A 22,570-yr record of vegetational and climatic change from Wenhai Lake in the Hengduan Mountains biodiversity hotspot, Yunnan, Southwest China

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Abstract

The Hengduan Mountains, with their strong altitudinal vegetation zonation, form a biodiversity hotspot which offers the potential for comparison between sites in order to understand how this zonation arose and how it has responded to climate change and human impacts through time. This paper presents a 22,570-yr pollen record of vegetational and climatic change based on a core 320 cm in depth collected from Wenhai Lake on the Jade Dragon Snow Mountain, one of the highest peaks in the Hengduan Mountains region of Yunnan, Southwest China. From 22,570 to 21,140 cal. yr BP, the vegetation was dominated by broad-leaved forest (comprising mainly *Quercus*, *Betula* and *Castanopsis*), accompanied by needle-leaved forest (mainly *Pinus* and *Abies*), indicating a rather cold and dry climate relative to the present followed by cold and wet conditions. In the period between 21,140 and 19,350 cal. yr BP, the vegetation was still dominated by broad-leaved forest and needle-leaved forest as before but with a notable increase in *Betula* pollen and a sharp decrease in *Quercus* pollen, implying a relatively cold and dry climate with several fluctuations in humidity. The period 19,350 to 17,930 cal. yr BP was a transition stage from broad-leaved forest to needle-leaved forest, with a dramatic decrease in *Quercus* pollen and a maximum reading for *Abies* pollen, reflecting the coldest and driest climate since 22,570 cal.

yr BP. The expansion in needle-leaved forest dominated by *Pinus* and *Abies* (22,570－17,930 cal. yr BP) along with an increase of *Betula* might correspond to the Last Glacial Maximum (LGM, the start of the LGM perhaps occurred prior to the basal age of the core). Between 17,930 and 9,250 cal. yr BP, needle-leaved forest declined and broad-leaved forest began to increase at first, suggesting increases in temperature and humidity, while towards the end of the period, needle-leaved forest expanded and broad-leaved forest shrank, indicating a colder and drier climate, possibly corresponding to the Younger Dryas. From 9,250 cal. yr BP to the present, the vegetation has been dominated by needle-leaved forest (comprising mainly *Pinus*, *Abies* and *Tsuga*), interspersed with broad-leaved *Quercus* and *Betula*, reflecting a significant decline in humidity from the early to late Holocene. During this period, human activity likely increased in this region, with impacts on the vegetation such as a distinct decrease in *Pinus* and *Quercus* pollen and an increase in Polygonaceae pollen in the upper 30 cm of the core. The marked decline in *Quercus* pollen compared with the early stage of this period, in particular, in the Wenhai core can be correlated with that observed in the Haligu core (situated about 2 km away) between 2,400 cal. yr BP and the present.

1 Introduction

The Hengduan Mountains are located in the north of the Mountains of Southwest China biodiversity hotspot, the most biologically diverse temperate ecosystem in the world (Conservation International, 2008), sandwiched between the Honghe Basin to the east and the Qinghai-Xizang Plateau to the west. They comprise five main ridge systems characterized by vertical vegetation zonation and separated by four deep drainage systems, created during the Himalayan orogeny beginning in the Tertiary Period and continuing into the Quaternary (Myers et al., 2000; Ying, 2001). The floristic diversity of the region is particularly high: the Hengduan Mountains are situated in Yunnan Province which, despite covering just 4% of China's land area, contains c. 15,000 species of higher plants, almost 50% of the country's total.

The marked altitudinal zonation of vegetation in the Hengduan Mountains offers the potential to compare between sites in order to build up an understanding of how this zonation arose and how it responds, through time, to climate change and human impacts. The Jade Dragon Snow Mountain (rising to 5,596 m a. s. l.) is one of the highest peaks in the Hengduan Mountains region, and is particularly appropriate for the study of past and present diversity using palynological data because it supports a number of natural wetlands and lakes containing abundant, well-preserved palynomorphs, at a range of altitudes. Thus, sampling of core sediments from different sites has the potential to generate pollen data relative to both time and altitude (at a given locality), which will ultimately enable us to estimate changes in both floristic composition and diversity over time and their response to climatic change.

During the past decade, pollen analysis has been employed extensively for understanding Quaternary vegetation and climate history in China (e.g., Xu et al., 2002; Xiao et al., 2004; Zhao et al., 2007; Li et al., 2011; An et al., 2013; Cao et al., 2013; Jiang et al., 2013). However, few such studies have been conducted in the Hengduan Mountains (Jiang et al., 1998; Shen et al., 2006; Jones et al., 2012; Song et al., 2012; Cook et al., 2013; Xiao et al., 2014). Previously, we have investigated changing climate and vegetation over the past 9,300 years based on pollen analyses of a core 400 cm in depth from a wetland site at Haligu (3,277 m) on the Jade Dragon Snow Mountain (Song et al., 2012). This paper presents a 22,570-yr record of vegetational and climatic change from Wenhai Lake, also on the Jade Dragon Snow Mountain. We aim to use pollen data to develop insights into changing floristic diversity and to draw inferences about past climate and anthropogenic influences in the region during the Late Quaternary.

2 Study area

Wenhai Lake (26°58′59″ N, 100°09′54″ E), an enclosed ice-scour lake at an altitude of 3,080 m, is located at the southern end of the Jade Dragon Snow Mountain in Yulong County of Lijiang City, northwestern Yunnan, Southwest China (Fig. 1). It forms part of Lashihai Swamp Natural Reserve and is approximately 23 km northwest of Lijiang City. The lake has a surface area of about 0.16 km^2, with a maximum water depth of c. 4 m. It is hydrologically recharged by rainfall and glacial melt-water from the surrounded mountains, without river water inputting into the lake. It is a seasonal lake, receiving abundant rainfall in rainy season

(May to October) and less rainfall in dry season (November to April). The outflow is dammed, with a dam constructed in 2012. Therefore, the source of lake sediment is relatively simple and stable. This area is a key region linking the Qinghai-Xizang Plateau with the Yungui Plateau, and also is a boundary region between the Hengduan Mountains area of northwestern Yunnan and the plateau area of eastern Yunnan. More than a thousand years ago, Wenhai was an important stop on the ancient "Tea-Horse Road," a route for trading tea and horses between inland agricultural and remote nomadic regions (Luo, 2003). Yulong County is home to several ethnic minority peoples, with the Naxi being most numerous.

The study area is strongly influenced by the southwest monsoon coming from the Indian Ocean. Thus the summers are warm and humid and the winters cool and dry. The mean annual temperature (MAT) and mean annual precipitation (MAP) measured at Lijiang (situated below the study site at about 2,200 m), are 12.8°C and 935 mm, respectively. About 90% of the annual precipitation falls in summer, between June and October. The warmest month is July, with a mean temperature of 17.9°C, and the coldest month is January, with a mean temperature of 5.9°C (Feng et al., 2006).

The regional vegetation and climate of the Jade Dragon Snow Mountain area are strongly related to elevation gradients. At increasing elevations on the mountain slopes, MAT shows a decreasing trend, while MAP displays a reverse trend. For example, MAT and MAP are 12.6°C and 772 mm, respectively, at 2,393 m, MAT decreases to 5.4 °C and MAP increases to 1,600 mm at 3,200 m, MAT further decreases to –3.3~ –4.7°C and MAP increases to more than 2,400 mm at the snow line (4,800 m; He et al., 2000a, 2000b). Four main vegetation zones can be recognized: Zone 1, semi-humid evergreen broad-leaved forest–pine forest (about 2,400–3,000 m); Zone 2, needle- and broad-leaved mixed forest- sclerophyllous evergreen broad-leaved forest (about 3,000–3,300 m); Zone 3, cold-temperate needle-leaved forest (about 3,300–4,200 m); and Zone 4, alpine heath scrub and meadow (above 4,200 m; Wu et al., 2006). From our personal observations, the present vegetation around the Wenhai Lake catchment is dominated by oaks (*Quercus pannosa* Hand.-Mazz) and pines, primarily *Pinus yunnanensis*, with *P. armandii* Franch at slightly lower elevations and smaller numbers of *Tsuga dumosa* (D.Don) Eichler and *P. densata* Mast. are also present. Here, the most abundant shrubs are ericaceous, including rhododendron species, especially *Rhododendron mucronatum* (Blume) G. Don, *R. racemosum* Franch., *R. yunnanense* Franch. and *R. delaveyi* Franch., together with *Vaccinium bracteatum* Thunb. and *Pieris formosa* (Wallich) D.Don. Herbaceous taxa are diverse with some of the most speciose genera being *Anemone, Gentiana, Primula* and *Roscoea*. This area is now heavily influenced by human activities, such as felling of timber and grazing, so some patches are barren of vegetation.

3 Materials and methods

3.1 Coring and sampling

A sediment core 320 cm in depth was obtained from Wenhai Lake in January 2005 using a Russian corer, which consists of a 40 cm long steel chamber (diameter 10 cm) and 1 m long steel rods. Coring was done in 40 cm overlapping steps (0–40 cm, 40–80 cm, 80–120 cm, etc.). To avoid contamination, the chamber was cleaned carefully before starting each new round of coring. The core was labelled in the field, wrapped in plastic foil and placed in halved PVC tubes. A detailed lithological description of the core is presented in Fig. 2.

3.2 Radiocarbon dating

Two samples from the core, at 155 cm and 320 cm in depth, were taken for Accelerator Mass Spectrometry (AMS) radiocarbon dating, which was performed at the Scottish Universities Environmental Research Centre (SUERC) in Glasgow, Scotland, UK. The ^{14}C ages are quoted in conventional years BP (before 1950 AD). Bulk samples from the core were used because fragments of plant material suitable for analysis were not present. Age calibration was set up using the calibration curve from Reimer et al. (2004) by means of the calibration program OxCal v3.10 (Bronk, 2005). Date ranges are cited in calibrated years AD/BC at 95% probability, with end points rounded to the nearest 10 years (Mook, 1986; Foster et al., 2008).

3.3 Pollen analysis

Six surface soil samples near the core were collected for comparison with the preserved pollen assemblage. Thirty-two samples were taken from the core itself, at 10 cm intervals, for pollen analysis. Thirty grams of each sample were processed by the method of heavy liquid separation (Moore et al., 1991; Li and Du, 1999) followed by acetolysis (Erdtman, 1960). Pollen grains and spores were identified using modern pollen slides, palynological literature and monographs (IBCAS, 1976; IBSCIBCAS, 1982; Wang et al., 1995). All samples yielded abundant, well-preserved palynomorphs. Pollen samples were examined using a Leica DM 2500 light microscope at a magnification of 400 × and at least 300 pollen grains and spores were counted in each sample. Pollen grains and spores were divided into four categories: trees and shrubs, herbs, pteridophytes and aquatic taxa. Pollen data were expressed as percentages and graphed using Tilia.Graph, and pollen zones were determined with CONISS in the Tilia program (Grimm, 1997).

4 Results

4.1 Chronology

Two AMS radiocarbon dates, 14,075±40 yr BP (17,150–16,350 cal. yr BP) at depth of 155 cm and 19,075±50 yr BP (22,760–22,380 cal. yr BP) at depth of 320 cm, give a relatively reliable basis for deciphering the vegetation and climate history in and surrounding Wenhai Lake. The lithology of the entire core is mainly characterized by clay with the exception of peat deposit at depth of 45–55 cm. Given continuity and stability of sedimentation during the past 22,570 yr, an age-depth curve in cal. yr B.P., reflecting the sedimentation pattern, can be constructed for the core (See the supplementary material). Although the age-depth model is obtained based on two dates, it roughly shows the sedimentation rates are c. 0.1 mm/yr and 0.28 mm/yr for the depths of 0–155 cm and 155–320 cm, respectively. Ages of other depths are deduced by assuming that the sedimentation rate is constant for the lower and upper sections of the core, i.e., 9,250 cal. yr BP at 80 cm depth, 17,930 cal. yr BP at 190 cm, 19,350 cal. yr BP at 230 cm, and 21,140 cal. yr BP at 280 cm, which are determined as the timing of the changes of the pollen zones.

4.2 Pollen analysis

4.2.1 Surface samples

Fifty palynomorphs were identified from the six surface soil samples collected in close proximity to the core, including 29 families and seven genera of angiosperms, three genera of gymnosperms, nine families and one genus of pteridophytes, and one genus of alga (See the supplementary material). The pollen assemblage is dominated by trees and shrubs, at percentages ranging from 79.5% to 97.0% of the total pollen and spores. *Pinus* pollen (62.3–87.1%) dominates in all six surface samples, followed by *Abies* (3.3–10.7%), *Quercus* (0–5.5%) and Ericaceae (0–4.1%), Herb pollen is present at low percentages (1.8–4.1%), and comprises *Artemisia*, other Compositae, Caryophyllaceae, Chenopodiaceae, Convolvulaceae, Cruciferae, Cyperaceae, Gramineae, Labiatae, Liliaceae and Polygonaceae. Pteridophyte spores account for 0.3–15.3%, including Athyriaceae, Cyatheaceae, Gymnogrammaceae, Hymenophyllaceae, Loxogrammaceae, Lygodiaceae, Plagiogyriaceae, Polypodiaceae, *Pteris* and Sinopteridaceae. Aquatic plants are recorded at low percentages (0–3%), comprising *Myriophyllum* and *Zygnema*. This pollen assemblage is consistent with the local vegetation of the lake basin and the surrounding mountains, reflecting a needle-leaved forest dominated by *Pinus* and accompanied by some broad-leaved components, e.g. *Quercus* and Ericaceae.

4.2.2 Pollen diagram zonation and description

Pollen analysis of the core samples shows a high degree of taxonomic diversity. The palynoflora comprises 83 palynomorphs, which can be identified to 45 families and 13 genera of angiosperms, one family and seven genera of gymnosperms, 12 families and three genera of pteridophytes and two genera of algae (See the supplementary material). Some of the selected palynomorphs extracted from the core are illustrated in the supplementary material.

A greater diversity of palynomorphs was recovered from the core samples than from the surface samples. However, many of the taxa found in the core but missing from surface samples are not present in the upper part of the core and are no longer present in the immediate area so do not contribute to the local pollen rain. Examples include *Cedrus*, *Dacrydium* and *Taxodium* amongst the gymnosperms and the angiosperm taxa Actinidiaceae, Anacardiaceae, *Carpinus*, Clethraceae, Flacourtiaceae, Icacinaceae, Juglandaceae, *Liquidambar,* Myrsinaceae, Palmae and *Tilia.* Some of these taxa have a subtropical distribution and their closest occurrence to the study site is at much lower elevation near the Jinsha River or considerably further south in Yunnan. Other taxa such as Araceae, Araliaceae, Campanulaceae, Caprifoliaceae, Caryophyllaceae and Umbellifereae are present in the immediate area but are entomophilous plants with relatively lower pollen production which might be expected to be under-represented in the local pollen rain.

A cluster analysis performed using Tilia (with CONISS) divided the pollen diagram into five distinct zones (Fig. 2). Brief descriptions of each zone are as follows.

Pollen zone 1 (320–280 cm: 22,570–21,140 cal. yr BP):

This zone is characterized by a dominance of tree and shrub pollen (72.9–81.3%), followed by herbs (6.3–20%), ferns (4.2–12.5%) and aquatics (0–4.2%). Among the trees and shrubs, the percentage of broad-leaved elements (42.2–70.8%) is higher than that of conifers (10.4–33.9%). The trees and shrubs are dominated by the broad-leaved taxa *Quercus* (20–62.5%, including *Quercus* sp. 1 and sp. 2), *Betula* (1.8–7.6%), *Castanopsis* (0–6.7%) and the coniferous taxa *Pinus* (6.3–24.4%) and *Abies* (4.2–10.1%). Pollen grains of other coniferous plants such as *Picea* and *Tsuga*, and broad-leaved plants such as *Corylus*, *Ulmus* and Ericaceae are also present in minute quantities. Herbs are represented by *Artemisia* (0–11.5%), coupled with Chenopodiaceae (0–4.4%), Compositae (0–4.4%), Labiatae (0–4.2%), and Polygonaceae (0–3.7%). Fern taxa include Athyriaceae (3.7–6.7%), Polypodiaceae (0–4.6%), Gymnogrammaceae (0–4.2%) and *Pteris* (0–2.1%). Two taxa of aquatic plants, *Myriophyllum* and *Pediastrum,* are recorded, at 0–3.1% and 0–1.0%, respectively.

The pollen assemblages of pollen zone 1 and the surface samples are both dominated by tree and shrub pollen, represented by 72.9–81.3% and 79.5–97%, respectively. *Quercus* pollen (20–62.5%) dominates the trees and shrubs of pollen zone 1, followed by *Pinus*, *Abies*, *Betula* and *Castanopsis*. In contrast, *Pinus* pollen (62.3–87.1%) dominates the trees and shrubs of the surface samples, followed by *Abies*, *Quercus* and Ericaceae. The percentage of herb pollen is comparatively high in pollen zone 1 (6.3–20%) compared to the surface samples (1.8–4.1%). Similar percentages of pteridophyte spores (pollen zone 1: 4.2–12.5%, surface samples: 0.3–15.3%) and aquatics (pollen zone 1: 0–4.2%, surface samples: 0–3%) are recorded in pollen zone 1 and the surface samples.

Pollen zone 2 (280–230 cm: 21,140–19,350 cal. yr BP):

In this zone, two distinct characteristics are observed: firstly a sharp increase in the aquatic pollen percentage, reaching a maximum (16.7%) for the entire profile at a depth of 270 cm, which is attributed to the prevalence of *Myriophyllum* and *Pediastrum*. Secondly, trees and shrubs continue to dominate in this zone. The percentage of trees and shrubs ranges from 52.3% to 79.6%. As in pollen zone 1, broad-leaved trees (34.4–65.2%) still occupy a higher percentage than conifers (8.6–45.2%). Among the conifers, it should be noted that *Pinus* pollen reaches its lowest value (2.1%) for the whole profile at a depth of 230 cm. Broad-leaved trees, i.e. *Quercus* (4.1–56.5%), *Betula* (3.4–13.7%), *Castanopsis* (0–8.5%) and *Corylus* (0–6.3%), together with herbaceous taxa, i.e. *Artemisia* (0–12.8%) and Polygonaceae (2.2–6.9%), continue to play an important role in this zone. In addition, some new broad-leaved elements, *Alnus*, *Carpinus*, Actinidaceae, *Ilex*, Leguminosae, *Tilia*, Cruciferae and Plantaginaceae, are found sporadically for the first time. The percentage of fern spores (1.3–13.8%) remains at almost the same level as in pollen zone 1. Athyriaceae spores show a slight increase (up to 10.9%), but Gymnogrammaceae (0–0.4%), Polypodiaceae (0–1.1%) and *Pteris* (0–1.1%) display minor decreases.

Tree and shrub pollen dominates the pollen assemblages of both pollen zone 2 and the surface samples, but its percentage in pollen zone 2 (52.3–79.6%) is lower than in the surface samples (79.5–97%). *Quercus* pollen dominates the trees and shrubs of pollen zone 2 (4.1–56.5%), compared to the dominance of *Pinus* pollen (62.3–87.1%) in the surface samples. The percentages of herb pollen (pollen zone 2: 2.2–21.2%, surface samples: 1.8–4.1%) and aquatics (pollen zone 2: 4.1–16.7%, surface samples: 0–3%) are comparatively high in pollen zone 2 compared to the surface samples. Pteridophyte spores account for 1.3–13.8% and 0.3–15.3%, respectively, in pollen zone 2 and the surface samples.

Pollen zone 3 (230–190 cm: 19,350–17,930 cal. yr BP):

In this zone, tree and shrub pollen maintains a dominant status (79.7–92.2%), followed by herbs (5.2–13.7%), ferns (0.7–7.1%) and aquatics (0–5.8%). The percentage of trees and shrubs reaches its highest value (92.2%) of the profile, at a depth of 200 cm. The conifers (28.4–66.8%) show a higher percentage than broad-leaved trees (19–51.4%). *Pinus* (19.2–50.0%) and *Abies* (9.0–43.4%) pollen shows a sharp increase, and *Abies* pollen in particular maintains a peak value (43.4%) throughout the profile. The broad-leaved trees *Quercus* (9.5–31.1%) and *Betula* (1.3–9.6%), and herbaceous *Artemisia* (0–11.2%), also play an important role. The ferns are dominated by Athyriaceae, ranging from 0.2% to 7.1%. Six other types of ferns, i.e. Polypodiaceae, Selaginellaceae, Sinopteridaceae, Hymenophyllaceae, *Pteris* and Lygodiaceae, occur at low percentages, less than 2%. The prevalence of *Myriophyllum* (0–2.8%) and *Pediastrum* (0–5.8%) declines sharply and one new aquatic taxon, Potamogetonaceae, appears in this zone at a low percentage (0–0.1%).

The percentage of tree and shrub pollen in pollen zone 3 (79.7–92.2%) is more similar than the previous zones to that of the surface samples (79.5–97%). As in the surface samples, *Pinus* pollen dominates in pollen zone 3, followed by *Abies* and *Quercus.* The percentages of herb pollen (pollen zone 3: 5.2–13.7%, surface samples: 1.8–4.1%) and aquatics (pollen zone 3: 0–5.8%, surface samples: 0–3%) in pollen zone 3 are higher than in the surface samples. However, a comparatively lower percentage of pteridophyte spores is recorded in pollen zone 3 (0.7–7.1%) than in the surface samples (0.3–15.3%).

Pollen zone 4 (190–80 cm: 17,930– 9,250 cal. yr BP):

Tree and shrub pollen dominates in this zone (75.8–90.4%). Herbs rank second (7.5–18.4%), followed by ferns (0–12.1%) and aquatics (0–4%). Coniferous *Pinus* (12.6–46.9%) and *Abies* (1.8–30.3%), and broad-leaved *Quercus* (9.1–37.8%) and *Betula* (0–13.5%) are the dominant elements of trees and shrubs. Additionally, three other coniferous taxa, *Picea*, *Tsuga* and

Taxodiaceae, and 28 broad-leaved tree species including *Corylus*, *Castanopsis*, *Liquidambar* and Myrsinaceae are recorded at low percentages. Herbs are represented by *Artemisia* (0–9.9%), Labiatae (0–6.1%) and Polygonaceae (0.4–4.7%), accompanied by Chenopodiaceae, Cyperaceae, Plantaginaceae and Gramineae in minute quantities. Nine types of ferns are found in this zone, among which Athyriaceae and Polypodiaceae possess relatively high percentages of 0–12.1% and 0–2.2%, respectively. Three aquatic plants occur: *Myriophyllum* (0–3.7%), *Pediastrum* (0–0.6%), and *Zygnema* (0–0.2%).

Tree and shrub pollen maintains a dominant status in pollen zone 4 (75.8–90.4%) and in the surface samples (79.5–97%). *Pinus* pollen dominates the pollen assemblage of pollen zone 4 (12.6–46.9%), but its percentage is much lower than in the surface samples (62.3–87.1%). The percentages of *Quercus* (pollen zone 4: 9.1–37.8%, surface samples: 0–5.5%) and *Abies* pollen (pollen zone 4: 1.8–30.3%, surface samples: 3.3–10.7%) in pollen zone 4 are generally higher than in the surface samples. A comparatively higher percentage of herb pollen is documented in pollen zone 4 (7.5–18.4%) relative to the surface samples (1.8–4.1%). Pteridophyte spores (pollen zone 4: 0–12%, surface samples: 0.3–15.3%) and aquatics (pollen zone 4: 0–4%, surface samples: 0–3%) occur in similar percentages in pollen zone 4 and the surface samples.

Pollen zone 5 (80–0 cm: 9,250 cal. yr BP – present):

This zone is dominated by tree and shrub pollen (47–84.2%), followed by herbs (4.9–37.4%), ferns (7.8–24.8%) and aquatics (0–3%). The pollen percentage of conifers (31.3–79.9%) is higher than that of broad-leaved trees (4.3–37.6%). From the beginning to the end of this zone, *Pinus* (14–56.8%) shows a decrease then increases sharply, while *Quercus* (1–29.1%) and *Betula* (0–7.4%) show a decreasing trend, and *Abies* (7.4–27.2%) an increasing one. *Tsuga* (1.1–7.5%) reaches its highest percentage in this zone. Pollen of other trees and shrubs such as *Picea*, *Alnus*, *Corylus*, *Carpinus*, Ericaceae, Anacardiaceae, Dipsacaceae, Flacourtiaceae and Meliaceae are found in some samples, at percentages of less than 1%. Herbs are characterized by a distinct decrease in *Artemisia* (0–3.4%) and an increase in Polygonaceae (2–20.8%) and Labiatae (0.7–15.4%). Among the fern spores, Polypodiaceae

(4.5–17.9%) shows a remarkable increase and Athyriaceae (0–6.3%) a notable decrease. The percentage of aquatics changes little compared to pollen zone 4, but *Myriophyllum* disappears in this zone. Thus only two types are recorded, *Pediastrum* (0–0.6%) and *Zygnema* (0–3%).

Tree and shrub pollen dominates the pollen assemblages of both pollen zone 5 and the surface samples, represented by 47–84.2% and 79.5–97%, respectively, among which *Pinus*, *Abies*, and *Quercus* are the dominant taxa. The percentages of herb pollen (pollen zone 5: 4.9–37.4%, surface samples: 1.8–4.1%) and pteridophyte spores (pollen zone 5: 7.8–24.8%, surface samples: 0.3–15.3%) are generally greater in pollen zone 5 than in the surface samples. Aquatics occur at the same percentage (0–3%) in pollen zone 5 and the surface samples.

5 Discussion and conclusions

5.1 Climatic implications of the principal palynomorphs from Wenhai Lake

The palynoflora found in the Wenhai core includes a large number of potential climate indicators. For example, *Pinus* is currently distributed below 3,200 m elevation in Southwest China and is commonly found in slightly warm and moderately dry habitats. *Pinus yunnanensis* Franch., *P. densata* Mast. and *P. armandi* Franch. are the dominant species on the mountains of northwestern Yunnan (KIBCAS, 1986). *Tsuga* is a cold-tolerant and hygrophilous conifer, requiring a MAT of 8.4 to 10.5°C and a MAP of about 1,000 mm for favorable growth in Yunnan (WGYV, 1987). One species, *Tsuga dumosa* (D. Don) Eichler, and one variety, *T. chinensis* (Franch.) E. Pritz. var. *forrestii* (Downie) Silba are recorded in northwestern Yunnan (KIBCAS, 1986; Wang et al., 2007). *Abies* is strongly associated with cold and dry habitats with a MAT of 2–8°C and MAP ca. 600 mm in the mountains of Southwest China (CCCV, 1980; Jarvis, 1993). Five species, viz. *Abies delavayi* Franch, *A. forrestii* C. Rogers, *A. georgei* Orr, *A. nukiangensis* W. C. Cheng & L. K. Fu, *A. ferreana* Bordères & Gaussen, and two varieties, *A. ernestii* Rehd. var. *salouenensis* (Borderes et Gaussen) W. C. Cheng et L. K. Fu, and *A. georgei* Orr var. *smithii* (Viguie et Gaussen) W. C. Cheng et L. K. Fu, occur in northwestern Yunnan (KIBCAS, 1986). *Betula* is viewed as a cold- and drought-tolerant element. Eleven species and two varieties occur in Yunnan, among which five species and two varieties grow in Lijiang, including *B. calcicola* (W. W. Smith) Hu, *B. delavayi* Franch, *B. platyphylla* Suk., *B. utilis* D. Don, *B. potaninii* Batal, *B. utilis* D. Don var. *sinensis* (Franch.) H. Winkl, and *B. delavayi* Franch var. *polyneura* Hu ex. P. C. Li (KIBCAS, 1991). *Alnus* usually grows on riverbanks or at village margins, in moist temperate habitats. One species, *A. nepalensis* D. Don is found in northwestern Yunnan (KIBCAS, 1991). Evergreen sclerophyllous *Quercus* displays considerable ecological adaptability, and can grow in either dry or humid environments. This genus is widely distributed in the fog zone (with higher humidity, at about 3,100 m) on the Jade Dragon Snow Mountain, where it forms a montane needle- and broad-leaved mixed forest along with *Tsuga* and *Picea* (WGYV, 1987). From our personal observations, some small *Quercus* trees are present up to about 3,800 m. *Artemisia* is mainly distributed in temperate areas of mid to high latitudes of the Northern Hemisphere, usually in arid or semi-arid environments (Valles and McArthur, 2001). The genus *Artemisia* is considered an indicator of steppe climate (Erdtman, 1952) and moderate precipitation (El-Moslimany, 1990). There are 54 species and eight varieties growing in Yunnan (KIBCAS, 2003a). Cyperaceae is a cosmopolitan family with ca. 5,000 species and 104 genera. Many species of this family commonly grow in wetlands and surrounding areas, adapted to open and sunny conditions. About 26 genera and 272 species occur in Yunnan. The high frequency of Cyperaceae pollen may indicate humid conditions (KIBCAS, 2003b; Sun et al. 2003).

5.2 Vegetation and climate history at Wenhai

Based on the climatic preferences of the major taxa recovered from the Wenhai core, the palynological record reveals a detailed history of shifting vegetation and climate change in this region during the past 22,570 yrs (Fig. 3). From 22,570 to 21,140 cal. yr BP (Pollen zone 1), the vegetation surrounding the lake catchment was dominated by broad-leaved forest (composed mainly of *Quercus*, *Betula* and *Castanopsis*), accompanied by needle-leaved forest (mainly *Pinus* and *Abies*). The herbaceous plants *Artemisia*, Labiatae, Compositae and Polygonaceae, and ferns Athyriaceae, Polypodiaceae, Gymnogrammaceae and *Pteris*, grew around the lake or under coniferous or broad-leaved trees. This pollen assemblage indicates a rather cold and dry climate relative to the present followed by cold and wet conditions.

Between 21,140 and 19,350 cal. yr BP (Pollen zone 2), the vegetation was dominated by broad-leaved forest and needle-leaved forest as before, with a notable increase in *Betula* pollen and a sharp decrease in *Quercus* pollen, reflecting a relatively cold and dry climate with several fluctuations in humidity during this period. From 19,350 to 17,930 cal. yr BP (Pollen zone 3), the coniferous trees *Pinus* and *Abies* showed a distinct increase, with *Abies* especially reaching its maximum proportion during this period. In contrast, broad-leaved *Quercus* displayed a remarkable decrease compared to the previous stage. This pollen assemblage suggests a transition from broad-leaved forest to needle-leaved forest, pointing to the coldest and driest climate conditions since 22,570 cal. yr BP. In the period from 22,570 to 17,930 cal. yr BP, needle-leaved forest dominated by *Pinus* and *Abies* gradually expanded and reached a maximum extent, and at the same time, the extent of *Betula* increased. This period might correspond to the cold Last Glacial Maximum (LGM). However, the exact start and end dates of the LGM in Southwest China has been the subject of much debate. For example, Chen et al. (2014) reported that the LGM occurred between 29,200 and 17,600 cal. yr BP, based on the expansion and maximum extent of cold-temperature coniferous forest (mainly *Abies*/*Picea*) in the Xingyun Lake catchment of central Yunnan. Long et al. (1991) identified that the LGM occurred from 30,000 to 15,000 yr BP, with coverage of conifer and broad-leaved mixed forest in the Qilu Lake catchment of central Yunnan. Jiang et al. (2001) concluded that the LGM occurred from 33,000 to 16,000 yr BP, with vegetation comprising montane mixed coniferous and broad-leaved forest and sclerophyllous evergreen oaks in the Heqing Basin of northwestern Yunnan. Thus, previous palynological records from Yunnan tend to provide broader estimates for the LGM. In the present paper, because the basal age of the Wenhai core reaches only to 22,570 cal. yr BP, we cannot deduce the date of the start of the LGM, which perhaps occurred prior to the inferred basal age, as evidenced by the relatively low pollen sum compared with pollen zones 4 and 5. Between 17,930 and 9,250 cal. yr BP (Pollen zone 4), coniferous forest and broad-leaved forest began to decline and increase, respectively, until 140 cm depth of the core, reflecting increases in temperature and humidity relative to pollen zone 3. From 140 cm to 110 cm, coniferous forest expanded, but broad-leaved forest gradually shrank, which indicates colder and drier climate conditions, likely corresponding to the Younger Dryas cold event (YD). The YD is also recorded by other studies in Yunnan. For example, Shen et al. (2006) pointed to the relatively cold period of 12,950 to 11,750 cal. yr BP as the YD, based on the dominance of *Betula* and deciduous oaks in the Erhai Lake catchment. Xiao et al. (2014) identified a relatively cold phase between 12,230 and 11,510 cal. yr BP, based on the dominance of open alpine meadow around Tiancai Lake. From 9,250 cal. yr BP to the present day (Pollen zone 5), *Pinus* underwent a process of decrease at the depth of 50–80 cm (from 38.1% to 14%), increase from 30 to 50 cm (from 14% to 56.8%, this shows a trend consistent with the Haligu core between 4,000–2,400 cal. yr BP), and decrease again at 0–30 cm (from 56.8% to 14.5%), while *Tsuga* displays an opposite trend. *Abies* shows a distinct increase during this period. *Quercus* increased at the beginning of the stage, then decreased after that. This pollen assemblage indicates that needle-leaved forest (comprising mainly *Pinus*, *Abies* and *Tsuga*) dominated the areas surrounding Wenhai Lake during the Holocene, interspersed with broad-leaved elements (mainly *Quercus* and *Betula*), reflecting a significant decline in humidity from the early to late Holocene, which might be related to a strong Asian summer monsoon over Southwest China during the early Holocene and a reduced monsoon intensity in the mid-late Holocene (Dykoski et al., 2005; Kramer et al., 2010).

5.3 Palynological signals of human activity detected in the Wenhai core

Based on pollen and other evidence, human influences on postglacial vegetation have been inferred in Europe and North America (e.g., Brugam, 1978; Hirons and Edwards, 1986; Smith and Cloutman, 1988; Russell et al., 1993; Parker et al., 2002), as well in China (e.g., An et al., 2002; He et al., 2002; Xu et al., 2002; Song et al., 2012). The present authors have previously published another palynological investigation within the Hengduan Mountains (Song et al., 2012). The altitude of the previous study site, Haligu, is 3,277 m, where there is no current human settlement. The present study area, about 2 km far from Haligu, is close to a Naxi ethnic minority settlement at Wenhai village. Moreover, Wenhai was an important stop on the ancient “Tea-Horse Road” (Luo, 2003), making it likely that a wide variety of cultivated plants were introduced into the agricultural system around the lake, as evidenced by an ethnobotanical survy of traditional edible plants (including 45 cultivated plants) used by Naxi people in Wenhai village (Zhang et al., 2013).

In the Wenhai core, several observations may be interpreted in terms of increasing anthropogenic impact in the region. First, *Pinus* and *Quercus* pollen decreased distinctly at the depth of 0–30 cm, which is probably linked with the fact that local people felled the trees for house construction or fuel wood. We detected that *Quercus* pollen decreased steadily in the Haligu core during the period from 2,400 cal. yr BP to the present day and observed heavy present-day coppicing of *Quercus* for firewood, resulting in much reduced pollen production. The comparison of both cores may substantiate the existing human impacts in the region. Second, the occurrence of abundant Labiatae pollen also indicates increasing human activity. From our personal observation, the Naxi people in Wenhai village currently cultivate several Labiatae species, including *Perilla frutescens* (L.) Britton and *Mentha* spp. as edible herbs and for medical utilization. Third, the increase in Polygonaceae pollen (likely to be *Fagopyrum*) could be an important indicator of human activity in the region, as the Naxi people continue to plant buckwheat as an important crop today. Although we have no absolute way to confirm these signals correlated with increased human settlement in the region, we believe a further ongoing study of two soil pit profiles with high resolution of dating and sampling from the village of Wenhai will give us even more information about human activity on the Jade Dragon Snow Mountain.

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Figure legends

Figure 1. a. The location of Wenhai Lake in northwestern Yunnan, China, b. The position of core and surface soil samples, c. The location of Wenhai Lake in the Hengduan Mountains, d. The location of Wenhai Lake on the Jade Dragon Snow Mountain, e. An enlarged photograph of Wenhai Lake (c, d and e are cited from Google Earth)

Figure 2. Pollen percentage diagram from Wenhai Lake, northwestern Yunnan, China

Figure 3. Schematic diagrams showing vegetation succession over the past 22,570 yrs at Wenhai

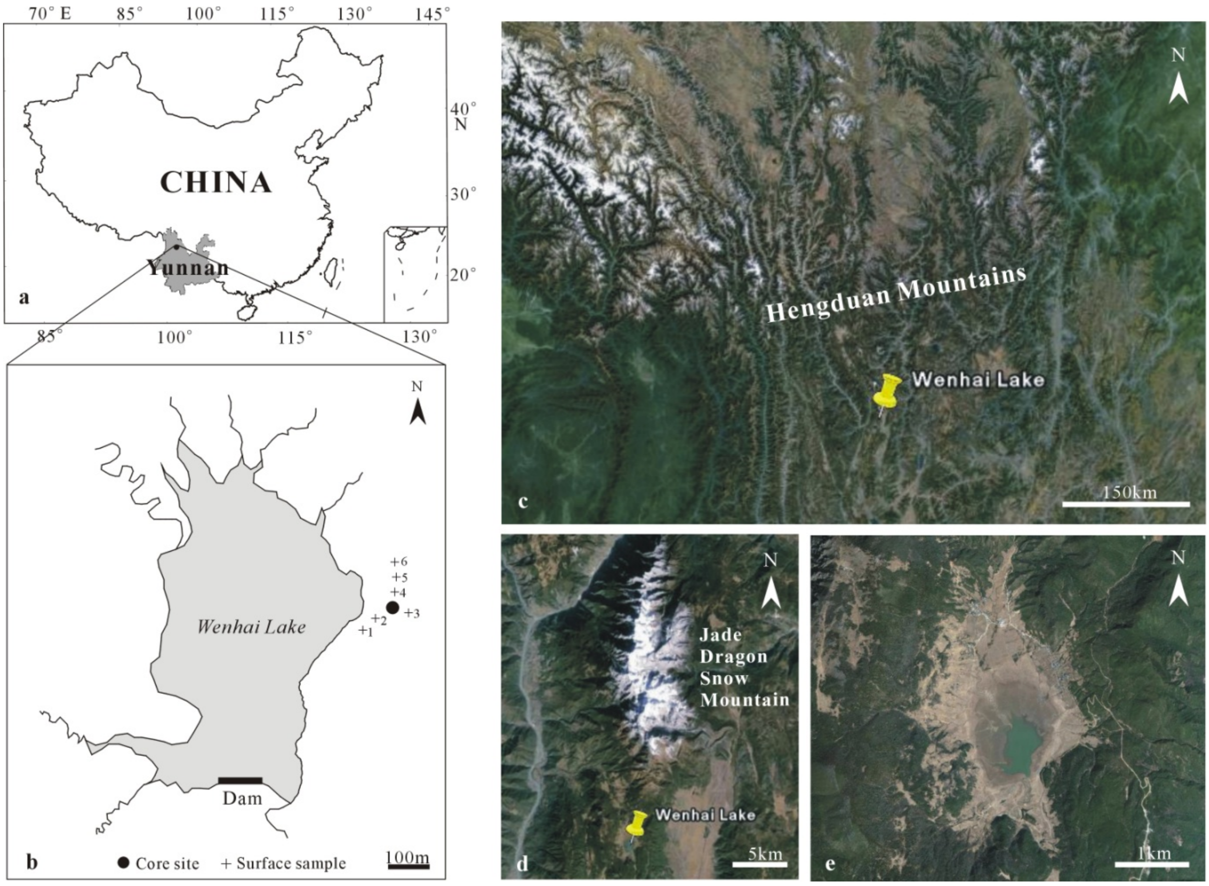
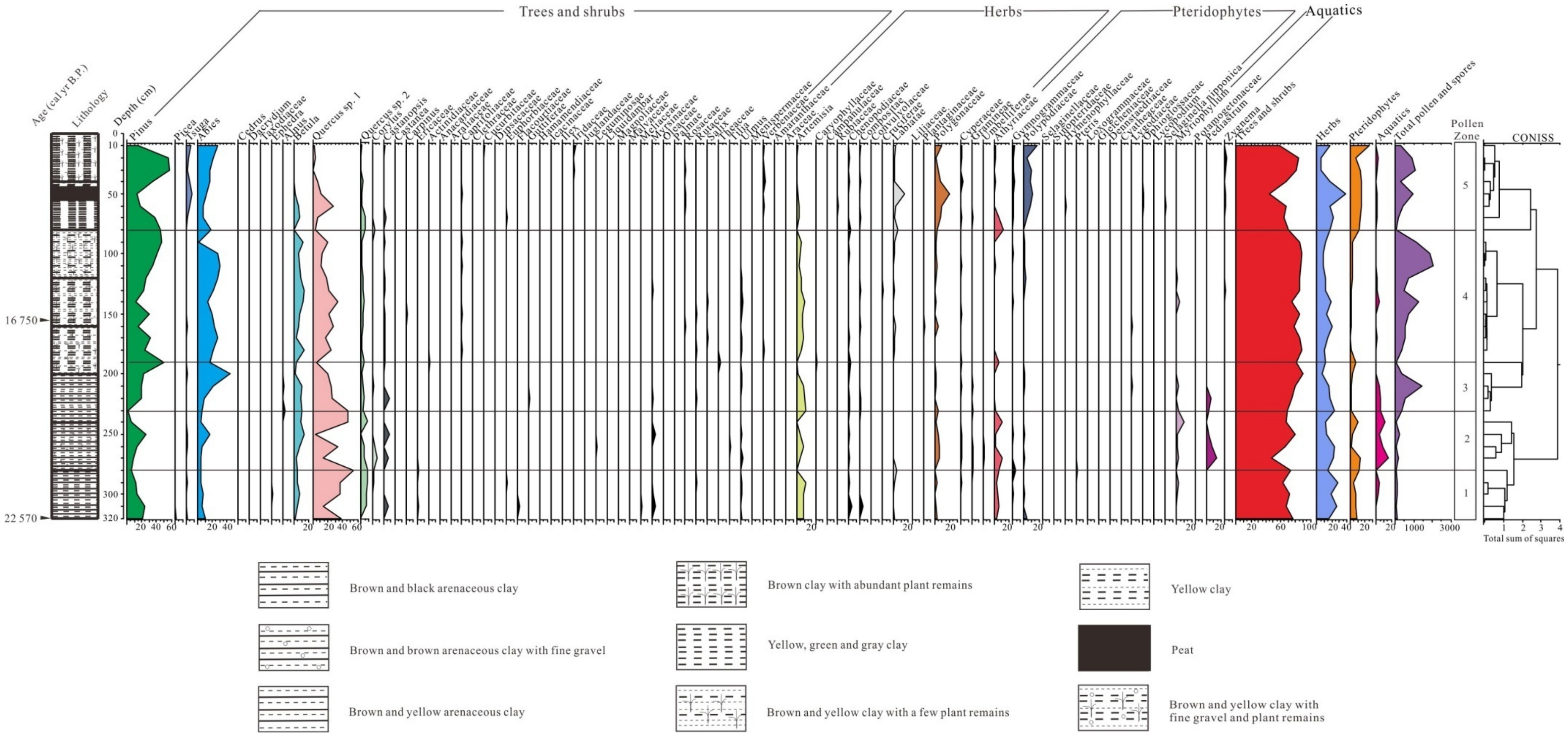

70° E
85°
100°
115°
130°
145°
40° N
30°
20°
CHINA
Yunnan
a
b
Wenhai Lake
Dam
Core site
+ Surface sample
100m
+1
+2
+3
+4
+5
+6
N
c
Hengduan Mountains
Wenhai Lake
150km
d
Jade Dragon Snow Mountain
Wenhai Lake
5km
e
1km

Figure 1



Trees and shrubs
Herbs
Pteridophytes
Aquatics
Age (cal yr B.P.)
Lithology
Depth (cm)
16 750
22 570
Pollen Zone
CONISS
Total sum of squares
Brown and black arenaceous clay
Brown and brown arenaceous clay with fine gravel
Brown and yellow arenaceous clay
Brown clay with abundant plant remains
Yellow, green and gray clay
Brown and yellow clay with a few plant remains
Yellow clay
Peat
Brown and yellow clay with fine gravel and plant remains

Figure 2

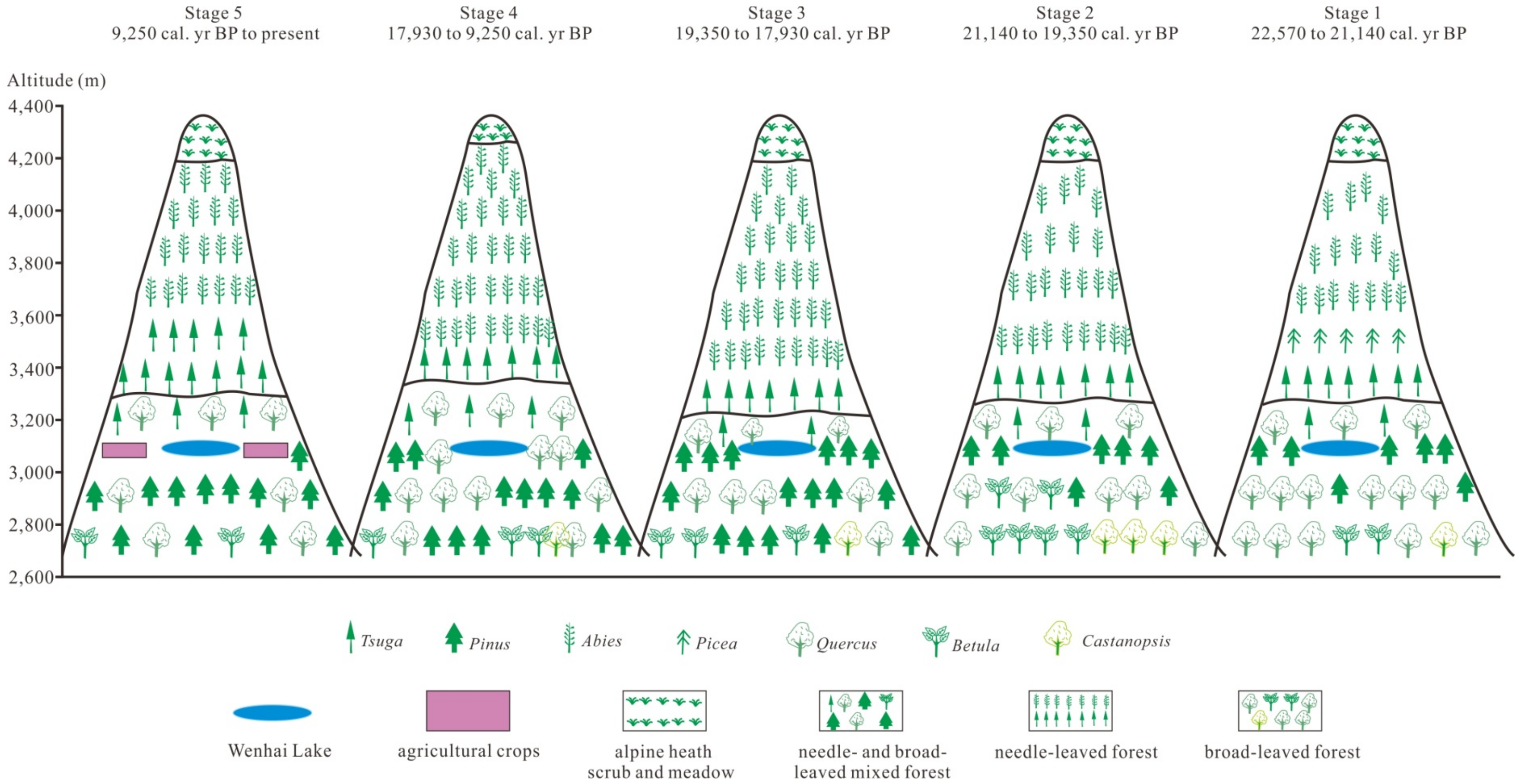

Stage 5
9,250 cal. yr BP to present
Stage 4
17,930 to 9,250 cal. yr BP
Stage 3
19,350 to 17,930 cal. yr BP
Stage 2
21,140 to 19,350 cal. yr BP
Stage 1
22,570 to 21,140 cal. yr BP
Altitude (m)
4,400
4,200
4,000
3,800
3,600
3,400
3,200
3,000
2,800
2,600
Tsuga
Pinus
Abies
Picea
Quercus
Betula
Castanopsis
Wenhai Lake
agricultural crops
alpine heath scrub and meadow
needle- and broad-leaved mixed forest
needle-leaved forest
broad-leaved forest

Figure 3