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Changes in the volume and salinity of Lake Khubsugul (Mongolia) in response to global climate changes in the upper Pleistocene and the Holocene

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Abstract

Two gravity cores (1.1 and 2.2 m long) of deep-water bottom sediments from Lake Khubsugul (Mongolia) were studied. The Holocene, biogenic silica and organic matter-rich part of the first core was subjected to AMS radiocarbon dating which placed the date of dramatic increase of pelagic diatoms (40 cm below sediment surface) at a calendar age of 11.5 cal ky BP. ICP-MS analysis of weak nitric acid extracts revealed that the upper Pleistocene, compared to the Holocene samples, were enriched in Ca, C_{inorg}, Sr, Mg and depleted of U, W, Sb, V and some other elements. Transition to the Holocene resulted in an increase of total diatoms from 0 to 10^8 g^{-1}, of BiSi from 1% to 20%, of organic matter from $<1\%$ to $>6\%$. The Bølling–Allerød–Younger Dryas–Holocene abrupt climate oscillations manifested themselves in oscillations of geochemical proxies. A remarkable oscillation also occurred at 22 cm (ca. 5.5 ky BP). The Pleistocene section of the second, longer core was enriched in carbonate CO_2 (up to 10%) and water-extractable SO_4^{2-} (up to 300 times greater than that in Holocene pore waters). All this evidence is in an accord with the earlier finding of drowned paleo-deltas at ca. 170 m below the modern lake surface of the lake [Dokl. Akad. Nauk 382 (2002) 261] and suggests that, due to low (ca. 110 mm) regional precipitation at the end of the Pleistocene, Lake Khubsugul was only 100 m deep, and that its volume was ca. 10 times less than today.

Keywords: Paleoclimate; Lake Khubsugul level change; LGM; Holocene; Mongolia

1. Introduction

Lake Khubsugul in North Mongolia occupies a depression in the Baikal Rift Zone; its centre is at 51°00′00″N, 100°30′00″E, 1645 asl (Fig. 1). Moun-

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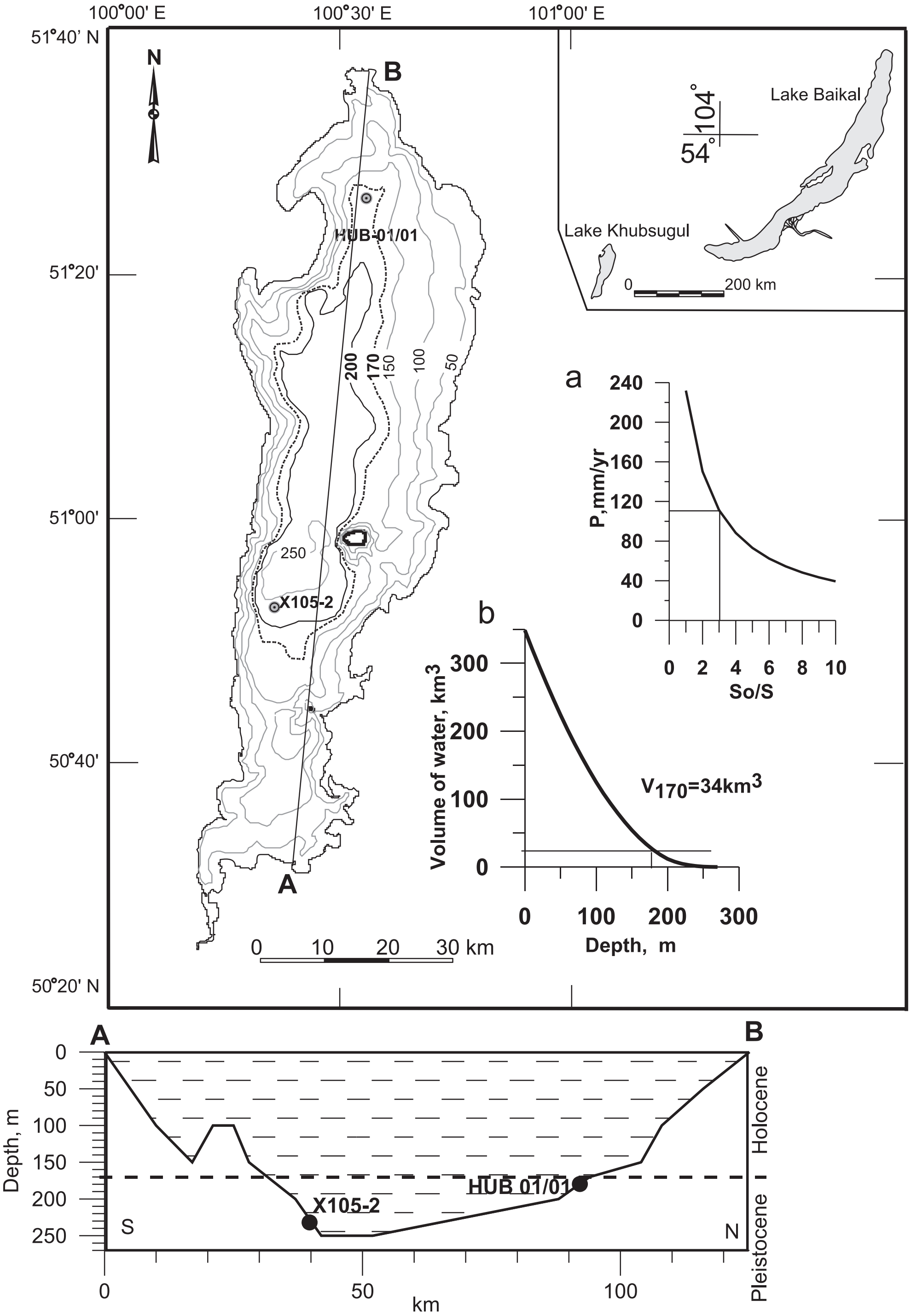

Fig. 1. Bathymetric map of Lake Khubsugul (upper panel) and its cross-section A–B from south to north (lower panel). Inserts: (a) the calculated dependence of the precipitation on the area of paleo-Khubsugul to its present area (upper insert); (b) dependence of the volume of Lake Khubsugul on its depth (lower insert).

tains to the north and west of the lake reach an altitude of 2800–3400 m asl. It is the second-largest (after Lake Baikal) lake of East Asia and stores 383 km^3 of water of a total salinity of 180–200 mg/l, with HCO_3^- contributing 92% of anions, and Ca^{2+} 63% of cations equivalents (2.1–2.5 and 2.0–2.5 meq/l, respectively). Its water is almost saturated with $CaCO_3$ and the mineral at times precipitates from the water body. Maximum depth is 262 m. The area of the lake is 2760 km^2, of its watershed—5130 km^2. The outlet from the lake is the Egerin River running from its southernmost part. Mean atmospheric precipitation in the catchment in winter is 10–50 mm, in summer—300 mm (Atlas of Lake Khubsugul, 1989). The majority of this moisture is delivered from the North Atlantic via Kazakhstan and Middle Asia (Kuznetsova, 1978).

The bottom sediments of Lake Khubsugul and of other lakes of Mongolia have attracted a great deal of interest from paleoclimatologists and were studied by Soviet–Mongolian expeditions in the end of the 20th century. It was found that many Mongolian lakes were dry in the Pleistocene and filled at the beginning of the Holocene. As for Lake Khubsugul, a few sediment cores were taken and subjected to qualitative analysis. Reportedly, the upper parts of the cores consisted of silt, the lower of clays (Altunbaev and Samarina, 1977).

A core was taken in the southern part in shallow water (< 50 m) near the outlet. It was radiocarbon dated at 1 (3910 years BP) and 2 m (5800 years BP), but the description of this core is obscure (Dorofeyuk and Tarasov, 1998). Golubev (1992), having measured the heat flows, noticed that the uppermost sediments consist of two units—diatom silts and underlying clays, respectively, and suggested that clays belonged to Pleistocene, and silts—to the Holocene. No dating was done.

Fedotov et al. (2000) studied a core taken in a deep part of the lake and found signs of an abrupt climate transition evidenced by a dramatic decrease in the concentration of carbonate and ostracods, a sharp increase (from analytical zero to 10^8 frustules/g) of the content of diatoms, an increase in the content of pollen of trees, e.g. *Pinus silvestris*, at ca. 75 cm below sediment surface. However, the core was not subjected to radiocarbon dating, and the time of the abrupt transition (tentatively the beginning of the Holocene) remained unconfirmed.

In 2001, a Russian–Belgian team performed a geophysical study of Lake Khubsugul and, among other features, found young drowned paleo-deltas at ca. 200 m below the water surface (Fedotov et al., 2002). This, together with the data of Fedotov et al. (2000), suggested that the lake in the Pleistocene was only about 70 m deep, and was filled to its present level to reach the outlet after a dramatic increase in precipitation in the Holocene. The area of the lake in the Pleistocene, as suggested by geophysical data, was only 905 km^2, three times smaller than today, and the volume was 34 km^3, 10 times smaller (see Fig. 1). If this was the case, the lake could not have had any outlet and should have been brackish.

The purpose of the present study was to date the boundary at which Lake Khubsugul filled to its present volume, and to look for possible connections between the properties of the sediments and global climate change.

2. Materials and methods

The studies were done with Core X105-2 (110 cm) taken by a gravity tube in the deepest central part of Lake Khubsugul at 50°56′40″N, 100°21′25″E (water depth 241 m) and Core HUB-01/01 (212 cm) taken in the shallower northern basin of the lake at 51°26′09″N, 100°33′07″E (water depth 170 m). The cores were cut longitudinally into two halves and samples taken at 1-cm intervals from the middle.

Water content (WC) was determined by weighing wet sediment and the residue after drying at 60 °C. Carbonate was determined by titration with acid (Arinushkina, 1970). Soluble cations and SO_4^{2-} were determined in solutions obtained by extraction of 1-g sediment samples with 10 ml of water followed by centrifugation (10 min at 8000 rpm); Mg^{2+} was determined by AAS, K^+, Na^+ by AES (Rusin, 1990), SO_4^{2-} by HPLC (Baram and Vereshchagin, 1999). Diatom analysis and determination of BiSi were performed as described in Grachev et al. (1997). Determination of elements by ICP-MS was performed essentially as described by Chebykin et al. (2002) with extracts obtained with weak (15 ml 1% HNO_3/50 mg of sediment) followed by strong nitric acid (0.5 ml 70% HNO_3). Organic carbon C_{org} was determined by bichromate oxidation according to Arinushkina (1970). Inorganic carbon C_{inorg} was determined in relative units of intensity of the ^{13}C peak by ICP-MS of weak nitric acid extracts. AMS radiocarbon dating of total organic matter was performed according to a commercial contract with the Pozna Radiocarbon Laboratory (Poland). The crude radiocarbon dates and the calendar ages calculated according to Stuiver et al. (1998) after subtraction of a reservoir effect of 530 years are presented in Fig. 2.

Stacks were calculated according to Goldberg et al. (2001) by averaging depth (z) profiles of relative concentrations $R(z)$ of individual proxies:

$$R(z) = (c - c_{\min})/(c_{\max} - c_{\min}) \tag{1}$$

where c is the running, and $c_{\max}$ and $c_{\min}$ are the maximum and minimum concentrations of a given proxy over its profile. Mass sediment accumulation rates (MSR, mass units/cm^2/year) were calculated from water content using Eq. (2):

$$\mathrm{MSR} = \rho_{\mathrm{wet}} \times V, \tag{2}$$

where ρ_{wet} is density of wet sediment (g/cm^3), V-linear sediment accumulation rate (cm/ky), found

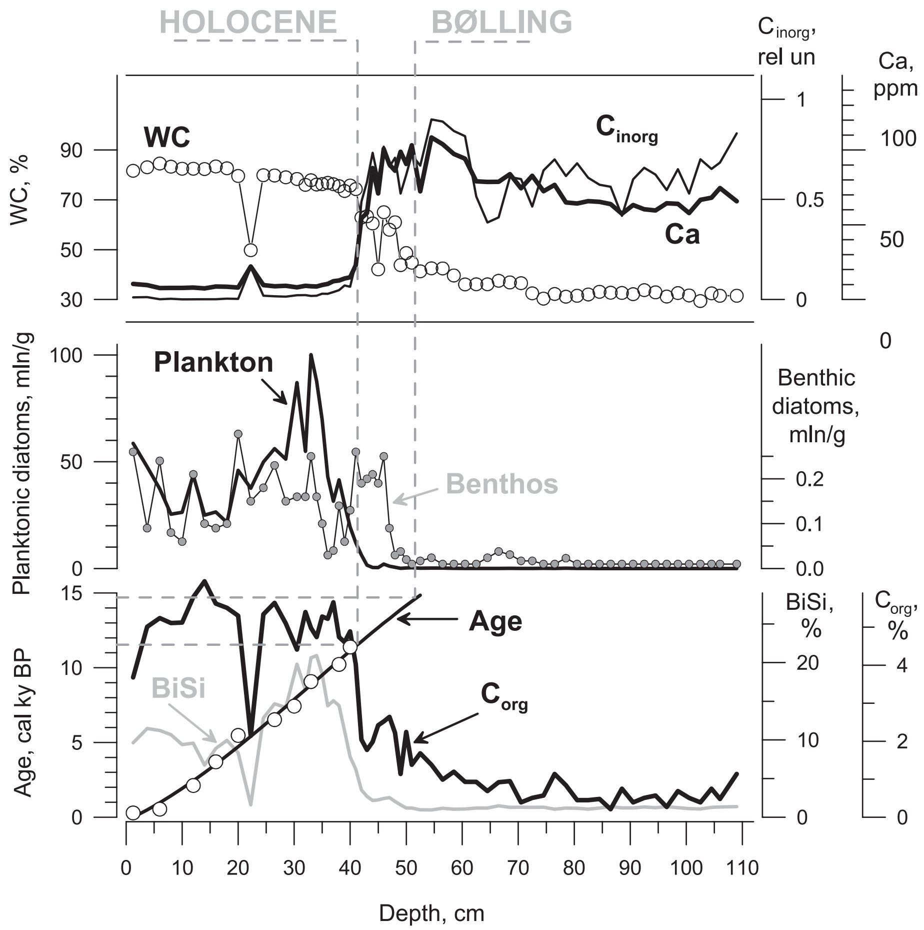

Fig. 2. Profiles of some climate proxies in the sediments of Lake Khubsugul (Core X105-2). The lower panel presents the depth-age model discussed in the text.

from the depth-age model (Fig. 2). We did not measure ρ_{wet} directly, but rather calculated it from water content ($WC + f_{rock} = 1$) according to Eq. (3):

$$\rho_{wet} = 1/(WC + f_{rock}/\rho_{rock}) \qquad (3)$$

assuming that ρ_{rock} (picnometric rock density) is equal to 2.63 g/cm^3, a value found for clays of Lake Baikal.

3. Results

3.1. Lithology of sediments

The upper parts of both cores consist of diatomaceous silt (0–41.5 cm in the deep-water Core X105-2 and 0–30 cm in the shallow-water Core HUB-01/01. Their lower parts (41.5–110 and 30–212 cm, respectively) consist of clay with lenses and laminations of non-sorted, non-reworked (apparently, glacial, as revealed by SEM) sands of variable grain size. The former core contained a turbidite-like layer at 21 cm. The latter core contained well-preserved re-deposited fossil moss remains at 151, 185 and 202 cm.

3.2. Analysis of the deep-water core

Fig. 2 presents some data for Core X105-2. The depth-age model presented in the lower panel is based on the dates obtained by means of AMS radiocarbon analysis of total organic matter (Table 1); radiocarbon ages were transformed into calendar years, as described in Section. The data were approximated by a third-degree polynomial (solid line), $age = -0.221 + 0.172z + 0.0469z^2 - 0.0000476z^3$. It is seen in the upper panel of Fig. 1 that C_{inorg} and Ca (both extracted with weak nitric acid) dramatically dropped ca. 12 cal ky BP. WC in the Holocene sediments is much greater, than in those of the Pleistocene. The WC profile contains a small peak at 13.5 ky BP, following the Bølling–Allerød warming. The strongest signal is in the diatoms: the concentration of the frustules of pelagic species (>99% *Cyclotella ocellata*, the dominating diatom of the modern lake; subdominating *C. bodanica* and *Stephanodiscus* aff. *alpinus*) is below analytical zero (<7000 g^{-1}) in the Pleistocene clay, and ca. 10^8 g^1 in the Holocene diatomaceous silt (Fig. 2, middle panel). The behaviour of diatom species is remarkable. The concentration of benthic diatoms (*Achnanthes* Bory., *Cocconeis* Ehr., *Navicula* Bory., *Cymbella* Ag. et al.) starts to grow about 13.5 ky BP (Fig. 2, middle panel), much earlier than that of the pelagic ones. Biogenic silica (BiSi) and organic carbon (C_{org}) profiles (Fig. 2, lower panel) reveal an abrupt increase in primary production in the beginning of the Holocene; minor peaks of these proxies are centred at ca. 13 cal ky BP, following the Bølling–Allerød warming. Going up the core, we see troughs and peaks of some proxies at 21 cm (ca. 5.5 cal ky BP). BiSi and WC are proxies of the content of diatoms: the former are the material of frustule walls, the latter reflects the inner volume of diatom frustules, which are permeable to water, but impermeable to clay.

Table 1
AMS radiocarbon dating of total organic matter

Depth, cm	Crude AMS radiocarbon age, years[a]	Calculated calendar age, ky[a]
1.25	730 ± 30	0.285
6	1070 ± 40	0.540
12	2660 ± 30	2.120
16	4010 ± 40	3.705
20	5260 ± 40	5.470
26.5	6270 ± 50	6.525
30	7100 ± 50	7.430
33	8680 ± 55	9.075
38	9600 ± 50	10.220
40	10570 ± 60	11.385

[a] Crude radiocarbon dates and calendar ages calculated according to Stuiver et al. (1998) after subtraction of a reservoir effect of 530 years.

Fig. 3 presents profiles of elements extracted from the sediments by weak nitric acid (with one exception: Cu was extracted with weak followed by strong nitric acid). The broad grey box in Fig. 3 marks the Bølling–Allerød–Younger Dryas–Holocene (BAYDH) oscillation.

Proxies fall into three groups: those which drop in the Holocene (we name them Class 1, "cold"), those which produce high peaks near the surface (Class 2) and those which increase in the Holocene (Class 3, "warm").

The elevated content of the elements of Class 1, Mg, Sr (Fig. 3), C_{inorg} and Ca (Fig. 2), in the Pleistocene section suggests that the sediment is about 20% carbonaceous rock.

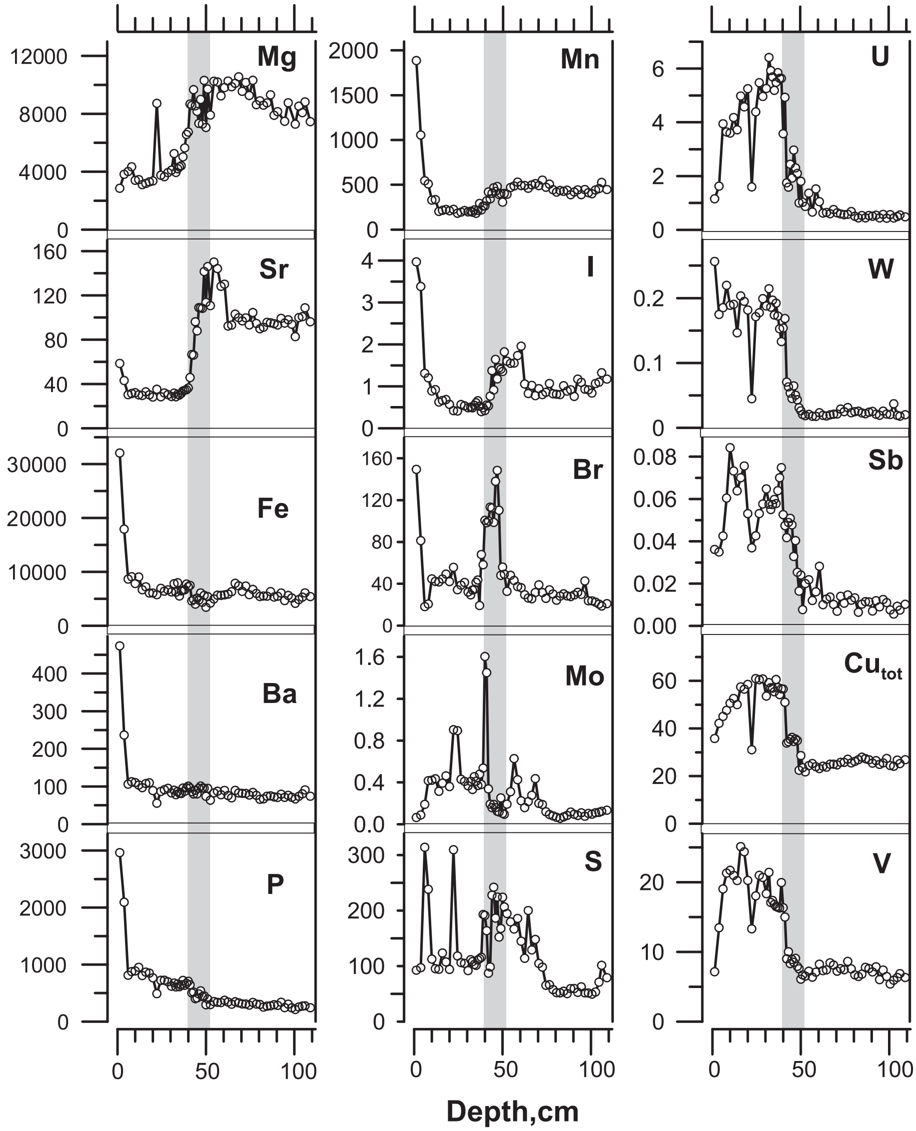

Fig. 3. Profiles of some climate proxies in the sediments of Core X105-2. Mg and Sr (as well as Ca and C_{inorg}, see Fig. 2)—elements of Class 1 ("cold"); Fe, Ba, P and Mn—elements of Class 2; I, Br, Mo and S—elements producing complicated profiles, tend to give peaks near the BAYDH oscillation (gray boxes); U, W Sb, Cu_{tot}, V—elements of Class 3 ("warm"). Concentrations of elements are given as ppm.

The increase of P, Mn, Fe and Ba (elements of Class 2) near the surface can be explained by diagenetic enrichment. E.g., Mn is reduced in the organic-rich section, diffuses as Mn^{2+} towards the surface and precipitates as manganese oxide in the oxygenated zone. The same happens with Fe. Phosphorus can be released from its organic forms in the anoxic zone by bacteria and precipitate near the surface as hydroxyapatite after reaction with Ca^{2+} and OH^{-} (cf. Brooks and Edgington, 1994). Ba^{2+} can be released from insoluble $BaSO_4$ by sulfate-reducing bacteria, diffuse to the surface and precipitate due to reaction with SO_4^{2-} (Dickens, 2001).

Elements of Class 3 are highly abundant in sediments belonging to the Holocene and correlate with

C_{org}.(cf. Fig. 2)—they probably belong to complexes with the highly abundant organic matter.

Elements such as I, Br, Mo, S (we do not place them into any class) produce diverse complicated profiles suggesting a sequence of reduction–oxidation events, and, probably, covalent binding with organic matter. They tend to produce peaks near the BAYDH oscillation.

Fig. 4 presents profiles of "warm" and "cold" element stacks (the vertical scale for the latter stack is descending), along with the profile of $\delta^{18}O$ in Greenland ice (Grootes and Stuiver, 1997). General correlation of the Khubsugul record with the North Atlantic climate is evident. The Younger Dryas cooling manifests itself as a distinct step. Remarkably, both stacks indicate, as a deep trough, a mid-Holocene abrupt event at ca. 5.5 cal ky BP which is not revealed by the Greenland ice record. Above the trough, subdominant pelagic *Cyclotella bodanica* disappears, suggesting that the 5.5 ky BP event resulted in a significant change in the ecological system of Lake Khubsugul (vide infra).

Fig. 5 shows a few mass sediment accumulation profiles. The rates of accumulation of total sediment, of Ca, Co, Mo and S (all extracted with weak nitric acid), although in a different manner, follow the

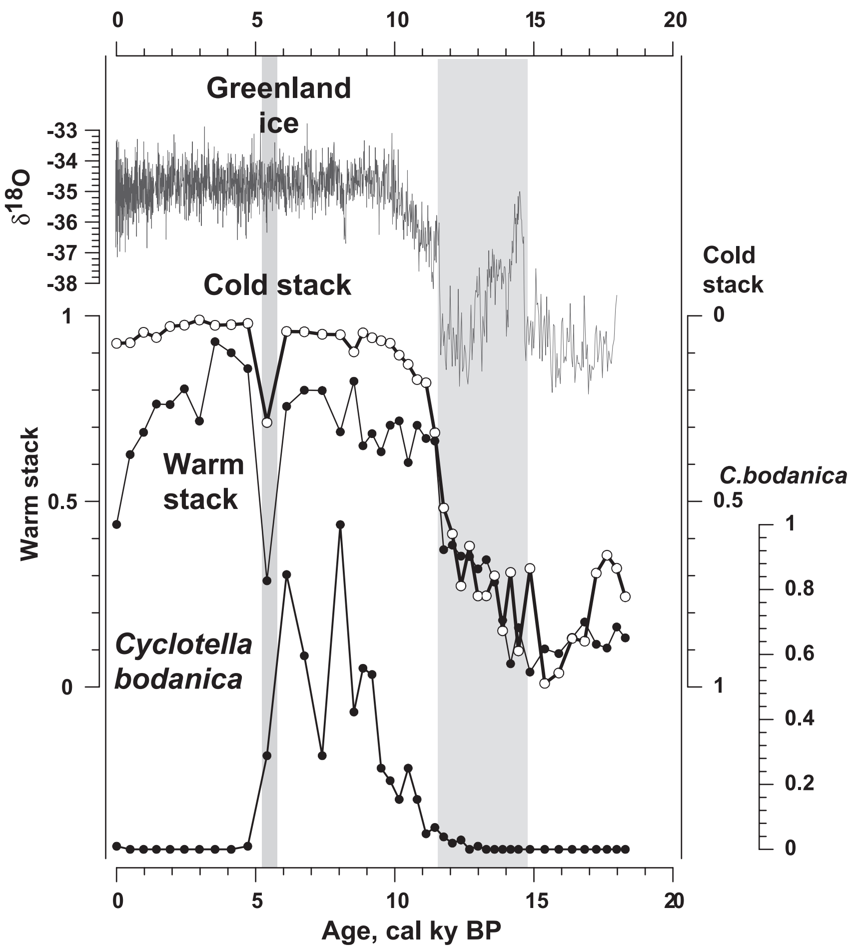

Fig. 4. Stacks of elements of Classes 1 ("cold"; C_{inorg}, Mg, Ca, Sr) and 3 ("warm"; U, W, Sb, Cu_{total}, V, Sc, Ni, Zn, Y, REE; crude data for the latter five proxies are not shown in Fig. 3) and $\delta^{18}O$ in Greenland ice (Grootes and Stuiver, 1997). Upper horizontal axis-calendar ages based on the depth-age model shown in Fig. 2. Broad gray box—Bølling–Allerød, narrow gray box—the 5.5-ky BP event. The lower panel-concentration of *Cyclotella bodanica*. Core X105-2; all units are relative (see text).

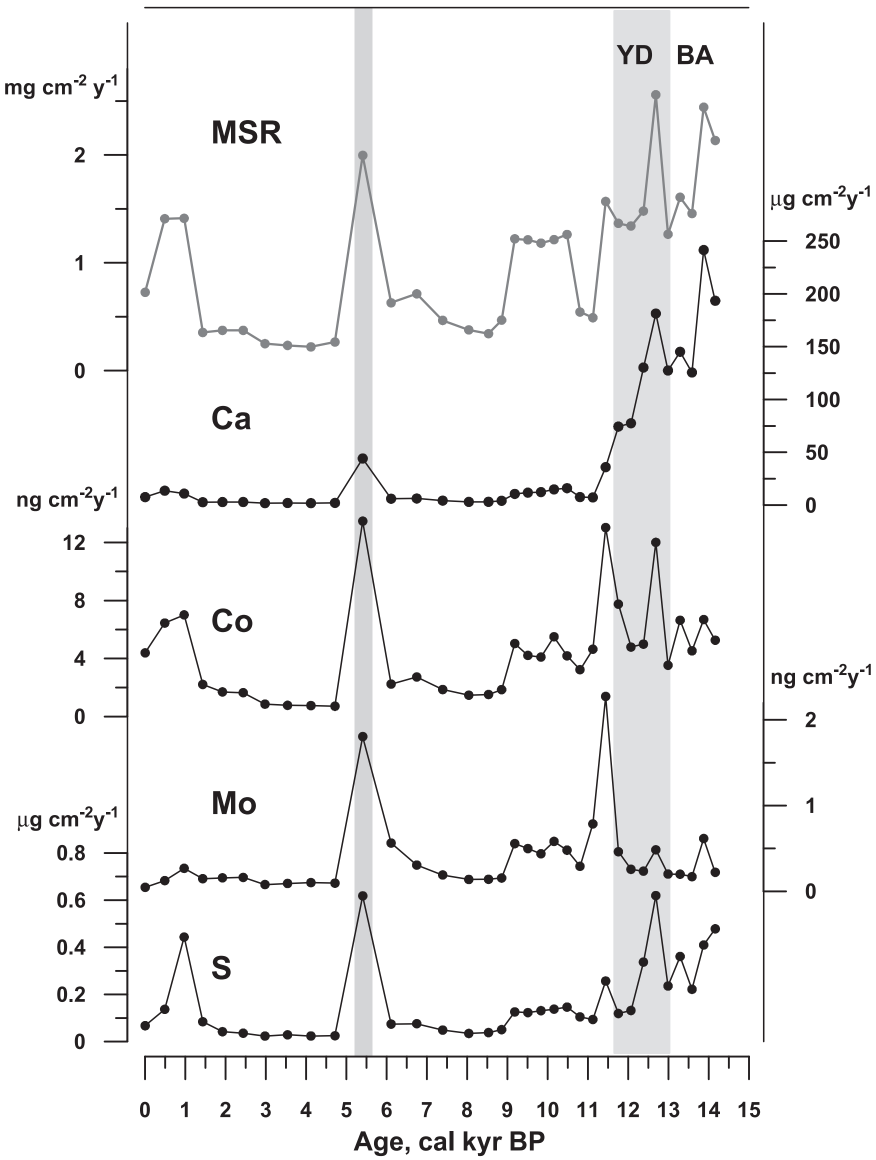

Fig. 5. Mass sediment accumulation profiles in Core X105-2. Horizontal axis-ages following from the depth-age model shown in Fig. 2.

BAYDH oscillation and produce peaks in the beginning of the Holocene (11–9 ky BP), when, as we shall see it below, the lake was rapidly filled with water. High peaks are also present at ca. 5.5 ky BP.

3.3. Analysis of the shallow-water core

Fig. 6 presents the results of analysis of Core HUB-01/01. This core was correlated with the radiocarbon-dated deep-water Core X105-2 by diatom analysis (see the three upper panels in Fig. 6). Analysis of water extracts, combined with data on water content gave evidence on the concentration of SO_4^{2-} in the paleo-pore waters (Fig. 6, panel 4). It is seen that the concentration of sulfate in Pleistocene clays is very high, ca. 300 times higher than that in the modern lake and in the sub-recent and Holocene pore waters. The concentrations of water-

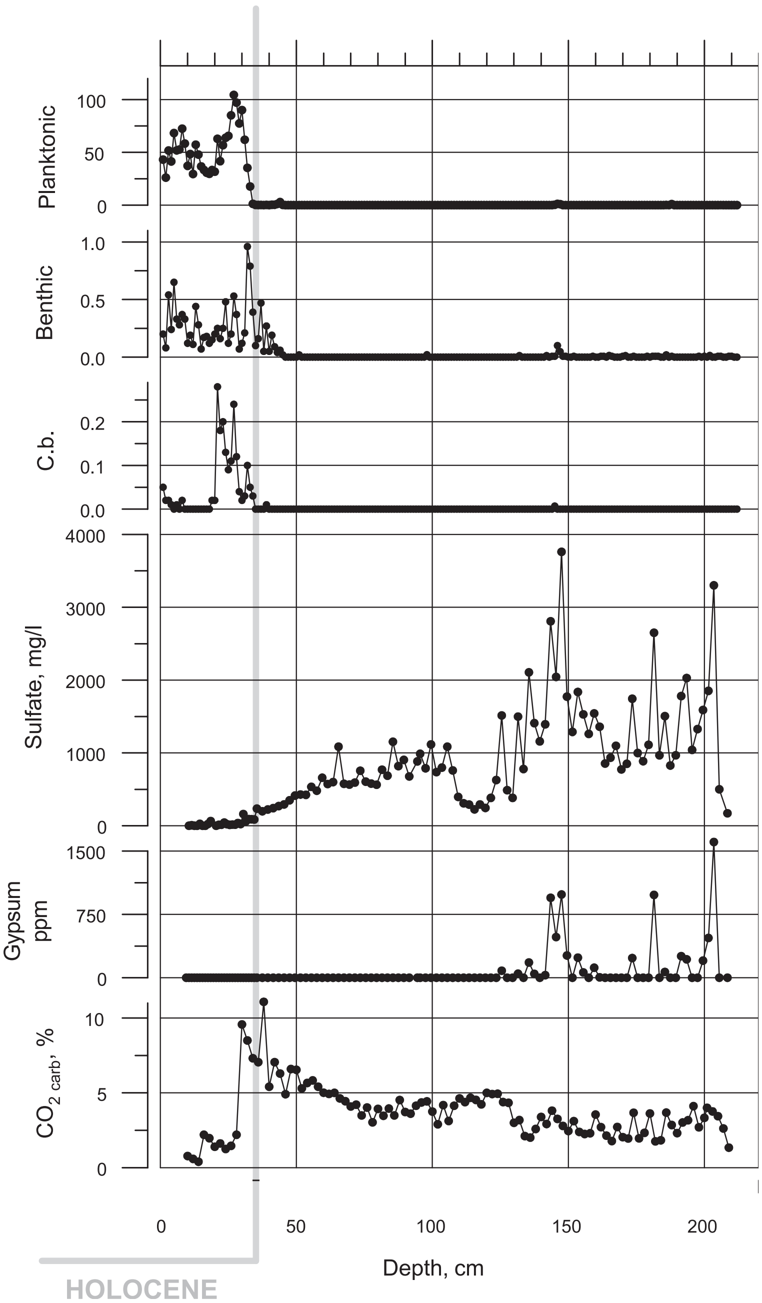

Fig. 6. Profiles of climate proxies in Core HUB 01/01. The three upper panels—diatoms, mln/g. The middle panel—calculated concentrations of sulfate ions in paleo-pore water, based on the concentrations in water extracts. Note that the calculated concentrations of sulfate greater than 1350 ppm, taking into account the high concentration of Ca^{2+}, are higher than those allowed by the solubility of $CaSO_4 \cdot 2H_2O$. Excess was believed to be present in the sediment as gypsum; the profiles of the content of this mineral and of carbonate CO_2 are presented in the lower panels. Vertical gray line—boundary of the Holocene.

soluble Ca^{2+}, Mg^{2+}, Na^{+}, K^{+} are also high (data not shown). At 130–160 and 180–200 cm, the calculated pore water concentrations of SO_4^{2-} and Ca^{2+} are greater than those necessary to form a saturated solution of $CaSO_4{\cdot}2H_2O$ (>2 g/l), suggesting that gypsum in these sections precipitated from the water body (panel 5 in Fig. 6). Indeed, gypsum crystals were detected using scanning electron microscopy (Fig. 7). Above 100 cm, the concentrations of soluble ions gradually decrease. Another profile shown in Fig. 6 (the lowermost panel) is that of carbonate CO_2, which strongly increases between 80 and 30 cm. The concentration of carbonate CO_2 abruptly drops in the beginning of the Holocene, indicating that the water was rapidly diluted below the solubility product $[Ca^{2+}]{\cdot}[CO_3^{2-}]=10^{-8}$. A peak is visible near YD and a small peak in the mid-Holocene.

A different nature of the sediment in the lower part of Core HUB 01/01 is clear. The core is not yet dated, and it is too early to suggest any detailed explanations, but it is evident, that Lake Khubsugul sediments store footprints of small, but gradually increasing humidity within the Last Glaciation, as well as signatures of millennial-scale climate oscillations which are well documented in the North Atlantic (Bond et al., 2001) and elsewhere, including Lake Baikal in East Siberia (Goldberg et al., 2001).

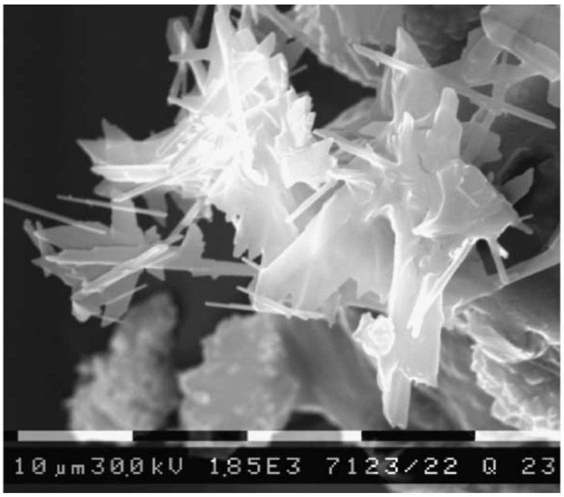

Fig. 7. Crystals of gypsum detected at 150 cm in Core HUB 01/01; scanning electron microscopy.

4. Discussion

At present, the water budget of Lake Khubsugul (in mm/year) is the following: riverine input $R_{mod}=354$, direct atmospheric precipitation $P_{mod}=300$, evaporation from the lake surface $E=508$, riverine output $F_{mod}=146$:

$$R_{mod}+P_{mod}=E+F_{mod}=354+300$$
$$=146+508=654. \tag{4}$$

If total precipitation drops, the level of the lake will decrease, and at a certain moment riverine output will become zero. The area of the lake ($S_0=2760$ km^2) will not change. Assuming that evaporation will not change, the budget at zero riverine output will become

$$R_0+P_0=E=508. \tag{5}$$

As a first approximation, we can assume that a decrease in regional precipitation P_R (its present value $P_{R,mod}=300$, see Section 1) affects the riverine input and direct precipitation to the same extent, by a factor of 508/654 (precipitation drops by a factor of 0.78). Hence, the input components will become $R_0=275$, $P_0=233$ and $P_{R,0}=233$.

Geophysical data (Fedotov et al., 2002) suggest that the smaller regional precipitation in Pleistocene established a lower level of the lake with its depth equal to ca. 170 m. The area S of the lake, compared to the present S_0, was smaller by a factor of 3, the volume—by a factor of 10 (Fig. 1). Let us assume, as first approximation, that E in the Pleistocene was the same as today and that regional precipitation P_R was smaller than $P_{R,0}$ by the same factor as P, i.e., that $P_R/P_{R,0}=P/P_0$. To sustain the lower level, the riverine term R would have to be multiplied by a factor of P/P_0, and by a factor of $S_o/S=3$, because the same R, at a smaller S, would result in a three times faster growth of the level. The budget would be

$$(R_0\times P\times S_0)/(S\times P_0)+P=E=508. \tag{6}$$

Hence, $P=E/[(S_0{*}R_0/(S{*}P_0)+1]=112$, $P_{mod}/P=2.7$—precipitation during the low lake stand was 2.7 times less than today. According to Velichko (1999), precipitation in Siberia in the Pleistocene was smaller than that at present by a factor of 2. Taking into account the possible errors in the assumptions of our "zero approximation", the Pleistocene P value found seems to be reasonable.

A more precise estimate of paleo-humidity and of other characteristics can be obtained by modelling, based, inter alia, on the chemical composition of the sediments, thermodynamic constants of precipitating diagenetic phases, such as calcite and gypsum, and kinetic factors like seasonal changes of temperature and biotic components. At this stage, it is sufficient to mention that the inferred increase of the volume of Lake Khubsugul by a factor of 10 in the beginning of the Holocene is in an accord with the ten-fold decrease of the concentrations of soluble cations Mg^{2+}, K^+, $Na^{+\cdot}$ in paleo-pore waters estimated by analysis of water extracts (data not shown).

5. Conclusions

Now, we can discuss the course of the events that took place on Lake Khubsugul, beginning from a time belonging to Marine Isotope Stage 2, presumably, during the LG maximum. The lake level (Fig 1) was, most probably, still above the point sampled by Core HUB 01/01, as revealed by lithology; it was mentioned in Section 3 that moss remains which were found in the core were re-deposited, rather than of in situ origin. In our earlier study (Fedotov et al., 2000), we found that ostracods were highly abundant throughout the clay layer, suggesting an aquatic environment. The water of the lake was saturated with calcite and, at times, with gypsum (Figs. 6 and 7). The flux of terrigenic matter and sulfate associated with soils was high because the climate was dry and the winds strong. After a while (above 130 cm in Core HUB 01/01, Fig. 6), there was a period when the contribution of calcite became greater and the deposition of sulfate decreased.

Before the Bølling warming, the deposition of carbonate increased (80–45 cm in Core HUB 01/01, Fig. 6) and 65–56 cm in Core X 105-2 (cold stack, Fig. 4). A possible explanation is the melting of glaciers that covered carbonate rocks in the mountains to the north and northwest of Lake Khubsugul (Fedotov et al., 2002). Melting of glaciers could be due to an increase in insolation. Horiuchi et al. (2000) report that deglaciation of mountains around Northern Baikal started 18–15 ky BP. Complete melting of glaciers could bring, according to our estimate of the paleoglaciological setting, 12–15 km^3 of water carrying huge amounts of carbonate rocks. However, melting of glaciers could only increase the level of the lake by 15–20 m, and the total salinity for this reason could not change much.

The most dramatic oscillations of climate proxies occurred during the BAYDH oscillation and in the Holocene. The water chemistry of the lake changed, and diatoms appeared. Both cores reveal (Figs. 2 and 6) that the contribution of benthic diatoms to total diatoms abundance in Bølling–Allerød was much greater than it became in the Holocene, evidently, because the lake was shallower. The change in water chemistry that allowed diatoms to exist was, in our opinion, the onset of delivery of nutrients, especially dissolved silica, from the catchment due to increased atmospheric precipitation. Proxies for this change are elements of the warm stack (Figs. 3 and 4) and of organic matter (Fig. 2). The suggested increase in nutrients flux was proposed earlier to explain the profiles of diatoms and other climate proxies in the sediments of Lake Baikal (Chebykin et al., 2002). Severinghaus and Brook (1999) established that the temperature gradient following the onset of the Bølling warming in Greenland was the steepest at ca. 14.7 cal ky BP and was followed in 20–80 years by an abrupt increase of CH_4 in the atmosphere induced by increased atmospheric precipitation and formation of wetlands in the tropics. The increase in precipitation was apparently caused by an abrupt change in the pattern of global atmosphere circulation, i.e., that of the storm tracks, induced by a change in the circulation of waters in the North Atlantic. As proposed by Chebykin et al. (2002), soon after the onset of Bølling, precipitation also abruptly increased in the catchment basin of Lake Baikal, and induced release of nutrients, which led to a dramatic increase of the abundance of diatoms. Assuming that precipitation in the Bølling–Allerød (14.7–12.5 ky BP) was the same as that in the Holocene, it would take Lake Khubsugul about 1500 years to reach the modern level, i.e., raise by 170 m (cf. modern outflow of 126 mm/year, equivalent to 126 m/ky). Evidently, this did not happen, because the climate oscillated, as revealed by both the Greenland and the Khubsugul records (Figs. 2 and 4). All the Khubsugul proxies reached their Holocene values only in the beginning of the

Holocene, and their change was retarded or even reversed in the cold and dry Younger Dryas.

Availability of an AMS-based depth-age model makes it possible to discuss the Holocene section in more detail. It is seen in Fig. 5 that mass sedimentation rates fluctuated during the BAYD transition. It is noteworthy that there is a significant peak of MSR between 11 and 9 ky BP. This peak may reflect input of clastic matter from the flooded walls of the depression during increase of the lake level. An important feature is the event at ca. 5.5 ky BP (see Figs. 2–5). The mass sedimentation profiles, as well as lithology described under Section 3, suggest that the sediment layer at 22 cm contains terrigenic matter, i.e., is turbidite-like. The input of clastic matter may have been caused by a temporary decrease in lake level due to climate aridification. This changed the water chemistry. Without assuming such a change, it would be difficult to explain why the event, if it was just a turbidite, was followed by complete extinction of pelagic *Cyclotella bodanica* (Fig. 4). However, the decrease of the level was small and short-term. Data on C_{inorg} and Ca^{2+} (Figs. 2 and 5) suggest that the layer at 22 cm contains about 10 mg of calcium carbonate above 1 cm^2, about 1% of the stock of Ca^{2+} in the water column (ca. 1000 mg). Hence, a short-term draught that happened 5.5 ky BP could only decrease the level by ca. 2.5 m. For this purpose, precipitation had to drop by a factor of <0.7 (see above). It is remarkable that the inferred draught in Mongolia 5.5 ky BP, within the accuracy of dating, was contemporary with the change of the North Atlantic circulation which induced abrupt termination of the African Humid Period and desiccation of the Sahara Desert (DeMenocal et al., 2000; Swezey, 2001), and temporary advance of prairies near the Elk Lake in North America (Dean, 1997; Smith et al., 2002).

Hence, the Lake Khubsugul sedimentary record of paleoclimates is highly informative, giving direct evidence of changes in atmospheric precipitation in the Upper Pleistocene and Holocene. More detailed and accurate analyses, along with quantitative modelling based on thermodynamic properties of authigenic phases, will allow more accurate reconstruction of the climate components at a location which is important for global climate modelling—at the limit of influence by moisture from the North Atlantic.

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References

Altunbaev, V.H., Samarina, A.V., 1977. Kharacteristika donnykh otlozheniy Khubsugula (Characteristics of the Khubsugul Lake bottom sediments). Prirodnie Usloviya i Resursi Prikhubsuguliya v MNRTrudi Sovetsko–Mongolskoi Kompleksnoi Khubsugulskoi Ekspeditsii, Irkutsk University Press, Irkutsk, vol. 5, pp. 80–90. In Russian.

Arinushkina, E.V., 1970. Rukovodstvo po Khimicheskomu Analizu Pochv (Treatise for Chemical Analysis of Soils). MGU, Moscow. In Russian.

Bogoyavlensky, B.A. (Ed.), 1989. Atlas of Lake Khubsugul. GUGK, Moscow, p. 119.

Baram, G.I., Vereshchagin, A.D., 1999. Microcolumn liquid chromatography with UV detection for determination of anions in the environment. Zh. Analit Khym. 54 (9), 962–965.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evants, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent solar influence on North Atlantic climate during the Holocene. Science 294, 2345–2348.

Brooks, A.S., Edgington, D.N., 1994. Biogeochemical control of phosphorus cycling and primary production in Lake Michigan. Limnol. Oceanogr. 39, 961–968.

Chebykin, E.P., Edgington, D.N., Grachev, M.A., Zheleznyakova, T.O., Vorobyova, S.S., Kulikova, N.S., Azarova, I.N., Khlystov, O.M., Goldberg, E.L., 2002. Abrupt increase in precipitation and weathering of soils in East Siberia coincident with the end of the last glaciation (15 cal kyr BP). Earth Planet. Sci. Lett. 200 (1–2), 167–175.

Dean, W.E., 1997. Rates, timing and cyclicity of Holocene eolian activity from north–central United States: evidence from varved lake sediments. Geology 25, 331–334.

DeMenocal, P., Ortiz, J., Guilderson, T., Adkins, J., Sarnthein, M., Baker, L., Yarusinsky, M., 2000. Abrupt onset and termination of the African humid period: rapid climate responses to the global insolation forcing. Quat. Sci. Rev. 19, 347–361.

Dickens, G.R., 2001. Sulfate profiles and barium fronts in sediment on the Blake Ridge: present and past methane fluxes through a large gas hydrate reservoir. Geochim. Cosmochim. Acta 65 (4), 529–543.

Dorofeyuk, N.I., Tarasov, P.E., 1998. Vegetation and levels of the lakes in the north of Mongolia during the last 12500 years, by the data of palynological and diatom analyses. Stratigr. Geol. Correl. 6 (1), 73–87 (In Russian).

Fedotov, A.P., Bezrukova, E.V., Chebykin, E.P., Khlystov, O.M, Velichko, A., Levina, O.V., Mazepova, G.P., Mizandrontsev, I.B., Semenov, A.R., Vorobyova, S.S., Zheleznyakova, T.O., Grachev, M.A., 2000. Potential value of bottom sediments of Lake Khubsugul (Mongolia) for paleoclimate reconstructions. Berl. Geowiss. Abh., Reihe A, Geol. Paläontol. 205, 107–112.

Fedotov, A.P., De Batist, M., Shapron, E., De Ryker, K., Pauls, T., 2002. Seismic profiling of the sediments of Lake Khubsugul. Dokl. akad. nauk 382 (2), 261–263.

Goldberg, E.L., Phedorin, M.A., Grachev, M.A., Zolotarev, K.B., Khlystov, O.M., 2001. Geochemical indicators of paleoclimate changes in sediments of Lake Baikal. Russ. Geol. Geophys. 42 (1–2), 76–86.

Golubev, V.A., 1992. Dense clays in the uppermost layer of bottom sediments of Lake Khubsugul (Mongolian Peoples' Republic). Dokl. Akad. Nauk SSSR 324, 1091–1095.

Grachev, M.A., Likhoshwai, E.V., Vorobiova, S.S., Khlystov, O.M., Bezrukova, E.V., Veinberg, E.V., Goldberg, E.L., Granina, L.Z., Kornakova, E.G., Lazo, F.I., Levina, O.V., Letunova, P.P., Otinov, P.V., Pirog, V.V., Fedotov, A.P., Yaskevich, S.A., Bobrov, V.A., Sukhorukov, F.V., Rezchikov, V.I., Fedorin, M.A., Zolotarev, K.V., Kravchinsky, V.A., 1997. Signals of the paleoclimates of upper Pleistocene in the sediments of Lake Baikal. Russ. Geol. Geophys. 35 (5), 994–1018.

Grootes, P.M., Stuiver, M., 1997. Oxygen 18/16 variability in Greenland snow and ice with 10^3–10^5 years time resolution. J. Geophys. Res.-Oceans 102, 26455–26470.

Horiuchi, K., Minoura, K., Hoshino, K., Oda, T., Nakamura, T., 2000. Paleoenvironmental history of Lake Baikal during the last 23000 years. Palaeogeogr. Palaeoclimatol. Palaeoecol. 157, 95–108.

Kuznetsova, L.P., 1978. Perenos Vlagi v Atmosfere nad Territoriey SSSR (Transfer of Moisture over the Territory of the USSR). Nauka, Moscow.

Rusin, G.G., 1990. Fiziko–Himicheskie Metody Analiza v Agrohimii (Physical–Chemical Methods in Agricultural Chemistry) Agropromizdat, Moscow. In Russian.

Severinghaus, J.P., Brook, E.J., 1999. Abrupt change at the end of the last glacial period inferred from trapped air in polar ice. Science 286, 930–934.

Smith, A.J., Donovan, J.J., Ito, E., Engstrom, D.R., Panek, V.A., 2002. Climate-driven hydrologic transients in lake sediment records: multiproxy record of mid-Holocene draught. Quat. Sci. Rev. 21, 625–646.

Stuiver, M., Reimer, P.J., Bard, J.E., Beck, W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., Plicht, J.V.D., Spurk, M., 1998. INTCAL98 radiocarbon age calibration, 24,000–0 cal BP. Radiocarbon 40, 1041–1083.

Swezey, C., 2001. Eolian sediment responses to late Quaternary climate changes: temporal and spatial patterns in the Sahara. Palaeogeogr. Palaeoclimatol. Palaeoecol. 167, 119–155.

Velichko, A., 1999. Changes of the Climates and Landscapes during the last 65 million years (Cenozoic—from Paleocene to Holocene). GEOS, Moscow.