Climate Reconstruction based on Pollen Analysis in Inner Mongolia, North China from 51.9 to 30.6 kaBP

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Abstract: The palynomorph assemblage of lake sediments younger than 51.9 kaBP from Wulagai Gobi in Inner Mongolia was analyzed to reconstruct the vegetation and climate. From 51.9 to 30.6 kaBP, the vegetation was arid to semi-arid grassland with only slight changes. According to the palynomorphs, trees and shrubs were very rare. The large number and diversity of algae indicate the presence of a lake. Quantitative climatic conditions were reconstructed using the Best Analogues Method. The results indicate that the annual mean temperature was higher than that at present. The combination of temperature and annual precipitation suggests a change in the climate from cool dry to warm dry and then cool humid. Our results show that the annual precipitation values were mostly higher than that at present but were lower than 400 mm. It infers that the study area was already within the arid to semi-arid regions but with a stronger influence of the summer monsoon during 51.9 to 30.6 kaBP than at present. With slight differences mainly in time scale, the changing trend of the annual temperature curve is consistent with the other climatic records from Antarctica, Greenland, Hulu Cave (East China), and the Tibetan Plateau during the last glacial period. From 30.6 kaBP to present, very few palynomorphs were detected in the samples. Hence, no information about the vegetation and climate could be extracted. Combined with other studies during Late Pleistocene, we presume that the reason for the lack of pollen during this period was caused by an abrupt temperature fall after 30.6 kaBP or that the lacustrine conditions were unsuitable for pollen deposition. It was probably incurred by the oxidation on land prior to deposition. But for those samples only with algae, it might be caused by the fact that algae could finish their life history in a very short time in a seasonal lake.

Key words: paleoclimate, paleovegetation, pollen analysis, Late Pleistocene, Inner Mongolia

1 Introduction

The last glacial period (73.5–14.7 kaBP) (Sanchez Goñi and Harrison, 2010) has been studied very well by many researchers (e.g., Lorius et al., 1985; Anklin et al., 1993; Thompson et al., 1997). It is clearly characterized by millennial-scale oscillations (Heinrich, 1988; Johnsen et al., 1992; Dansgaard et al., 1993; Grootes et al., 1993). Two types of climatic changes, Heinrich (Heinrich, 1988) and Dansgaard-Oeschger (DO) (Dansgaard et al., 1984) events, alternated throughout most of the time. Although the last glacial period is a worldwide climatic event, it has regional features as well, such as the differences in timing and variability because of the landscape and other climatic influences (e.g., the monsoon).

Those areas only marginally influenced by the Asian monsoon are considered sensitive to climatic changes. How did these areas react to the frequent climatic oscillations during the late last glacial? Did this delay or advance the response time compared with other records? To build a complete picture of the last glacial period, more research based on other materials must be undertaken in different regions. In the present work, a shallow section of 405 cm was excavated in Wulagai Gobi Lake of Inner Mongolia for pollen analysis. The vegetation succession

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and climatic history were reconstructed based on the palynomorphs since 51.9 kaBP. In addition, the results were compared with other relevant works to investigate the regional differences on climatic changes during the last glacial period.

2 Locality, Material and Methods

Our sampling site, Wulagai Gobi (45°30′N, 117°33′E), a dried-up lake, is set in a semi-arid region in the mid-temperate zone, Ujimqin Banner, eastern Inner Mongolian Plateau (Zheng et al., 2010). The altitude here is 823 m with a surface area of 230 km^2. The mean annual temperature is 6.7°C and the mean annual precipitation 278 mm (data estimated by the Interpolation method using POLATION software). Typical grasslands develop in this area. The main plant species include the grasses *Stipa sareptana*, *Leymus chinensis*, and *Cleistogenes hackelii*; a lily species *Anemarrhena asphodeloides*; an onion species *Allium anisopodium*; and *Artemisia frigida* (Xin et al., 2012). In addition, there are also abundant plants of Chenopodiaceae (*Kalidium foliatum*, *Salsola laricifolia, Chenopodium album*, etc.), *Nitraria* (*Nitraria sibirica* and *N. tangutorum*), *Tamarix* (*Tamarix ramosissima)*, Caryophyllaceae (*Silene jenisseensis, Dianthus superbus,* etc.), Brassicaceae (*Descurainia sophia, Pugionium cornutum,* etc.), Polygonaceae (*Polygonum aviculare*, *P. sibiricum, Fagopyrum esculentum,* etc.) (Wan and Wei, 1999). The lake used to be fed by surface runoff and precipitation. One of the main inflow rivers is Wulagai River, which is one of the largest inland rivers in Inner Mongolia. Following the damming of the river by the Wulagai Reservoir in 2003, wetlands and lakes in the middle and lower reaches of the Wulagai River gradually disappeared, and finally the Wulagai Gobi dried up. Meanwhile, serious vegetation degradation occurred and the typical grassland vegetation turned into a saline meadow with bare patches of land (Su et al., 2011).

A shallow section with a depth of 405 cm was obtained by manual digging in the southeastern part of Wulagai Gobi (Fig. 1). The digging was terminated at 405 cm due to difficulties caused by groundwater. The lithology of the Wulagai Gobi (WLG) section is shown in Fig. 2.

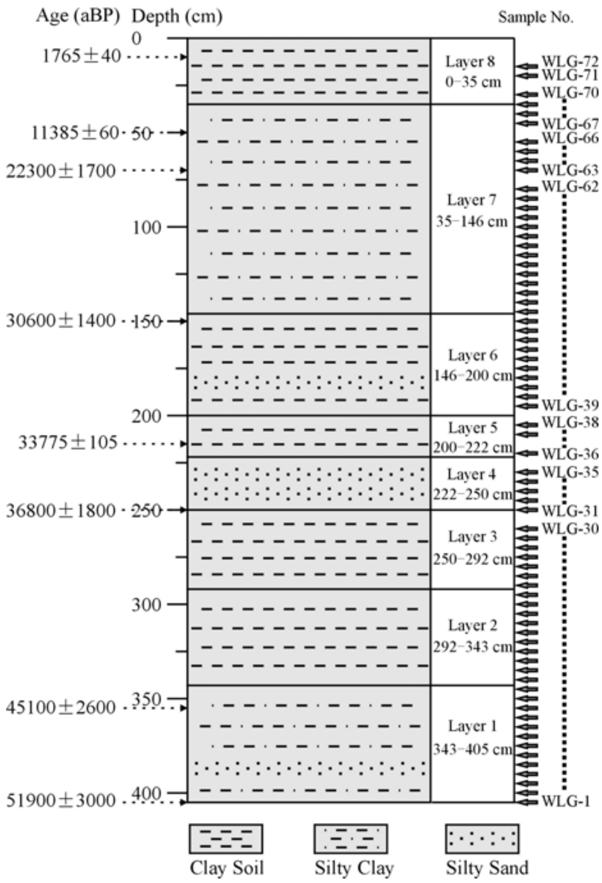

Fig. 2. Lithological sequence of the Wulagai Gobi profile, Inner Mongolia.

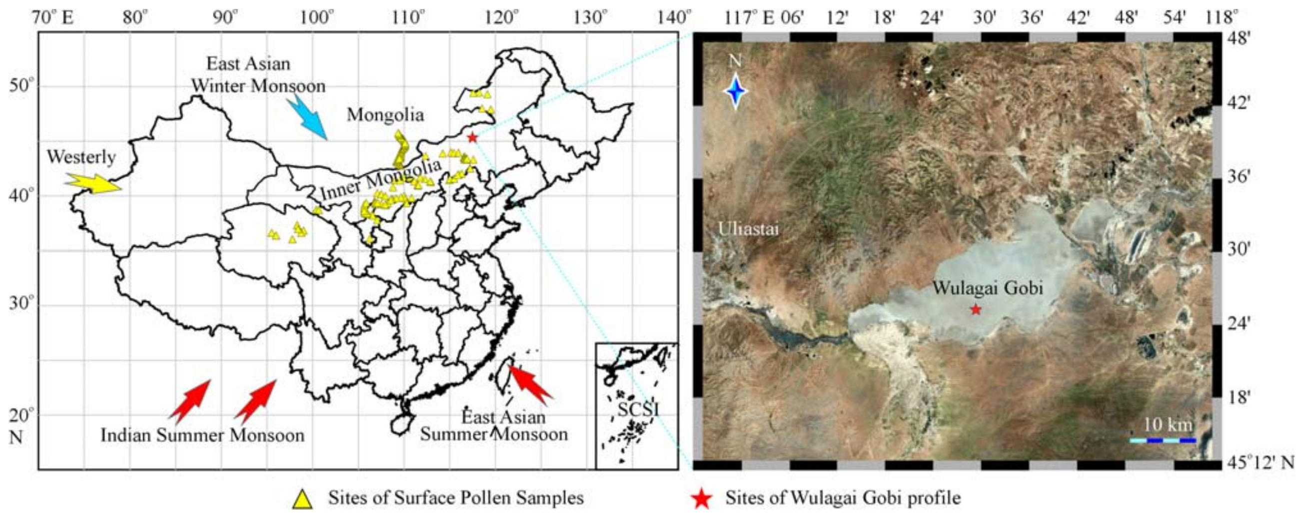

Fig. 1. Location of the sampling site in Wulagai Gobi, Inner Mongolia, and the 161 sites of the compiled surface pollen samples.

Four samples for ^{14}C dating were obtained at depths of 10 cm, 50 cm, 215 cm, and 317 cm. Another five samples were collected for Optically Stimulated Luminescence dating (abbreviated as OSL dating) at depths of 70 cm, 150 cm, 250 cm, 335 cm, and 405 cm. The ^{14}C dating was carried out in the Laboratory of Accelerator Mass Spectrometry (AMS), Peking University. OSL dating was undertaken in the Groundwater Mineral Water and Environmental Supervising and Testing Center, Ministry of Land and Resources. The age of the bottom is 51.9 kaBP and the detailed results are shown in Table 1. Other dates were obtained by linear interpolation.

A total of 72 samples (10 of 82 were consumed for other analysis before this work) were collected for pollen analysis at intervals of 5 cm. The palynomorphs were extracted using the acid-alkali-free method (Moore et al., 1991; Li and Du, 1999). Ten grams of each sample were analyzed. The palynomorphs were examined using an Olympus CX41 light microscope, the single-grain technique (Ferguson et al., 2007) was applied, and photographs were taken using a JEOL JSM-6400 scanning electron microscope (Plates I–III). The identifications of the palynomorphs were mainly based on monographs such as *Pollen Flora of China* (Wang et al., 1995) and *Sporae Pteridophytorum Sinicorum* (IB-CAS, 1976), and other relevant palynological literature (Moore et al., 1991; Xi and Ning, 1994).

To reconstruct the climatic parameters, the Best Analogues Method was carried out using the POLYGON 2.2.4 program (http://dendro.naruto-u.ac.jp/~nakagawa/). The amount of pollen data from surface samples is important when applying the Best Analogues Method. In this study, a total of 161 surface pollen sites (as shown in Fig. 1) (in which one sample is the top sample of our profile) were sampled, data from six sites were compiled from unpublished data (Qin, 2012, personal communication), while others were digitalized from published papers (Li et al., 2005a; Li et al., 2005b; Ma et al., 2008; Xu et al., 2009). Three hundred and seventy three modern observed climatic data from 1961 to 1990 were obtained from the POLATION sample files (http://dendro.naruto-u.ac.jp/~nakagawa/) for estimating the modern climate at the 161 surface pollen sites by an interpolation method using the POLATION program. Six climatic parameters were estimated, i.e., annual mean temperature (TANN), mean temperature of the warmest month (MTWA), mean temperature of the coldest month (MTCO), annual mean precipitation (PANN), precipitation in January (PJAN) and precipitation in July (PJUL).

Table 1 Dating results of the Wulagai Gobi profile, Inner Mongolia

Sample No.	Depth (cm)	Date (cal. BP)
BA09634	10	1765±40
BA09635	50	11385±60
09G-279	70	22300±170
09G-280	150	30600±14 00
BA09636	215	33775±105
BA09637	317	35880±160
09G-281	250	36800±1800
09G-282	355	45100±2600
09G-283	405	51900±3000

Note: BA09634-BA09637 are samples used for ^{14}C Dating; 09G–279–09G–383 are samples used for OSL Dating.

3 Results

3.1 Palynomorph analysis

Pollen and spores are abundant between the depths of 150 cm and 405 cm, while only two samples contain sufficient pollen grains, spores, and algae above the depth of 150 cm. In total 59 taxa of palynomorphs (based on a total of 42778 grains and 856 in each sample on average), including 21 taxa of trees and shrubs, 26 herbs, 6 ferns together with 6 types of algae, were extracted from the WLG section. The dominant palynomorphs were identical throughout the section. With the exception of algae, *Artemisia* and Chenopodiaceae pollen were predominant. The pollen diagram showing the percentage values was produced using the TILIA program (Figs. 3 and 4). The whole section was divided into two zones, which were separated at the depth of 150 cm. Zone 1 was further divided into three subzones based on the results of cluster analysis by CONISS. The palynomorphs and their percentages (average values) of each zone are listed in Table 2.

Zone 1 (51.9–30.6 kaBP)

The 59 taxa extracted from the samples in Zone 1 consisted of 6 taxa of algae, 21 of trees and shrubs, 26 of herbs, and 6 of ferns. Algae very frequently appeared at percentages varying from 41.92% to 62.48%, and among those, *Botryococcus* colonies were predominant, followed by herbs with percentage values ranging from 33.11% to 55.33%, of which *Artemisia* and Chenopodiaceae were the most common taxa. Trees and shrubs were represented by only 3.84%–19.7% and ferns by as little as 0.04%–0.58%. According to the CONISS analysis, three subzones could be recognized in this zone.

Zone 1-1 (51.9–43.9 kaBP)

This subzone yielded a total of 40 taxa, comprising 5 algae (56.15%), 16 trees and shrubs (1.97%), 17 herbs (41.83%), and 2 ferns (0.04%). *Botryococcus* colonies occurred at percentages of 19.84%–78.26% (average of 50.13%). Zygospores of *Spirogyra* were present at lower percentages (0.25%–15.54%, average of 4.52%) than those in the other two subzones. The mean B/F (brackish species/ freshwater species) value in this period was 17.57. Of the

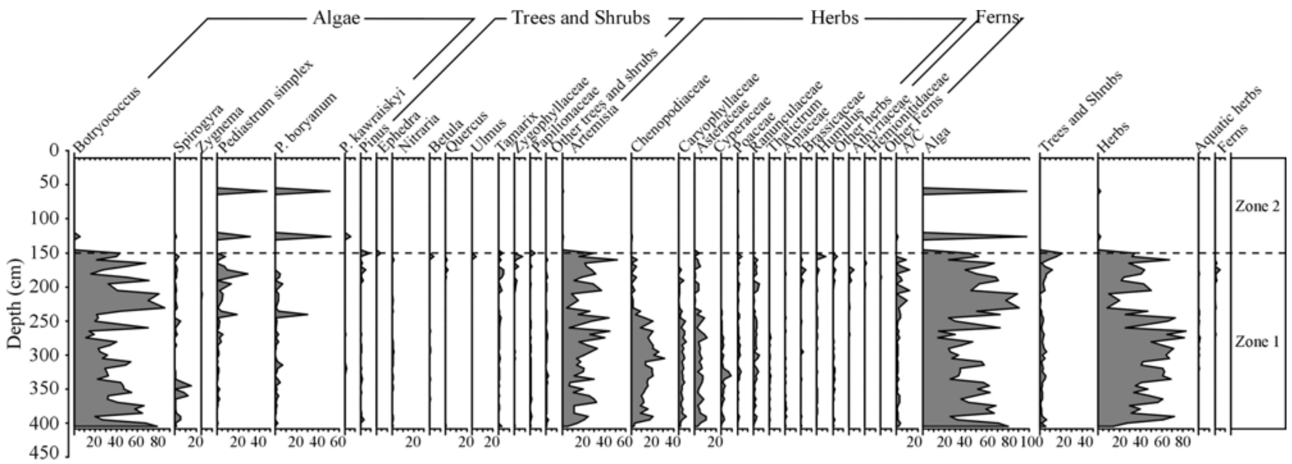

Fig. 3. Pollen diagram showing percentage values of the main taxa from the Wulagai Gobi profile, Inner Mongolia.

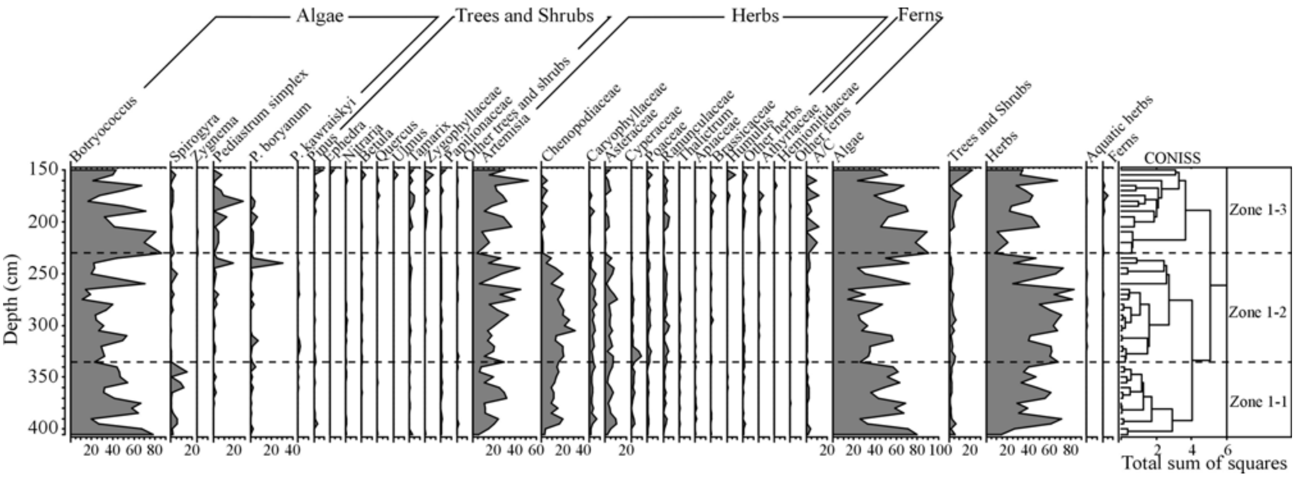

Fig. 4. Pollen diagram showing percentage values of Zone 1.

trees and shrubs, *Pinus* (0–3.14%, average of 0.65%), *Tamarix* (0–3.04%, average of 0.41%), and *Nitraria* (0–0.87%, average of 0.29%) were the most common taxa. *Artemisia* (5.22%–32.36%, average of 16.32%) and Chenopodiaceae (2.61%–20.37%, average of 11.73%) were the predominant herbaceous pollen, followed by Asteraceae (2.51%–10.63%, average of 5.23%). *Artemisia*/Chenopodiaceae ratios (A/C) averaged 1.73.

Zone 1-2 (43.5–35.9 kaBP)

The palynomorphs obtained from this subzone consist of 50 taxa, comprising 5 algae (41.92%), 18 trees and shrubs (2.66%), 24 herbs (55.33%), and 3 ferns (0.10%). Algae decreased during this period. *Botryococcus* colonies were still common, but showed an obvious decrease to 32.42% (range from 11.33% to 70.20%) compared with Subzone 1. *Spirogyra* also declined to 1.08% (0–7.84%), while three types of *Pediastrum* all increased with *P. simplex* and *P. boryanum* reaching peak values of 19.03% and 30.54%, respectively, at the end of this period. The B/F value decreased and averaged 13.7. Herbaceous pollens of *Artemisia* (6.45%–45.05%, average of 22.23%) and Chenopodiaceae (4.30%–31.65%, average of 16.04%) both increased compared to the previous subzone with an A/C value of 1.5 on average. Fern spores displayed a slight increase to 0.10%.

Zone 1-3 (35.6–30.6 kaBP)

Thirty-nine palynomorphs including 5 taxa of algae (62.48%), 12 trees and shrubs (3.84%), 19 herbs (33.11%), and 3 ferns (0.58%) were identified in this subzone. *Botryococcus* colonies increased to 62.48% (16.39%–85.95%), which was the highest value within Zone 1. *Zygnema* spores only appeared in this subzone at percentages of 0–0.64% (average of 0.11%). Among *Pediastrum* coenobia, *P. simplex* showed an increase to 6.10% (0–28.69%), while *P. boryanum* dropped to 1.89% (0–6.76%), and *P. kawraiskyi* disappeared altogether. The mean value of B/F dropped abruptly to 5.06. Of the herbaceous pollens, *Artemisia* slightly increased to 23.75% (4.13%–52.11%) but Chenopodiaceae displayed an abrupt drop to 2.10% (0–5.63%), which led to an obvious rise in the A/C value (4.19 on average). The percentage of fern spores increased to 0.58% with the

Table 2 Palynomorphs and their percentages of each zone in the Wulagai Gobi profile, Inner Mongolia

Taxa	Zone 1			Zone 2
	1	2	3	
Algae				
Botryococcus	50.13	32.42	53.07	3.35
Spirogyra	4.52	1.08	1.31	0.96
Zygnema	\	\	0.11	\
Pediastrum simplex	0.62	3.31	6.1	38.28
P. boryanum	0.82	4.71	1.89	51.67
P. kawraiskyi	0.06	0.38	\	3.35
Trees and shrubs				
Pinus	0.65	0.5	0.63	\
Picea	\	0.01	\	\
Tsuga	0.01	\	\	\
Abies	0.03	0.01	\	\
Ephedra	0.04	0.04	0.05	\
Tamarix	0.41	0.9	1.68	\
Castanea	0.01	0.02	\	\
Castanopsis	0.1	0.1	0.05	\
Oleaceae	0.04	0.04	0.16	\
Quercus	0.06	\	0.21	\
Ulmus	\	\	0.05	\
Juglans	\	0.01	0.11	\
Alnus	0.03	0.06	\	\
Corylus	\	0.02	\	\
Betula	0.07	0.28	0.16	\
Celtis	0.01	0.06	0.11	\
Ilex	0.07	0.14	\	\
Nitraria	0.29	0.37	0.11	\
Stellera	\	0.02	\	\
Caprifoliaceae	0.1	0.04	\	\
Zygophyllaceae	0.01	0.04	0.53	\
Herbs				
Artemisia	16.32	22.23	23.75	0.96
Chenopodiaceae	11.73	16.04	2.1	0.48
Caryophyllaceae	2.86	3.94	0.58	\
Asteraceae	5.23	5.52	1.84	\
Poaceae	0.6	1.46	0.84	0.96
Ranunculaceae	1.53	2.55	2.36	\
Polygonaceae	0.25	0.1	0.16	\
Gentianaceae	0.21	0.28	\	\
Araliaceae	0.06	0.09	\	\
Thalictrum	0.29	0.43	\	\
Cyperaceae	1.4	1.46	\	\
Papilionaceae	0.49	0.38	0.21	\
Lilium	0.15	0.1	0.05	\
Sanguisorbae	0.04	0.06	0.05	\
Apiaceae	0.4	0.24	0.05	\
Rosaceae	\	0.03	0.05	\
Brassicaceae	0.04	0.1	0.42	\
Humulus	0.24	0.1	0.37	\
Typha	\	0.13	0.05	\
Sparganium	\	0.02	\	\
Rubiaceae	\	0.02	0.05	\
Lamiaceae	\	0.01	\	\
Convulvulaceae	\	0.01	\	\
Urticaceae	\	\	0.05	\
Papaveraceae	\	\	0.05	\
Euphorbiaceae	\	0.02	0.05	\
Ferns				
Athyriaceae	0.03	0.09	0.42	\
Selaginellaceae	\	\	0.05	\
Pteris	\	0.01	\	\
Ceratopteris	\	0.01	\	\
Gymnogrammaceae	\	\	0.11	\
Dennstaedtiaceae	0.01	\	\	\

main component being Athyriaceae (0–4.65%, average of 0.58%).

Zone 2 (30.6–0 kaBP)

In Zone 2 (30.6–0 kaBP), two samples at depths of 125 cm (WLG-53) and 60 cm (WLG-65) yielded only eight taxa of palynomorphs of which most were algae (five algae, i.e., *Botryococcus*, *Spirogyra*, *Pediastrum simplex*, *P. boryanum*, and *P. kawraiskyi*; three sporomorphs of *Artemisia*, Chenopodiaceae, and Poaceae). The vast majority of the palynomorphs were algal spores with percentages as high as 97.39% and 97.87%, respectively. *Botryococcus* appeared in the sample from WLG-53 at a percentage of only 6.09%, which was far less than that observed in the sample from Zone 1, and it had disappeared by WLG-65. *Pediastrum* was the most common taxon in the two samples, including *P. simplex* (31.30% in WLG-53; 46.81% in WLG-65), *P. boryanum* (52.17%; 51.06%), and *P. kawraiskyi* (6.09% in WLG-53, none in WLG-65).

3.2 Algae in the paleolake

The remains of algae are considered to be important and useful for paleoecological interpretations as indicative of the depth, salinity, temperature, pH value, and nutrient status parameters of aquatic paleoenvironments (Jankovská and Komárek, 2000; Komárek and Jankovska, 2001; Medeanic et al., 2003; Tell and Zamaloa, 2004; Zamaloa and Tell, 2005; Medeanic, 2006). In total six taxa of algae were identified in this study.

Botryococcus

Botryococcus mainly occurs in temperate and tropical regions, and is one of the most common palynomorphs of coccal algae in lagoonal and lacustrine sediments (Medeanic, 2006). It is more widespread in brackish water basins than other green algae and is usually abundant in shallow water pools in areas with little precipitation (Guy-Ohlson, 1992). The predominance of *Botryococcus* usually indicates shallow water and clear, mesotrophic conditions (Reynolds et al., 2002; Medeanic et al., 2003).

Pediastrum

Coenobial green algae of *Pediastrum* has been recorded all over the world in a great number of studies (e.g., Komárek and Jankovska, 2001; Rull et al., 2008; Whitney and Mayle, 2012). It is largely used as a biological indicator of freshwater paleoenvironments and temperate (or warm) climate (Zamaloa and Tell, 2005), but can occur in a wide range of environmental conditions (Batten, 1996). *Pediastrum* species are highly sensitive to changes in salinity and depth of the water body, and are common in hard-water eutrophic lakes (Nielsen and Sorensen, 1992; Jankovská and Komárek, 2000). The alga *Pediastrum* is considered to indicate a large water body and high levels of precipitation. Sun and Wu (1987) pointed out that *Pediastrum* grows at a water depth of more than 6 m, while Wan (1992) considered that the water depth where *Pediastrum* grows is no deeper than 15 m. Species of *Pediastrum* can be differentiated in paleoecological studies (Komárek and Jankovska, 2001). In this study, three species of coenobia were found. *P. simplex* is an indicator of deeper water (Whitney and Mayle, 2012). *P. boryanum* is reported to be cosmopolitan and a generalist, and therefore, thought to be a poor indicator of past environmental conditions (Komárek and Jankovska, 2001). Its occurrence with the macrophyte-associated taxa *P. argentiniense* and *P.* cf. *angulosum* might suggest that it is associated with shallow water, but this cannot be confirmed because of the limited modern dataset (Whitney and Mayle, 2012). *P. kawraiskyi* evidently indicates oligotrophic lakes and ponds with water plants, and cold and clear water (Komárek and Jankovska, 2001).

Zygnemataceae

Zygnemataceae are widely distributed throughout the world except for Antarctica, especially the three genera *Spirogyra*, *Zygnema*, and *Mougeotia*, which constitute 85% of the 784 described species in the family (Hoshaw and McCourt, 1988). Zygospores of both *Spirogyra* and *Zygnema* were found in this study, and their occurrence indicates shallow, eutrophic freshwater, with warm pluvial periods that supplied fluvial sediments (Van Geel et al., 1989; Medeanic, 2006). Hoshaw (1968) pointed out that the optimal growth temperature for *Zygnema* is 15–20°C, and for *Spirogyra* is over 20° C. For most of the Zygnemataceae species their optimal temperature lies between 14 and 22°C. A pH value of 7.0–8.0 was inferred from the zygospores of *Spirogyra* (Grote, 1977).

3.3 Quantitative reconstruction of climate

Quantitative reconstruction was obtained through the Best Analogues Method by the POLYGON program. Variance/Covariance matrix type for principal component analysis (PCA), which is also known as empirical orthogonal function (EOF) analysis, was chosen. The envelope analysis, which starts with EOF analysis, was performed by applying POLYGON. The fossil pollen spectra lie within the area covered by the surface pollen dataset, which (theoretically) illustrates that the results are reliable.

Six meteorological parameters were deduced from the results of pollen analysis in Zone 1 using the Best Analogues Method and the curves of these meteorological data are listed in Table 3 and shown in Fig. 5. Zone 2, as mentioned previously, is not suitable for quantitative analysis as only a few taxa were detected. For a better comparison with the qualitative reconstruction results, the boundaries of the three subzones in Zone 1 are indicated by a dashed line. The mean value of TANN is 11.6°C, 12.3° C, and 11.8° C for Zone 1-1 to Zone 1-3, respectively. PANN values are 295.3 mm, 279.7 mm, and 317 mm. The data shows that the changing trends corresponded well with the results of qualitative reconstruction.

The correlation coefficients between reconstructed and observed values are shown in Table 4. Based on the results, correlation coefficient of PJAN is especially low and we consider the reconstructed data unreliable. The

Table 3 The reconstructed values of six meteorological parameters based on palynomorphs in Zone 1

Age (kaBP)	TANN (°C)	MTWA (°C)	MTCO (°C)	PANN (mm)	PJAN (mm)	PJUL (mm)
30.6	11.5	27.8	−7.3	354.2	2.1	93.1
30.9	10.2	26.9	−9.1	360.4	2.1	99.7
31.2	11.4	28.4	−8.2	307.9	1.9	80.3
31.5	11.7	28.4	−7.6	326.5	2	84.3
31.8	12	28.4	−6.9	346.5	2.1	87.9
32.2	11.6	27.8	−7.2	358.3	2	94.2
32.5	11.3	28.3	−8.3	311.4	1.9	81
32.8	13	29.1	−5.4	310.6	1.7	78.7
33.1	11.3	27.8	−7.7	304.4	1.8	81
33.4	12.1	28.4	−6.7	338.9	2	88.1
34	11.3	28.4	−8.3	309.9	1.9	80.5
34.3	12.6	28.8	−5.8	304	2	75.6
34.9	11.1	28.4	−8.8	273.3	1.7	72.3
35.6	13.6	29.4	−4.7	232	1.6	55.1
35.9	13.6	29.2	−4.3	316.1	2.1	78
36.2	12.4	28.7	−6.3	314.8	2	79.6
36.5	13.3	29.2	−4.8	328.2	1.9	81.1
36.8	11.1	28	−8.2	284.3	1.7	75.6
37.6	11.5	28.2	−7.5	261.3	1.5	69.3
38	16.5	31.1	−0.1	228.3	1.7	50
38.4	11.9	28.4	−6.8	280.4	1.6	72.7
38.8	12.7	28.8	−5.8	288.2	2	74
39.2	10.5	27.7	−9	272.1	1.5	74.7
39.6	11.5	28.3	−7.6	265.4	1.6	69.9
40	12.9	28.9	−5.4	275	1.8	71.1
40.4	11.4	28.2	−7.8	264.2	1.5	69.8
40.8	11.5	28.3	−7.7	250	1.5	66.2
41.1	14.1	29.6	−3.4	267	1.9	65.8
41.5	11	27.9	−8.4	287.6	1.7	77
41.9	10.3	27.5	−9.4	286.9	1.6	78.9
42.3	11	28	−8.4	266	1.5	70.8
42.7	11	27.9	−8.3	259.6	1.5	70.7
43.1	9.9	27.1	−9.8	311.2	1.7	88.7
43.5	12.6	28.6	−5.7	286.8	1.6	73.8
43.9	10.9	27.8	−8.2	288	1.8	80.3
44.3	12.5	28.8	−5.8	272.7	1.9	72.8
44.7	12.2	28.5	−6.5	277.4	1.7	71.9
45.1	10.2	27.5	−9.4	277.2	1.5	77
45.8	13.4	29.3	−4.8	281.1	2	69.6
46.5	12.8	28.8	−5.6	286.8	2	73.4
47.1	13.5	29.4	−4.6	306.9	1.8	74.8
47.8	11.7	28.3	−7.2	269.8	1.6	69.7
48.5	9.6	27.2	−10.3	290.2	1.6	80.7
49.2	10.2	27.4	−9.4	308.6	1.7	85.3
49.9	10.2	27.4	−9.4	304.4	1.7	84
50.5	10.3	27.3	−9.1	322.8	1.7	89.7
51.2	11.1	27.8	−8.2	365.6	2.2	95
51.9	13.3	28.8	−4.6	282.6	1.6	71.9

Note: TANN = annual mean temperature; MTWA = mean temperature of the warmest month; MTCO = mean temperature of the coldest month; PANN = annual mean precipitation; PJAN = precipitation in January; PJUL = precipitation in July.

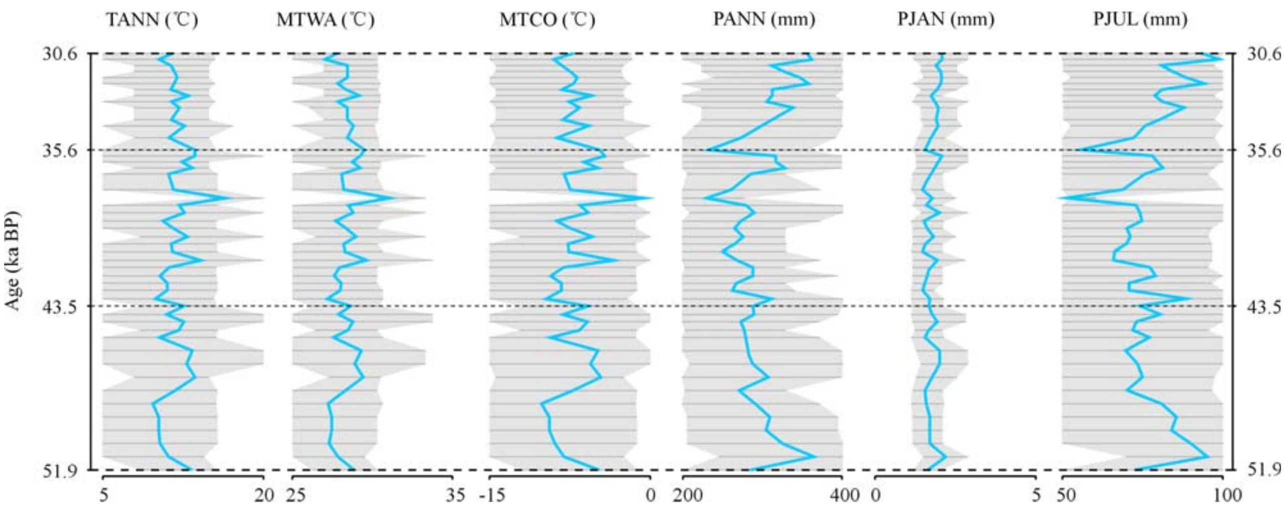

Fig. 5. Climate reconstruction based on the Best Analogues Method in the Wulagai Gobi area, Inner Mongolia.
The black curve is the raw reconstruction data; the gray line indicates the conventional error bars; the black dashed-lines show the boundary of the three sub-zones in Zone 1. TANN = annual mean temperature; MTWA = mean temperature of the warmest month; MTCO = mean temperature of the coldest month; PANN = annual mean precipitation; PJAN = precipitation in January; PJUL = mean precipitation in July.

Table 4 Correlation coefficients between reconstructed and observed values

	TANN	PANN	MTWA	MTCO	PJUL	PJAN
R1	0.9908	0.9508	0.9864	0.986	0.8818	0.9709
R2	0.6016	0.5702	0.5671	0.6061	0.5294	0.1342

Note: R1 is the correlation coefficient between observed values and estimated values; R2 is the correlation coefficient between estimated values and reconstructed values.

other reconstructed results are all higher than 0.50 (which usually denotes moderate correlation) and are considered convincing.

4 Discussions

In China, steppe or grassland vegetation already developed to the north of the Yangtze River during the middle-late Miocene cooling (Jiang and Ding, 2009). Herbs and shrubs became dominant in Inner Mongolia then. The change in the biological component (i.e., vegetation) can reflect the climatic (e.g., precipitation and temperature) fluctuations. Moreover, the green algae found in the profile can reveal the ecological conditions of the water body, as well as the water level of the lake.

Of the palynomorphs, Chenopodiaceae shows negative correlation coefficients with mean annual precipitation, and can be used as an indicator of regional moisture regimes. *Artemisia*, like Chenopodiaceae, grows in open, continental sites with a Mediterranean rainfall regime, but requires more moisture (El-Moslimany, 1990). A/C (*Artemisia*/Chenopodiaceae) values are indicative of potential humidity in semi-arid and arid areas, and lower values of A/C usually denote drier conditions (El-Moslimany, 1990; Van Campo et al., 1996; Cour et al., 1999).

Botryococcus colonies are more common in brackish water, while *Pediastrum*, *Spirogyra*, and *Zygnema* species are mostly found in freshwater as mentioned in Section 3.2. The ratio of brackish species to freshwater species (B/F) is therefore indicative of the degree of salinity.

4.1 Vegetation and climatic history

We reconstructed the paleovegetation (Fig. 6) based on the palynomorphs extracted from the sediment. The pollen assemblages suggest an arid to semi-arid grassland around Wulagai Gobi. Trees and shrubs are extremely uncommon throughout the section. The water body conditions and the water level fluctuations were inferred from the green algal component in the palynomorphs. Climatic parameters estimated by the Best Analogues Method provide us with an opportunity for reconstructing the climate in the Wulagai Gobi area since 51.9 kaBP. Both the vegetation succession and climatic changes of each zone (or subzone) will be discussed separately.

Zone 1-1 (51.9–43.9 kaBP)

The dominance of algae indicates that the lake or a water body was already in existence at 51.9 kaBP. *Botryococcus* and *Spirogyra* were the most abundant algal taxa. Considering the habitat of these two algae, the water temperature must have been around 20–22°C and the water was probably shallow enough to allow the water temperature to rise that high. The pH value of the water was about 7.0 to 8.0. Grassland vegetation developed around the lake, which mainly consisted of *Artemisia*, Chenopodiaceae, Asteraceae, and Caryophyllaceae. The A/C value is relatively low, indicating that the climate was warm and arid, which is further confirmed by the B/F value.

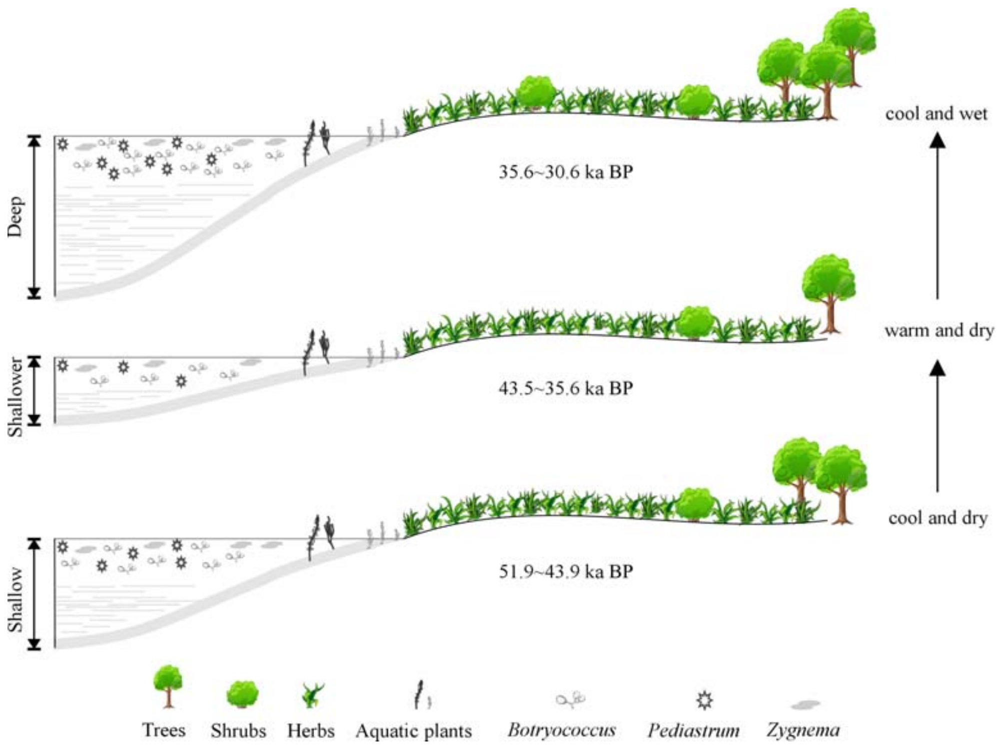

Fig. 6. Reconstruction of the vegetation in and around the paleolake of Wulagai Gobi during 51.9 to 30.6 kaBP.

The reconstructed values of TANN first experienced a decrease from 13.3°C to 9.6°C at 48.5 kaBP in this subzone, but recovered afterwards and increased to 13.6°C at 47.1 kaBP followed by a slight decrease to 10.9°C at the end of this subzone (43.9 kaBP). The PANN value was 282.6 mm at the bottom, but quickly increased to 365.6 mm. After that the precipitation slowly decreased to 288 mm at the end of the subzone. Generally speaking, the climate reflected by the results of quantitative reconstruction was tending to be cool and dry from 51.9 ka to 43.9 kaBP.

Zone 1-2 (43.5–35.9 kaBP)

Algae decreased as the herbaceous pollen increased during the period 43.5–35.9 kaBP. The reduction in *Botryococcus* and *Spirogyra* suggests that the precipitation at this stage was lower than during Zone 1-1. The surrounding vegetation did not change much compared to the former period, and A/C and B/F values did not show significant variations. The climate would appear to have been drier than that in Zone 1-1.

During this period, TANN and PANN both fluctuated frequently. At the beginning of the subzone TANN was 12.6°C, but increased slightly to 13.6°C by the end of Zone 1-2. During this period, the climate experienced two warm periods at 41.1 kaBP (14.1°C) and 38.0 kaBP (16.5°C), and three cooler phases at 43.1 kaBP (9.9°C), 41.9 kaBP (10.3°C) and 39.2 kaBP (10.5°C). At first PANN values slightly decreased, then increased sharply at the end, reaching 316.1 mm, which is 29.3 mm higher than that at the beginning. At 38.0 kaBP, the precipitation even dropped to 228.3 mm. The climatic trend was towards warmer and even drier conditions from 43.5 ka to 35.9 kaBP.

Zone 1-3 (35.6–30.6 kaBP)

Algae and woody plants both occurred at higher frequencies, while herbs decreased to lower levels. Concurrently, diversity increased in this zone. The vegetation changed from steppe to meadow grassland. *Pediastrum simplex* became more abundant compared to that in the former two periods. This suggests that the water was much deeper than before, which is confirmed by the abrupt decrease in the B/F value. *Zygenema* only appear in this subzone, which denotes cooler climate than that in the former two periods. Chenopodiaceae decreased considerably, leading to an abrupt increase in the A/C value, indicating an increase in humidity. Ferns displayed a higher frequency than before, which can also be attributed to a higher humidity. On the whole, the climate between 35.6–30.6 kaBP was cool and humid, attaining the highest humidity in Zone 1.

TANN values show a decreasing trend from 13.6°C to 11.6°C, while PANN was 232 mm at the beginning but increased to 354.2 mm at the end. These parameters also prove that the climate tended to be cool and humid in this subzone, which represents the most humid period of Zone 1.

Zone 2 (30.6–0 kaBP)

This zone is characterized by the disappearance of most of the palynomorphs in the majority of the samples. Only eight taxa were identified, including five algae (*Botryococcos*, *Spirogyra*, *Pediastrum simplex*, *P. boryanunum*, and *P. kawraiskyi*) and three sporomorphs (*Artemisia*, Chenopodiaceae, and Poaceae) in samples WLG-53 and WLG-65. Although only few pollen types were found in the samples, it does not mean that there was no vegetation. The vegetation at this period could have been simpler, of a xerophytic nature, i.e., *Artemisia*, Poaceae, because of a decrease in the precipitation. Nevertheless, this could still not explain the comparative rarity of pollen grains in the sediments. The most reasonable explanation for this phenomenon would be that the lake regularly dried up since the beginning of this period. Although the annual rainy season normally coincides with the growing season of the plants, it is also the warmest period in a year. Considering the vegetation type (no arboreal canopy) and climatic features (normally with strong winds), the evaporation and transpiration rates would be very high. Hence, it is not surprising that the lake dried up during the flowering season of the plants and thus few pollen grains were detected in the sediments. Campbell (1991) inferred that pollen grains can be easily damaged by oxidation and desiccation during fluvial transport. That might be another possibility for the lack of pollen. On the other hand, green algae can multiply in large numbers in a short time in shallow water when the environmental conditions are suitable. At the time the two samples with abundant algae and few pollen grains were deposited, the lake must still have had some water. In those samples without any algae or pollen the sediments may have dried out and became oxidized after their deposition. Another possibility for the absence of microfossils after 30.6 kaBP is the unfavorable climate which was also recorded in other studies. A research on the Dunde ice core showed that the temperature dropped abruptly after 31 kaBP and entered MIS 2 (Thompson et al., 1990). Liu et al. (2012) also pointed out that the climate turned to cool and dry since 29 kaBP in Shuidonggou. In addition, the coldest sea surface temperatures of Lakshadweep Sea were observed at 32–25 kaBP (Mahesh et al., 2011). During 35.6 to 30.6 kaBP, the climate became colder and there was a great increase in precipitation, which provided favorable conditions for the expansion of the glacier.

As there are only two samples containing a few taxa from this period, it would be senseless to carry out the Best Analogues Method. The quantitative climatic parameters are therefore unknown for this period.

4.2 Climatic comparison with other records

The last glacial period (73.5–14.7 kaBP) recorded in the ice core happened almost simultaneously throughout the world and is marked by an abrupt drop in the temperature (Lorius et al., 1985; Anklin et al., 1993; Thompson et al., 1997). In different regions, the climatic changes during this period had global characteristics, but regional features such as slight differences in timing and variability also existed.

TANN and PANN are the most critical climatic parameters for plants. The changing curves from 51.9 to 30.6 kaBP in Inner Mongolia are shown in Fig. 5. Temperatures during this period were about 2.9–9.8°C higher than today, which indicate the occurrence of warm phases during the last glacial period. Many studies have proved that between 58 kaBP and 30 kaBP, the temperature was even higher (Paterson et al., 1977; Lorius et al., 1985; Anklin et al., 1993; Grootes et al., 1993; Thompson et al., 1997; Yao et al., 1997) and more humid than that at present (Zheng et al., 2011). At 38 kaBP, the climate was at its warmest, which as Winograd (2001) pointed out, resulted in a decrease in the ice volume at 35 kaBP. The PANN we reconstructed were mostly higher (maximum 87.2 mm higher) than at present, but the values are all lower than 400 mm. Therefore, we assume that the Wulagai Gobi area was already within the arid to semi-arid region but that the summer monsoons were stronger than today. Two relatively humid periods were observed during 51.9 to 47.8 kaBP and 35.6 to 30.6 kaBP. The humid period between 35.6 and 30.6 kaBP, which has also been recorded in other places in China, was characterized by a high water level, which suggests a strong summer monsoon (Li et al., 1991; Rhodes et al., 1996; Zheng et al., 2005).

Isotopic fractionation of the heavier oxygen-18 (^{18}O) and deuterium (D) in snowfall are temperature-dependent, so the isotopic content ($\delta^{18}O$ and δD) and the annual mean temperature display a positive linear correlation. For a better comparison with other paleorecords in the world, our TANN curve between 51.9 and 30.6 kaBP was compared with δD records from Vostok, Antarctica (Petit et al., 1999), $\delta^{18}O$ records from GISP2, Greenland (Brook et al., 1996), Hulu Cave, SE China (Wang et al., 2001), and Guliya, Tibetan Plateau (Thompson et al., 1997) in Fig. 7 and five phases could be recognized, which are marked with different colors. Generally speaking, from 51.9 to 30.6 kaBP, the annual mean temperature recorded at all five sites experienced cyclical changes, albeit with differences in timing. Our results are well matched with records in Antarctica and Greenland. The first decrease in temperature occurred at about 48.5 kaBP in Inner Mongolia with a drop of 2.9°C from 51.9 kaBP. A similar

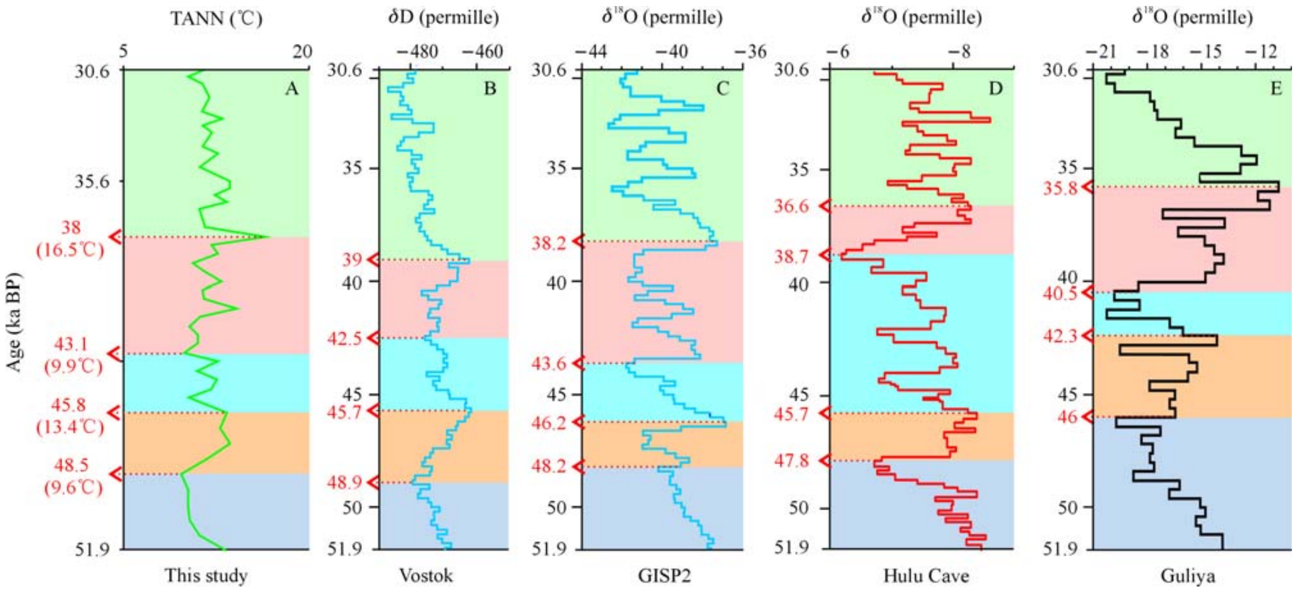

Fig. 7. Comparisons between the annual mean temperature reconstructed in Inner Mongolia and other paleorecords during 51.9 to 30.6 kaBP.

(a), curve of TANN (annual mean temperature) achieved in this study; (b), δD records from Vostok, Antarctica (Petit et al., 1999); (c), δ^{18}O curves from GISP2, Greenland (Brook et al., 1996); (d), δ^{18}O curves from Hulu Cave, East China (Wang et al., 2001); (e), δ^{18}O curves from Guliya, Tibetan Plateau (Thompson et al., 1997). Five phases were divided using different colors based on the changing trend.

decrease occurred at 48.9 kaBP and 48.2 kaBP in Antarctica and Greenland, respectively. During the second phase, the temperature recovered and increased by 13.4°C at 45.8 kaBP, while the turning point happened in Antarctica at 45.7 kaBP and on Greenland at 46.2 kaBP. During the third period, the climate became cooler again and reached a low point at 43.1 kaBP with a temperature decline of 9.9°C, which occurred in the other two records at 42.5 kaBP and 43.6 kaBP, respectively. Another warm period subsequently occurred at 38 kaBP (increased to 16.5°C), while the same event occurred in Antarctica at 39 kaBP and on Greenland at 38.2 kaBP. During the final phase, all the places experienced a climatic cooling, which in our case consisted of a 2°C decrease.

Although the timing of the other two curves shows considerable differences, the changing trends coincide with our results. The δ^{18}O values were obtained from stalagmites in Hulu Cave. Hulu Cave, being located near the North Pacific Ocean, is under the control of the summer monsoon. The climate is warmer and more humid than that at other places. The decrease in temperature reflected by δ^{18}O was slower and therefore the timing was different. However, the first decrease in temperature happened at about 47.8 kaBP, which approximates our results. The Tibetan Plateau is assumed to be sensitive to climatic changes. However, the comparison shows that the knickpoints appeared later here than that at other places. The different indices used such as pollen, δ^{18}O, and δD, were sampled from profile, ice core, and stalagmites, which can surely cause the timing differences to some extent. The climate can be influenced by the topography, geomorphology, ocean current, monsoon, etc. Under the control of the global climatic change, typical regional characteristics of climate also existed in different study areas. Those may lead to the time differences when reacting to the global climate. Furthermore, the dating errors based on different materials and methods would also cause the timing differences, more or less.

5 Conclusions

The palynological study of Wulagai Gobi enables us to reconstruct the paleovegetation and paleoclimate in Late Pleistocene.

(1) The vegetation was arid to semi-arid grassland with minor changes throughout the profile. Trees and shrubs were rare. The presence of abundant algae in most of the samples provided information about the water body. By combining the pollen and algae, a more complete picture of the paleoenvironment of Wulagai Gobi area is achieved.

(2) At 51.9 kaBP, the lake or water body to some extent already existed in Wulagai Gobi area. It experienced three phases of shallow, much shallower, and deeper from 51.9 to 30.6 kaBP. Annual or seasonal drying up happened after 30.6 kaBP.

(3) Quantitative climatic parameters estimated by using the Best Analogues Method provide us with an opportunity to reconstruct the climate in more detail. Our results of the TANN indicate that during 51.9 to 30.6 kaBP, the annual temperature was higher than that at

present in the study area. Combining this evidence with the PANN values, the area would appear to have experienced three climatic regimes: first a cool dry, then a warm dry, and finally a cool humid climate.

(4) Our results show that the PANN values were mostly higher than that at present but all were lower than 400 mm. This infers that the Wulagai Gobi area was already within the arid to semi-arid region, but the summer monsoon was fractionally stronger than today.

(5) The reasons for the absence of pollen grains after 30.6 kaBP are also discussed. One possibility is the unfavorable climate for the development of the vegetation. The other explanation, which seems more reasonable, is that the pollen grains were easily damaged by oxidation and desiccation because of the phasic drying up of the lake.

(6) The changing trend of the TANN curve is consistent with other climatic records from Antarctica, Greenland, Hulu Cave, and the Tibetan Plateau during the last glacial period, although there were slight differences in the timing. We presume that those differences were most likely correlated with the sensitivity of different regions and indices used as paleorecords. Furthermore, the existing of dating errors can also cause timing differences. Our results further proved that palynological studies are applicable to high resolution climatic research, at least in the Quaternary Era.

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Plate I

1, *Nitraria*; 2, *Artemisia*; 3, Asteraceae; 4, Ranunculaceae; 5, Apiaceae; 6, Poaceae.

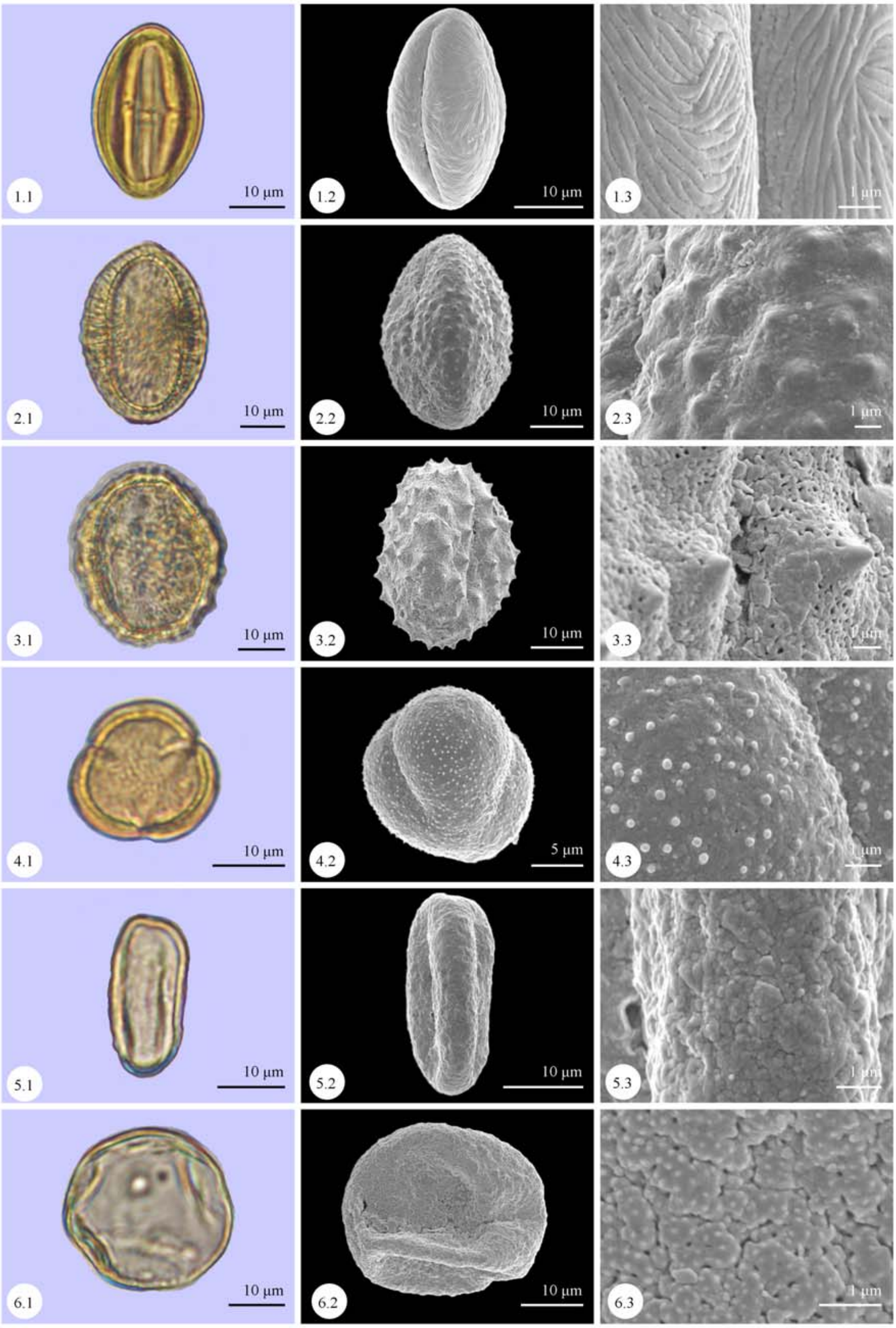

Plate II

1, *Alnus*; 2, Liliaceae; 3, Chenopodiaceae; 4, Caryophyllaceae; 5, *Polygonum*; 6, *Sanguisorba*.

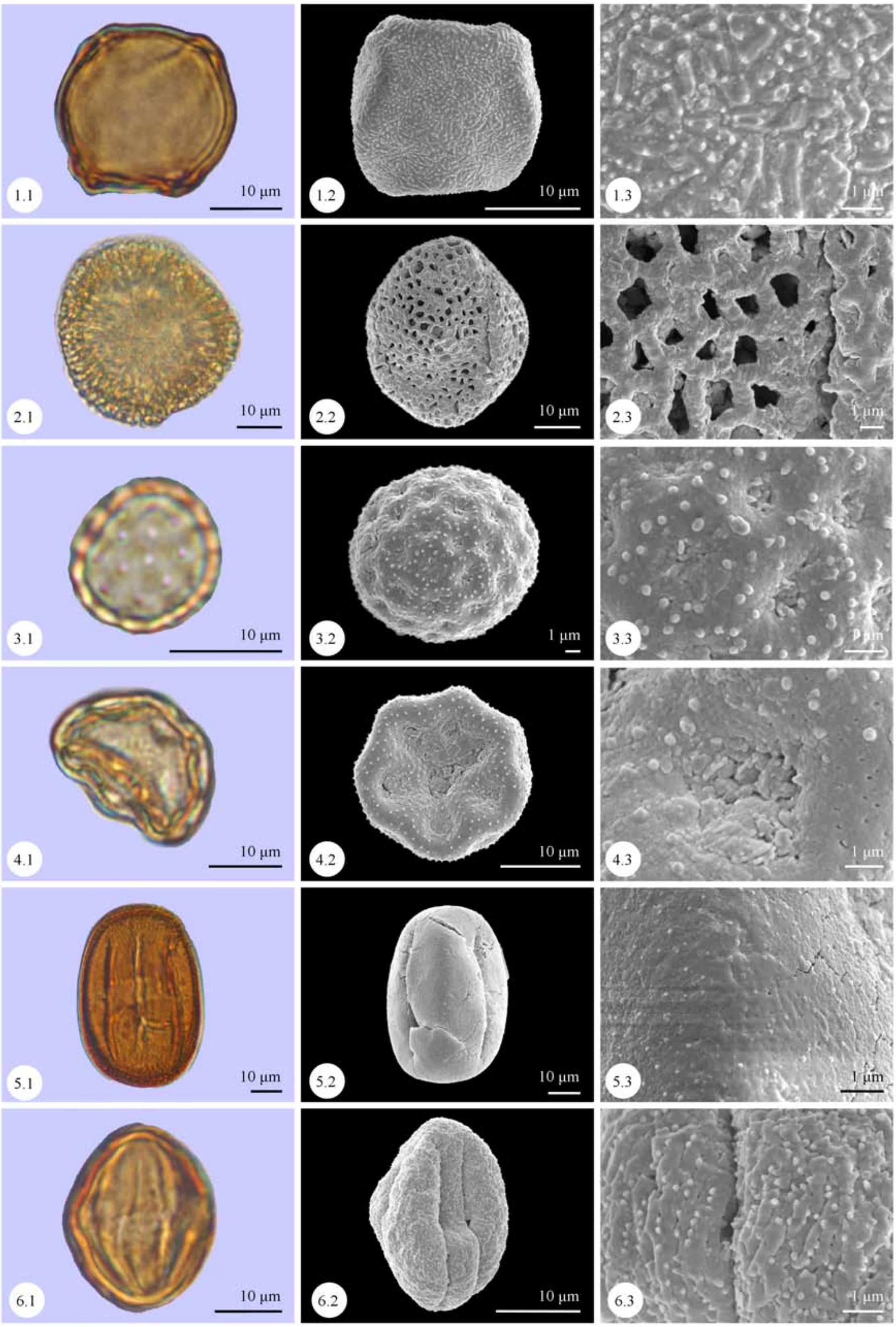

Plate III

1, *Pinus*; 2, *Ephedra*; 3–4, *Pediastrum*; 5, *Botryococcus*; 6, *Spirogyra*.