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An arid early Holocene revealed by palynological evidence for the north-east Tibetan Plateau

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Abstract. Situated in the triangle of the East Asian monsoon, the Indian monsoon, and the westerlies, the Holocene patterns of climate and vegetation changes on the north-east Tibetan Plateau are still unclear or even contradictory. By investigating the distribution of modern pollen taxa on the east Tibetan Plateau, we infer the past vegetation and climate since the last 14.2 ka BP (thousand years before present) from a fossil pollen record extracted from Gahai Lake (102.3133°E, 34.2398°N; 3444 m a.s.l.) together with multiple proxies (grain-size, contents of total organic carbon and total nitrogen) on the north-east Tibetan Plateau. Results indicate that the Gahai Basin was covered by arid alpine steppe or even desert between 14.2 and 7.4 ka BP with a mild and dry climate, and high percentages of arboreous pollen are thought to be long-distance wind transported grains. Montane forest (dominated by *Abies*, *Picea*, and *Pinus*) migrated into the Gahai Basin between 7.4 and 3.8 ka BP driven by wet and warm climatic conditions (the climate optimum within the Holocene) but reverted to alpine steppe between 3.8 and 2.3 ka BP, indicating a drying climate trend. After 2.3 ka BP, vegetation shifted to alpine meadow represented by increasing abundances of Cyperaceae, which may reflect a cooling climate. The strange pollen spectra with high abundances of Cyperaceae and total pollen concentrations after ca. 0.24 ka BP

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(1710 CE) could be an indication of disturbance by human activities to some extent, but needs more direct evidence to be confirmed. Our study confirms the occurrence of a climate optimum in the mid-Holocene on the north-east Tibetan Plateau, which is consistent with climate records from the fringe areas of the East Asian summer monsoon, and provides new insight into the evolution of the Asian monsoon system.

Keywords: Gahai Lake; pollen; climate reconstruction; vegetation evolution; last deglacial

1 Introduction

Vegetation, as an essential component in the terrestrial ecosystem, responds to and represents environmental and climatic changes well. Investigating the patterns and mechanisms of past vegetation changes can provide a reliable analogue for predicting future climate and vegetation changes (Mykleby et al., 2017; Zhao et al., 2017). Since the sharp climate warming during the last deglacial (after ca. 15 ka BP in the Northern Hemisphere; Wang et al., 2001; Andersen et al., 2004; Dykoski et al., 2005; Xu et al., 2013), the response of vegetation to climate warming could be a valuable palaeo-analogue for understanding current vegetation changes under global warming and for predicting future vegetation trends (Birks, 2019).

The north-east Tibetan Plateau lies in the transition between the East Asian summer monsoon, the Indian summer monsoon, and the westerlies; it is sensitive to climate change and is an ideal region to study past vegetation and climate variation (Bryson, 1986; An et al., 2012; Chen et al., 2016). Nevertheless, the climate records from different lacustrine sediments on the north-east Tibetan Plateau show a lack of consistency, for example, regarding the climatic conditions during the early Holocene. Some records reveal that the climate was relatively dry on the north-east Tibetan Plateau and controlled by the East Asian monsoon during the early Holocene (Shen et al., 2005; Herzschuh et al., 2006; Cheng et al., 2013), while other records such as those from Hala Lake and Genggahai Lake show that there was maximum water depth and hence climatic optimum in the early Holocene (Qiang et al., 2013; Yan and

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Wünnemann, 2014; Wang et al., 2021). Therefore, more studies are needed to clarify the early Holocene climatic conditions, which are necessary to resolve the environmental evolution of the north-east Tibetan Plateau.

Pollen plays an important role in reconstructing the past vegetation and climate owing to its preservation in various sediment types (Chevalier et al., 2020). However, pollen-based vegetation and climate reconstructions on the Tibetan Plateau are also confronted with challenges, for instance, the current quantitative reconstructions of vegetation and climate are based on pollen percentages, which can be biased when there is much exogenous arboreal pollen, especially in strata with extremely low pollen concentrations because the exogenous arboreal pollen will enlarge its proportion in the pollen spectra (Herzschuh. 2007; Ma et al., 2017; 2019). Exogenous arboreal pollen can be recognised in areas far away from forested regions, mainly because no trees grow around the lake or its adjacent areas nowadays, such as Luanhaizi Lake (Herzschuh et al., 2010), Donggi Cona Lake (Wang et al., 2014), Hala Lake (Hu et al., 2016), and Kuhai Lake (Wischnewski et al., 2011). Arboreal pollen can then be excluded in subsequent analysis to ensure the correct interpretation of vegetation and environment. However, it is somewhat difficult to recognise the contribution of exogenous pollen from areas near the forest on the eastern part of the Tibetan Plateau, which could seriously impact the results of pollen reconstruction, such as from Naleng Lake (Kramer et al., 2010a) and Qinghai Lake (Shen et al., 2005). Solving this issue of clarifying the influence of exogenous pollen is an important prerequisite for a better understanding of the early Holocene climate. Understanding the spatial distribution characteristics of modern pollen and their relationships may be an effective way to identify such arboreal pollen.

In this study, we integrate multi-proxy records (pollen, grain size, total organic carbon (TOC), total nitrogen (TN)) of Gahai Lake to reconstruct the climate and vegetation evolution since the last deglacial. We assess the dispersal ability and biotopes of the main pollen taxa in the pollen record by investigating the distribution of modern pollen and their relationship with climate. We attempt to recognise exogenous pollen

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and evaluate its influence on reconstruction results to determine whether the early Holocene of the north-east Tibetan Plateau was dry or wet.

2 Study area

Gahai Lake (102.3133°E, 34.2398°N; 3444 m a.s.l.) is situated in the upper reaches of the Yellow River on the north-east Tibetan Plateau, a transitional zone between the Tibetan Plateau, the mountainous area of Longnan, and the Loess Plateau (Fig. 1). Gahai Lake is a typical plateau interior freshwater lake, with a total area of 15 km^2 and a mean water depth ranging from 2 to 2.5 m. The water supply of the lake is mainly from precipitation, groundwater recharge, and surface runoff from surrounding mountains to the south and south-east including Qiongmuqiequ, Wenniqu, and Geqiongkuhe rivers, and there is a single outflow stream at the north-western end of the basin (Duan et al., 2016; Fig. 1). Gahai Lake belongs to the alpine humid climate zone, which is influenced by the West Pacific Subtropical High in summer and controlled by westerlies in winter. Climate characteristics are rain in the warm season, and large seasonal and diurnal temperature differences (Liang, 2006). Mean annual temperature of this region is 1.2℃ and mean annual precipitation is 782 mm, with about 80% of precipitation falling in the rainy season (from June to September), and mean annual evaporation is 1150 mm (Duan et al., 2016).

Vegetation cover in Gahai Basin exceeds 90%. There are abundant species in the grassland community, which is the intersection between various flora, and perennial herbs predominate. The dominant plant species include *Poa annua*, *Carex*, *Clintoniaudensis*, *Polygonum*, *Ranunculus japonicus*, *Potentilla fruticosa*, *Neyraudia reynaudiana*, and *Elymus nutans*. Forest is found in the eastern low mountains with a mosaic distribution of meadow and shrub, dominated by *Abies*, *Picea*, *Betula*, and Cupressaceae. *Picea* is found in damp areas at the foot of mountains and replaced by *Betula* as a transitional community after being cut down; *Abies* occurs on shady and semi-shady slopes between 3200 and 3400 m a.s.l.; Cupressaceae is distributed mostly on sunny and semi-sunny slopes of more than 35 degrees. This region belongs to a

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typical stockbreeding district, and the grazing activity focuses on the grassland. In addition, there is small-scale agricultural along the river valley at low elevations (Liang et al., 2006; Duan et al., 2016).

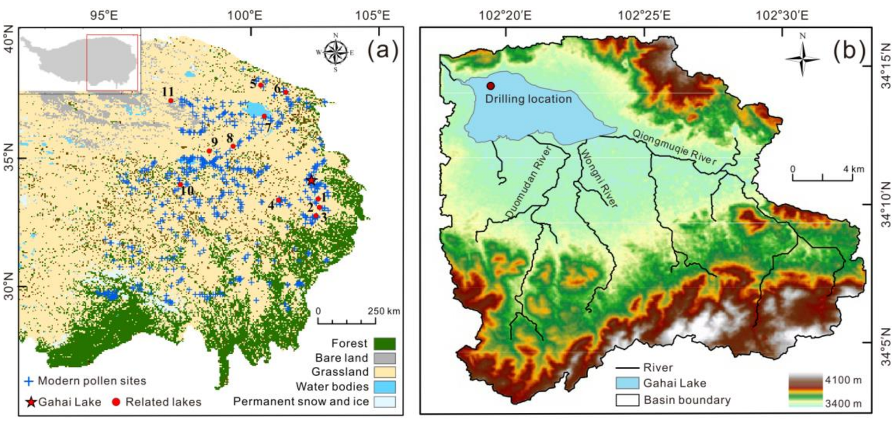

Figure 1. (a) Land-use map of the eastern Tibetan Plateau (Du, 2019). Lakes referred to in the text: 1, ZB08-C1; 2, ZB10-C14; 3, Hongyuan peatland; 4, Ximencuo Lake; 5, Dalianhai Lake; 6, Luanhaizi Lake; 7, Qinghai Lake; 8, Kuhai Lake; 9, Donggi Cona Lake; 10, Koucha Lake; 11, Hurleg Lake. (b) Catchment map of Gahai Lake.

3 Material and methods

3.1 Modern pollen data and their climate data

Our modern pollen dataset (n=731) is derived from the east Tibetan Plateau ranging from 94.07 to 103.02°E and from 29.13 to 38.48°N, with elevations from 2515 to 5008 m a.s.l.. These modern pollen data are mainly from the modern pollen database of China and Mongolia (Cao et al., 2014) and recently published pollen data for the east Tibetan Plateau (Cao et al., 2021; Wang et al., 2022). The pollen sites are generally evenly distributed across the east Tibetan Plateau, covering subalpine forest, alpine meadow, alpine steppe, and alpine desert (Fig. 1). Pollen sample types include topsoil, lake surface-sediments, and moss polsters mainly.

We selected four important climate variables including mean annual precipitation (P_{ann}), mean temperature of the warmest month (Mt_{wa}), mean temperature of the coldest month (Mt_{co}), and mean annual temperature (T_{ann}), together with elevation (Elev) to investigate the relationship between pollen assemblages and environment following previous studies (Lu et al., 2011; Herzschuh et al., 2011; Cao et al., 2021; Wang et al., 2022). Modern climatic data were obtained from the Chinese Meteorological Forcing Dataset (CMFD; gridded near-surface meteorological dataset), and each sample is assigned to the nearest pixel of the CMFD using the *fields* package version 13.3 (Nychka et al., 2021) of R (version 4.0.3; R Core Team, 2021). The detailed processes of obtaining climatic data are presented in the Fig. A1.

3.2 Sediment sampling and radiocarbon dating

A 329-cm-long sediment core (named GAH) was obtained using a UWITEC platform from the deepest part of Gahai Lake (ca. 2 m) in January 2019 (Fig. 1), and then transported to the Institute of the Tibetan Plateau Research for preservation. GAH was sub-sampled at 1 cm intervals, and all sub-samples were freeze-dried.

The age-depth model for GAH was established by ^{210}Pb, ^{137}Cs, and accelerator mass spectrometry (AMS) radiocarbon dating. The top 20 cm of the sediment at 1-cm intervals was measured for ^{210}Pb and ^{137}Cs at the School of Geographical Science, Nantong University. The constant rate of supply (CRS) model was selected to calculate the dates due to the non-monotonic variation of unsupported ^{210}Pb activity, as the results revealed that the ^{210}Pb dates were inconsistent with the ^{137}Cs peak of 1963 CE (Appleby, 2001). To solve this problem, the core was divided into two sections using $^{210}Pb_{ex}$ activity variation data using different formulae to calculate the dates and obtain a good effect. Finally, an age-depth model based on a ^{210}Pb-CRS model corrected by ^{137}Cs peak was generated (Fig. 4a). Twelve bulk organic sediment samples of 1-cm thickness were sent for AMS ^{14}C dating by Beta Analytic Inc., USA, owing to a lack of macrofossils (Table 2). The age-depth model was established using the Bayesian age–depth modelling in the *rbacon* package (version 2.5.7; Blaauw and Christen 2011; Blaauw et al., 2021) in R (R Core Team 2021) and the IntCal20 radiocarbon calibration curve (Reimer et al., 2020).

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3.3 Laboratory analysis

The pollen samples (0.6–22 g; *n*=111; at 1 to 2 cm intervals) were treated with hydrofluoric acid sieving-analysis (Fægri and Iversen, 1975). *Lycopodium* spores (ca. 27,560 grains) were added to the samples to calculate the pollen concentration, then samples were processed with 10% HCl, 10% KOH, and 36% HF, and sieved through a 7 μm nylon mesh, followed by acetolysis (9:1 mixture of acetic anhydride and sulphuric acid) treatment. Finally, glycerin was added to preserve the samples. The pollen taxa were identified and counted with a 400x LEICA DM 2500 optical microscope, with the aid of modern pollen reference slides collected from the eastern and central Tibetan Plateau (including 401 common species of alpine meadow; Cao et al., 2020) and published atlases for pollen and spores (Wang et al., 1995; Tang et al., 2017). At least 100 terrestrial pollen grains were counted for most samples, except for 10 samples owing to extremely low pollen concentration; and more than 3000 *Lycopodium* spores were counted for each sample above 176 cm. Because of the low pollen concentrations below the depth 176 cm, only pollen data for the upper part of the core are presented and discussed.

For the grain-size analysis, freeze-dried samples (1 g; *n*=176; above 176 cm) were treated with 30% H_2O_2 to remove organic matter and 10% HCl to remove carbonate, cleaned with deionized water and kept stable for 24 h, before adding 0.5 N sodium hexametaphosphate (10 ml) and undergoing ultrasonic cleaning for 10 minutes. A laser diffraction particle size analyser MASTERSIZER 3000 (Chen et al., 2013) was used, with each sample being tested 3 times and their average value used in the final grain-size data.

A total of 176 samples were analysed to obtain organic matter change since the last deglacial, including TN and TOC. Catalysts were added to freeze-dried samples and reacted quickly. TN was measured with an Elementar element analyser (CNS analyser, Vario MAX Cube)/Elementar Vario EL III which has a measurement accuracy of 0.001. TOC was measured with a Vario MAX C analyser, and has the same accuracy as TN. All samples were ground to ensure sufficient reaction before testing. The C/N

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ratio was calculated by dividing TOC by TN.

3.4 Numerical analyses

Ordination analyses were employed to investigate the modern relationship between pollen taxa and climatic variables for the eastern Tibetan Plateau. Pollen taxa (with ≥10% maximum and ≥30 occurrences) from the 731 modern pollen assemblages were used for detrended correspondence analysis (DCA; Hill and Gauch, 1980). The length of the first axis of the pollen data was 3.29 SD (standard deviation units), indicating that a linear response model is suitable for the modern pollen dataset (ter Braak and Verdonschot, 1995). Hence, we performed redundancy analysis (RDA) to visualise the distribution of pollen species and sampling sites along the climatic gradients. We used the variance inflation factor (VIF) to determine high collinearities within the model, and stopped adding variables to ensure all VIF values are lower than 20 (ter Braak and Prentice, 1988; Table 1). All ordination analyses were run using the *rda* function in the *rioja* package version 0.9–26 (Oksanen et al., 2019) in R, using square-root transformed modern pollen percentages to optimise the signal-to-noise ratio (Prentice, 1980).

For the fossil pollen dataset obtained from GAH, 22 pollen taxa (those present in at least 3 samples and with a ≥3% maximum) with square-root transformed percentages were selected for ordination analyses. The length of the first axis was 1.67 SD, indicating a principal component analysis (PCA) is suitable to investigate the relationship between the pollen taxa. PCA was run using the *rda* function in the *vegan* package (version 2.5-4; Oksanen et al., 2019) in R.

In addition, weighted-averaging partial least squares (WA-PLS) was employed to establish a pollen–climate transfer function using the modern pollen dataset, and to quantitatively reconstruct past climate for the GAH pollen record. More details of the reconstruction are presented in the Supplement.

Table 1. Summary statistics for redundancy analysis (RDA) with 19 pollen taxa and four climate variables. VIF: variance inflation factor; P_{ann}: mean annual precipitation (mm); Mt_{co}: mean

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temperature of the coldest month (°C); Mt_{wa}: mean temperature of the warmest month (°C); T_{ann}: mean annual temperature (°C); and Elev: elevation (m a.s.l).

Climate variables	VIF (without T_{ann})	VIF (add T_{ann})	Climate variables as sole predictor	Marginal contribution based on climate variables	
			Explained variance (%)	Explained variance (%)	*p*-value
P_{ann}	3.0	3.1	5.2	7.1	0.001
Mt_{co}	4.5	133.6	4.9	0.3	0.001
Mt_{wa}	6.5	111.7	3.7	5.7	0.001
Elev	2.5	3.0	4.5	0.2	0.001
T_{ann}	-	403.9	-	-	-

4 Results

4.1 Relationships of pollen taxa to climatic variables and elevation

The modern pollen dataset for the east Tibetan Plateau contains 107 pollen taxa and covers a long P_{ann} gradient (161–963 mm) and broad Mt_{wa} gradient (1.8–18.5 °C) (Fig. 2; A1). High abundances of arboreal pollen taxa occur in areas with warm and wet climate, for instance, *Abies*, *Quercus* (evergreen, E), *Corylus*, and *Carpinus* are mainly distributed in regions with high P_{ann} and Mt_{co} (Fig. 2; A1). Although high abundances of *Pinus*, *Picea*, and *Betula* are also restricted to warm and wet areas, they are widely distributed and appear even in extreme drought sampling sites (Fig. 2). Drought-tolerant species such as Chenopodiaceae and *Ephedra* are restricted to regions with low P_{ann} and high Mt_{wa}, and they have quite low abundances in wet areas (Fig. 2).

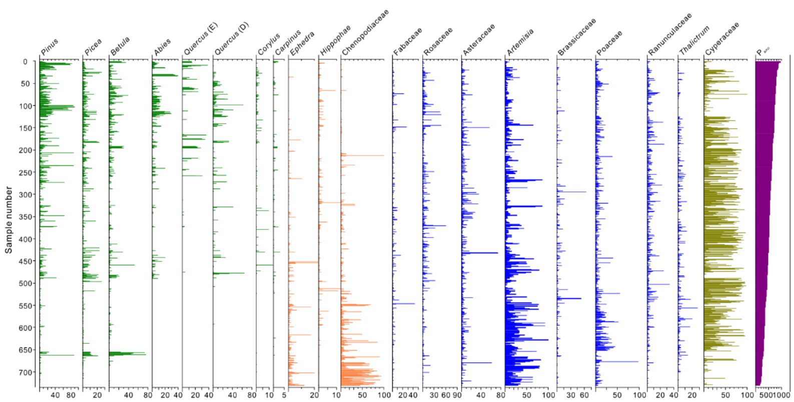

Figure 2. Pollen assemblages of surface sediment samples with annual precipitation (P_{ann}) from

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the eastern Tibetan Plateau.

Redundancy analysis shows that the first two axes explain 28% of the pollen data (axis 1: 15.5%; axis 2: 12.5%; Fig. 3). Arboreal pollen taxa are located in the left of the biplot and are positively correlated with P_{ann} and Mt_{co}. Asteraceae, Poaceae, *Thalictrum*, Ranunculaceae, Caryophyllaceae, and Cyperaceae show a negative relationship with Mt_{wa} and Mt_{co} while positive with Elev, and are situated in the lower right of the biplot. Drought-tolerant pollen including Chenopodiaceae, *Artemisia*, and *Ephedra* are situated at the upper right of the biplot, showing positive correlations with temperature variables and negative correlations with precipitation (Fig. 3).

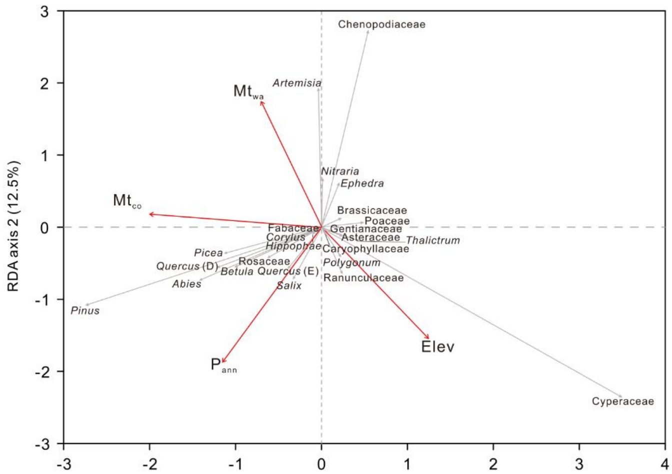

Figure 3. Redundancy analysis (RDA) of modern pollen samples along with three climate variables and elevation.

4.2 Sedimentary lithology and chronology

The sedimentary lithology of the GAH core is comprised of black silt in the upper part (0–99 cm), brown clay in the central part (99–240 cm), and dark-brown fine silt in the lower part (240–329 cm; Fig. 4). Our study concentrates on the vegetation and environment evolution of the upper 176 cm due to the extremely low pollen concentrations in the lower part, insufficient for statistical analyses.

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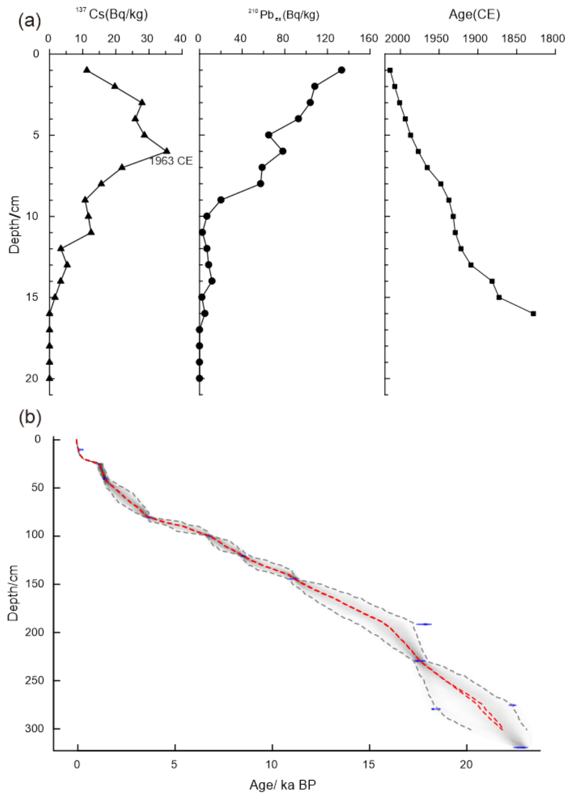

Figure 4. Age-depth model of the Gahai Lake sediment core derived from ^{137}Cs, ^{210}Pb, and ^{14}C dating. (a) Black line with triangles: ^{137}Cs age; black line with solid circles: ^{210}Pb:^{210}Pbex age; black line with squares: mean age based on annual lamination counting. (b) Age-depth curve based on a ^{210}Pb profile of recent sediments and 13 AMS radiocarbon dates from Gahai Lake. The range of the two grey dashed lines indicate the 95% confidence intervals, and the red dashed lines show the single "best" model based on the weighted mean age for each depth.

The chronology of the upper 20 cm sediment is established by the ^{210}Pb-CRS model, with dates falling between 1828 and 2013 CE. The AMS ^{14}C ages of GAH exhibit a linear regression with depth, and the ages of the upper 20 cm are calculated based on their relationship (Table 2). The age difference between ^{14}C and ^{210}Pb of the same depth is considered as the reservoir age. We selected two depths (6 cm and 10 cm) to calculate an average to reduce errors and obtained a reservoir age of 483 years. The age-depth model suggests that the basal age of GAH is about 24 ka BP, and the

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sedimentation rate is relatively stable (Fig. 4).

Table 2. AMS radiocarbon dates for Gahai Lake

Lab ID	Depth (cm)	$\delta^{13}C$ (‰)	^{14}C age (yr BP)	Error (±yr)
Beta-546102	10	-25.6	440	30
Beta-546103	25	-25.1	1740	30
Beta-539751	40	-25.7	1960	30
Beta-539752	80	-24.8	3880	30
Beta-546104	99	-24.3	6390	30
Beta-539753	120	-22.1	8180	40
Beta-546105	144	-22.9	10240	30
Beta-575823	191	-24.4	15070	40
Beta-546120	229	-25.4	14870	50
Beta-550230	275	-23.5	18930	60
Beta-546121	279	-22.6	15550	50
Beta-546122	319	-20.5	19440	70

4.3 Pollen record of GAH since the last deglacial

In our study, 52 pollen taxa were identified in the 111 samples from the upper part of GAH (0–176 cm), with Cyperaceae, *Pinus*, Asteraceae, and *Artemisia* as dominant taxa, while Poaceae, Ranunculaceae, *Ulmus*, and *Picea* are common taxa. The pollen record can be demarcated into four zones (Fig. 5). Pollen concertation is extremely low (mean 33.5 grains/g) before 7.4 ka BP, and the pollen spectra are dominated by arboreal pollen taxa including *Pinus*, *Picea*, *Ulmus*, and *Betula*, together with abundant drought-tolerant pollen taxa (such as Chenopodiaceae and *Ephedra*). Pollen concertation increases remarkably after 7.4 ka BP, and drought-tolerant pollen taxa decrease while *Pinus* increases in the pollen spectra. Between 7.4 and 2.3 ka BP, *Pinus* and *Picea* decrease sharply, while *Artemisia*, Poaceae, Asteraceae, and *Thalictrum* increase significantly. Pollen concertation increases greatly and the pollen spectra are dominated by Cyperaceae after 2.3 ka BP. Cyperaceae rises sharply and becomes overwhelmingly dominant in the pollen spectra, and the pollen concentration also increases strongly in the last 0.24 ka BP (Fig. 5).

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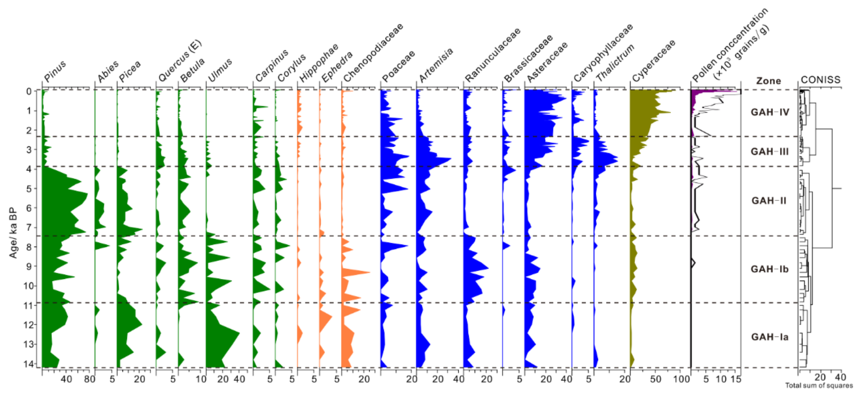

Figure 5. Pollen diagram of the main fossil pollen taxa in Gahai Lake, north-east Tibetan Plateau.

4.4 PCA results

The first two axes of the principal component analysis (PCA) explain 72% of the total pollen data (axis 1: 59.2%; axis 2: 12.8%; Fig. 6a). The PCA divides arboreal pollen taxa (such as *Pinus*, *Picea*, *Betula*, *Ulmus*), alpine steppe taxa (including *Artemisia*, Poaceae, Asteraceae), and meadow taxa (Cyperaceae) into three clear groups. In addition, pollen samples of Zones I and II are consistent with arboreal taxa, pollen samples from Zone III contain abundant steppe taxa, while samples in Zone IV are dominated by Cyperaceae (Fig. 6b).

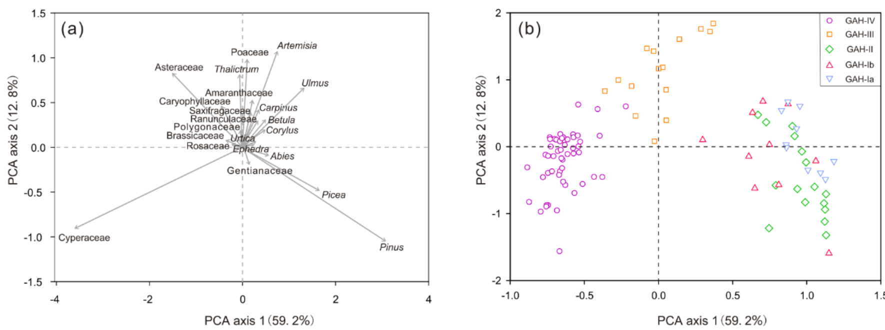

Figure 6. Principal component analysis (PCA) of fossil pollen taxa (a) and pollen zones (b) from Gahai Lake (see Fig. 5 for the pollen zones).

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4.5 Sedimentology and conventional geochemistry

The grain-size results of GAH suggest an increasing trend generally which could be divided into four stages, with the silt fraction (4–63 μm) accounting for the maximal proportion (58–75%; mean 66%) in general (Fig. 7). The clay fraction (<4 μm; 15–33%; mean 23%) forms the highest proportion during 14.2–10.8 ka BP, while median grain size is very low. The silt fraction increases while the clay fraction decreases during 10.8–3.8 ka BP, and the sand fraction (>63 μm) and median grain size first increase and then decrease. The sand fraction and median grain size slightly increase while the clay fraction tends to decrease after 3.8 ka BP, and the silt fraction increases first and then decreases.

TOC, TN, and C/N ratios fluctuate greatly since 14.2 ka BP, and TOC and TN present simultaneous change trends (Fig. 7). TOC and TN values are remarkably low and C/N ratios are lower than 10 between 14.2 and 7 ka BP. TOC, TN, and C/N ratios increase significantly and C/N ratios are higher than 10 between 7 and 4 ka BP. TOC, TN, and C/N ratios reduce slightly but are still higher than 10 after 4 ka BP. TOC and TN values increase drastically while C/N ratios have no obvious change during the last 0.24 ka BP (since 1710 CE).

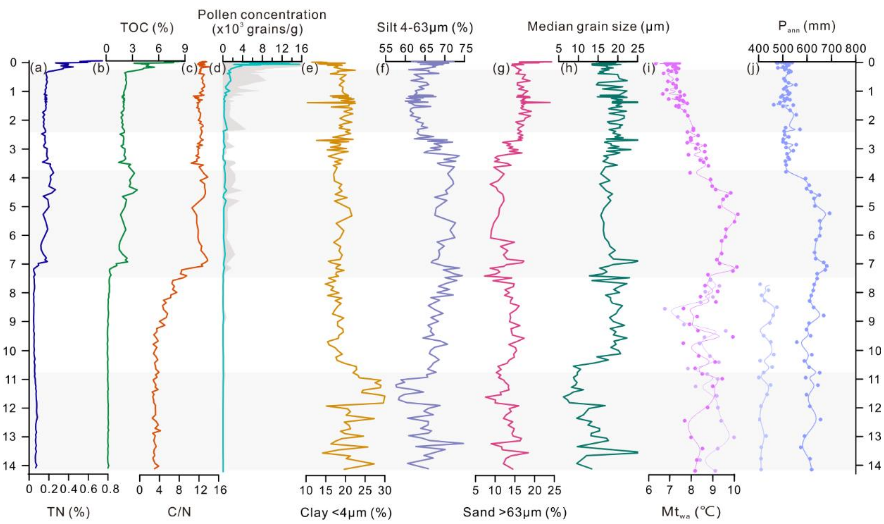

Figure 7. Comparison of the multi-proxy records from Gahai Lake. (a) Total nitrogen (TN), (b)

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total organic carbon (TOC), (c) C/N ratio, (d) pollen concentration, (e-h) grain size distribution and median grain size, (i) quantitative reconstruction of mean temperature of the warmest month (Mt_{wa}). Purple curve indicates the reconstruction based on the pollen assemblages including the arboreal pollen and the light purple curve represents the reconstruction based on the pollen assemblages removing the arboreal pollen (before 7.4 ka only). (j) quantitative reconstruction of mean annual precipitation (P_{ann}). Blue curve is the reconstruction based on the pollen assemblages including the arboreal pollen and the light blue curve is the reconstruction based on the pollen assemblages without the arboreal pollen (before 7.4 ka only). The grey shading denotes the different pollen zones of Gahai Lake.

5 Discussion

5.1 Patterns and interpretation of the proxies

TOC is a proxy for the abundance of organic matter which originates from aquatic organisms and terrestrial vegetation, and TN represents the nutritional conditions of the lake. C/N ratios are used to trace the plant source of the organic matter. C/N ratios of the nonvascular aquatic plants and algae are generally between 4 and 10, and C/N ratios >20 indicate that organic matter mainly originates from terrestrial vascular plants. Ratios ranging from 10 to 20 suggest that the organic matter is derived from a mixture of aquatic and terrestrial plants (Meyers and Ishiwatari, 1993; Meyers, 2003; Kasper et al., 2015).

The grain-size composition of lake sediments can be used to trace the source of clastic particles, aeolian activity, and water-level fluctuations, which reflect the regional climate conditions (Håkanson and Jansson, 1983; Liu et al., 2016). The sources of lacustrine sediments include clastic materials carried by inflow rivers, aeolian inputs, and authigenic chemical deposition (Xiao et al., 2013). Particle-size analyses from lacustrine sediments and modern surface sediments suggest that the sand fraction (>63 μm) or particles >50 μm are mainly transported by wind and could be an indicator of aeolian activity (Qiang et al., 2014; Wang et al., 2015; Liu et al., 2016). Particle-size variation can reflect changes in water level, with coarser grains indicating a rise in water level as river discharge would need to be greater to transport the heavier grains, and hence suggesting an increase in precipitation (Håkanson and Jansson, 1983; Liu et al., 2008). Therefore, we speculate that a high silt fraction (4–63 μm) in Gahai Lake reflects an increase in the lake water level, while a high clay fraction (<4 μm) content reflects a low stand. In addition, a high proportion of the sand fraction (>63μm) indicates aeolian activity intensity. The variation of the median grain size is consistent with the sand fraction thus also reflecting aeolian deposition.

5.2 Determination of exogenous pollen grains

According to modern pollen research from the Tibetan Plateau and northern China, *Pinus*, *Picea*, and *Betula* are dominant pollen taxa in forest samples, and these taxa have a good diffusion capacity and are easily transported for long distances from their pollen source (Lu et al. 2004; Ma et al., 2008; Ma et al., 2015). *Ulmus* also has a good diffusion and can spread up to 40 km away, and can therefore be a regional vegetation component (Xu et al., 2007). The main arboreal pollen taxa in the GAH core are thus highly diffusive species which may bias the interpretation of the source of arboreal pollen.

The main pollen taxa have notable spatial distribution characteristics owing to their ecological environment based on modern pollen research and the modern pollen dataset. Arboreal taxa including *Pinus*, *Picea*, and *Betula* are mainly distributed in a warm and humid environment (Lu et al., 2004). *Ulmus* is a drought-tolerant and light-demanding plant which can survive at precipitation levels lower than 200 mm per year (Shen et al., 2005). Previous modern pollen studies reveal that Chenopodiaceae and *Ephedra* are commonly found in the desert, indicating a tolerance for dry climatic conditions (Yu et al., 2001; Huang et al., 2018; Qin et al., 2021); and our modern pollen dataset for the east Tibetan Plateau suggests that xerophilous taxa such as *Ephedra* and Chenopodiaceae are restricted to areas with P_{ann} lower than 400 mm, and almost absent in samples with high precipitation (Fig. 2). Fossil pollen spectra from the Tibetan Plateau with abundant arboreal pollen taxa together with low pollen

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concentrations are considered to represent extreme arid conditions and sparse vegetation (Kramer et al., 2010b; Ma et al., 2019). Therefore, we argue that the arboreal pollen including *Pinus*, *Picea*, and *Ulmus* has been transported by wind from beyond the watershed, and that the high abundance of drought-tolerant herbaceous taxa (weak dispersal ability) and low pollen concentrations indicate a sparse vegetation cover around the lake between 14.2 and 7.4 ka BP, suggesting an extremely arid climate.

5.3 Evolution of vegetation and climate history since the last glacial

Palaeo-vegetation and palaeo-climate is reconstructed based on the fossil pollen, TOC, TN, C/N ratios, and grain-size record of Gahai Lake since the last deglacial.

From 14.2 to 10.8 ka BP, alpine steppe or desert covered the study area with the arboreal pollen derived from the surrounding mountains in the south-east of the basin. Pollen-based past P_{ann} reconstructions are likely to be overestimated since the exogenous arboreal pollen has not been excluded from the pollen spectra. Remarkably, however, reconstructed Mt_{wa} shows no bias from these exogenous arboreal pollen, thus the climate was probably mild and arid during this period (Fig. 7). Quite low TOC and TN contents, and C/N ratios below four suggest that the organic matter is mainly derived from aquatic plants, and also imply low terrestrial biomass productivity (Fig. 7; Zhu et al., 2015). Clay fraction reaches its maximum value, reflecting a low water level and weak aeolian activity (Fig. 7). In summary, Gahai was probably a small and shallow pond under a mild, arid climate during this period, with the surrounding vegetation dominated by alpine steppe or desert.

From 10.8 to 7.4 ka BP, Ranunculaceae and Cyperaceae show a slight increase, and alpine steppe occurs across the region (Fig. 5). The reconstruction suggests that Mt_{wa} decreases compared with the former stage, whereas reconstructed P_{ann} still reflects the exaggerated contribution of exogenous arboreal pollen (Fig. 7). TOC and C/N ratios rise during the early Holocene, implying an increase in biological productivity although still mainly from aquatic plants (Fig. 7). The silt and sand fractions and

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median grain size significantly increase, while the clay fraction decreases sharply, indicating that the water level rose and that aeolian activity strengthened during the early Holocene (Fig. 7). Therefore, we infer that the Gahai Basin had a cold and arid climate with enhanced wind strength during the early Holocene, and an alpine steppe vegetation while the lake had an increased water level.

The pollen concentration, silt fraction, TOC, and TN remarkably increase, and C/N ratios above 10 suggest that the climate and vegetation greatly improved after 7.4 ka BP to reach an optimum. Gahai Lake was at a high stand with increased terrestrial organic matter input (Fig. 7). We infer that Gahai Lake grew from a small pond and that the pollen spectra mainly reflect vegetation change within the catchment, with the reconstructed P_{ann} and Mt_{wa} reflecting the regional climate variation with weak influence from exogenous pollen during the mid-Holocene (Fig. 7). The pollen spectra are dominated by *Pinus* and *Picea* while drought-tolerant taxa (such as Chenopodiaceae and *Ephedra*) have a low abundance, indicating a vegetation shift from alpine steppe to montane forest between 7.4 and 3.8 ka BP (Ma et al., 2008; Zhao et al., 2009), under a warm and wet climate (P_{ann} and Mt_{wa} reach their peaks; Fig. 7). In addition, the sand fraction and median grain size slightly decline suggesting weaker aeolian activity during this period (Fig. 7).

During 3.8 to 2.3 ka BP, the pollen spectra are characterised by a high percentage of Poaceae, *Artemisia*, and Asteraceae (major component of alpine steppe), and arboreal pollen taxa, especially *Pinus* and *Picea*, sharply decrease, indicating the tree-line retreated to a lower elevation and a shift in vegetation type to alpine steppe (Herzschuh et al., 2010; Shen et al., 2021; Fig. 5). Reconstructed P_{ann} and Mt_{wa} decrease significantly, suggesting mild and arid climatic conditions (Fig. 7). TOC, TN, and C/N ratios slightly decrease compared with the previous stage, suggesting the weakened input of organic matter although the source remains unchanged (Fig. 7). The silt fraction substantially decreases while the sand fraction and median grain size have an increasing trend, suggesting weaker hydrodynamic conditions and strengthened aeolian activity (Fig. 7). In brief, the climate turned mild and arid and aeolian activity strengthened. Alpine steppe dominated across the region during this period.

From 2.3 to 0.24 ka BP, the dominant taxa change from alpine steppe (Poaceae, *Artemisia*, and Asteraceae) components (Ma et al., 2015; Qin et al., 2021) to alpine meadow (Cyperaceae) (Herzschuh et al., 2007; 2010; Fig. 5), and Mt_{wa} reconstruction reveals a cold environment (Fig. 7). TOC, TN, and C/N ratios suggest the total biogenic productivity input and its source has little changed compared with the previous stage (Fig. 7). Silt fraction decreases while the sand fraction and median grain size increase, indicating weaker water dynamics and enhanced aeolian activity.

After 0.24 ka BP (1710 CE), the pollen spectra are dominated by Cyperaceae (maximum, 95%; Fig. 5). Previous vegetation investigations suggest that overgrazing causes the proportion of Cyperaceae to increase and become the dominant taxon, and thus could be an indicator of human activities (Yuan et al., 2004; Dong et al., 2004; Miehe et al., 2014; Lin et al., 2016). Hence the vegetation during this period could have been disturbed by human activities. In addition, TOC, TN, and pollen concentration notably increase, indicating terrestrial material input strengthened, possibly as a result of increased surface erosion (silt fraction increases; Fig. 7) due to the destruction of vegetation by human activities.

5.4 Comparison of the regional climate and vegetation records from the north-east Tibetan Plateau in the early Holocene

Climate and vegetation as revealed by pollen records covering the early Holocene on the north-east Tibetan Plateau are inconsistent, which may be due to the following reasons: local factors have a greater effect than regional climate (Chen et al., 2020); the distance of sampling sites from forested areas affects the results of vegetation reconstruction (Sun et al., 2017); and different climatic factors influence the regional vegetation distribution of the eastern Tibetan Plateau (Zhao et al., 2011). Based on the results of TOC, TN, grain size, and pollen analysis, we infer that Gahai Lake was surrounded by alpine steppe vegetation under cool and arid climatic conditions, and

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that the arboreal pollen was mainly transported by wind from the surrounding mountains during the early Holocene. Other records from the north-east Tibetan Plateau confirm these general features of climate and vegetation during the early Holocene. For example, results from an adjacent peatland show that the climate and vegetation of the Zoige Basin and Nianbaoyeze Mountains reached their optimum during the mid-Holocene and had a cooler temperature and lower humidity during the early Holocene (Zhou et al., 2010; Zhao et al., 2011; Sun et al., 2017; Herzschuh et al., 2014). A reconstruction from Hurleg Lake also indicates that it was at a low stand during the early Holocene and that the vegetation type was desert or desert steppe (Zhao et al., 2007; Fan et al., 2014). Cheng et al. (2009) analyse the pollen record of Dalianhai Lake (from 16 ka BP) and conclude that this region had a dry climate and was covered by steppe desert during the early Holocene. Multi-proxy records from Qinghai Lake including pollen, carbonate, TOC, TN, $\delta^{13}C$ of organic matter (Shen et al., 2005), redness records (Ji et al., 2005), and lake level (Liu et al., 2015) reveal that this region had a dry climate and weak East Asian summer monsoon (Chen et al., 2016). Similar records are found from Koucha Lake (Herzschuh et al., 2009), Kuhai Lake (Wischnewski et al., 2011), Luanhaizi Lake (Herzschuh et al., 2005; 2010), and the arid region of central Asian moisture variation based on eleven records integrated during the early Holocene. (Chen et al., 2008; 2020). The pollen assemblages of Donggi Cona Lake show a high percentage of *Ephedra*, which suggests an arid environment in the early Holocene, although the quantitative reconstruction shows this period was the wettest stage in the Holocene (Tian et al., 2014; Huang et al., 2018). Based on the above investigations, we can conclude that the climate was arid on the north-east Tibetan Plateau during the early Holocene.

6. Conclusions

Based on modern pollen investigations for the east Tibetan Plateau, arboreal pollen can be determined as exogenous taxa when they appear together with drought-tolerant taxa and low pollen concentrations in fossil pollen spectra. The Gahai Basin was covered by the alpine steppe or desert under a cold and dry climate during 14.2–7.4 ka BP; montane forest migrated into the basin and the climate reached an optimum between 7.4 and 3.8 ka BP according to the evidence of TN, TOC, C/N, and grain-size records; the vegetation reverted to alpine steppe owing to a drying climate during 3.8 and 2.3 ka BP, after which steppe was replaced by alpine meadow as the climate cooled. In addition, the vegetation showed signs of being influenced by human activity during the last 0.24 ka BP.

Data availability. The data used in this study can be obtained from the corresponding author Xianyong Cao (xcao@itpcas.ac.cn).

Author contribution. NW extracted and identified pollen samples, analyzed pollen data and wrote manuscript; LL, XH, and YZ participated in sample collecting and data analysis; HW contributed to the detailed comments; XC designed this study and led interpretation. All authors commented and improved manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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Appendix

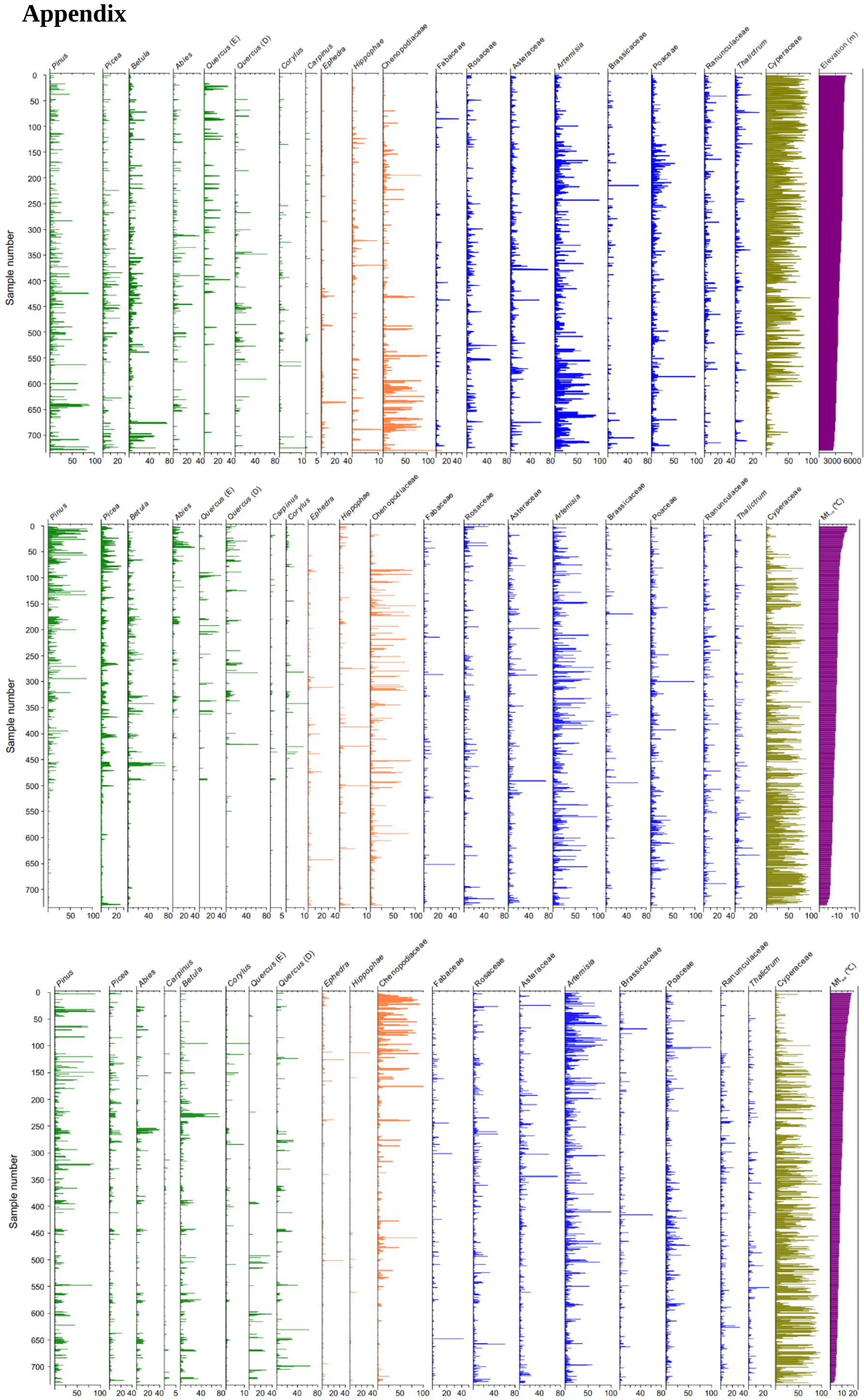

Figure A1. Pollen assemblage of the surface sediment samples with climate data (Elev, Mt$_{co}$, and

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Mt_{wa}) from eastern Tibetan Plateau. Elev: Elevation (m); Mt_{co}: mean temperature of the coldest month (°C); Mt_{wa}: mean temperature of the warmest month (°C).