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Vegetation and climate of the Lop Nur area, China, during the past 7 million years

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Abstract Lop Nur in Xinjiang, Northwest China, is located in the lowest part of the Tarim Basin at an altitude of 780 m and experiences an extremely dry climate with an annual precipitation of only 17 mm and a high evaporation rate of 2,728 mm. The pollen and spores from the Late Miocene strata of a borehole in Lop Nur were analyzed with a view to interpreting the paleoenvironmental evolution of Lop Nur. Main types of pollen such as Chenopodiaceae, *Nitraria*, *Ephedra* and *Artemisia* reflect an arid climate. By collating the palynological data in this area as recorded in other literature and by applying the method of Coexistence Analysis, we have obtained the paleoclimatic parameters from Late Miocene to Holocene in Lop Nur. These suggest that temperatures increased from the Late Miocene (10.2°C) to the Pliocene (13.4°C), decreased from Pliocene to Pleistocene (4.7°C), and were more stable from Holocene (12.1°C) until now (11.5°C). The precipitation was stable (about 900 mm) from Late Miocene to Early Pleistocene, then decreased markedly (to about 300 mm) in Middle and Late Pleistocene, and reached its lowest value (17.4 mm) in the Holocene. The changes in paleoclimate at Lop Nur provide new evidence for understanding the uplift of the Qinghai-Tibetan Plateau.

1 Introduction

Lop Nur (39°40′~41°20′ N, 90°00′~91°30′ E), Xinjiang, is the lowest place in the Tarim Basin (Fig. 1) with an altitude of 780 m. The mean annual temperature of Lop Nur is 11.5°C

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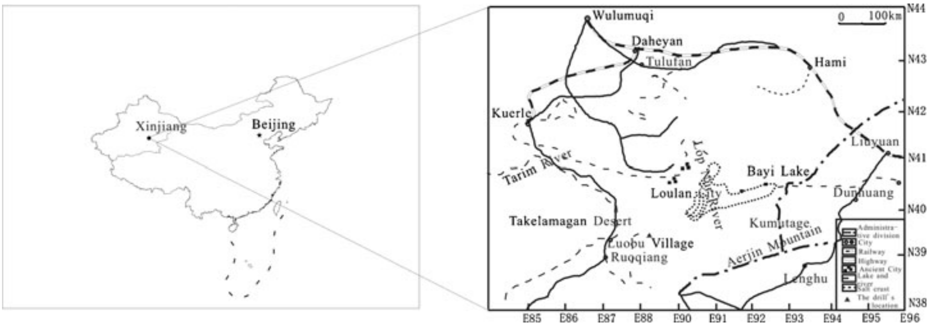

Fig. 1 The geographical location of Lop Nur

(IDBMC 1984a, b, c, d). Due to a low annual precipitation of 17 mm and high evaporation rate of 2,728 mm (Wang and Liu 2001), the climate of Lop Nur is extremely dry.

Many vegetation and climate studies in the Lop Nur area have been undertaken (Yan et al. 1983; Wu 1994; Yan et al. 1998, 2000; Wang et al. 2000, 2004; Wang and Zhao 2001; Zhao et al. 2001; Zhong et al. 2005; Luo et al. 2007), but with the exception of Zhao et al. (2001), who dealt with the history of Lop Nur in the Neogene (Pliocene), all this research focused on the Quaternary. In the present paper, the paleovegetation and paleoclimate of Lop Nur in the late Miocene were investigated, and the trend of climatic and altitudinal changes in the Lop Nur area from late Miocene until present analyzed based on our work and the published pollen records.

2 Materials and methods

The borehole Ls2 is located at 39°47′N, 88°23′E in Lop Nur. Based on mineral components, grain-size, bedding, color, and structural features, the borehole can be divided into four lithologic units from bottom to top. (I) 1,050–801 m, gray and bluish grey argillaceous limestone intercalated with brown and bluish-grey clay. (II) 801 m–711 m, grey, bluish-grey and brown clayey silt with intercalations of brown and grey clay. (III) 711–35 m, grey, bluish-grey and brownish-red clayey silt with brownish red clay, and bluish grey and grey silt. (IV) 35–0 m, consists of grey sand in the core.

A total of 342 samples were collected from the borehole of Ls2. Pollen/spores were obtained using heavy liquid separation (Moore et al. 1991; Li and Du 1999). More than 200 palynomorphs were found in 119 samples, while they were absent or very rare (< 50 grains) in the remaining 223 samples. These 223 samples were not included in the pollen diagram. The pollen grains and spores were identified by comparison with the modern palynological literature (IBCAS 1976; IBCAS and SCIBCAS 1982; Wang et al. 1995).

The pollen percentage ratio of *Artemisia* to Chenopodiaceae (A/C ratio) can be used as an indicator of moisture in arid and semi-arid areas (El-Moslimany 1990). It is suggested that A/C ratios are less than 0.5 in desert, 0.5–1.2 in desert steppe and more than one in typical steppe in the Xinjiang area (Li and Yan 1990; Yan 1991).

The reconstruction of paleoclimate in the Lop Nur area was attempted utilizing the Coexistence Approach (CoA) (Mosbrugger and Utescher 1997; Xu et al. 2000). The basic principle of CoA is that fossil plants are regarded as having the same or similar climatic tolerances as their nearest living relatives (NLRs). The climatic parameters are distilled from the coexistence interval of the climatic tolerance of the NLRs. We established the NLRs of palynomorphs and fossil plants according to Song (1999). Seven modern climatic parameters of the NLRs recorded by the meteorological stations in China were obtained from publications of the Information Department of Beijing Meteorological Center (IDBMC) (1983a, b, 1984a, b, c, d). We also referred to the database of PALAEOFLORA (Utescher and Mosbrugger 1990–2007) in deciding the MAT of NLRs. The climatic tolerances of the NLRs were obtained from the climatic records within their modern distributional areas (Wu and Ding 1999; Kou et al. 2006).

3 Results

3.1 Palynological assemblage in Lop Nur area

Thirty-eight taxa were identified in the palynological assemblages from the Lop Nur core (Table 1, Fig. 2). There were 29 taxa of angiosperms in the assemblages, including 11 families such as Chenopodiaceae, Compositae, Polygonaceae, Gramineae and 18 genera such as *Nitraria*, *Artemisia*, and *Betula*. Angiosperms predominated (76.3% of all palynomorph taxa) in the assemblages from Lop Nur. Four taxa of gymnosperms (10.5% of all the palynomorphs) were found, i.e. *Ephedra*, *Pinus*, *Abies*, *Picea*. In addition, five pteridophytes constitute 13.2% of the total palynomorphs.

Table 1 The palynomorph types from Lop Nur core in Late Miocene

Pteridophyta(5)	
Pteridaceae	Athyriaceae
Polypodiaceae	*Selaginella*
Gymnogrammaceae	
Gymnosperm(4)	
Ephedra	*Pinus*
Abies	*Picea*
Angiosperm(29)	
Nitraria	Chenopodiaceae
Compositae	*Artemisia*
Betula	*Corylus*
Typha	*Potamogeton*
Cruciferae	*Ulmus*
Hydrocharis	Polygonaceae
Alnus	Boraginaceae
Pterocarya	Gramineae
Juglans	Rutaceae
Euphorbiaceae	*Ostryopsis*
Elaeagnaceae	*Quercus*
Tilia	*Castanopsis*
Ranunculaceae	*Castanea*
Labiatae	*Urtica*
Salix	

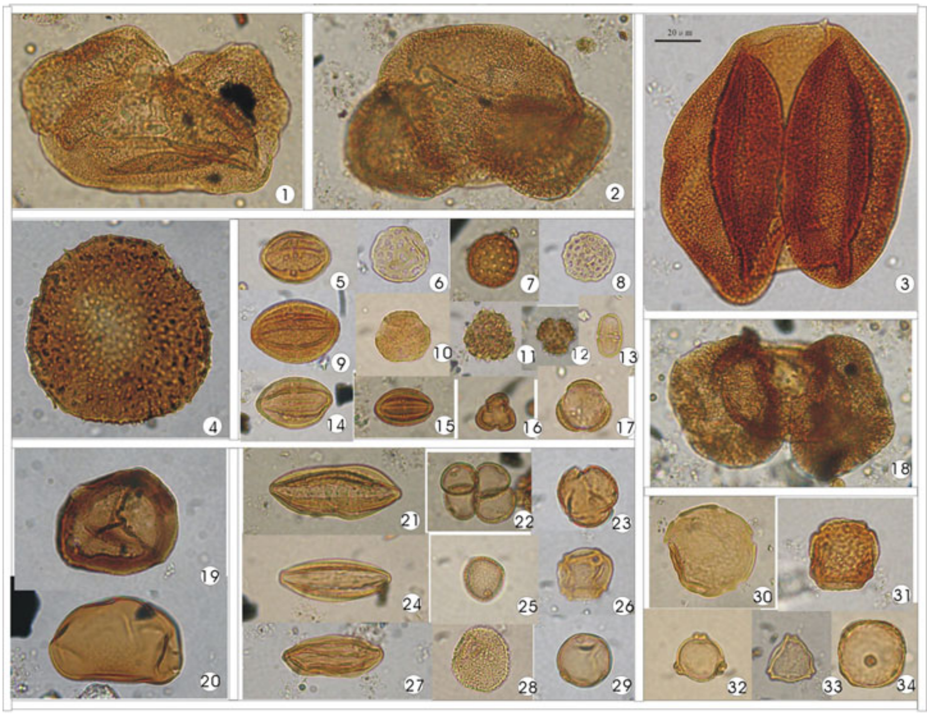

Fig. 2 The palynomorphs from Lop Nur core. 1 *Abies* 2,18 *Pinus* 3 *Picea* 4 *Hydrocharis* 5,9,14 Polygonaceae 6,7,8 Chenopodiaceae 10,11,12 Compositae 13 Boraginaceae 15 *Nitraria* 16,17 *Artemisia* 19 *Selaginella* 20 Athyriaceae 21,24,27 *Ephedra* 22,25 *Typha* 23 *Quercus* 26 *Alnus* 28 *Potamogeton* 29 *Ostryopsis* 30,31,34 *Ulmus* 32,33 *Betula*

Almost all the pollen and spores were found at depths from 831.2 m to 1059.49 m of the core, corresponding to ages of ~7.1 Ma (1050.60 m) to ~5.3 Ma (741 m) (Paleomagnetic results from Chang Hong, personal communication). Only a few pollen and spores were observed at depths from 828.7 to 0 m (Figs. 3 and 4). Consequently, the palynological research was focused mainly on the lower part of the core (at depths from 831.2 m to 1059.49 m).

The palynological diagram displays the main palynomorphs, such as Chenopodiaceae, *Nitraria*, *Ephedra*, *Artemisia*, *Typha*, *Pinus* and *Abies*, which occurred throughout the lower part of the core. From 1059.49 to 831.2 m, *Artemisia*/Chenopodiaceae ratios (A/C) change from below 0.5 at most depths to over 2 at 841.25 m, 1010.85 m, 1043.56 m and 1044.16 m. Thus in addition to the changes of palynological taxa and their percentages, we used A/C as an aridity index to recognize changes in the vegetation (Fig. 5). The pollen/spore assemblages in the lower part of the diagram were divided into four zones, while the upper part from 0 to 831.2 m was regarded as zone 5:

> Zone 1 (1059.49–1044.36 m): The ratios of A/C remain below 0.5, except for 1.33 at 1044.36 m and 1 at 1058.9 m. The tree and shrub pollen predominate in this zone (from 29.9% to 88.9%), with *Nitraria*, *Ephedra*, *Abies*, *Pinus* and *Betula* being the chief components. The average percentage of herbaceous pollen is 29.8 of which the Chenopodiaceae and *Artemisia* are the most important taxa. Aquatic pollen peaks at 1054.43 m with 17.1%, of which *Typha* is the main taxon. Spores are scarce in this zone. The pollen of *Nitraria* is predominant throughout, reaching 53.1% of the pollen

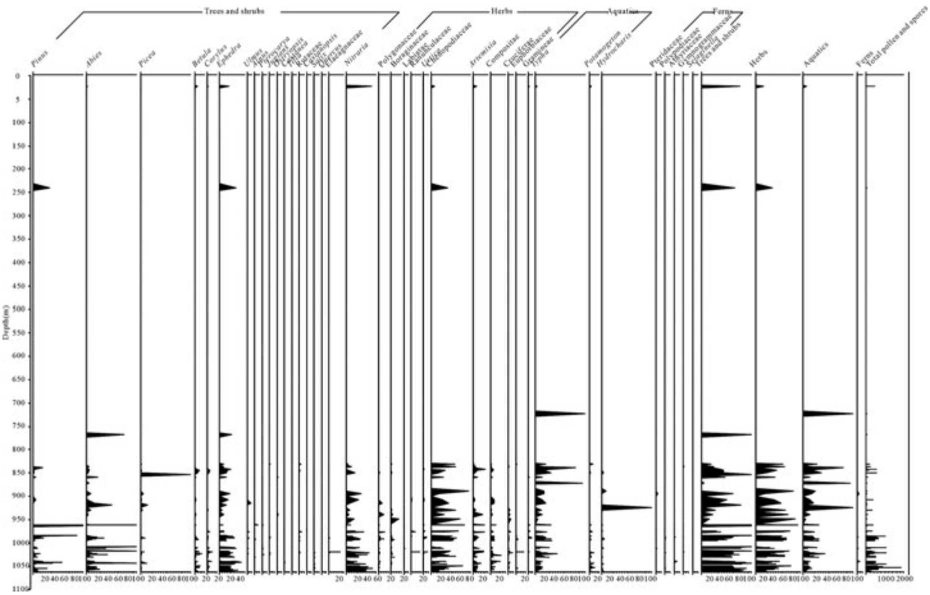

Fig. 3 The pollen diagram of the core from Lop Nur area

sum at 1055.45 m. *Nitraria* is followed by the Chenopodiaceae at 22.3%. In general, its pollen increases from the lower to the upper part. The percentage of *Ephedra* pollen is 15.8. Except for depths of 1049.9 m, 1052.4 m, 1053.93 m, 1055.45 m and 1059.49 m, *Typha* appears in most samples, with a percentage of not less than 13.8.

Zone 2 (1044.36–1011.35 m): The ratios of A/C are higher than 2 at the depths of 1043.56 m and 1044.16 m; between 0.5 and 1.2 at the depths of 1029.84 m, 1021.87 m, 1020.38 m, 1019.88 m, 1017.88 m, 1011.86 m; and below 0.5 at other

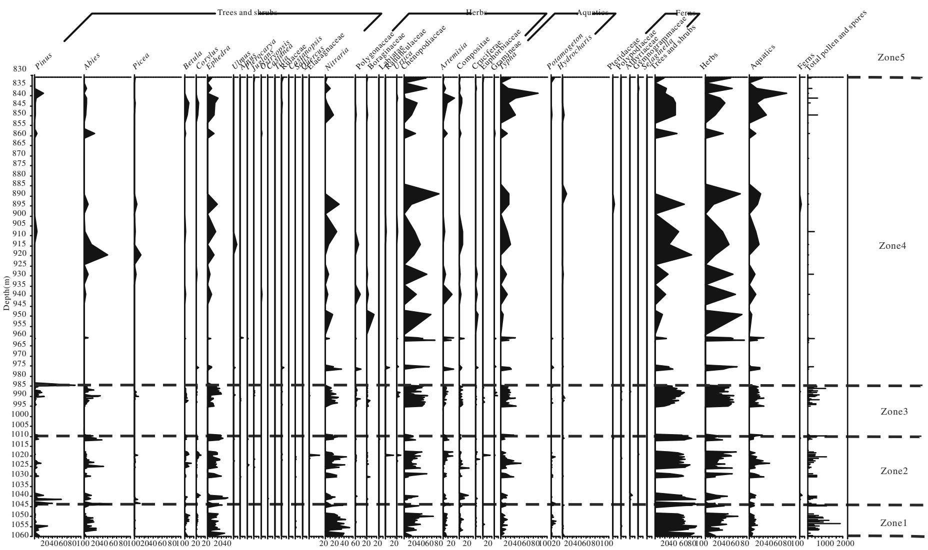

Fig. 4 The pollen diagram of the core from the Lop Nur area (from 1059.49 m to 831.2 m)

depths. The tree and shrub pollen still predominates in this zone with a percentage of 56.77, while the percentage of herbaceous pollen is only 29.96. Aquatic pollen varies from 0% to 42.9%, while the percentage of *Typha* pollen is 11.4 in this zone. Few spores are found. The percentage of *Ephedra* pollen (20.98%) is highest in this zone, followed by Chenopodiaceae (18.3%) and *Nitraria* (17.8%) pollen. *Abies*, *Pinus* and *Betula* are the chief trees with percentages similar to those in Zone 1.

Zone 3 (1011.35–984.8 m): The ratios of A/C are below 0.5 except for 5 at 1010.85 m. The percentage of herbaceous pollen (38.88%) is higher than that in the last zone (29.96%), and trees and shrub pollen constitute 45.78%. The amount of aquatic pollen is stable in different samples of this zone with a higher percentage (15.2%) than in Zone 1 (7.7%) and Zone 2 (11.6%). The percentages of spores remain below 0.25 in the different samples. Chenopodiaceae is the most important pollen type, followed by *Typha*, *Nitraria* and *Ephedra*.

Zone 4 (984.8–831.2 m): Except for three higher A/C ratios of 15.5 (841.25 m), 0.7 (939.2 m) and 0.75 (960.75 m), the A/C ratio remained below 0.5. Pollen/spores occur irregularly and their percentages change continuously. Tree and shrub pollen is replaced by herbaceous pollen with an average percentage of 43.34 and a maximum value of 59.8% at a depth of 961.25 m. The percentage of aquatic pollen is 21.9.

Zone 5 (831.2–0 m): Few pollen/spores are found in this zone except for the depth of 22.84 m. Tree and shrub pollen predominate with 77.38%, followed by herbs (16.3%) and ferns (6.3%).

3.2 Related vegetation

Based on the palynomorph diagram, Chenopodiaceae, *Nitraria*, *Ephedra*, *Artemisia*, *Typha*, *Pinus* and *Abies* were the main plant types at Lop Nur. During the late Miocene (from 1059.49 to 831.2 m of the core), the Chenopodiaceae remained predominant (surpassing 25%) in 45 samples (39% of a total of 115 samples), followed by *Nitraria* in 21 samples, *Ephedra* in 18 samples, *Typha* in 10 samples, while *Abies* was predominant in 8 samples and *Pinus* the principal taxon in 3 samples.

The predominance of Chenopodiaceae suggests that the vegetation was largely herbaceous. However, the shrubs *Nitraria* and *Ephedra* constitute two other important elements. Another significant element, *Typha* dominates in Zone 2 (1022.37 m, 1023.38 m, 1030.34 m), Zone 3 (991.05 m, 994.8 m, 1009.35 m) and Zone 4 (841.25 m, 849.4 m, 871.38 m, 960.75 m). Although alpine trees *Pinus* and *Abies* have a percentage of up to 50% in some samples, they were most likely growing on the slopes of the mountains around Lop Nur and blown downhill by katabatic winds. The vegetation at Lop Nur in the late Miocene was mainly composed of steppe types, with some shrubs and a few trees. Chenopodiaceae, *Nitraria*, *Ephedra* and *Artemisia* were the main elements. *Abies* and *Pinus*, as well as *Betula* were located on the surrounding hills. Ferns were scarce in the Lop Nur area. Aquatic plants such as *Typha* lived at the edge of Lop Nur Lake.

3.3 Related climate

Chenopodiaceae are noted as halophytes and are assumed to be indicators of salinity in more mesic regions (El-Moslimany 1990), while *Nitraria* is the strongest salt-tolerant shrub among desert plants (Wang and Chen 2006; Li et al. 2005). The ratios of *Artemisia* to Chenopodiaceae from 1056.95 to 831.2 m changed between < 0.5 and >2 (Fig. 5),

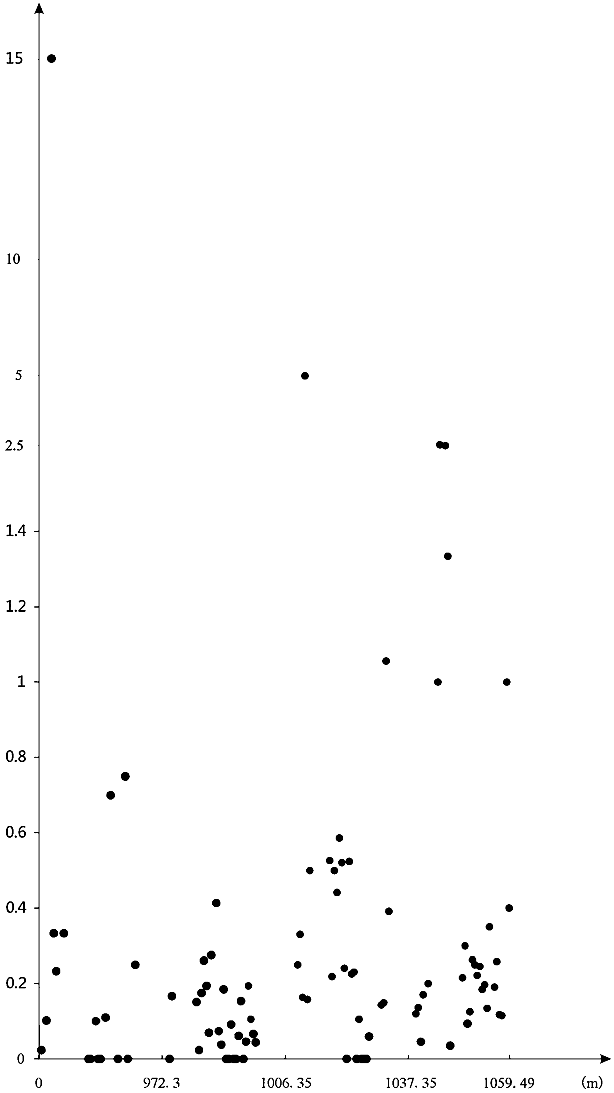

Fig. 5 A/C ratio (*Artemisia*/ Chenopodiaceae) from the depths of 1059.49 m to 831.2 m

suggesting that the climate fluctuated between wet and arid conditions in the late Miocene. Wet periods are indicated at the depths of 841.25 m, 1010.85 m, 1043.56 m and 1044.16 m, which peaked at 841.25 m with an A/C ratio of 15 (Fig. 5). In the meantime, the high percentages of Chenopodiaceae and *Nitraria* suggest that the climate was generally getting more arid. Other important types such as *Ephedra* and *Artemisia* also reflect a temperate and dry climate. An increase in herbs with 29.8% in Zone 1, 29.96% in Zone 2, 38.88% in Zone 3 and 43.34% in Zone 4 indicates that the drought became increasingly severe through time. However *Typha* pollen also occurs (13.8% in zone 1; 11.4% in zone 2, and still a very important taxon in zone 3) (see Fig. 3) and suggests the presence of wetland with high precipitation in some periods.

Based on Coexistence Analysis (CoA), we obtained seven climatic parameters for the Lop Nur area in the late Miocene: the difference of temperature between the coldest and warmest months (DT) of 24.3 to 26°C, mean coldest monthly temperature (MCMT) of −3.8 to 2°C, mean warmest monthly temperature (MWMT) of 15.4 to 24.8°C, mean annual temperature (MAT) of 5.4 to 14.9°C, monthly minimum precipitation (MMiP) of 7 to 23.6 mm, monthly maximum precipitation (MMaP) of 138.5 to 183.6 mm, and mean annual precipitation (MAP) of 642 to 1,031 mm (Fig. 6).

We also collated other previously published palynological data from Lop Nur (Wang et al. 2000; Yan et al. 2000; Zhao et al. 2001; Wu 1994; Yan et al. 1998; Yan et al. 1983) (Table 2). The published palynological data were cataloged in the time sequence from Pliocene to the early to middle to late Pleistocene, and then to Holocene. Based on these data, the climate from Pliocene to Holocene was reconstructed using CoA. All the coexistence results from late Miocene to Holocene are shown in Table 3. The climatic data of Lop Nur today are also listed (the data are from IDBMC (1983a, b, 1984a, b, c, d) (Information Department of Beijing Meteorological Center)).

The average DT values were similar with 25.2°C in late Miocene, 23.7°C in Pliocene and 24.6°C in early Pleistocene. After that, they increased to 30.6°C in middle Pleistocene, 30.8°C in late Pleistocene, followed by a decrease to 28.7°C in the Holocene. The mean values of MCMTs were higher in the late Miocene, Pliocene and early Pleistocene with −0.9°C, −2.6°C and 0.9°C, respectively, followed by a low value of −12.4°C in middle Pleistocene, −9.4°C in late Pleistocene and −12.7°C in the Holocene. The average values of MWMTs were 20.1 in late Miocene, 20.4 in Pliocene, 23 in early Pleistocene, 19.7 in middle Pleistocene, 22.2 in late Pleistocene, and 25.4 in the Holocene. The mean MAT values in late Miocene and Pliocene were 10.2°C and 13.4°C, respectively, after which the value decreased to 10.9°C in early

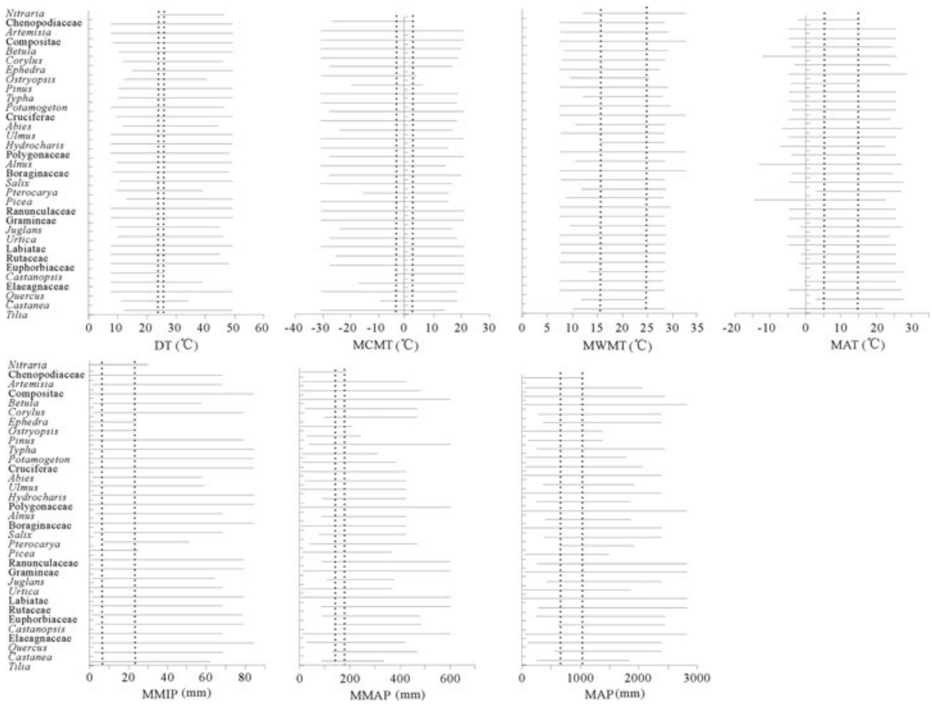

Fig. 6 Coexistence of climatic parameters of nearest living relatives of palynomorphs from Lop Nur core

Table 2 Other palynological literatures about Lop Nur

Name	Time	Locations	Authors and literatures
Bayi profile	Middle Pleistocene to late Pleistocene(dating by palynologic research)	Central of Aqike, east of Lop Nur Lake	Wang et al. 2000 *Arid land geography*
The drilling of K1	Early Pleistocene to Holocene (dating by paleomagnetic research)	Centre of Lop Nur Lake (40.17 N, 90.15 E)	Yan et al. 2000 *Acta Micropalaeontologica Sinica*
AK1 drilling	Pliocene to Holocene (dating by paleomagnetic, palynologic and other research)	South of Ba Yi Quan profile, east of Lop Nur Lake (40.4 N, 92.3E)	Zhao et al. 2001 *Arid land geography*
pit F_4	Late Pleistocene to Holocene (dating by ^{14}C research)	East of Lop Nur area (40–40.5 N, 90–90.5E)	Wu 1994 *Arid land geography*
Luo 4 drilling	Late Pleistocene to Holocene (dating by palynologic and ^{14}C research)	South of Lop Nur Lake	Yan et al. 1983 *Seismology and geology*

Pleistocene, 4.7°C in middle Pleistocene and 8.1°C in late Pleistocene. The mean MAT increased to 12.1°C in the Holocene. Average values of MMiP were 15.3 mm, 13.6 mm, 15.4 mm, 2.8 mm, 5.2 mm and 5.9 mm, while mean values of MMaP were 161.1 mm, 170.6 mm, 183.3 mm, 57.7 mm, 90.6 mm and 179.6 mm respectively. High MAP values existed in late Miocene, Pliocene and early Pleistocene with 836.5 mm, 990.2 mm and 842.7 mm, then decreased to 364.6 mm in middle and late Pleistocene, and only 275.1 mm in the Holocene.

4 Discussion

4.1 Climatic changes in Lop Nur

From the late Miocene to Pliocene, it became warmer at Lop Nur with temperatures rising from 10.2°C (mvMAT) to 13.4°C (mvMAT). The climate at Lop Nur coincides with the global changes at this time (Zachos et al. 2001). The mvMAT at Lop Nur decreased from 13.4°C in the Pliocene to 10.9°C in early Pleistocene, with the lowest value of 4.7°C in middle Pleistocene and 8.1°C in late Pleistocene. The temperature in the Holocene (mvMAT of 12.1°C) is close to the MAT of today (11.5°C), which suggests that the temperature was stable from the beginning of the Holocene until now. The trend of temperature decreased from Pliocene to Pleistocene at Lop Nur, which coincided with a global temperature fall and the beginning of the ice age, respectively.

The precipitation at Lop Nur was stable before early Pleistocene, with 836.5 mm (mvMAP) in late Miocene, 990.2 mm in Pliocene and 842.7 mm in early Pleistocene. But it then decreased markedly to 364.6 mm (middle and late Pleistocene) and was further reduced to 275.1 mm in the Holocene and 17.4 mm today. Based on the times of precipitation change, we conclude that it was between the early and middle Pleistocene that the evident uplift of the Tian Mountains (north of Lop Nur), Aerjin Mountains (east of Lop Nur), Kunlun Mountains and Qinghai-Tibetan Plateau (south of Lop Nur) took place, which prevented moist air from reaching the Lop Nur area.

Table 3 The coexistence of climatic data in Lop Nur area from Late Miocene to Holocene

	DT(°C)	MCMT(°C)	MWMT(°C)	MAT(°C)	MMiP(mm)	MMaP(mm)	MAP(mm)
Late Miocene	24.3–26 (25.2)	−3.8–2 (−0.9)	15.4–24.8 (20.1)	5.4–14.9 (10.2)	7–23.6 (15.3)	138.5–183.6 (161.1)	642–1031 (836.5)
Pliocene	14.8–32.6 (23.7)	−8.7–3.6 (−2.6)	13.2–27.5 (20.4)	4.7–22.1 (13.4)	3.3–23.9 (13.6)	129.4–211.8 (170.6)	590.9–1389.4 (990.2)
Early Pleistocene	24.3–24.8 (24.6)	−0.3–2 (0.9)	18.4–27.5 (23)	7.8–13.9 (10.9)	6.9–23.9 (15.4)	183–183.6 (183.3)	654–1031.3 (842.7)
Middle Pleistocene	25.6–35.6 (30.6)	−16.7–(−8) (−12.4)	16.9–22.5 (19.7)	1–8.4 (4.7)	1.6–3.9 (2.8)	33.7–81.6 (57.7)	361–368.2 (364.6)
Late Pleistocene	25–36.6 (30.8)	−12–(−6.7) (−9.4)	16.9–27.5 (22.2)	7.8–8.4 (8.1)	1.6–8.7 (5.2)	86.8–94.4 (90.6)	361–368.2 (364.6)
Holocene	26.9–30.4 (28.7)	−16.7–(−6.7) (−12.7)	23.2–27.5 (25.4)	10.2–13.9 (12.1)	3–8.7 (5.9)	175.6–183.6(179.6)	272.6–277.6 (275.1)
Modern	35.9	−8.5	27.4	11.5	0.2	5.6	17.4

Mean values of the ranges are marked in the brackets

4.2 Comparison with climatic changes in nearby localities in China

The Lop Nor area is located in the northwestern part of the Qinghai-Tibetan Plateau (in NW China), and the reconstruction of the paleo-climatic parameters there provides the possibility to compare them with those from related localities in China, some from Yunnan at the southeast margin of the plateau (in SW China) (Table 4), and some from Shandong and Shanxi in East China (Table 5). Because we lack the paleo-coordinates and paleo-altitudes of these localities, we can compare the climatic changes only in general terms, and try to consider/analyze the influences of the coordinates and altitudes on the climates. No paleo-climatic parameter has been estimated in the central part of the Qinghai-Tibetan Plateau in the Cenozoic period, so it is not possible to compare the climatic changes in Lop Nor with those in the central plateau quantitatively.

4.2.1 Comparison of the climates of the Lop Nor area with Yunnan

Lühe, Eryuan, Yangyi and Longling are located in the western part Yunnan at the southeast margin of the Qinghai-Tibetan Plateau, while Kaiyuan is in the central part of Yunnan, SW China.

The Late Miocene mvMAT in Lühe and Kaiyuan were 17.1°C and 17.9°C individually. Considering the latitude of Lop Nor (39°47′N) is higher than the both localities (compared to 25°01′N at Lühe and 23°48′N at Kaiyuan) and the latitudinal temperature gradient in the Miocene is estimated to have been 0.45°C per degree latitude (Hao et al 2010), the Late Miocene mvMAT in Lop Nor could be 17.0°C (0.45°C×15+10.2°C=16.95°C) at the latitude of Lühe, and 17.4°C (0.45°C×16+10.2°C) at the latitude of Kaiyuan, and below 0.1 (17.1–17.0°C) and 0.5°C (17.9–17.4°C) than mvMAT of Lühe and Kaiyuan. In other words, it was colder about 0.1 or 0.5°C in Lop Nor than in SW China in the Late Miocene. mvMAP in Lop Nur was 836 mm and less than about 200 to 400 mm than in Lühe and Kaiyuan in the Late Miocene (Table 4).

The Late Pliocene mvMAT in Eryuan, Yangyi and Longling were 15.9°C, 17.1°C and 20.4°C, respectively. The latitude of Lop Nur is higher about 14° to 15° than these three localities (26°00′N, 24°57′N and 24°41′N), and the latitudinal temperature gradient in the Pliocene is estimated to have been 0.55°C (Hao et al 2010). The Late Pliocene mvMAT in Lop Nur could be 16.4°C (0.55°C×14+8.1°C=16.35°C) at the latitude of Yangyi. Given that the altitude of Yangyi is about 740 m higher than that of Lop Nur (using the recent data, Table 4), mvMAT in Yangyi could be 21.5°C (0.6°C/100 m×740 m+17.1°C=21.54°C) at the altitude of Lop Nur. It was about 5.1°C colder in Lop Nur than in Yangyi in the Late Pliocene. mvMAP in Lop Nur was 364 mm and less than about 700 mm in Eryuan, Yangyi and Longling, SW China in the Late Pliocene (Table 4). Until today, it was very warm and wet in Yunnan with MAT of 13. 9 to 19.7°C and MAP from 815 to 2,122 mm, while it was cold and arid in Lop Nur (11.5°C, 17 mm).

4.2.2 Comparison of the climate of the Lop Nor area with East China

The (Middle) Miocene mvMAT in Shanwang, Shandong Province was 12.7°C. The latitude of Lop Nor is about 3° higher than Shanwang (36°33′N) (Table 5). The (Late) Miocene mvMAT in Lop Nur could be 11.6°C (0.45°C×3+10.2°C=11.55°C) at the latitude of Shanwang, and below 1.1°C than the mvMAT of Shanwang. That means that it would be colder about 1.1°C in Lop Nur than in East China in the Miocene. mvMAP in Lop Nur was less about 600 mm than in Shanwang in Miocene (Table 5).

Table 4 The comparison of climatic parameters of Lop Nur, NW China with localities in Yunnan, SW China

Period	Coordinate/ altitude	MAT (mvMAT) (°C)	MAP (mvMAP) (mm)	Location	Coordinate/ altitude	MAT (mvMAT) (°C)	MAP (mvMAP) (mm)
Middle Miocene	Lop Nor						
Late Miocene	39°40′–41°20′N 90°00′–91°30′E	5.4–14.9 (10.2)	642–1031 (836.5)	Luhe		13.3–20.9 (17.1)	803.6–1254.7 (1029.2)
				Kaiyuan		16.7–19.2 (17.9)	1215–1639 (1427)
Late Pliocene		7.8–8.4 (8.1)	361–368.2 (364.6)	Eryuan		13.3–18.6 (15.9)	619.9–1484.3 (1052.1)
				Yangyi		13.3–20.9(17.1)	797.5–1254.7(1026.1)
				Longling		18.6–22.1(20.4)	815.8–1254.7(1035.2)
Present	Borehole: 39°47′N, 88°23′E 780 m	11.5	17.4	Luhe	25°01′N, 101°32′E 1772 m asl	15.6	815.9
				Kaiyuan	23°48′N, 103°12′E 1050 m asl	19.7	820.5
				Eryuan	26°00′N, 99°49′E 2279 m asl	13.9	650.2–1456.5(1053.3)
				Yangyi	24°57′N, 99°15′E 1521 m asl	15.5	966.4
				Longling	24°41′N, 98°50′E 1802 m asl	14.9	2122

References: Parameters of Lop Nur from this work;

Parameters of Luhe form Xu et al. 2008;

Parameters of Kaiyuan from Xia et al. 2009;

Parameters of Eryuan, Yangyi, Longling from Kou et al. 2006;

Present climatic parameters from IDBMC 1984a, b, c, d

Table 5 The comparison of climatic parameters of Lop Nur, NW China with Shanwang and Zhangcun, East China

Period	Coordinate/ altitude	MAT (mvMAT) (°C)	MAP (mvMAP) (mm)	Location	Coordinate/ altitude	MAT (mvMAT) (°C)	MAP (mvMAP) (mm)
Middle Miocene	Lop Nor 39°40′–41°20′N, 90°00′–91°30′E			Shanwang		10.9–14.5 (12.7)	1107.3–1880.0 (1493.6)
Late Miocene		5.4–14.9 (10.2)	642–1031 (836.5)				
Late Pliocene		7.8–8.4 (8.1)	361–368.2 (364.6)	Zhangcun		8.5–15.1 (11.8)	845.6–1050.9 (948.2)
Present	Borehole: 39°47′N, 88°23′E 780 m asl	11.5	17.4	Shanwang	36°33′N, 118°44′E 200–400 m asl	12.3	671.5
				Zhangcun	36°58′N, 112°51′E 1043 m asl	8.8	578.9

References: Parameters of Lop Nur from this work;
Parameters of Shanwang from Yang et al. 2007;
Parameters of Zhangcun from Qin et al. 2011;
Present climatic parameters from IDBMC 1984a, b, c, d

The Late Pliocene mvMAT in Zhangcun, Shanxi Province, was 11.8°C. The latitude of Lop Nur is about 2.5° higher than Zhangcun (36°58′N). The Late Pliocene mvMAT in Lop Nur could be 9.5°C (0.55°C×2.5+8.1°C=9.48°C) at the latitude of Zhangcun. The altitude of Zhangcun is about 260 m higher than Lop Nur (using the recent data, Table 5). mvMAT in Zhangcun could be 13.4°C (0.6°C/100 m×260 m+11.8°C=13.36°C) at the altitude of Lop Nur. It is about 3.9°C colder in Lop Nur than in Zhangcun in Late Pliocene. mvMAP in Lop Nur was less about 580 mm than in Zhangcun, East China in the Late Pliocene (Table 5). In recent time, it is very hot and arid in summer in Lop Nur and cold and dry in winter with the MAT of 11.5°C and MAP of 17 mm, comparing to the MAT of 12.3°C in Shanwang and 8.8°C in Zhangcun, and MAP of 671 mm and 578 mm individually.

In the Paleocene, the water from the Tethys Sea extended west of the Tian Shan Mountains and flowed eastward into the Tarim Basin. It was not until the late Eocene that the water receded and land was uplifted in the Tarim Basin. A marine regression started in the Oligocene and accelerated in the Miocene (Fig. 7). The collision of the Indian and Eurasian Plates resulted in the uplift of the Qinghai-Tibetan Plateau. Since then, Tibet moved northwards over time (Mulch and Chamberlain 2006). The uplift of the Qinghai-Tibetan Plateau strongly impacted climatic changes in Asia, especially, the origin and development of the Asian monsoon.

The Lop Nur area was located to the north of the Qinghai-Tibetan Plateau and was close to ancient Mediterranean from the Paleocene to the Miocene (Fig. 7), and contained a large freshwater lake controlled by the westerly winds that brought more precipitation at that time. During the uplift of the Qinghai-Tibetan Plateau, Lop Nur area gradually influenced by the northwest (winter) monsoon from Siberia, and became a dry lake in desert. The Yunnan region in SW China is influenced by both the southwest (summer, from the Indian Ocean) and northwest (winter) monsoons, with the alternation of wet and dry seasons. East China is impacted by the southeast (summer) monsoon from Pacific Ocean and northwest (winter) monsoons. The influence of the uplift of the Qinghai-Tibetan Plateau on the climates around it in the Miocene was not so strong as in the Pliocene and today, and caused the mvMATs in NW China, SW China and East China to be closer, with the differences of 0.1 to 0.5°C between NW and SW China, and 1.1°C between NW and East China. But the disappearance of the ancient Mediterranean, the increasing height of the

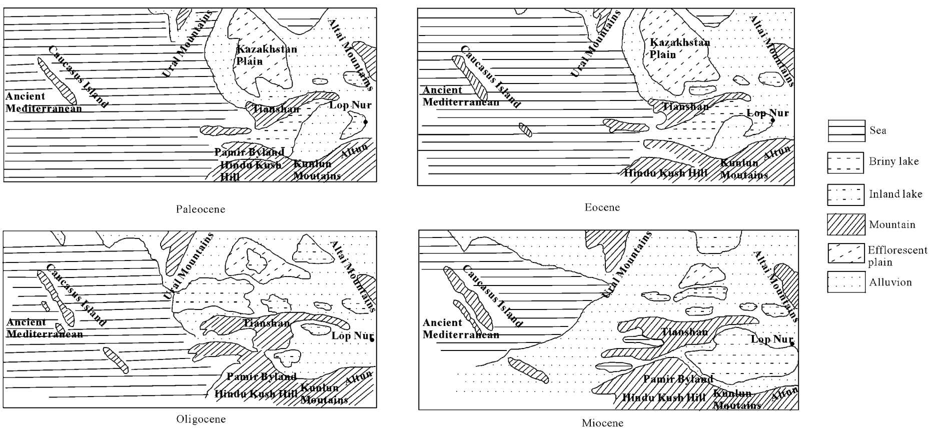

Fig. 7 The geographic position of Middle Asia and Tarim Basin in Tertiary

Qinghai-Tibetan Plateau, and global cooling in the Pliocene greatly influenced climatic changes in China, with the differences of the mvMAT becoming 5.1°C and 3.9°C separately. The summer monsoons bring the currents from Indian and Pacific Ocean, and caused the richer precipitation in SW and East China than in NW China since the Miocene.

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