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Mineral magnetism of lacustrine sediments and Holocene palaeoenvironmental changes in Dali Nor area, southeast Inner Mongolia Plateau, China

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Abstract

Mineral-magnetic measurements and analysis of total organic carbon (TOC) and carbon/nitrogen (C/N) were performed on two AMS ^{14}C-dated lacustrine sequences recovered from Xiaoniuchang and Jiangjunpaozi (~ 42°N, 117°E). The two sites lie in the Dali Nor area of southeast Inner Mongolia Plateau where the semi-humid climate transforms into a semi-arid one. SIRM, low-frequency magnetic susceptibility (χ_{lf}), IRM_{20mT}, HIRM and IRM_{20mT}/SIRM may largely reflect the erosion of catchment materials and dilution effect of organic matter on deposited magnetic minerals. IRM_{-100mT}/SIRM and IRM_{-300mT}/SIRM likely indicate the aeolian activities. SIRM/χ_{lf} positively correlated to sand percentage of sediments is diagnostic of changes of lake levels or effective humidity. Complemented by the data of TOC and C/N and of previously accomplished analyses of grain-size, loss-on-ignition (LOI) and pollen, the variations in mineral magnetism reveal Holocene palaeoenvironmental changes. Conditions were quite dry and cool before 9970 years BP and then humidified in Jiangjunpaozi. The effective humidity maximised prior to ~ 8000 years BP and subsequently declined in the two sites. The less wet but warmer conditions persisted in Jiangjunpaozi until 6600 years BP and Xiaoniuchang until 5600 years BP. Deterioration occurred since then and culminated during 4300–1300 years BP in Jiangjunpaozi and 3000–730 years BP in Xiaoniuchang, which was followed by a moderate but probably very short amelioration in the two sites.

Keywords: Holocene; Magnetism; Environment; Lake sediments; Inner Mongolia China

1. Introduction

Landscapes in climatic and vegetational transition zones are usually particularly sensitive to climatic changes (e.g., Clarke and Rendell, 1998; Peck et al., 2002). In north-central China, the southeast edge of the Inner Mongolia Plateau is such a zone where, from the southeast to northwest, the temperate broad-leaved forest is gradually replaced by the steppe (Fig. 1) with the transformation from a semi-humid climate to a semi-arid one. The Dali Nor (Dalang-nur or Dalainoer) area (42°00′–43°45′N, 115°45′–117°45′E) falls largely in this transitional zone (Fig. 1). In planning global-change investigations in the framework of PEP II, Zhang and Yang (1995) suggested that further studies should be concentrated particularly on the three transects, NECT (~ 43°30′N), CENT 1 (109°30′–

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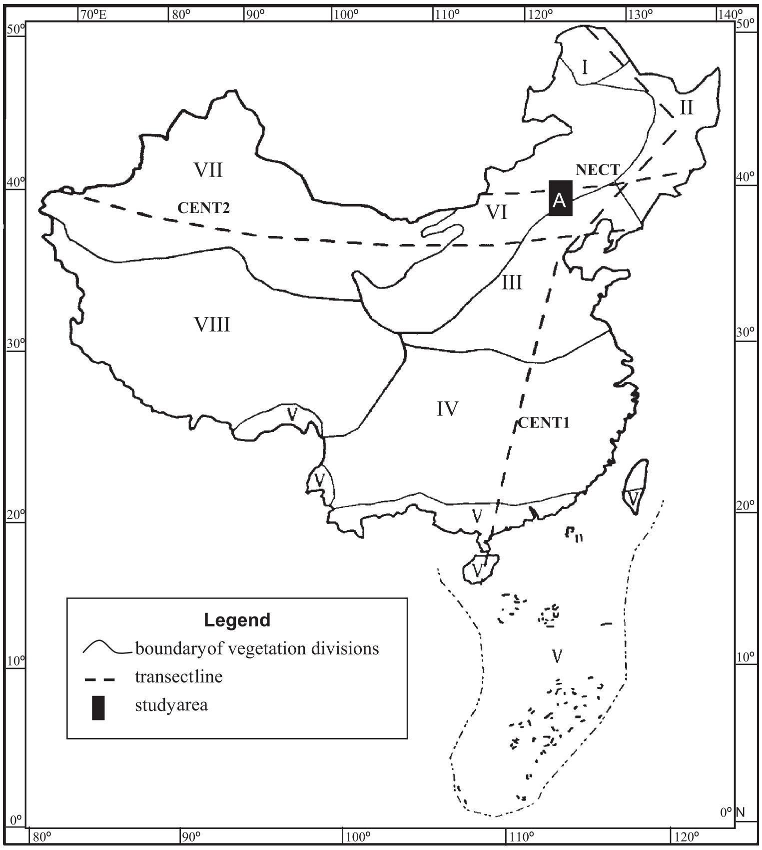

Fig. 1. Vegetation divisions of China (after Wu, 1995, attached map 1). Study area (Dali Nor area) shown, NECT, CENT 1 and CENT 2 identify three transects on which global-change investigations are concentrated in China within the framework of PEP II. (I) Cold temperate coniferous forest, (II) temperate coniferous and broad-leaved mixed forest, (III) temperate deciduous broad-leaved forest, (IV) sub-tropical evergreen broad-leaved forest, (V) tropical rainforest and monsoon forest, (VI) temperate steppe, (VII) temperate desert, (VIII) Qinghai–Tibet Plateau highland vegetation.

128°00′E, 18°44′–53°00′N) and CENT 2 (40°00′N) in China (Fig. 1). The Dali Nor area is closely proximal to the intersect of the three (Fig. 1) and hence regarded as one of the very significant regions for understanding environmental change in north-central China.

During the last two decades, investigations on the Quaternary palaeoenvironments have been carried out in the Dali Nor area (e.g., Geng and Zhang, 1988; Cui et al., 1997) and, more broadly, in the whole southeast Inner Mongolia Plateau (e.g., Wang and Feng, 1991; Liu and Li, 1992; Bernasconi et al., 1997). More recently, Liu (1998) and Liu et al. (2002) completed AMS ^{14}C dating and pollen, grain-size and chemical analyses of lake sediments sampled from four sites, Haoluku (42°57.38′N, 116°45.42′E and 1295 m a.s.l.), Liuzhouwan (42°42.44′N, 116°40.98′E and 1365 m a.s.l.), Xiaoniuchang (42°37.05′N, 116°49.02′E and 1460 m a.s.l.) and Jiangjunpaozi (42°22.44′N, 117°28.20′E and 1490 m a.s.l.), in the Dali Nor area (Fig. 2). Furthermore, mineral-magnetic measurements and analyses of total organic carbon (TOC) content and carbon/nitrogen (C/N) ratio were performed on the sediments from Haoluku and Liuzhouwan (Wang et al., 2001). This paper presents the results of newly accomplished mineral-magnetic measurements and analyses of TOC and C/N on sediments from Xiaoniuchang and Jiangjunpaozi. Complemented by the results of analyses of grain-size,

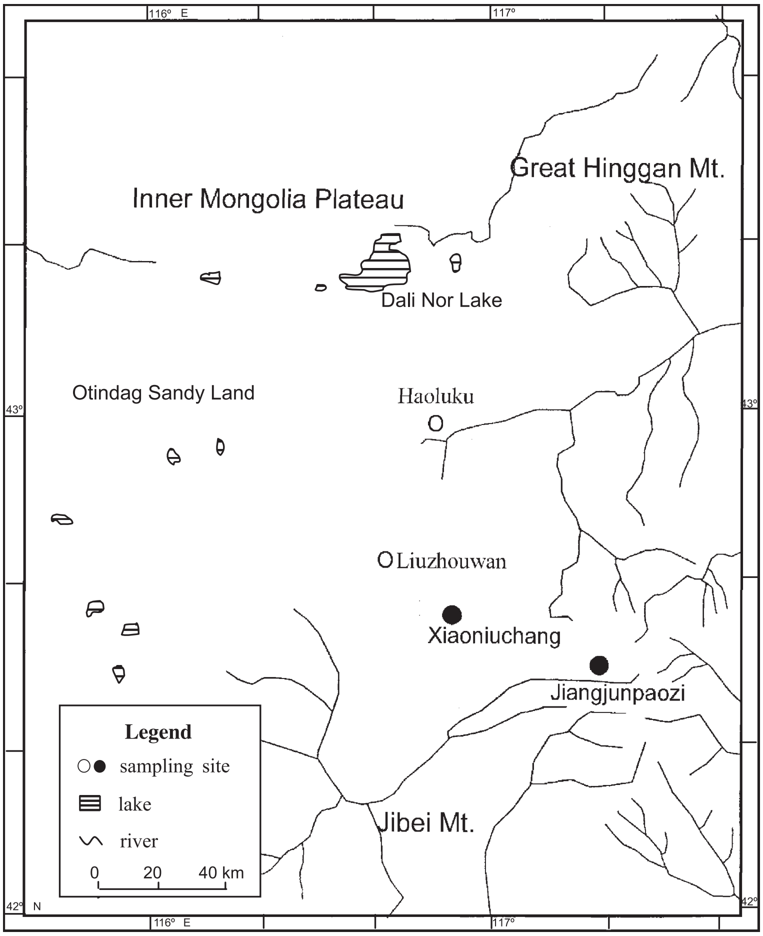

Fig. 2. Sampling sites (Xiaoniuchang and Jiangjunpaozi) with another two sites mentioned in text (Haoluku and Liuzhouwan) in Dali Nor area.

loss-on-ignition (LOI) and pollen previously accomplished and of analyses of TOC and C/N, mineral magnetism of the sediments from the two sites gave further information on Holocene palaeoenvironments in the Dali Nor area. These palaeoenvironmental inferences are fairly in agreement with what was inferred from mineral magnetism of the sediments from Haoluku and Liuzhouwan (Wang et al., 2001) and have enhanced our understanding of the Holocene in this area.

2. Study area

The study area is referred to as 'Dali Nor area' and Dali Nor Lake, the second largest fresh-water lake in Inner Mongolia, is located in its northern part (Fig. 2). The major part of this area is situated in the southeastern edge of Inner Mongolia Plateau, close to the Great Hinggan Mountains to the northeast and the Jibei Mountains to the south and southeast (Fig. 2). Most of the Dali Nor area is generally at altitudes of 1100–1400 m while altitudes of the valleys are only 500–700 m and the highest mountain is as high as ~ 2000 m.

The Otindag Sandy Land, the second largest of three such sandy lands in Inner Mongolia, occupies the western part of this area (Fig. 2). The Land is composed of dunes oriented roughly in the east–west direction. It is generally accepted that the Land was formed during the mid-Pleistocene to early Holocene (e.g., Chen, 1991). Its formation can be attributed to deposition of 'allochthonous', long-distance transported grains from the inland deserts and/or sandy lands lying further north and northwest by winds (e.g., Li et al., 1990, p. 12). Alternatively, accumulation of 'autochthonous', loose lacustrine particles exposed and reworked locally by aeolian activities after lakes desiccated, may have also contributed to the development of the Land (Yang and Song, 1992).

At present, a warm temperate semi-humid climate gradually changes to a moderate semi-arid one from the southeast to northwest across this area. Contemporary regimes of temperature and precipitation were interpolated for the whole area (Fig. 3) from meteorological records for periods longer than 20 years from 15 local stations. Mean annual temperature varies with altitude, ranging from −1 to +2 °C. Mean annual precipitation ranges between 350 and 450 mm and declines markedly from the southeast to northwest.

Parallel to this climatic transect, a floristic change also takes place. From the southeast to northwest, temperate forest is gradually superseded by steppe, with four vegetation zones identified (Liu et al., 1998): (1) the woodland zone; (2) the woodland–grassland zone; (3) the woodland–steppe zone; and (4) the steppe zone.

Soils progressively change across the same climatic and vegetational transect. From the south and southeast to north and northwest, brown earths are succeeded by gray forest soils, chernozems, light chernozem soils and, finally, dark chestnut soils (Shi, 1982, pp. 80–94). In addition, relatively small soil patches related to more local features also exist. For instance, aeolian sandy-soil occurs in the Otindag Sandy Land and sub-alpine meadow soil in the high-altitude peaks.

Dali Nor Lake and several small lakes are presently located in the northern part of this area. A few much smaller lakes are distributed in the western and northwestern part. In the central and southern part, large lakes existed until the later stage of the mid-Pleistocene and then gradually shrank and dried out during the later stage of the late Pleistocene, leaving considerable geomorphologic and sedimentary evidence of their occurrence (e.g., Geng and Zhang, 1988).

As in other areas in north-central China, environments in the Dali Nor area have been predominantly influenced by the East Asian monsoon at least since

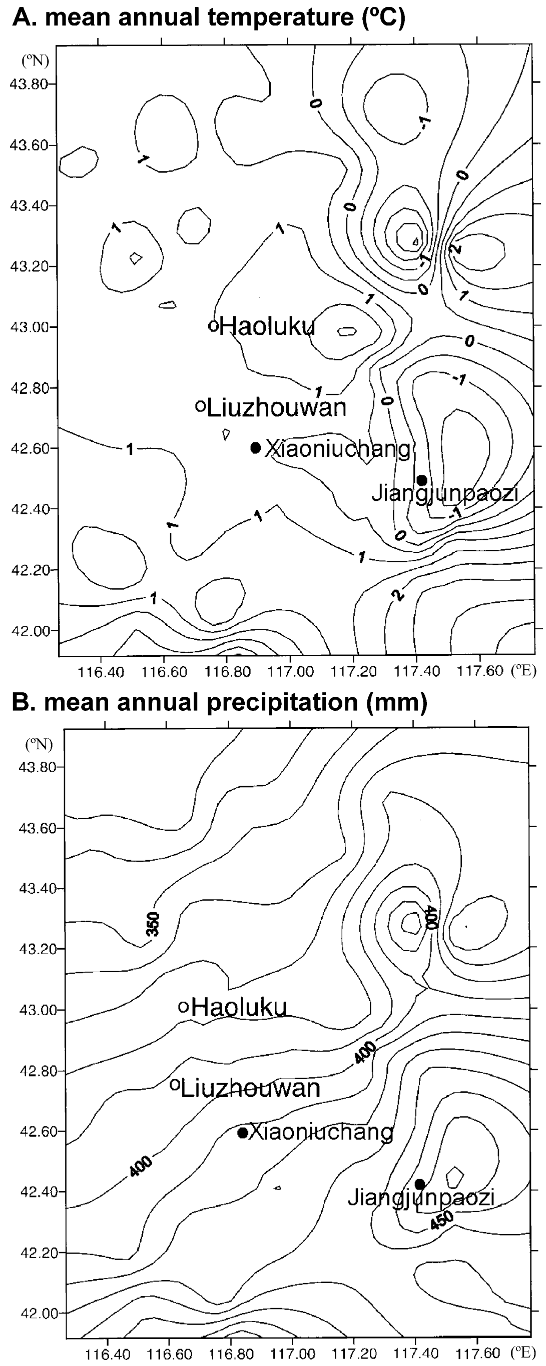

Fig. 3. (A) Mean annual temperature and (B) mean annual precipitation in Dali Nor area (data are from records longer than 20 years of 15 local stations).

the onset of the Quaternary (e.g., Li et al., 1990, pp. 11–12). In dry or dry-and-cold periods when the winter monsoon prevails, the northwest and/or north winds are intense, aeolian activities are strong, dunes expand and lakes shrink, shallow or even disappear. Conversely, aeolian activities are weak, dunes stabilise or shrink, and lakes expand and deepen when the summer monsoon predominates during wet or wet-and-warm episodes.

3. Xiaoniuchang and Jiangjunpaozi sequence

Xiaoniuchang (Fig. 2) is near the centre of a dried-out palaeo-lake occupied by sand. These sand sheets are covered with steppe vegetation. Jiangjunpaozi (Fig. 2) is a tiny lake with some water still in places particularly during wet seasons but gradually decreasing in recent years.

A 202-cm-deep pit was dug in Xiaoniuchang and a 110-cm-deep pit in the dry part close to the centre of Jiangjunpaozi. Sediments were sampled with boxes of $\sim 20 \times 10$ cm from the two pits. The samples were transported to Beijing and stored in the Department of Urban and Environmental Sciences, Peking University. They were then sub-sampled in the laboratory at intervals of 5–6 cm; 40 specimens were thus acquired from the Xiaoniuchang sequence and 23 from the Jiangjunpaozi sequence.

3.1. Stratigraphy, grain-size, LOI and pollen

The two sequences consist of sands, sandy silts and clays. Their main lithological characteristics are described in Tables 1 and 2. Grain-size analysis, LOI determination and pollen analysis were performed on the 63 specimens (Liu, 1998); these data are included in Figs. 4 and 5.

Table 1
Main lithological characteristics of Xiaoniuchang sequence

Depth (cm)	Lithology
0–20.0	Grey black *sandy silt* with minor clay as modern soil with relatively abundant roots of plants
20.0–38.0	Grey brown *sand* with minor silt, clay and roots
38.0–98.5	Dark grey black to grey yellow *sand* with minor silt and clay
98.5–167.0	Grey green or grey *sand* with minor clay and silt and relatively large rusty yellow iron-nodules
167.0–185.0	Brown *silty sand* with minor clay and silt as 1–2 cm nodules and with iron-nodules
185.0–200.0	Grey brown *sandy silt* with relatively abundant clay and obvious rusts

Table 2
Main lithological characteristics of Jiangjunpaozi sequence

Depth (cm)	Lithology
0–11.5	Black *silty sand* with minor clay and with roots of modern plants
11.5–89.5	Black *sandy silt* with minor clay
89.5–105.0	Light yellow *silty sand* with minor clay

3.2. TOC and C/N

Analyses of TOC and C/N were carried out with the conventional anti-titration method in the Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences (CAS). They were done for all the 40 specimens from the Xiaoniuchang sequence and, however, only 22 of the 23 from the Jiangjunpaozi sequence (Fig. 4) due to exhaustion of sediment for the specimen from the depth of 110 cm.

TOC of lacustrine sediments is positively proportional to the organic input to lakes. Sediment organic matter is usually relatively abundant in ameliorating environments and scare in deteriorating ones (e.g., Talbot and Livingstone, 1989; Beuning et al., 1997). TOC is thus indicative of environmental conditions. Both aquatic organisms living in and terrestrial plants growing around lakes contribute organic matter to lake sediments; the contained nitrogen is mainly from the former. Therefore, increases in C/N imply relative increases of terrestrial (allochthonous) contribution and relative decreases of aquatic (autochthonous) contribution and vice versa (e.g., Talbot and Livingstone, 1989; Finney and Johnson, 1991; Beuning et al., 1997).

3.3. Chronology

Specimens from three horizons in the Xiaoniuchang sequence and from two in the Jiangjunpaozi sequence were selected for AMS ^{14}C dating (Table 3). As there were no macrofossils found in the specimens, the humid acid fraction of bulk sediment was dated. For each of the chosen specimens, particularly the one from the depth of 9.5–10.5 cm within the rooted zone of the Jiangjunpaozi sequence, roots of modern plants were very carefully removed in a preliminary treatment to minimise modern carbon contamination. The deposits of the top part of the Xiaoniuchang sequence are mainly sand and appear very slightly pedogenically affected. In Jiangjunpaozi, although the surface of the sampling site was dry when sampled, the floor of the whole depression is still often submerged during wet seasons. The pedogenical processes acting on the top materials of the Jiangjunpaozi sequence are hence also generally weak. Therefore, contamination of modern soil may be relatively slight even to the uppermost specimens of the both sequences.

All the dating results are expressed in ^{14}C years (years BP), rather than calibrated years for convenience in comparing them with relevant results that are in ^{14}C years. The results indicate that the two sequences were deposited during the Holocene (Table 3). Though largely occupied by sand, the dried lake-floor of Xiaoniuchang is still quite densely vegetated. At the sampling spot, vegetation cover, composed mainly of *Artemisia frigida* and *Cleistogenes squarrosa*, is about 40%. The floors of Xiaoniuchang and also Jiangjunpaozi, the small seasonally inundated lake, are thus only somewhat deflated. We therefore assume the "0" depth of the two sequences represents "0" years. Assuming constant deposition rates between dated adjacent hori-

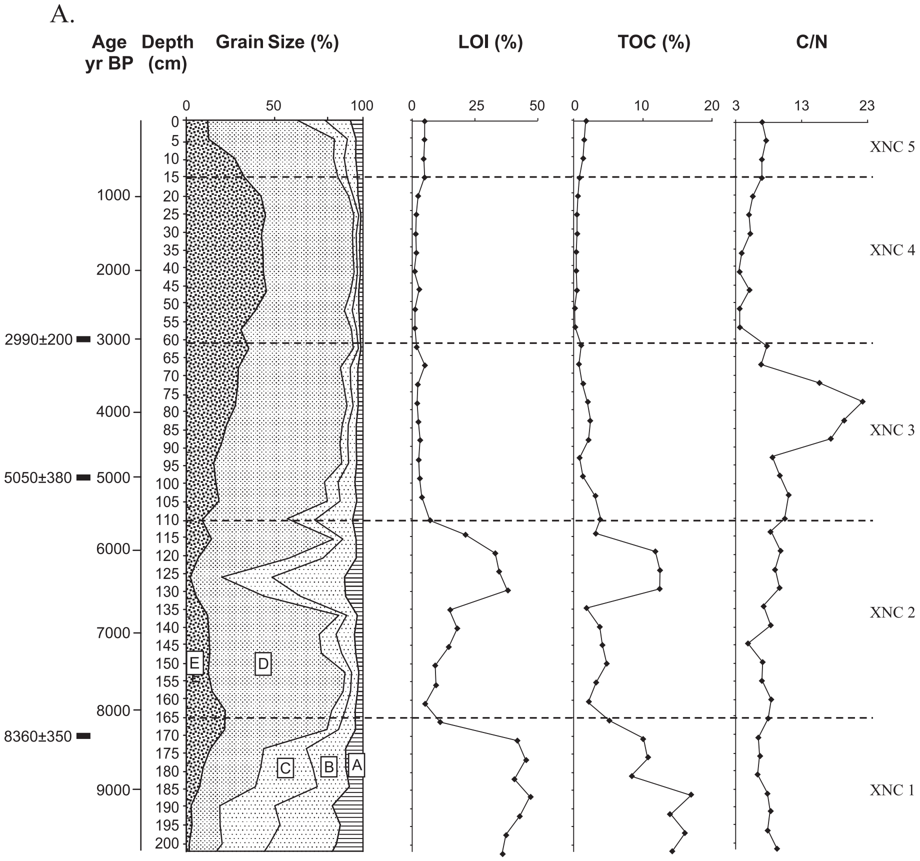

Fig. 4. Variations in grain-size, loss-on-ignition (LOI), total organic carbon (TOC) content and carbon/nitrogen (C/N) ratio for (A) Xiaoniuchang sequence and (B) Jiangjunpaozi sequence (data of grain-size and LOI are from Liu, 1998). Letter designations for grain-size classes are as follows: (A) clay (< 0.002 mm), (B) very fine to fine silt (0.002–0.016 mm), (C) medium to coarse silt (0.016–0.0625 mm), (D) very fine to fine sand (0.0625–0.2 mm), (E) medium to coarse sand (>0.2 mm).

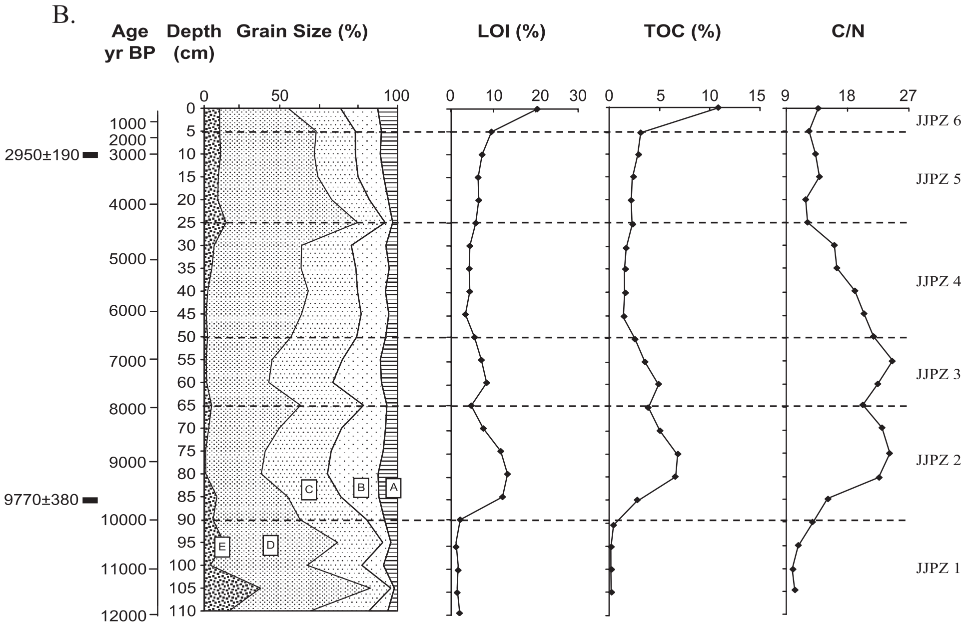

Fig. 4 (*continued*).

zons or the surface, ages of different depths in the two sequences are estimated. However, since there are only three dates spanning the 8360 years section in Xiaoniuchang and two spanning the 9770 years section in Jiangjunpaozi, the age model is of relatively low resolution.

4. Mineral magnetism

Mineral-magnetic measurements were performed on the 62 specimens (40 from the Xiaoniuchang sequence and only 22 from the Jiangjunpaozi sequence) in the Palaeomagnetism Laboratory, Institute of Geology and Geophysics, CAS and some of the results are presented in Fig. 6.

Low-frequency magnetic susceptibility (χ_{lf}) was measured with a Bartington MS2 susceptibility meter with a MS2B dual frequency sensor at 0.46 kHz. Isothermal remanent magnetisations (IRM) were induced with magnetic fields of 20 and 1000 mT and then with reversed fields of 100 and 300 mT using a 2G660 Pulse Magnetiser. These isothermal remanent magnetisations, respectively termed 'IRM_{20mT}', 'IRM_{1000mT}' or 'SIRM', 'IRM_{-100mT}' and 'IRM_{-300mT}', were then measured on a Geofyzika JR-5A Spinner Magnetometer.

All measurements were repeated five times, averages taken for each specimen, and mass specific parameters were then calculated. Hard isothermal remanent magnetisation (HIRM), defined as '$[1+(IRM_{-100mT}/SIRM)]SIRM/2$]' (e.g., Sohlenius, 1996), and four 'inter-parametric ratios', IRM_{20mT}/SIRM, IRM_{-100mT}/SIRM, IRM_{-300mT}/SIRM and SIRM/χ_{lf}, were also calculated.

Magnetic susceptibility (χ) often reflects the concentration of ferrimagnetic minerals in sediments (e.g., Thompson et al., 1975). In many cases, ferrimagnetic minerals are the most significant component of magnetic-mineral assemblages, thus χ is also accepted as an indicator of the amount of total magnetic minerals (e.g., BDP-93 Baikal Drilling Project Members, 1997). IRM_{20mT} reflects the concentration of ferrimagnetic minerals and IRM_{20mT}/SIRM the relative proportion of 'soft' ferrimagnetic, either multidomain or fine viscous single domain, component (e.g., Oldfield, 1991). SIRM manifests the amount of remanence-carrying magnetic minerals (ferrimagnetic and anti-ferromagnetic minerals) and is hence used as an indicator of the content of total magnetic minerals in sediments, while HIRM is diagnostic of the concentration of anti-ferromagnetic minerals (e.g., Oldfield, 1991).

Magnetic minerals in lake sediments have been regarded as overwhelmingly allogenic though authigenic and diagenetic ones may also exist (e.g., Thompson and Oldfield, 1986, p. 102). In the Dali Nor area, erosion around lakes has chiefly controlled the concentrations of total magnetic minerals in sediments recovered from these lakes as shown by variations in SIRM of these sediments (Wang et al., 2001). Intensification in erosion may move more magnetic minerals into lakes and SIRM of lacustrine sediments may be thus high. In contrast, SIRM may be low due to the low detrital magnetic-mineral input to lakes when erosion is slight. Changes in erosion and sediment yield are usually related to those in climate, vegetation and their

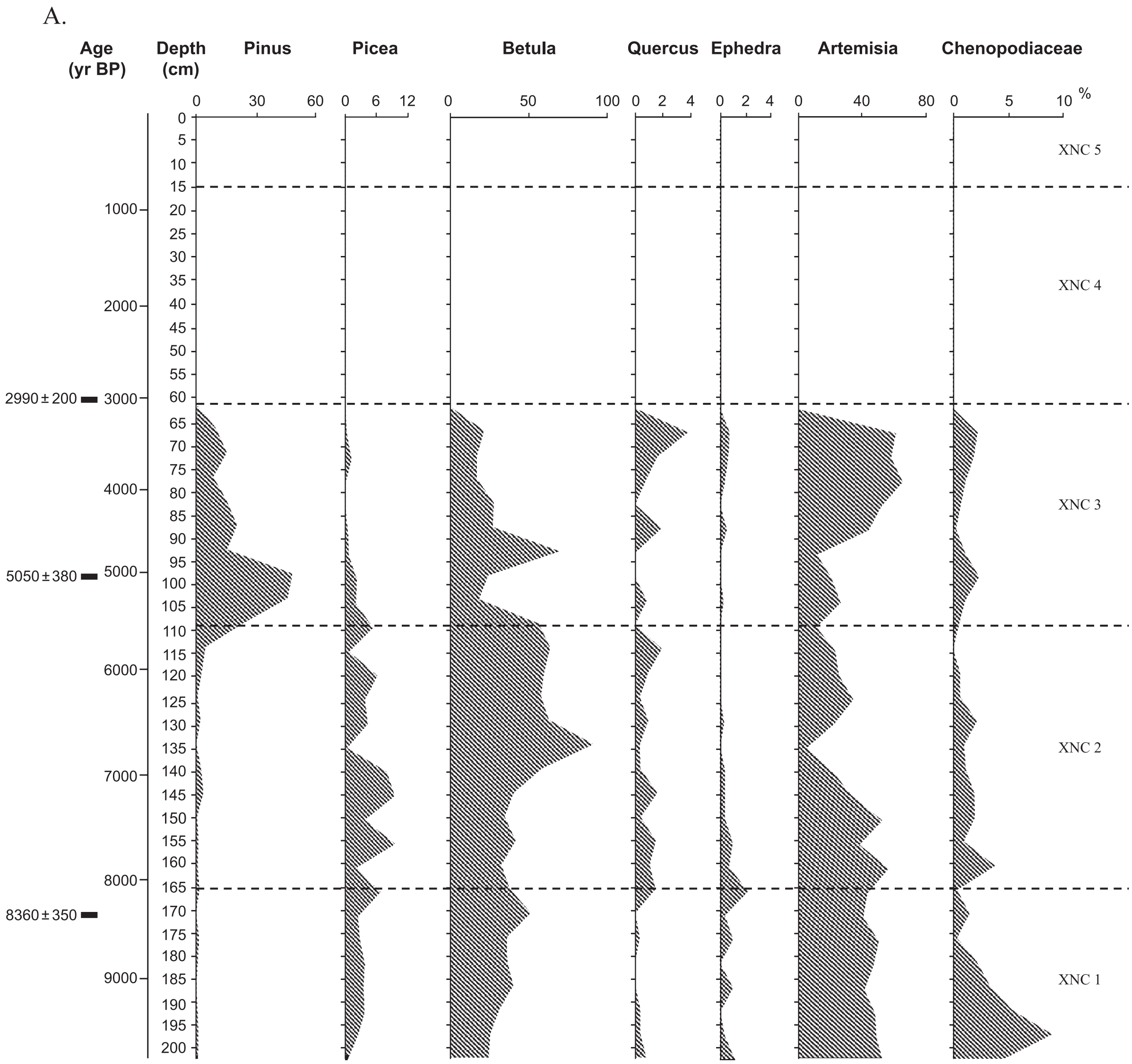

Fig. 5. Pollen percentages for (A) Xiaoniuchang sequence and (B) Jiangjunpaozi sequence (data are from Liu, 1998).

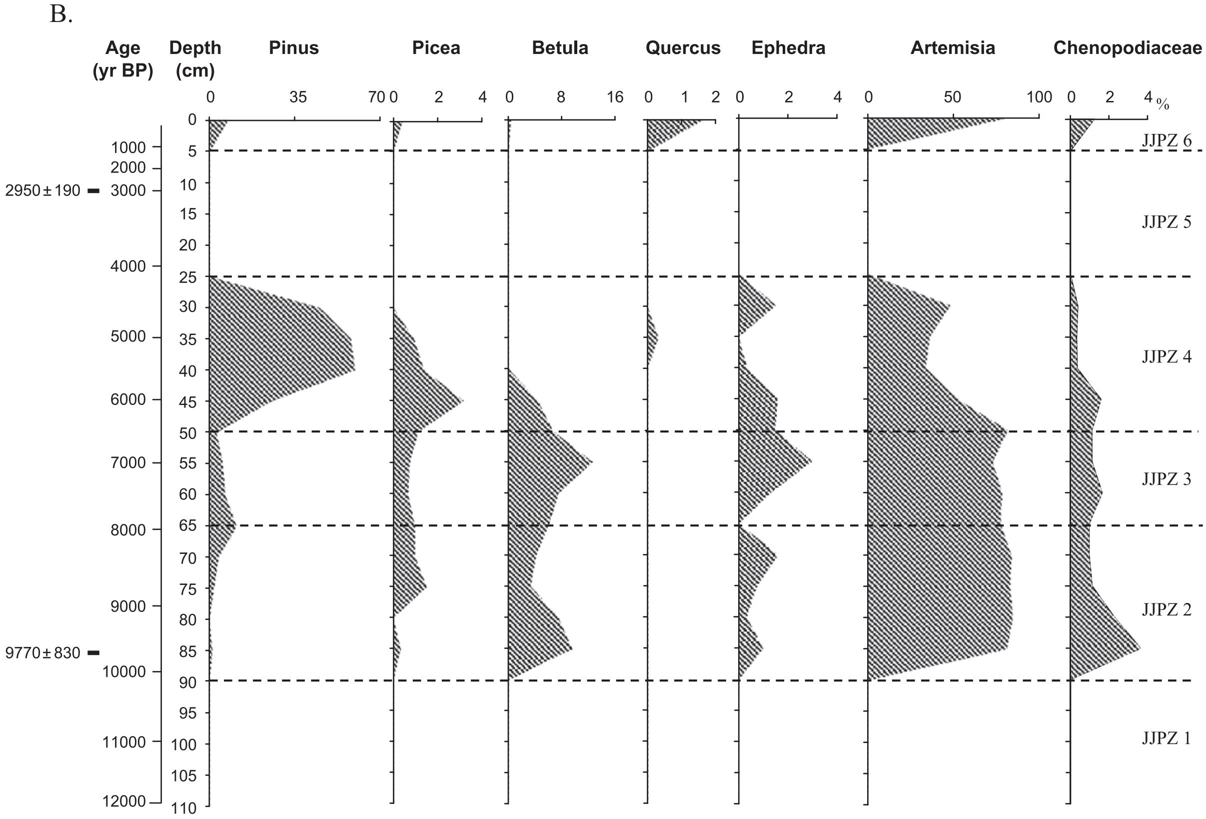

Fig. 5 (*continued*).

interactions (e.g., Langbein and Schumm, 1958; Walling and Webb, 1983; Creer and Morris, 1996). When the climate is extremely dry and particularly the effective humidity is very low, erosion is usually very weak as rainfall and particularly surface-runoff are very rare. With increases of rainfall and surface-runoff, erosion may intensify. In particular, erosion may be very intensive during some very short amelioration and/or initial stages of amelioration when rainfall and surface-runoff have already increased but vegetation has not well developed yet. However, erosion may also weaken due to soil binding effects of thicker vegetation promoted by more abundant rainfall. On the other hand, magnetic

Table 3
Radiocarbon dates for Xiaoniuchang and Jiangjunpaozi sequence

Sequence	Laboratory code	Depth of sample (cm)	Age ^{14}C years BP ($\pm 1\sigma$) ($T_{1/2}$: 5730 years)	Material dated
Xiaoniuchang	BA95122	61.0–62.0	2990 ± 200	Bulk sediment
Xiaoniuchang	BA95121	98.0–99.0	5050 ± 380	Bulk sediment
Xiaoniuchang	BA95118	170.5–171.5	8360 ± 350	Bulk sediment
Jiangjunpaozi	BA96089	9.5–10.5	2950 ± 190	Bulk sediment
Jiangjunpaozi	BA96088	84.5–85.5	9770 ± 380	Bulk sediment

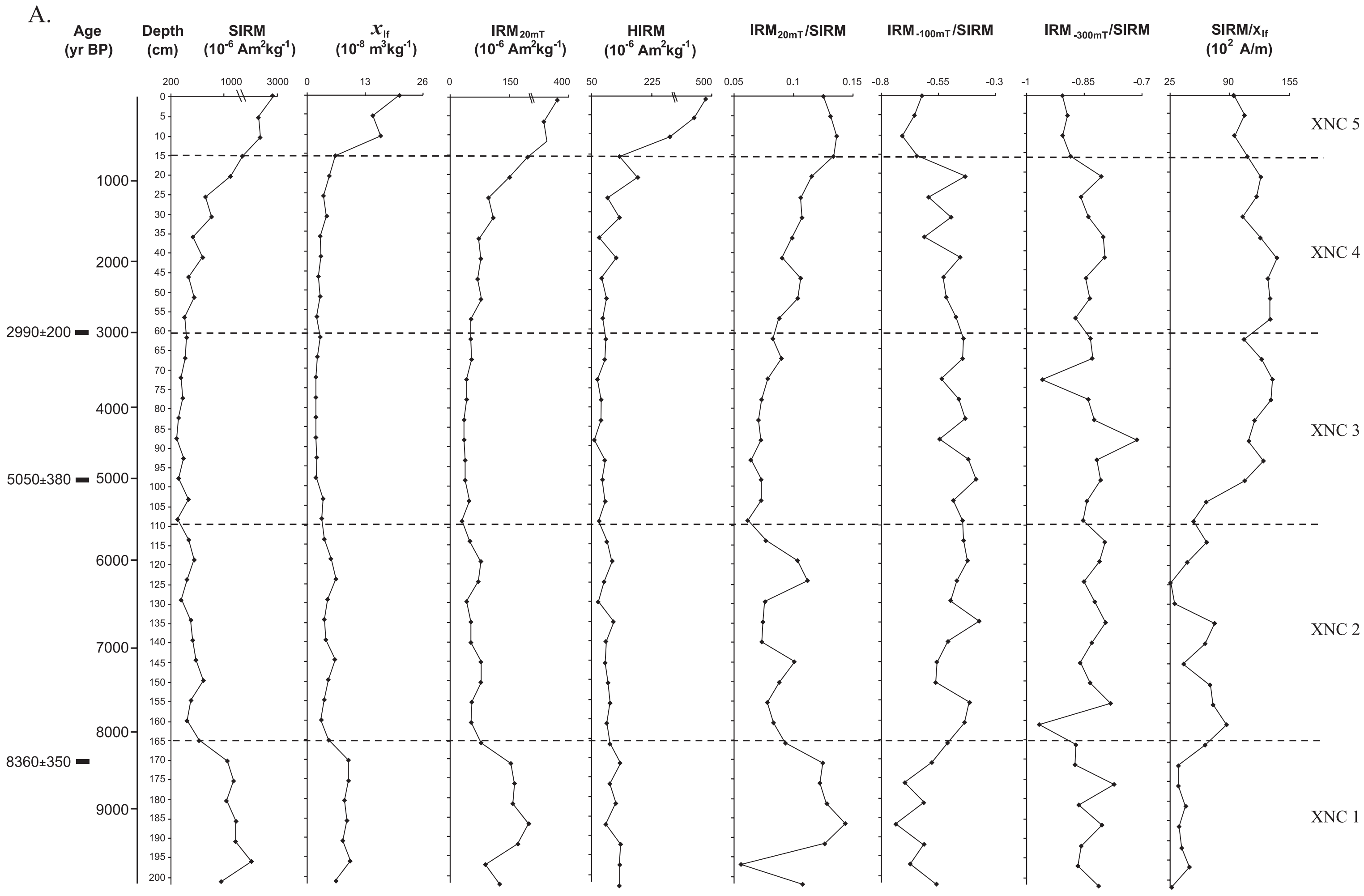

Fig. 6. Variations in mineral magnetism for (A) Xiaoniuchang sequence and (B) Jiangjunpaozi sequence.

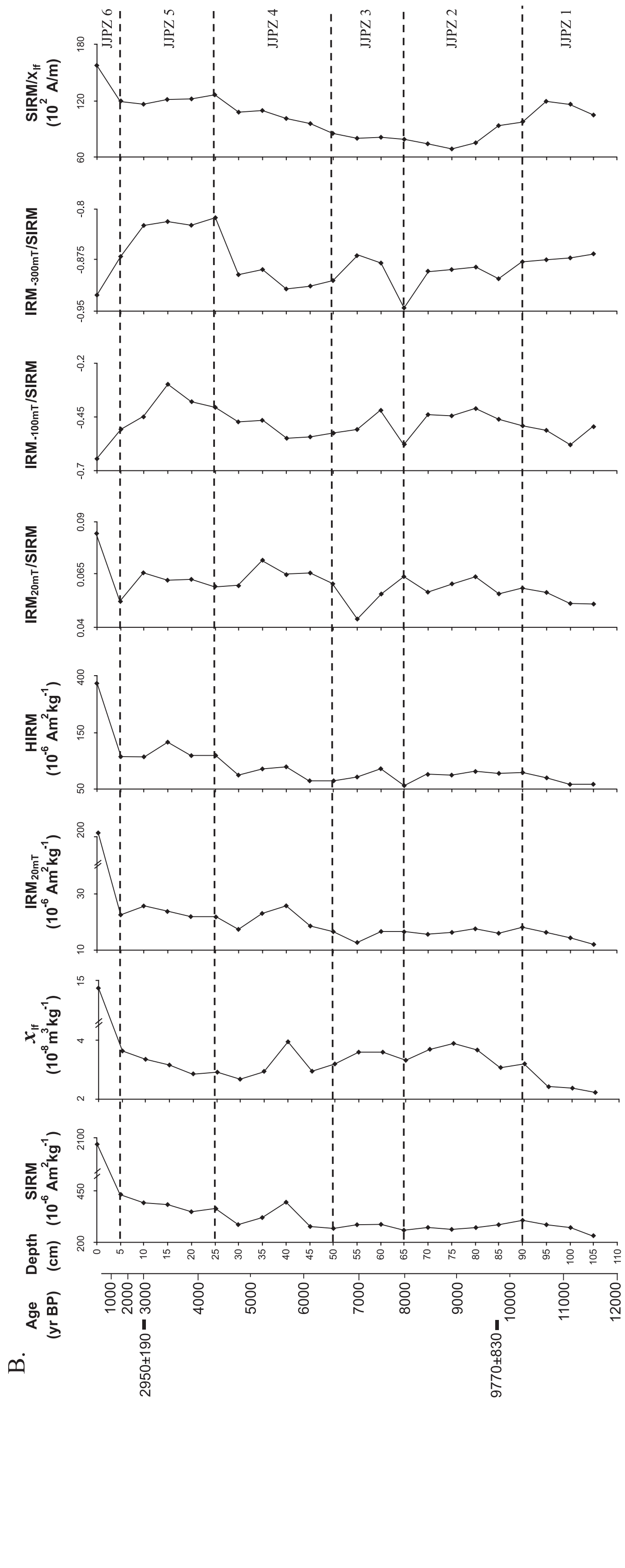

Fig. 6 (*continued*).

minerals and thus SIRM of these sediments can be also influenced by organic input to the lakes at this area (Wang et al., 2001). Organic matter is diamagnetic and causes no remanence. Therefore, when the organic content of the lake sediment increases greatly it has a diluting effect yielding lower SIRM values and vice versa. Furthermore, variations in organic input may be related to changes in environmental conditions: ameliorating environments often increase aquatic and/or terrestrial vegetation in and around lakes and hence increase organic productivity and preservation.

As in the previously analysed sequences recovered in this area (Wang et al., 2001), there are also signs of the mobilisation, transformation and deposition of Fe bearing phases in the Xiaoniuchang sequence (Table 1). However, ARM/SIRM calculated with the measured anhysteretic remanent magnetisation (ARM) (not presented in this paper) has actually given very few signals of reductive diagenesis. We thus preliminarily assume that influences of reductive diagenesis on magnetic variations are less significant than erosion and dilution in the Xiaoniuchang sequence.

In the two sequences, variations in χ_{lf}, IRM_{20mT} and HIRM are very similar to those in SIRM (Fig. 6). Thus, the concentrations of both ferrimagnetic and anti-ferromagnetic minerals, the two main components of the magnetic-mineral assemblage, may be also predominantly influenced by erosion and dilution. In addition, variations in IRM_{20mT}/SIRM roughly resemble those in SIRM too, implying that changes in erosion and dilution may also particularly alter the proportion of 'soft' ferrimagnetic component. We will therefore adopt this simplified erosion/dilution model in the following interpretations of variations in the four 'concentration-dependent variables' and IRM_{20mT}/SIRM.

Both IRM_{-100mT}/SIRM and IRM_{-300mT}/SIRM, also referred to as 'S-ratios', reflect the relative proportion of anti-ferromagnetic minerals in the magnetic assemblage (e.g., Robinson, 1986; Bloemendal et al., 1988; Hesse, 1997). Aeolian grains originating in arid and semi-arid regions are usually rich in anti-ferromagnetic minerals (e.g., Oldfield et al., 1985; Maher and Thompson, 1995; Walden and White, 1997). Higher relative proportions of anti-ferromagnetic minerals have been thus interpreted as higher aeolian-particle contents in sediments, stronger wind activities and drier conditions and vice versa (e.g., Oldfield et al., 1985; Robinson, 1986; Bloemendal et al., 1988; Peck et al., 1994). The Dali Nor area may have been always subject to influences of the northwesterly and/or north winds though their intensity varied throughout the Quaternary (e.g., Li et al., 1990, pp. 11–12). During drier episodes, the strengthening northwesterly and/or north winds were probably capable of deflating and transporting more grains from the Otindag Sandy Lands and/or other deserts and sandy lands located further northwest and/or north and deposit them in lakes downwind. The reversed situation may have occurred in wetter episodes. The relative proportion of anti-ferromagnetic minerals as shown by IRM_{-100mT}/SIRM and IRM_{-300mT}/SIRM in the sequences from Haoluku and Liuzhouwan, another two sites in the Dali Nor area seem to have been indicative of past aeolian activities occurring during the terminal Pleistocene and Holocene (Wang et al., 2001). Therefore, IRM_{-100mT}/SIRM and IRM_{-300mT}/SIRM in the Xiaoniuchang and Jiangjunpaozi sequences will be also employed as proxy indicators of wind activity and environmental aridity or humidity.

SIRM/χ_{lf} may be affected by either magnetic mineralogy or grain-size. Higher SIRM/χ_{lf} values may indicate the presence or abundance of anti-ferromagnetic minerals or of relatively fine, stable single domain ferrimagnetic grains in the magnetic-mineral assemblage (e.g., Oldfield, 1991). Moreover, sedimentary grain-size is also likely to influence this ratio (e.g., Thompson and Oldfield, 1986, p. 191; Yu et al., 1990). For instance, SIRM/χ_{lf} has been found high in sand fractions of some lacustrine sediments (Yu et al., 1990). For our two sequences, there is a near perfect match when the grain-size curves (Fig. 4) are compared to the SIRM/χ_{lf} curves (Fig. 6); coarser grained intervals correspond to higher SIRM/χ_{lf} values. Furthermore, SIRM/χ_{lf} has a positive correlation exclusively to sand (>0.0625 mm), while it is negatively correlated to all the other, relatively fine fractions. Increases of sand coarsening sediments have been attributed to lowering of lake levels and environmental changes towards dry and vice versa in this area (Wang et al., 2001). Thus, increases of SIRM/χ_{lf} may imply lowering of lake levels and thus decreasing of effective humidity or environmental aridification while its decreases indicate the opposite situation.

Changes in SIRM/χ_{lf} of the two sequences will be so interpreted.

5. Interpretation

Examination of the variations in mineral magnetism as well as grain-size, LOI, TOC, C/N and pollen allows five units to be differentiated in the Xiaoniuchang sequence (XNC 1–5) and six in the Jiangjunpaozi sequence (JJPZ 1–6) (Figs. 4–6). As implied by the low χ_{lf} values (mostly $< 20\ 10^{-8}\ m^3\ kg^{-1}$), concentrations of magnetic minerals are generally low (Fe_3O_4 content generally $< 0.03\%$) in the two sequences. However, the words, 'low' and 'high' are still used in the following interpretation to describe variations of magnetic-mineral concentrations for convenience.

5.1. Xiaoniuchang sequence

5.1.1. XNC 1: >8100 years BP (202–165 cm)

SIRM, χ_{lf} and IRM_{20mT} are high and HIRM is relatively low, indicating high concentrations of total magnetic minerals and ferrimagnetic ones and relatively low concentration of anti-ferromagnetic minerals in the sediments. The relative proportion of 'soft' ferrimagnetic minerals is also high as the IRM_{20mT}/SIRM suggests. Organic matter is abundant as shown by the high LOI and TOC and thus has a rather strong diluting effect on magnetic remanence parameters. After being 'diluted', concentrations of total magnetic minerals and ferrimagnetic ones are still high in the sediments, suggesting that erosion is particularly intensive around the lake. Though IRM_{-300mT}/SIRM is relatively high, low IRM_{-100mT}/SIRM still suggests that the relative proportion of anti-ferromagnetic component is low in the magnetic-mineral assemblage and aeolian grains are rare in the sediments and wind activities are thus weak. SIRM/χ_{lf} is very low, suggesting very high lake level or greatly enhanced wetness. The intensive erosion may be initiated by the abundant rainfall and surface-runoff.

Sediments are fine, also implying that the lake level is very high. The very high LOI and TOC indicate that aquatics in and/or terrestrial plants around the lake are thriving. C/N is moderately low, particularly suggesting relatively high contribution from autochthonous source to the sedimentary organic matter and further hinting at increasing aquatics and thus an expansive and deep water-body. The percentage of *Picea* is relatively high, indicating wet and cool conditions. The relatively low percentages of deciduous trees such as *Quercus* and *Betula* also imply a cool environment. Therefore, the climate is very wet. The lowest SIRM/χ_{lf} may indicate the highest effective humidity resulting from high rainfall and low temperature.

5.1.2. XNC 2: 8100–5600 years BP (165–109 cm)

SIRM, χ_{lf}, IRM_{20mT}, HIRM and IRM_{20mT}/SIRM have decreased compared with in XNC 1. These decreases suggest that either erosion has weakened or dilution strengthened. The decreased LOI and TOC show that organic input has decreased and dilution weakened. Therefore, the decreased magnetic concentrations are likely due to weakened erosion. IRM_{-300mT}/SIRM remains rather high as in XNC 1 while IRM_{-100mT}/SIRM has increased. The variations in the latter point to the somewhat strengthened aeolian activities. So the weakened erosion may have resulted from decreases in rainfall and surface-runoff. However, SIRM/χ_{lf}, though having increased, is still quite low, hinting that lake level is still high and conditions are hence still moderately wet. Thus, the relatively abundant rainfall and surface-runoff still enable rather intensive erosion as shown by the decreased but still rather high SIRM, χ_{lf}, IRM_{20mT}, HIRM and IRM_{20mT}/SIRM.

Though having coarsened, sediments are still rather fine, which also suggests that the dropped lake level is still quite high. The still rather high LOI and TOC, while lower than in XNC 1, indicate that aquatics and/or terrestrial plants are still flourishing. As shown by the slightly increased C/N, the autochthonous contribution to the sedimentary organic matter has relatively declined, hinting a minor decrease of aquatics and thus shrinkage of water-body. The increased percentages of deciduous trees such as *Quercus* and *Betula* suggest a wet and warm environment. Therefore, the climate is still generally wet though the effective humidity may be lower than during >8100 years BP due to the increased temperature and thus evaporation.

5.1.3. XNC 3: 5600–3000 years BP (109–61 cm)

SIRM, χ_{lf}, IRM_{20mT}, HIRM and IRM_{20mT}/SIRM have further declined and are thus very low. Although the organic input is very low as shown by LOI and TOC and dilution thus very slight, magnetic concentrations and proportion are still very low. Magnetic input is thus very low and erosion very weak. IRM_{-100mT}/SIRM and IRM_{-300mT}/SIRM are almost the same as in XNC 2, remaining high and implying similar intensity of wind activity. SIRM/χ_{lf} has remarkably increased and is thus very high, indicating very low lake level. The greatly weakened erosion can be thus ascribed to decreases in rainfall and/or surface-runoff caused by the enhanced aridity.

The coarsened sediments also indicate the markedly lowered lake level. The very low LOI and TOC suggest the considerably decreased aquatics and/or terrestrial plants. The very high C/N hints a significantly relative decrease of autochthonous contribution to the organic matter and thus a decrease of aquatics and a contracted water-body. The percentages of *Pinus* and *Artemisia* have markedly increased, showing that conditions are arid and warm. Therefore, the climate is dry and effective humidity is apparently low.

5.1.4. XNC 4: 3000–730 years BP (61–15 cm)

SIRM, χ_{lf}, IRM_{20mT}, HIRM and IRM_{20mT}/SIRM have increased, which may be caused by intensification in erosion and/or weakening in dilution. LOI and TOC have decreased, indicating the decrease of organic input. So the increases in magnetic concentrations and proportion can be at least partly attributed to decrease in dilution. IRM_{-100mT}/SIRM and IRM_{-300mT}/SIRM are still very high, indicating that aeolian activities are still very strong. SIRM/χ_{lf} is still very high, suggesting very low lake level. Thus, erosion may have also intensified probably due to further decreases in vegetation caused by the further deteriorated conditions.

The coarsest sediments imply the lowest lake level. The extremely low LOI and TOC hint the extraordinarily sparse aquatics and/or terrestrial plants. C/N has dramatically declined, meaning a greatly relative decrease of allochthonous contribution to the sedimentary organic matter and thus a major decrease in vegetation. Pollens are very rare, suggesting the very low vegetation cover, which is in agreement with the inference. Hence, the climate may be very dry or dry-and-cool.

5.1.5. XNC 5: <730 years BP (15–0 cm)

Accompanied by somewhat increased LOI and TOC, SIRM, χ_{lf}, IRM_{20mT}, HIRM and IRM_{20mT}/SIRM are extremely high. Therefore, though the organic input and hence dilution has increased, magnetic concentrations and proportion are still very high and erosion is very intensive. Aeolian activities have waned as shown by the declined IRM_{-100mT}/SIRM and IRM_{-300mT}/SIRM. Decreasing SIRM/χ_{lf} indicates raising lake level. Thus, the intensified erosion may be induced mainly by the increased rainfall and/or surface-runoff.

Fining sediments also hint that the lake level is rising. LOI, TOC and C/N tend to increase, showing that organisms and particularly terrestrial plants tend to increase. However, pollen data suggest that vegetation has not begun to flourish yet. A climatic amelioration, probably rather short, may thus have just started.

5.2. Jiangjunpaozi sequence

5.2.1. JJPZ 1: >9770 years BP (110–90 cm)

SIRM, χ_{lf}, IRM_{20mT}, HIRM and IRM_{20mT}/SIRM are very low. Although the low organic input as indicated by LOI and TOC may have only 'diluted' very few magnetic minerals deposited, the magnetic concentrations and proportion are still very low, hinting that the erosion is too slight. However, IRM_{-100mT}/SIRM and IRM_{-300mT}/SIRM are not markedly high and aeolian activities are thus not very strong. SIRM/χ_{lf} is high, indicating low lake level or low effective humidity. Thus, the very weak erosion may be due to scarcity of rainfall and surface-runoff.

Sediments are very coarse as shown by the grain-size, also indicating the low lake level. Low LOI and TOC imply sparse organisms in and around the lake. Low C/N particularly indicates the relatively low contribution from allochthonous source to organic matter of the sediments. Pollen data suggest that vegetation cover is very low around the lake and are thus in agreement with the inference. Therefore, the climate is dry or dry-and-cool.

5.2.2. JJPZ 2: >9770–8000 years BP (90–65 cm)

Coinciding with the dramatic increases in LOI and TOC, SIRM, χ_{lf}, IRM_{20mT}, HIRM and IRM_{20mT}/SIRM have somewhat increased. So, despite the markedly increased organic input may have 'diluted' considerable amount of deposited magnetic minerals, the magnetic concentrations and proportion are still fairly high. Thus, erosion has rather remarkably increased. IRM_{-100mT}/SIRM has slightly increased while IRM_{-300mT}/SIRM somewhat decreased, giving contradictory indications on variations in the relative proportion of anti-ferromagnetic minerals and hence in wind activities. However, noticeably decreased SIRM/χ_{lf} unambiguously suggests the raised lake level or increased effective humidity. The intensification in erosion can be thus attributed to increases in rainfall and surface-runoff.

Sediments have fined, also hinting at the raised lake level. The remarkably increased, very high LOI, TOC and C/N imply flourishing aquatics in and plants around the water body and relatively high allochthonous contribution to the sedimentary organic matter. As shown by pollen data, both trees and grasses are abundant around the lake. The percentages of both *Picea* and *Betula* are relatively high, implying wet and cool conditions. Therefore, the climate has apparently humidified. The lowest SIRM/χ_{lf} may suggest that the effective humidity is the highest, as precipitation is high and temperature and hence evaporation is low.

5.2.3. JJPZ 3: 8000–6600 years BP (65–50 cm)

SIRM, χ_{lf}, IRM_{20mT}, HIRM and IRM_{20mT}/SIRM are generally the same as in JJPZ 2. The organic input represented by LOI and TOC has decreased and may thus leave more deposited magnetic minerals 'undiluted' compared with in JJPZ 2. Thus, erosion around the lake, while rather intensive, may have weakened compared with during >9770–8000 years BP. IRM_{-100mT}/SIRM is also roughly the same as in JJPZ 2. Slightly increased IRM_{-300mT}/SIRM indicates that aeolian activities may have somewhat strengthened. SIRM/χ_{lf} has also slightly increased but is still rather low, implying a somewhat dropped but still quite high lake level. Therefore, there may be a very small increase in aridity, which has slightly decreased the rainfall and particularly surface-runoff and thus weakened erosion.

Sediments are still fine, confirming that the lake level is high. The considerably decreased LOI and TOC imply decreases of aquatics and/or terrestrial plants. However, as in JJPZ 2, C/N is still very high, hinting that the decreases in sedimentary organic matter are mainly caused by relative decreases of autochthonous contribution. Hence, the aquatic organisms may have declined and lake slightly shrunk. The percentage of *Betula* has considerably increased, hinting a wet and relatively warm environment. In addition, the increase in percentage of *Ephedra* is even more apparent, displaying an enhanced aridity. In general, though the effective humidity may have slightly declined owing to the increased temperature and thus evaporation, the climate is still wet.

5.2.4. JJPZ 4: 6600–4300 years BP (50–25 cm)

Though χ_{lf} seems the same as or even slightly lower than in JJPZ 3, SIRM, IRM_{20mT}, HIRM and IRM_{20mT}/SIRM have increased. As LOI and TOC have decreased, the generally increased magnetic concentrations and proportion may be partly ascribed to decrease of dilution. IRM_{-100mT}/SIRM and IRM_{-300mT}/SIRM are generally the same as in JJPZ 3 though both ratios display increases towards the upper part of this interval, suggesting an increase in aeolian activities. SIRM/χ_{lf} has rather remarkably increased, suggesting a lowered lake level and increased aridity. So intensification in erosion may also likely happen as the enhanced dry conditions may decrease vegetation.

Sediments have coarsened, also indicating the dropped lake level. The obviously decreased LOI, TOC and C/N indicate the decreased organic input and particularly significantly decreased allochthonous contribution and thus decreased plants around the lake. The percentage of *Pinus* has dramatically increased suggesting further enhanced dry-and-warm conditions. Therefore, the effective humidity has apparently further decreased and climate tended to become drier.

5.2.5. JJPZ 5: 4300–1300 years BP (25–5 cm)

Though IRM_{20mT}/SIRM has even slightly decreased, SIRM, χ_{lf}, IRM_{20mT} and HIRM are very high. Very slight dilution by the very low LOI and TOC may partly contribute to the high magnetic concentrations. IRM_{-100mT}/SIRM and IRM_{-300mT}/SIRM have obviously increased, indicating that aeolian activities have greatly strengthened. SIRM/χ_{lf} has apparently increased, hinting very low lake level or very low effective humidity. So it seems that, although rainfall and surface-runoff are relatively rare, the very dry conditions may have tremendously reduced vegetation and hence enhanced erosion.

Sediments are coarse, also implying the very low lake level. Though having somewhat increased, LOI and TOC are still very low, hinting very scarce aquatics and terrestrial plants. C/N has also further declined and is thus very low. Such decreased C/N indicates further relatively decreased allochthonous contribution to the sedimentary organic matter and thus very sparse vegetation. As shown by the pollen data, vegetation may have virtually almost disappeared around the lake. Therefore, the climate is very dry or dry-and-cool.

5.2.6. JJPZ 6: <1300 years BP (5–0 cm)

Though the organic input as shown by LOI and TOC and hence dilution has dramatically increased, SIRM, χ_{lf}, IRM_{20mT}, HIRM and IRM_{20mT}/SIRM are still extremely high. The very high magnetic concentrations and proportion accompanied by the strong dilution corroborate the occurrence of very intensive erosion. IRM_{-100mT}/SIRM and IRM_{-300mT}/SIRM have decreased, suggesting waning wind activities and thus environmental humidification. However, SIRM/χ_{lf} has apparently increased, implying a lowering of lake level and aridification or a totally opposite change in environmental conditions.

Sediments tend to fine, implying the raising lake level. Greatly increased LOI and TOC indicate increases in aquatics and/or terrestrial plants. C/N tends to increase, displaying the sign of relative increases of allochthonous contribution to organic matter contained in the sediments. Pollen data indicate that vegetation, though still sparse, has anyhow re-occurred around the lake. Taken together, a moderate humidification is likely to have happened. Probably as the wet pulse is too transient to promote vegetation well develop, the increased rainfall and surface-runoff are capable of considerably intensifying erosion. The increase in SIRM/χ_{lf} of this interval may not be caused mainly by variations in sand, as the percentage of sand has not significantly increased. Frequency dependence susceptibility (χ_{fd}) (not presented in this paper) is not particularly high. So the high SIRM/χ_{lf} is not due to presence or abundance of superparamagnetic grains and thus pedogenic effects. The mineral-magnetic and environmental implications of the increase in SIRM/χ_{lf} in this interval remain to be explored.

6. Discussion

In the Dali Nor area (Fig. 2), the high level of Dali Nor Lake located in the most northern part began to occur at as early as ~ 12,000 years BP (Geng and Zhang, 1988); conditions began to ameliorate apparently later in our four investigated sites located relatively south and/or southeast, at ~ 10,300 years BP in Haoluku, the most northwestern one of the four sites, and at ~ 9400 years BP in Liuzhouwan located further southeast (Wang et al., 2001). The environment was still rather arid or arid-and-cool before 9770 years BP in Jiangjunpaozi, the most southeastern site. Only after 9770 years BP and particularly 9300 years BP (80 cm), conditions were markedly wet there. The maximum precipitation belt has been used to define the Eastern Asian summer monsoon maximum (An et al., 2000; Porter, 2001). Due to the southeastward shift of this belt across China over the last 12,000 years, the Holocene optimum occurred asynchronously in different regions (An et al., 2000; Porter, 2001). Even within a relatively small area particularly located in the climatic and vegetational transition zone, coeval conditions might still differ between sites that are relatively closely spaced. The earlier onset of the amelioration around Dali Nor Lake than in our four sites might be at least partly due to the earlier arrival of the maximum precipitation belt in this northern site during its southeastward shift. Nevertheless, relatively limited ^{14}C dating data use in the palaeolimnological studies for Dali Nor Lake (Geng and Zhang, 1988) and our four sites (Wang et al., 2001; Section 3.3, this paper) may also partly account for these differences in timing. In north-central China including the Inner Mongolia Plateau, the Holocene optimum occurred at 10,000–7000 years BP, earlier than in the further southeastern regions (e.g., An et al., 2000). Humid conditions prevailed in some parts of Inner Mongolia before ~ 8000 years BP (e.g., Chen et al., 2003). The highest effective humidity as characterised typically by the lowest SIRM/χ_{lf}, lowest sand percentage and finest bulk sediment grain-size suggests the highest levels of the two small lakes persisted until

8100 years BP in Xiaoniuchang and until 8000 years BP and particularly during 9300–8400 years BP (80–70 cm) in Jiangjunpaozi. These lake high stands are temporally consistent with the Holocene optimum in this region. The moistest conditions prevailing in the two sites might result from the combination of high precipitation with low temperature, as the climate was wet and cool as suggested by the pollen data. After ~8000 years BP, the effective humidity has somehow lowered though the environment was still rather wet. As implied by the pollen data, the climate was warmer. The raised temperature might increase evaporation and thus decrease the effective humidity. The slightly less wet but warmer conditions lasted until 6600 years BP in Jiangjunpaozi and 5600 years BP in Xiaoniuchang. The equivalent wetness terminated at 5600 years BP in Haoluku and 4700 years BP in Liuzhouwan (Wang et al., 2001). The level of Dali Nor Lake began to drop at ~7000 years BP (Geng and Zhang, 1988), marking an earlier end of the Holocene optimum than in our four sites. Once again, this earlier termination of the humid conditions may be ascribed to the earlier departure of the maximum precipitation belt from this northern site. Conditions were increasingly drier since 6600 years BP in Jiangjunpaozi and 5600 years BP in Xiaoniuchang. The deterioration culminated during 4300–1300 years BP in Jiangjunpaozi and 3000–730 years BP in Xiaoniuchang where the climate was very dry and cool. A moderately amelioration began at 1300 years BP in Jiangjunpaozi and 730 years BP in Xiaoniuchang. No such a humidification has been identified in Dali Nor Lake and Haoluku. However, a similar brief amelioration might occur in Liuzhouwan at 2100–700 years BP (Wang et al., 2001), though starting earlier than in Jiangjunpaozi and Xiaoniuchang. The absence of this humidification in Dali Nor Lake and Haoluku suggests that a transient strengthening of the summer monsoon may have only affected the southern and southeastern part of this area as the maximum precipitation belt has already oriented further south and southeast during the late Holocene. The asynchronous environment changes in the northern Dali Nor Lake and further south and southeast part of this area where our four sites are situated appear to have been fairly well explained with the suggested southeastward shift of the maximum precipitation belt.

Although we have previously attempted to attribute the differences in environmental changes in Haoluku and Liuzhouwan to the shift of the maximum precipitation belt (Wang et al., 2001), however, the inter-site variability of Haoluku, Liuzhouwan, Xiaoniuchang and Jiangjunpaozi seems difficult to be explained with this hypothesis. Over these smaller distances, the wetter conditions did not necessarily begin and end earlier in the north and northwest than in the south and southeast. Some more site-specific factors such as topography seem to have strongly influenced local conditions. In addition, the apparent differences in the four sites may result partly from dating precision.

7. Summary

The concentration of total magnetic minerals, ferrimagnetic and anti-ferromagnetic ones indicated by SIRM, χ_{lf}, IRM_{20mT} and HIRM and relative proportion of soft ferrimagnetic minerals in the magnetic-mineral assemblage as shown by IRM_{20mT}/SIRM were likely primarily controlled by the erosion around and dilution in the lakes at Xiaoniuchang and Jiangjunpaozi. The changes in the intensity of erosion can be in turn related to those in climate, vegetation and their interactions. IRM_{-100mT}/SIRM and IRM_{-300mT}/SIRM representing the relative proportion of anti-ferromagnetic minerals in the magnetic-mineral assemblage are positively correlated to the strength of aeolian activities. SIRM/χ_{lf} positively correlated to percentage of sand is diagnostic of changes of lake levels and effective humidity. Supplemented with the data of grain-size, LOI, TOC, C/N and pollen, these mineral-magnetic variations reveal the Holocene palaeoenvironmental changes in Xiaoniuchang and Jiangjunpaozi.

The environment was quite dry or dry-and-cool prior to 9770 years BP and had markedly humidified since then and particularly since 9300 years BP in Jiangjunpaozi. The highest effective humidity thus reached during 9300–8400 years BP in this site. In Xiaoniuchang, the wettest conditions persisted until 8100 years BP. The effective humidity has somehow lowered though the environment was still rather wet since then. The slightly less humid but warmer conditions lasted in Jiangjunpaozi until 6600 years BP and in Xiaoniuchang until 5600 years BP. Then drier and cooler conditions have gradually occurred and climaxed during 4300–1300 years BP in Jiangjunpaozi and 3000–730 years BP in Xiaoniuchang. A mild amelioration began to happen at 1300 years BP in Jiangjunpaozi and 730 years BP in Xiaoniuchang but probably did not last long in both sites.

These results together with those previously acquired from Haoluku and Liuzhouwan seem to imply the Holocene amelioration started and ended later in our four sites than around Dali Nor Lake located further north. In addition, the short late Holocene humidification present in the south and southeast appeared absent in the north and northwest part of the study area. These may be due to the southeastward shift of the maximum precipitation belt over the Holocene. The among-site differences of Haoluku, Liuzhouwan, Xiaoniuchang and Jiangjunpaozi spaced more closely may result from some unidentified site-specific controls (e.g., local topography) and/or the relatively low dating precision.

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