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Pollen-based reconstructions of Holocene vegetation and climatic change of Tibetan Plateau

Tang Lingyu(唐领余)[1], Li Chunhai(李春海)[1], Yu Ge(于革)[2] and Shen Caiming(沈才明)[3]
1 Nanjing Institute of Geology and Palaeontology, CAS, Nanjing 210008, China
2 Nanjing Institute of Geography and Limnology, CAS, Nanjing 210008, China
3 Louisiana State Uuniversity, Baton Rouge, LA 70803, USA

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Abstract A synthesis of Holocene pollen records from the Tibetan Plateau shows the history of vegetation and climatic changes during the Holocene. Palynological evidences from 24 cores/sections have been compiled and show that the vegetation shifted from subalpine/alpine conifer forest to subalpine/alpine evergreen sclerophyllous forest in the southeastern part of the plateau; from alpine steppe to alpine desert in the central, western and northern part; and from alpine meadow to alpine steppe in the eastern and southern plateau regions during the Holocene. These records show that increases in precipitation began about 9 ka from the southeast, and a wide ranging level of increased humidity developed over the entire of the plateau around 8-7 ka, followed by aridity from 6 ka and a continuous drying over the plateau after 4-3 ka. The changes in Holocene climates of the plateau can be interpreted qualitatively as a response to orbital forcing and its secondary effects on the Indian Monsoon which expanded northwards during the early Holocene and retreated from the plateau since the mid-Holocene. Also, there is teleconnection between the Tibetan Plateau and North Atlantic.
Key words pollen, spatial pattern, alpine vegetation, Holocene, Tibetan Plateau.

1 Introduction

The Tibetan Plateau is a large-area of highland (4000 - 4500 m a. s. l.) on the Eurasian continent. It brings the Indian Monsoon to the plateau and adjacent regions of East Asia (Kutzbach 1981; Zhang *et al.* 1991). Its huge area with various alpine vegetation types is unique in the world (Zhang 1978). Climatic changes in Tibet since the LGM have caused changes in distribution of vegetation, which are well-documented in pollen records (Liu 1991; Tang and Shen 1996; Yu *et al.* 2001). During the last two decades, pollen data from the Tibetan Plateau have therefore been used to reconstruct quantitative changes in vegetation and climate (Tang and Wang 1976a, b; Thompson *et al.* 1989; Gasse *et al.* 1991; Van Campo and Gasse 1993; Jarvis 1993; Van Campo *et al.* 1996, Shen *et al.* 1996). Pollen records from the Tibetan Plateau have therefore provided evidence for tree and/or treeless vegetation changes which are mainly governed by changes in precipitation, while spatial coherent regional patterns are controlled by changes in the position and intensity of westerly belts and air mass which are determined by changes in Indian Monsoon circulation. Thus, reconstruction of climate change here is based on the assumption understanding that changes in pollen records and the regionally-synchronous vegetation pattern can be interpreted as a direct consequence of changes in the Indian Monsoon.

The aim of this paper is to document changes in the regional vegetation and infer climatic conditions that control major distributions and evolution of vegetation on Tibetan Plateau, as shown from 24 sites during the Holocene (Fig. 1). Despite the wealth of palaeoenvironmental evidence from this region, there have been few attempts to examine the patterns of regional vegetation and climate changes across the plateau or to use these evidences to investigate the mechanisms of climate change. The modern pattern of regional climates is largely determined by the interplay of the Westerlies and Indian Monsoon. Modelling studies have suggested that there have been fundamental changes in the strength and extent of the Indian Monsoon in response to changes in orbitally-induced insolation (Kutzbach 1981; COHMAP 1988). Also, there is teleconnection between the Tibetan Plateau and North Atlantic (Overpeck 1996; Tang *et al.* 2003; Shen *et al.* 2002). The unique geomorphological setting and the absence of major human impact up to now make Tibet an ideal place to corroborate these assertions, and compilations of pollen data from the region make it possible to do so.

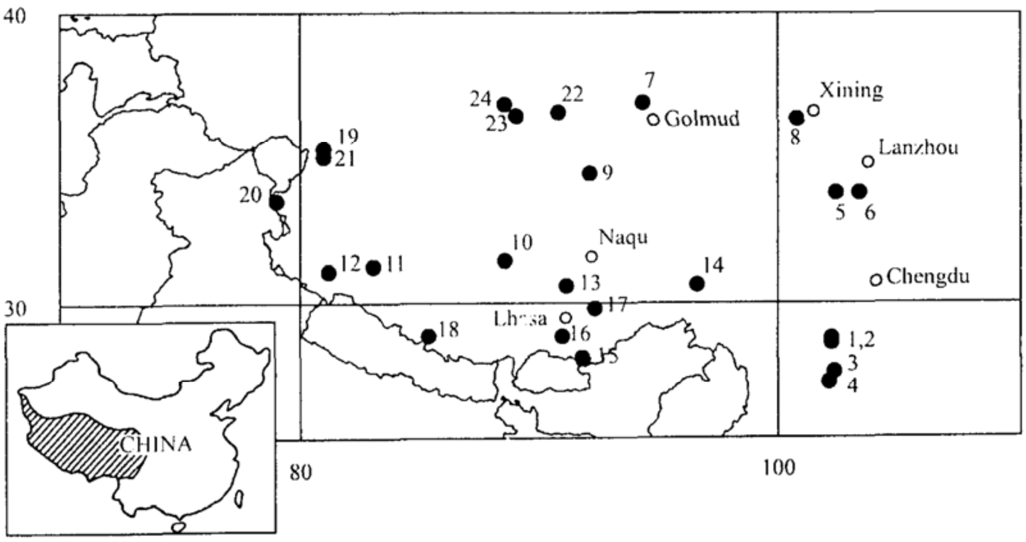

Fig. 1. Scope of Tibetan Plateau and sites of pollen stratigraphy on the plateau.

2 Modern climate and vegetation

Ranging between 75°E - 105°E and 25°N - 40°N, the Tibetan Plateau with an high elevation reaching the stratosphere causes the Westerlies to separate into a north and south branch so that the plateau has a specific climate system (Ren *et al.* 1979). As a large landmass, it deepens the land-sea contrast for the Indian Monsoon system (Zhang *et al.* 1991). In addtion, the plateau blocks the humid airmass from the Indian Ocean penetrating into inland Asia, causing aridity of the desert/salt basins in the Tibetan interior and in northwestern China (Zhang *et al.* 1991). The southern and eastern margins of the plateau experience wet conditions from the Indian Monsoon, but for the most part the plateau is dominated by year-around dry and cold conditions (Chinese Academy of Science 1988). These climate patterns control the distribution of Tibet vegetation types, such that forest biomes occur in the southeast, the type transitional to tree-less biomes in the interior, and grass-less desert in the northwest (Zhang 1978; Tibetan Investigation Group 1988). Modern climate-vegetation associations occur as in six individual regions on the plateau as described below:

2.1 Subalpine/alpine conifer forest on the southeastern plateau

The topography in eastern margin of the plateau on this region is characteristically steeply-sloped mountains and deep valleys in which elevation is mostly more than 3000 m. The prevailing climate is subtropical mountain monsoon. In winter, surface air flow is controlled by the Westerlies from the dry Eurasian continent, leading to low precipitation. In summer, warm and moist Indian monsoon from leads to 90% of the mean annual precipitation 850 - 1500 mm being concentrated in the period from May to October (Editorial Board of Sichuan Vegetation 1980; Editorial Committee of Chinese Vegetation 1980). It leads to a seasonal humidity alternation with dry winters and wet summers. Mean annual temperatures are 12.5°C - 19.5°C with 4.3°C - 11.1°C in the coldest month and 18°C - 24.9°C in the warmest month.

Altitudinal vegetation zonation on the mountains shows four major vegetation belts (Editorial Board of Sichuan Vegetation 1980). Subtropical open-tree and shrub lands occur in the mountains below 1500 m a. s. l. *Pinus yunanensis* forest grows between 1500-2500 m a. s. l., and conifer and broad-leaved evergreen mixed forest is also found in this zone, including *Quercus variables*, *Q. acutissima*, *Cyclobalanopsis delavayi*, *C. glaucoides*, *Lithocarpus dealbatus*, *L. variulosus*, *L. cleistocar*, *Machilus yunanensis*, *Illicium yunanensis* and *Alnus nepalensis*. Conifer and broad-leaved deciduous mixed forests occur in the mountains between 2500 and 3000 m a. s. l., typical are *Tsuga chinensis*, *T. dumosa*, *P. yunanensis*, and species of *Acer*, *Betula*, *Corylus*, *Carpinus*, *Lonicera*, *Rhododendron* and *Cinarundiaria*. *Abies fabri* forest with *Rhododendron* shrubs is found in the mountains between 3500 and 4000 m a. s. l. Alpine shrub and sparse steppe occur above 4000 m a. s. l.; these include *Sabina pingis* var. *wilsonii*, also with species of Gramineae and Compositae (Editorial Board of Sichuan Vegetation 1980).

2.2 Alpine shrub-meadow on the eastern plateau

This region is a highland with elevations of 3400-4500 m a. s. l. The climate has low temperatures and evaporation rates throughout the year, with mean annual temperature of 0.6°C to 1.2°C, −8.2°C to −1.2°C in the coldest month, and 9.1 to 11.4°C in the warmest month. Total annual precipitation is ca 560 to 860 mm and relative humidity ca 64% - 73% (Chai *et al.* 1965; Editorial Board of Sichuan Vegetation 1980).

Modern vegetation is characteristically meadow in swamp areas and alpine steppe in the mountains (Chai *et al.* 1965). The meadow vegetation is dominated by forbs, such as *Polygonum viviparum*, *Anemone demissa*, *Potentilla anserina*, *Anaphalis*, and graminoids such as *Festuca ovina*, *Clinelymus sibiricus*, *Koeleria cristata*, and swamp plants such as *Kobresia* sp. and *Carex* species. *Picea purpurrea* and *Abies likiangensis* grow wet areas as small areas of pure stands (Chai *et al.* 1965; Shen *et al.* 1996; Editorial Board of Sichuan Vegetation 1980).

2.3 Alpine meadow on the southern plateau

In elevations above 4000 m a.s.l., the climate is very cold with mean annual temperatures of 0°C to 3°C, −5°C to −11°C in the coldest month and 7 to 12°C in the warmest month. An extreme temperature of −30°C has been recorded (Tibetan Investigation Group 1988). The annual precipitation is ca 400 - 550 mm but the area is relatively humid because the low temperature leads to a low evaporation and a positive budget of P-E (Zhou *et al.* 1976; Wang 1987). *Kobresia* and *Stipa* steppes with *Artemisia wellbyi* and *A. stracheyi* occur in areas below 4400 m a.s.l. Shrubs grow between 4400 - 4700 m a.s.l., mainly containing *Sabina pingii var. wilsonii*, *Caragana versicolor*, and *Potentilla*. Alpine steppes with *K. pygmaea* occur from 4700 to 5200 m a.s.l. while sparse vegetation is found above 5200 m a.s.l. (Editorial Board of Sichuan Vegetation 1980).

2.4 Alpine steppe on the central plateau

In the interior of the plateau, the climate is characterised by high insolation receive, less moisture airflow entered, short growing degree days, and aridity conditions. For example, Selin Co at 4530 m a.s.l. has a mean annual temperature −3°C which rises to 7.5°C in the warmest month, 290 mm in annual precipitation and 2176 mm in annual evaporation (Editorial Committee of Chinese Vegetation 1980; Sun and Chen 1991; Sun *et al.* 1993). Alpine steppe dominated by *Stipa subsessiliflora* occurs in the most places between 4500 - 5100 m a.s.l. Swamp meadows with *Kobresia littledalei* grow around the lakes of this region (Editorial Committee of Chinese Vegetation 1980; Tibetan Investigation Group 1988).

2.5 Alpine steppe and mountain forest on the northern plateau

Large arid basins below 2500 m a.s.l. and the surrounding mountains up to 4000 m a.s.l are common geomorphic features units in this region. The dry and cold alpine climate of this region has annual mean temperatures of −12.7°C in the coldest month (coldest record of −30°C), and 12.4°C in the warmest month (Lanzhou Glaciology Institute, 1979; Editorial Committee of Chinese Vegetation 1980). The annual precipitation, for example at Qinghai Lake is 377 - 395 mm, but evaporation is 3.8 times the rainfall of the area. The vegetation is dominated by alpine steppe and shrubs. Around Qinghai Lake *Stipa splendeus* steppe and *Kobresia* meadow occurs (Chen 1987). In the mountains between 2500 - 3000 m a.s.l., conifer forest with *Picea crassifolia*, *P. wilsonii* and *Sabina przowalskii* are found on rainshadow northern slopes, and conifer and broad-leaved deciduous forest on the wetter southeast slopes, Forests *Picea crassifolia*, *P. wilsoni*, *Quercus*, *Pinus* and *Ostryopsis davidiana* *are typical of the area. Low trees and shrubs grow where the mountains are above 3000 m a. s. l. , including Populus suaveolens*, *P. davidiana*, *Sabina chinensis*, *Rhododendron* sp. as well as spcies of *Sorbus*, *Ulmus*, *Salix* and *Betula* (Lanzhou Glaciology Institute 1979).

2.6 *Alpine desert vegetation on the western plateau*

This region has elevations above 4500 m a. s. l. As distance increases from the oceans and where areas are blocked by mountains, the climate is extremely arid (mean annual precipitation of 60 mm) and relative humidity of 31 - 33%. Seven months have mean daily temperatures below 0(C (Editorial Committee of Chinese Vegetation 1980; Tang and Shen 1996; Shen and Tang 1996). Vegetation is mostly alpine desert with sparse plants of Chenopodiaceae, Gramineae, Compositae and Cyperaceae, as well as small amounts of Leguminosae, Cruciferae and Rosaceae species (Tibetan Investigation Group 1988).

3 Data and methods

Pollen data from 24 sites were obtained from published literature and unpublished data which are available currently for this region (Table 1). The location of the sites ranges between 27 - 38°N and 79 - 103°E which is representative of most areas of the Tibetan Plateau region. Tibet is little affected by human impact. A chronology for each site is reconstructed from radiocarbon ages. It should be pointed out that carbon-14 dates for some sites were not enough for reconstructing high resolution Holocene vegetation changes. Reconstructions of vegetation are based on pollen-indicator patterns, calibrated by modern pollen studies (Tang *et al.* 1999,2000). Interpretations of climate are then based on an understanding of modern climatology of the region.

4 Holocene pollen records and vegetation

The pollen records obtained from Tibet provide evidence of change in the six modern vegetation divisions described above. In the discussion that follows selected pollen spectra are show to illustrate the change for each region.

4.1 *The southeastern plateau*

Pollen records of this region has been obtained from five lake cores, including Shayema Lake at 2433 m a. s. l. (Jarvis 1993), Yihai at 2250 m a. s. l. (Chen and Zheng 1984; Liu and Wang 1984), Honghai and Dahaizi at 3660 m a. s. l (Li and Liu 1988), and Ren Co at 4450 m a. s. l. (Liu 1991; Tang and Shen 1996, Tang *et al.* 1999, 2000).

Table 1. Summary for pollen data from Tibetan Plateau

Code	Name	Province	Long(m)	Lat(m)	Elev. (m)	Sample type	Modern vegetation	References
1	Shayema Lake	Sichuan	102.21	28.58	2453	lake core	subalpine conifer	Jarvis 1993
2	Yihai Lake	Sichuan	102.23	28.73	2250	lake profile	subalpine conifer	Liu and Wang 1984
3	Dahaizi	Sichuan	102.33	27.5	3660	lake core	alpine conifer	Li and Liu 1988
4	Honghai	Sichuan	102.1	27.1	3660	lake core	alpine conifer	Li and Liu 1988
5	Zioig? RH	Ganshu	102.35	33.95	3400	peat core	alpine meadow	Liu *et al.* 1995
6	Zioig? RM	Ganshu	103.35	33.95	3400	peat core	alpine meadow	Shen *et al.* 1996
7	Qarhan Salt Lake	Qinghai	94.41	37.1	2680	lake core	salt desert	Du and Kong 1983
8	Qinghai Lake	Qinghai	100.79	36.55	3196	lake core	sub-alpine steppe	Du *et al.* 1983
9	Gounong Co	Qinghai	92.15	34.63	4670	lake core	alpine steppe	Shan *et al.* 1996
10	Selin Co	Xizang	88.51	31.57	4530	lake core	alpine steppe	Sun *et al.* 1993
11	Chaby Lake	Xizang	83.1	31.35	4421	lake core	alpine steppe	Xiao *et al.*, 1996; Wu and Xiao 1996
12	Cuoqing	Xizang	81.17	31.17	4675	lake profile	alpine steppe	Huang *et al.* 1983
13	Dangqiong	Xizang	91.17	30.67	4370	peat core	alpine meadow	Wang *et al.* 1981
14	Ren Co	Xizang	96.67	30.71	4450	lake core	alpine forest/steppe	Tang and Shen 1996
15	Nariyong Co	Xizang	91.83	28	4760	lake profile	alpine forest/steppe	Huang *et al.* 1983
16	Chen Co	Xizang	91	28.83	4450	lake profile	alpine meadow	Huang *et al.* 1983
17	Hidden Lake	Xizang	92.33	29.82	5000	lake core	alpine shrub/meadow	unpublished
18	Peiku Co	Xizang	85.33	28.83	4660	lake profile	alpine meadow	Tang and Shen 1996
19	Sumxi Co	Xizang	81	35.5	5058	lake core	alpine desert	Van Campo and Gasse 1993
20	Bangong Co	Xizang	79	33.67	4241	lake core	alpine desert	Huang *et al.* 1983; Van Campo *et al.* 1996
21	Longmu Co	Xizang	81	35.17	5008	lake core	alpine desert	Huang and Liang 1983
22	Xiaoshaozi Lake	Xizang	90.83	36.78	4106	lake profile	alpine desert	Huang *et al.* 1996
23	Beilike Kule	Xizang	89	36.67	4680	lake profile	alpine desert	Huang *et al.* 1996
24	Aqike Kule	Xizang	88.5	37.05	4250	lake profile	alpine desert	Huang *et al.* 1996

Between 11-10 ka Shayema Lake had similar *Betula* and deciduous *Quercus*, but less *Tsuga* or *Pinus* than today. This suggests colder and drier conditions than the present. The best modern vegetation analogue is the area between 1500-2000 m of the Zhongtiao Mt. (35.5°N, 110.5°E) (Yao 1989). It is estimated that the coldest month temperature was at least 10°C lower than today and annual precipitation was 500-600 mm less than today.

During 10-9 ka, a variety of deciduous broad-leaved taxa are presented in the pollen records. Pollen assemblages show that *Abies*, *Cedrus*, *Betula* and *Quercus* are present together with *Fraxinus*, *Carpinus*, *Acer*, *Celtis*, *Juglans*, *Rhus* and *Euptelea*, suggesting a cold winter but a warming early-summer, and increased rainfall. Around 9.1 ka, deciduous *Quercus* appears abruptly, which can be interpreted as an increase in mean annual temperature.

Pollen assemblages after 9.1 ka are characterised by increases in *Tsuga* and *Cunninghamia*, suggesting wetter conditions than today. *Cunninghamia lanceolala* is an important component of subtropical humid-type forests in southern China that grows in areas with mean annual precipitation 1000-1800 mm and an even year-around distribution of the rainfall (Editorial Board of Sichuan Vegetation 1980; Jarvis 1993). This implies a stronger summer monsoon influence than today. Pollen assemblages after 7.8 ka are characterised by the presence of abundant *Tsuga* with *Platycarya*, *Keteleeria*, *Podocarpus*, and *Mallotus*, indicating higher annual temperatures and precipitation than the present.

There is an increase in evergreen sclerophyllous taxa of *Lithocarpus/Castanopsis*, Ericaceae, *Aralia*, *Ilex* and *Viburnum* around 5.3 ka, which replaced the mesophilous broad-leaved deciduous forest, indicating increased temperature in winter and decreased precipitation in spring and early summer, and therefore suggesting a weakened summer monsoon.

Pollen data from Yihai (Chen and Zheng 1984; Liu and Wang 1984), 20 km away from Shayema Lake, are consistent with records in Shayema Lake. The importance of *Tsuga* with various deciduous taxa after ca 6.7 ka suggests increased precipitation. Decreases in *Tsuga*, *Pseudotsuga* and increases in evergreen sclerophyllous taxa after 4.5 ka suggested decreases in growing season precipitation. Pollen assemblages from Honghai and Dahaizi (Li and Liu 1988; Fig. 2) are characterised by evergreen sclerophyllous plants; these replaced conifer and deciduous forest after ca 5 ka, and is therefore consistent with conditions at Shayema Lake. These imply changes in conditions from warmer and wetter than the present, to warmer and drier than the present, possibly resulting from a weakened summer monsoon after 5.3 ka. The dominance of sclerophyllous taxa lasts until 4 ka, suggesting a further decrease in rainfall in spring and early summer as a result of the retreat of the summer monsoon.

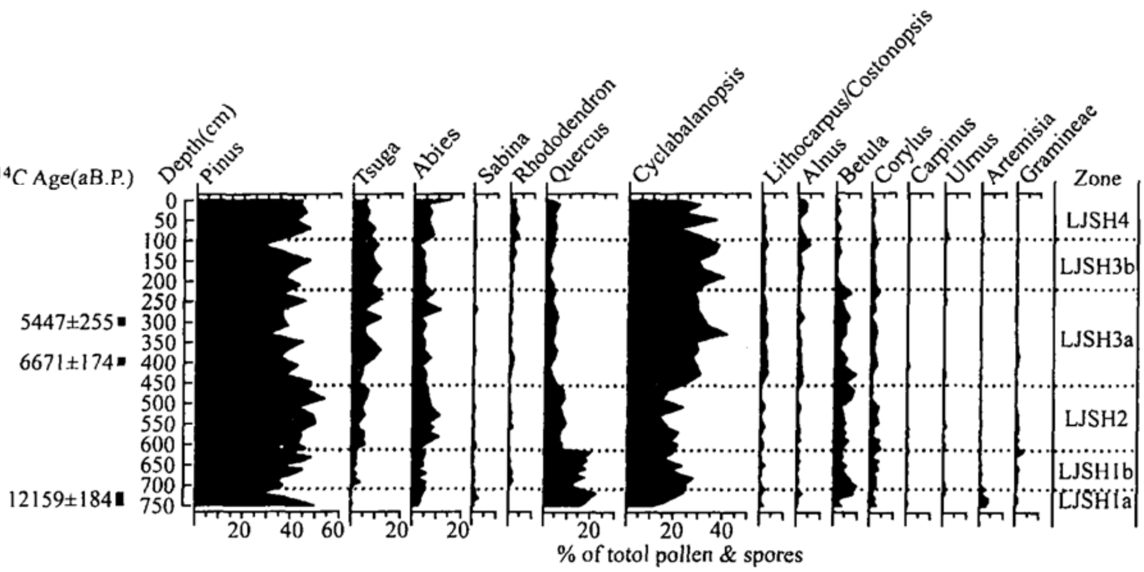

Fig. 2. Pollen diagrams from Dahaizi (from Li and Liu, 1988). Pollen percentages are based on the total pollen sum.

A lacustrine core from Ren Co (Liu 1991; Tang and Shen 1996, Tang *et al.* 1999, 2000; Fig. 3) provides pollen records with low pollen concentrations, mainly Chenopodiaceae before 13 ka. The site is characterised by increases in *Betula* and *Quercus* after 13 ka, increases in *Picea* and *Abies* with species of *Polygonum* and *Plantago* after 10 ka, and a decrease in *Betula* after 6 ka. These suggest an increase in precipitation after 13 ka, a rainfall similar to the present after 10 ka, a maximum in precipitation during 10-6 ka when it was about 100 mm higher than the present, then a decrease in rainfall after 5 ka till to the present.

4.2 *The eastern plateau*

Two cores of RM (Shen and Tang 1994; Shen *et al.* 1996; Fig. 4) and RH (Liu

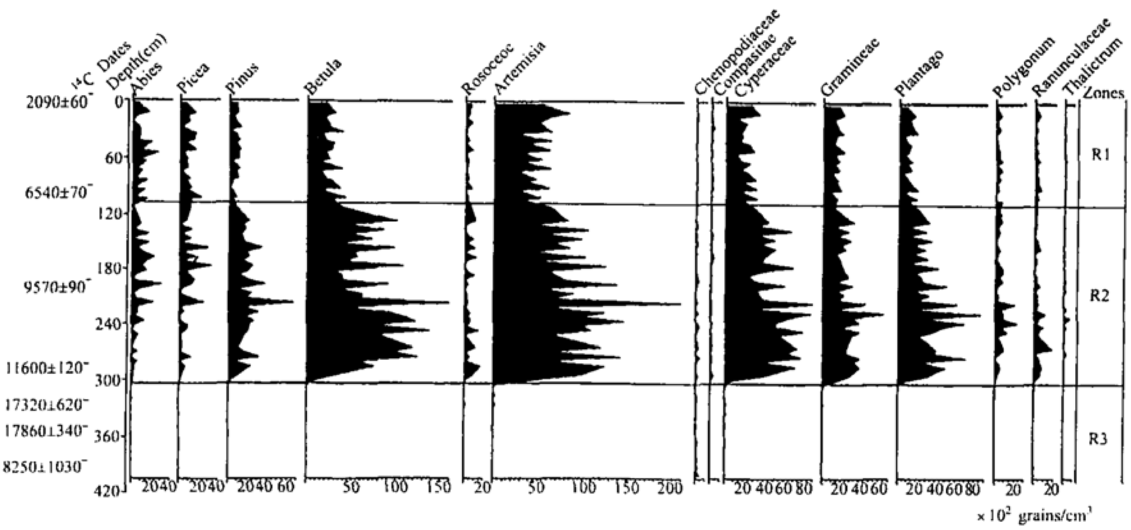

Fig. 3. Pollen diagrams from Ren Co (redrawn from Tang and Shen1996). Pollen concentrations are in 100 times of grains /cm^3.

et al. 1995) from the Zoigê region provide pollen records back to the pre-Holocene. About 15% of *Picea* and *Abies* and 10% of *Betula* in the total assemblage during 12-11 ka reflect a subalpine conifer forest. The nonarboreal components are mostly Gramineae and Cyperaceae, representing a subapline meadow vegetation. These data suggest that annual precipitation was similar to the present.

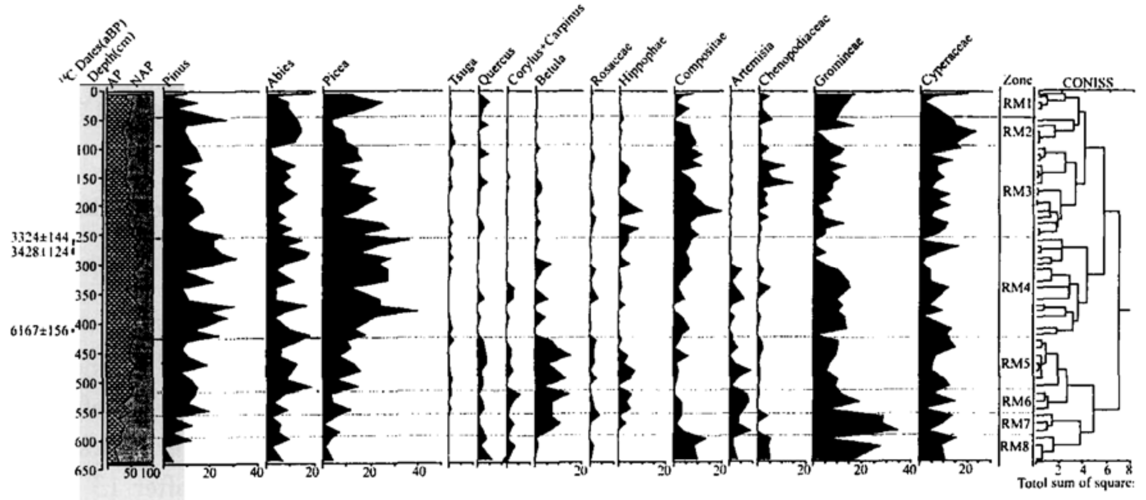

Fig. 4. Pollen diagrams from Core RM, Zoigê (redrawn from Shen *et al.* 1996). Pollen percentages are based on the total pollen sum.

A change in arboreal pollen percentage during 11-7 ka, characterised by increases in *Picea* from 3.8% to 16.3% and *Abies* from 3.8% to 16.3% respectively, and decreases in *Pinus* and *Betula*. Increase in Cyperaceae together with and a decrease in Gramineae in the nonarboreal component these suggest that a stable subapline conifer forest developed in the region, and the area of meadows / swamp was extended while steppe areas were reduced. This implies a precipitation that is much higher than the present. The humid conditions in the early Holocene reflect an expansion of Indian Monsoon over this region.

Between the 7-3.3 ka, the pollen assemblages show a high percentage of conifer pollen taxa including *Picea*, *Pinus* and *Abies* in which *Picea* reaches a maximum of 40.5%. These indicate a period when alpine evergreen conifer forest was better developed, than the present due to an enhanced Indian Monsoon during the mid-Holocene.

A marked decrease in *Picea* and *Abies* and an increase in Compositae and Chenopodiaceae after 3 ka indicate a retreating conifer forest and an expanded forb-grass steppe, suggesting decreases in precipitation and weakened summer monsoon.

4.3 The southern plateau

Pollen data from Peiku Co (Tang and Shen 1996; Huang 2000; Fig. 5), Hidden Lake (Tang *et al.* 1999, 2000; Fig. 6), Nariyong Co and Chen Co (Huang *et al.* 1983) and Dangxiong (Wang *et al.* 1981) of the region, commonly show that pollen assemblages are dominated by Cyperaceae (70%-80%) with some *Betula*, *Picea* and *Abies* during 11-8 ka, suggesting cooler conditions than today.

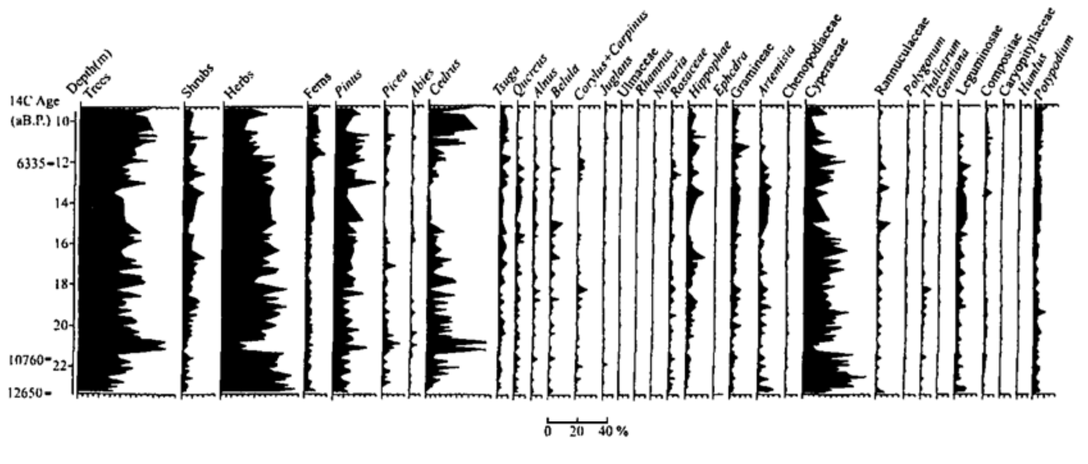

Fig. 5. Pollen diagrams from Peiku Co (redrawn from Tang and Shen 1996). Pollen percentages are based on the total pollen sum.

Between 8-3 ka, there were increases in *Betula*, *Quercus*, *Tsuga*, Rosaceae and Ericaceae, suggesting forest development led by warmer and wetter conditions than today. In the north of this region, pollen assemblages are dominated by Caragana and Rosaceae with *Betula*, *Salix*, *Pinus* and *Quercus*, indicating *Carex* meadow domination in the region. These suggested changes in conditions colder and wetter in the early Holocene shifted towards a warmer and wetter in mid-Holocene. In the western region, increases in *Betula*, *Quercus*, *Corylus*, *Cedrus* and *Tsuga* are consistent with warm and wet conditions. The pollen flora after 3 ka is characterised by decreases and/or disappearances of arboreal types Pinus, Rosaceae, Ericaceae, *Betula* and *Quercus* from 40% to zero. Grass and shrubs dominated in the pollen percentage up to 73%-89%. These suggest that conditions were colder and drier than today.

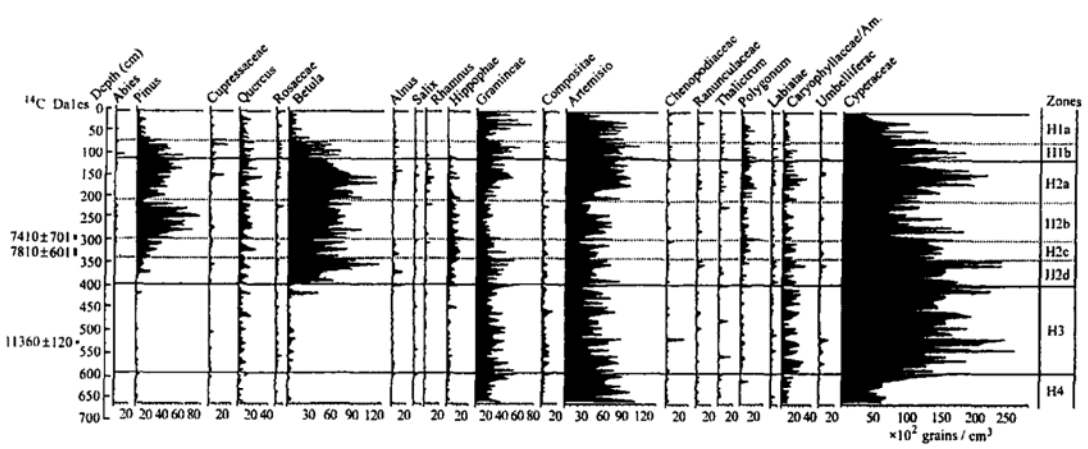

Fig. 6. Pollen diagrams from Hidden Lake. Pollen concentrations are in 100 times of grains /cm^3.

4.4 *The northern plateau*

Several lacustrine cores from this area provide pollen records back to the early Holocene. Pollen assemblages in Core QH85-14C from Qinghai Lake (Du *et al.* 1989; Fig. 7) show high values (60%) of shrub-grass pollen taxa including *Artemisia*, Chenopodiaceae and *Ephedra* during 11-8 ka, indicating a steppe vegetation and dry conditions. Then a sharp change with about *Betula* (38%) and *Picea/Abies* (15%) are present in the pollen assemblage, reflecting a mixed forest with spruce-fur conifer and birch deciduous developed between 10.6-9.1 ka.

Pollen assemblages are dominated by arboreal types during 8-3.5 ka when *Pinus* and *Picea* reach to 40% and 20% respectively. There occurred some temperate broad-leaved deciduous *Ulmus* and a decrease in boreal species of *Betula*. These suggest that *Betula* occurred from before 9 ka, followed by *Picea* and *Pinus* and then increases in temperate deciduous between 8-3.5 ka. The conditions during the mid Holocene were therefore warmer and wetter than the present. Meanwhile, changes in nonarboreal types, such as a decreasing *Artemisia* reflect an increase in annual precipitation, ca 500 mm more than today. The pollen record after 3.5 ka shows a decrease in arboreal types, to less than 20%, while an increase to ca 60% in *Artemisia* and ca 30% in Chenopodiaceae occurred. These suggest development of a drying climate. The forests nearly disappeared after 1.5 ka, indicating increased aridity over the region due to a less influence from marine airmases.

Lacustrine cores from Gounong Co (Li *et al.* 1994; Shan *et al.* 1996; Fig. 8), Bunan Lake and Ulan Ula Lake (Shan *et al.* 1996) in the northwestern plateau also provide records that show extremely low pollen concentrations during 11.5-10.4 ka, suggesting dry and cold conditions. Shrubs in the pollen assemblage include Chenopodiaceae (8-96 grain/cm^3), *Artemisia* (5-56 grain/cm^3) and Gramineae (0-28 grain/cm^3) between 10.4-9.8 ka. Arboreal types have very low pollen concentrations in which the total amount of *Betula*, *Abies*, *Pinus* and *Corylus* are less than 20 grain/cm^3. A change in arboreal types after 9.8

ka show an increase in species of *Pinus*, *Abies*, *Betula*, *Corylus*, *Quercus*, *Alnus*, *Juglans*, *Ulmus* and *Salix*. A maximum of tree pollen concentration up to 75 grain/cm^3 occurred during 8-5 ka, suggesting a rise in tree line and the development of forest vegetation nearby. A change in pollen types after 5.5 ka is characterised by domination of steppe dry species and salt-enduring desert species.

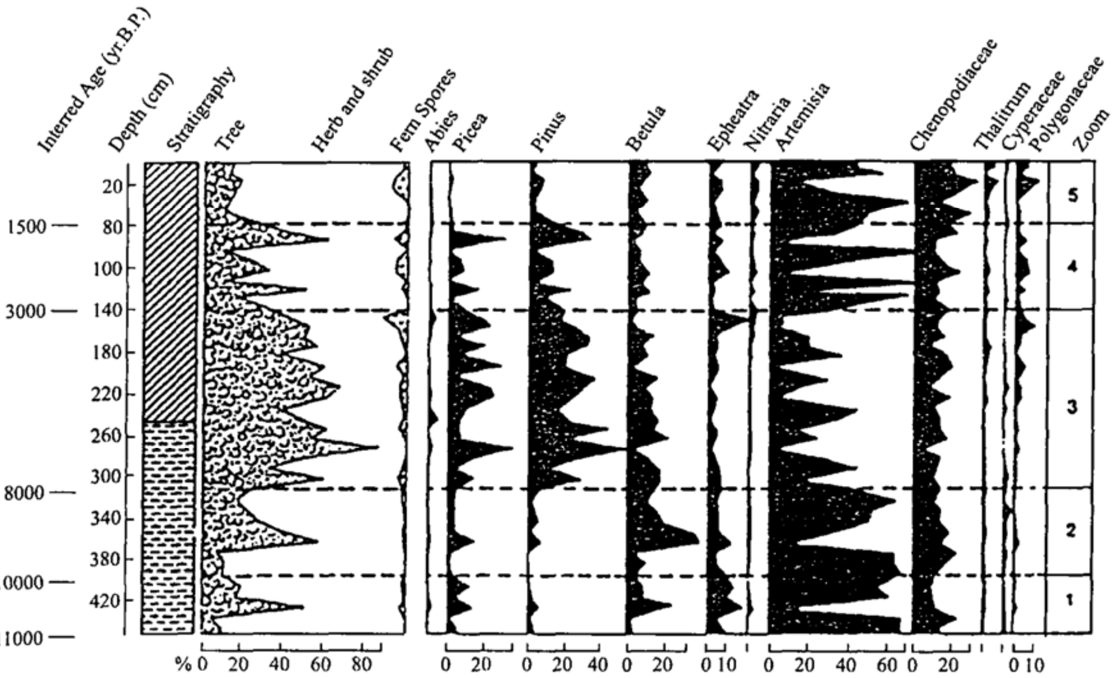

Fig. 7. Pollen diagrams from Qinghai Lake (from Du *et al.* 1989). Pollen percentages are based on the total pollen sum.

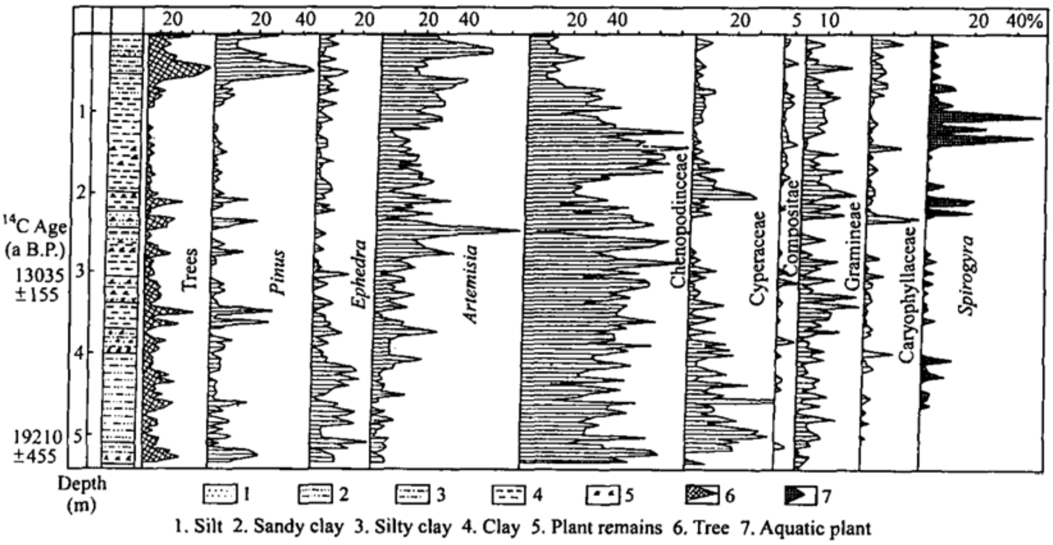

Fig. 8. Pollen diagrams from Gounong Co (from Shan *et al.* 1996). Pollen percentages are based on the total pollen sum.

4.5 *The central plateau*

A lake core from Selin Co (Sun *et al.* 1993; Fig. 9) provides pollen records back to 11 ka. The pollen assemblage is characterised by very low pollen concentrations with generally only species of Compositae and Artemisia dominant during 11-9.6 ka, indicating sparse alpine plants under cold and dry conditions. It is estimated that the annual mean temperature was 4.5-5.5°C lower than today.

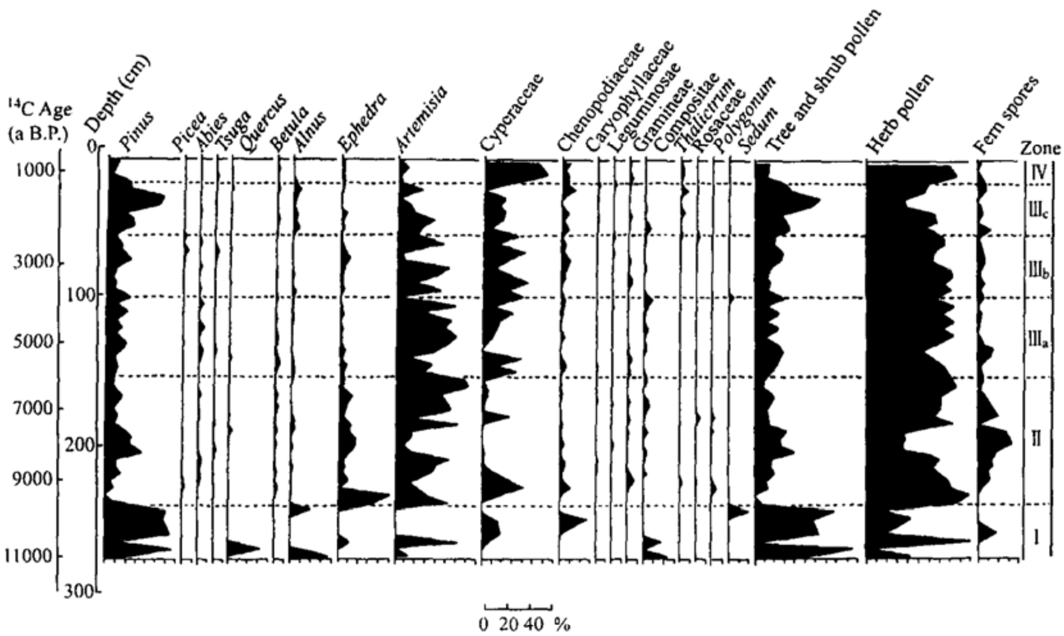

Fig. 9. Pollen diagrams from Selin Co (redrawn from Sun *et al.* 1988). Pollen percentages are based on the total pollen sum.

A marked increase in pollen concentration after 9.6 ka is owning mostly to increased Cyperaceae and *Artemisia*. During 7.5-6 ka, the pollen assemblage is characteristic of an increase in *Pinus* in tree taxa, and increases in Cyperaceae and *Artemisia* in non-tree taxa. The presence of abundant Cyperaceae indicates that swamp plants around Selin Co developed. The pollen includes low amounts in total arboreal types (10-170 grain/cm^3) through the Holocene, but increases in *Pinus*, *Tsuga*, *Picea* and *Abies* occurred around 8-7 ka. This record is consistent with increases in arboreal pollen observed from other sites at Cuoqing (Huang *et al.* 1983) and Chabyer Lake (Xiao *et al.* 1996) during the mid Holocene. These imply that conditions were warmer than the present after ca 9.5 ka and wetter than the present after ca 8 ka.

The pollen assemblage is characterised by mainly nonarboreal pollen (52%-81%) with increases in abundant Cyperaceae and *Artemisia* after 6 ka, where arboreal types of pollen taxa increased to 28%, including *Pinus* and *Abies*. These suggest that the vegetation in Selin Co area was dominated by alpine grassland after 6 ka. The high percentage of tree pollen could be related to an enlarged area of forests in central Tibet, and the influence of the areas of alpine vegetation. A decrease in pollen concentration of *Picea* after 5 ka indicates colling and drying conditions for the late Holocene.

4.6 *The western plateau*

A 10.5 m-long core from Sumxi Co (Van Campo and Gasse 1993) provides pollen records back to 12.7 ka. A lowest pollen concentration (180-3000 grain/cm^3) dominated by Chenopodiaceae and *Ephedra* is found at the core bottom, suggesting a barren vegetation and a dry climate during 12.7-10 ka. There is a short time slice when increaseas in aquatic pollen and macrofossils occurred, suggesting wet conditions during 12.7-12.5 ka; afterwards a change in the pollen record implies drying conditions during 10.5-9.9 ka.

Increases in *Artemisia* and Rosaceae and decreases in Chenopodiaceae (high A/C ratio) indicate wetter conditions during 10-8 ka, as compared with today. A change back to low ratio of A/C indicates that conditions were getting drier between 8-7.7 ka. An maximum in the A/C ratio between 7.7-6.2 ka indicates peak humid conditions in the record. Increased planktonic diatoms and high 18-Oxygen isolate ratio (−1.5‰) (Van Campo and Gasse 1993) are consistent with warm and wet conditions as a result of increased summer precipitation. A decrease in the A/C ratio after 6.2 ka reflects a drier climate in the region. The A/C ratio is the lowest at ca 4.3 ka, indicating the most arid phase. The lowest lake level is described by Van Campo and Gasse (1993) is consistent with this record. The A/C ratio varied between 0.8 and 3.5 after 4 ka indicates climate fluctuation and that most conditions were dry still. Decreased planktonic diatoms and the low $^{18}O/^{16}O$ value (−3‰) (Van Campo and Gasse 1993) of the lake is consistent with this.

A lake core from Bangong Co (Huang and Liang 1983; Huang *et al.* 1983; Van Campo *et al.* 1996), ca 200 km from Sumxi Co, shows that the pollen records are characteristically contain *Artemisia* (20%) and *Ceratoides* with low concentration (650 grain/cm^3) during 9.9-9.6 ka. These suggest sparse plants and plants in a desert under cold and dry conditions. After 9.6 ka, an increase in pollen concentration up to 2200 grain/cm^3, with domination of *Artemisia* (70%) and Gramineae (15%-38%) indicated changes in steppe vegetation and warmer and wetter conditions. During 7.8-3.5 ka, a concentration up to 12290 grain/cm^3 in pollen with decreases in *Artemisia* (57%) and Chenopodiaceae (5%), suggests enhancement of warm and wet conditions. After 3.5 ka, the pollen assemblages are dominated by *Ceratoides* and *Ajania*, suggesting further changes in desert vegetation.

Pollen assemblages from Xiaoshaozi Lake, Beilike Kule and Aqike Kula (Huang *et al.* 1996) in the northern part of this area also show similar changes in vegetation types as Bangong Co and Sumxi Co, in which increases in Cyperaceae, Compositae and *Artemisia* and decreases in Chenopodiaceae after ca 7.8 ka. These indicate steppe vegetation developed and suggest warmer and wetter conditions than the present in the mid Holocene. The increases in Chenopodiaceae after ca 3.5 ka can be interpreted that desert replaced steppe with the evolution of a drying climate in the late Holocene.

A summary of Tibetan vegetation reconstruction drawn from the above results is shown in Fig. 10.

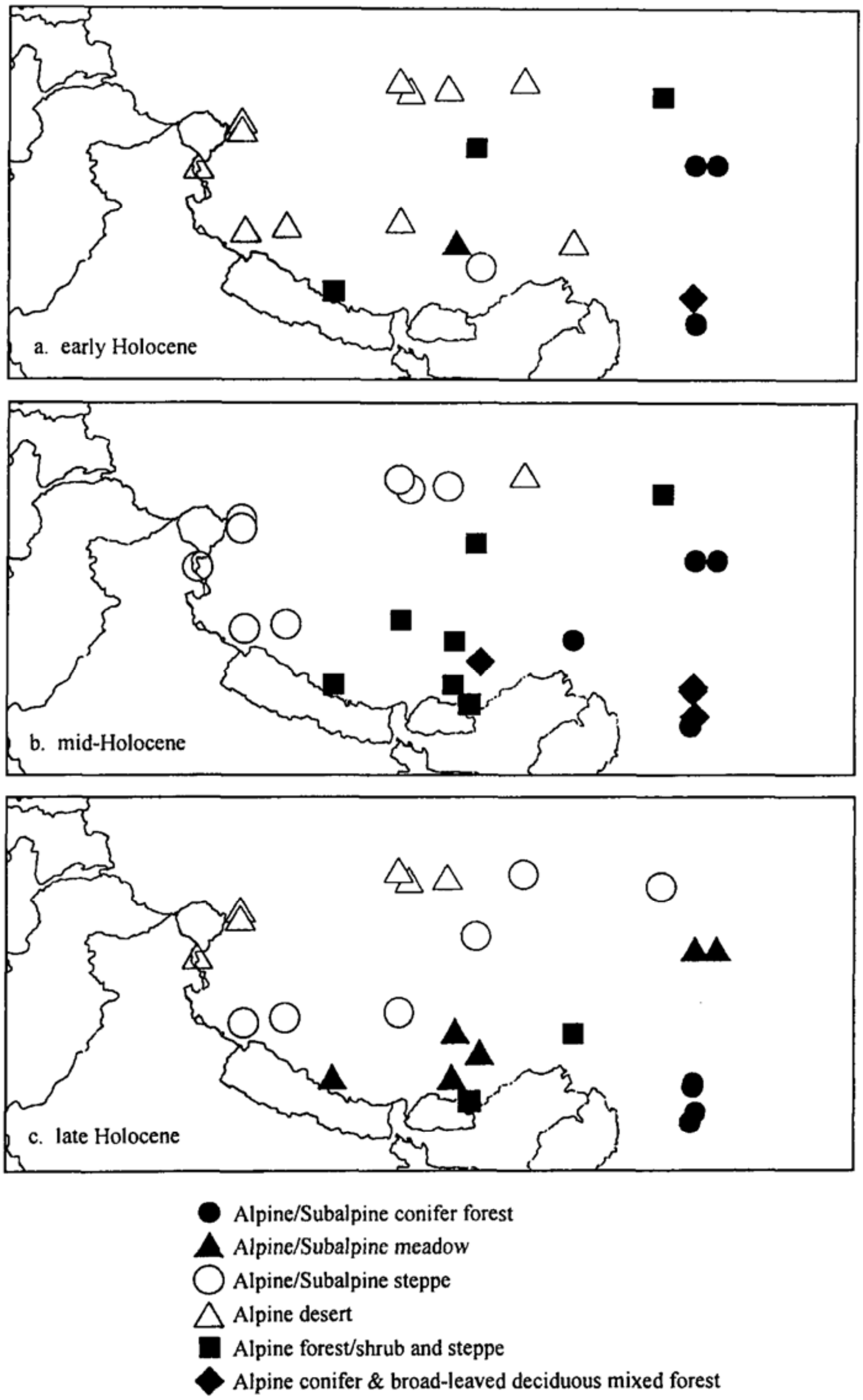

Fig. 10. Reconstructions of Holocene vegetation types on Tibetan Plateau: early-Holocene (a); mid-Holocene (b) and late-Holocene (c).

5 Discussion and conclusions

Based on evidence from pollen assemblages a series of changes and trends in vegetation cover have occurred during the Holocene for Tibet. Pollen concentrations have sharp changes into an extremely low concentrations from Hidden Lake at ca 10.5 ka and Sumixi Co at 10.5 - 10 ka, while pollen spectra show marked changes into sparse pollen taxa and low pollen abundance at Zoigê at 10.2 - 10 ka, Gounong Co at 11.5 - 10.4 ka and Qinghai Lake at ca 10.6 ka. These records possibly indicate short-lived decreases in temperature and/or precipitation, suggesting a cold and dry event in the Tibetan Plateau. This possible correspond to a time when the atmospheric circulation regime underwent a significant reorganisation. Reduction of monsoon after 11ka also recorded in India and the Arabian region (Anjum and Vaz 2000; Overpeck 1996). The possible nature of this circulation change is an unsolved issue, although it appears to match the European Younger Dryas chronozone around 11 ka, suggesting a possible teleconnection between Tibet and the region (Kenneth 1991). It has been recovered that the Indian monsoon has correction with Greenland climate oscillations (Schultz *et al.* 1998). New evidences possibly tends support to the hypothesis that there exits teleconnection between the Tibetan Plateau and the North Atlantic region (Overpeck 1996; Tang *et al.* 2003; Shen *et al.* 2002).

During the early Holocene, the first signal of wet condition from an expansion of Indian Monsoon circulation is captured from pollen records on the western plateau where cobresia steppe replaced Chenopodiaceae desert vegetation at ca 10 ka. Then a mixed forest with evergreen and deciduous *Quercus* at ca 9 ka developed on the southeastern plateau, with increases in *Tsuga* and *Cunninghamia* that suggests an increase in rainfall up to 1000 mm/year. Subalpine conifer forest and shrub-meadows also appeared on the eastern plateau at ca 8 ka. The variability in the southeastern alpine forest reflects significant dry-wet season alternations, particularly spring drought and heavy summer rainfall (ca 90% of total annual amount), resulting from an enhancement of the Indian Monsoon northwards in the early Holocene. Vegetation remained mainly alpine steppe with *Artemisia* and Chenopodiaceae on the northeastern plateau during 11-8 ka, and sparse shrub-steppe on the southern plateau during 11-8 ka. These records reflect that central and the northern areas of Tibet still had a little annual rainfall and continuing cold and experienced dry conditions of the late glacial.

An increase in evergreen sclerophyllous from southeast alpine forest suggest a warm winter, a dry spring and early summer resulting from a weakened summer monsoon after 7-8 ka. In most areas of Tibet, in contrast, forest-shrub meadow developed after 8 ka on the southern plateau; a sub-alpine conifer forest expanded after 8 ka in the Qinghai Basin on the northern plateau region; Cyperaceae swamp developed after 7.5 ka in the central plateau; an alpine conifer forest expanded after 7 ka from the Zoigê region on the eastern plateau. In addition the area of cobresia steppe continuously expanded from the western plateau also with high lake level stands. These records indicate that the greatest increases in precipitation occurred in the eastern, central, western and northern plateau during the mid-Holocene, as result of a further expansion of Indian Monsoon.

During the late Holocene, desert replaced steppe at 5.5 ka as registered by changes in the ratio of A/C in the western plateau. A return to an alpine steppe after 3.8 ka reflects drying conditions occurred in the center of the plateau. An alpine steppe dominated by *Artemisia* and Chenopodiaceae occurred in the Qinghai Basin from 3.5 ka. Conifer forest retreated from the Zoigê region after 3.3 ka. An area of shrub meadows was expanded on the southern plateau after 3 ka. These records reflect a return to a more arid climate, firstly recorded at 5.5 ka in the northwest, while at ca 4-3.5 ka in the centre and northeast, at ca 3.3 ka in the southeast, and finally at ca 3 ka in southern plateau.

Thus, reconstructions of vegetation show a broad-scale pattern of Indian Monsoon expansion northwards in the early Holocene and retreat southwards in the mid-Holocene, but the impact was recorded with different timing across Tibet. It was first recorded at ca 10 ka from northwestern sites, about ca 1000 years earlier than Shayema Lake in the southeast and about 2000 years earlier than Qinghai Lake in the northeast of Tibet. The various vegetation types have time-delays in response to changes in climate. The first signal of wet conditions on the western plateau possibly reflected that grass-less desert vegetation has a shorter-response time to changes in moisture than treeless steppe, and much shorter than forests. Despite vegetation response time difference to moisture changes, our vegetation reconstruction nevertheless patterns reflects changes in the strength and extent of Indian Monsoon expansion and retreat which started at ca 10 ka from the southeastern plateau, attained to its peak over the entire of the plateau around 8 - 7 ka, weakened after 6 ka and decreased during 4-3 ka from the north to south of the Tibetan Plateau. Records of Holocene monsoon variation from India and the Arabian Sea and terrestrial sites indicate that the southwestern monsoon increased 10 to 9 ka, but weakened about 5.5 ka(Overpeck 1996, Enzel *et al.* 1999). It seems that records from the northwestern Tibetan Plateau could match the monsoon variation exactly. The factor that caused different monsoon expansion timing across the Tibetan Plateau shown by this paper may be accurate chronology (no-nature), regional different response to monsoon , albedo (nature) and others. To solve this problem need more research to be done

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