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Holocene abrupt climate shifts recorded in Gun Nuur lake core, northern Mongolia

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Abstract **A continuous 7.44 m lake core was successfully drilled at Gun Nuur Lake, northern Mongolia, and analyses on environment magnetic parameters, organic matter content and organic δ^{13}C were conducted in an attempt to retrieve the Holocene chronosequence of climatic changes based on 6 AMS ^{14}C dates. We found that the Holocene climate in northern Mongolia has been alternating between cold (or cool)/wet conditions and warm/arid conditions, and also punctuated with a series of abrupt climate shifts. The abrupt climate shifts occurred around 1750, 2800, 4000, 5200, 7200, and 9200 aBP (^{14}C age), being chronologically correlative to those abrupt climatic events recorded in the high-latitude North Atlantic Ocean. The correlation indicates that the climatic changes in northern Mongolia were linked with those in the North Atlantic Ocean probably via the North Atlantic Oscillation-affected westerly winds. The strength and position of westerly winds might have modulated the Siberian-Mongolian high pressure system (winter monsoon), directly influencing the climate in China.**

Keywords: Mongolian Plateau, Holocene, Gun Nuur Lake, abrupt climatic event.

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The Holocene abrupt climatic change on millennial- and centennial-scales is one of the hottest scientific issues in global change research because it may provide direct hints for our future climatic change. The δ^{18}O records from the Greenland ice core suggested a stable Holocene climate[1]. Yet, O'Brien et al.[2] demonstrated from the measurements of soluble impurities in Greenland ice core that the Holocene atmospheric circulation above the ice cap was punctuated by a series of millennial-scale shifts. Subsequently, Holocene climatic instability has been reported from many places[3—9]. Based on the study of sediments in the high-latitude North Atlantic Ocean, Bond et al.[3] extended the well-documented last glacial periodicity (about 1500 years) of climatic change into the Holocene and proposed a plausible explanation that the Holocene climatic variations might have been paced by the solar activities[10]. Bond et al. also attributed the documented lower amplitude of the Holocene climatic variations to the lack of amplifier of North American ice sheet that dominated the Last Glacial. When elucidating the significance of the North Atlantic Oscillation (NAO), Visbeck[11] proposed that the NAO dominates the winter atmospheric variability in the extratropical Northern Hemisphere, which not only influences the climates in the regions surrounding the North Atlantic, but also affect the strength of the westerly winds across the mid-latitudes. The westerly winds influence the climate in the Mongolian Plateau, which in turn affect the Siberian-Mongolian high-pressure system (Winter monsoon) and thus affect the climate in China[12].

If above hypotheses are correct, the Holocene abrupt climate shifts recorded in North Atlantic Ocean might have left geological imprints in northern Mongolia. However, the previous studies[13—20] on the Holocene climate in northern Mongolian did not find abrupt climate shifts correlative to those recovered from the North Atlantic Ocean although the Holocene climatic instability was reported from lacustrine and eolian sequences in the Lake Baikal and northern Mongolia. This uncertainty in the chronological correlation between northern Mongolian records and the North Atlantic records might result from any or a combination of the following possibilities. First, the accumulation rate of lacustrine sediments was too low and the sampling resolution was not adequate to capture the signature of abrupt climate shifts. Second, the climate proxies used were insensitive to the abrupt climate shifts and thus failed to record the abrupt climate shifts. Third, the chronologies established in the previous studies may be highly problematic. This uncertainty may also imply that the abrupt climatic shifts documented in the North Atlantic Ocean did not occur in northern Mongolia. Therefore, it is of paramount importance to scrutinize the Holocene climatic changes in northern Mongolia for depicting the temporal and spatial patters and thus understanding the mechanisms and processes of global Holocene abrupt climatic changes.

The focus of this study is on Gun Nuur (50° 15′ N, 106° 36′ E), a lake near the border between Mongolia and Russia (about 100 km south to the Lake Baikal) situated at the core of the Siberian-Mongolian high-pressure system. Compared with the Holocene portion of the Lake Baikal core (only 1.6 m thick), the Gun Nuur core (7.44 m thick) should have recorded much greater details of the changes in Siberian-Mongolian High-related climate. In this paper, we present the Holocene chronosequence of climatic changes in northern Mongolia in attempts to uncover the temporal patterns of the Holocene abrupt climatic changes and to enhance our understanding of global Holocene climatic instability.

1 Field sampling and laboratory methods

Gun Nuur (50° 15′ N, 106° 36′ E) is a closed depressing basin with semi-saline to fresh water and flat bottom, and the maximum of water depth is 5 m. The mean annual precipitation is 300—400 mm and the vegetation is a forest-steppe. The forest-steppe gives way to steppe first and then to desert (Gobi) due to the southward decrease in precipitation. From the Gobi southward to Inner Mongolia and the Chinese Loess Plateau, the vegetation turns into steppe again due to the increase in precipitation associated with the summer monsoon. It is apparent that the precipitation is of significant importance to the vegetation distributions in the Mongolian Plateau.

In 2002, we successfully drilled a 7.44 m lake core from Gun Nuur with a piston corer. To ensure the completeness of the sequences, two cores were drilled within a distance of 3 m and one more was drilled 10 m away to back up. To further ensure the continuousness of the core, different lengths of drilling tubes were adopted for each one of the three cores so that the tube-joining depths of a cores where sample contamination and distortion occur are surely sampled by another core. The tubes containing sampled cores were transported to Ulaan Baatar and split into two halves. A completely continuous sequence was then obtained by visually comparing the three cores (e.g. colors and textures).

The lake core was sub-sampled at 1 cm intervals and all samples were dried in an oven at a temperature of 40℃. The environment magnetic parameters, organic matter content and organic carbon isotope ($\delta^{13}C$) were measured at 2 cm, 4 cm and 7—8 cm intervals, respectively. Rock magnetic parameters were measured by the procedure of Maher et al.[21]. First, magnetic susceptibility (k) was measured using a Bartington MS2 susceptibility meter. Second, isothermal remanent magnetizations (IRM) were induced in a sequence of magnetic fields of increasing value up to 1T and then with reversed fields of 100 mT using an ASC IM10-30 Pulse Magnetiser. The IRM induced using the field of 1T is referred as saturation isothermal remanent magnetization (SIRM), while those installed using the reversed fields of 100 mT are abbreviated as 'IRM_{-100mT}'. Measurements of the IRM_{-100mT} and SIRM were performed with an Agico JR-5A Spinner magnetometer. After completion of the magnetic measurements, mass specific parameters were calculated. Hard isothermal remanent magnetization (HIRM) is defined as '[SIRM+IRM_{-100mT}]/2' and S-Ratio was calculated as '-IRM_{-100mT}/SIRM'[22—24].

Organic carbon isotope was measured by the following steps: the dried sediment sample powder was treated with HCl, then washed with distilled water and dried again at 100℃ in an oven. The processed samples were combusted with O_2 at around 800℃. The derived CO_2 produced by decomposing the organic matters was analyzed in the Delta Plus mass spectrometer as $\delta^{13}C$ relative to the PDB standard. For the total organic carbon content, samples were analyzed by the antititration method involving oxidation of the organic carbon in the medium of sulphuric acid (H_2SO_4) by excessive potassium dichromate ($K_2Cr_2O_7$) and antititration of the residual potassium dichromate by ammonium ferrous sulfate ($(NH_4)_2SO_4 \cdot FeSO_4 \cdot 6H_2O$). Dating material were sampled at the central part of the lake core at different intervals and measured by Beta Analytic Inc. (USA) with the Accelerator Mass Spectrometry(AMS)^{14}C dating technique.

2 Results

The AMS ^{14}C dates of the Gun Nuur lake core are shown in Table 1. The date of 9500a BP(10690—10760 cal. aBP) at the bottom of the core indicates that the lake core covers the entire Holocene history. The ages of all samples were calculated by linear interpolation based on the 6 AMS ^{14}C dates. According to the calculation, the temporal resolution of magnetic parameters at 2 cm intervals is 15—30 years. Because the ^{14}C dates against which we are comparing ours were given in ^{14}C years (aBP), the ages quoted in this paper are also given in ^{14}C years (aBP) although our AMS ^{14}C dates were calibrated to the calendar years (cal. aBP) according to the method of Stuiver et al's[25].

The variations of environmental magnetic parameters against depth and time are shown in Figs. 1 and 2. The magnetic susceptibility (κ) values in the lake core can be classfied into the following categories: (1) interval of a low κ with the susceptibility values below $2.5\times10^{-7}m^3/kg$; (2) interval of a moderate κ with the values ranging from 2.5 to $5\times10^{-7}m^3/kg$; (3) interval of a high κ with values ranging from 5 to $7.5\times10^{-7}m^3/kg$; and (4) interval of a very high κ with the susceptibility values exceeding 7.5×10^{-7} m^3/kg. Stratigraphically speaking, except for the bottom 24 cm of the core whose magnetic susceptibility is

Table 1 Radiocarbon dates of the Gun Nuur lake core

Sample	Lab. No.	Depth/cm	$^{13}C/^{12}C$ (‰)	^{14}C age/aBP	Calibrated age (1σ)/aBP
GN3	Beta-171822	64—65	−23.1	1900±40	1880—1820
GN8	Beta-171823	151—152	−24.1	2530±40	2580—2510
GN12	Beta-171824	240—242	−21.0	3250±40	3480—3440
GN16	Beta-171825	342—344	−22.7	4910±40	5660—5600
GN18	Beta-171826	391—392	−20.9	5820±50	6670—6560
GN34	Beta-171827	743—744	−26.8	9500±50	10760—10690

All samples were dated with AMS method by Beta Analytic Inc., Miami, Florida, USA.

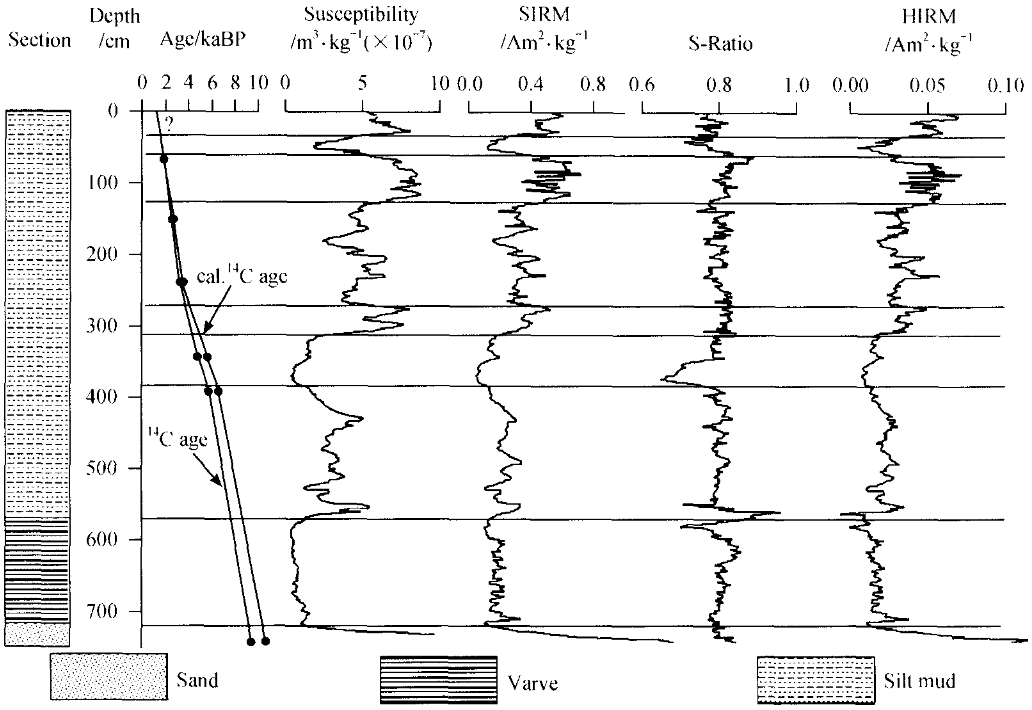

Fig. 1. Lothology, AMS ^{14}C dates and rock magnetic parameters of Gun Nuur lake core.

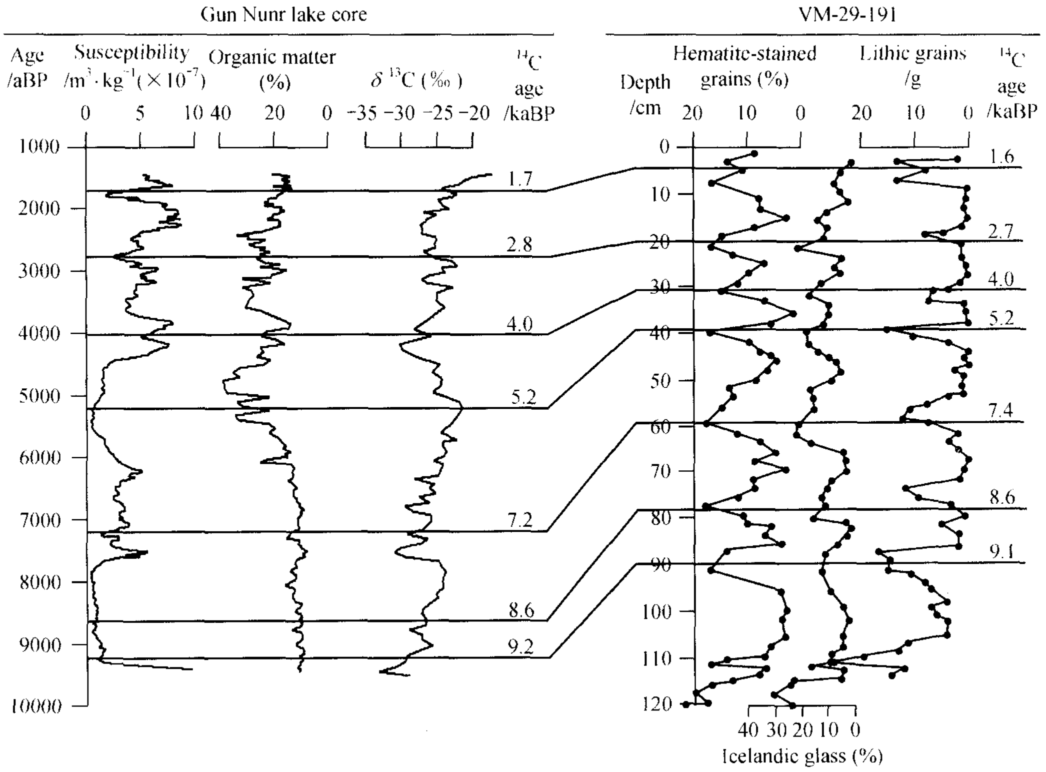

Fig. 2. The variations of magnetic susceptibility, organic matter content and organic carbon isotope in Gun Nuur lake core and the correlation of abrupt climate shifts with VM-29-191[13].

extremely high, the lake core can be divided into two parts: upper part (0—310 cm) and lower part (310—720 cm). The susceptibility is generally higher in the upper part of the core than in the lower part. The susceptibility values are low with minimal fluctuations in two separate segments: from 720 to 570 cm (9300—7700 aBP) and from 380 to 310 cm (5600—4400 aBP). The susceptibility values fall into moderate category and vary considerably from 570 to 380 cm (7700—5600 aBP) with a minimal interval around 525 cm (i.e. around 7210 aBP). In the upper part of the core, four peaks in the susceptibility values occur in following segments: a high peak in 270—310 cm (4400—3700 aBP), a moderate peak in 200—240 cm (3250—2900 aBP), a broad and high peak in 60—125 cm (1900—2300 a BP), and a narrow moderate peak in the top 30 cm of the core. Among the three magnetic susceptibility lows (270—240 cm, 200—125 cm and 60—30 cm) in the upper part, the 60—30 cm one is the lowest although the thinnest (likely the shortest). As for the other magnetic parameters, the SIRM, HIRM and S-Ratio (IRM $_{-100\mathrm{mT}}$/SIRM) are positively correlated to the susceptibility (see Fig. 1).

The core can be divided into two parts based on the linearly interpolated age framework (see Fig. 2): stably lower organic matter content in the lower portion from 9500 to 6100 aBP (<15%) and variably high in the upper portion from 6100 to the top (>15%). Two segments have very high organic matters: 5600—4500 aBP and 3700—3300 aBP. The organic δ^{13}C values of the lake core range from −33.5‰ to −17.4‰ with an average of −25.84‰. The organic δ^{13}C values are basically negatively correlated to the susceptibility and characterized by patterned fluctuations (see Fig. 2).

3 Discussions and conclusions

(i) Climatic and environmental significances of the proxies. Rock magnetic parameters have been intensively and successfully utilized to study the paleoclimate and paleoenvironmental change recorded in lacustrine sediments. The magnetic susceptibility is the most frequently used magnetic parameter in the study of lacustrine sediments and was found to be correlative with certain geochemical and palynological proxies[26,27], demonstrating its usefulness in paleoclimate and paleoenvironmental study. Generally, the susceptibility and SIRM reflect the concentration of remanence-carrying magnetic minerals[26,28]. High susceptibility and SIRM values may be attributable to an increase in magnetic mineral input and/or to a decrease in organic matter input resulted from a low productivity or a poor preservation[26,28]. Furthermore, the redox after deposition plays an important role in the change of magnetic minerals[29]. During the stage of ferriferous oxide reduction, the ferrimagnetic minerals were dissolved according to the order of particle size from fine to coarse[30], whereas redox exerts no influence on the antiferromagnetic minerals[31]. S-Ratio is a measure of relative proportions of antiferromagnetic to ferrimagnetic minerals in a sample and HIRM reflects the concentration of antiferromagnetic minerals[22,23,32].

The rock magnetism parameters of the Gun Nuur lake core indicate that the content of ferrimagnetic and antiferromagnetic minerals is higher in samples that have a higher magnetic susceptibility and SIRM value, and *vise verse*. The characteristics of the hysteresis are related to the species and grain size of magnetic minerals[26]. The hysteresis-assisted interpretation of the magnetic susceptibility values (see Fig. 3) shows that the primary magnetic minerals in all samples are multidomain ferrimagnetic ones. When susceptibility value is lower in a sample, the relative content of antiferromagnetic is higher, suggesting that redox occurred after deposition.

Except for the samples below 570 cm (7700 aBP), the magnetic susceptibility and the organic matter content are negatively correlated. The organic matter content is considered as an indicator of vegetation cover and biomass[33], related to effective precipitation and effective soil moisture as corroborated by the data from the sand/loess/palaeosol sequence in northern Mongolia[18]. The mechanism controlling the variation in the magnetic susceptibility might be associated with the following circumstances: (1) Under cold-wetter and possible reducing conditions, fine ferromagnetic particles were dissolved firstly resulting in a low content of magnetic minerals with a low value of magnetic susceptibility and SIRM; (2) under wetter conditions, the better vegetation coverage resulted in less erosion in the watershed contributing water to the lake and thus reduced magnetic mineral input; and (3) effective accumulation of organic matters diluted the concentration of magnetic minerals, thus lowering the magnetic signature.

The variation in the organic δ^{13}C values has been convincingly linked to climate changes[34—36]. According to Wu et al.'s study[37] in high-altitude area or high-latitude area where the contribution of C4 plant is very low or close to nil, higher values of δ^{13}C in lacustrine sediments are reportedly corresponding to colder intervals. The high-latitude Gun Nuur lake is beyond the northern limit of modern C4 grasslands[16,38]. Our analytical results show that except for the samples in the top of the core whose δ^{13}C value is relatively high, the values of δ^{13}C of other samples are basically constrained within the range of δ^{13}C value of C3 plants. The data from Lake Baikal, about 100 km north to the Gun Nuur Lake, show that the organic δ^{13}C values in the last glacial was higher than in the Holocene and a negative correlation between the organic δ^{13}C and the temperature was shown in the Lake Baikal

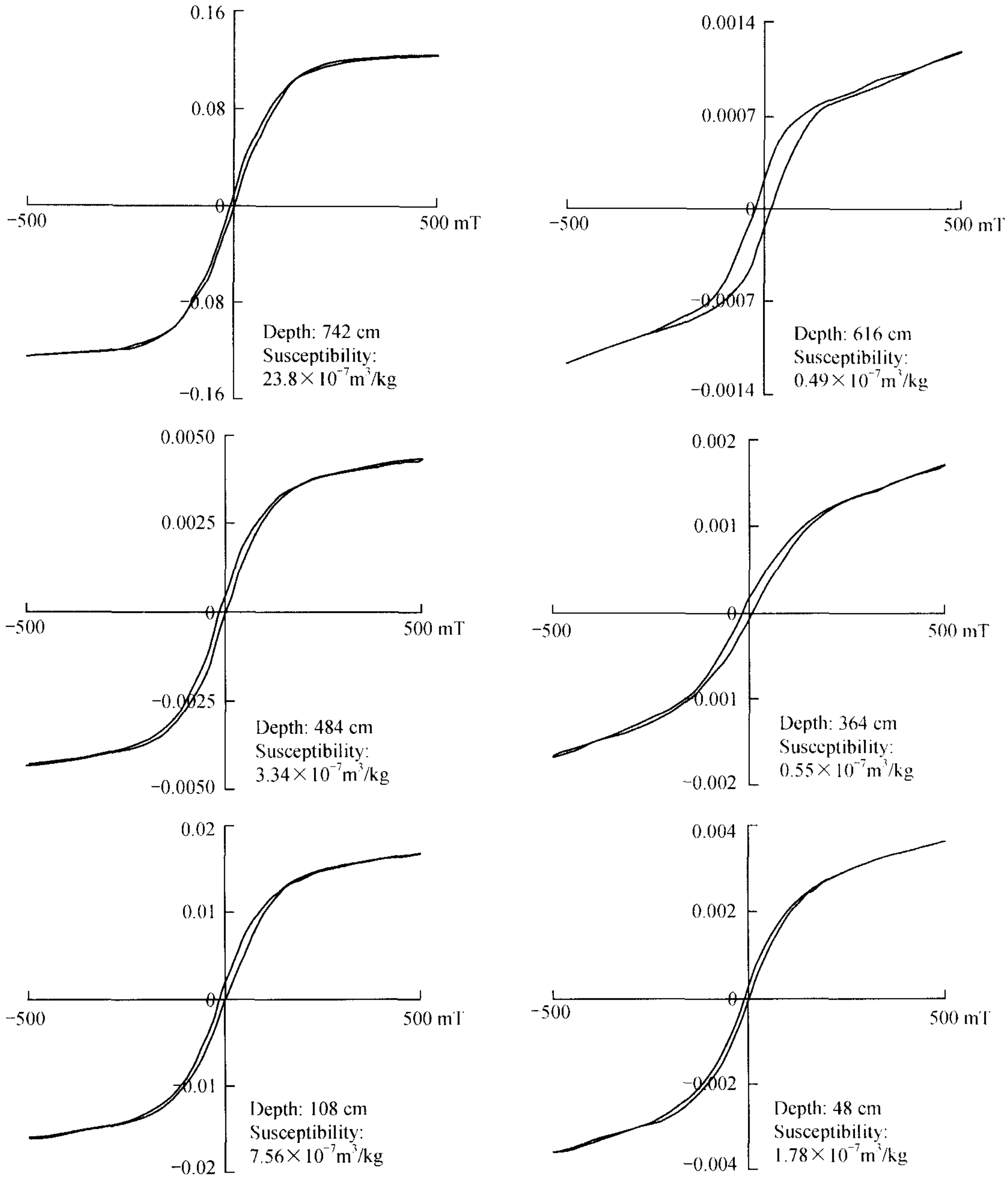

Fig. 3. Magnetic hysteresis loop from the samples of Gun Nuur lake core with different magnetic susceptibility values (units at the ordinates: emu).

although the authors did not mention that[13,15], being consistent with the conclusion of Wu et al.[37].

(ii) Interpretation of the results. Our reconstructed Holocene palaeoclimatic sequence from the Gun Nuur lake core can be correlated to those of previous studies. For example, two low susceptibility intervals of the core in 570—720 cm (9300—7700 aBP) and in 310—380 cm (5600—4400 aBP) seem to correspond to two distinct palaeosols in northern Mongolia dated at 8300±100 aBP and 4780±80 aBP and the eolian sand layer probably to the relatively high susceptibility interval in 380—570 cm depth (7700—5600 aBP) at Shaamar eolian/soil section 100 km west to the Gun Nuur[18,39]. It should be noted that the bottom 24 cm coarse sand of eolian origin suggests that the lake was dry before 9300 aBP. The period from 9300 to 7700 aBP (570—720 cm) is characterized by a poor correlation between magnetic susceptibility and organic matter content and a high $CaCO_3$ concentration (up to 70%) in this interval is held responsible for diluting the concentrations of magnetic minerals. It was a time of warming and the boreal forest treeline advanced to north significantly during that period[40]. The varve structure of sediments in this part of the core (570—720 cm) implies that the lake water was deep, reflecting a wet and relatively warm climate[16].

The peak in organic matter content in 310—380 cm (5600—4100 aBP) in the Gun Nuur corresponding to the palaeosol layer dated at 4780±80 aBP at Shaamar eolian/soil section suggests a better vegetation coverage. The diatom data from the Lake Baikal also suggested a relatively cold climate in this period[14]. Based on the high δ^{13}C values in the Gun Nuur lake core, the climate in northern Mongolia during the 5600—4100 aBP was cold (or cool) and wetter, chronologically being consistent with the generally cold climate in the northern Hemisphere[41—45].

The magnetic susceptibility values above 310 cm of the core is negatively correlated to the organic matter contents and organic δ^{13}C values, indicating that the low magnetic susceptibility corresponds to cold (or cool) climate. According to these proxies, relatively cold (cool) periods occurred at: 30—60 cm (1650—1900 aBP), 125—200 cm (2300—2900 aBP) and 240—270 cm (3250—3700 aBP). The organic matter content is generally high in 0—310 cm of the core, indicating a better vegetation coverage, which was probably resulted from the decreased temperature related lower evaporation in northern Mongolia[16]. To sum up, higher magnetic susceptibility in the core corresponds to warmer and drier climate, whereas lower magnetic susceptibility corresponds to colder (or cooler) and wetter climate. This type of Holocene water and heat combination in northern Mongolia differs from that in the Southern Mongolian Plateau and the Chinese Loess Plateau that have been affected by the summer Asian monsoon.

(iii) Abrupt climate shifts. Our better-dated Gun Nuur Holocene sequence also shows abrupt climate shifts that superimpose on longer timescale climatic changes. The ages of the more obvious events, as indicated by magnetic susceptibility and organic matter content are interpolated to have occurred around 1750, 2800, 4000, 5200, 7200, 9200 aBP, which can be correlated both to abrupt climate shifts recorded in the North Atlantic Ocean and to the Zoige Plateau in China[3,46]. The correlation implies existence of mechanism linkage of climate changes in the North Atlantic area, Mongolian Plateau and Tibetan Plateau. In Gun Nuur lake core, the event correlated to that in North Atlantic Ocean dated at 8600 aBP is not distinctive and the event dated at 9200 aBP might be mirror to that dated at 9100 aBP in the North Atlantic Ocean. The major event dated at 7200 aBP in Gun Nuur was correlative to that dated at 7400 aBP in the VM—29 and 7200 aBP in the VM—28. It should be reminded that the calibrated age of 7200 aBP is close to 8200 cal. aBP, and the 8200 cal. aBP event was the most prominent cold event in Holocene since the Younger Dryas event and has been well documented[47]. In the Gun Nuur lake core, the event presents an abrupt shift from warm and dry conditions to cold (or cool) and wet conditions at this time (8200 cal. aBP). The event of 5200 aBP is not so striking in the magnetic susceptibility curve, but a very high peak of organic matter content suggests this cold interval. The events of 2800 aBP and 1750 aBP exhibit discrepancy of 100 years and 150 years respectively from the correlated events in the North Atlantic Ocean. The event of 1750 a BP has a relatively large discrepancy from that in North Atlantic Ocean, which was probably resulted from skewed age extrapolation in the top 60 cm of the core. Taking into consideration of the chronological uncertainties (based on only six AMS ^{14}C dates so far), we suggest that the abrupt events in the Gun Nuur lake core are the chronological correlative to those recorded in the North Atlantic Ocean.

In conclusion, the data from the Gun Nuur lake core in northern Mongolia demonstrate that the Holocene climate was unstable and characterized by either a cold (or cool)/wet or warm/dry combination, being consistent with those reported from northwestern China[48]. Moreover, the data also documented abrupt climatic shifts that can be correlated to the ice rafting events in the high-latitude North Atlantic Ocean, suggestging that the NAO might have affected the climate in Siberia and northern Mongolia via influencing the strength of the westerly winds[11].

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