122), *Coniochaeta* cf *ligniaria* (HdV-172), *Glomus* (HdV-207) and *Podospora* (HdV-368). High frequencies of microcharcoal occur throughout the zone.

Zone DS-d (187.5–172.5 cm).

In this zone, which starts at about 1184 ± 96 ^{14}C yr BP, there is an increase in tree and shrub pollen frequencies, returning to almost 40% of total terrestrial pollen. Rises in frequency for *Quercus*/*Lepidobalanus*, *Fagus*, *Carpinus* and Moraceae mainly account for the rise, although some taxa including Oleaceae, *Castanea* and *Celtis* appear or increase their contribution. Subtropical trees continue to decline, particularly *Cyclobalanopsis*. Both size classes of Poaceae are reduced in value, particularly those >40 μm, as are most taxa indicative of open dry ground, Ranunculaceae ceasing to be recorded. *Artemisia* declines, but remains important. Aquatic pollen frequencies remain unchanged, as do most spores although *Pteridium* percentages rise. Significant fluctuations occur in the NPP assemblage with major contributors in the previous zone, *Glomus*, *Cercophora*, *Coniochaeta* cf *ligniaria*, no longer recorded.or greatly diminished. Some wetland NPPs fall sharply, particularly *Zygnema* and *Spirogyra*, while other wetland taxa rise sharply, notably HdV-119, HdV-121 and HdV-306. Microcharcoal frequencies fall sharply.

Zone DS-e (172.5–142.5 cm).

In this zone, which ends at about 821 ± 87 ^{14}C yr BP, tree and shrub frequencies continue to rise gradually, reaching above 40% of total terrestrial pollen. Subtropical and coniferous values mostly remain steady, although *Pinus* increases, and warm temperate taxa account for the modest rise, mainly because of a rise in *Quercus*/*Lepidobalanus*. Most other arboreal taxa remain unchanged, except *Carpinus* and *Pterocarya* which are almost no longer recorded. There are few changes in the herb pollen record, and the small overall decline in total herb frequences is accounted for by a major fall in Poaceae (<40 μm). *Artemisia* and Cruciferae percentages increase substantially. Aquatic herb pollen values are little changed, while among the spores *Ceratopteris* increases while *Pteridium* falls. Fluctuations in the NPP assemblage include major rises in *Zygnema*, *Spirogyra* and *Mougeotia*. While *Pediastrum* and *Botryococcus* rise after minima in the previous zone. Microcharcoal frequencies continue to fall.

Zone DS-f (142.5–125 cm).

The uppermost zone records a rise in arboreal pollen percentages to almost 60% of total terrestrial pollen, caused mainly by increases in the coniferous taxa Cupressaceae, *Pinus* and Taxodiaceae, although warm temperate types *Fagus* and *Pterocarya* also show moderate rises. *Quercus*/*Lepidobalanus* falls as a percentage of total arboreal pollen, but is unchanged as a percentage of total terrestrial pollen. Subtropical tree representation is very low except for Moraceae which maintains substantial percentages. All herb pollen taxa are reduced in frequency, although low levels of *Artemisia* and Cruciferae are maintained. Poaceae (>40 μm) is no longer recorded, and Poaceae (<40 μm) falls to its lowest frequencies of the whole diagram. Aquatic herb types are reduced, caused by a significant fall in percentages of *Typha*/*Sparganium*. Apart from undifferentiated Filicales, spores are almost absent. NPP types are greatly reduced in diversity, and are contributed mainly by HdV-128, with low frequencies of several other aquatic and wetland types. Microcharcoal falls to very low levels.

Highlights

We investigate environmental change during the last two and a half millennia at Lake Dianshan in the Yangtze coastal lowlands, eastern China

Pollen, non-pollen palynomorphs, microcharcoal and AMS radiocarbon analyses are used

After withdrawal of estuarine conditions freshwater wetlands of varying type became established

From about 1500 cal. yr B.P. sub-tropical and warm temperate woodlands were replaced by mainly cool temperate and coniferous trees

A major episode of deforestation and ‘paddy’ rice agriculture occurred between ca. 1500 and 1200 cal. yr B.P.

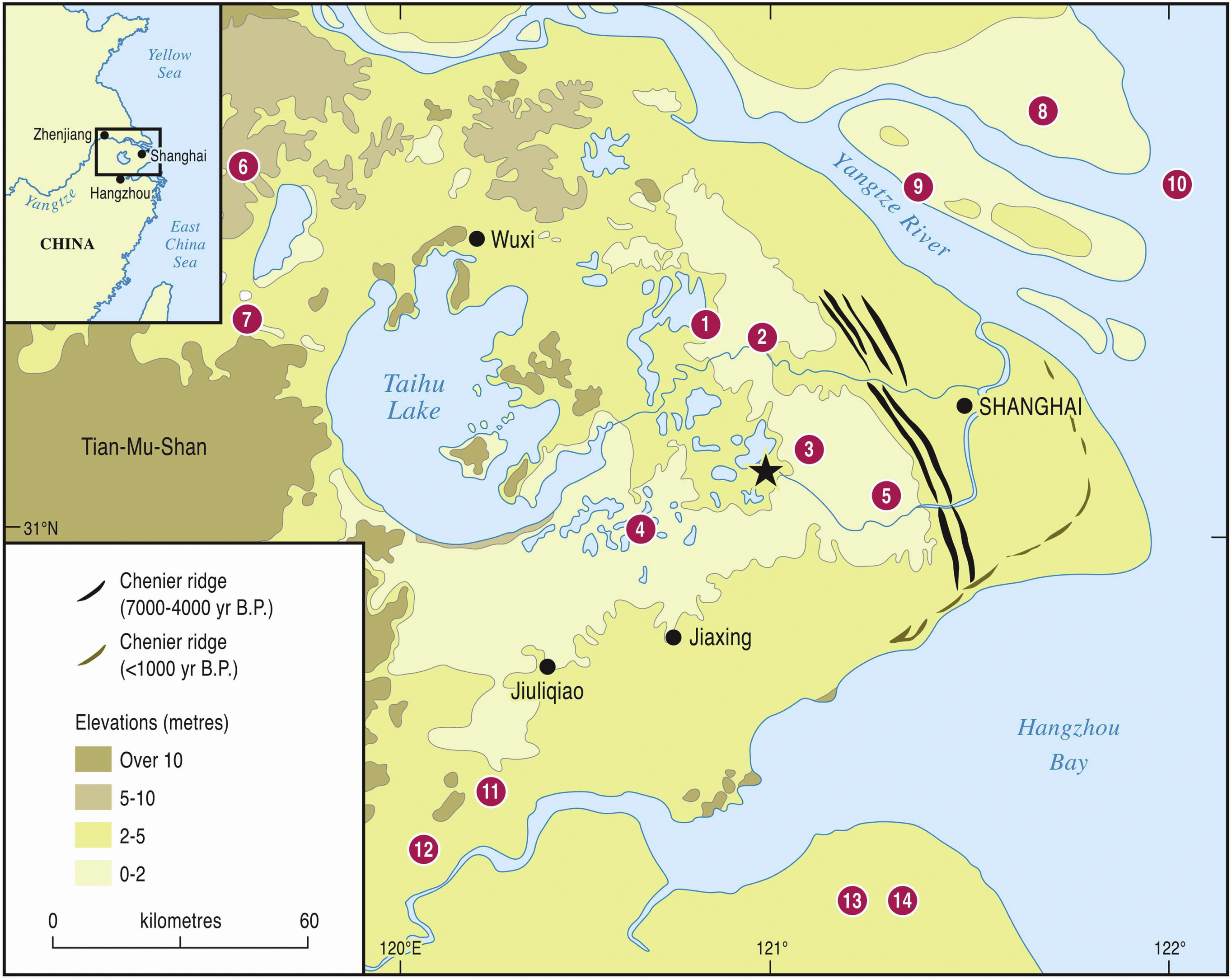
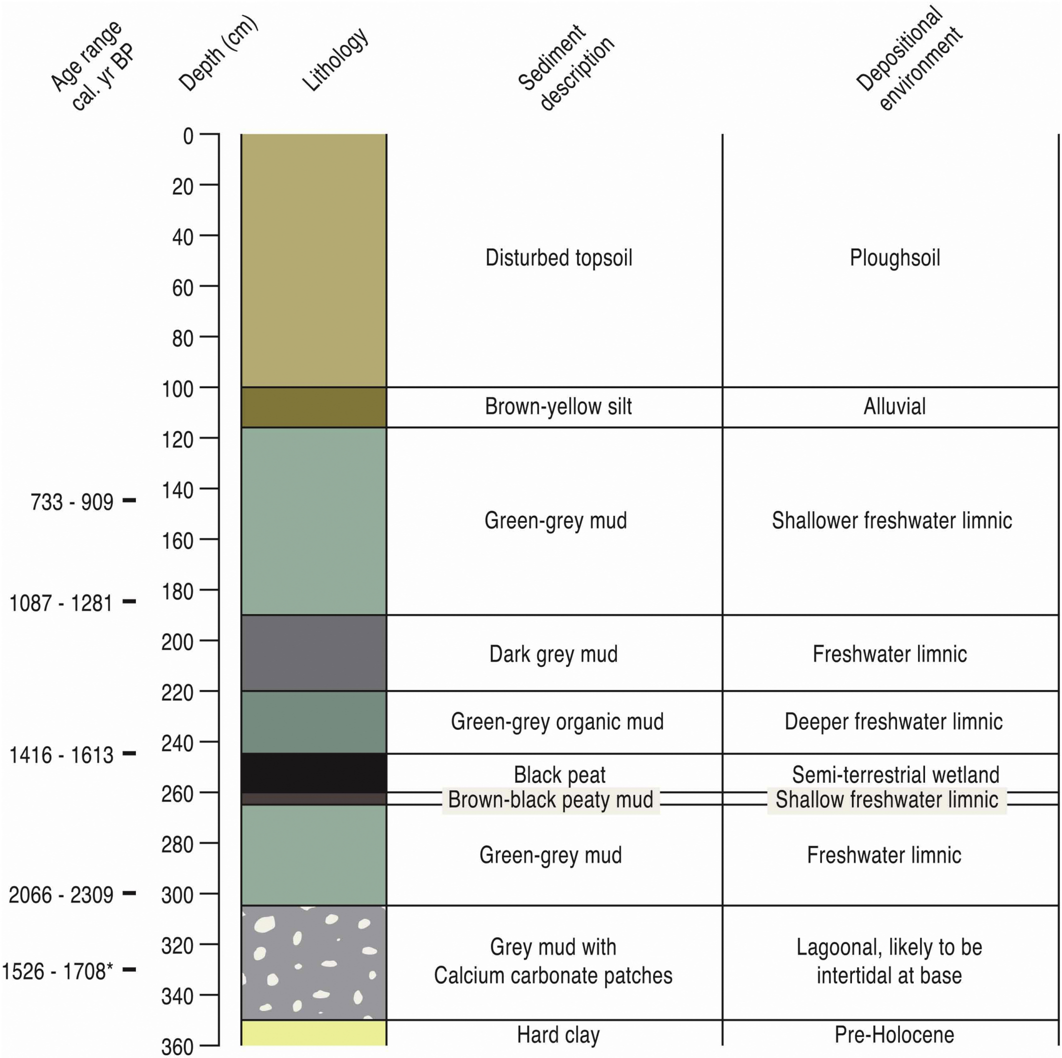

Yellow Sea
Zhenjiang
Shanghai
Hangzhou
Yangtze
CHINA
East China Sea
Wuxi
Taihu Lake
Tian-Mu-Shan
Yangtze River
SHANGHAI
Jiaxing
Jiuliqiao
Hangzhou Bay
31°N
120°E
121°
122°
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Chenier ridge (7000-4000 yr B.P.)
Chenier ridge (<1000 yr B.P.)
Elevations (metres)
Over 10
5-10
2-5
0-2
0
kilometres
60

Figure 1



Age range cal. yr BP
Depth (cm)
Lithology
Sediment description
Depositional environment
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
733 - 909
1087 - 1281
1416 - 1613
2066 - 2309
1526 - 1708*
Disturbed topsoil
Ploughsoil
Brown-yellow silt
Alluvial
Green-grey mud
Shallower freshwater limnic
Dark grey mud
Freshwater limnic
Green-grey organic mud
Deeper freshwater limnic
Black peat
Semi-terrestrial wetland
Brown-black peaty mud
Shallow freshwater limnic
Green-grey mud
Freshwater limnic
Grey mud with
Calcium carbonate patches
Lagoonal, likely to be
intertidal at base
Hard clay
Pre-Holocene

Figure 2

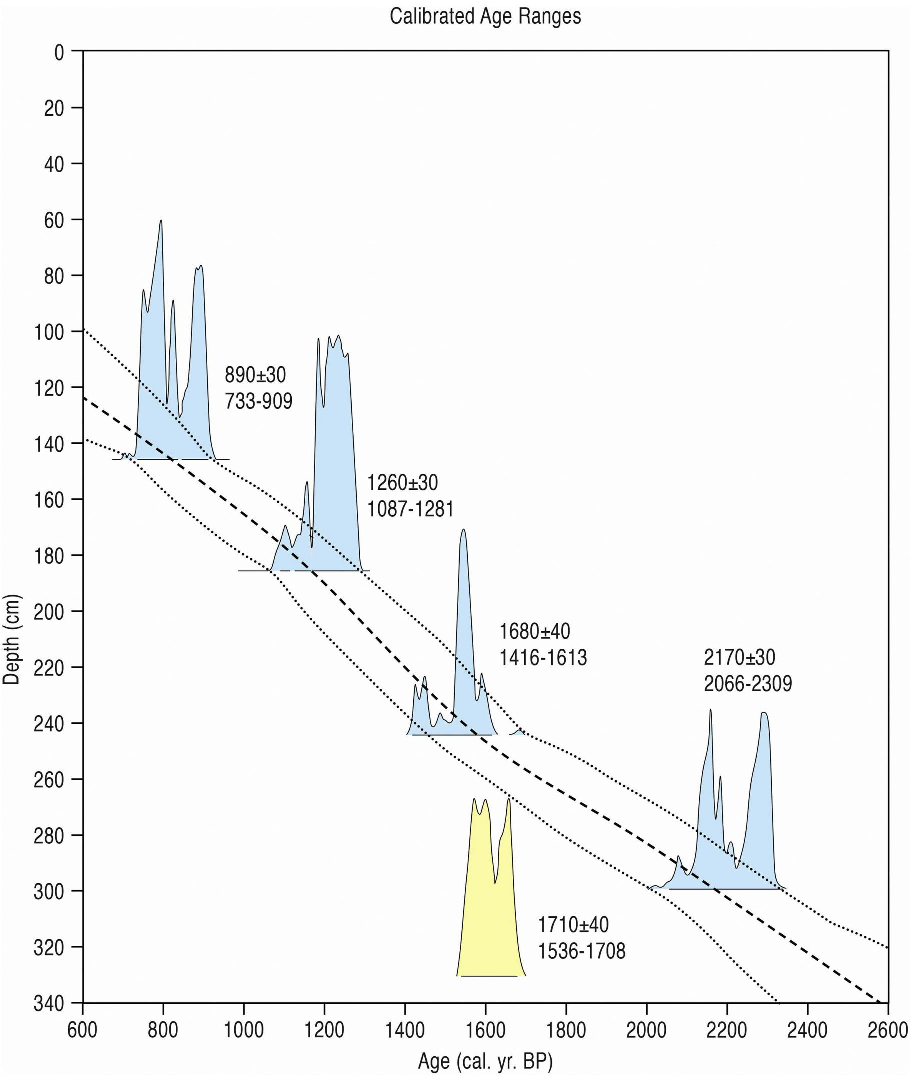

Calibrated Age Ranges
890±30
733-909
1260±30
1087-1281
1680±40
1416-1613
2170±30
2066-2309
1710±40
1536-1708
Depth (cm)
Age (cal. yr. BP)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600

Figure 3

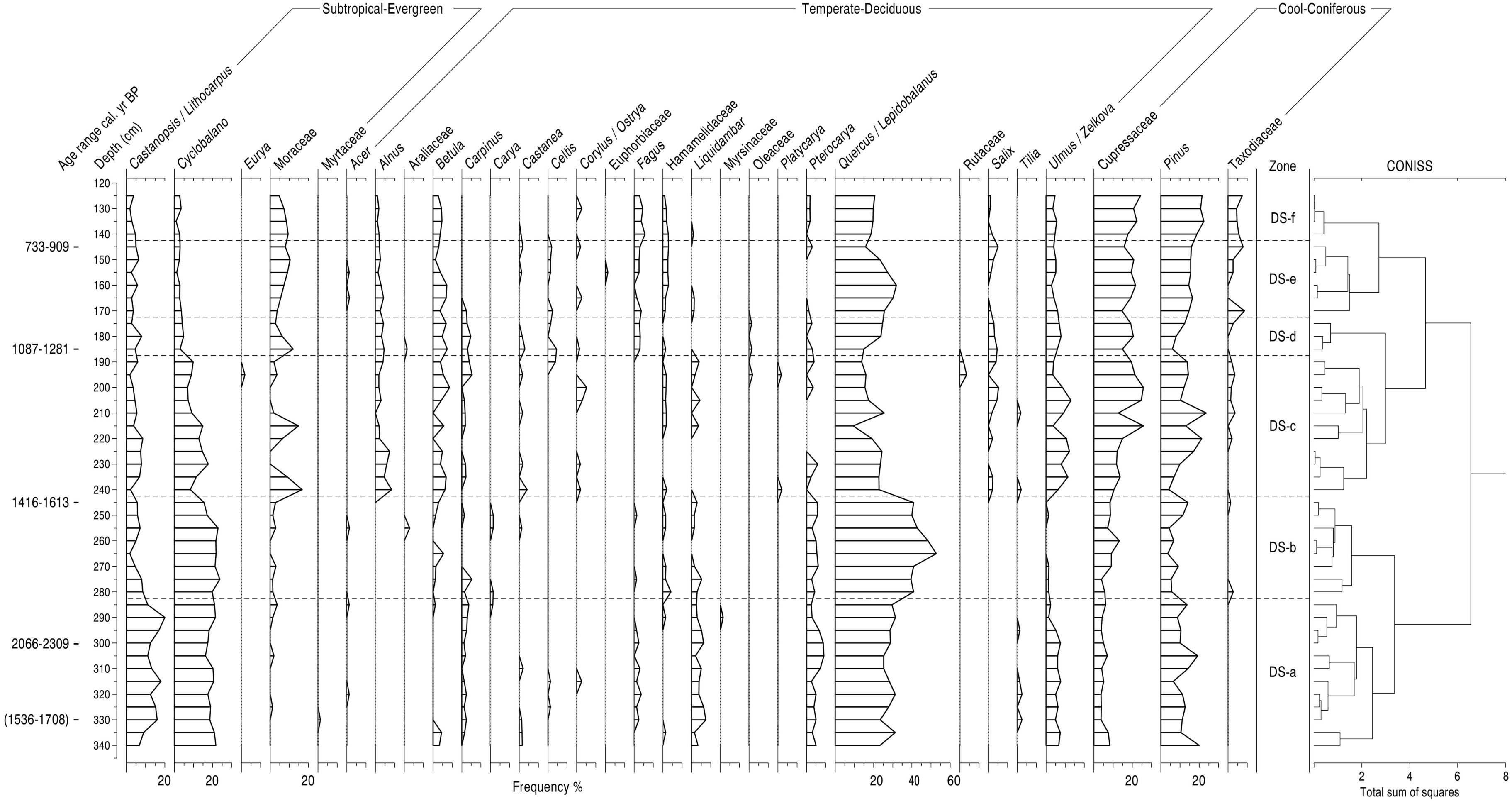

Subtropical-Evergreen
Temperate-Deciduous
Cool-Coniferous
Age range cal. yr BP
Depth (cm)
Castanopsis / Lithocarpus
Cyclobalano
Eurya
Moraceae
Myrtaceae
Acer
Alnus
Araliaceae
Betula
Carpinus
Carya
Castanea
Celtis
Corylus / Ostrya
Euphorbiaceae
Fagus
Hamamelidaceae
Liquidambar
Myrsinaceae
Oleaceae
Platycarya
Pterocarya
Quercus / Lepidobalanus
Rutaceae
Salix
Tilia
Ulmus / Zelkova
Cupressaceae
Pinus
Taxodiaceae
Zone
CONISS
733-909
1087-1281
1416-1613
2066-2309
(1536-1708)
DS-f
DS-e
DS-d
DS-c
DS-b
DS-a
Frequency %
Total sum of squares

Figure 4

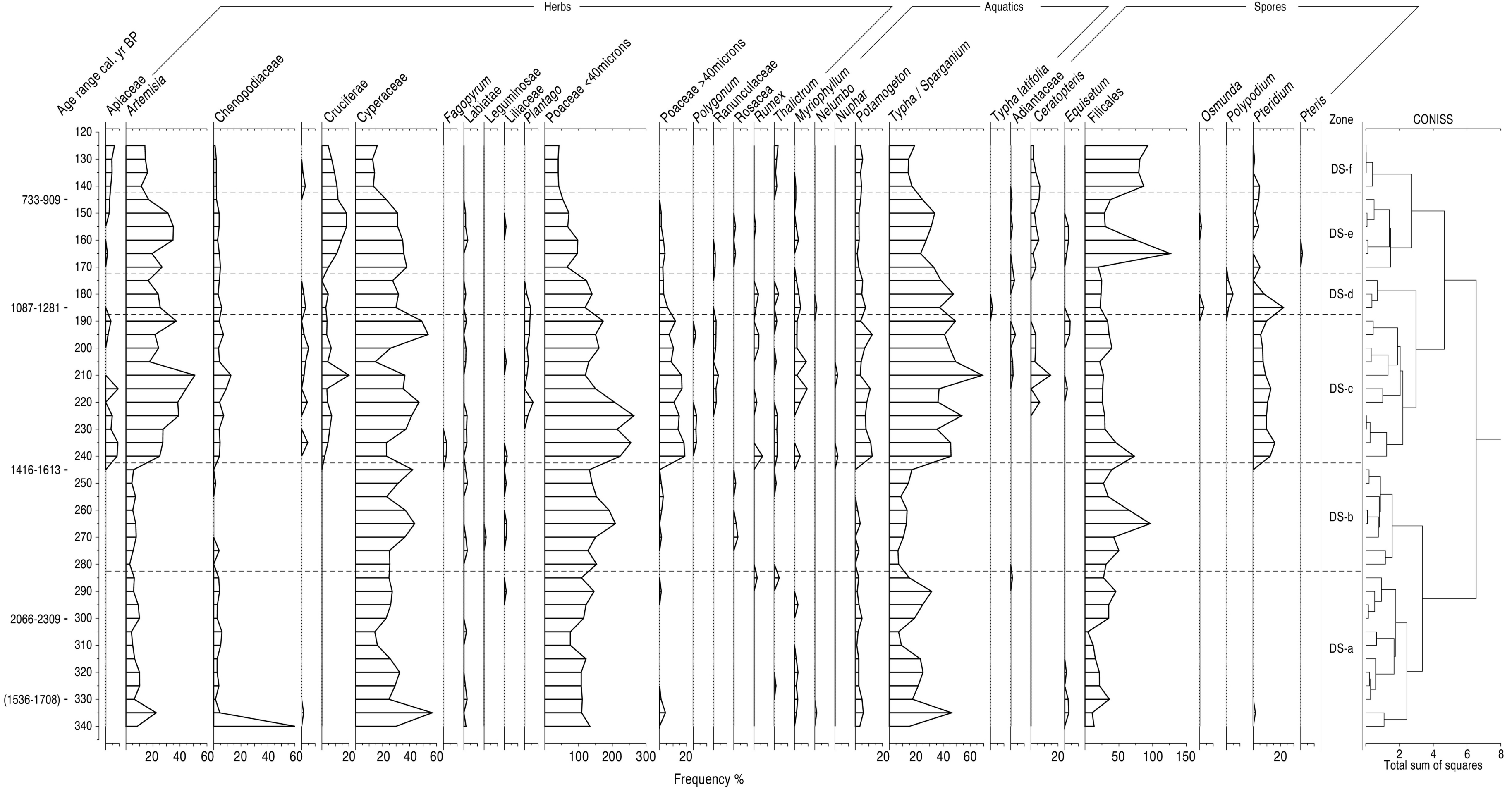

Herbs
Aquatics
Spores
Age range cal. yr BP
Apiaceae
Artemisia
Chenopodiaceae
Cruciferae
Cyperaceae
Fagopyrum
Labiatae
Leguminosae
Liliaceae
Plantago
Poaceae <40microns
Poaceae >40microns
Polygonum
Ranunculaceae
Rosacea
Rumex
Thalictrum
Myriophyllum
Nelumbo
Nuphar
Potamogeton
Typha / Sparganium
Typha latifolia
Adiantaceae
Ceratopteris
Equisetum
Filicales
Osmunda
Polypodium
Pteridium
Pteris
Zone
CONISS
733-909
1087-1281
1416-1613
2066-2309
(1536-1708)
DS-f
DS-e
DS-d
DS-c
DS-b
DS-a
Frequency %
Total sum of squares

Figure 5

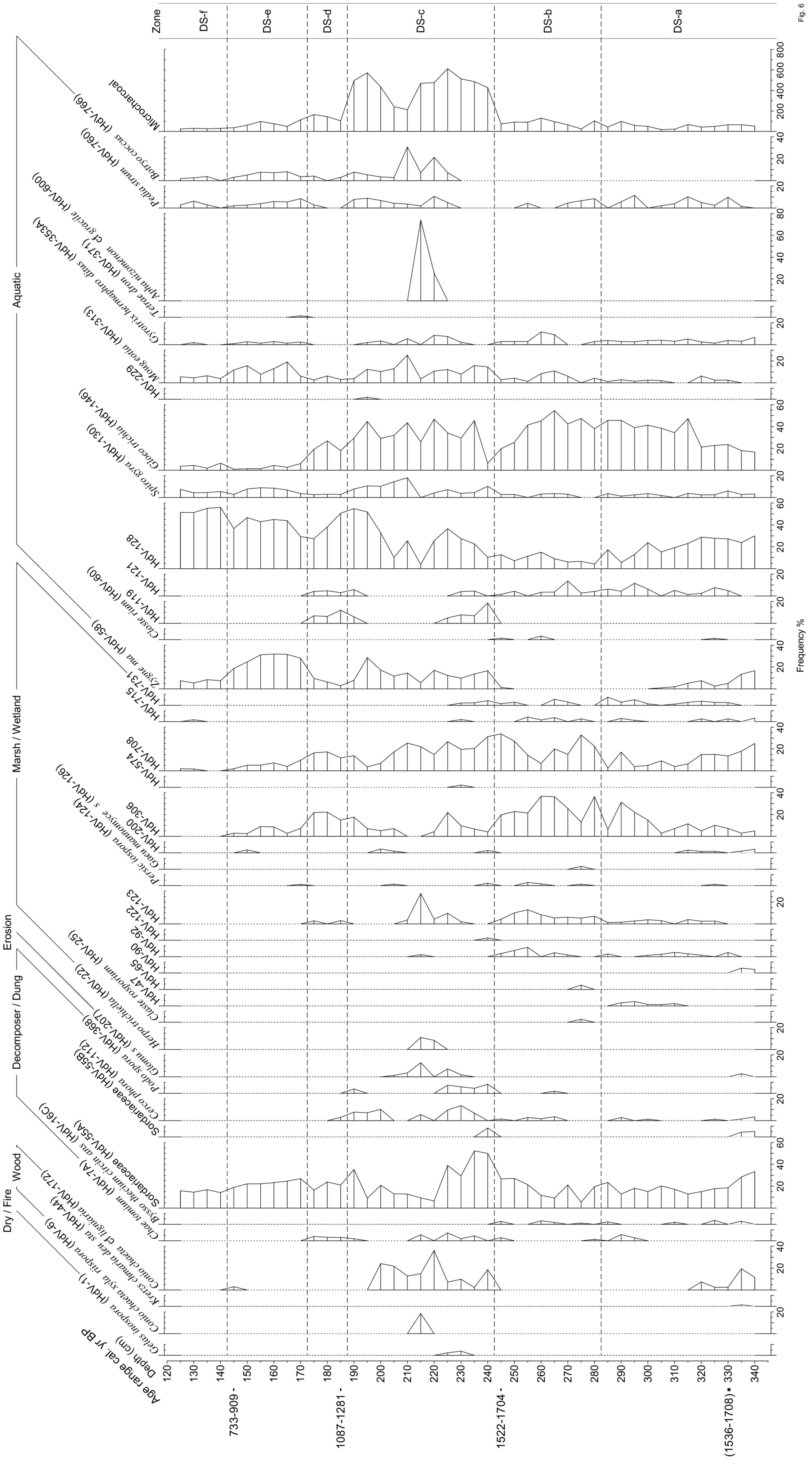


Fig. 6
Zone
DS-f
DS-e
DS-d
DS-c
DS-b
DS-a
Aquatic
Marsh / Wetland
Erosion
Decomposer / Dung
Wood
Dry / Fire
Microcharcoal
Frequency %
Depth (cm)
Age range cal. yr BP
733-909 -
1087-1281 -
1522-1704 -
(1536-1708) ▪

Figure 6

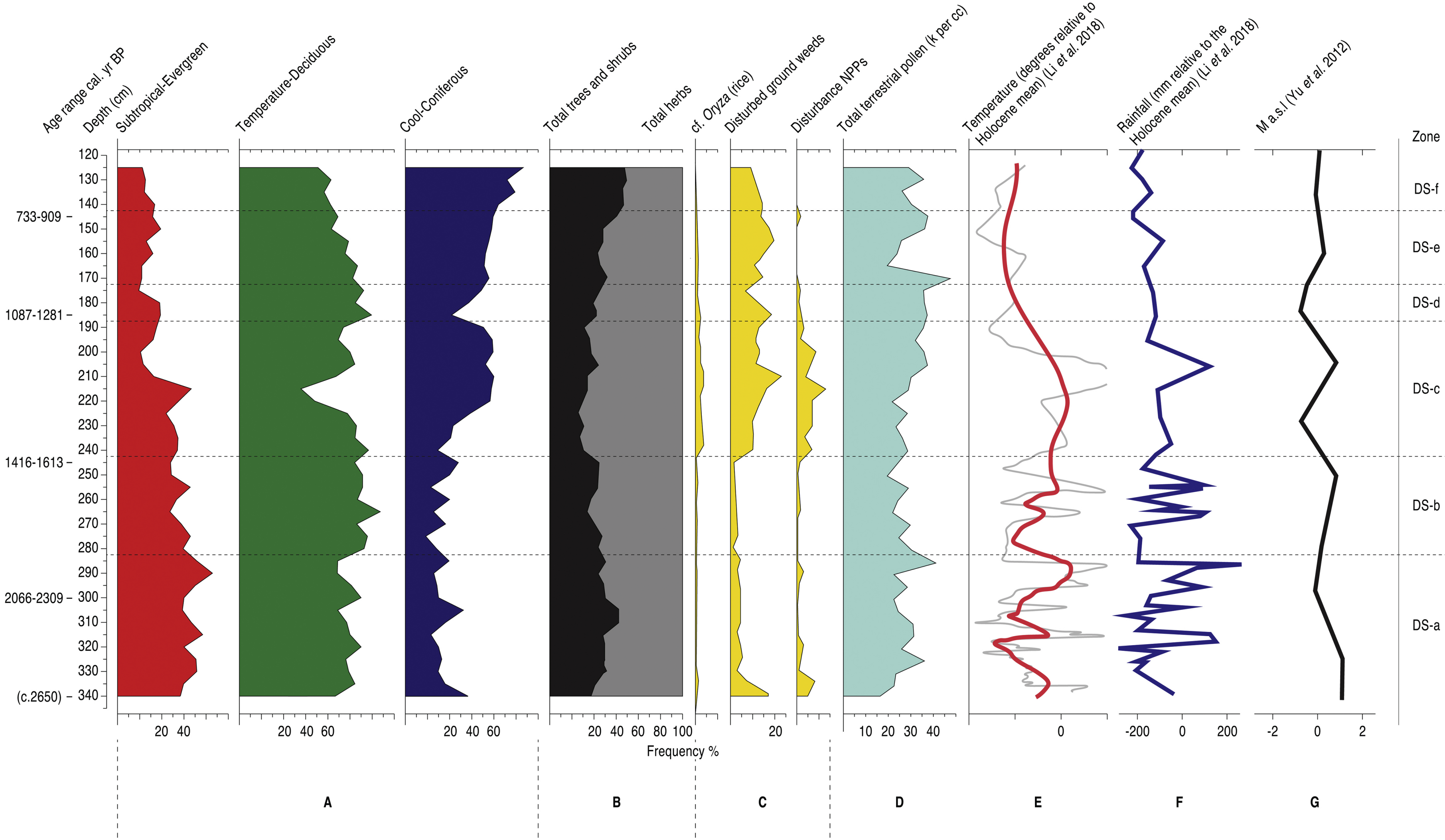

Age range cal. yr BP
Depth (cm)
Subtropical-Evergreen
Temperature-Deciduous
Cool-Coniferous
Total trees and shrubs
Total herbs
cf. Oryza (rice)
Disturbed ground weeds
Disturbance NPPs
Total terrestrial pollen (k per cc)
Temperature (degrees relative to Holocene mean) (Li et al. 2018)
Rainfall (mm relative to the Holocene mean) (Li et al. 2018)
M a.s.l (Yu et al. 2012)
Zone
733-909
1087-1281
1416-1613
2066-2309
(c.2650)
DS-f
DS-e
DS-d
DS-c
DS-b
DS-a
Frequency %
A
B
C
D
E
F
G

Figure 7