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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 is one of the studies covering a range of altitudes within this hotspot, and 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 coniferous *Pinus* and *Abies* and the drought-tolerant herb *Artemisia*, indicating a cool and dry climate. In the period between 21 140 and 19 350 cal. yr BP, the vegetation was still dominated by broad-leaved forest but with a notable increase in pollen of aquatic plants, implying a relatively warm and moderately humid climate. The period 19 350 to 17 930 cal. yr BP was a transition stage from broad-leaved forest to needle-leaved forest, reflecting a warm-humid climate at the beginning and a cold-dry one at the end. Between 17 930 and 9250 cal. yr BP, needle-leaved forest and broad-leaved forest alternated in dominance in the early stages, with the former taking the predominant position by the end of the period, suggesting a climate fluctuating between warm-humid and cold-dry. From 9250 cal. yr BP to present, the vegetation has been dominated by needle-leaved forest (comprising mainly *Pinus* and *Abies*), coupled with broad-leaved forest (mainly *Quercus* and *Betula*), reflecting a transition in climatic conditions from warm-humid to cold-humid. During this period, human activity increased in this region, with impacts on the vegetation which may be evidenced by the 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, in particular, in the Wenhai core can be correlated with that observed in the Haligu core (situated about 2 km away) between 2400 cal. yr BP and the present.

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1 Introduction

The Hengduan Mountains lie 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 ca. 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 and 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 5596 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, in this series of studies, we investigated

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changing climate and vegetation over the past 9300 years based on pollen analyses of a core 400 cm in depth from a wetland site at Haligu (3277 m) on the Jade Dragon Snow Mountain (Song et al., 2012). This paper in the series presents a 22 570 yr record of vegetational and climatic change from Wenhai Lake (3080 m), also on the Jade Dragon Snow Mountain. We aim to use pollen data to develop insights into the changing floristic diversity of the region during the Late Quaternary. This data will also be used to draw inferences about past climate and anthropogenic influences, and to compare study sites at different altitudes in the region to provide a better understanding of changes in the distinctly vertical vegetation zones that characterize the region.

2 Study area

Wenhai Lake (26°58′59″ N, 100°09′54″ E) 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 about 23 km northwest of Lijiang City. 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. Wenhai Lake is an open lake surrounded by high mountains, covering an area of about 0.16 km^2. It is a seasonal lake fed mainly by rainfall and glacial melt-water from the nearby mountains.

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 and precipitation measured at Lijiang (situated below the study site at about 2200 m), are 12.8 °C and 935 mm, respectively. About 90 % of the annual precipitation falls in summer, between June and October. The warmest

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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 study area is located within a vegetation "sub-domain" characterized by *Pinus yunnanensis* Franch. forest and *Picea-Abies* forest typical of northwestern-central Yunnan (WGYV, 1987). The local vegetation displays a distinct vertical zonation. On the mountains surrounding Wenhai Lake (3100–3500 m), the vegetation 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. 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 zone is now heavily influenced by human activities, such as felling of timber and grazing, so some patches are barren of vegetation. At higher elevations, between 3500 and 3800 m, the Jade Dragon Snow Mountain is cloaked in evergreen broad-leaved forest consisting of *Quercus pannosa* and *Cyclobalanopsis glauca* (Thunb.) Oerst, together with coniferous trees such as *Abies delaveyi* Franch., *Picea likiangensis* (Franch.) E. Pritz and *Larix potanini* Batalin. The forests are interspersed with meadows which are grazed by livestock. From 3800 to 4200 m, the vegetation is dominated by subalpine bush and meadow composed, among others, of *Rhododendron* spp., *Juniperus* spp., *Berberis* spp. and scattered *Sorbus* spp. Dwarf shrubs are present at this altitude, including *Caragana tibetica* (Maxim. ex C.K. Schenid.) Kom. and *Chesnya nubigena* (D.Don) Ali. Above 4200 m the vegetation is restricted mainly to herbaceous taxa including *Draba* spp., *Saxifraga* spp . and *Saussurea* spp.

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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 mod-

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ern 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 establishing a chronological control against which to decipher the vegetation and climate history in and surrounding Wenhai Lake. The sedimentation rates are ca. 0.1 mm yr^{-1} and 0.28 mm yr^{-1} for the depths of 0–155 cm and 155–320 cm, respectively. Ages of other depths are interpolated by assuming that the sedimentation rate is constant between the two dated samples.

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 Supplement). The palynomorphs were summed into four groups: conifers, broad-leaved plants, ferns and aquatics. Coniferous trees include *Pinus*, *Abies* and *Tsuga*. The broad-leaved taxa comprise angiosperm trees, shrubs and herbs, including *Quercus*, *Alnus*, *Artemisia*, Cyperaceae, Ericaceae and Polygonaceae. The ferns include Polypodiaceae, Athyriaceae and *Pteris*. The aquatic plants are *Myriophyllum* and *Zygnema*. The pollen assemblage is dominated by coniferous taxa, at percentages ranging from 66.8 % to 93.5 %, followed by broad-leaved elements (5.3–16.8 %), ferns (0.9–15.3 %) and aquatics (0–3.0 %). *Pinus* pollen (63–88.5 %) dominates in all six surface samples, accompanied by *Abies* (3.3–11.1 %), Polypodiaceae (0–10.6 %), *Quercus* (1.2–5.6 %), Ericaceae (0–4.1 %), Athyriaceae (0.2–2.8 %), Polygonaceae (0.2–2.4 %), Cyperaceae (0–1.1 %), and Gramineae (0–0.3 %). 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 Supplement). Some of the selected palynomorphs extracted from the core are illustrated in the Supplement.

A greater diversity of palynomorphs was recovered from the core samples than from the surface samples, which might suggest that surface samples fail to capture the local vegetation completely. 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

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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.

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

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(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.

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 %).

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Pollen zone 4 (190–80 cm: 17 930–9250 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 %).

Pollen zone 5 (80–0 cm: 9250 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 %).

5 Discussion and conclusions

5.1 22 570 yr vegetation and climate history at Wenhai

This present study provides a preliminary investigation into the vegetation and climate history at Wenhai Lake. The palynoflora found in the Wenhai core includes a large number of potential climate indicators. For instance, *Abies*, *Picea* and *Betula* are typically regarded as cold-tolerant taxa. *Pinus* usually grows in slightly warmer and moderately dry habitats. *Tsuga*, *Alnus*, Polygonaceae, Gramineae and Cyperaceae are considered to be hygrophilous plants. The occurrence of *Ephedra*, *Artemisia* and Chenopodiaceae normally indicates a dry environment. Evergreen sclerophyllous *Quercus* displays considerable ecological adaptability, and can adapt to dry or humid habitats (WGYV, 1987; Jarvis, 1993; Sun et al., 2003; Jiang et al., 2013).

Based on the climatic preferences of the major taxa recovered from the Wenhai core, the palynological record reveals a history of shifting vegetation and climate change in this region during the past 22 570 yr (Fig. 3). From 22 570 to 21 140 cal. yr BP (Pollen zone 1), the vegetation was dominated by broad-leaved forest (composed mainly of *Quercus*, *Betula* and *Castanopsis*) on the lower mountains surrounding the lake, with a few *Corylus*, *Ulmus* and Ericaceae trees also dispersed in the forest. Needle-leaved forest (mainly *Pinus* and *Abies*) was distributed on the upper mountains. *Picea* and *Ephedra* were also found in minute quantities. 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. Aquatic *Myriophyllum* and *Pediastrum* grew in the water at low concentrations. This pollen assemblage indicates a rather cold and dry climate during this period.

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The period between 21 140 and 19 350 cal. yr BP (Pollen zone 2) was marked by a notable increase in aquatic pollen and a continuing dominance of broad-leaved trees in the pollen sum of trees and shrubs. In addition, *Alnus* was found for the first time, while Polygonaceae and Athyriaceae showed a slight increase. This pollen assemblage suggests that the vegetation was dominated by broad-leaved forest as before, accompanied by needle-leaved forest, indicating a relatively warm and moderately humid climate condition with several climatic fluctuations during the 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 last stage. *Tsuga*, *Alnus*, Polygonaceae, Athyriaceae, *Myriophyllum* and *Pediastrum* were still visible, but their percentages gradually declined. This pollen assemblage reflects a transition from broad-leaved forest to needle-leaved forest. The climate of the period was warm and humid at the beginning, but shifted to cold and dry at the end.

Between 17 930 and 9250 cal. yr BP (Pollen zone 4), coniferous and broad-leaved trees dominated alternately to begin with, but coniferous trees become predominant by the end. This implies that the climate fluctuated between warm-humid and cold-dry, as evidenced by decreases and increases in conifers and *Quercus*, as well as the discontinuous occurrence of *Tsuga*, *Liquidambar*, Polygonaceae, Cyperaceae, *Myriophyllum*, *Pediastrum* and pteridophytes.

From 9250 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 4000–2400 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. The drought-tolerant herb *Artemisia* had a very low percentage. The hygrophilous herb Polygonaceae and fern Polypodiaceae experienced an increase, decrease and increase. This pollen assemblage indicates that the vegetation was dominated by needle-leaved forest (comprising mainly *Pinus* and *Abies*), coupled with broad-leaved forest (mainly *Quercus* and *Betula*), reflecting a transitional climate condition from warm-humid to cold-humid.

5.2 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 published the first of a series of studies covering a range of altitudes within the Hengduan Mountains (Song et al., 2012). The altitude of the previous study site, Haligu, is 3277 m, where there is no current human settlement. The present study area (3080 m), 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 2400 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

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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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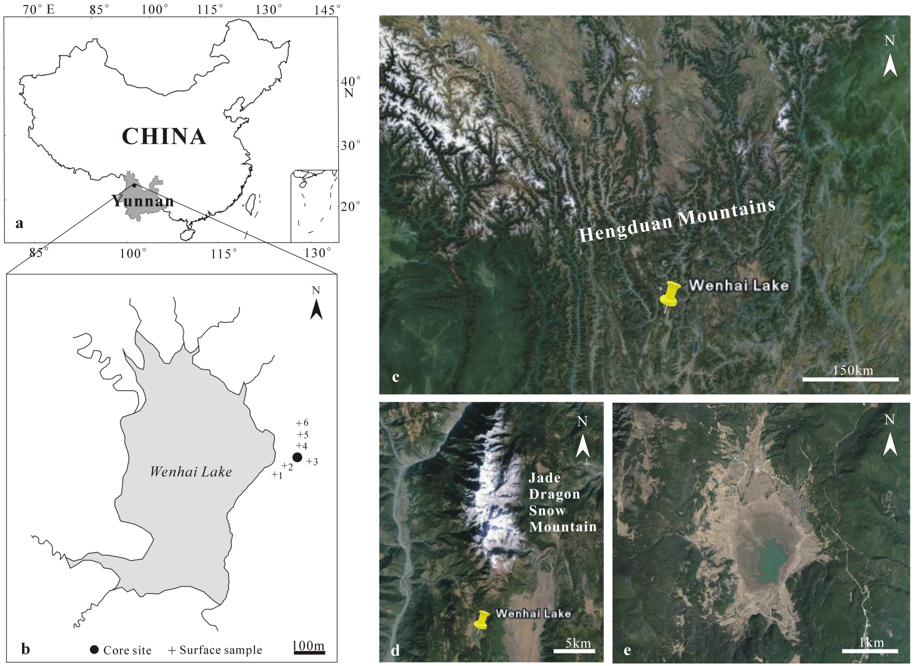

Figure 1. (a) The location of Wenhai Lake in northwestern Yunnan, China, **(b)** the position of core and surface soil samples, **(c)** the location of Wenhai Lake in the Hengduan Mountains, **(d)** the location of Wenhai Lake on the Jade Dragon Snow Mountain, **(e)** an enlarged photograph of Wenhai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

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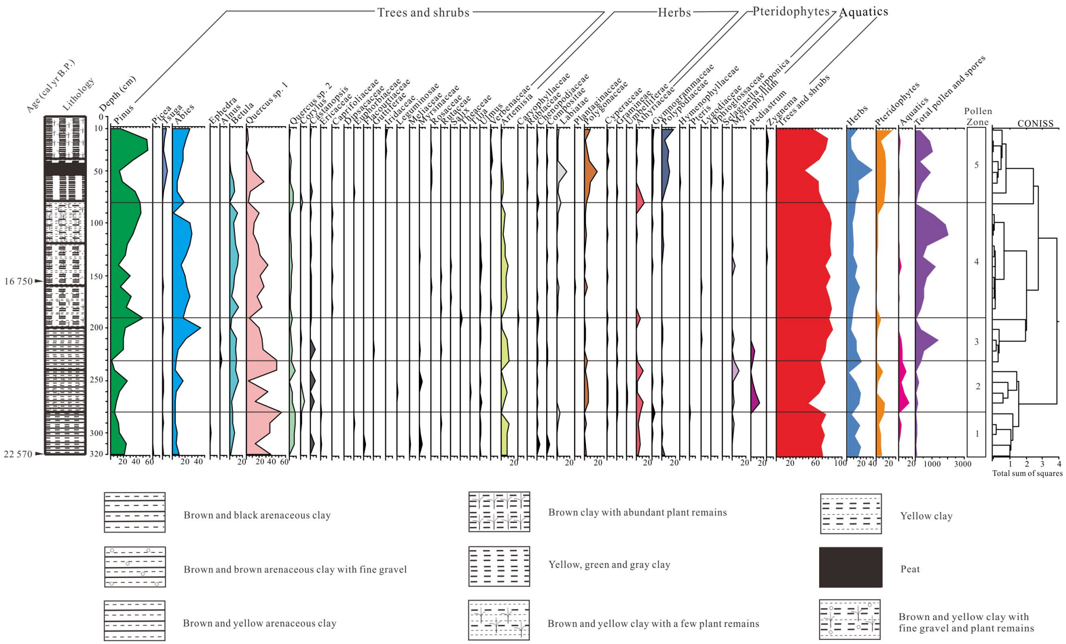

Figure 2. Pollen percentage diagram of selected taxa from Wenhai Lake, northwestern Yunnan, China.

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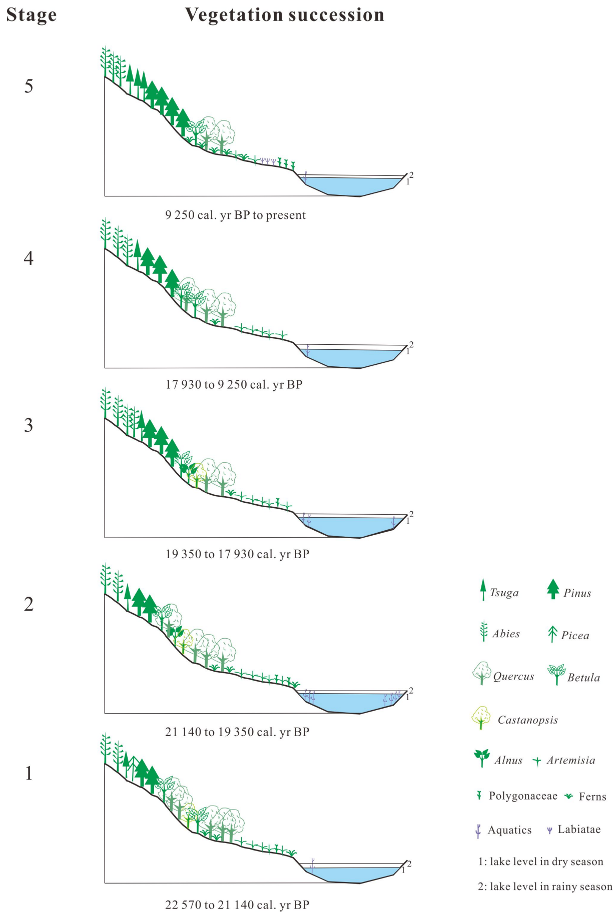

Figure 3. Inferred vegetation succession over the past 22 570 yr at Wenhai.

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