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Sediment record of environmental change at Lake Lop Nur (Xinjiang, NW China) from 13.0 to 5.6 cal ka BP*

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Abstract Lake Lop Nur is located in the eastern part of the Tarim Basin in Xinjiang, northwestern China. A 220-cm-long sediment core was collected from the center of the ear-shaped depression forming the basin and dated with AMS^{14}C. Grain size, total organic matter (TOC), total nitrogen (TN), and TOC/TN (C/N) analyses were used to reconstruct climatic conditions from 13.0 to 5.6 cal ka BP. The results showed five main climatic stages. Zone I (13.0–11.3 cal ka BP) was a wet–dry environment, whereas Zone II (11.3–8.9 cal ka BP) consisted of a primarily wet environment. Zone III (8.9–7.7 cal ka BP) was subdivided into Zone IIIa (8.9–8.2 cal ka BP) that indicated lake constriction and dry climate, and Zone IIIb (8.2–7.7 cal ka BP) in which the proxies indicated wet conditions. In Zone IV (7.7–6.6 cal ka BP), the climate presented a bit wet conditions. In Zone V (6.6–5.6 cal ka BP), abundant glauberite is present in the sediment and silt dominates the lithology; these results indicate the lake shrank and the overall climate was dry. Abrupt environmental events were also identified, including six dry events at 11.0, 10.5, 9.3, 8.6, 8.2, and 7.6 cal ka BP and one flood event from 7.8 to 7.7 cal ka BP in the Early–Middle Holocene.

Keyword: sediment record; environmental evolution; abrupt environmental changing events; Lop Nur; northwestern China

1 INTRODUCTION

The Earth's climate has experienced intense change since the Late Pleistocene, including the Younger Dryas event that had significant global influence (Alley, 2000; Garcin et al., 2007), and the 8 200 ka event, another abrupt cooling period (Alley et al., 1997; Klitgaard-Kristensen et al., 1998; Alley and Ágústsdóttir, 2005). Xinjiang Uygur Autonomous Region, in northwestern China, is the most arid region of central Asia and is sensitive to environmental change (Yang et al., 2013). Therefore, it can help us better understand the environmental evolution of arid regions.

Lacustrine sediments are particularly good archives for high-resolution climate records because they accumulate sediment continuously (Battarbee, 1999; Alve et al., 2009). Therefore, analyses using lake sediments can provide paleoclimate and paleoenvironmental information, which is helpful for arid regions where the sediments record both the environmental evolution of the lake as well as the surrounding area. Environmental information about the Xinjiang area has already been derived from lacustrine sedimentary records. An analysis of a 35 kyr record from Lake Barkol concluded this region was cold-moist during the glacial period whereas the interglacial climate was warm-arid (Han and Li, 1994). Rhodes et al. (1996) demonstrated that the Last Glacial Maximum was an arid period based on the study of three 5-m-long cores recovered from Lake Manas. Wu et al. (1996) showed that 10.2–8.3 cal ka BP was a warm-cool-dry climate stage followed (8.3–3.5 cal ka BP) by a warmer moist climate stage in the Lake Ebinur area. Xue and Zhong (2008) suggested that environmental conditions around the Lake Barkol region may have been cold and arid from 9.4 to 7.4 cal ka BP, warm-moist from 7.4 to 5.9 cal ka BP, and warm-arid from 5.9 to 3.1 cal ka BP.

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Liu et al. (2008) found that the climate was mainly warm-arid during the Early Holocene based on the sediment record of Lake Wulungu. Finally, Ma et al. (2008) proposed a warm and humid, fresh or brackish water environment in the Lop Nur region during the Medieval Warm Period. Some studies have concluded that the climate is mostly controlled by the westerly wind belt in the Lop Nur area and comprises a warm-arid or cold-wet synchronization (Luo et al., 2009; Yang et al., 2013). Despite the numerous studies, there is still debate over the interpretation of paleolake records around the arid Xinjiang area, and there is no consistent information about the evolution of Lop Nur from the Late Pleistocene to Middle Holocene. Thus, much more work remains with respect to the region's environmental evolution and precise chronological and paleoenvironmental information is necessary.

The Lop Nur depression is one of the largest playas in the world and is situated in the driest region of central Asia. Studies from this area are very important to understand environmental change in arid regions overall. In this study, sediment lithology, sensitive grain size parameters, total organic carbon (TOC) and total nitrogen (TN) concentrations, and the C/N ratio were examined along a sedimentary profile to reconstruct Lop Nur environmental change from 13.0 to 5.6 cal ka BP. Radiometric analyses enabled the construction of sediment chronology while environmental proxies, including grain size, TOC, TN, and C/N, statistical analysis, and written records, were used in conjunction to track environmental change.

2 MATERIAL AND METHOD

2.1 Geographical setting

Lake Lop Nur covers ~20 000 km^2 and is the drainage playa of the historical Tarim, Kongque, and Cheerchen Rivers. Lop Nur (elevation 780 m) is situated in the driest part of China (Fig.1a), the eastern part of the Tarim Basin in the Xinjiang region. The Altyn Tagh Mountains are located to the south, the Beishan Mountains to the east, and the Kuruk Tagh Mountains to the north. The lake appears to have formed as a result of the orogenic processes that produced these mountain ranges. Therefore, Lop Nur is located in the convergence part of the Tarim Basin (Wang et al., 2000; Dong et al., 2012).

The climate in the region is continental and dominated by westerly winds while local prevailing winds are northeasterly (Jia et al., 2012). Annual precipitation is <20 mm with annual potential evaporation >3 000 mm (Ma et al., 2008). Thus, currently, Lop Nur is a large dry lake with a 30- to 100-cm-thick salt crust.

2.2 Field and laboratory methods

A 220-cm-long sedimentary core (DHX) was recovered from the ear-shaped central depression of Lake Lop Nur (40°07′40.18″N, 90°28′51.77″E) in May 2013 (Fig.1b). The core was divided and sampled at 2 cm resolution. The resulting 110 sedimentary samples were subsequently analyzed for the full suite of paleolimnological proxies.

From Core DHX, five sediment samples were selected for dating. AMS^{14}C dates were obtained from bulk sediment samples at the Beta Analytic Radiocarbon Dating Laboratory (Miami, FL, USA). Using the Bacon age-depth model, the calibration of the obtained radiocarbon ages to calendar kilo-years before present (cal ka BP) was performed (Blaauw and Christen, 2011).

Potassium dichromate oxidation titration and potassium persulfate digestion were used for the determination of TOC and TN, respectively. These concentrations were then used to calculate C/N (TOC/TN) ratios. For TOC analysis, bulk sediment was dried at 50°C and then 0.2 g of each sample was placed into a tube (50 mL) to which 5 mL of $K_2Cr_2O_7$ (0.8 mol/L) and H_2SO_4 were added. The sample solution was boiled at 170–180°C and then titrated with $FeSO_4$ (0.2 mol/L). From this, the TOC content was calculated (%). For TN analysis, 30 mg of each dried sample was placed into a colorimetric tube (50 mL) and 25 mL of digesting solution was added; the volume was adjusted to 50 mL, then digested under high pressure for 30 min at 120°C. The supernatant was then analyzed with an ultraviolet spectrophotometer. For grain size analysis, 0.1–0.3 g of each sample was placed into a beaker (100 mL), and 10 mL of H_2O_2 (10%) was added to remove organic matter. Next, 10 mL of 10% HCl was added and the sample solution boiled to remove carbonates. The beaker was then filled with distilled water and the superstratum water was pumped away under static conditions for ~24 h. Finally, 10 mL of $(NaPO_3)_6$ (0.05 mol/L, used as a dispersant) was added, then all of the processed samples were surged for 10 min, after which they were analyzed with a Mastersizer 2000 (Malvern Instruments Ltd., UK, size range 0.02–2 000 μm).

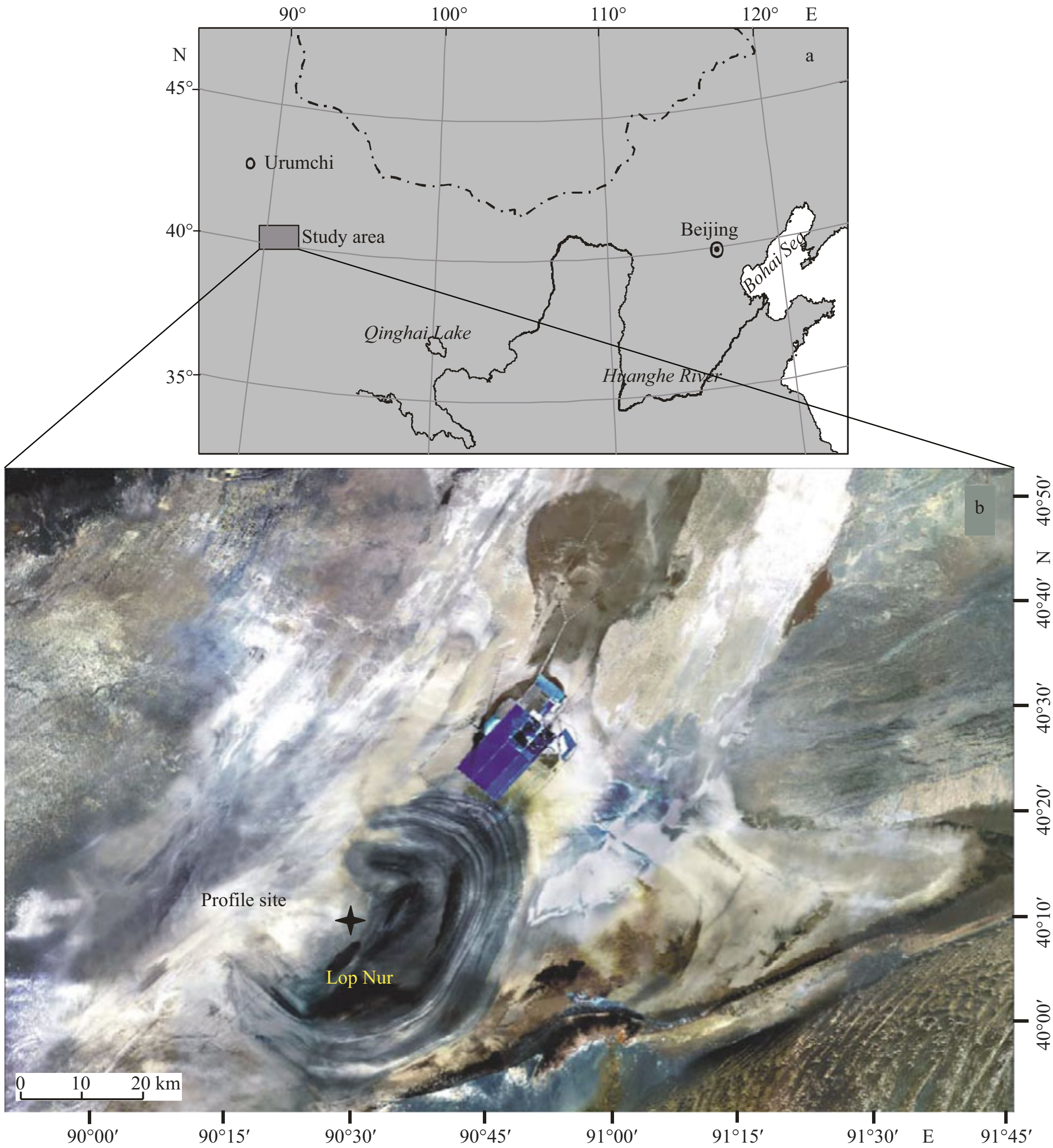

Fig.1 Location of study area (a), geographical location of Lop Nur and its profile site (b)

3 RESULT

3.1 Chronology and lithology

The age of Core DHX spanned the Late Pleistocene to the Middle Holocene. The sample ages were extrapolated from 40 cm to the upper core. Thus, the sedimentary sequence afforded the study on the paleoenvironmental evolution from 13.0 to 5.6 cal ka BP in the Lop Nur region (Fig.2). The overall sedimentary profile consists of relatively fine-grained sediment. It is dominated by clay, which is occasionally interrupted by thin layers of silt, found at 195–185 cm, 135–125 cm, 60–50 cm, and above 20 cm, and silty clay from 100 to 90 cm. There was abundant glauberite between 120–90 cm and 30–20 cm (Fig.2). These lithologic changes demonstrate the evolution of the depositional environment.

3.2 Grain size distribution

Figure 3a shows the mean size distribution, minimum and maximum volume range for each size class of all modeled samples. The average grain size distribution in Core DHX has a modal grain size near 15 μm. On the basis of the grain size frequency distribution curves, the highest standard deviations represented grain sizes of 8.0 μm and 35.6 μm with the demarcation at 15.9 μm (Fig.3b). According to environmentally sensitive grain size components, particle size can thus be split into two fractions: <15.9 μm and >15.9 μm. These showed dramatically opposite trends (Fig.4).

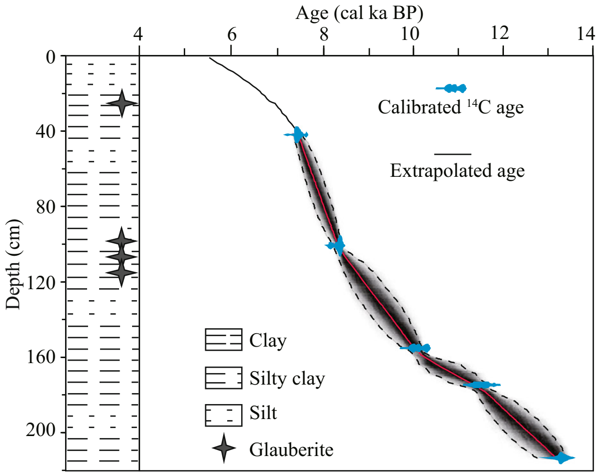

Fig.2 Lithology and Bacon age-depth model of Core DHX from Lake Lop Nur

On the age-depth profile, the calibrated distributions of individual dates are shown in blue, the dashed lines illustrate the model's 95% probability intervals and the solid red line shows the weighted mean ages for each depth.

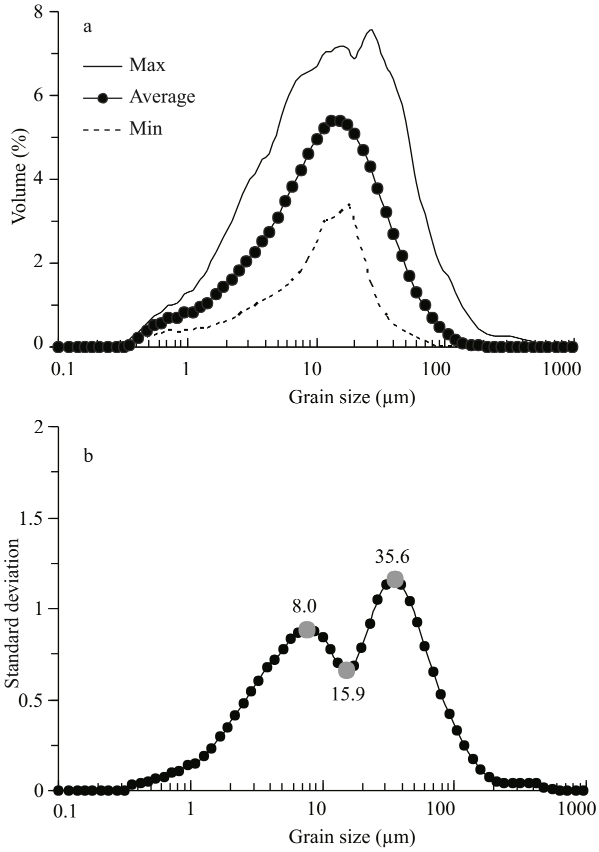

Fig.3 Mean grain size distribution, minimum and maximum volume range for each size class (a), and standard deviation distribution curve of Core DHX (b)

3.3 The characteristics of environmental proxies during 13.0–5.6 cal ka BP

Using constrained clustering analysis (CONISS) of TOC, TN, C/N, and grain sizes (<15.9 μm, >15.9 μm, and median particle diameter (Md), the different stages of regional environment development were identified, beginning with the Pleistocene and Holocene boundary at about 11.3 cal ka BP (Fig.4).

Zone I (13.0–11.3 cal ka BP) was characterized by average TOC content of ~0.63% and average Md of ~11.42 μm. It can be further subdivided into two parts up to ~12.3 cal ka BP and then 12.3 ka to 11.3 cal ka BP where Md and the >15.9 μm fraction (%) displayed a slightly increasing trend.

Zone II (11.3–8.9 cal ka BP) showed a slightly increased TOC up to 0.68% and relatively high C/N values, but there were significant fluctuations at 11.0, 10.5, and 9.3 cal ka BP (shaded bars in Fig.4). Grain size changes were not generally obvious; Md had a mean value of ~13.03 μm, but in some intervals (11.0, 10.5, and 9.3 cal ka BP) the particle size increased, shown by an increased percentage of the >15.9 μm fraction and Md values, and corresponded to decreasing TOC, TN, and C/N values.

Zone III (8.9–7.7 cal ka BP) exhibited an average TOC of ~0.56% with two minima (~0.22%) at 8.6 and 8.2 cal ka BP and maximum TOC (up to ~0.92%) from 7.8 to 7.7 cal ka BP; C/N values were relatively high throughout. The mean value of Md was ~12.66 μm, and both the >15.9 μm fraction and Md showed an obvious increase at 8.6 ka and 8.2 cal ka BP, in contrast to the changes in TOC, TN, and C/N.

Zone IV (7.7–6.6 cal ka BP) had an average TOC of ~0.65%, but TOC, TN, C/N, and the <15.9 μm fraction all clearly decreased at 7.6 cal ka BP when Md and the >15.9 μm fraction increased.

Zone V (6.6–5.6 cal ka BP) was characterized by a mean TOC content of ~0.26%. TOC, TN, and C/N showed a decreasing trend, which corresponded to increasing trends in Md (up to ~17.40 μm) and the >15.9 μm fraction (Fig.4).

4 DISCUSSION

4.1 Environmental significance of the proxies

Grain size analyses are approximate indicators for the hydrological conditions of lake systems (Håkanson and Jansson, 1983; Xiao et al., 2009; Chen et al., 2013). In lacustrine sediment, grain size can be affected by factors including the distance from central lake facies to the shore, the circulation kinetic energy and the sediment source (Lerman, 1978). In general,

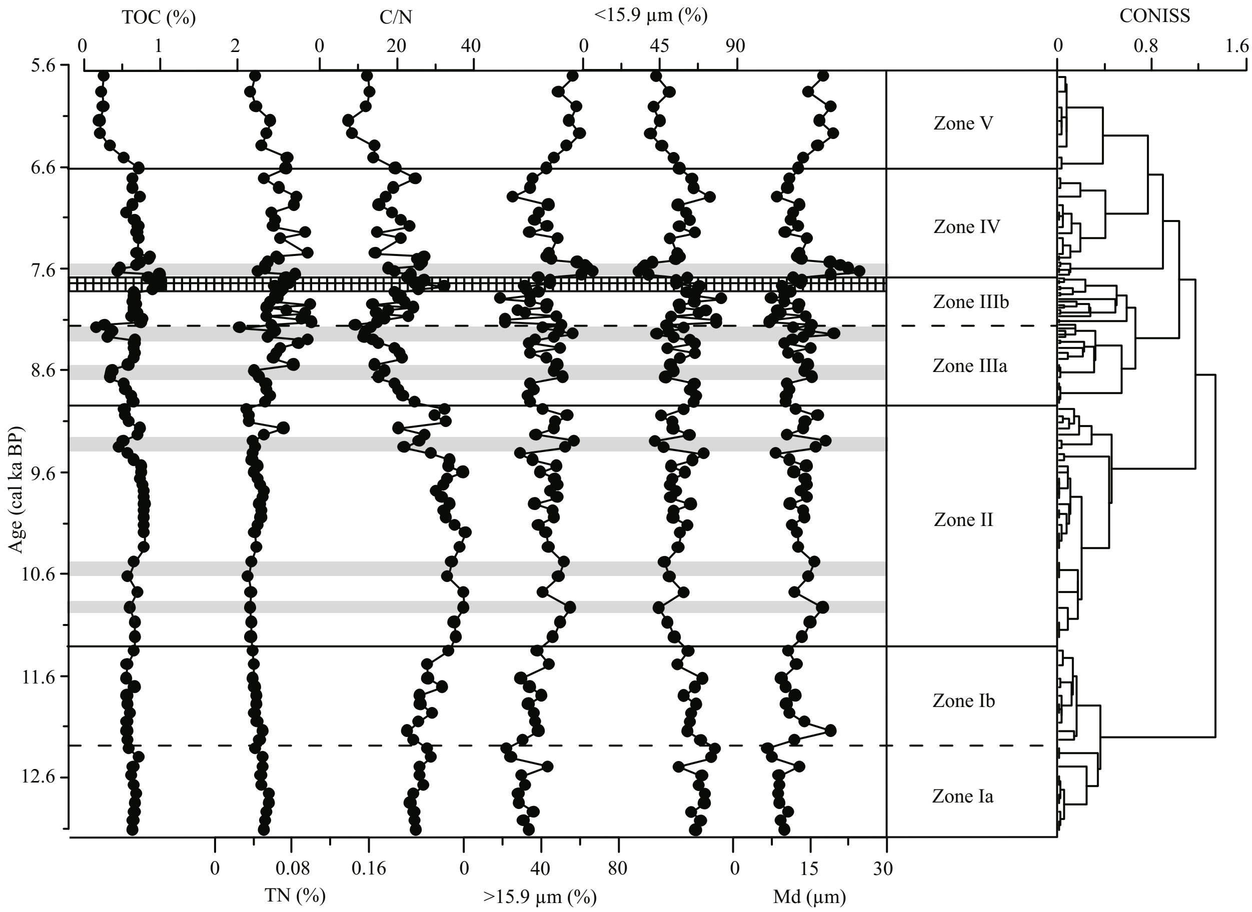

Fig.4 Environmental stages of the Lake Lop Nur region identified by proxies from Core DHX

fine- and coarse-grained sediment may represent the reduction and strengthening of hydrodynamic conditions, respectively. Additionally, sensitive grain size components within the sediment can indicate environmental change, acting as environmental proxies (Kranck et al., 1996a, b; Sun et al., 2002; Xiao et al., 2009). In Inner Mongolia, grain sizes are generally <20.0 μm with a modal grain size of 6.18 μm mainly dominated by fluviation into Lake Chenpu (Wang et al., 2015). In the arid region of Xinjiang, particularly around Lake Lop Nur, river runoff and flow velocity are relatively lower because of the low annual mean precipitation (<20 mm) and high potential evaporation (>3 000 mm). Fluvial waters mainly carry fine–grained sediments into lakes and the <15 μm particle size fraction has been the main component in the Lop Nur region. According to the grain size distribution curves produced in this study, the particle size composition was divided into two fractions: <15.9 μm and >15.9 μm. Therefore, grain sizes <15.9 μm are the same size as currently suspended particles, which indicates the influence of fluvial activity and deposition into the lake. In contrast, particle sizes >15.9 μm likely indicate a drop in the lake level and eolian input intensification, which suggest the overall climate was dry. But if ice meltwater and river runoff decreased in this area, when temperature is relatively low, grain-size could be mainly affected by the kinetic energy of the lake circulation in Lake Lop Nur. Then fine grained sediment increasing may represent the reduction of hydrodynamic conditions, and the lake could be large and deep, and vise versa.

TOC and TN reflect lacustrine primary productivity while the C/N ratio infers the organic matter source (terrestrial vs. aquatic) to the lake sediments. In general, low C/N ratios (<10) reflect a mainly aquatic organic matter source and higher C/N ratios indicate a predominantly terrestrial source (Meyers and Teranes, 2001; Wu et al., 2013).

4.2 Environmental evolution from 13.0 to 5.6 cal ka BP

Based on statistical analysis, sensitive environmental proxies, and the sedimentary profile of Core DHX, environmental changes from 13.0 to

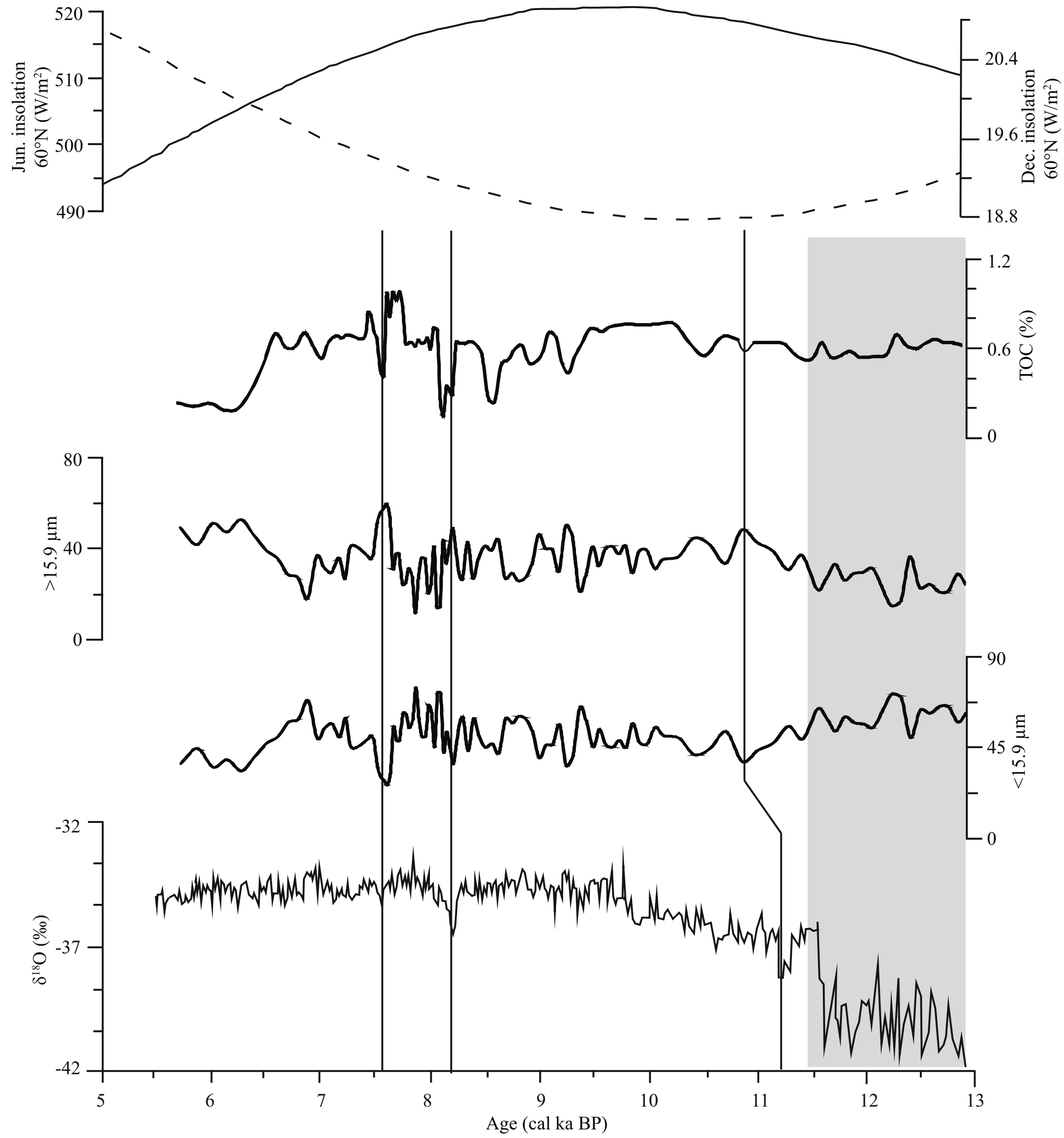

Fig.5 Comparisons of TOC, grain size fractions (<15.9 μm and >15.9 μm), the Northern Hemisphere Insolation at 60°N (soild line and dashed lines shows Jun. and Dec. respectively) and the δ^{18}O from the GRIP core record

The gray bar shows that the period is in Late Glacial, and the boundary at the onset of the Holocene is at about 11.3 cal ka BP.

5.6 cal ka BP were reconstructed for Lake Lop Nur and consist of five distinct zones (Fig.4).

During Zone I (13.0–11.3 cal ka BP), the content of fine grained relatively high, but dropping tread. As a result of summer insolation weakening (Fig.5), river runoff was less in this area, which meant that the grain size distribution mainly reflected the kinetic energy of lake circulation. So, the lake was still in large condition and was subdivided into two stages. Zone Ia (13.0–12.3 cal ka BP), corresponding to the Allerød oscillation, was characterized by a slight temperate climate in this region (Mischke and Wünnemann, 2006). Zone Ib (12.3–11.3 cal ka BP), corresponding to the Younger Dryas, was characterized by slightly decreasing TOC and increasing Md values, which suggested mildly intensified hydrodynamic conditions and a cold and dry climate, and consistent with many areas, such as sediment in North Atlantic (Bond et al., 1997), Lake Masoko (Tanzania) (Garcin et al., 2007), ice-core records of Greenland (Alley, 2000) and stalagmite record from southeast of the Loess Plateau, China (Cai et al., 2008). A general assumption is that the Younger Dryas began when the density of North Atlantic surface waters decreased. This reduced North Atlantic deep water formation and possibly enabled cross-equatorial flow of warm surface waters to the

North Atlantic (Broecker et al., 1990; Keigwin and Lehman, 1994). So, cold centered in the North Atlantic but extending well beyond, and probably containing most of the globe (Denton and Hendy, 1994; Steig et al., 1998).

Zone II (11.3–8.9 cal ka BP) was a mainly wet climatic stage, and characterized by increasing the TOC and C/N values, which showed that terrestrial organic matter dominated. Because of strengthening summer insolation but weakening winter insolation in the Northern Hemisphere (Fig.5), ice meltwater increased and evaporation decreased, suggested enhanced fluviation and a wet climate. Additionally, the intensification of the Asian summer monsoon during this time might also have affected the study region (Dykoski et al., 2005; Li et al., 2011).

Zone III (8.9–7.7 cal ka BP) was separated into two sub zone. Within Zone IIIa (8.9–8.2 cal ka BP), abundant glauberite was present in the sediment and the >15.9 μm fraction and Md showed clear increase. This indicated that the lake shrank and climate was dry overall. However, in Zone IIIb (8.2–7.7 cal ka BP), the C/N, TOC, and <15.9 μm grain size fraction significantly increased, implying a high lake level and a wet climate.

In Zone IV (7.7–6.6 cal ka BP), the proxy records showed that the climate presented a bit wet conditions. But at 7.6 cal ka BP, variations in TOC, TN, and C/N values displayed decreased values, but the grain size increased; this suggested that the lake level dropped, eolian activity strengthened and thus had a higher sand content, all of which suggested a dry climate.

Zone V (6.6–5.6 cal ka BP) was characterized by a dry climate. From ~6.6 cal ka BP, abundant glauberite was present in the sediment, which was dominated by silt-sized particles. Besides that, TOC, TN, and C/N values manifested decrease. This indicated that the lake shrank and the climate was dry.

4.3 Abrupt environmental change during the Early–Middle Holocene

Figure 5 shows that grain size <15.9 μm and >15.9 μm have obvious change around the Late Glacial/Holocene transition. As mentioned above, from 13.0 to 11.3 cal ka BP (Zone I), the content of fine grained fraction was relatively high, but with dropping trend and was mainly affected by the kinetic energy of circulation in Lake Lop Nur causing the weakening of the summer insolation and less river runoff. While, grain size differed markedly during the Early–Middle Holocene when summer Insolation strengthened but weakening winter insolation in the Northern Hemisphere. As a result of temperatures going up, ice meltwater increasing, fluviation intensifying, grain size <15.9 μm fraction became the suspended particles in rivers and then joined in lake sediment.

According to the environmental proxy records generated from Lake Lop Nur sediment, such as TOC and grain size fractions (<15.9 μm and >15.9 μm), there is good evidence for abrupt climate events during the Holocene. Three abrupt events at 11.0, 8.2, and 7.6 cal ka BP, are consistently represented by the TOC and grain size distribution of Core DHX and $\delta^{18}O$ of the Greenland Ice Core Project record (Stuiver and Grootes, 2000) (Fig.5).

At 11.0, 10.5, 9.3, and 8.2 cal ka BP, the >15.9 μm size fraction and Md clearly increased, which corresponded to decreases in TOC, TN, and C/N values; this showed that the lake level lowered and eolian supply to the lake intensified, consistent with dry events at these times (Bond et al., 1997; Alley and Ágústsdóttir, 2005). In contrast, C/N, TOC, and <15.9 μm grain size significantly increased and TOC reached a maximum value between 7.8 and 7.7 cal ka BP. This resulted from enhanced fluvial activity where rivers carried exogenous organic matter and fine-grained particles into Lake Lop Nur, implying a high lake level and flood events. Many other enclosed lakes in the arid and semi-arid region of China, such as Lake Dalinor (Inner Mongolia) and Lake Chaiwopu (Xinjiang), also displayed high lake levels during 7.8–7.4 cal ka BP (Wang and Wang, 1992). At 7.6 cal ka BP, TOC, TN, and C/N values decreased while grain size increased, indicating a lowered lake level, stronger eolian activity that delivered sand to the lake, and a dry climate. This was approximately consistent with records from Lake Bosten (Mischke and Wünnemann, 2006).

In conclusion, the dry events at 8.2, 9.3, 10.5, and 11.0 cal ka BP evident in Core DHX corresponded to North Atlantic ice-rafted debris events 5, 6, 7, and 8 respectively (Bond et al., 1997). Additionally, the climate was also dry at 8.6 and 7.6 cal ka BP. However, during 7.8–7.7 cal ka BP, the TOC, C/N, and <15.9 μm size fraction increased, suggesting that the climate was humid and there was a high lake level, all evidence for a flood event.

5 CONCLUSION

Sedimentary characteristics were assessed in a core recovered from Lake Lop Nur in Xinjiang, northwest China. Variations in different proxy parameters (TOC, TN, C/N, grain size) were found to reflect environmental changes during 13.0–5.6 cal ka BP and the record can be divided into five zones. Zone I (13.0–11.3 cal ka BP) was a wet–dry climatic environment whereas Zone II (11.3–8.9 cal ka BP) was a wet climatic stage. Zone III (8.9–7.7 cal ka BP) was subdivided into Zone IIIa (8.9–8.2 cal ka BP) that contained abundant glauberite, larger sized grains (>15.9 μm), and increased Md values, indicating lake constriction and dry climate, and Zone IIIb (8.2–7.7 cal ka BP) in which the proxies indicated wet conditions. In Zone IV (7.7–6.6 cal ka BP), the climate presented a bit wet conditions. Zone V (6.6–5.6 cal ka BP) was characterized by a dry climate. Abundant glauberite was present and silt–sized grains dominated, suggesting lake constriction and a dry climate. In the Early–Middle Holocene, six dry events (11.0, 10.5, 9.3, 8.6, 8.2, and 7.6 cal ka BP) and a flood event from 7.8 to 7.7 cal ka BP were identified from the Lake Lop Nur sediment record.

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References

Alley R B, Ágústsdóttir A M. 2005. The 8ka event: cause and consequences of a major Holocene abrupt climate. *Quaternary Science Review*, **24**(10-11): 1 123-1 149.

Alley R B, Mayewski P A, Sowers T, Stuiver M, Taylor K C, Clark P U. 1997. Holocene climatic instability: a prominent, widespread event 8200 yr ago. *Geology*, **25**(6): 483-486.

Alley R B. 2000. The Younger Dryas cold interval as viewed from central Greenland. *Quaternary Science Reviews*, **19**(1-5): 213-226.

Alve E, Lepland A, Magnusson J, Backer-Owe K. 2009. Monitoring strategies for re-establishment of ecological reference conditions: possibilities and limitations. *Marine Pollution Bulletin*, **59**(8-12): 297-310.

Battarbee R W. 1999. The importance of palaeolimnology to lake restoration. *Hydrobiologia*, **395**: 149-159.

Blaauw M, Christen J A. 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis*, **6**(3): 457-474.

Bond G, Showers W, Cheseby M, Lotti R, Almasi P, deMenocal P, Priore P, Cullen H, Hajdas I, Bonani G. 1997. A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science*, **278**(5341): 1 257-1 266.

Broecker W S, Bond G, Klas M, Bonani G, Wolfli W. 1990. A salt oscillator in the glacial Atlantic? 1. The concept. *Paleoceanography*, **5**(4): 469-477.

Cai B G, Edwards R L, Cheng H, Tan M, Wang X, Liu T S. 2008. A dry episode during the Younger Dryas and centennial-scale weak monsoon events during the early Holocene: a high-resolution stalagmite record from southeast of the Loess Plateau, China. *Geophysical Research Letters*, **35**(2): L02705.

Chen G Q, Yi L, Chen S L, Huang H J, Liu Y X, Xu Y H, Cao J R. 2013. Partitioning of grain-size components of estuarine sediments and implications for sediment transport in southwestern Laizhou Bay, China. *Chinese Journal of Oceanology and Limnology*, **31**(4): 895-906.

Denton G H, Hendy C H. 1994. Younger Dryas age advance of Franz Josef glacier in the southern alps of New Zealand. *Science*, **264**(5164): 1 434-1 437.

Dong Z B, Lv P, Qian G Q, Xia X C, Zhao Y J, Mu G J. 2012. Research progress in China's Lop Nur. *Earth-Science Reviews*, **111**(1-2): 142-153.

Dykoski C A, Edwards R L, Cheng H, Yuan D X, Cai Y J, Zhang M L, Lin Y S, Qing J M, An Z S, Revenaugh J. 2005. A high-resolution, absolute-dated Holocene and deglacial Asian monsoon record from Dongge Cave, China. *Earth and Planetary Science Letters*, **233**(1-2): 71-86.

Garcin Y, Vincens A, Williamson D, Buchet G, Guiot J. 2007. Abrupt resumption of the African Monsoon at the Younger Dryas—Holocene climatic transition. *Quaternary Science Reviews*, **26**(5-6): 690-704.

Håkanson L, Jansson M. 1983. Principles of Lake Sedimentology. Springer, Berlin. 316p.

Han S T, Li Z Z. 1994. The accumulating regulation of deposit geochemistry of Balikun Lake, Xinjiang. *Oceanologia Et Limnologia Sinica*, **25**(4): 429-437. (in Chinese with English abstract)

Jia H J, Qin X G, Liu J Q. 2012. Environmental changes recorded by major elements in Loulan Stupa Section during Early–Middle Holocene. *Journal of Earth Science*, **23**(2): 155-160.

Keigwin L D, Lehman S J. 1994. Deep circulation change linked to Heinrich event 1 and Younger Dryas in a middepth North Atlantic core. *Paleoceanography*, **9**(2): 185-194.

Klitgaard-Kristensen D, Sejrup H P, Haflidason H, Johnsen S, Spurk M. 1998. A regional 8200 cal. yr BP cooling event in northwest Europe, induced by final stages of the Laurentide ice-sheet deglaciation? *Journal of Quaternary Science*, **13**(2): 165-169.

Kranck K, Smith P C, Milligan T G. 1996a. Grain-size characteristics of fine-grained unflocculated sediments I: 'one round' distributions. *Sedimentology*, **43**(3): 589-596.

Kranck K, Smith P C, Milligan T G. 1996b. Grain-size characteristics of fine-grained unflocculated sediments II: 'multi-round' distributions. *Sedimentology*, **43**(3): 597-606.

Lerman A. 1978. Lake: Chemistry, Geology, Physics. Springer-Verlag, Berlin. p.79-83.

Li X Q, Zhao K L, Dodson J, Zhou X Y. 2011. Moisture dynamics in central Asia for the last 15 kyr: new evidence from Yili Valley, Xinjiang, NW China. *Quaternary Science Reviews*, **30**(23-24): 3 457-3 466.

Liu X Q, Herzschuh U, Shen J, Jiang Q F, Xiao X Y. 2008. Holocene environmental and climatic changes inferred from Wulungu Lake in northern Xinjiang, China. *Quaternary Research*, **70**(3): 412-425.

Luo C, Peng Z C, Yang D, Liu W G, Zhang Z F, He J F, Chou C L. 2009. A lacustrine record from Lop Nur, Xinjiang, China: implications for paleoclimate change during Late Pleistocene. *Journal of Asian Earth Sciences*, **34**(1): 38-45.

Ma C M, Wang F B, Cao Q Y, Xia X C, Li S F, Li X S. 2008. Climate and environment reconstruction during the Medieval Warm Period in Lop Nur of Xinjiang, China. *Chinese Science Bulletin*, **53**(19): 3 016-3 027.

Meyers P A, Teranes J L. 2001. Sediment organic matter. *In:* Last W M, Smol J P eds. Tracking Environmental Change Using Lake Sediments: Physical and Geochemical Methods. Springer, Netherlands. p.239-269.

Mischke S, Wünnemann B. 2006. The Holocene salinity history of Bosten Lake (Xinjiang, China) inferred from ostracod species assemblages and shell chemistry: possible palaeoclimatic implications. *Quaternary International*, **154-155**: 100-112.

Rhodes T E, Gasse F, Lin R F, Fontes J C, Wei K Q, Bertrand P, Gibert E, Mélières F, Tucholka P, Wang Z X, Cheng Z Y. 1996. A late Pleistoncene-Holocence lacustrine record from Lake Manas, Zunggur (northern Xinjiang, western China). *Palaeogeography, Palaeoclimatology, Palaeoecology*, **120**(1-2): 105-121.

Steig E J, Brook E J, White J W C, Sucher C M, Bender M L, Lehman S J, Morse D L, Waddington E D, Clow G D. 1998. Synchronous climate changes in Antarctica and the North Atlantic. *Science*, **282**(5386): 92-95.

Stuiver M, Grootes P M. 2000. GISP2 oxygen isotope ratios. *Quaternary Research*, **53**(3): 277-284.

Sun D H, Bloemendal J, Rea D K, Vandenberghe J, Jiang F C, An Z S, Su R X. 2002. Grain-size distribution function of polymodal sediments in hydraulic and aeolian environments, and numerical partitioning of the sedimentary components. *Sediment Geology*, **152**(3-4): 263-277.

Wang J Z, Wu J L, Zeng H A. 2015. Sediment record of abrupt environmental changes in Lake Chenpu, upper reaches of Yellow River Basin, north China. *Environmental Earth Sciences*, **73**(10): 6 355-6 363.

Wang M L, Pu Q Y, Liu C L, Chen Y Z. 2000. Quaternary climate and environment in the Lop Nur, Xinjiang. *Acta Geologica Sinica*, **74**(2): 273-278.

Wang S M, Wang F B. 1992. The Limnological record of Holocene fluctuation. *In:* Shi Y F ed. The Climates and Environments of Holocene Megathermal in China. China Ocean Press, Beijing, China. p.146-152. (in Chinese)

Wu J L, Ma L, Yu H, Zeng H A, Liu W, Abuduwaili J. 2013. Sediment geochemical records of environmental change in Lake Wuliangsu, Yellow River Basin, north China. *Journal of Paleolimnology*, **50**(2): 245-255.

Wu J L, Wang S M, Wu Y H. 1996. The Holocene sedimental Characteristic and paleoclimatic evolution of Ebinur Lake, Xinjiang. *Chinese Geographical Science*, **6**(1): 78-88.

Xiao J L, Chang Z G, Si B, Qin X G, Iton S, Lomtatidze Z. 2009. Partitioning of the grain-size components of Dali Lake core sediments: evidence for lake-level changes during the Holocene. *Journal of Paleolimnology*, **42**(2): 249-260.

Xue J B, Zhong W. 2008. Holocene climate change recorded by lacustrine sediments in Barkol Lake and its regional comparison. *Quaternary Sciences*, **28**(4): 610-620. (in Chinese with English abstract)

Yang D, Peng Z C, Luo C, Liu Y, Zhang Z F, Liu W G, Zhang P X. 2013. High-resolution pollen sequence from Lop Nur, Xinjiang, China: implications on environmental changes during the late Pleistocene to the early Holocene. *Review of Palaeobotany and Palynology*, **192**: 32-41.