Postglacial changes in the Asian summer monsoon system: a pollen record from the eastern margin of the Tibetan Plateau

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A new pollen record constrained by 32 AMS radiocarbon dates from the Hongyuan peatland in the Zoige Basin reveals the long-term dynamics of an alpine wetland ecosystem on the eastern margin of the Tibetan Plateau over the last 13 500 years. Changes in pollen assemblages and influxes suggest that local vegetation has experienced three distinct stages, from alpine coniferous forest–meadow (13 500–11 500 cal. a BP), through alpine coniferous forest (11 500–3000 cal. a BP), back to alpine coniferous forest–meadow (3000 cal. a BP–present). This record reflects an ecosystem response along a transition zone where the South Asian and East Asian monsoon systems may have had different palaeoclimatic influences. A comparison of this record with other pollen records across the Tibetan Plateau shows common features with regard to large-scale Holocene climatic changes, but highlights a

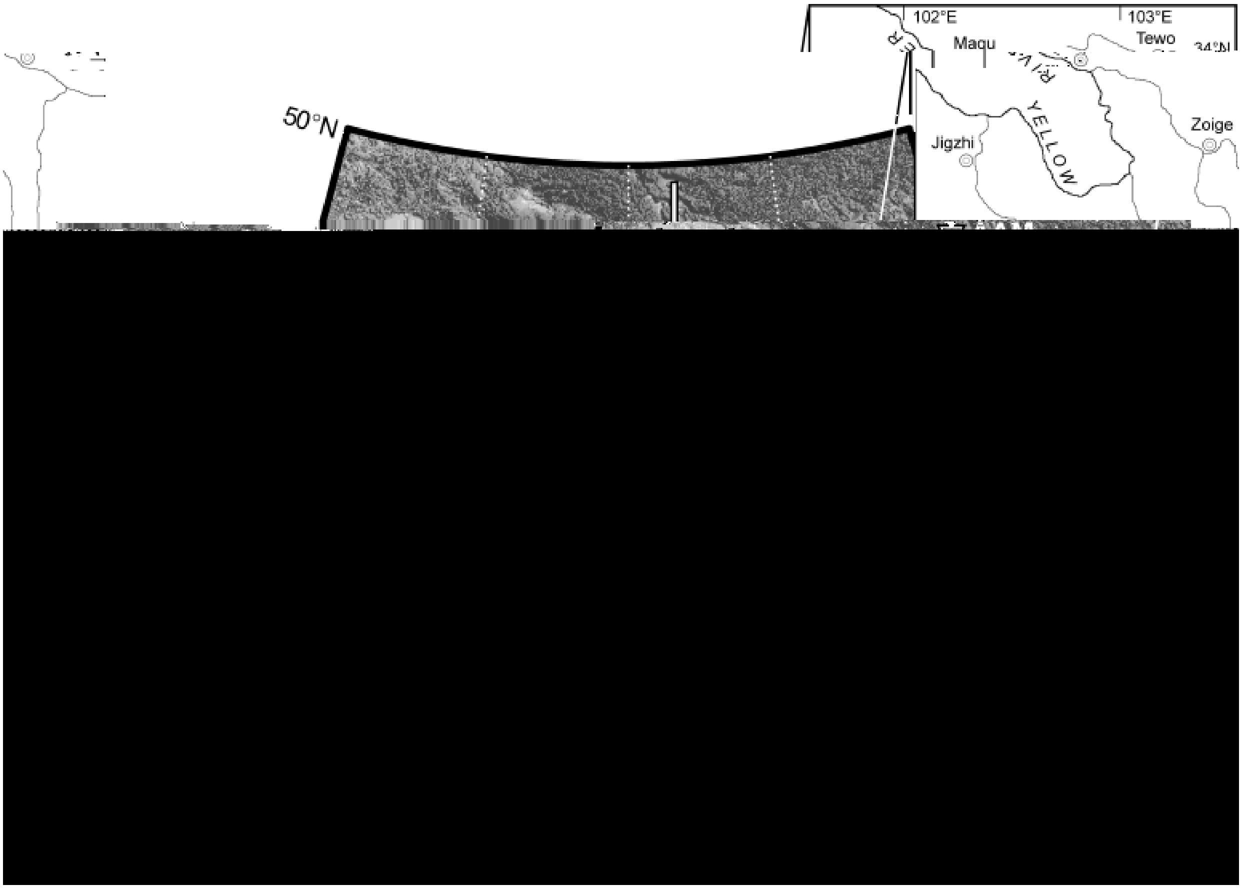

Fig. 1. Map showing the locations of Holocene pollen records from the Tibetan Plateau. 1 = Hongyuan peatland (this study); 2 = Lake Shayema (Jarvis 1993); 3 = Lake Qinghai (Shen J *et al.* 2005); 4 = Lake Hurleg (Zhao *et al.* 2007); 5 = Lake Naleng (Kramer *et al.* 2010); 6 = Ren Co (Tang *et al.* 2004); 7 = Lake Haideng (Tang *et al.* 2004); 8 = Lake Zigetang (Herzschuh *et al.* 2006); 9 = Selin Co (Sun *et al.* 1993); 10 = Lake Sumxi (Van Campo & Gasse 1993); 11 = Bangong Co (Van Campo *et al.* 1996). The right upper map shows the detail of Hongyuan peat coring site (solid circle) in the Zoige Basin, east Tibetan Plateau. AAM = Arctic airmass; WJS = westerly jet stream; SAM = South Asian monsoon; EAM = East Asian monsoon.

temporal resolution (e.g. Morrill *et al.* 2003; Colman *et al.* 2007; Yu *et al.* 2009). This paper focuses on pollen records from the northern extent of the Asian monsoon domain, as both the production and transport of pollen in this area are directly related to the summer monsoon during the growing season, which is also an important limiting factor of the alpine ecosystem on the Tibetan Plateau (Yu *et al.* 2001).

This study documents a record of Holocene climatic changes in the transition zone along the eastern margin of the Tibetan Plateau (Fig. 1) that spans the last 13 500 years. Our record is based on detailed palynological studies and high-resolution AMS radiocarbon dating of a 4.5-m-long peat and clay sequence from the Hongyuan peatland in the Zoige Basin (Fig. 1). The Hongyuan peatland is the world's largest high-altitude marsh, covering an area of about 500 000 ha with a thickness of peat varying from 3 to 5 m (Thelaus 1992; Björk & Thelaus 1996). Previous studies reveal that sedge (Cyperaceae) peat accumulated continuously in the Zoige Basin during the Holocene under cold and wet conditions (Zhou *et al.* 2002). Records of peat accumulation contain useful information about past climatic changes (Wang *et al.* 1993, 2004; Yan *et al.* 1999; Hong *et al.* 2003). The goal of this work is essentially to refine the chronology of climatic changes during the Holocene. This record also complements other palaeoclimatic records from the Tibetan Plateau, which, taken together, may enhance our knowledge about the dynamics of the Asian monsoon systems across the Tibetan Plateau during the Holocene.

Study area and site description

The Zoige Basin (latitude 32°10′–34°10′N, longitude 101°45′–103°25′E) is located on the eastern edge of the Tibetan Plateau, ~2 km southwest of Hongyuan, the capital of Hongyuan County (Fig. 1). It is an intermontane basin controlled by three major fault zones that strike WNW, NE and NW. The average elevation of the basin is 3400 m a.s.l. Previous drillings reveal that a large freshwater lake existed within the basin between about 900 and 30 ka BP (Wang & Xue 1997; Chen *et al.* 1999), leaving thick sediments (~300 m) with an areal extent of about 6300 km^2. Peat initiation (Yan *et al.* 1999) suggests that the basin was drained at about 30 ka BP owing to the piracy of the Yellow River, when it cut through the mountain barrier on the east, and flowed out along a zigzag channel (Sun & Zhang 1987).

Temperature and precipitation are positively correlated in the Zoige Basin and both exhibit distinctly seasonal variations, characteristic of a monsoonal climate. Annual mean temperature is ~1 °C, with the lowest monthly mean temperatures of −10.9 °C in January and the highest monthly mean temperature of 11 °C in July. The annual mean precipitation is ~700 mm, most of which occurs in summer months, providing favourable climatic conditions for sedge growth and thus peat accumulation.

Following a climate gradient, vegetation on the Tibetan Plateau exhibits distinct zonality. The Zoige Basin is located on the ecotones of temperate steppe, high-cold meadow and temperate desert, and local vegetation shows remarkable vertical variations (Wu 1980). For example, most of the study area is vegetated by high-cold meadow, where *Carex muliensis* and *Kobresia humilis* are the two major species that form peat. Other species include *Polygonum viviparum* and *Chamaesium paradoxum*. Alpine shrub-meadow covers the mountains above 3800 m a.s.1., whereas mountains between 3800 and 3000 m a.s.l. are covered by alpine coniferous forests composed mainly of *Picea purpurea*, *P. likiangensis* and *P. asperata* as well as of *Abies fabri* and *A. faxoniana*. Mixed forests with *Tsuga chinensis*, *Pinus densata*, *P. armandii*, *P. tabulaeformis*, *Betula platyphylla*, *Populus davidiana*, *Quercus liaotungensis*, *Q. baronii*, *Tilia intonsa*, *Fraxinus chinensis*, *Acer davidii* and *Hippophae rhamnoides* occur below 3000 m a.s.l.

Methods

An undisturbed 4.5-m-long sequence of monolithic peat and clay complex was recovered from the Hongyuan peatland in the Zoige Basin (32°46′42″N, 102°31′00″E), by digging a trench and pushing a tin box corer into the cleaned exposure. The core was logged in the Xi'an State Key Laboratory of Loess and Quaternary Geology using greyscale measurements. The greyscale values exhibit cyclic changes parallel to total organic carbon (TOC) content along the core. Sediment description, detailed results of greyscale, and the TOC data have been published elsewhere (Zhou *et al.* 2002).

Bulk peat samples for radiocarbon dating from selected levels were pretreated with 10% HCl and NaOH solutions, and then rinsed repeatedly with distilled water through a 60-μm mesh sieve to remove fine sedge roots. To minimize the 'hard water effect', we endeavoured to date remains of emerged wetland herbs in this treeless swampy landscape. To this end, the residual peat cellulose and leaf fragments with sizes less than 180 μm were picked out and dried in an electric oven for radiocarbon dating. Details of this method are given in Zhou *et al.* (2002). Dating was conducted in the AMS Laboratory at the University of Arizona. The $\delta^{13}C$ value of these samples was also measured simultaneously to infer the source of these herbaceous remains in terms of C_3 versus C_4 plants. Radiocarbon dates were calibrated using the INTCAL 98 tree-ring data set using the CALIB 4.2 computer program (Stuiver *et al.* 1998). The calibrated ages are quoted with two standard deviation uncertainties. We formulated an age–depth model based on median-probability ages of the calibrated dates using the cubic-spline regression method (Heegaard *et al.* 2005).

The core was subsampled at various intervals for pollen analyses. For example, the sections above 1 m and below 4 m were sampled at 2–4 cm intervals, whereas the section in between was sampled at 8-cm intervals. Aliquot bulk samples of 5 cm^3 were processed following the guidelines of Berglund & Ralska-Jasiewiczowa (1986). Samples were pretreated with a 10% HCl solution to remove carbonates, and then treated with 10% NaOH in a hot water bath to get rid of humic and fulvic acids. Prior to these chemical treatments, one tablet of exotic *Lycopodium clavatum* with a known number of spores (e.g. 18 583 grains per tablet in this study) was added as marker grains to enable the calculation of fossil pollen concentrations expressed as grains cm^{-3} (Stockmarr 1971), which were then converted to pollen influxes by multiplying accumulation rates known from age–depth model.

Terrestrial pollen taxa, such as trees, shrubs and upland herbs, are used to infer regional-scale changes in vegetation. Their relative abundance is expressed as a percentage based on the sum of all palynomorphs excluding wetland herbs, algae and ferns, which represent local vegetation and thus can provide complementary information about past climatic changes in terms of water-level fluctuations. For these local taxa, their abundances are relative to the sum of all palynomorphs. Given the poor pollen concentrations in this treeless landscape, several slides were made for each sample, and at least 600 pollen grains were counted to ensure statistical significance for the relative abundance of pollen taxa. For most of the samples, this number

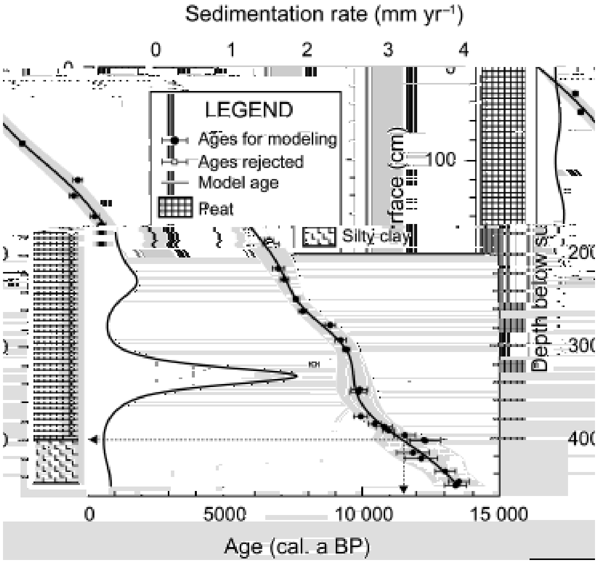

Fig. 2. Biplot of calibrated AMS radiocarbon dates against depth, and calculated sedimentation rates. The heavy line is the age–depth model formulated by the cubic-spline fit. The grey-shaded envelope denotes the 95% confidence level. Arrows indicate the timing of peat initiation at this coring site.

Results

Stratigraphy, chronology and sedimentation rates

Our trenching in the Zoige Basin reveals a peat–clay dual complex (Fig. 2). We stopped at about 4.5 m depth because of the waterlogged condition of the trench. Sediments below 4.0 m are grey-green silty clay with abundant remains of leaves. The section above this level is brownish peat, comprising abundant undecomposed sedge (Cyperaceae) remains. Dark-brown bands occur frequently along the core, revealing repeated changes in redox conditions, probably associated with fluctuations in water level (Zhou *et al.* 2002). Our coring reveals that these textural characteristics are similar to those in adjacent bogs (Yan *et al.* 1999; Hong *et al.* 2003).

A total of 32 AMS radiocarbon dates were obtained (Table 1). The average value of $\delta^{13}C$ of these samples is about −27‰, slightly above the end-member value (−30‰) of C_3 plants. This difference implies the presence of the radiocarbon 'hardwater effect' in this system, which is estimated to be about 50 years according to the core-top age defined by regression analyses. To obtain a precise chronology, this error was removed

Table 1. Radiocarbon dates of the Hongyuan peat section, east Tibetan Plateau.

Lab access ID	Depth (cm)	Materials dated	$\delta^{13}C$ (‰ vs. PDB)	^{14}C age (a BP)	Error (1σ)	2σ calibrated age range (a BP)
AA-29614	2	Peat cellulose	−27.39	2245	50	2350–2130
AA-29612	30	Peat cellulose	−25.00	1540	40	1530–1330
AA-29611	50	Peat cellulose	−27.10	1705	45	1720–1520
AA-29610	82	Peat cellulose	−27.57	2725	50	2950–2750
AA-29608	121	Peat cellulose	−27.85	4310	55	5050–4700
AA-29609	138	Peat cellulose	−28.11	4235	55	4880–4570
AA-29605	160	Peat cellulose	−27.40	4815	55	5660–5330
AA-29604	169	Peat cellulose	−27.10	4970	55	5890–5590
AA-29603	186	Peat cellulose	−26.91	5810	65	6760–6440
AA-29602	190	Peat cellulose	−26.63	5840	110	6950–6350
AA-29607	216	Peat cellulose	−27.25	6040	60	7160–6720
AA-29606	228	Peat cellulose	−27.06	6280	65	7330–7000
AA-29601	249	Peat cellulose	−27.43	6745	60	7690–7480
AA-29600	262	Peat cellulose	−27.11	7035	65	7970–7690
AA-29599	277	Peat cellulose	−27.68	7985	70	9030–8630
AA-29598	293	Peat cellulose	−27.56	8200	70	9410–9010
AA-29597	303	Peat cellulose	−26.91	8455	70	9550–9280
AA-29596	319	Peat cellulose	−27.14	7480	75	8410–8060
AA-29594	346	Peat cellulose	−27.05	8835	90	10 200–9600
AA-29593	349	Peat cellulose	−27.02	8775	80	10 150–9550
AA-29592	375	Peat cellulose	−27.29	8850	70	10 190–9690
AA-29591	383	Peat cellulose	−26.93	9255	90	10 680–10 220
AA-31639	386	Peat cellulose	−26.71	9460	70	11 100–10 500
AA-31640	390	Peat cellulose	−27.27	9630	70	11 180–10 740
AA-31641	395	Peat cellulose	−27.38	9950	95	11 950–11 150
AA-31642	400	Leaf fragments	−27.66	10 315	70	12 850–11 650
AA-29590	401	Leaf fragments	−27.99	10 360	80	12 850–11 750
AA-29589	414	Leaf fragments	−26.83	10 185	100	12 450–11 250
AA-31643	420	Leaf fragments	−27.04	10 280	75	12 750–11 550
AA-29588	434	Leaf fragments	−27.38	11 040	95	13 400–12 650
AA-31644	445	Leaf fragments	−27.02	11 550	80	13 900–13 150
AA-29587	449	Leaf fragments	−26.91	11 395	85	13 800–13 000

systematically from the modelled ages. The calibrated ages are, with one exception, stratigraphically consistent along the core (Fig. 2), and provide a firm chronological framework for the past 13 500 years. According to the age–depth model, peat did not accumulate until 11 500 cal. a BP (Fig. 2), corresponding to regional climate amelioration following the Younger Dryas climatic event on the eastern margin of the Tibetan Plateau (Lister *et al.* 1991; Gasse & Van Campo 1994; Yan *et al.* 1999). Rates of peat accumulation continued to rise and culminated at about 9700 cal. a BP (Fig. 2), indicating a progressive increase of wetland biomass in response to the gradual strengthening of the summer monsoon (Jarvis 1993; Sirocko *et al.* 1993; Wang *et al.* 1999; Gupta *et al.* 2003; Morrill *et al.* 2003; Dykoski *et al.* 2005; Yu *et al.* 2009).

Pollen analysis

Pollen concentrations in this core are generally low, and for most of the samples only about 600 pollen grains were identified and counted. Nevertheless, this quantity is sufficiently statistically significant for pollen percentages to represent local vegetation (Yu *et al.* 2001). Furthermore, the local vegetation appears to have a low species diversity. The tree and shrub taxa are dominated by *Abies*, *Picea*, *Pinus*, *Tsuga*, *Betula* and Rosaceae. *Artemisia*, Asteraceae p.p., *Ephedra* and Poaceae are the major upland taxa. The wetland taxa are mainly Cyperaceae, *Myriophyllum*, *Ranunculus* and Umbellifereae. Relative abundances of these species vary along the core (Fig. 3), and their changes in influxes are presented in Fig. 4. A total of three pollen assemblage zones can be assigned numerically, based on changes in both pollen percentage and influx, and are referred to here as Z-1, Z-2 and Z-3.

Zone Z-1 (450–400 cm; 13 500–11 500 cal. a BP). – Pollen assemblages of this zone are dom

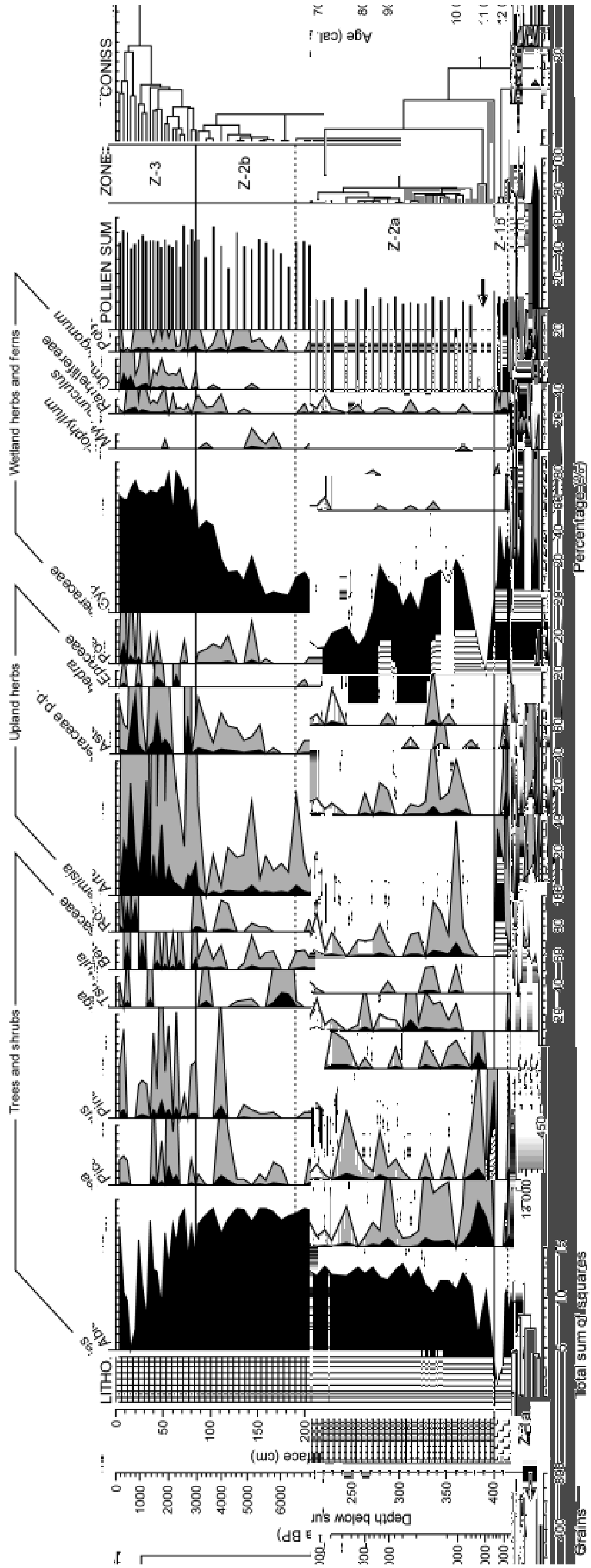

Fig. 3. Pollen percentage diagram for the Hongyuan peat core in the Zoige Basin, east Tibetan Plateau. The abundance of rare species is exaggerated by 10 times and indicated with hatching. Arrows indicate analysed levels with pollen counts lower than 200 grains.

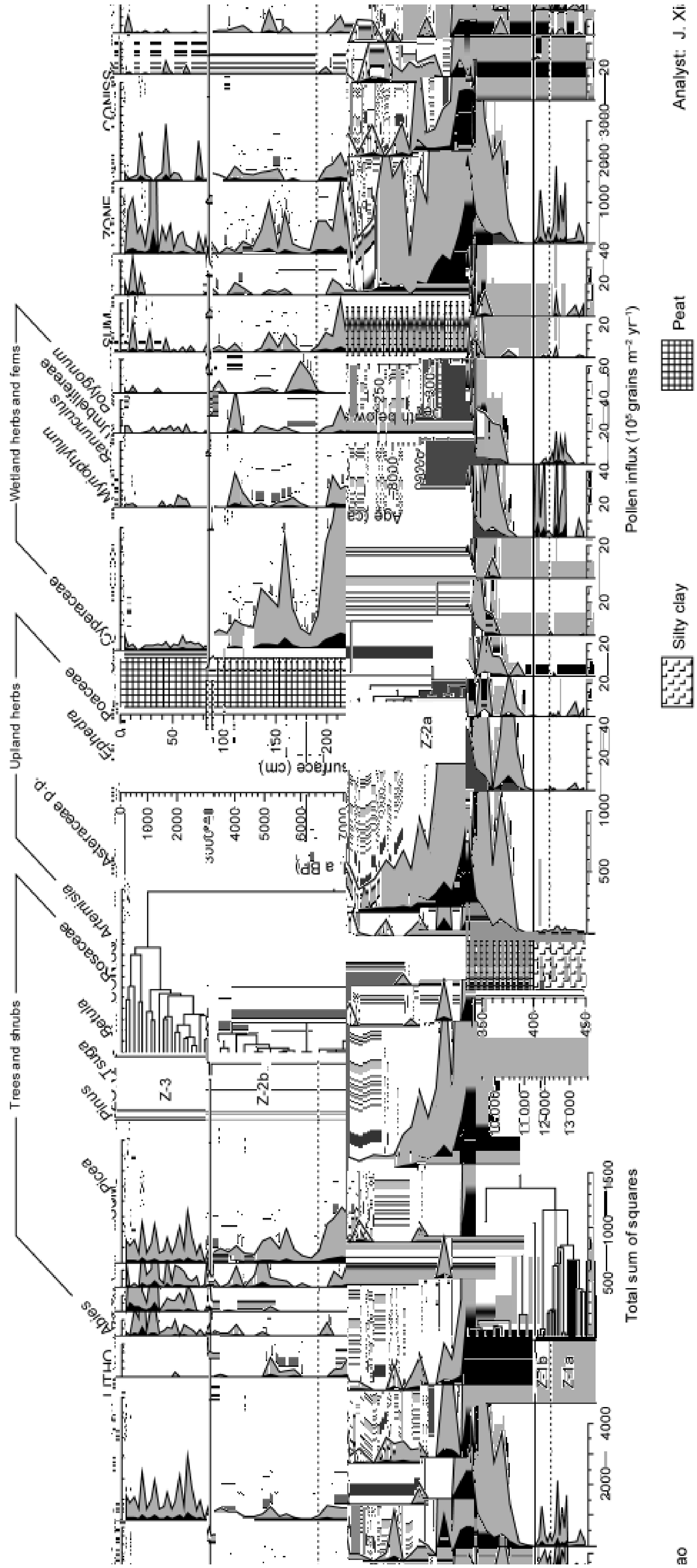

Fig. 4. Pollen influx diagram for the Hongyuan peat core in the Zoige Basin, east Tibetan Plateau.

shows a substantial reduction in tree pollen. Anthropogenic deforestation during the late Holocene has been reported in southwestern China (Dearing 2008), and traces of human activity have been found in the Lake Qinghai area (Rhode *et al.* 2007). This area should not be an exception, although archaeological evidence of human agricultural and/or pastoral activities during the late Neolithic Age and early dynastic period has not been reported to date. In summary, our pollen record shows that local vegetation has experienced three major stages.

Stage I (13 500–11 500 cal. a BP) – Alpine coniferous forest–meadow landscape. – The meadow community is dominated by *Artemisia* and Asteraceae p.p., which are the two major components of the high-cold meadow community that occurs on the western Tibetan Plateau today (Yu *et al.* 2001). *Abies*, along with other conifers and shrubs, appears to occur in the entire basin during this period (Yan *et al.* 1999). Stratigraphically, this stage is characterized by a lacustrine environment in this basin, representing cold and wet conditions that can be correlated with the Younger Dryas event, as observed in the Guliya ice-core record from the northwest Tibetan Plateau (Thompson *et al.* 1989) and in climate proxy records from the Chinese loess Plateau (Zhou *et al.* 1996, 1998, 2001).

Stage II (11 500–3000 cal. a BP) – Alpine coniferous landscape. – Local vegetation was dominated by *Abies*. The establishment of alpine coniferous forests in the catchment during this period is consistent with warm and wet conditions, as expected for the mid-Holocene climate optimum (An *et al.* 2000). Pollen percentage data indicate that the summer monsoon began to be enhanced immediately after the Younger Dryas stadial (Figs 3, 4). Note that this inference might be unreliable because of the possible existence of a sedimentary hiatus across the transition from silty clay to peat. However, pollen influx data indicate that the summer monsoon front did not reach this area until *c.* 10 800 cal. a BP, as supported by other studies elsewhere (e.g. Hong *et al.* 2003; Shen 2003; Shen *et al.* 2008).

Stage III (3000 cal. a BP–present) – Alpine coniferous forest–meadow landscape. – The gradual decreases in the value of *Abies* pollen, along with the expansion of upland herbs, indicate that alpine coniferous forest–meadow landscape was established in the catchment once again. This floristic change reveals a cooling trend during the late Holocene (Herzschuh *et al.* 2006), which can be correlated with the substantial weakening of the summer monsoon in this area (Jarvis 1993; Sirocko *et al.* 1993; Gupta *et al.* 2003; Morrill *et al.* 2003; Dykoski *et al.* 2005).

Other Holocene pollen records from the same basin show similar characteristics. For example, Yan *et al.* (1999) described four distinct stages of local vegetation succession over the past 14 200 years. Hong *et al.* (2003) described a similar pattern of climatic changes from this area based on $\delta^{13}C$ measurements of sedge cellulose, including single species. The timing of their isotopic record broadly corresponds to that of our record. Our record is also consistent with the pollen data of Shen C.M. *et al.* (2005), who described a long pollen record from the Hongyuan area. Their record documents 18 pollen zones that reflect climatic changes over the past 180 ka. The uppermost section of their core overlaps with our peat sequence and has a broadly similar pollen zonation, but it does not have .4(b)-.9(asin)TJ0f1.79I9(of)-occuraT(can)-258con-17319beth2frth2f-548.(

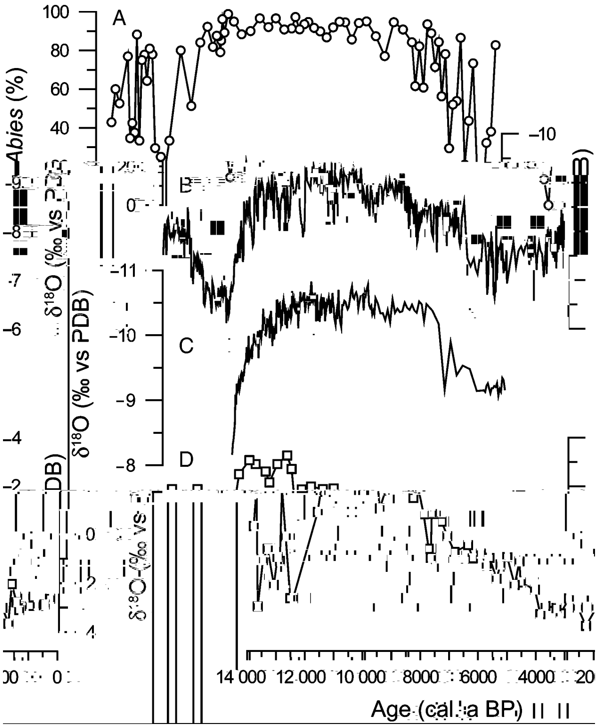

Fig. 5. Comparison of palaeoclimate records from the east Tibetan Plateau and neighbouring areas. A. *Abies* pollen percentage data from this study. B. Dongge cave speleothem $\delta^{18}O$ record (Dykoski *et al.* 2005). C. Shanbao cave speleothem $\delta^{18}O$ record (Shao *et al.* 2006). D. Lake Qinghai ostracode $\delta^{18}O$ record (Lister *et al.* 1991).

with the $\delta^{18}O$ records of Dongge and Shanbao caves, now generally regarded as a good proxy of the South Asian monsoon. The oxygen isotope record from Lake Qinghai shows a different trend between 11 500 and 8000 cal. a BP, as compared with the other three records, with progressively higher $\delta^{18}O$ values during this period. This deviation is interpreted here as reflecting regional differences in climatic conditions between the various sites. The most obvious cause for such variability is the relative contributions made by the South Asian and East Asian monsoon systems.

Holocene climatic variability across the Tibetan Plateau as a function of topography

Speleothem studies, such as the Dongge cave (Dykoski *et al.* 2005; Wang *et al.* 2005) and the Shanbao cave (Shao *et al.* 2006; Wang *et al.* 2008) $\delta^{18}O$ records, provide a persuasive argument that summer monsoon variability in China is controlled primarily by the Northern Hemisphere summer insolation on orbital time scales. However, regional climatic fluctuations, such as those seen between Lake Qinghai and the Zoige Basin, are probably influenced by geographic differences, especially regarding topography and position relative to the South Asian or East Asian monsoon fronts. Because the South Asian and East Asian monsoon systems are not synchronized, there will be times when they are out of phase (Hong *et al.* 2003), and regional variations may be amplified at these times. When this occurs, different parts of the Tibetan Plateau should be influenced, to a greater or lesser extent, by either the South Asian or East Asian monsoon system, according to their location. Such an effect could contribute to long-term climatic effects such as an asynchronous Holocene climate optimum (An *et al.* 2000; He *et al.* 2004).

In order to examine this possibility further, we plotted inferred relative palaeoclimate information from a number of pollen records on the Tibetan Plateau, along with the Hongyuan pollen data (Fig. 6). The locations of these studies include sites from western Tibet (Van Campo & Gasse 1993; Van Campo *et al.* 1996), central Tibet (Sun *et al.* 1993; Tang *et al.* 2004; Herzschuh *et al.* 2006), and eastern Tibet (Jarvis 1993; Shen *et al.* 2005b; Zhao *et al.* 2007; Kramer *et al.* 2010), as shown in Fig. 1. The compilation plotted in Fig. 6 identifies relative growth conditions from each site, as interpreted by the authors of the studies. Absolute growth conditions vary from site to site, but relative optimal conditions are well characterized, with the most favourable growth conditions generally corresponding to the mid-Holocene optimum. Sustained temporal changes in growth conditions for each site may be induced by long-term changes in summer precipitation or temperature. Highly variable growth conditions are also shown in Fig. 6 for some sites, according to published interpretations. The sites are arranged by decreasing elevation.

Figure 6 offers a plateau-wide picture of Holocene climatic changes. All of the sites show persistent changes during the Holocene, with up to six identifiable pollen zones, or subzones, during that time. A distinct regional variability is observed in the timing, duration and stability of climatic conditions across the plateau. However, no consistent north–south or east–west variability is discernible from this small data set. In contrast, a topographic effect is apparent. This is seen in the mid-Holocene climate optimum, which started earlier and ended later at the lower-elevation site. Situated in a desert setting, Lake Hurleg appears to be an exception, where dry climate prevailed during the middle Holocene. The Hurleg Lake site is different from the other sites in other respects as well, as emphasized by Zhao *et al.* (2007). In this context, the most notable difference in the Hurleg Lake site is the improvement in growth conditions in the late Holocene, in sharp contrast to the progressively drier climate exhibited at most other sites. Temperature, as a limiting factor for vegetation growth, appears to be a function of elevation - the higher the elevation, the lower the temperature. Therefore, these elevation differences should inevitably result in a spatial variation in climatic conditions. It is also true that topographic features directly influence modern monsoon rainfall (Hoyos & Webster 2007).

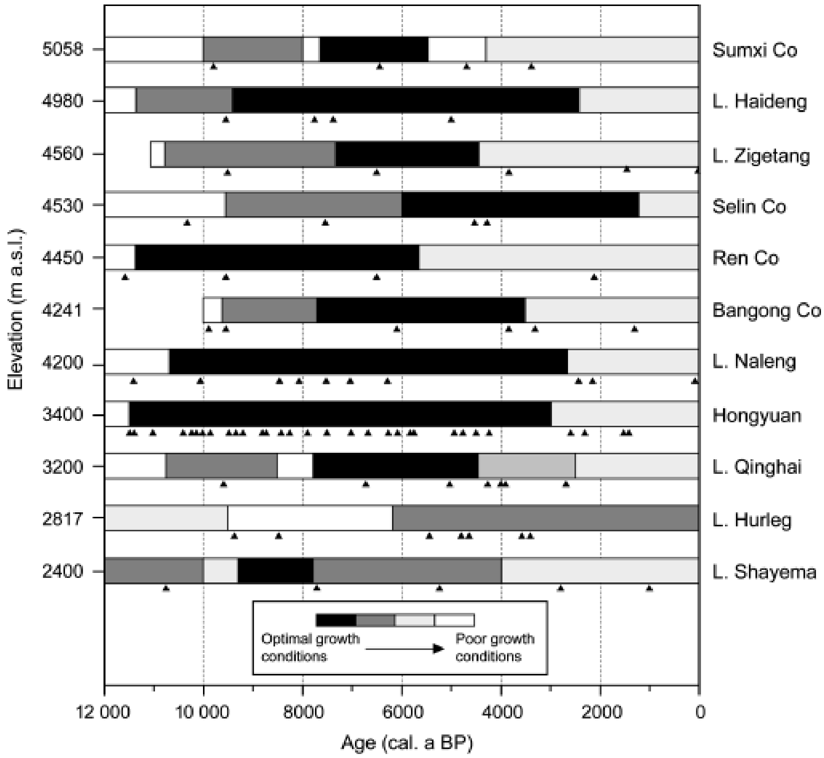

Fig. 6. Summary diagram of Holocene pollen studies from the Tibetan Plateau. The sites are arranged by elevation. Site-specific relative growth conditions are shown for each record. Relative growth conditions were taken from each reference (see text). Locations of the sites are shown in Fig. 1. Triangles denote ^{14}C age control.

Conclusions

A detailed and well-dated pollen record from the Zoige Basin sheds new light on the postglacial dynamics of the alpine ecosystem on the eastern Tibetan Plateau. Local vegetation has experienced significant changes, from alpine coniferous forest–meadow, through alpine coniferous forests, back to an alpine coniferous forest –meadow landscape during the last 13 500 years, presumably regulated by the rise and fall of the Asian summer monsoon system. The pollen record from the Zoige Basin is broadly consistent with oxygen isotope records from Donge and Shanbao caves, and highlights differences between Holocene climate histories at Lake Qinghai. The timing, nature and duration of climatic changes as expressed in pollen records across the Tibetan Plateau suggest a relationship with sample elevation, and highlight distinct geographic differences. All of the sites examined in this study are strongly influenced by monsoon precipitation, and this is probably the major controller of Holocene vegetation on the Tibetan Plateau.

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