Quaternary Research 73 (2010) 59–69

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Late Holocene vegetation and climate oscillations in the Qaidam Basin of the northeastern Tibetan Plateau

Yan Zhao [a,*], Zicheng Yu [a,b], Xiuju Liu [c], Cheng Zhao [b], Fahu Chen [a], Ke Zhang [a]

[a] MOE Key Laboratory of Western China's Environmental System, College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China
[b] Department of Earth and Environmental Sciences, Lehigh University, 31 Williams Drive, Bethlehem, PA 18015, USA
[c] Large Lakes Observatory, University of Minnesota, 2205 East 5th Street, Duluth, MN 55812, USA

ARTICLE INFO

Article history:
Received 14 April 2008
Available online 28 February 2009

Keywords:
Late Holocene
Artemisia/Chenopodiaceae pollen ratio
Fossil pollen
Climate change
Qaidam Basin
Tibetan Plateau

ABSTRACT

Pollen evidence from sediment cores at Hurleg and Toson lakes in the Qaidam Basin was obtained to examine vegetation and climatic change in the northeastern Qinghai-Tibetan Plateau. The chronologies were controlled by ^{210}Pb and ^{137}Cs analysis and AMS ^{14}C dating. Pollen assemblages from both lakes are dominated by Chenopodiaceae (~40%), *Artemisia* (~30–35%) and Poaceae (~20–25%), with continued occurrence but low abundance of *Nitraria*, *Ephedra*, and Cyperaceae. *Artemisia*/Chenopodiaceae (A/C) pollen ratios from two lakes show coherent large oscillations at centennial timescale during the last 1000 yr. A/C ratios were high around AD 1170, 1270, 1450, 1700 and 1920, suggesting that the vegetation was more "steppe-like" under a relatively moist climate than that during the intervening periods. Wet-dry climate shifts at the two lakes (2800 m asl) are in opposite phases to precipitation changes derived from tree-ring records in the surrounding mountains (>3700 m asl) and to pollen and snow accumulation records from Dunde ice core (5300 m asl), showing that a dry climate in the basin corresponds with a wet interval in the mountains, especially around AD 1600. This contrasting pattern implies that topography might have played an important role in mediating moisture changes at regional scale in this topographically complex region.

Introduction

Central Asia in the interior Eurasian continent has experienced increasing aridity and desertification during the 20th century. However, the causes of these moisture changes, which have been attributed to changes in regional human activities, human-induced global warming, or natural climate variability, are still poorly understood. Paleoclimatic and paleoecological data should provide useful long-term perspective and insight into evaluating the mechanism of climatic and ecological changes.

There are several high-resolution paleoclimate studies using tree rings and ice cores during the late Holocene on the Tibetan Plateau. Tree-ring records at annual resolution from the northeastern Tibetan Plateau show possible regularities of climate change at centennial scale during the last 2000 yr (Zhang et al., 2003; Sheppard et al., 2004; Shao et al., 2005). Ice-core oxygen-isotope record over the last 1000 yr at 50-yr time resolution from Dunde icecap shows large-magnitude shifts in regional temperature (Thompson et al., 1993, 2003) or monsoon precipitation (Liu et al., 1998; Davis et al., 2005). A high-resolution (at 1–100 yr resolution over the late Holocene) pollen record from the Dunde ice core shows large shifts in total pollen concentration (interpreted as reflecting vegetation productivity) and pollen assemblages (reflecting vegetation composition) (Liu et al., 1998). Most of these proxy climate records have been collected at high elevations, which may show different climate responses to large-scale climate forcing compared to low elevations, due to topography effects.

We have analyzed pollen and other sedimentary proxies from two lakes in the Qaidam Basin located at a low elevation of ~2800 m above sea level. We found that the climate history at Hurleg Lake over the Holocene appeared to show an opposite pattern to that of Qinghai Lake at higher elevation, 300 km away (Zhao et al., 2007). *Artemisia*/Chenopodiaceae (A/C) pollen ratios from an annual-resolution pollen record at Gahai Lake in the Qaidam Basin were well correlated with relative humidity during the past 50 yr from instrumental measurements at a nearby weather station (Zhao et al., 2008). Comparison with pollen and snow accumulation data from Dunde ice core suggests that effective moisture at low and high elevations shows the opposite relationship, especially during extreme precipitation periods, possibly due to topography-induced uplifting and subsiding air dynamics. However, there are no high-resolution records covering the last 2 millennia from lake sediments in the low-elevation Qaidam Basin. Also, lake sediments can provide additional information on ecological and hydrologic responses to climate changes.

* Corresponding author. Fax: +1 86 931 891 2330.
E-mail address: yanzhao@lzu.edu.cn (Y. Zhao).

0033-5894/$ – see front matter © 2008 University of Washington. Published by Elsevier Inc. All rights reserved.
doi:10.1016/j.yqres.2008.11.007

In this paper, we present fossil pollen data and discuss their climatic interpretations from two paired hydrologically connected lakes in the extremely arid Qaidam Basin on the northeastern Tibetan Plateau. The objectives of this study were to provide a detailed reconstruction of regional vegetation history, to document centennial-scale wet-dry climate oscillations and to understand possible mechanisms of vegetation and climate changes during the last 2 millennia. The paleo-records and insights will help us in understanding and projecting possible future droughts in this arid region in the coming decades and centuries.

Study region and study sites

Hurleg Lake (37°14′–37°20′N, 96°51′–96°57′E) and Toson Lake (37°04′–37°13′N, 96°50′–97°03′E) are located at the northeastern edge of the Qaidam Basin on the NE Tibetan Plateau (Fig. 1). The

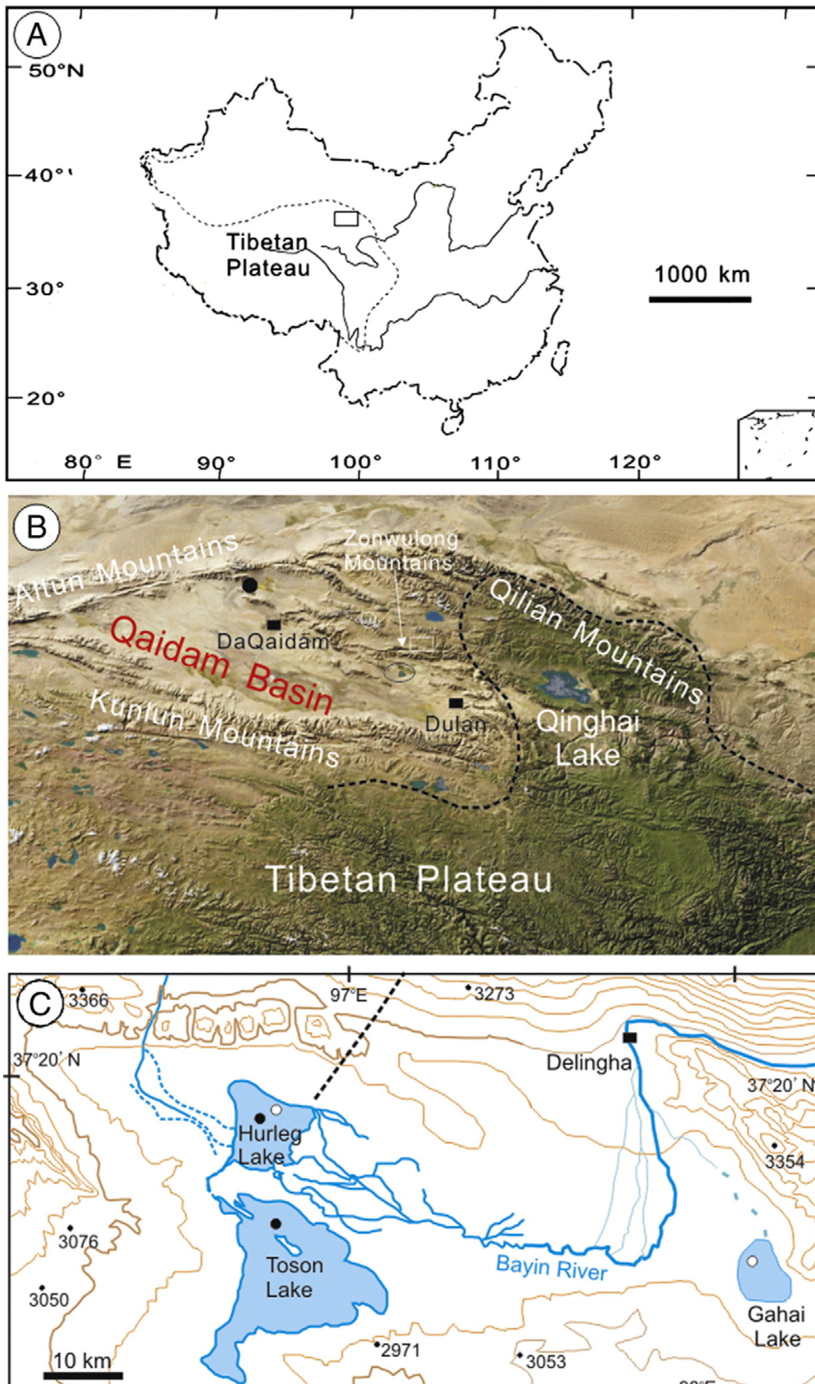

Figure 1. Location map and settings. (A) Map of China showing location of study region (rectangle area as shown in detail in B). (B) Satellite image (EROS data) showing the topography and vegetation cover (an indication of precipitation) and other paleoclimate sites discussed in the text. The dashed line shows the approximate boundary between highland meadow and temperate desert. The black ellipse shows the location of the study lakes, the black solid dot Sugan Lake, the white rectangle and white circle the locations of Delingha tree-ring sites and Dunde icecap, respectively. (C) Hydrological and topographical settings around Hurleg Lake and Toson Lake. The contours are of 100-m intervals. The black solid dots show the coring locations of HL06-2 at Hurleg Lake and TL06-1 at Toson Lake. The open circles show other cores at Hurleg Lake (core HL05-2) and Gahai Lake (core GL05-2) mentioned in the text. The dashed line shows the transect of surface pollen samples.

https://doi.org/10.1016/j.yqres.2008.11.007 Published online by Cambridge University Press

Table 1
Settings of the two study lakes on the northeastern Tibetan Plateau, China (based on Wang and Dou, 1998 and our field measurements).

Lake	Latitude (N)	Longitude (E)	Elevation (m asl)	Lake area (km^2)	Maximum depth (m)	Total dissolved solids (g/L)
Hurleg Lake	37°14′–37°20′	96°51′–96°57′	2817	56.7	9.6	0.98
Toson Lake	37°04′–37°13′	96°50′–97°03′	2808	165.9	25.7	38.7

Qaidam Basin, with an area of 120,000 km^2, is surrounded by the Kunlun Mountains to the south, the Altun Mountains to the west and the Qilian Mountains to the north and east. The surrounding mountains rise to an elevation of >5000 m above sea level, while the average elevation of the basin is 2800 m. The region is in an extremely arid desert climate. The annual precipitation is about 100 mm and annual mean temperature is 4°C, based on climate data from the nearby Delingha meteorological station. Most precipitation falls as rain during the summer months. The potential evapotranspiration is about 2000 mm.

Modern vegetation of this region is dominated by desert plant communities, mainly consisting of Chenopodiaceae (including *Salsola abrotanoides*, *Kalidium gracile*, *Ceratoides aritim*, *Haloxylon ammodendron* and *Sympegma regelii*), *Ephedra*, *Nitraria* and Asteraceae (including *Artemisia*, *Ajania fruticulosa* and *Asterothamnus centrali-asiaticus*) (Zhou et al., 1990). Distinct vegetation types occur along an elevational gradient from the mountain in the north to Hurleg Lake (see location in Fig. 1C) based on our field observations. With decreasing elevation from ca. 4100 m to 3000 m, vegetation type changes from Cyperaceae-dominated alpine meadow, through Poaceae- and Fabaceae-dominated alpine steppe and Poaceae- and *Artemisia*-dominated steppe, to Chenopodiaceae-dominated desert.

Hurleg Lake is surrounded mostly by Quaternary lacustrine and alluvial deposits, and Toson Lake by Tertiary fine-grained deposits with limited groundwater storage capacity (Yi et al., 1992). Freshwater Hurleg Lake is mainly fed by Bayin River from surrounding mountains and is situated upstream of the saline Toson Lake (Fig. 1C). Hurleg Lake discharges through a small outlet stream to Toson Lake. The general limnological features of the two lakes are listed in the Table 1. Hurleg Lake is surrounded by dense marsh vegetation dominated by *Phragmites communis* along the littoral zone, while there is no marsh vegetation around Toson Lake (see Fig. 2).

Materials and methods

Collection of surface pollen samples and sediment cores

A total of 14 surface pollen samples were collected from moss polsters, topsoil and lake sediments from the Zongwulong Mountains (see approximate transect location in Fig. 1C). Vegetation at each sampling site was described in the field (Table 2).

Sediment cores used in this study were taken from Hurleg Lake at 7.6 m water depth (85-cm-long core HL06-2) and from Toson Lake at 5-m water depth (82-cm-long core TL06-1) using a plastic tube sampler (6 cm in diameter) fitted with a piston. The Hurleg Lake core was subsampled at contiguous 0.5-cm intervals for the top 30 cm and at 1-cm intervals below 30 cm, while the Toson Lake core was subsampled at 1-cm intervals, both in vertical positions shortly after core collections in the field.

Loss-on-ignition and radiometric dating analyses

Loss-on-ignition analysis (LOI) were carried out to estimate organic matter content after combustion at 550°C and to estimate the carbonate content in the sediments after combustion at 1000°C (Dean, 1974). The chronologies of the sediment cores were controlled by ^{210}Pb and ^{137}Cs analysis and AMS ^{14}C dating. A total of 22 sediment slices from the top 30 cm of core HL06-2 were analyzed for ^{210}Pb activities and 20 slices for ^{137}Cs using a gamma spectrometer (Hyperpure Ge detector) at the University of Manitoba, Canada—Environmental Radiochemistry Laboratory. A total of 16 sediment slices of the top 30 cm of core TL06-1 were also analyzed for ^{210}Pb and ^{137}Cs activities at the same laboratory. Ages at the top sections from both Hurleg Lake and Toson Lake were determined according to the Constant Rate of Supply (CRS) model (Binford, 1990).

Five plant macrofossil samples were picked from the Hurleg core and were dated using accelerator mass spectrometry (AMS) at Keck AMS Dating Laboratory at the University of California Irvine. Four samples of plant macrofossils from the Toson core were picked; however, the sample from the depth of 13 cm was too small and only three dates were obtained also from Keck laboratory. All ^{14}C dates were calibrated with the program CALIB Rev. 5.0.1 using IntCal04 calibration data set (Reimer et al., 2004). ^{14}C dates at Hurleg Lake were calibrated after old carbon reservoir correction based on the paired dates by AMS and ^{210}Pb methods at the same depth. The AMS age–depth model at Hurleg Lake was established based on a 2nd order polynomial curve. The AMS age–depth model at Toson Lake was

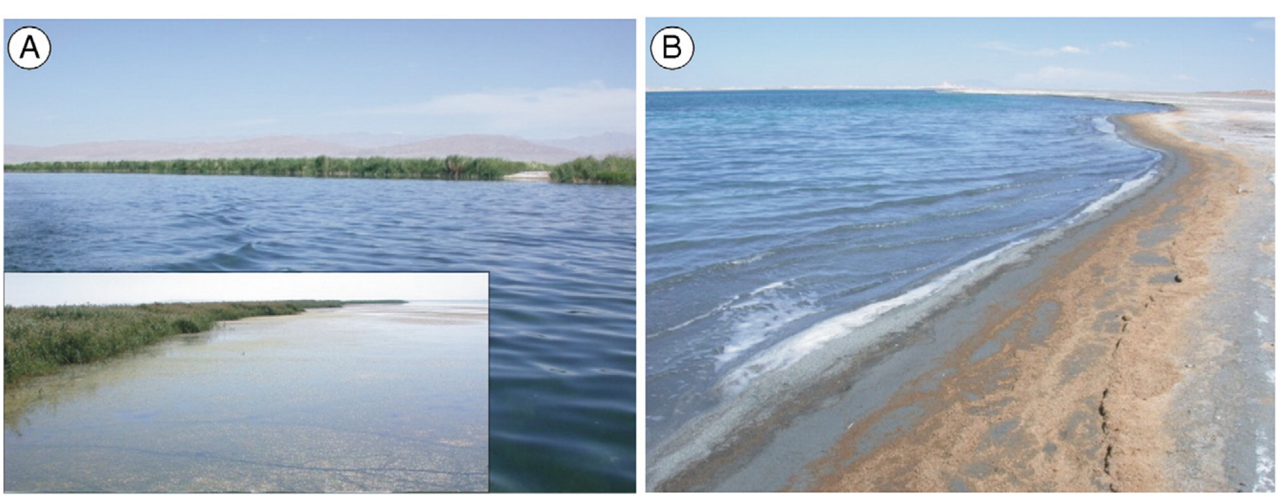

Figure 2. Photos of two study lakes in the Qaidam Basin, northeastern Tibetan Plateau. (A) Hurleg Lake with abundant aquatic and wetland vegetation around the lake, as also shown in the inset; (B) Toson Lake with no surrounding marsh vegetation. Photos taken in August 2004 by Z.C. Yu.

https://doi.org/10.1016/j.yqres.2008.11.007 Published online by Cambridge University Press

Table 2
Location and surrounding vegetation types of surface pollen samples from the NE Tibetan Plateau.

Sample number	Latitude (°N)	Longitude (°E)	Elevation (m asl)	Sample type	Vegetation type	Major plant taxa	Note
1	37.29	97.26	4087	Moss	Alpine meadow	Poaceae, Fabaceae, *Leontopodium*, *Caragana*, Asteraceae	Baishu Mountain
2	37.29	97.25	3914	Moss	Alpine meadow	Poaceae, *Leontopodium*, Fabaceae, *Gentiana*, *Sabina* and *Artemisia* on nearby slope	Baishu Mountain
3	37.29	97.24	3772	Moss	Alpine steppe	Poaceae, Fabaceae, *Leontopodium*,	Baishu Mountain
4	37.29	97.23	3682	Moss	Alpine steppe	Poaceae, Fabaceae, *Achnatherum*	Baishu Mountain
5	37.29	97.22	3575	Moss	Alpine steppe	*Achnatherum*, Poaceae, Fabaceae, *Artemisia*, *Plantago*	Baishu Mountain
6	37.27	97.2	3428	Moss	Steppe	Fabaceae, Poaceae, *Caragana*, *Artemisia*, Ranunculaceae	Baishu Mountain
7	37.27	97.21	3426	Moss	Steppe	*Achnatherum*, Fabaceae, Poaceae, Ranunculaceae	Baishu Mountain
8	37.26	97.2	3300	Moss	Desert steppe	*Achnatherum*, Chenopodiaceae, Poaceae, *Nitraria*, Fabaceae, *Caragana*, *Artemisia*	Baishu Mountain entrance
9	37.25	97.21	3137	Moss	Desert	Chenopodiaceae, *Artemisia*, *Caragana*, *Allium*	Baishu Mountain foot
10	37.22	97.19	3027	Top soil	Desert	Chenopodiaceae, *Allium*, *Artemisia*, Poaceae	Near Delingha
11	37.21	96.54	2850	Top soil	Desert	*Kalidium*, *Artemisia*	Near Hurleg
12	37.08	97.31	2848	Lake sediment	Desert	*Kalidum*, *Nitraria*, *Phragmites*, Compositae, Poaceae	Gahai Lake
13	37.18	96.55	2850	Lake sediment	Desert	*Phragmites*, *Nitraria*, Chenopodiaceae	Hurleg Lake
14	37.08	97.00	2813	Lake sediment	Desert	*Phragmites*, *Nitraria*, *Artemisia*	Toson Lake

established by correlations of *Artemisia*/Chenopodiaceae (A/C) ratios and carbonate abundance with Hurleg Lake.

Pollen analysis method

Pollen subsamples of 1.4 cm^3 were taken at 1-cm intervals from both cores. The subsamples were treated with a modified acetolysis procedure (Fægri and Iversen, 1989), including HCl, KOH, HF and acetolysis treatments, and fine sieving to remove clay-sized particles. The concentrate was mounted in silicone oil. A known number of *Lycopodium clavatum* spores (batch # 938934) were initially added to each sample for calculation of pollen concentration (Maher, 1981). Each pollen sample was counted under a light microscope at 400× magnification in regularly spaced traverses. Pollen sums were usually >300 terrestrial pollen grains. Identifications followed Wang et al. (1995) aided by modern reference collections. Pollen percentages were calculated based on the total terrestrial pollen sum, while *Pediastrum* percentages were calculated based on the terrestrial pollen sum plus *Pediastrum* colony counts. Pollen diagrams were plotted using TGView 2.0 (E. Grimm of Illinois State Museum, Springfield, Illinois, USA). Pollen zonation was divided based on CONISS cluster analysis program (Grimm, 1987) using pollen taxa with percentages >2% in at least one sample.

Results

Modern pollen assemblages

The modern pollen assemblages are mostly composed of *Artemisia*, Chenopodiaceae, Poaceae, Cyperaceae, Fabaceae, and non-*Artemisia* Asteraceae. Arboreal pollen content is very low, usually having percentages <2% mainly from *Pinus*, *Betula* and *Sabina* (=*Juniperus*) (Fig. 3). At the alpine meadow vegetation zone, the pollen assemblages are dominated by Cyperaceae pollen (up to 62.9%) (originating from several *Kobresia* species), *Artemisia* (up to 25.8%) and Poaceae (>5%), with some *Thalictrum* and *Polygonum* in low abundances. In the alpine steppe zone, Fabaceae (up to 38%), Poaceae and *Artemisia* are the dominant taxa, with some Asteraceae (with abundant *Leontopodium* in the vegetation) and *Gentiana*. In the steppe zone, Poaceae (up to 26.9%) and *Artemisia* (up to 67.8%) dominate the pollen assemblages. The pollen assemblage of desert steppe zone is composed of *Artemisia* (50.8%), Chenopodiaceae (4%) and Poaceae (11.9%). Chenopodiaceae (up to 97.2%) dominates the pollen assemblages of desert vegetation zone, with some *Artemisia* (mostly <20%) and Poaceae (mostly <10%). Samples from lake sediments (Toson Lake #14 and Gahai Lake #12) have higher *Artemisia* (up to 35%) than the samples from the desert soil (#11; only 2%), suggesting that lakes have a larger pollen source area than top soils. However, the sample from Hurleg Lake (sample # 13) has lower *Artemisia* percentage than the ones from Toson Lake and Gahai Lake. Higher Poaceae pollen at Hurleg comes from *Phragmites* surrounding the lake (Fig. 2A). A/C ratios are slightly >2 in the alpine meadow, are highest in steppe zone with a value of 33, and decrease to <1 in the desert.

Lithology and chronology

Sediments of Hurleg Lake core HL06-2 and Toson Lake core TL06-1 are dominated by carbonate and silicates, with low organic matter (Fig. 4). Percent carbonate oscillates between 30 and 60% at HL06-2 and between 15 and 35% at TL06-1.

Cores HL06-2 and TL06-1 show an increase in total and excess ^{210}Pb activities from 19 cm and 28 cm, respectively, to the sediment top. ^{137}Cs activity peaks occur at the depths of 10 cm in core HL06-2 and of 19 cm in core TL06-1, marking the maximum impact of atmospheric nuclear testing in the year AD 1963. Excess ^{210}Pb and ^{137}Cs data together indicate that the top 19 cm of core HL06-2 was deposited after AD 1864 and the top 28 cm of TL06-1 was deposited after 1872, based on CRS model (Fig. 4).

The five AMS dates on plant macrofossils from core HL06-2 were all in order (Table 3); however, the paired ^{210}Pb and AMS dates at the depth of 12–13.5 cm indicate an old carbon reservoir effect of 2758 ^{14}C yr BP. The δ^{13}C values of −11.5 to −8.8‰ (relative to VPDB) suggest that the macrofossils used for dating might have come from aquatic plants using CAM photosynthesis pathway. Therefore all AMS dates from Hurleg core were corrected by 2758 yr before calibration. As shown in Table 3 and Figure 4A, the chronology of core HL06-2 based on a 2nd order polynomial curve of calibrated ages and ^{210}Pb dates shows a continuous trend in sediment accumulation over the last 1700 yr. Three AMS dates from core TL06-1 show dating reversals (Table 3), and no AMS ^{14}C dating materials available at the top section of the sediments to compare with ^{210}Pb dates for possible old carbon

https://doi.org/10.1016/j.yqres.2008.11.007 Published online by Cambridge University Press

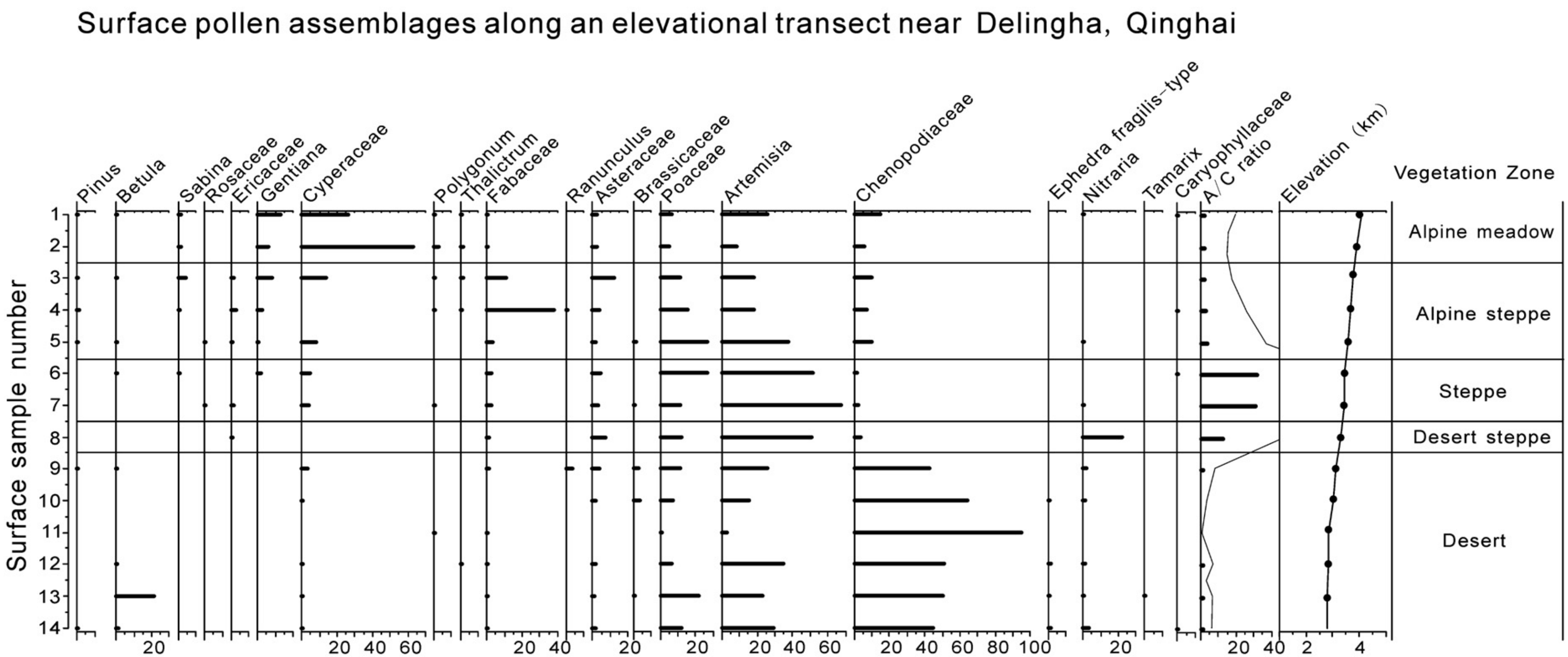

Figure 3. Surface pollen assemblages along an elevational gradient from Toson and Hurleg lakes to the mountains north of our study sites. Open curve for A/C ratio is 10× exaggeration.

https://doi.org/10.1016/j.yqres.2008.11.007 Published online by Cambridge University Press

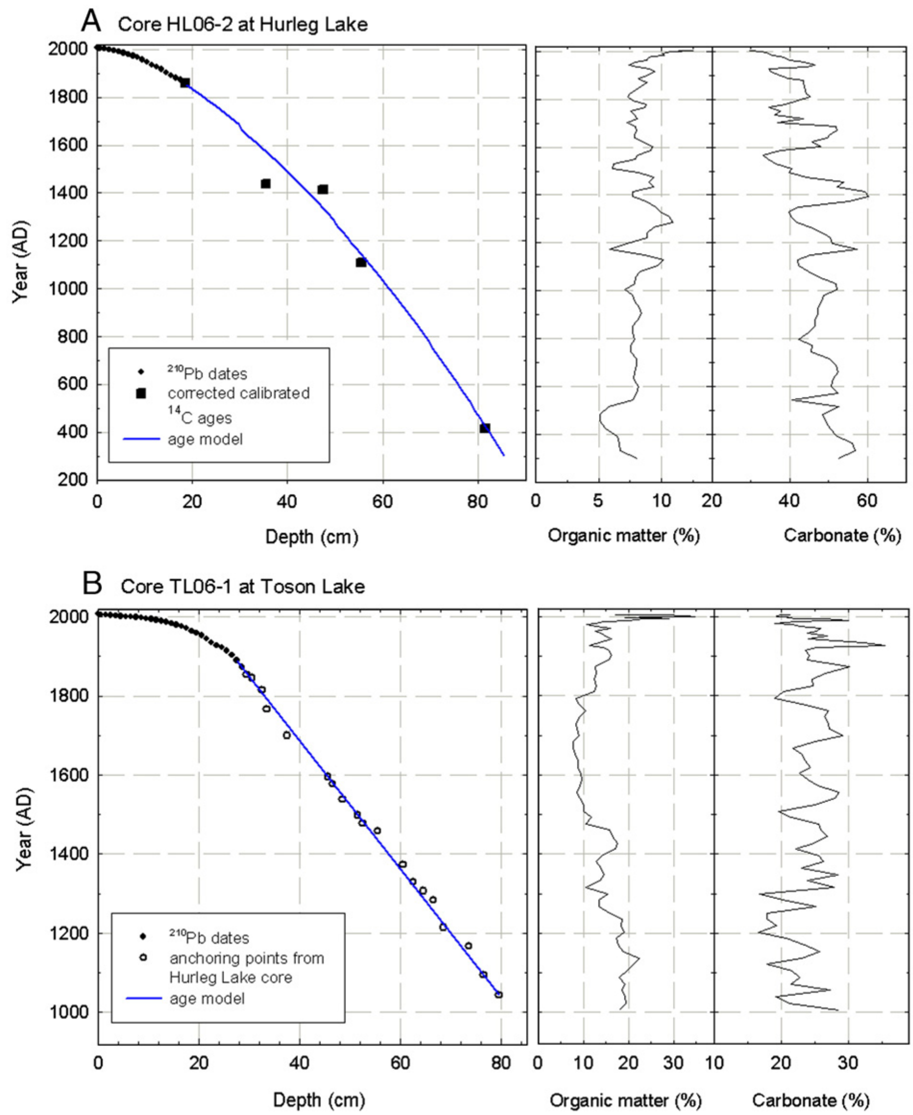

Figure 4. Chronology and lithology. (A) Core HL06-2 at Hurleg Lake; (B) Core TL06-1 at Toson Lake. The upper part chronology from both cores was established based on CRS model of ^{210}Pb and ^{137}Cs dating analysis. The AMS age–depth model at core HL06-2 was established based on a 2nd order polynomial curve. The AMS age–depth model at core TL06-1 was established by correlations of A/C ratios and carbonate abundance between dated core HL06-2 and core TL06-1, shown as open circles for selected anchoring tie points (maxima and minima). Also shown are organic matter and carbonate contents for HL06-2 and TL06-1.

correction. Therefore we use inter-site correlation of peaks and valleys in A/C pollen ratios and carbonate abundance at both cores HL06-2 and TL06-1, together with ^{210}Pb dates from Toson Lake, to establish the age–depth model for core TL06-1 for the last 1000 yr (Fig. 4B). Although this relative dating procedure may cause greater age uncertainty at core TL06-1, the age model appears to follow the sedimentation trend as extrapolated from ^{210}Pb ages.

Fossil pollen assemblages

Fossil pollen data from Hurleg Lake

Eighty-six pollen samples from core HL06-2 were analyzed for the last 1700 yr (Fig. 5A), resulting in a sampling resolution of ca. 20 yr. We identified 22 pollen types in these samples. *Artemisia* (up to 37%), Chenopodiaceae (up to 51%) and Poaceae (up to 35%) are the dominant pollen types, with relatively low *Ephedra* and *Nitraria* pollen percentages (<2%). Tree pollen percentages are less than 2% through the pollen sequence. A/C ratio shows large changes between 0.4 and 1.1.

The percentage pollen diagram was divided into 4 pollen assemblage zones based on CONISS analysis (Fig. 5A).

Zone HL-1 (1650–610 cal yr BP, AD 300–1340; 85–46 cm)

The pollen assemblages are dominated by *Artemisia* (20–35%), Chenopodiaceae (up to 51%), and Poaceae (~28%). A/C ratio is mostly 0.5–0.9. *Pediastrum* is very high (up to 98%). This zone has a fluctuating total pollen concentration of about 15,000–46,000 grains/cm^3.

Zone HL-2 (610–300 cal yr BP, AD 1340–1650; 46–30 cm)

Artemisia is <30%, with A/C ratio of mostly <0.8 in this zone. *Pediastrum* (around 30%) is lowest, but with large fluctuations. Total concentration shows large fluctuations between 12,000 and 46,000 grains/cm^3.

Zone HL-3 (300–0 cal yr BP, AD 1650–1950; 30–9 cm)

Chenopodiaceae reaches a maximum value of 50%, with generally low (0.5–0.7) and fluctuating A/C ratios. *Pediastrum* is high (up to 96%) in this zone. Pollen concentration fluctuates between 10,000 and 35,000 grains/cm^3.

Zone HL-4 (0 to −56 cal yr BP, AD 1950–2006; 9–0 cm)

The pollen assemblages are dominated by *Artemisia* (16–30%), Chenopodiaceae (~40%), and Poaceae (~45%). Poaceae shows a clear

https://doi.org/10.1016/j.yqres.2008.11.007 Published online by Cambridge University Press

Table 3
AMS radiocarbon dates from Hurleg Lake (core HL06-2) and from Toson Lake (core TL06-1), northeastern Tibetan Plateau.

Lab number	Sediment core	Depth (cm)	Material dated	$\delta^{13}C$ (‰ − VPDB)[a]	^{14}C date ± Error (yr BP)	Corrected ^{14}C date (yr BP)[b]	Calibrated age (cal yr BP)[c]	Year (AD)
UCIAMS-34681	HL06-2	12–13.5	Plant macrofossils	–	2795 ± 20	37 ± 20	37–67	1883–1913
UCIAMS-34682	HL06-2	35–36	Plant macrofossils	− 11.5	3215 ± 15	457 ± 15	500–523	1437–1450
UCIAMS-34683	HL06-2	47–48	Plant macrofossils	− 11.6	3290 ± 20	532 ± 20	516–555	1395–1434
UCIAMS-38090	HL06-2	55–56	Plant macrofossils	− 7.9	3700 ± 15	942 ± 15	795–875	1075–1155
UCIAMS-34684	HL06-2	81–82	Plant macrofossils	− 8.8	4385 ± 15	1627 ± 15	1509–1562	388–441
UCIAMS-34678	TL06-1	42–43	Plant macrofossils	–	990 ± 60	–	294–336	1614–1656
UCIAMS-34679	TL06-1	55–56	Plant macrofossils	− 28.5	1425 ± 15	–	468–518	1432–1482
UCIAMS-34680	TL06-1	75–76	Plant macrofossils	− 28.3	1395 ± 15	–	761–901	949–1189

Note. Calibrated age and year (AD) for core TL06-1 were based on inter-site correlation with HL06-2 as described in the text.
[a] Sample UCIAMS-34681 and 34678 were too small to provide sufficient extra CO_2 for an IRMS ^{13}C measurement.
[b] Corrected by 2758 ^{14}C years based on the ^{210}Pb and AMS date at the depth of 12–13.5 cm.
[c] Calibrated based on IntCal04 calibration data set (Reimer et al., 2004) using the program CALIB Rev.5.0.1.

increase (to 35%). A/C ratio is low (mostly <0.65). Pollen concentration is mostly <20,000 grains/cm^3.

Fossil pollen data from Toson Lake

Eighty-two samples were analyzed for fossil pollen, with the time resolution of 10–20 yr per sample. We identified 12 pollen types in these samples from core TL06-1. A summary percentage pollen diagram is shown in Figure 5B. The pollen assemblages were dominated by *Artemisia* (up to 42%), Chenopodiaceae (up to 55%) and Poaceae (up to 25%), with relatively low *Ephedra* and *Nitraria* pollen percentages (mostly <2%). Tree pollen percentages are low (<2%) throughout the pollen sequence. A/C ratio shows large changes between 0.5 and 1.4.

The percentage pollen diagram was divided into 4 pollen assemblage zones based on CONISS analysis (Fig. 5B).

Zone TL-1 (940–390 cal yr BP, AD 1010–1560; 82–49 cm)
The pollen assemblages are dominated by *Artemisia* (>30%), Chenopodiaceae (>35%), and Poaceae (10–20%). A/C ratio is high (mostly >0.9). This zone has a total pollen concentration of up to 9700 grains/cm^3, with large fluctuations.

Zone TL-2 (390–135 cal yr BP, AD 1560–1815; 49–32 cm)
Artemisia decreases to <30%, with A/C ratio showing a corresponding decrease (mostly <0.8). Total concentration shows large fluctuations between 900 and 5800 grains/cm^3.

Zone TL-3 (135–10 cal yr BP, AD 1815–1960; 32–19 cm)
Pollen assemblages are still characterized by *Artemisia*, Chenopodiaceae and Poaceae. However, *Artemisia* (>35%) increases while Chenopodiaceae (<40%) decreases, resulting in high A/C ratios of mostly >0.9. Total pollen concentration fluctuates between 1100 and 7200 grains/cm^3.

Zone TL-4 (−10 to −56 cal yr BP, AD 1960–2006; 19–0 cm)
Artemisia decreases (16–30%), while Chenopodiaceae increases (up to 55%), resulting in low A/C ratio (<0.7). Poaceae is mostly <15%. Pollen concentration has fluctuating values of 670–3800 grains/cm^3.

Discussion

Between-lake similarities and differences in pollen assemblages

Pollen assemblages from both Hurleg Lake (HL06-2) and Toson Lake (TL06-1) over the last 1000 yr are consistently dominated by Chenopodiaceae, *Artemisia*, and Poaceae, with low abundances of *Nitraria*, *Ephedra*, Fabaceae, Cruciferae, and Cyperaceae. However, Poaceae pollen percentages are lower (mostly <10%) at Toson Lake than at Hurleg Lake (around 20%). Surface pollen assemblages from Inner Mongolia, Xinjiang and the Tibetan Plateau indicate that Poaceae percentages in arid and semi-arid China are normally <10% and are under-represented in comparison with *Artemisia* and Chenopodiaceae (e.g. Yan, 1991; Cour et al., 1999; Liu et al., 1999; Yu et al., 2001; Herzschuh et al., 2003; Li et al., 2005; Shen et al., 2006). Our surface pollen assemblages along a regional transect from Qinghai Lake west to Sugan Lake also showed that desert was represented by high percentages of Chenopodiaceae and *Artemisia,* with generally <10% Poaceae (Zhao et al., 2007; Zhao and Herzschuh, 2008). However, Poaceae pollen abundance is high in wetlands with *Phragmites* and in agricultural areas, such as at Hurleg Lake surrounded by *Phragmites* marshes.

Another difference between the two pollen diagrams is that Toson Lake has higher *Artemisia* percentages (mostly >30%) and higher A/C ratios (mostly 0.8–0.9) than Hurleg. The lower Poaceae percentage might partly account for the higher *Artemisia* at Toson Lake, but A/C ratio should be independent of other taxa's abundance. Toson Lake is almost three times larger than Hurleg Lake (Table 1), so as a result Toson might have larger pollen source area than Hurleg (e.g., Sugita, 1994). The high percentages of *Artemisia* at Toson Lake likely reflect the contributions from both local/regional sources and longer-distance transport of *Artemisia* pollen grains from surrounding regional vegetation that has high *Artemisia.* Our surface pollen results along an elevational transect from the Zongwulong Mountain (ca. 25 km north of Hurleg Lake) to Toson Lake (Fig. 3) and a regional transect in Qinghai (Zhao et al., 2007) show that modern pollen percentages at Hurleg Lake and Toson Lake are dominated by pollen from local and regional sources (mainly including *Artemisia* and Chenopodiaceae), with low abundances of extra-regional sources. Considering that the mountains to the south of Toson Lake are several hundreds of kilometers away, the limited extra-regional pollen sources should have mostly come from the mountains to the north of Hurleg and Toson lakes. However, a minor long-distance contribution of pollen, for example of *Artemisia*, from mountains around our study sites would not distort the regional vegetation signals. Even though Toson Lake has larger pollen source area, extra-regional sources of *Artemisia* pollen would mostly come from surrounding low elevation area and from the mountain–lowland boundary areas, rather than from the mountains where tree-ring reconstructions were done by Shao et al. (2005). This can be also seen from our surface pollen data along the elevational gradient (Fig. 3) and from a regional transect (Zhao et al., 2007).

Despite these differences in pollen assemblages and in magnitude of A/C ratios from the two lakes, variations in A/C ratios at both sites demonstrate similar and corresponding shifts over the common period of the last 1000 yr, given the age uncertainty (Fig. 6). These coherent patterns suggest that changes in relative abundances of *Artemisia* ("steppe" plants) and Chenopodiaceae (desert plants) reflect changes in regional vegetation and effective moisture of the region as discussed below.

Late Holocene vegetation and moisture changes inferred from fossil pollen records

The pollen assemblages from Hurleg Lake (HL06-2) suggest that for the past 1700 yr, the Hurleg region has been covered by open vegetation that was consistently dominated by desert plants, mainly from the family Chenopodiaceae, with some *Artemisia* and Poaceae and low abundances of *Nitraria*, *Ephedra*, Fabaceae, Cruciferae, and Cyperaceae. *Nitraria* and *Ephedra* are typical desert plants, and their abundance has been used to distinguish between steppe and desert pollen assemblages. However, the low values of *Ephedra* and *Nitraria* at HL06-2 give very limited information for climatic interpretation due to strong dispersal ability of their pollen grains (Maher, 1964; Li et al., 2005; Zhao and Herzschuh, 2008). Yet changes in A/C ratios (from 0.4 to 1.1) demonstrate large shifts in relative abundances or pollen productivity of *Artemisia* and Chenopodiaceae plants, responding to effective moisture change. Both *Artemisia* and Chenopodiaceae are characteristic of dry summers (El-Moslimany, 1990); however, *Artemisia* requires more moisture than Chenopodiaceae during the growing season (El-Moslimany, 1990; Liu et al., 1999; Herzschuh, 2007; Zhao et al., 2008). A/C ratio has been applied to the pollen sequences from arid regions (e.g., El-Moslimany, 1990; Van Campo et al., 1996; Tarasov et al., 1997; Gunin et al., 1999; Cohen et al., 2000; Davis and Fall, 2001; Herzschuh, 2007; Zhao et al., 2008) to distinguish steppe from desert and to reconstruct changes in the local precipitation.

In the past 1700 years, A/C ratio at Hurleg Lake (HL06-2) shows high values at AD 390–460, 550–650, 790–860, 950–1050, 1120–1180, 1230–1320, 1400–1500, 1620–1700, and 1760–1800 (Fig. 6), suggesting the vegetation was more "steppe-like" under a relatively moist

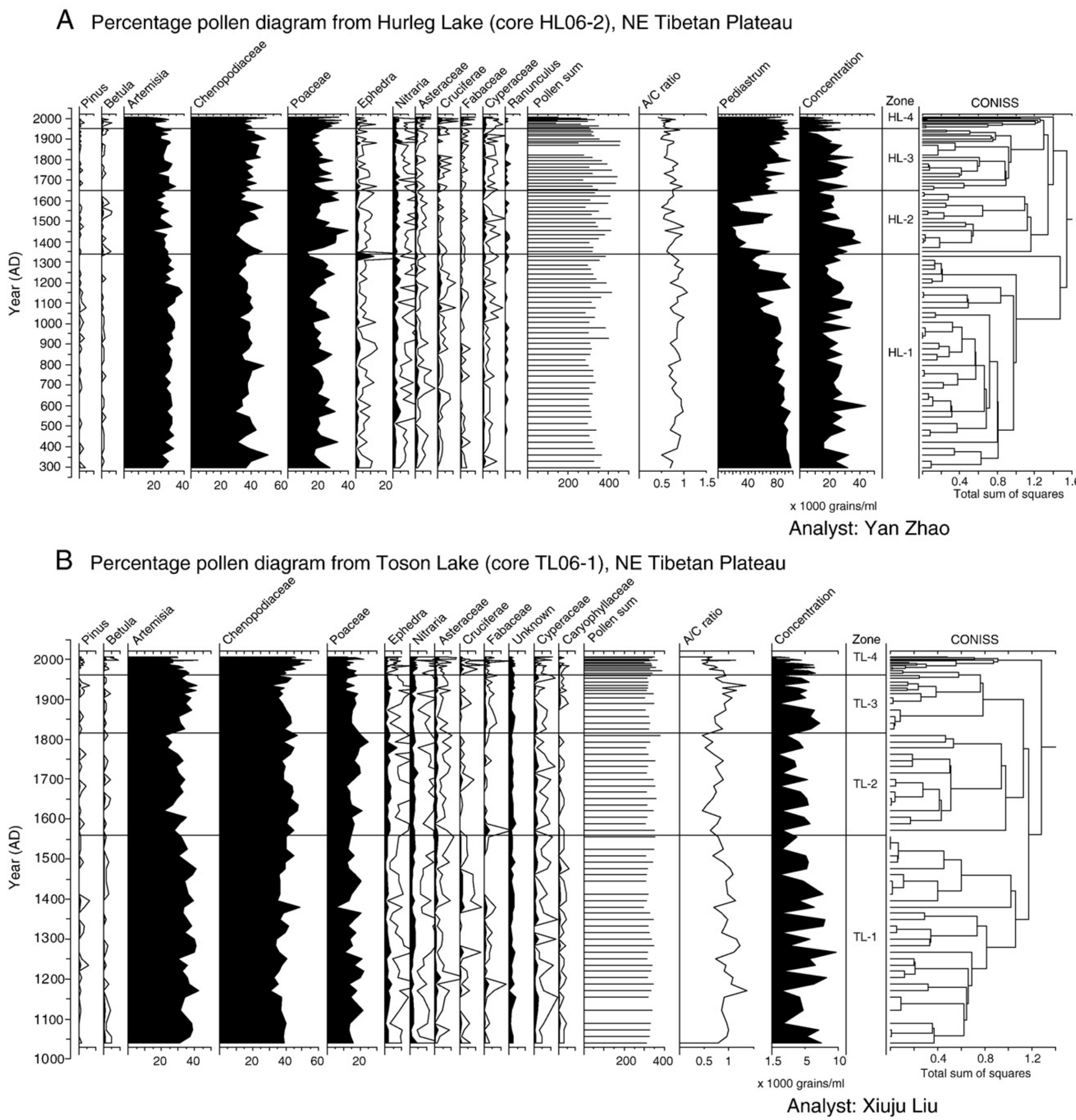

Figure 5. Percentage pollen diagram. (A) Core HL06-2 at Hurleg Lake; (B) Core TL06-1 at Toson Lake. Only selected taxa are shown. Open curves for low abundant taxa are 5× exaggeration.

https://doi.org/10.1016/j.yqres.2008.11.007 Published online by Cambridge University Press

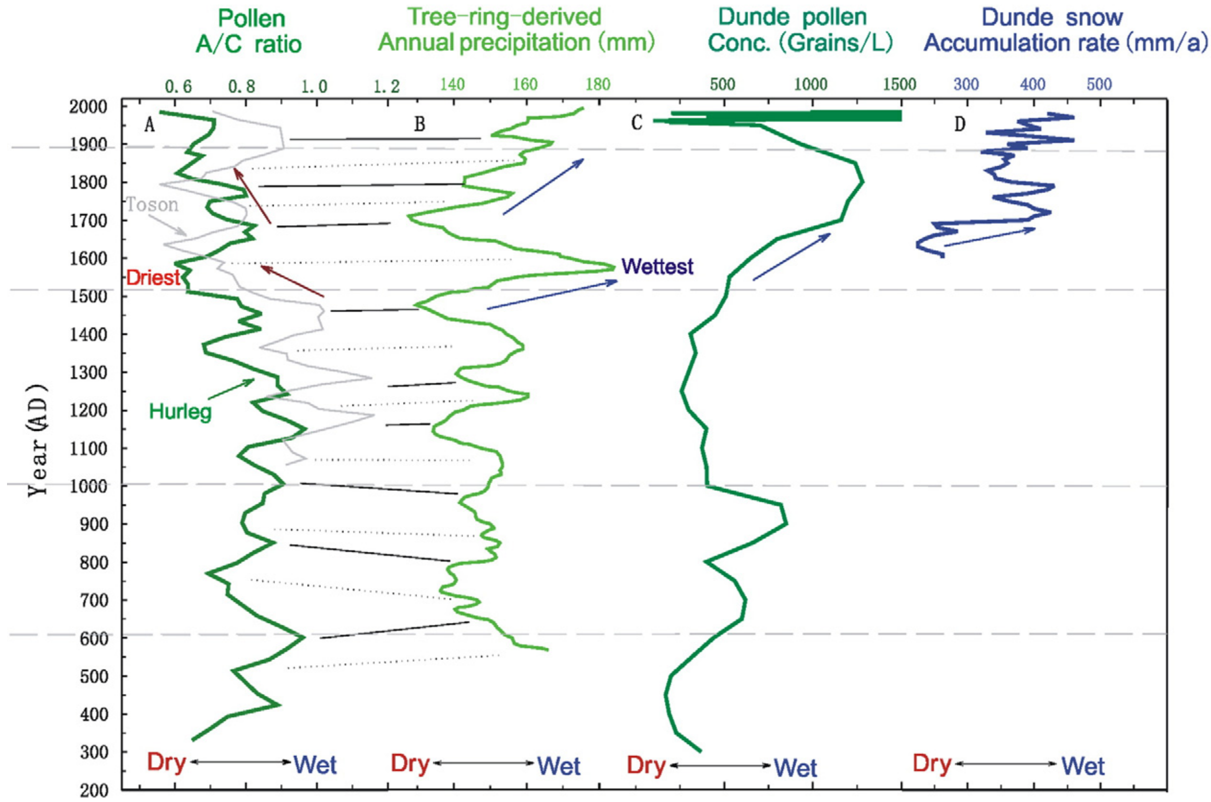

Figure 6. Correlation of paleoclimate proxies. (A) A/C ratio curves (three-point moving average) from Hurleg Lake (black line) and from Toson Lake (gray line); (B) Tree-ring-derived precipitation from the mountains north of our study sites (Shao et al., 2005); (C) Pollen concentration (grains/L) from Dunde icecap (Liu et al., 1998); (D) Snow accumulation rate at Dunde icecap (mm water equivalent) (Yao et al., 1991).

climate; while during the intervening periods, Chenopodiaceae dominates with low A/C ratio, representing more "desert-like" vegetation under a relatively dry climate. After AD 1700, A/C ratios decrease from >0.8 to <0.6, following a long-term trend which started at AD 1150, suggesting a drying climate. Visually A/C ratios show 150–200 yr oscillations at Hurleg Lake. Pollen assemblages from Toson Lake also show that the vegetation was consistently dominated by Chenopodiaceae, *Artemisia* and Poaceae. During the last 1000 yr, A/C ratios at Toson Lake show a generally similar change as at Hurleg Lake (Fig. 6), except at AD 1760–1800 and AD 1880–1930 due possibly to the dating uncertainty and variable sampling resolution.

Pediastrum, a green algae, shows the same sharp decreasing trend as A/C ratio at Hurleg Lake during the period AD 1350–1650, while it shows an opposite trend to A/C ratio after AD 1700. The increasing (decreasing) *Pediastrum* at Hurleg Lake might be due to high (low) lake level (e.g., Tell and del Zamaloa, 2004; Jiang et al., 2006), as suggested by our previous study from a long core over the Holocene (Zhao et al., 2007). However, the increase in *Pediastrum* since AD 1700 might be related to human-induced eutrophication as has been documented elsewhere (Prat and Daroca, 1983). Although the Qaidam Basin has been sparsely populated throughout history, people might have settled around some lakes in this region (Brantingham et al., 2007). The absence of *Pediastrum* at Toson Lake is due to its high salinity of 40 g/L.

Other multi-proxy records from the core HL06-2 support the climate interpretation inferred from fossil pollen data, with low A/C ratios tending to occur during periods having low-carbonate and high ostracode and mollusc shell abundances, while our unpublished data suggest that high A/C ratios occur during periods having high-carbonate and low ostracode and mollusc shell abundances. Our modern process study and multiple proxy downcore data from Hurleg Lake during the entire Holocene show that high (low) carbonate represents high (low) lake levels (Zhao et al., 2007). Increased shallow water ostracode species and mollusc shells suggest littoral environment. All these proxies at Hurleg Lake show a general drying trend after AD 1700 and consistent wet/dry climate oscillations at ~200-yr spacing during the last 1000 yr, and together with our unpublished data these suggest possible solar forcing of drought frequency in the Qaidam Basin.

Fossil pollen records at different temporal resolutions over various time scales

Pollen data over the past millennia at a resolution of ca. 10–20 yr from our studied cores (HL06-2 and TL06-1) suggest that vegetation change might reflect changes in relative plant abundances of *Artemisia* and Chenopodiaceae in the source vegetation, as regional climate change at decadal time scales would facilitate and induce plant composition change. Similarly, fossil pollen record at ca. 150-yr sampling resolution from a long core at Hurleg Lake (core HL05-2; see location in Fig. 1C) shows vegetation composition changes during the Holocene (Zhao et al., 2007). A/C ratios suggest that vegetation around Hurleg Lake changed from Chenopodiaceae and *Artemisia*-dominated steppe desert before 10.2 cal ka BP (corrected by old carbon reservoir effect from the chronology presented in Zhao et al., 2007), through Chenopodiaceae-dominated desert at 10.2–8.7 cal ka BP, steppe desert at 8.7–6.5 cal ka BP, and desert at 6.5–3 cal ka BP, to steppe desert after 3 cal ka BP. The climate reconstruction from Hurleg Lake contrasts with that from Dunde icecap (~150 km to the west; Liu et al., 1998) and Qinghai Lake (~300 km to the east; Shen et al., 2005) at higher elevations.

The near-annual resolution pollen record over the past 50 yr from nearby Gahai Lake (Fig. 1C) shows that pollen assemblages were consistently dominated by Chenopodiaceae and *Artemisia*, with some *Nitraria*, *Ephedra*, Poaceae and other Asteraceae (Zhao et al., 2008).

https://doi.org/10.1016/j.yqres.2008.11.007 Published online by Cambridge University Press

Because the record only covers the last 50 yr at a near annual resolution, it may be more appropriate to interpret changes in A/C ratios and pollen abundance as reflecting changes in pollen production rather than changes in plant population size or vegetation composition. Therefore changes in A/C ratios (from <0.2 to 0.95) at Gahai Lake demonstrate large shifts in relative pollen productivity of existing *Artemisia* and Chenopodiaceae plants, still reflecting change in weather (effective moisture) on an annual and interannual basis. Also, A/C ratio variations at Gahai Lake show good correlation with relative humidity from instrumental climate data from the nearby weather station during the period AD 1956–2004 (Zhao et al., 2008). We observe an opposite relationship between effective moisture at Gahai Lake (2848 m asl) and at Dunde icecap (at 5325 m asl), especially in the 1970s when it was dry at Gahai but wet at Dunde icecap (Zhao et al., 2008).

Fossil pollen records during the entire Holocene, the late Holocene and the last 50 yr in the Qaidam Basin indicate that A/C ratio variations faithfully convey information on changes in vegetation composition or pollen production, both reflecting change in effective moisture at annual, centennial to millennial time scales. It should be noted, however, that in paleoecologic and paleoclimatic reconstructions the magnitude of pollen and vegetation responses to regional climate change at these different time scales could vary in responding to the magnitude and frequency of regional climate change.

Contrasting climate variations and ecological responses along the elevation gradient

A/C ratios from our study cores (HL06-2 and TL06-1) appear to show a general negative correlation with precipitation record derived from tree-ring data from the mountain just north of our lakes (Shao et al., 2005), with periods having a high A/C ratio correlating with low precipitation (Fig. 6). During the wet periods at Hurleg Lake in the Qaidam Basin centered at AD 600, 840, 1000, 1150, 1250, 1460, 1680, 1770 and 1920, tree-ring data show low precipitations in surrounding mountains. These anti-correlations are especially striking after the 17th century, when A/C ratio showed a general decreasing trend while tree-ring-derived precipitation increased. The Qilian junipers (*Sabina przewalskii*) collected for tree-ring width analysis mostly grow at elevations of 3700–4000 m in the mountains north of Delingha and Hurleg Lake. Qilian juniper growth in their study area was mainly limited by moisture conditions, responding to precipitation change in high elevation sites (Shao et al., 2005; Yin et al., 2008). Effective moisture and soil moisture conditions are likely similar to precipitation trends due to low temperature and thus low evaporation at high elevations. Interestingly, both tree-ring and A/C ratio time series appear to show a similar trend at low frequencies (for example, from AD 1000 to 1500).

A/C ratios from Hurleg Lake (HL06-2) also show a generally negative correlation with pollen concentration from Dunde icecap, about 150 km northwest of Hurleg Lake at an elevation of 5325 m. High A/C ratio at Hurleg correlates with low pollen concentration at Dunde during the periods of AD 300–600, 1000–1520, and post-1880, while low A/C ratio correlates with high pollen concentration during AD 600–1000 and 1500–1880 (Fig. 6; Liu et al., 1998). Liu et al. (1998) interpreted total pollen concentrations in the Dunde ice core as a proxy for moisture availability in the region, based on the correlations with climate data from three stations (Delingha, Dulan, and DaQaidam) in the northern part of the Tibetan Plateau. A negative correlation also existed between A/C ratio from Hurleg Lake and snow accumulation at Dunde ice core over the last four centuries (Fig. 6; Yao et al., 1991).

These comparisons suggest that the effective moisture at high elevations (Dunde icecap and mountain tree-ring sites) and low elevations (Qaidam Basin) appear to show opposite patterns over the past 1700 yr. This opposite relationship was also suggested by Toson pollen data and nearby Gahai pollen data over the last 50 yr (Zhao et al., 2008) and by Hurleg pollen data for the entire Holocene (Zhao et al., 2007). We realize the age uncertainty at our study sites, and therefore we attempt to discuss about the general patterns rather than details at finer time scale.

Why does the effective moisture indicated by our records in the low elevations show opposite phase relationship with precipitation inferred from mountain tree-ring and Dunde pollen concentration at the highlands at millennial, centennial and decadal time scales? Local topography may have played an important role in modifying regional climate responses to broad-scale climate controls. Hurleg Lake and Toson Lake in the Qaidam Basin lie in an arid low-lying basin on the northeastern Tibetan Plateau, while tree-ring and Dunde records were derived from high-elevation mountains. This difference in topography might cause different dynamics and effects of vertical air motions. The intense heating and upward motion of air over the Tibetan Plateau during strong monsoon causes strong air subsidence to the northwest and north of the plateau, inducing a dry climate in central Asia (He et al., 1987; Broccoli and Manabe, 1992). This mechanism also appears to operate at a regional scale as shown in regional climate simulations, in that uplifting air in the surrounding mountains and plateau causes the air subsidence to extend into the Qaidam Basin (Sato and Kimura, 2005). Precipitation in the northeastern Tibetan Plateau may have been affected primarily by Eurasian continental processes; however, the expressions of tropical Pacific and Indian oceanic/atmospheric processes may be noticeable when the Asian summer monsoon intensified and influenced summer climate farther to the north and west (Davis et al., 2005). The interactions between subsiding air flow and monsoon precipitation (direct or recycled) into the Qaidam Basin might have been responsible for the observed opposite change in effective moisture at different elevations. It should be noted that this opposite relationship might exist only when monsoon was very strong, and as a result the strong uplifting–subsiding air mass dynamics induced the moisture contrast in low and high elevations.

Conclusions

Our high-resolution pollen records from Hurleg Lake and Toson Lake in the northeastern Tibetan Plateau show that during the late Holocene the study region has been covered by open vegetation, consistently dominated by desert plants, inferred from the pollen assemblages dominated by desert and steppe plants/pollen including Chenopodiaceae (~40%), *Artemisia* (~30%), and Poaceae (20–25%). *Artemisia*/Chenopodiaceae (A/C) pollen ratios from the two lakes show corresponding large oscillations at centennial timescale during the last 1000 yr. A/C ratios were high around AD 1170, 1270, 1450, 1700, and 1920, suggesting that the vegetation was more "steppe-like" under a relatively moist climate; while during the intervening periods, Chenopodiaceae dominated with low A/C ratio, representing more "desert-like" vegetation under a relatively dry climate. After AD 1700, A/C ratios decreased from >0.8 to <0.6, following a long-term decreasing trend started at AD 1150, suggesting a drying climate. Our results suggest that fossil pollen records in the Qaidam Basin at different sampling resolutions (from annual to centennial) and time scales (the entire Holocene, the late Holocene and the last 50 yr) reflect changes in vegetation composition, relative abundances of parent plants, or pollen production, with all of these reflecting changes in effective moisture at different time scales.

The ~200-yr time spacing between wet and dry climate periods indicated by the A/C ratio variations suggests a possible solar forcing of effective moisture changes in the region. These wet-dry climate shifts show a generally opposite phase relationships at our study lakes in the Qaidam Basin and from mountain tree-ring and Dunde ice core pollen records in the surrounding mountains, with a dry climate in the basin corresponding with a wet interval in the mountains. This contrasting phasing was especially striking around AD 1600 during the first centuries of the Little Ice Age, when the basin was driest and the mountains were wettest during the last 1500 yr. This suggests that local topography might have played an important role in mediating regional climate changes, as induced by regional uplifting and subsidence of air masses.

Acknowledgments

We thank Emi Ito and Aifeng Zhou for field and laboratory assistance, Paul Wilkinson and Eva Slavicek for ^{210}Pb and ^{137}Cs dating analysis, and the University of California Irvine Keck AMS laboratory for ^{14}C dating. Thanks to two anonymous reviewers and Xiaoping Yang for helpful comments. This work was supported by the Chinese National Natural Science Foundation (Grants #40528001, 40771212 and 40721061) and US National Science Foundation (EAR #0518774).

References

Binford, M.W., 1990. Calculation and uncertainty analysis of ^{210}Pb dates for PIRLA project lake sediment cores. Journal of Paleolimnology 3, 253–267.

Brantingham, P.J., Gao, X., Olsen, J.W., Ma, H.Z., Rhode, D., Zhang, H.Y., Madsen, D.B., 2007. A short chronology for the peopling of the Tibetan Plateau. In: Madsen, D., Chen, F.H., Gao, X. (Eds.), Late Quaternary Climate Change and Human Adaptation in Arid China. . Developments in Quaternary Science, vol. 9. Elsevier, Amsterdam, pp. 129–151.

Broccoli, A.J., Manabe, S., 1992. The effects of orography on midlatitude Northern Hemisphere dry climates. Journal of Climate 5, 1181–1201.

Cohen, A.S., Palacios-Fest, M.R., Negrini, R.M., Wigand, P.E., Erbes, D.B., 2000. A paleoclimate record for the past 250,000 years from Summer Lake, Oregon, USA: Π. Sedimentology, paleontology and geochemistry. Journal of Paleolimnology 24, 151–182.

Cour, P., Zheng, Z., Duzer, D., Calleja, M., Yao, Z., 1999. Vegetational and climatic significance of modern pollen rain in northwestern Tibet. Review of Palaeobotany and Palynology 104, 183–204.

Davis, C.P., Fall, P.L., 2001. Modern pollen precipitation from an elevational transect in central Jordan and its relationship to vegetation. Journal of Biogeography 28, 1195–1210.

Davis, M.E., Thompson, L.G., Yao, T.D., Wang, N.L., 2005. Forcing of the Asian monsoon on the Tibetan Plateau: evidence from high-resolution ice core and tropical coral records. Journal of Geophysical Research 110, D04101, doi:10.1029/2004DJ004933.

Dean, W.E., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. Journal of Sedimentary Petrology 44, 242–248.

El-Moslimany, A.P., 1990. The ecological significance of common nonarboreal pollen: examples from dryland of the Middle East. Review of Palaeobotany and Palynology 64, 343–350.

Fægri, K., Iversen, J., 1989. Textbook of Pollen Analysis, 4th Edition. John Wiley and Sons, London, UK.

Grimm, E.C., 1987. CONISS: a Fortran 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Computers & Geosciences 13, 13–35.

Gunin, P.D., Vostokova, E.A., Dorofeyuk, N.I., Tarasov, P.E., Black, C.C., 1999. Vegetation Dynamics of Mongolia. Kluwer Academic Publishers, Dordrecht, pp. 46–54.

He, H.Y., McGinnis, J.W., Song, Z.S., Yanai, M., 1987. Onset of the Asian summer monsoon in 1979 and the effect of the Tibetan Plateau. Monthly Weather Review 115, 1966–1995.

Herzschuh, U., 2007. Reliability of pollen ratios for environmental reconstructions on the Tibetan Plateau. Journal of Biogeography 34, 1265–1273.

Herzschuh, U., Hueschner, H., Ma, Y.Z., 2003. The surface pollen and relative pollen production of the desert vegetation of the Alashan Plateau, western Inner Mongolia. Chinese Science Bulletin 48, 1488–1493.

Jiang, W.Y., Guo, Z.T., Sun, X.J., Wu, H.B., Chu, G.Q., Yuan, B.Y., Hattée, C., Guiot, J., 2006. Reconstruction of climate and vegetation changes of Lake Bayanchagan (Inner Mongolia): Holocene variability of the East Asian monsoon. Quaternary Research 65, 411–420.

Li, Y.C., Xu, Q.H., Zhao, Y.K., Yang, X.L., Xiao, J.L., Chen, H., Lu, X.M., 2005. Pollen indication to source plants in the eastern desert of China. Chinese Science Bulletin 50, 1632–1641.

Liu, K.B., Yao, Z.J., Thompson, L., 1998. A pollen record of Holocene climatic changes from dunde ice cap, Qinghai-Tibetan Plateau. Geology 26, 135–138.

Liu, H.Y., Cui, H.T., Pott, R., Speier, M., 1999. The surface pollen of the woodland-steppe ecotone in southeastern Inner Mongolia, China. Review of Palaeobotany and Palynology 105, 237–250.

Maher, L.J., 1964. *Ephedra* pollen in sediments of the Great Lakes region. Ecology 45, 391–395.

Maher, L.J., 1981. Statistics for microfossil concentration measurements employing samples spiked with marker grains. Review of Palaeobotany and Palynology 32, 153–191.

Prat, N., Daroca, M.V., 1983. Eutrophication processes in Spanish reservoirs as revealed by biological records in profundal sediments. Hydrobiologia 103, 153–158.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, F.G., Manning, S.W., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. Intcal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. Radiocarbon 46, 1029–1058.

Sato, T., Kimura, F., 2005. Impact of diabatic heating over the Tibetan Plateau on subsidence over northern Asian arid region. Geophysical Research Letters 32, L05809, doi:10.1029/2004GL022089.

Shao, X.M., Liang, E.Y., Huang, L., Wang, L.L., 2005. A 1437-year precipitation history from Qilian juniper in the northeastern Qinghai-Tibetan Plateau. PAGES News 13 (2), 14–15.

Shen, J., Liu, X.Q., Wang, S.M., Mastsumoto, R., 2005. Palaeoclimatic changes in the Qinghai Lake area during the last 18,000 years. Quaternary International 136, 131–140.

Shen, C.M., Liu, K., Tang, L.Y., Overpeck, J.T., 2006. Quantitative relationships between modern pollen rain and climate in the Tibetan Plateau. Review of Palaeobotany and Palynology 140, 61–77.

Sheppard, P.R., Tarasov, P.E., Graumlich, L.J., Heussner, K.-U., Wagner, M., Oesterle, H., Thompson, L.G., 2004. Annual precipitation since 515 BC reconstructed from living and fossil juniper growth of northeastern Qinghai Province, China. Climate Dynamics 23, 869–881.

Sugita, S., 1994. Pollen representation of vegetation in Quaternary sediments: theory and method in patchy vegetation. Journal of Ecology 82, 881–897.

Tarasov, P.E., Jolly, D., Kaplan, J.O., 1997. A continuous late glacial and Holocene record of vegetation changes in Kazakhstan. Palaeogeography, Palaeoclimatology, Palaeoecology 136, 281–292.

Tell, G., del Zamaloa, M.C., 2004. A Miocene algal assemblage dominated by *Pediastrum leonensis* n. sp. (Chlorophyceae) from Patagonia, Argentina: paleoenvironmental implications. Journal of Paleolimnology 32, 247–254.

Thompson, L.G., Thompson, E.M., Davis, M.E., Lin, P.N., Yao, T., Dyurgerov, M., Dai, J., 1993. "Recent warming": ice core evidence from tropical ice cores with emphasis on Central Asia. Global and Planetary Change 7, 145–156.

Thompson, L.G., Thompson, E.M., Davis, M.E., Lin, P.N., Henderson, K., Mashiotta, T.A., 2003. Tropical glacier and ice core evidence of climate change on annual to millennial time scales. Climatic Change 59, 137–155.

Van Campo, E., Cour, P., Hang, S.X., 1996. Holocene environmental changes in Bangong Co basin (Western Tibet). Part 2: the pollen record. Palaeogeography, Palaeoclimatology, Palaeoecology 120, 49–63.

Wang, S.M., Dou, H.S., 1998. Lakes in China. Science Press, Beijing. (in Chinese).

Wang, F.X., Qian, N.F., Zhang, Y.L., 1995. Pollen Flora of China. Science Press, Beijing. (in Chinese).

Yan, S., 1991. The characteristics of Quaternary sporo-pollen assemblage and the vegetation succession in Xinjiang. Arid Land Geography 14, 1–9 (in Chinese with English abstract).

Yao, T.D., Xie, Z.C., Yang, Q.Z., 1991. Temperature and precipitation fluctuations since 1600a provided by dunde ice cap, China. Presented in International Symposium on Glacial-Ocean-Atmosphere Interactions, International Association of Hydrological Sciences Publication 208, 61–70.

Yi, X.X., Yang, D.S., Xu, W.D., 1992. China Regional Hydrogeology Survey Report-Toson Lake Map (J-47-[25] 1:200,000). Qaidam Integrative Geological Survey, Golmud, Qinghai, China. 123 pages, plus tables, drill core lithology, and maps (in Chinese).

Yin, Z.Y., Shao, X.M., Qin, N.S., Liang, E.Y., 2008. Reconstruction of a 1436-year soil moisture and vegetation water use history based on tree-ring widths from Qilian junipers in northeastern Qaidam Basin, northwestern China. International Journal of Climatology 28, 37–53.

Yu, G., Tang, L.Y., Yang, X.D., Ke, X.K., Harrison, S.P., 2001. Modern pollen samples from alpine vegetation on the Tibetan Plateau. Global Ecology and Biogeography 10, 503–519.

Zhang, Q.B., Cheng, G.D., Yao, T.D., Kang, X.C., Huang, J.G., 2003. A 2,326-year tree-ring record of climate variability on the northeastern Qinghai-Tibetan Plateau. Geophysical Research Letters 30, 1439–1442.

Zhao, Y., Herzschuh, U., 2008. Surface pollen representation of source vegetation in the Qaidam Basin and the surrounding mountains, the northeastern Tibetan Plateau. Vegetation History and Archaeobotany, doi:10.1007/s00334-008-0201-7.

Zhao, Y., Yu, Z.C., Chen, F.H., Ito, E., Zhao, C., 2007. Holocene vegetation and climate history at Hurleg Lake in the Qaidam Basin, northwest China. Review of Palaeobotany and Palynology 145, 275–288.

Zhao, Y., Yu, Z.C., Chen, F.H., Liu, X.J., Ito, E., 2008. Sensitive response of desert vegetation to moisture change based on annually-resolved pollen record from Gahai Lake in the Qaidam Basin, northwest China. Global and Planetary Change 62, 107–114.

Zhou, L.H., Sun, S.Z., Chen, G.C., 1990. Vegetation Map of Qinghai Province (1:1,000,000). China Science and Technology Press, Beijing, pp. 23–24 (in Chinese).