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Pollen-inferred climate changes and vertical shifts of alpine vegetation belts on the northern slope of the Nyainqentanglha Mountains (central Tibetan Plateau) since 8.4 kyr BP

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Abstract

Fossil pollen from Nam Co and modern pollen from altitudinal vegetation belts around the lake are investigated to reveal alpine vegetation succession in response to climate changes during the Holocene in the central Tibetan Plateau. The discriminant analysis on 37 topsoil samples shows that pollen samples from alpine steppe at lower elevations (<4800 m) and alpine meadow on upper slopes (4800–5200 m) can be distinguished by their pollen assemblages. Samples from alpine steppe contain more *Artemisia* (25.1%) and Poaceae pollen (11.5%), whereas those from alpine meadow are dominated by Cyperaceae pollen (>60%). Our result indicates that the pollen ratio of *Artemisia* to Cyperaceae (A/Cy) can be used as an indicator of the vertical shift of vegetation belts and temperature changes in the central Tibetan Plateau as suggested by previous studies. A history of the vertical shift of vegetation belts on the northern slope of Nyainqentanglha Mountains and climate changes since 8.4 kyr BP are thus recovered by 198 fossil pollen assemblages from a 332 cm core of Nam Co. Paleovegetation reconstructed from fossil pollen assemblages through discriminant analysis shows a general downward shift of altitudinal vegetation belts, suggesting a decline in the temperature trend since 8.4 kyr BP. This result is consistent with the reduction of A/Cy ratios. The fossil pollen record also reveals warm and wet climate during the early to mid Holocene, and cold and dry conditions during the late Holocene in the Nam Co area. A comparison of Holocene climatic reconstructions across the Plateau indicates that termination of maximum moisture at around 6–5.5 kyr BP in our record is associated with the southeastward retreat of the Southwest Monsoon.

Keywords

discriminant analysis, Holocene, Nam Co, pollen analysis, Tibetan Plateau, vegetation belt

Introduction

Vegetation distribution in the Tibetan Plateau (TP) with an average elevation above 4000 m is very vulnerable to climate change (Shen et al., 2008a; Song et al., 2004; Zheng, 1996). As major archives of Holocene paleoenvironmental changes, lake sediments in the TP have been widely studied (e.g. Gasse et al., 1991; Morrill et al., 2006; Shen J et al., 2005; Wu et al., 2006; Zhu et al., 2009). Among them, lacustrine pollen records have provided paleovegetation and paleoclimate reconstructions qualitatively (e.g. Lu et al., 2001; Shen et al., 2005; Shen J et al., 2005; Sun et al., 1993; Van Campo and Gasse, 1993; Van Campo et al., 1996), semi-quantitatively (e.g. Herzschuh et al., 2006a, b; Shen and Tang, 1996; Tang et al., 2009), and quantitatively (e.g. Herzschuh et al., 2009a, b, 2010a, b; Shen, 2003; Shen et al., 2006, 2008a, b; Tang et al., 2004). However, climatic conditions reconstructed from pollen records revealed the occurrence of regional differences in the TP. For instance, a descending trend in temperature and an increasing trend in precipitation occurred from the early to late Holocene in the northeast (Herzschuh et al., 2009b), whereas warm/wet climate during the early to mid Holocene and cold/dry during the late Holocene occurred in the central, southeast, and south Plateau (e.g. Herzschuh et al., 2006a; Tang et al., 1999; Zhu et al., 2009). Therefore, more well-dated and high-resolution pollen records are essential for characterising the nature and causes of spatial patterns of Holocene climate in the TP. To date, most of the published Holocene pollen records are located in the margins of the Plateau (e.g. Gasse et al., 1991; Herzschuh et al., 2006b, b; Kramer et al., 2010; Shen J et al., 2005; Tang et al., 2004; Van Campo et al., 1996), only a few are from the central Plateau (e.g. Herzschuh et al., 2006a; Shen et al., 2008a; Sun et al., 1993).

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The ecotone of meadow and steppe in the central TP is sensitive to climate change (Shen et al., 2008a). Shen et al. (2008a) revealed a history of the horizontal shift of this ecotone in response to the intensity of the Southwest monsoon during the mid–late Holocene based on a pollen record from a large lake (Co Ngion) in the central TP. A pollen record from another large lake (Zigetang) in the central Plateau revealed a major vegetation change from 'warm temperate steppe' (*Artemisia*-dominated) to alpine steppe (Cyperaceae-dominated) in the mid Holocene (Herzschuh et al., 2006a). They attributed this change to a drop in temperature. Both studies focused on the horizontal movement of vegetation communities. Up to now, little attention has been paid to the altitudinal vegetation zones and their variations in response to climate changes, although they develop well in the mountainous regions of the TP and its peripheries under fragile high-alpine environmental conditions (Herzschuh et al., 2006b; Miehe and Miehe, 2000).

The Nam Co is located in the meadow-steppe transitional region of TP, lying on the northern foot of Nyainqentanglha Mountains occupied by altitudinal vegetation belts consisting of non-forest alpine vegetation types. Previous paleoclimate studies in Nam Co and its adjacent areas mainly focused on long-term environmental changes based on lake terrace deposits (e.g. Wu et al., 2004; Zhao et al., 2003; Zhu et al., 2004), or lacustrine sediments (e.g. Li et al., 2008; Lin et al., 2008; Mügler et al., 2010; Xie et al., 2009; Zhu et al., 2008). Herrmann et al. (2010) analysed fossil pollen and other palynomorphs from a set of peat samples to reconstruct the Holocene vegetation changes in the Nam Co area. However, their results are limited in explanation of vegetation changes on the regional scale and in time resolution because of the small spatial scale of the peat pollen source (relatively local) and a small amount of peat samples. To date, there is still little knowledge of regional vegetation history in the Nam Co area and its vicinity during the Holocene. In this study, we conduct an investigation on modern pollen assemblages from alpine steppe and meadow around Nam Co and on the northern slope of Nyainqentanglha Mountains, and present a Holocene lacustrine pollen record from a deep water core in Nam Co to study shifts of altitudinal vegetation belts and climate changes in the central TP.

Study area

Nam Co (90°15′–91°10′E, 30°40′–31°00′N, 4718 m a.s.l.), the second largest lake of the TP, is located on northern slope of Nyainqentanglha Mountains. It covers 1982 km^2 water area and its maximum depth is about 95 m in the central lake (Figure 1a, b) (Wang et al., 2009). It has a catchment area of 10 610 km^2. It is a closed-basin lake with no outflow rivers. Precipitation and inflow of glacial meltwater are the main sources of lake water while evaporation is its main loss. The mean annual temperature is around 0°C, and mean annual precipitation about 280 mm in the Nam Co area (Nam Co Monitoring and Research Station, 90°59′E, 30°46′N, 4730 m a.s.l.). In this area, westerly winds dominate from January to May while southerly winds prevail between June and October, showing the alternate influences of the Westerlies and Southwest Monsoon on its climate conditions (You et al., 2007).

Alpine steppe and alpine meadow are two major vegetation types in the central TP (Chen et al., 2011; Institute of Geography, 1990; Lu, 2008; Miehe and Miehe, 2000; Tibetan Investigation Group, 1988; Zhang et al., 1981). Details of an altitudinal vegetation zonation in the Nam Co area are described as follows (Figure 1c):

(1) Alpine steppe (<4800 m elevation) occupies the lakeshore around Nam Co and most of its catchment area. It mainly consists of *Artemisia stracheyi*, *A. wellbyi*, *Stipa purpurea*, *S. subsessifliflora* var. *basiplumosa*, *Carex moorcroftii* and *Poa*, accompanied by *Astragalus, Oxytropis*, *Festuca*, etc.
(2) Alpine meadow (4800–5200 m) forms a dense vegetation belt with a vertical extent of 400 m on upper slopes of the Nyainqentanglha Mountains, and occurs in patches on hills around the lake. It is dominated by Kobresia sedges (e.g. *K. pygmaea*, *K. humilis*) along with *Festuca*, *Poa*, *Polygonum macrophyllum*, *P. viviparum*, *Caltha scaposa*, etc.
(3) Alpine sparse vegetation (5200–5700 or 5900 m) occurs below the ice and snow belt. It is mainly composed of *Saussurea*, *Waldheimia glabra*, with some *Meconopsis*, *Soroseris glomerata*, *Draba*, *Rhodiola*, *Saxifraga*, *Thylacospermum*, and cushion plants such as *Androsace, Arenaria*, etc.

In addition, marsh meadow with hummocks of dominant *Kobresia tibetica* (=*K. schoenoides*, see Zhang, 2004) and *Blysmus* is distributed along riverbanks and on low wetland around the lake. Associated species include *K. humilis*, *Festuca*, *Polygonum*, *Gentiana,* and hydrophyte taxa such as *Antenoron* and *Batrachium bungei*.

Material and methods

Sampling and dating

Modern pollen samples (top 2 cm of soil) were collected from different vegetation types around Nam Co in 2006, including 14 samples from alpine steppe, 7 from alpine meadow, and 16 from marsh meadow. According to the vegetation map (Institute of Geography, 1990) and field investigation (Lu, 2008), these topsoil samples cover the major vegetation types in the Nam Co catchment (Figure 1c). The elevations of alpine meadow samples are higher than those of alpine steppe by 50–100 m.

Lacustrine core NMLC-1 (59.5 m water depth, core length 332 cm) was obtained in the east part of the lake in May 2005 using a piston corer. An age–depth model for core NMLC-1 has been developed by Zhu et al. (2008). Twelve samples were used for AMS ^{14}C dating at the AMS & Quaternary Chronology Laboratory of Peking University. The ^{14}C dates were calibrated to calendar ages using the IntCal04 calibration data (Reimer et al., 2004) and the OxCal3.1 program (Bronk Ramsey, 2005, https://c14.arch.ox.ac.uk/embed.php? File=oxcal.html #program, version 78, April 2008). ^{210}Pb/^{137}Cs dating and the calculation of sedimentation rate of a short gravity core (NMCS-10) collected from the same location were used to estimate the carbon reservoir effects. The depth–age sequence of NMLC-1 core was corrected by subtracting this reservoir effect. One date at 190 cm suggested an age reversal was not used in the final age model. The dating results show that core NMLC-1 covers the last 8330 years (Zhu et al., 2008).

Sediments for pollen analysis were sampled at 1 cm intervals at depths of 332–260 cm (time resolution of ~100 yr/sample), and at 2 cm intervals for the upper parts (~20 yr/sample). In total, 198 sediment samples were analysed palynologically in this study.

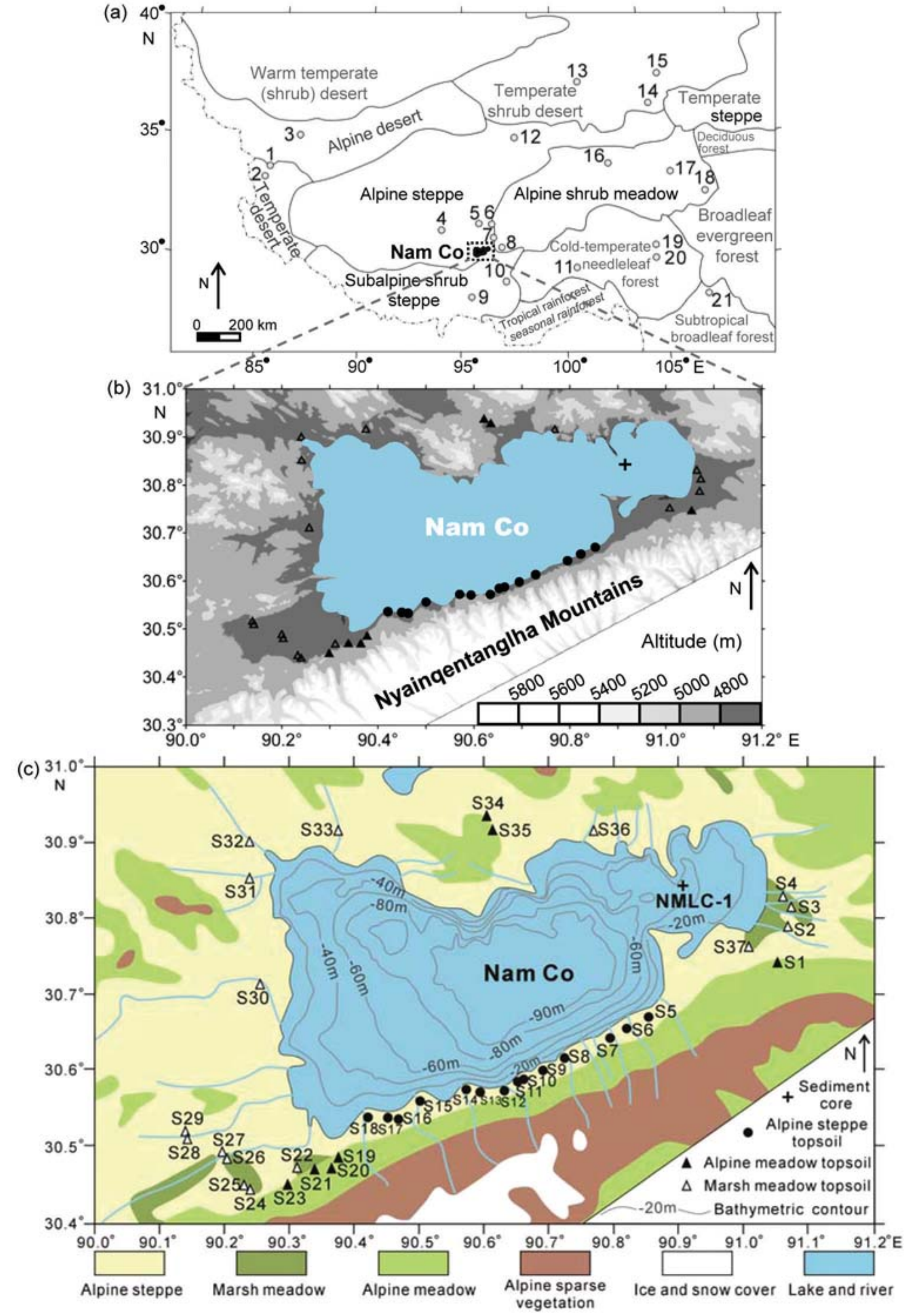

Figure 1. (a) Vegetation zones of Tibetan Plateau; (b) topographic map and sampling sites in Nam Co area; (c) vegetation map of Nam Co area, and locations of topsoil samples and core NMLC-1. Solid circles in (a) indicate sites of paleoclimate records mentioned in the text. See Table 1 for site information and references. The terrain elevation data set used for (b) is provided by International Scientific & Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (http://datamirror.csdb.cn)

Pollen analysis and numerical methods

Samples were treated with a modified acetolysis procedure (Fægri and Iversen, 1989), including 10% HCl, 5% KOH, 40% HF, acetolysis treatments, and sieving with a 7μm screen to remove clay-sized particles. One tablet of *Lycopodium* marker spores (27 637 grains/tablet) was added to each sample for estimating pollen concentration. The average number of counted pollen and spores is 316 grains per sample. Pollen identification was carried out by comparisons with published literature (Wang et al., 1997; Xi and Ning, 1994) and our modern pollen collections. Pollen percentages were computed with the sum of all pollen and spores. Pollen concentrations (grains/g of dried sample), pollen ratio of *Artemisia* to Cyperaceae (A/Cy), and sum of percentages of dryness indicators, including Chenopodiaceae, Cruciferae, *Ephedra, Nitraria* and Tamaricaceae (Herzschuh et al., 2006b; Tang et al., 2009; Yu et al., 2001), were calculated for the interpretation of fossil pollen records.

Table 1. List of mentioned paleoclimate records in Tibetan Plateau

Code	Site name	Altitude (m)	Latitude and longitude(N, E)	Proxies	Reference
1	Sumxi Co	5058	34°30′, 81°30′	pollen, diatom	Van Campo and Gasse (1993)
2	Bangong Co	4241	33°40′, 79°00′	pollen	Van Campo et al. (1996)
3	Guliya	6710	35°17′, 81°29′	e.g. $\delta^{18}O$, dust, Cl^-	Thompson et al. (1997)
4	Selin Co	4530	31°34′-57′, 88°31′-89°21′	pollen	Sun et al. (1993)
5	Zigetang	4560	32°00′, 90°54′	pollen	Herzschuh et al. (2006a)
6	Co Ngion	4515	31°28′, 91°30′	pollen	Shen et al. (2008a)
7	Cuoe Lake	4532	31°30′, 91°32′	Sr, TOC, C/N, $\delta^{13}C$	Wu et al. (2006)
8	Ahung Co	4575	31°37′, 92°04′	e.g. $CaCO_3$, C/N, $\delta^{13}C$	Morrill et al. (2006)
9	Chen Co	4420	28°53′-59′, 90°33′-39′	e.g. grain size, TOC, TN, Fe/Mn, pollen	Zhu et al. (2009)
10	Hidden Lake	4980	29°49′, 92°32′	pollen	Tang et al. (1999)
11	Ren Co	4450	30°44′, 96°41′	pollen	Tang et al. (1999)
12	Kusai Lake	4475	35°37′-50′, 93°15′-38′	TOC, grain size	Liu et al. (2009)
13	Dunde	5325	38°06′, 96°24′	pollen	Liu et al. (1998)
14	Qinghai Lake	3200	36°15′-37°32′, 99°36′-100°47′	pollen, $CaCO_3$, TOC, TN, $\delta^{13}C$	Shen J et al. (2005)
15	Luanhaizi	3200	37°36′, 101°21′	pollen	Herzschuh et al. (2006b)
16	Koucha Lake	4540	34°00′, 97°12′	pollen	Herzschuh et al. (2009b)
17	Ximencuo	4000	33°23′, 101°06′	e.g. TOC, $CaCO_3$, grain-size, magnetic susceptibility	Zhang and Mischke (2009)
18	Hongyuan peat	3466	32°46′, 102°30′	$\delta^{13}C$	Hong et al. (2003)
19	Naleng Lake	4200	31°06′, 99°45′	pollen	Kramer et al. (2010)
20	Yidun Lake	4470	30°18′, 99°33′	pollen	Shen et al. (2008b)
21	Shayema Lake	2400	28°35′, 102°13′	pollen	Jarvis (1993)

Discriminant analysis has been used as an effective mathematical technique to reconstruct paleovegetation (Liu and Lam, 1985; Shen et al., 2005, 2008b; Sugden and Meadows, 1989), and to investigate the relationship between modern pollen assemblages and vegetation types on a regional scale (Li et al., 2009; Lynch, 1996). Here, we use discriminant analysis to determine whether modern pollen assemblages could represent source vegetation types from an altitudinal vegetation zone on a local scale. The procedure is as follows. Modern pollen samples are classified into three a priori groups (alpine steppe, alpine meadow and marsh meadow) based on vegetation types at sampling sites. Then percentage data of major pollen types are applied to establish the discriminant functions and classify samples into predicted groups. The comparison between a priori groups and predicted groups is used to assess the consistency of modern pollen assemblages and vegetation types. Then, the discriminant functions derived from modern samples are applied to fossil pollen data from core NMLC-1 to predict the group membership (i.e. vegetation type with the largest contribution to pollen assemblage) of each fossil sample. Two indices are used to summarize the results of discriminant analysis. One is the 'probability of modern analog', which represents the similarity between modern or fossil pollen assemblages and predicted vegetation types. Another is 'vegetation zonal index', which is converted from probabilities of group membership between the predicted and the second most probable group (Liu and Lam, 1985). The detailed process and interpretation of results follow the procedures of Liu and Lam (1985) and Shen et al. (2008b). Software used for discriminant analysis is SPSS 10.0 (SPSS Inc., 1999).

Results

Modern pollen assemblages

Modern pollen assemblages from various vegetation types show marked differences (Figure 2). Pollen assemblages from alpine steppe mainly consist of *Artemisia* (up to 66.5%, mean 25.1%) and Poaceae (up to 29.8%, mean 11.5%). Fabaceae (mean 3.3%), *Thalictrum* (2.8%), Chenopodiaceae (2.7%), *Polygonum* (1.8%), Caryophyllaceae (1.7%) and arboreal pollen types (10.7%) are commonly present. Percentages of Cyperaceae (13.6%) and total pollen concentrations (2452 grains/g) of samples from alpine steppe are much lower than those from meadows.

Pollen assemblages of meadow samples (alpine meadow and marsh meadow) are characterized by high percentages of Cyperaceae (up to 95.1%, mean 63.1%). Other pollen types present include Poaceae (7.6%), Ranunculaceae (>2%), *Polygonum* (1.9%), and *Thalictrum* (1.9%). Compared with alpine steppe samples, pollen assemblages of meadows have much less *Artemisia* (7.0%). Samples from alpine meadow have the highest pollen concentrations (7681 grains/g), while marsh meadow samples have relatively low pollen concentrations (3432 grains/g).

Pollen ratios of A/Cy are characteristic for individual vegetation type. A/Cy values are generally higher than 1.0 in alpine steppe (mean 4.9), while lower than 1.0 in meadows (mean 0.1).

Discriminant analysis on modern pollen assemblages

Discriminant analysis of topsoil samples is conducted on percentage data of 16 major pollen types (more than 2% at least in one sample and of ecological importance), including *Artemisia*, Poaceae, Cyperaceae, *Thalictrum*, Polygonaceae, Chenopodiaceae, *Saussurea*-type, *Aster*-type, Ranunculaceae, Caryophyllaceae, Cruciferae, Rosaceae, Fabaceae, *Gentiana, Pinus* and *Alnus*. Three major vegetation types in the Nam Co area are assigned certain values as their vegetation zonal indices in advance (value of 1 for alpine steppe, 2 for alpine meadow and 3 for marsh meadow).

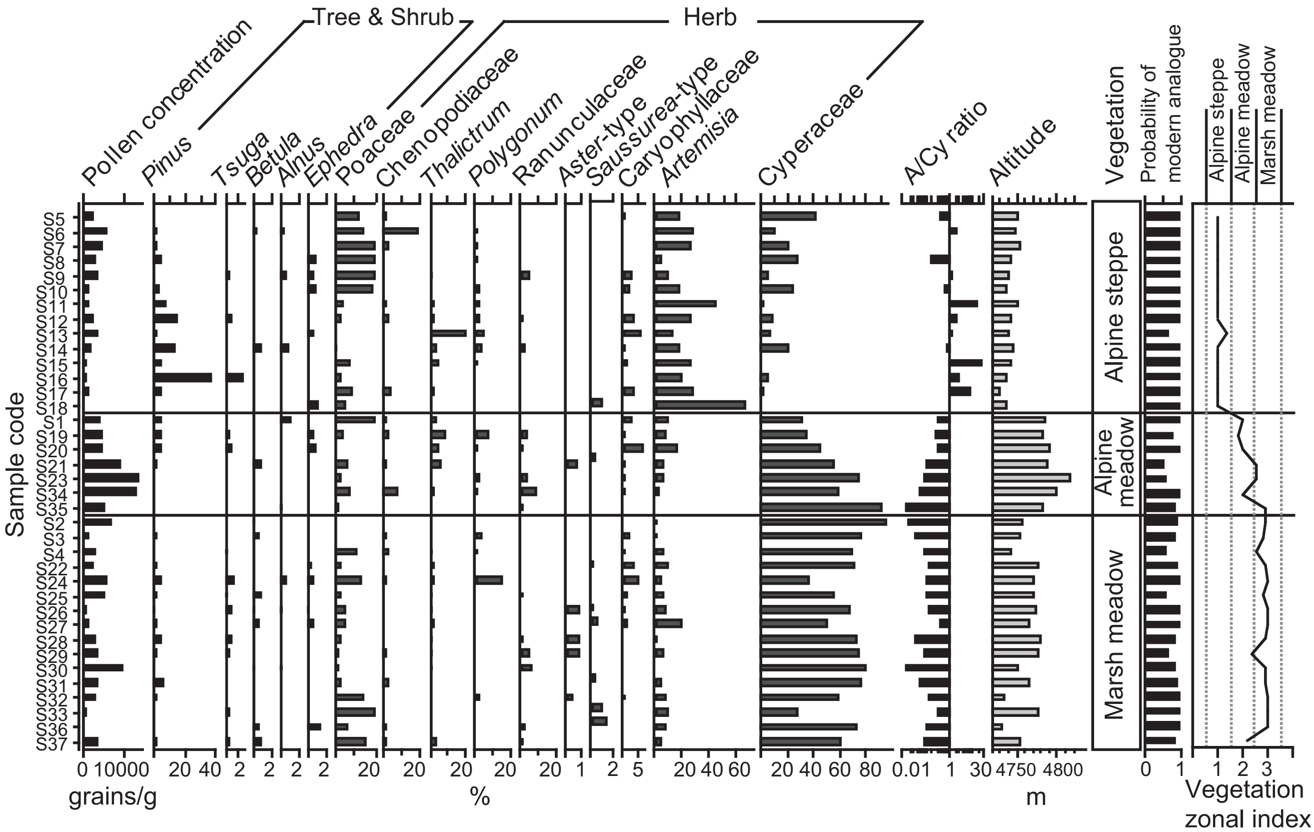

Figure 2. Pollen percentage diagram of topsoil samples from Nam Co area, with altitudes of sampling sites and results of discriminant analysis

Table 2. Discriminant analysis results of topsoil samples from Nam Co catchment in central Tibetan Plateau

Predicted group membership				
Actual group	No. of samples	Alpine steppe	Alpine meadow	Marsh meadow
Alpine steppe	14	14[a] (100)[b]	0	0
Alpine meadow	7	0	4 (57.1)	3 (42.9)
Marsh meadow	16	0	2 (12.5)	14 (87.5)

Total number of samples: 37
Number of misclassified samples: 5
Percentage of samples correctly classified: 86.5%

[a]Number of samples classified as that group.
[b]Percentage of samples classified into that group.

The results show that 86.5% of the samples are correctly classified (Table 2). The samples from the alpine steppe belt are most distinct from those from meadows according to discriminant function 1, which accounts for 91.7% of variance (Figure 3). However, a few samples of alpine meadow (S21, S23, S35) and marsh meadow (S29, S37) are misclassified between these two meadow types (Figures 2 and 3). This could reflect the similarities in both vegetation compositions and pollen assemblages between alpine and marsh meadows, since they share most taxa under a predominance of Cyperaceae.

In summary, three major vegetation types are well distinguished by discriminant analysis. High values of probability of modern analogue (mean 0.9) for modern pollen samples indicate that major vegetation types are fairly reflected by their pollen assemblages. All three major vegetation types are taken into consideration in conducting discriminant analysis on fossil pollen data of core NMLC-1.

Fossil pollen assemblages of core NMLC-1

A total of 75 pollen types are identified in the fossil pollen record of NMLC-1 core from Nam Co. Fossil pollen assemblages are dominated by *Artemisia*, Cyperaceae, and Poaceae. Three pollen types account for 72% to 88% of the total pollen count for each sample. Other herb pollen types with low percentages include Chenopodiaceae, *Thalictrum*, *Aster*-type, Ranunculaceae, Caryophyllaceae, *Polygonum*, *Saussurea*-type, *Taraxacum*-type, *Gentiana*, Crassulaceae, and Cruciferae, etc. Tree and shrub pollen types (6.2%) comprise *Pinus*, *Betula*, *Alnus*, *Abies*, *Picea*, *Ephedra*, etc. Three pollen zones can be divided based on the percentage variations of major pollen types from core NMLC-1 (Figure 4).

Zone NC1 (332–313 cm, 8400–7200 yr BP). This zone is characterized by a predominance of *Artemisia* pollen (48.8%–64.6%,

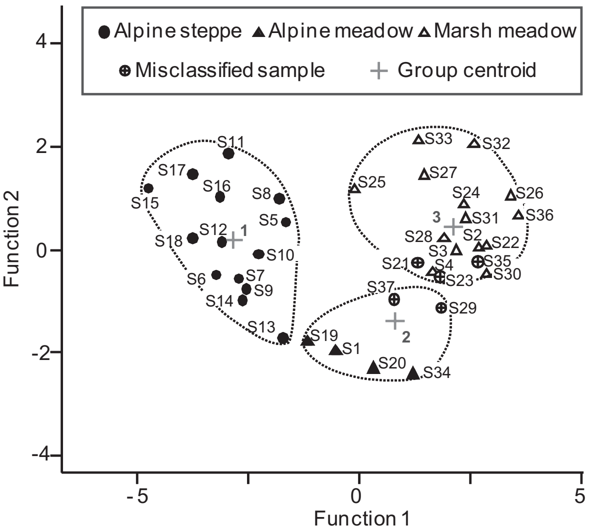

Figure 3. Ordination of 37 topsoil samples along discriminant functions 1 and 2

mean 57.3%) and high pollen concentrations (1.4×10^5grains/g). Cyperaceae show an increase trend from the bottom to the top of the zone (from 15.1% to 26.2%, mean 21.2%). Poaceae (5.0%), *Thalictrum* (3.4%), *Aster* (1.8%), Ranunculaceae (1.2%) and *Polygonum* (1.1%) are common. Percentages of tree and shrub types (3.7%) and dryness indicators (1.3%) exhibit low values. A/Cy ratios gradually decline from 4.0 to 1.8. *Artemisia* percentages dramatically decrease from 60.8% to 53.3% at the upper part of the zone (7600–7200 yr BP), where Cyperaceae increases.

Zone NC2 (313–270 cm, 7200–2800 yr BP). Percentages of *Artemisia* consistently decline from 59.9% to 30.6%, whereas an increase occurs in Cyperaceae pollen (from 16.9% to 42.7%) and Poaceae pollen (from 1.7% to 9.1%). There is also an increase for Ranunculaceae, *Polygonum*, Caryophyllaceae, tree and shrub types within this zone. A/Cy ratios continually decline (from 3.4 to 0.7). Pollen concentration reached its highest value (2.6×10^5 grains/g) throughout the core around 5700 yr BP. The lowest value of dryness indicators occurred around 7000–6000 yr BP, and then it sharply increased during 6000 and 5500 yr BP. In a period of 3200–2800 yr BP, Cyperaceae pollen markedly increased to 42.1% at the expense of *Artemisia* pollen, associated with declines of pollen concentrations and A/Cy ratios, and an increase of dryness indicators.

Zone NC3 (270–5 cm, 2800–40 yr BP). There are increases in the percentages of *Saussurea*-type, *Taraxacum*-type, *Gentiana*, Crassulaceae, *Androsace*, Caryophyllaceae, Saxifragaceae, dryness indicators of Chenopodiaceae and Cruciferae, and gymnosperm pollen types such as *Pinus*, *Picea* and *Abies*. Pollen concentration sharply declines to 8.7×10^4 grains/g. This zone is divided into two subzones. Subzone NC3-1 (270–214 cm, 2800–1800 yr BP) is distinguished from NC3-2 (214–5 cm, 1800–40 yr BP) by higher values of *Artemisia* (47.5%) and A/Cy ratio (1.8), and lower values of Cyperaceae (28.0%) and Poaceae (5.0%). In subzone NC3-2, percentages of Cyperaceae markedly increase to 36.0% with a decrease of *Artemisia* (39.6%), and A/Cy ratios fluctuate around the value of 1.0. In the periods of 1700–1500 yr BP and 800–150 yr BP, Cyperaceae apparently increased along with a decrease of *Artemisia*. Cyperaceae pollen decreased, and *Artemisia* increased together with dryness indicators at 1100–800 yr BP.

Discussion

Modern pollen indications of alpine vegetation and climate

Pollen analysis on topsoil samples from the Nam Co area shows that alpine vegetation types from altitudinal vegetation belts on northern slope of Nyainqentanglha Mountains can be distinguished by their modern pollen assemblages. Pollen assemblages are characterized by high percentages of *Artemisia* (25.1%) and Poaceae (11.5%) for samples from alpine steppe with an average elevation of 4745 m (range from 4732 to 4757 m). Alpine meadow samples with an average elevation of 4800 m (range from 4785 to 4819 m) and marsh meadow samples (mean elevation of 4763 m, range from 4735 to 4781 m) are distinguished by predominating Cyperaceae pollen (>60%) (Figure 2). Results of discriminant analysis further demonstrate that most of the modern pollen samples are typical for major vegetation types along an elevation gradient, as suggested by high values of probability of modern analogue (Figures 2 and 3). Thus, the discriminant functions based on modern pollen assemblages from the Nam Co area can be used to identify modern analogs for fossil pollen assemblages.

Artemisia and Cyperaceae are the two major pollen types in the Nam Co area as well as the central TP (Shen et al., 2008a; Yu et al., 2001). Pollen ratio of A/Cy has been used as a semi-quantitative measure for summer temperature changes in the central and eastern Plateau, and as a useful indicator to distinguish meadow and steppe vegetation (Herzschuh et al., 2006a). Previous studies showed that Cyperaceae dominates alpine meadow (*Kobresia*) and alpine steppe (*Carex*), and thus modern pollen assemblages in cold high-alpine environments of the east and central TP, while high frequency of *Artemisia* occurs in both vegetation and modern pollen assemblages of subalpine and alpine (shrub) steppe in the south and temperate steppe in the northeast under warmer conditions (Herzschuh et al., 2006a; Yu et al., 2001). Herzschuh (2007) further validated the applicability of A/Cy ratio in reconstructions of temperature and vegetation in alpine meadow and steppe regions using a set of lake surface sediments from the eastern and central TP.

Owing to low temperature and relatively high humidity on the upper slopes, alpine meadow of *K. pygmaea* occurs between the alpine steppe belt below and the alpine sparse vegetation belt above in the central and western TP (Miehe and Miehe, 2000). In the Nam Co area, the alpine steppe belt of *Artemisia* and Poaceae with abundant *Artemisia* pollen and high A/Cy ratio (>1.0) is located on the lakeshore below 4800 m, while the alpine meadow belt of *Kobresia* with dominant Cyperaceae pollen and low A/Cy ratio (<1.0) occupies the upper slopes between 4800 m and 5200 m where temperature is lower according to the lapse rate, and higher effective moisture due to the lower degree of evaporation than in the alpine steppe belt. Therefore, the relative percentage changes of *Artemisia* and Cyperaceae pollen (i.e. A/Cy ratio) in lake sediments can be used to recover the shift of altitudinal vegetation belts which are considered sensitive to temperature changes in alpine mountain regions (Herzschuh et al., 2006b; Weng et al., 2007). If the temperature declines, altitudinal vegetation belts would

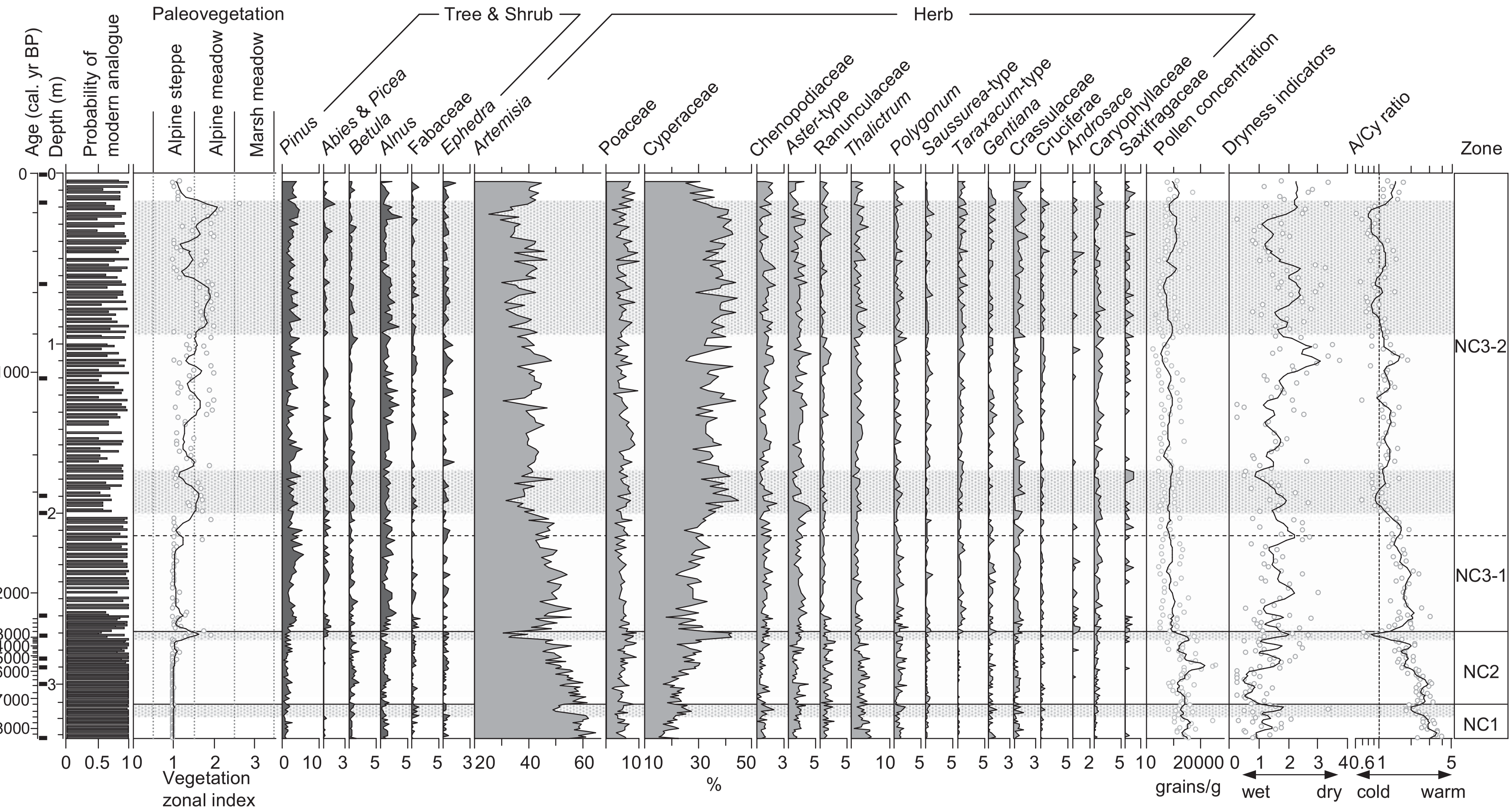

Figure 4. Pollen spectra of core NMLC-1 and paleovegetation reconstruction based on discriminant analysis. Dotted frames mark the major cold periods. Curves of reconstructed paleovegetation, pollen concentration, dryness indicators and A/Cy ratio are exhibited in lowess smoothing lines (span 0.04). Black bars between the axes of age and depth show dating points

shift downward to the lakeshore. Consequently, the alpine steppe belt around the lake shrinks with a decline of its upper altitude limit, and the alpine meadow belt distributes more close to the lake basin and inputs more Cyperaceae pollen, resulting in lower A/Cy ratios in the sediments. On the contrary, altitudinal vegetation belts move upwards with increasing temperature. Alpine steppe would expand to upper slopes, and alpine meadow belt and alpine sparse vegetation belt above would shift to upper slopes far away from the lake basin, causing a reduction of Cyperaceae pollen but an increase of *Artemisia* pollen in lake sediments which lead to higher A/Cy ratios. In the interpretation of NMLC-1 pollen assemblages, we use the A/Cy ratio to indicate temperature change and vertical shift of alpine vegetation belts.

The pollen ratio of *Artemisia* to Chenopodiaceae (A/C) is widely used as an indicator for effective moisture and desert/steppe transition in the Middle East (El-Moslimany, 1990), central arid Asia (Sun et al., 1994), and the western and northeastern TP (Cour et al., 1999; Gasse et al., 1991; Liu et al., 1998; Van Campo et al., 1996; Zhao and Herzschuh, 2009). A higher A/C value points to more steppe-like vegetation and wetter conditions, while a lower A/C value indicates more desert-like vegetation and drier conditions (Herzschuh, 2007). However, there is such few Chenopodiaceae and abundant *Artemisia* in modern and fossil pollen records in the steppe and meadow regions of the TP that A/C ratios are commonly high (>50) with large statistical errors. Therefore, we use the pollen abundance of dryness indicators instead of the A/C ratio to reveal drought periods and moisture changes in the Nam Co area.

Modern pollen assemblages from topsoil samples in the Nam Co area are dominated by herb pollen such as *Artemisia*, Cyperaceae and Poaceae. The results of discriminant analysis suggest that modern pollen assemblages are consistent with local vegetation. Lu et al. (2010) analysed airborne pollen assemblages in the Nam Co area, and found that they were dominated by local herbaceous taxa (87%) including Cyperaceae and *Artemisia*. Peak concentrations of these pollen types occurred in the flowering seasons of spring, summer, and early autumn. Therefore, these results suggest that vegetation within the catchment area of Nam Co is the dominant pollen source for this lake.

Arboreal pollen types take up a very small proportion in modern pollen assemblages of the Nam Co area. Nowadays there is no forest in this region. It has been reported that arboreal pollen types such as *Pinus* could be transported over 400 km to the central and western TP by atmospheric circulation (Wu and Xiao, 1995). Lu (2008) demonstrated that Pinaceae pollen could be transported to the Nam Co area over long distances from conifer forests located in the southern and southwestern regions, and that *Betula* pollen could come from birches growing in the southern and northeastern Plateau. Therefore, arboreal pollen types with very low percentages in both modern and fossil pollen assemblages of Nam Co area are considered as exotic types from far-distant vegetation sources.

Inferred vertical shifts of alpine vegetation belts and climate changes

Fossil pollen assemblages of core NMLC-1 and results of discriminant analysis reveal a detailed history of vertical shifts of altitudinal vegetation belts and climate changes in the Nam Co area since 8400 yr BP (Figure 4).

During the period 8400–7200 yr BP, a high probability of modern analogue (0.96) and stable values of vegetation zonal indices (1.0) indicate that alpine steppe prevailed over the Nam Co area. The typical steppe element of *Artemisia* (57.3%) dominated pollen assemblages. Its percentages markedly exceed the average value of topsoil samples from alpine steppe (25.1%). Cyperaceae pollen occurred in the lowest percentage of the core. Pollen assemblages suggest that *Artemisia*-dominated steppe had much greater distribution range and higher upper altitude limit, while alpine meadow belt and alpine sparse vegetation belt occurred only on slopes at elevations higher than that of today with very limited vertical extents. High values of A/Cy ratio and relatively low percentages of dryness indicators suggest that the climate in the Nam Co area was characterized by high temperature and moderate moisture during this period. This warm and moderate humid condition is also supported by the increases of TOC and *n*-alkanes of benthonic and terraneous plants (Zhu et al., 2008), and ostracod assemblages (Xie et al., 2009) recorded in the same NMLC-1 core. A cold and slight drought interval around 7600–7200 yr BP is indicated by a decline of A/Cy ratio, an increase of dryness indicators, and a peak value of $CaCO_3$ content (Zhu et al., 2008). This cold/dry interval seems a centennial event in the central and western TP. Rapid decrease of precipitation between 7500 and 7000 yr BP is found in a geochemical record from Ahung Co (Morrill et al., 2006). Fossil pollen assemblages from Lake Zigetang with decreases of pollen concentration and A/Cy ratio around 7.4 kyr BP indicate the regression of *Artemisia*-dominated steppe (Herzschuh et al., 2006a). Paleoenvironmental records from Bangong Co in the western Plateau show a drought around 8–7.7 kyr BP (Van Campo et al., 1996).

In the mid to late Holocene (7200–2800 yr BP), results of discriminant analysis show that vegetation around the lake was still dominated by alpine steppe. However, *Artemisia* gradually decreased to 30.6%, whereas Cyperaceae, Ranunculaceae, Caryophyllaceae and *Saussurea*-type increased. The variations in pollen percentages indicate that the alpine steppe belt gradually shrank, while the alpine meadow belt and the alpine sparse vegetation belt on the upper slopes extended downwards towards the lake, associated with lowering of their lower altitude limits. Temperature in the Nam Co area continually declined, and moisture was highest during 7000–6000 yr BP and then sharply dropped, as reflected by decreasing A/Cy ratios and fluctuations of dryness indicators. A severe cold/dry event occurring at 3200–2800 yr BP led to alpine meadow thriving in the Nam Co area, as indicated by vegetation zonal indices of ~1.6, low A/Cy ratios around 0.8, and relatively high percentages of dryness indicators (~2%). This event, characterized by downward expansion of alpine meadow belt in our pollen record, is consistent with westward movement of the meadow-steppe ecotone and an establishment of typical alpine meadow around 2800 yr BP in the Co Ngion area northeast of Nam Co under precipitation near present values and cold conditions (Shen et al., 2008a).

During the late Holocene (2800 yr BP to the present), vegetation and climate were characterized by their instability. The marked increases in typical components of alpine sparse vegetation such as *Saussurea*-type, *Gentiana*, Crassulaceae, *Androsace*, Caryophyllaceae and Saxifragaceae since 2800 yr BP indicate that the alpine sparse vegetation belt markedly extended during the late Holocene. In the first stage, between 2800 and 1800 yr BP, an average vegetation zonal index of 1.1 indicated that alpine steppe recovered with a probable ascension of its upper limit, while the alpine meadow belt withdrew towards the upper slopes, under relatively warm conditions as indicated by A/Cy ratios of 1.8. In the last stage from 1800 yr BP to the present, vegetation zonal index gradually increased with frequent fluctuations around value of 1.5 (boundary between alpine steppe and alpine meadow), suggesting an extension of alpine meadow belt and instability of altitudinal vegetation belts under climate cooling, indicated by reduction of A/Cy ratios. Furthermore, variations of A/Cy ratios and percentages of dryness indicators revealed two cold/wet intervals at 1700–1500 yr BP and 800–150 yr BP ('Little Ice Age', LIA) and a relatively warm/dry interval at 1100–800 yr BP ('Medieval Warm Period', MWP) (Mügler et al., 2010; Zhang et al., 2002; Zhu et al., 2008).

Regional comparison of Holocene climate in the TP

Holocene climate in the Nam Co area is characterized by warm/wet conditions in the early to mid Holocene, and frequent fluctuations during the late Holocene as inferred from pollen assemblages of core NMLC-1.

A decreasing trend of A/Cy ratios and a general downward shift of altitudinal vegetation belts on northern slope of Nyainqentanglha Mountains indicate a climatic cooling throughout the last 8400 years (Figure 4). It seems to agree with reconstructed climates in other regions of the TP. Fossil pollen assemblages of Lake Zigetang suggest a general cooling trend in the Holocene and zonal vegetation transition from *Artemisia*-dominated steppe to Cyperaceae-dominated alpine steppe at 4.4 kyr BP (Herzschuh et al., 2006a). The pollen record of Lake Koucha in the northeastern TP indicates a temperature decline since 8–7 kyr BP and a vegetation transition from warm/semi-wet temperate steppe to cold/wet alpine meadow around 6.6 kyr BP (Herzschuh et al., 2009b). This cooling trend of Holocene climate is correlated well with variations of summer solar insolation at 30°N (Berger and Loutre, 1991), reflecting a consistent influence of insolation forcing on vegetation and climate changes in high-alpine environments of the central TP (Herzschuh et al., 2006a).

The moisture in the Nam Co area culminated at around 7–6 kyr BP, as indicated by low percentages of dryness indicators and high pollen concentrations in the pollen record of NMLC-1 core, and by low contents of $CaCO_3$ due to an increasing lake water volume (Zhu et al., 2008). This maximum moisture in the mid Holocene widely recorded in the central TP (Herzschuh et al., 2006a; Wu et al., 2006) could be attributed to an integrated function of many factors, including lower degree of evaporation due to temperature decline since the early Holocene (Herzschuh et al., 2009b; Wu et al., 2006), soil moisture supply from melting ice and snow (Kashiwaya et al., 1995) on the Nyainqentanglha Mountains, and above all, an enhanced monsoon precipitation which was caused by the intensification of Southwest Indian Monsoon lasting from 9.2 to 6 kyr BP, lagging the insolation maximum of the Northern Hemisphere by about 2000 to 3000 years because of the control from glacial boundary conditions in high northern latitudes (Fleitmann et al., 2003; Overpeck et al., 1996).

Warm and wet climate during the early and mid Holocene is widely suggested by numerous paleoenvironment records with a temporal succession across the Plateau, e.g. (1) western TP: pollen and diatom records from Sumxi Co (11.4–6.5 kyr BP, Gasse et al., 1991; Van Campo and Gasse, 1993) and Bangong Co (9.5–6.2 kyr BP, Van Campo et al., 1996), oxygen isotope record of Guliya ice core (warm condition during 11.5–7.2 kyr BP, Thompson et al., 1997); (2) central TP: paleoclimate records from Selin Co (9.6–6 kyr BP, Sun et al., 1993; maximum monsoon precipitation during 8.4–5.5 kyr BP, Gu et al., 1994), NMLC-1 pollen record (warm/wet climate during 8.4–6 kyr BP) and higher lake level of Nam Co during 9.6–5.2 kyr BP (Schütt et al., 2010), sedimentary record from Lake Cuoe (10–5.7 kyr BP, Wu et al., 2006), Lake Zigetang pollen record (10.8–4.4 kyr BP, Herzschuh et al., 2006a) and geochemistrical evidence (9–5.6 kyr BP, Wu et al., 2007); (3) southern TP: pollen records from Hidden Lake and Ren Co (about 8–5 kyr BP, Tang et al., 1999); multiproxy records from Lake Chen Co (warm/wet condition at 9–6 kyr BP, Zhu et al., 2009); (4) northern and northeastern TP: pollen records from Dunde ice core (10–4.8 kyr BP, Liu et al., 1998), Lake Qinghai (around 10.2–4 kyr BP, Herzschuh et al., 2010a; Shen et al., 2005), and Lake Luanhaizi (9–6 kyr BP, Herzschuh et al., 2010b); (5) eastern TP: multiproxy records from Ximencuo (10–4.4 kyr BP, Zhang and Mischke, 2009), carbon isotope record from Hongyuan peat (10.8–5.5 kyr BP, Hong et al., 2003), pollen records from Lake Naleng (10–4.4 kyr BP, Kramer et al., 2010), Yidun Lake (9.8–2.5 kyr BP, Shen et al., 2006), and Lake Shayema (10.9–2.3 kyr BP, Jarvis, 1993; Shen, 2003). In summary, from recent studies mentioned above, the termination of maximum monsoon precipitation or moisture condition occurred at around 6.5–6.2 kyr BP in the western TP, 6–4.4 kyr BP in the central and southern Plateau, about 6–4 kyr BP in the northern and northeastern regions, and around 4.4–2.3 kyr BP in the eastern margins (Figure 5). This temporal succession from the northwest to the southeast TP illustrates a hypothesized southeastward retreat of Southwest Monsoon front along a modern precipitation gradient during the mid to late Holocene (as reviewed by Liu et al., 1998; Shen, 2003; Shen and Tang, 1996; Shen et al., 2008b), although dating uncertainty exists among these records. Some exceptions with maximum precipitation in the late Holocene were presented in the northeastern TP (e.g. Lake Koucha) and attributed to regional effects such as a decline of evaporation–precipitation ratio in association with decreasing temperatures after the early Holocene (Herzschuh et al., 2009b; Kramer et al., 2010).

Frequent fluctuations of late-Holocene climate under cooler and drier conditions, reflected by pollen record and other proxies (e.g. contents of TOC and $CaCO_3$, Zhu et al., 2008) in Nam Co, can be also deduced from other sites of the TP, e.g. Lake Qinghai (Shen et al., 2005), Hongyuan peat (Hong et al., 2003), Lake Kusai (Liu et al., 2009), Lake Cuoe (Wu et al., 2006), Lake Zigetang (Herzschuh et al., 2006a) and Co Ngion (Shen et al., 2008a). Despite dating uncertainty, three centennial-scale cooling intervals in the Nam Co area around 0.8–0.15 kyr BP, 1.7–1.1 kyr BP and 3.2–2.8 kyr BP can be chronologically correlated to cold intervals documented in the oxygen isotope record of Guliya ice core (Thompson et al., 1997), and to LIA and ice-rafted debris events in the North Atlantic that culminated around 0.4 kyr BP, 1.4 kyr BP and 2.8 kyr BP (Bond et al., 2001), while two of the relatively warm periods coincide with the in-between warm intervals in the North Atlantic (Figure 6). A warm/dry interval during 1100–800 yr BP in the Nam Co area could correspond to the MWP (Liu et al., 1998; Zhang, et al., 2002), and the latest cold/wet interval of 800–150 yr BP to the LIA recorded widely in the TP (Liu et al., 1998, 2009; Shen et al., 2008a; Zhang et al., 2002; Zhu et al., 2008). Correlation of late-Holocene climate between the central, western TP and

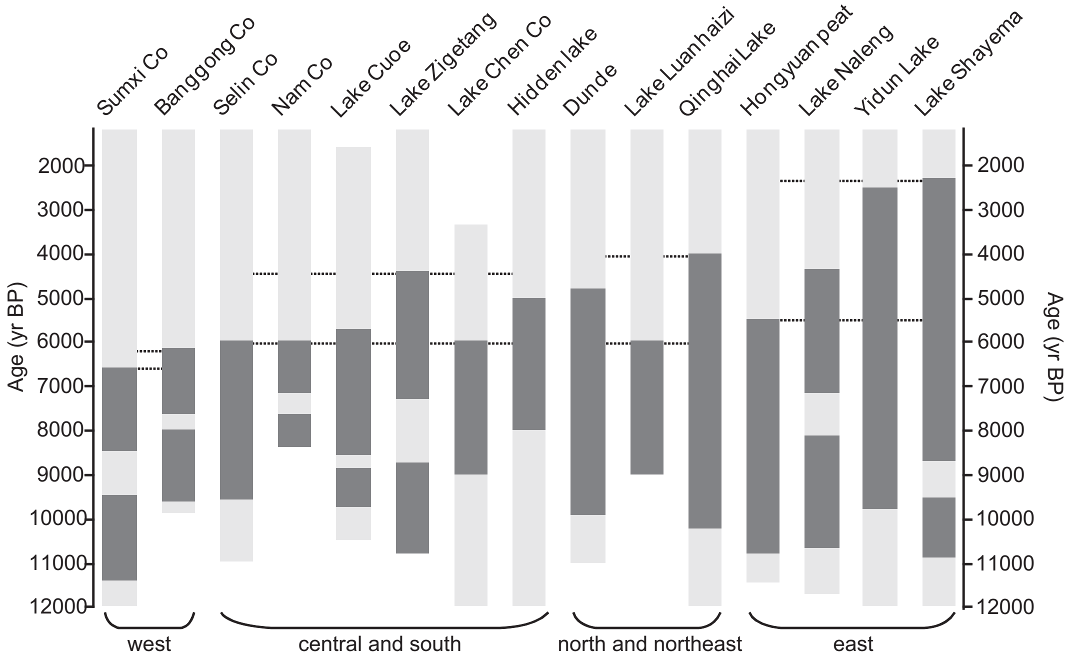

Figure 5. Summary of inferred SWM records across the TP during the early to mid Holocene. Dark and light grey frames represent wet and dry periods, respectively. Dotted horizontal lines highlight the time span for the termination of maximum precipitation or moisture in various regions. References are given in the text and Table 1

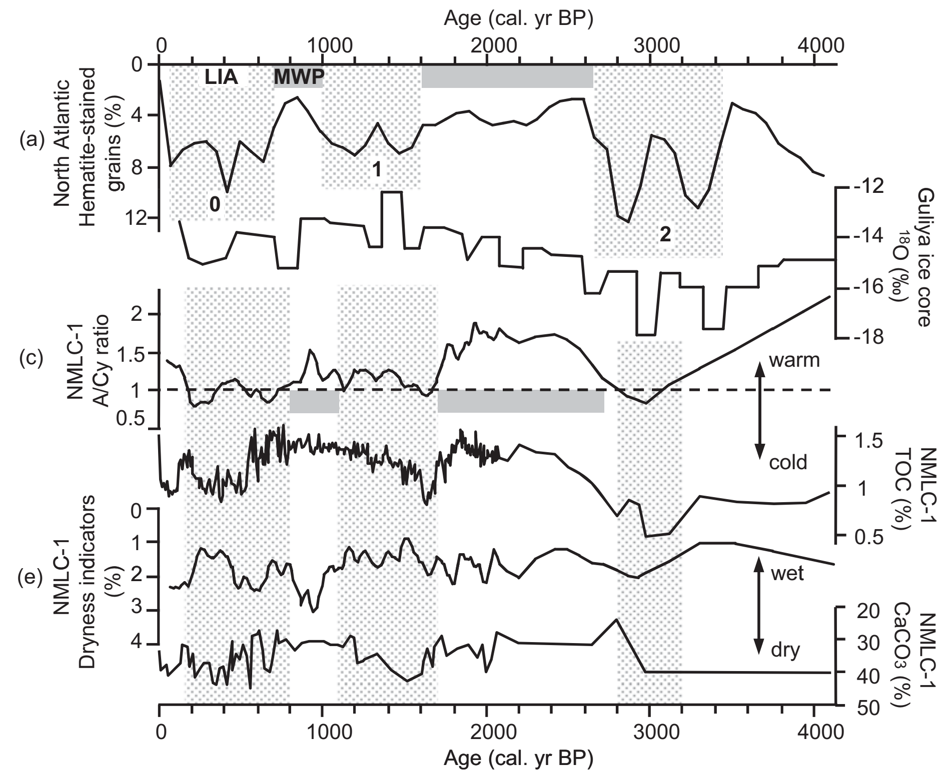

Figure 6. Comparisons among paleoclimate records in Nam Co, ice-core oxygen isotope records in the western TP, and drift ice records in high northern latitudes in the late Holocene. (a) Stack of drift ice records from MC52-VM29191 and MC21-GGC22 cores in the North Atlantic (Bond et al., 2001). Numbers of 0, 1 and 2 indicate LIA and other two ice-rafted debris events, respectively. (b) $\delta^{18}O$ record of Guliya ice core (Thompson et al., 1997); (c) and (e) are 5-point smoothed curves of A/Cy ratio and dryness indicators from NMLC-1 pollen records; (d) and (f) show the variations of contents of TOC and $CaCO_3$ from NMLC-1 core (Zhu et al., 2008). Dotted frames highlight cold intervals, while grey bars indicate warm intervals

the North Atlantic implies that influences from abrupt climatic events in the high northern latitudes reached the central TP via the Westerlies after the marked weakening of both insolation and Southwest Monsoon during the mid to late Holocene (Overpeck et al., 1996; Shen et al., 2008b). Therefore, the modern climate in the central TP, characterized by alternate influences from the Westerlies and the Southwest Monsoon (Lin et al., 2008; You et al., 2007; Zhu et al., 2008), was possibly established within the late Holocene (Shen and Tang, 1996; Tang et al., 2009; Wu et al., 2006).

Conclusions

Modern pollen rains around Nam Co are investigated in this study. The results are then applied to interpret fossil pollen assemblages of core NMLC-1 from Nam Co for recovering the history of vegetation and climate changes in the central TP since 8400 yr BP. The main conclusions are summarized below.

(1) Pollen analysis on 37 topsoil samples from altitudinal vegetation belts on the northern slope of Nyainqentanglha Mountains shows that alpine steppe and alpine meadow along an elevation gradient can be distinguished by their modern pollen assemblages. Samples from alpine steppe contain high proportions of *Artemisia* and Poaceae, while those from alpine meadow on upper slopes and patchy marsh meadow are characterized by a predominance of Cyperaceae. Results of discriminant analysis correctly classify 86.5% of topsoil samples in terms of vegetation types.
(2) The NMLC-1 pollen record reveals a general downward shift of altitudinal vegetation belts since 8.4 kyr BP, and a major extension of alpine meadow belt and alpine sparse vegetation belt towards the lakeshore in the late Holocene.
(3) Pollen-inferred Holocene climate in the Nam Co area is characterized by a climatic cooling throughout the last 8400 years following the decline of solar insolation, with warmer and wetter climate in the early to mid Holocene resulting from an intensified Southwest Monsoon and strong insolation, and frequent climate fluctuations in the late Holocene, which can be linked to the high northern latitudes on a centennial scale.
(4) The termination timing of maximum moisture in the Nam Co area around 6000–5500 yr BP provides a link between the northwest and southeast TP for an interpretation of southeastward movement of Southwest Monsoon during the mid to late Holocene.

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