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Late Pleistocene–Holocene records from Lake Ulaan, southern Mongolia: implications for east Asian palaeomonsoonal climate changes

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ABSTRACT: A 5.88-m-long core taken from Lake Ulaan was studied for high-resolution paleoclimatic changes during the last 17 000 years. The core sediments are divided into three units based on grain-size distribution: unit 1 (top to 392 cm depth, covering the last 11 200 years), unit 2 (392–530 cm, 11.2–15 ka) and unit 3 (530–588 cm, 15.0–16.7 ka). These sediments were transported by local westerly winds (units 1 and 3) and fluvial processes (unit 2). Based on major element compositions and geological setting of adjacent areas, provenance of unit 1 sediments was interpreted to be the Lake terrane, and that of unit 2 to be the Idermeg terrane. Unit 3 sediments were derived from the Gobi Altai terrane. The records of total organic carbon, C/N ratio and weathering intensity suggest that paleoclimate in the source area of Lake Ulaan sediment was most humid during the Early Holocene, humid during the mid-Holocene and dry in the Late Holocene. The decrease of humidity through the Holocene is a typical characteristic of the East Asian monsoon region. Comparison with lacustrine records of other Mongolia regions suggests that the northern boundary of East Asian summer-monsoon influence could have been located further north than previously assumed. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS: East Asian monsoon; Holocene; lake sediment; Mongolia; paleoclimate.

Introduction

Holocene climatic changes have been in the spotlight as a means of establishing baselines for predicting future warming and associated ecological responses. Information on Holocene climatic changes is being compiled, but more high-resolution data from climatically sensitive regions are needed.

Arid and semi-arid Continental Asia, including southern Mongolia, is one of the most sensitive regions to large-scale climatic changes (D'Arrigo *et al.*, 2000). The location of Mongolia is particularly important for climate reconstructions because it is situated at the junction of two large-scale northern hemispheric climate systems: (i) the Westerlies, modulated by the North Atlantic Oscillation (NAO) (Visbeck, 2002) and (ii) the East Asian monsoon, which is associated with the El Niño-Southern Oscillation (ENSO) and the Intertropical Convergence Zone (Tudhope *et al.*, 2001). Influenced by both the NAO and the ENSO, Mongolia is important for recording and thus retrieving global Holocene climatic signals.

Despite the importance for our understanding of large-scale regional Holocene climatic changes, research on paleoclimates in southern Mongolia has rarely been conducted (e.g. Felauer *et al.*, 2012). Previous studies have focused in northern (Tarasov *et al.*, 1996; Fowell *et al.*, 2003; Fedotov *et al.*, 2004) and western Mongolia (Grunert *et al.*, 2000; Tarasov *et al.*, 2000). Due to the lack of study in southern Mongolia coeval paleoclimatic data from northern China have been used for understanding the regional paleoclimate changes (i.e. An *et al.*, 2008). The pattern of Holocene climate evolution in Central Asia inferred from loess deposits and lacustrine sediments has been recently reported by An *et al.* (2012), Peng *et al.* (2005) and Xiao *et al.* (2004, 2008), but it still remains poorly understood due to the discontinuity of these records, the lack of suitable material for radiocarbon dating, and the absence of useful paleoclimatic proxies.

The present study examined the sedimentary record of Lake Ulaan, located in southern Mongolia, to analyse humidity variation in southern Mongolia during the Holocene and Late Pleistocene. Mostly composed of sediment transported to the lake by eolian processes with a minor glacio-fluvial component, Lake Ulaan sediment represents an approximately 17 000-year-long paleoclimate record (Lee *et al.*, 2011). Because eolian transportation was dominant in this record, a provenance study was done before the paleoclimatic history of the Lake Ulaan sediment could be reconstructed. Geochemical data from the lake sediment were used to determine source areas and to present a continuous and high-resolution record (50- to 60-year sampling interval) of paleoclimatic changes since the Last Glacial Maximum.

Mongolia is currently situated far beyond the generally recognized northern limit of the East Asian summer monsoon (EASM), and Wünnemann *et al.* (2007b) reported that the record of desert lakes in northern Inner Mongolia and China correlates well with the climatic records of the Atlantic region during the past 45 000 years due to the dominant influence of the Westerlies. A different view was raised by Tarasov *et al.* (2000) and Rudaya *et al.* (2009), who proposed that during the Holocene the EASM influenced east of the Mongolian Altai Mountains, a larger area than previously suggested, based on records from Hoton Nuur (lake) located in the western end of Mongolia. One of the purposes of this study was to test between these two different views by examining the controlling factors of the Holocene paleoclimatic characteristics of the studied lake.

Environmental and geological settings

Lake Ulaan is located east of the south-eastern Gobi Altai Mountains in Mongolia, about 120 km north-west of Dalanzadgad, Omnogovi Province (Fig. 1). It is the easternmost

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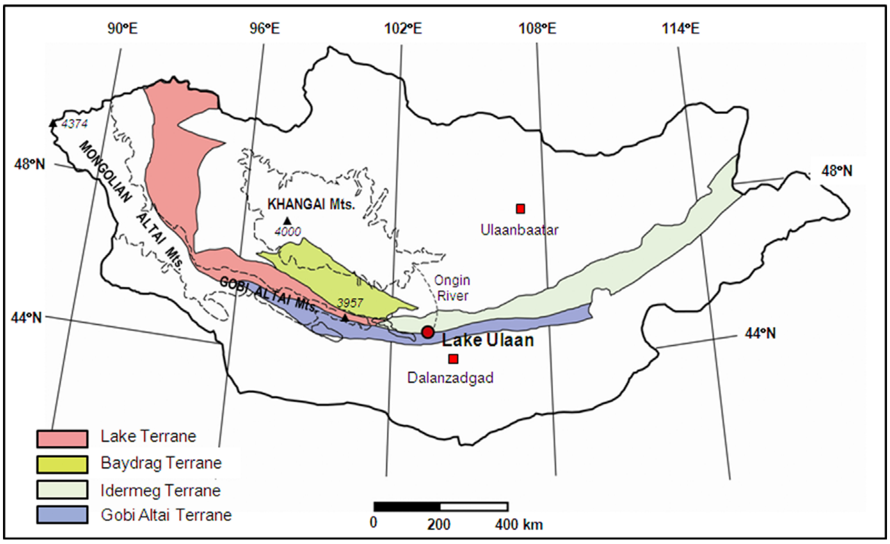

Figure 1. Map of Mongolia showing the location of Lake Ulaan and the associated tectonostratigraphic terranes (modified from Badarch *et al.*, 2002). The highest peak of the Mongolian Altai Mountains (Khuiten), Gobi Altai Mountains (Ikg Bogd) and the Khangai Mountains (Otgontenger) is marked by a black triangle with its height. This figure is available in colour online at wileyonlinelibrary.com

lake in the Valley of Gobi Lakes and is known to have been fed only by the Ongin River which originates from the southern part of the Khangai Mountains. Lake Ulaan occupied about 65 km^2 in the 1960 s, but at present the lake bottom is exposed. The elevation of Lake Ulaan is about 1110 m, and the uppermost reach of the Ongin River is approximately at an elevation of 1900 m. In the southern Khangai Mountains, the maximum extent of Pleistocene valley glaciers was down to the elevation of 2200 m during the last glaciations and the age of maximum ice advance was determined as about 21 ka (Lehmkuhl and Lang, 2001, and references therein). The permafrost developed in the Gobi Desert of southern Mongolia between 22 and 15 ka, and degradation of permafrost occurred between 13 and 10 ka (Owen *et al.*, 1998).

Lake Ulaan is located far beyond the northern limit of the EASM (Gao, 1962), but seems to have been close to the maximum areal extent of the EASM during the mid-Holocene, which was proposed to have been located at about 44° N at 6 ka BP (Winkler and Wang, 1993). The present climate of the study area is extremely arid and continental. The average annual rainfall in the lake basin area is about 100–150 mm. Precipitation is associated with rare incursions of Pacific air during the warm season, and rainfall from June to August makes up 66% of the annual precipitation. The mean annual evaporation is 1500 mm, mainly occurring from April to July. In Dalanzadgad, mean monthly temperatures were as low as −18.6 °C in winter and as high as 25.0 °C in summer between 2000 and 2005 (NNDC Climate Data Online, cdo.ncdc.noaa.gov/cgi-bin/cdo/cdostnsearch.pl). Due to the prevailing Siberian High over Mongolia throughout the year, local westerly and south-westerly winds are dominant in the study region. The orientation and shapes of partially vegetated sand dunes near the northern margin of the lake confirm the prevalence of westerly winds during the recent past.

Mongolia is divided into several tectonostratigraphic terranes, and Lake Ulaan is located at the boundary between the Neoproterozoic–Cambrian Idermeg terrane, consisting of marble, quartzite, conglomerate, sandstone and limestone, and the Cambrian–Mississippian Gobi Altai terrane, composed of sandstone, siltstone, mudstone, conglomerate, limestone, olistostrome, pillow basalt, andesite and tuff (Badarch *et al.*, 2002) (Fig. 1).

Materials

We used the 5.88-m-long core (ULB) that was studied by Lee *et al.* (2011). It was taken with a piston corer from the southern part of the lake basin (44°30′50.1′′N, 103°39′16.0′′E) in July 2007. The chronology and sedimentological characteristics of core ULB reported by Lee *et al.* (2011) are briefly summarized (Fig. 2). They compared accelerator mass spectrometry (AMS) radiocarbon and optically stimulated luminescence (OSL) age data to establish the chronology of Lake Ulaan, and concluded that OSL dating provides a reliable geochronological framework (Fig. 2a). Lee *et al.* (2011) divided the ULB core into three units based on grain-size distribution. Unit 1 (top 392 cm; up to 11.1 ka) sediments were mainly composed of silt and clay, with a unimodal size distribution, between 8 and 12φ (Fig. 2b,c). They appear massive without discernible sedimentary structures and do not show any distinguishable color change except for the uppermost part (<30 cm depth) where pedogenic carbonate micronodules occur. Unit 2 (392–530 cm depth; 11.1–15 ka) sediments consist of sand and clay with a distinctive bimodal size distribution, with modes between 2 and 4φ and between 8 and 12φ (Fig. 2b,c). Unit 3 (530–588 cm depth; 15.0–16.7 ka) sediments were dominated by clays (8–12φ) with a small amount of sands (2–4φ), showing a weak bimodal grain-size distribution (Fig. 2b,c). Units 1 and 3 were dominantly composed of airbone dust deposited by suspension settling in the offshore lacustrine environment, whereas unit 2 was mainly transported by glacio-fluvial processes.

Methods

For geochemical analyses, dried bulk samples at 2-cm intervals were powdered using a mortar and pestle. The powdered samples were dried in an oven at 105 °C to remove H_2O and cooled at room temperature in a desiccator. Chemical analyses of major elements were performed at the Korea Basic Science Institute using a Phillips PW 1480 X-ray fluorescence spectrometer with sample intervals of 2–6 cm. Total Fe was reported as Fe_2O_3. Uncertainties for geochemical sedimentary standards (SCo-1 and Ipt-61) were within ± 1%. Each sample was analysed three times, and then the results were averaged.

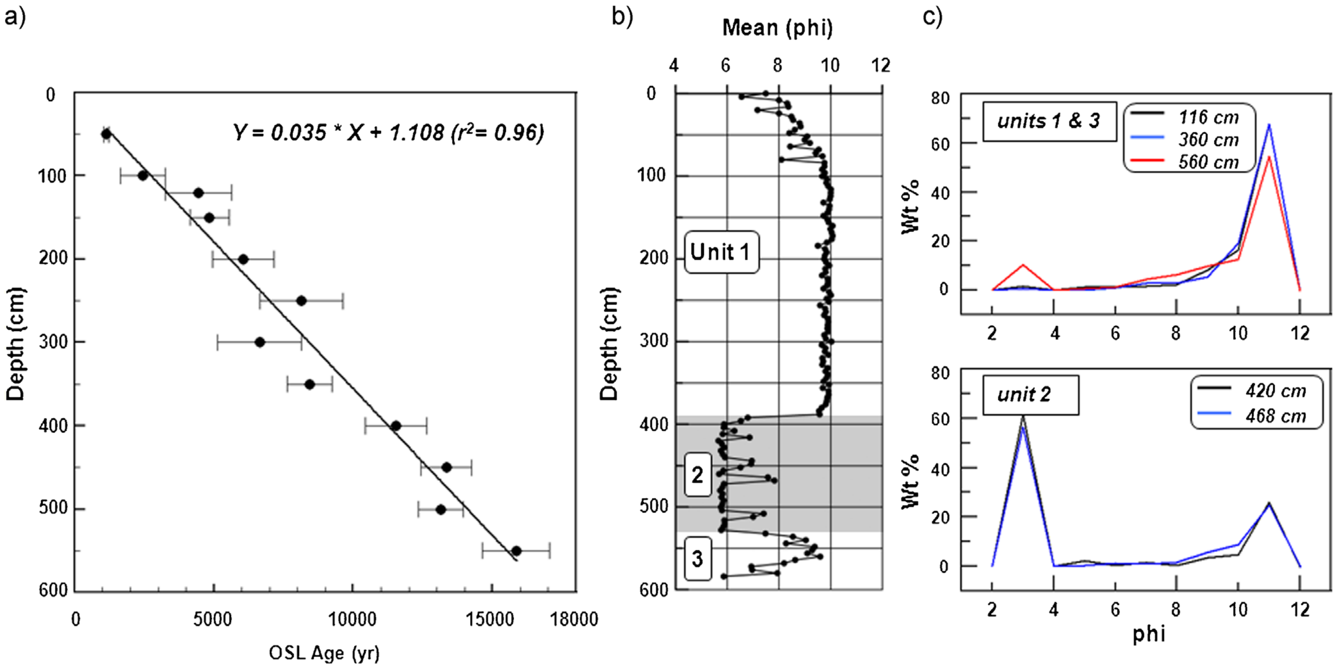

Figure 2. OSL age v. depth (a), mean grain size curve with depth (b) and representative grain size distribution of the units 1 and 3 and unit 2 (c). Depth is given in centimeters below the core top (modified from Lee *et al.*, 2011). This figure is available in colour online at wileyonlinelibrary.com

Total carbon (TC) and total nitrogen (TN) contents were analysed using an elemental analyser (FlashEA 1112). Total inorganic carbon (TIC) contents were analysed using a UIC carbon dioxide coulometer by measuring the carbon dioxide gas generated by the reaction of 50 mg powdered samples with 42.5% phosphoric acid at 80 °C for 10 min. Total organic carbon (TOC) contents were calculated as the difference between TC and TIC contents.

Results

Major element compositions

Major element compositions of the ULB core sediments are listed in the Supporting information (Table S1). Six oxides (SiO_2, Na_2O, CaO, K_2O, Fe_2O_3 and TiO_2) versus Al_2O_3 are plotted in Fig. 3. Unit 1 sediments are relatively high in Al_2O_3, CaO, Fe_2O_3 and TiO_2, whereas unit 2 sediments are high in SiO_2 (65.8–75.0 wt%) except for one sample (53.3 wt %). Sediments of each unit are distinguishable based on their compositions, with some overlap. In general, unit 3 sediments have concentrations of SiO_2, Fe_2O_3 and TiO_2 intermediate between those of units 1 and 2, whereas they are similar to unit 2 sediments in Na_2O and CaO contents. Al_2O_3 correlates positively with CaO, Fe_2O_3 and TiO_2, while it correlates negatively with SiO_2. However, the contents of Na_2O and K_2O are almost similar in units 2 and 3 sediments independently of Al_2O_3 contents although Na_2O seems to correlate positively with Al_2O_3 within unit 1 sediments.

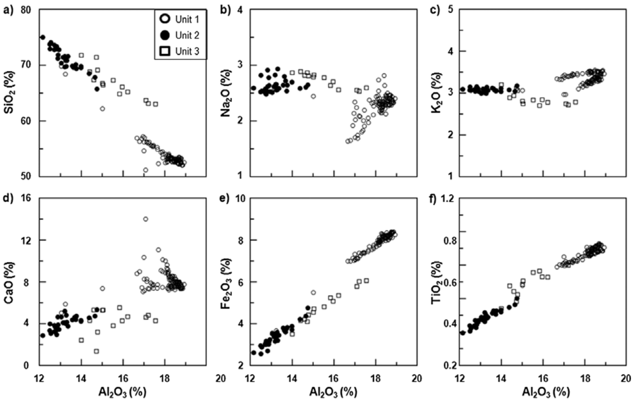

Figure 3. Major element compositions of the Lake Ulaan sediments.

Organic carbon, nitrogen and $CaCO_3$ content with C/N ratio

The concentrations of TOC, TN and $CaCO_3$, and the C/N ratio are listed in supporting Table S2. The TOC content of the ULB sediments ranges from 0.11 to 1.23 wt% (Fig. 4), with high values (0.7–1.2 wt%) occurring between approximately 9.5 and 11 ka. The $CaCO_3$ content ranges from 0.67 to 19.08 wt%, and the $CaCO_3$ and TOC contents are generally covariant ($r^2 = 0.76$) (Fig. 4). The TN content is <0.05 wt%, except for high values near 0.08 wt% between 10 and 10.4 ka, when the TOC content is also anomalously high, as well as near the core top. Moreover, the TN content variation mirrors that of TOC ($r^2 = 0.68$) and $CaCO_3$ ($r^2 = 0.78$) content. The C/N ratio ranges from 0.5 to 22 (Fig. 4) and is generally low (<10) between 0 and 2.7 ka and between 13 and 14 ka, but ranges between 10 and 22 during the other intervals.

Discussion

Source rock composition and tectonic setting

Lake Ulaan sediments were mainly transported by eolian (units 1 and 3) and fluvial (unit 2) processes (Lee *et al.*, 2011). Therefore, the provenance of each unit should be somewhat different. Sediments of units 1 and 2 are distinguishable based on major element compositions (Fig. 3). The slight difference in major element composition between the sediments of units 2 and 3 seems likely to be due to the difference in source rocks. Alternatively, it might have resulted from grain-size differences related to different sediment transport processes. K_2O and Na_2O in silicate minerals are reported to behave in company with Al_2O_3 and SiO_2, but show almost same values in units 2 and 3 despite different Al_2O_3 and SiO_2 contents.

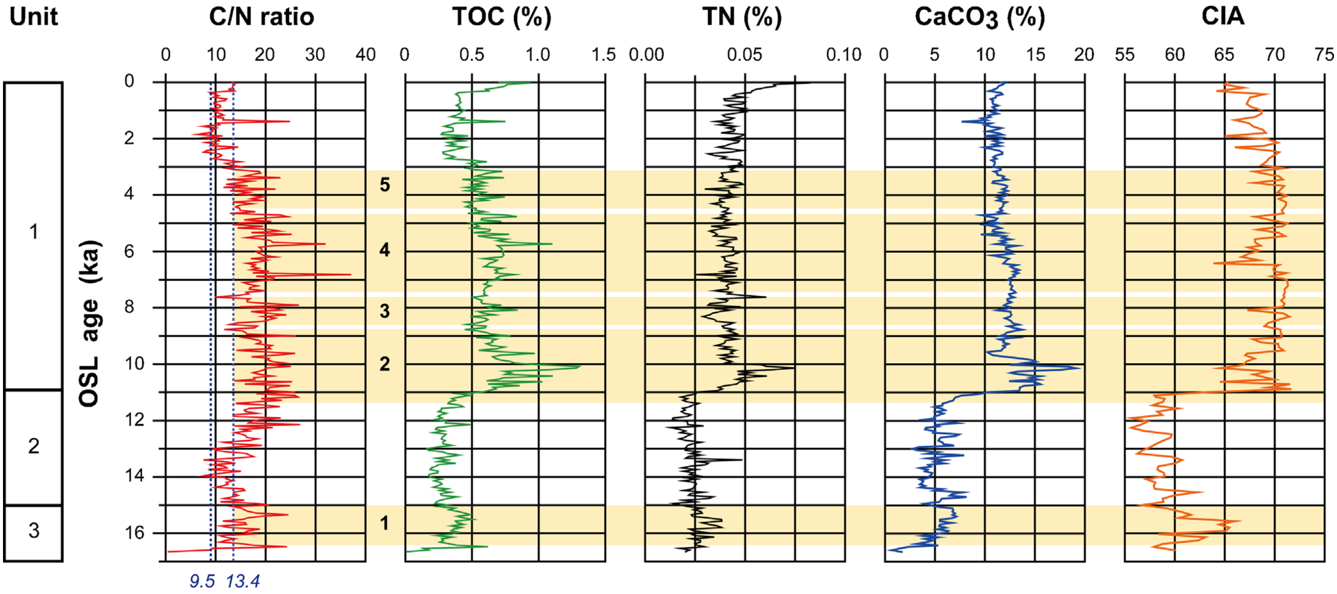

Figure 4. Vertical variation in total organic carbon (TOC), total nitrogen (TN), C/N ratio, $CaCO_3$ and chemical index of alteration (CIA) values of the Lake Ulaan sediments. The five shaded bands mark relatively humid periods (1–5) in the study area. The two vertical dotted lines in the C/N ratio graph represent the range of C/N ratios in the Mongolian steppe region (9.5–13.4) (Li and Chen, 2004). This figure is available in colour online at wileyonlinelibrary.com

Therefore, the difference in major elemental composition between units 2 and 3 is interpreted to have resulted from different source rather than grain-size sorting.

A discriminant function diagram based on major element compositions (Roser and Korsch, 1988) defined two main types of source rock for the Lake Ulaan sediments (Fig. 5). In Fig. 5, unit 1 sediments show a mafic igneous provenance, unit 2 shows a quartzose sedimentary provenance, and unit 3 sediments are spread over the mafic igneous and quartzose sedimentary provenance fields. Additionally, we used Bhatia's (1983) TiO_2 versus $Fe_2O_3 + MgO$ and Al_2O_3/SiO_2 versus $Fe_2O + MgO$ relationships to determine tectonic settings of the source areas of Lake Ulaan sediments (Fig. 6). The higher TiO_2, Fe_2O_3, MgO and Al_2O_3 contents of unit 1 sediments suggest derivation from rocks in an oceanic-arc setting, whereas the lower content of unit 2 sediments indicates an active continental margin source. A continental arc setting was indicated as the source for the unit 3 sediments.

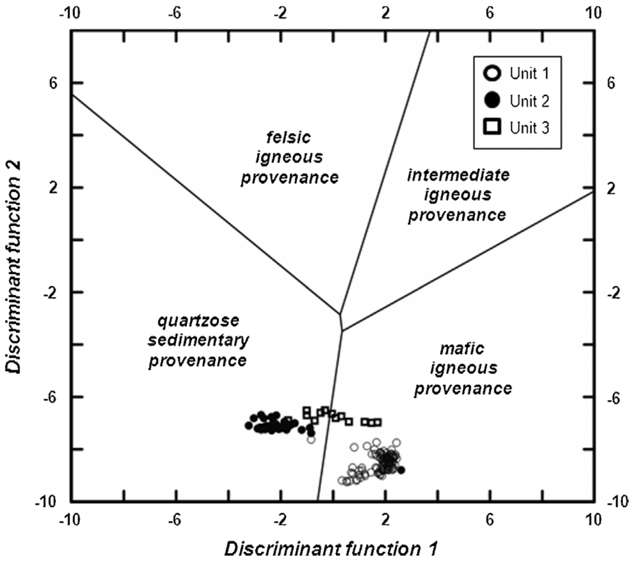

Figure 5. Discriminant function diagram for the provenance signatures of Lake Ulaan sediments using major element compositions (after Roser and Korsch, 1988). Fields of dominantly mafic igneous and quartzose sedimentary provenances are recognized in this study.

These results (Figs 5 and 6) suggest that unit 1 sediments were derived from mafic igneous rocks formed in an oceanic island-arc setting, most likely from the Lake terrane. The Lake terrane is an oceanic-arc terrane, and occurs mainly in the Valley of Lakes, east of the Mongolian Altai and north of the Gobi Altai ranges (Fig. 1). This terrane consists mainly of Cambrian island-arc volcanic rocks with fragments of ophiolites (Badarch *et al.*, 2002). It is more than 200 km from Lake Ulaan and there is no linked drainage system between the Lake terrane and Lake Ulaan. Therefore, the interpretation that unit 1 sediments were transported by strong westerly winds blowing along the valley between the two high mountains to Lake Ulaan is supported. In comparison, unit 2 consists of sandy and clayey sediment that was primarily transported by the Ongin River flowing from the north possibly supplied by glacial (+permafrost) meltwater. The source rock of unit 2 sediments is interpreted to be the sedimentary and crystalline basement rocks of the Idermeg terrane, representing a continental margin setting (Badarch *et al.*, 2002). Finally, the sediment of unit 3 may have been mainly derived by westerly winds from the adjacent Gobi Altai terrane, which is composed of felsic–intermediate igneous and sedimentary rocks of arc provenance (Badarch *et al.*, 2002).

Palaeoclimatic changes during the last 17 000 years

The organic matter content of lacustrine sediments is considered a useful indicator of primary productivity in the lake and of the amount of vegetation cover and biomass in the catchment area (Meyers, 1997). In the Chinese Loess Plateau and in many lakes in East Asia, the elevated TOC content of sediment is related to summer monsoon precipitation and warm and humid climates (e.g. Yamada, 2004). The amount of sedimentary organic matter that originates from aquatic as opposed to land sources can be distinguished by the C/N ratio: lacustrine algae have atomic C/N ratios between 4 and

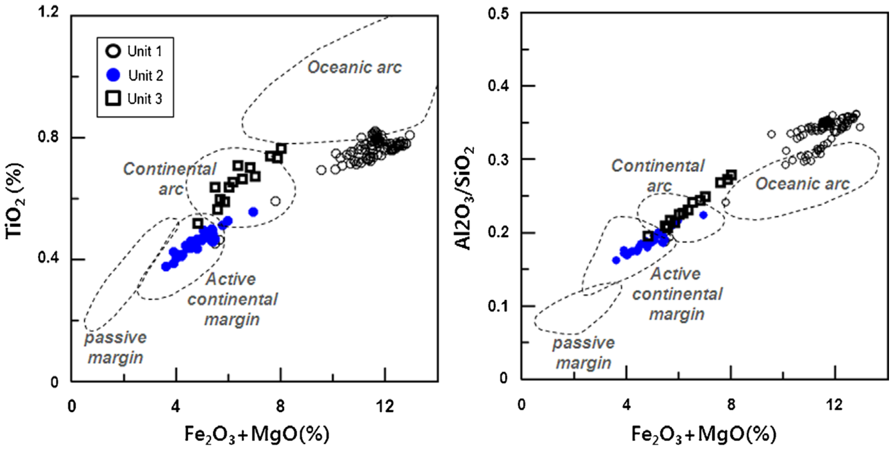

Figure 6. Tectonic discrimination diagram for Lake Ulaan sediments. Boundary lines for different tectonic settings are from Bhatia (1983). PM = passive margin; ACM = active continental margin; CA = continental arc setting; OA = oceanic arc setting. This figure is available in colour online at wileyonlinelibrary.com

10, whereas vascular land plants have C/N ratios equal to or greater than 20 (Meyers, 1994). In sediments where the organic carbon concentration exceeds 0.3 wt%, inorganic nitrogen concentration is very low compared with that of organic nitrogen (Meyers and Teranes, 2001). Therefore, the C/N ratios of most of the ULB core sediments are interpreted to represent an organic matter origin except for in the periods of ca. 11.8–15.0 ka and 16.0–16.8 ka (Fig. 4).

The C/N ratios (6–22) of ULB core sediments, except for one bottom-most sample (Fig. 4), suggest that the organic matter in these sediments is a mixture of autochthonous and allochthonous materials. However, low TOC contents (<1.5 wt%) throughout the profile of the ULB core seem to indicate low productivity in Lake Ulaan, and most of the C/N ratios are >10. Eolian transportation was dominant in units 1 and 3, and thus organic matter contained in the ULB core sediments could have been largely derived from allochthonous sources. Moreover, the period between 3 and 11 ka, when TOC content remains relatively high (>0.5 wt%), C/N ratios are maintained above 10. Thus, the organic matter in the Lake Ulaan sediments was interpreted to be dominantly composed of allochthonous organic carbon derived from plants and soils in the source areas. On the basis of Mongolian vegetation zone classification (Dill *et al.*, 2006, and references therein), the area including Lake Ulaan and its provenance belongs to the desert steppe region, and the C/N ratio of soils in the present Mongolian steppe region (including steppe and desert steppe) ranges from 9.5 to 13.4 (Li and Chen, 2004) (Fig. 4). In this paper, C/N ratios were used as a climatic proxy on the assumption that C/N ratios higher than 13.4 represent a larger terrestrial plant cover in the source region compared with the present steppe region. The climate of the region where the terrestrial plants flourish would be more humid than that of the steppe region. The ULB core sediments revealed five periods when C/N ratios were higher than 13.4: 16.5–15, 11.3–8.8, 8.6–7.6, 7.5–4.7 and 4.6–3.1 ka (marked as yellow bands in Fig. 4).

Chemical weathering alters the composition of silicate rocks, which may be reflected in the derivative sedimentary record. The degree of chemical weathering recorded in sediments is determined primarily by source rock composition, and secondly by climatic conditions, such as temperature and precipitation, and thirdly by tectonic conditions such as denudation rate. Distinctive provenances for the three units of Lake Ulaan sediments were discussed in the previous section. No known crustal uplift or tectonic events have been documented in western and central Mongolia during the Pleistocene and Holocene and thus the effect of erosion or denudation in the source area on the weathering rate seems not to be significant during the Pleistocene and Holocene. Therefore, we consider that the degree of chemical weathering of Lake Ulaan sediments within each unit can be used as a proxy for past climatic conditions, such as temperature and/or precipitation, the most important factors in chemical weathering. In particular, in arid regions where available climate proxies are limited due to low productivity, the record of a geochemical weathering index can provide useful information about paleoclimatic changes. The chemical index of alteration (CIA) proposed by Nesbitt and Young (1982) quantitatively estimates the intensity of chemical weathering by comparing the quantity of CaO, Na_2O and K_2O included in plagioclase and alkali feldspar with that of Al_2O_3 which is generally considered immobile during weathering processes. It is represented by the formula

$$\mathrm{CIA} = [\mathrm{Al_2O_3}/(\mathrm{Al_2O_3} + \mathrm{CaO} * + \mathrm{Na_2O} + \mathrm{K_2O})] \times 100$$

where CaO^* represents calcium in the silicate fraction only. CIA values may indicate moisture availability in the source areas of Lake Ulaan sediments. CIA values increased from relatively low values during 16.7–11 ka to high values after 11 ka, and these values increased or remained high with slight fluctuations during the five warm and humid periods inferred from the C/N ratios (Fig. 4).

TOC and $CaCO_3$ contents, C/N ratios, and CIA values in particular show high values between 16.5 and 15 ka (period 1) (Fig. 4). These data suggest relatively warm and humid conditions following the first Heinrich event (H1) around 16.8k cal a BP (Hemming, 2004). After that, TOC contents, CIA values and C/N ratio decreased, which indicates that the paleoclimate deteriorated between 15 and 12 ka. During period 2 (11.3–8.8 ka), TOC, TN and $CaCO_3$ values were highest, especially at ca. 10 ka and CIA values increased abruptly after 11 ka. The highest values of TOC and TN between 11 and 10 ka in the entire core (except the topmost surface layer) may indicate abundant vegetation cover in the source region. A pollen study by C. H. Chung (unpublished data) using the same core in Lake Ulaan reveals that woody pollen increased between 10.7 and 11.5 ka, and the vegetation zone of this period is identified as forest steppe, in contrast to that for all the other periods, which were steppe and desert steppe vegetation zone. Abundant terrestrial plants and drastic changes in the degree of chemical weathering during this period could be reflect a phase shift from a cold/arid climate to warm/humid climate, representing the timing of maximum moisture. Increased rainfall and/or thawing of a local glacier/permafrost might have enhanced surface runoff and accelerated soil erosion. The resulting increased supply of allochthonous organic and minerogenic material may have contributed to the abundance of carbon, nitrogen and carbonate in Lake Ulaan. Between 11.5 and 9.5 ka in northern China and southern Mongolia, the summer monsoon boundary is thought to have been located 100 km north of its modern limit (i.e. Yan and Petit-Maire, 1993), which could have resulted in large amounts of rainfall, causing the development of widespread fluvial/alluvial fans along the southern margin of the non-glaciated Gobi Altai Mountains (Wünnemann *et al.*, 2007a). Lake Ulaan is located near the eastern end of the Gobi Altai Mountains, and the paleoclimatic conditions in the source area (Lake terrane) of the Lake Ulaan sediments during this period were also likely to have been humid.

C/N ratios and TOC values were similar between period 3 (8.6–7.6 ka) and 4 (7.5–4.7 ka), but relatively higher CIA values (70) were observed during period 4. The CIA value was particularly low (<65) at about 6.5 ka, which might represent an arid period. But this condition did not last long (<300 years) in the source area of Lake Ulaan sediments, as CIA values increased afterwards. The TN and $CaCO_3$ values were almost constant after 8.6 ka. All these proxy data indicate a reduction of sediment yield resulting from the development of vegetation cover. During period 5 (4.6–3.1 ka), the TOC and C/N ratio values were relatively low compared with those in periods 2–4. However, CIA values were high (67–72), and C/N ratios were still higher than those of the soil of the Mongolian steppe.

Since ca. 3 ka TOC and CIA values have decreased, and the C/N ratio decreased and has remained within the range of modern Mongolian steppe soil values (9.5–13.4). This indicates that after 3 ka the climatic conditions became dry and changed towards those of the present steppe vegetation zone. Mean grain size increased from 10 to 8φ after 3 ka (about 100 cm depth) (Fig. 2), which indicates increased eolian activity in the depth interval 30–100 cm. An increase of mean grain size by 6φ in the depth interval between the core top and 30 cm depth (Fig. 2) could be ascribed to the presence of pedogenic carbonate micronodules. In Bayan Tohomin Nuur (lake) located 110 km west of the Lake Ulaan, Felauer *et al.* (2012) reported that wet conditions prevailed from 11 to 3.5k cal a BP and after that aridity increased based on higher dune activity and lake desiccation. These findings in Bayan Tohomin Nuur are consistent with those of Lake Ulaan. Furthermore, the climatic changes towards arid conditions after 3 ka in the Lake Ulaan and Bayan Tohomin Nuur records correspond to the timing when southern Mongolia and Inner Mongolia of north-central China became arid during the Late Holocene (Chen *et al.*, 2003; Peng *et al.*, 2005).

Influence of the EASM on Holocene paleoclimatic changes

Effective moisture in arid regions determines the areal extent of deserts, the water level of lakes and the density of vegetation cover, so it has a strong influence on the ecological environment. The effective moisture in arid Central Asia (ACA hereafter) dominated by the Westerlies was lowest in the Early Holocene and highest in the mid-Holocene (Xiao *et al.*, 2004; Chen *et al.*, 2008). In the EASM-dominated regions, however, the moisture optimum occurred during the Early Holocene and the paleoclimate has become dry since then (Chen *et al.*, 2008; Zhang *et al.*, 2011).

Kutzbach and Guetter (1986) and Anderson *et al.* (1988) modeled variations in the tropical monsoon climate since the last glaciations in southern Asia. They showed that the monsoon systems of this region varied systematically in response to variations in solar insolation related to changes in the Earth's orbital parameters. About 11–10k cal a BP, summer (July) solar radiation in the northern hemisphere reached a maximum (8% higher than the present value; Prell and Kutzbach, 1987), and the EASM was enhanced by maximum summer insolation (Wang *et al.*, 2005). At that time, the northernmost frontal zone of monsoon rainfall advanced northward into the present arid and semi-arid regions, causing a peak in precipitation (An *et al.*, 2000). The EASM has gradually weakened since the mid-Holocene (e.g. Gupta *et al.*, 2003) because of decreased summer insolation in the northern hemisphere. During this period, the belt of maximum precipitation retreated southward to the middle and lower reaches of the Yangtze River at about 6k cal a BP, and then the regional precipitation peak shifted to southern China at about 3k cal a BP (An *et al.*, 2000). Since 3 ka, the effective moisture in the EASM-dominated areas has decreased because of gradual monsoon weakening (An *et al.*, 2000), whereas those areas dominated by Westerlies did not show a continuous decline in effective moisture from the Early to Late Holocene (Chen *et al.*, 2008). As a consequence of the attenuation of the monsoon in the Late Holocene, the geochemical records from China (Xiao *et al.*, 2008; An *et al.*, 2012) and the biostratigraphic records from Mongolia (Dorofeyuk and Tarasov, 1998; Gunin *et al.*, 1999) revealed a precipitation decrease and a transition to present-day conditions.

The carbon, nitrogen and CIA values in the Lake Ulaan sediments indicate that the Holocene climatic history of the area was typical of monsoonal Asia rather than ACA. The effective moisture in the source region of Lake Ulaan was highest during the Early Holocene, decreased afterwards and was the lowest during the Late Holocene. The paleoclimatic change towards arid conditions in the source regions of Lake Ulaan sediments since 3 ka indicates that the influence of the EASM in that area decreased due to the attenuation and southward migration of the EASM front. Increased influence of pasturage since the Middle Holocene in central Mongolia has been reported (Lehmkuhl *et al.*, 2011), but the influence of pasturage on the landscape in southern and western Mongolia has not been reported and thus its influence is difficult to prove.

Winkler and Wang (1993) suggested that the northernmost boundary of the EASM occurred at around 6 ka, but it was still located in the south of Lake Ulaan (Fig. 7). This boundary of the EASM was inferred from poorly dated records of coarse resolution (Department of Geography, 1984; Ren, 1985) from northern and north-eastern China, as no records from southern Mongolia were available then. Because Lake Ulaan sediments showed the paleoclimatic characteristics of monsoonal Asia during the Holocene, the maximum northern boundary of the EASM should be located somewhere north of Lake Ulaan and south-western Mongolia, the source region of the Lake Ulaan sediments (Fig. 7).

Meanwhile, Lake Juyan in the arid region of Inner Mongolia is located south of the EASM northern boundary proposed by Winkler and Wang (1993), but it shows the characteristics of ACA (Chen *et al.*, 2003, 2008). This discrepancy can be explained by a greatly enhanced evaporation rate over the monsoon precipitation levels resulting from

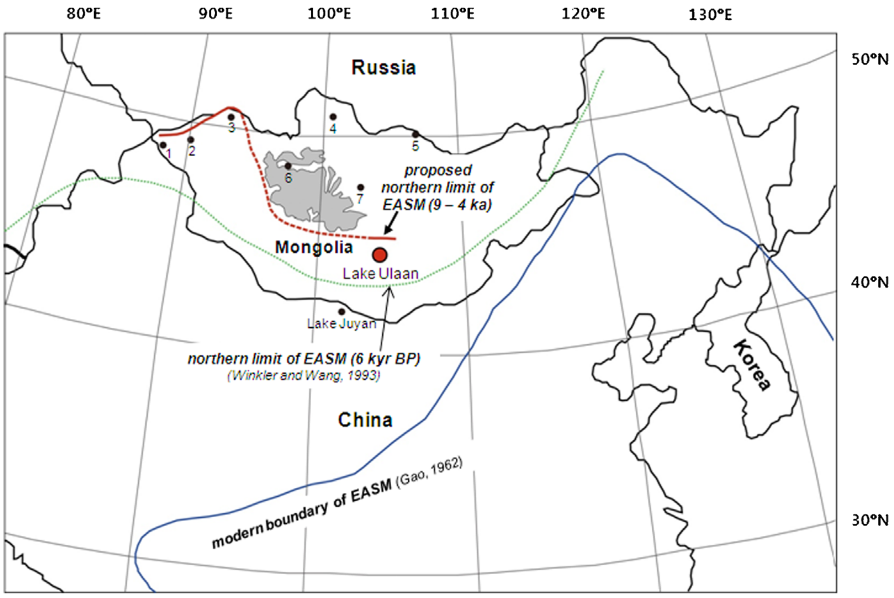

Figure 7. Map showing the location of Mongolian lakes discussed in the text and the suggested northern limit of the influence of the East Asian summer monsoon during the Holocene and at present. Lakes are numbered as follows: (1) Hoton Nuur, (2) Achit Nuur, (3) Uvs Nuur and Bayan Nuur, (4) Hovsgol, (5) Gun Nuur, (6) Telmen Lake, (7) Ugii Nuur. Blue line: the modern boundary of the EASM (East Asian summer monsoon), after Gao (1962). Dotted green line: the northern maximum boundary of the EASM at 6000 a, after Winkler and Wang (1993). Solid and dotted red line: the northern limit of the EASM between 9 and 4 ka proposed in this study. This figure is available in colour online at wileyonlinelibrary.com

large-scale temperature increases (Shi *et al.*, 1993, and references therein), even under the expanded EASM. Compared with Lake Ulaan, Lake Juyan is closer to the mid-latitude high-pressure belt, so the temperature and evaporation rate probably appeared to be higher. In addition, because of no neighboring topographic highs in the west, the Lake Juyan area is considered to have been influenced by the Westerlies, as compared with the Lake Ulaan area in the close vicinity to the Gobi Altai Mountains to the west.

Previous studies on four lakes in north-western Mongolia, Hoton Nuur, Achit Nuur, Uvs Nuur and Bayan Nuur, provide clues regarding the influence of the EASM in north-western Mongolia. The Hoton Nuur (site 1 in Fig. 7), located west of the Valley of the Lakes, was covered by steppe vegetation before 9 ka and by forest-steppe vegetation between 9 and 4 ka (Tarasov *et al.*, 2000). Around 4 ka, there were changes in vegetation and climate to conditions similar to the modern steppe. Records from Achit Nuur (site 2 in Fig. 7), where the modern vegetation is dry steppe, showed a major increase in the amount of tree pollen from <5% at 10 ka to 50% of the total pollen between 9397 ± 80 and 6540 ± 100 a (Gunin *et al.*, 1999; Tarasov *et al.*, 2000), suggesting development of forestal conditions in north-western Mongolia during the Early Holocene (Tarasov *et al.*, 2000). In the Hoton Nuur region, the last glaciation was represented only by valley or cirque glaciers, which are thought to have disappeared in the Late Pleistocene because of a rise in summer temperature (Tarasov *et al.*, 2000). In addition, steppe and desert steppe vegetation was dominant in the Achit Nuur area between 12.5 and 9 ka (Gunin *et al.*, 1999). Thus, the possibility of a moisture supply sourced from the melting of glaciers can be excluded for these two lakes. In the Uvs Nuur and Bayan Nuur basins (site 3 in Fig. 7), an accelerated decline in moisture balance since ca. 8 ka has been recognized in lake-level records (Grunert *et al.*, 2000). The evidence for increased moisture availability between 9 and 4 ka in north-western Mongolia is probably associated with the strengthening and northward displacement of the Pacific monsoon (Tarasov *et al.*, 2000, and references therein) in response to increased summer insolation, higher temperatures, and enhanced seasonality on the Asian landmass between 12 and 6 ka (Anderson *et al.*, 1988).

Despite intensification of the EASM in north-western Mongolia, Lake Hovsgol in northern Mongolia (site 4 in Fig. 7) recorded a lower lake level around 6 ka than the present (Tarasov *et al.*, 1996). Prokopenko *et al.* (2007) also reported warmer and drier conditions in Lake Hovsgol from ca. 6 to 3.5k cal a BP by diatom and pollen data. Gun Nuur (site 5 in Fig. 7) expanded under wetter conditions between 10.3 and 7k cal a BP, but it had three mid- and late-Holocene dry periods (7–5.7, 4.1–3.6 and 3–2.5k cal a BP) and wetter conditions were established after 2.5k cal a BP (Zhang *et al.*, 2012), whose characteristics are typical of ACA. In addition, the paleoclimate of Lake Telmen (site 6 in Fig. 7) was more arid between 7 and 4.5k cal a BP than the present, and maximum humidity occurred in this lake region between 4.5 and 1.6k cal a BP (Fowell *et al.*, 2003). The Holocene humidity history of these three lake (Hovsgol, Gun and Telmen lakes) records is not consistent with that of monsoonal Asia, indicating that these three lake regions of northern Mongolia appear not to have been influenced by the EASM. Schwanghart *et al.* (2009) interpreted the records of Ugii Nuur (site 7 in Fig. 7) in central Mongolia being similar to those obtained in the Westerlies-dominated region of Central Asia, and Wang *et al.* (2011) reported that a prolonged dry climate prevailed between 5830 and 3080 a in this lake, suggesting the paleoclimatic characteristics of ACA rather than monsoonal Asia.

The data from Lake Ulaan, Hoton Nuur, Achit Nuur, and Uvs Nuur and Bayan Nuur show the Early to Middle Holocene (between 9 and 4 ka) paleoclimatic signatures having characteristics typical of monsoonal Asia, suggesting that enhanced monsoon-induced rains reached further inland than they do today. Therefore, the northernmost boundary of the EASM between 9 and 4 ka was probably located along the line that connects Lake Ulaan, Hoton Nuur, Achit Nuur, and Uvs Nuur and Bayan Nuur (Fig. 7), but it should have been located to the south of Hovsgol, Gun Nuur, Lake Telmen and Ugii Nuur. Given that Lake Telmen and Ugii Nuur do not show the humidity history of monsoonal Asia despite their lower latitude compared with Hoton Nuur, the rain shadow effect of the Khangai Mountains probably contributed the aridity in the Lake Telmen and Ugii Nuur areas during the Early and Middle Holocene. With further paleoclimate studies in the eastern part of Mongolia, our understanding of the EASM history in East Asia can be enhanced.

Conclusions

1. The 5.88-m-long ULB core sediments collected from Lake Ulaan were divided into three sedimentary units. The inferred sediment provenances for three units are the Lake terrane, the Idermeg terrane and the Gobi Altai terrane, respectively.
2. The climatic optimum for the source area of the Lake Ulaan sediments occurred between ca. 8.8 and 11.3 ka. After 3 ka, the effective moisture in the region steadily decreased and the climate became arid, similar to that of the current Mongolian steppe region.
3. The paleoclimate of the Lake Ulaan area was influenced by the EASM between 11.3 and 3 ka, indicating that southern Mongolia was part of the EASM-influenced area during this time interval. The northern limit of the EASM during this period is interpreted to have been located to the north of Lake Ulaan. Comparison with lacustrine records from north-western Mongolia reveals that the western and southern Mongolian region was influenced by the EASM between 9 and 4 ka, considerably further north than previously assumed.

Supporting Information

Additional supporting information can be found in the online version of this article at the publisher's web-site.

Table S1. Major element concentrations in weight percent and CIA values for sediments of Lake Ulaan.

Table S2. Total organic carbon (TOC), nitrogen (TN), CaCO3 contents in weight percent and C/N ratios of Lake Ulaan sediments.

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Abbreviations. ACA, arid Central Asia; AMS, accelerator mass spectrometry; CIA, chemical index of alteration; EASM, East Asian summer monsoon; ENSO, El Niño-Southern Oscillation; NAO, North Atlantic Oscillation; OSL, optically stimulated luminescence; TC, total carbon; TIC, total inorganic carbon; TN, total nitrogen; TOC, total organic carbon.

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