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Abrupt increase in precipitation and weathering of soils in East Siberia coincident with the end of the last glaciation (15 cal kyr BP)

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Abstract

An abrupt increase in the temperature in Greenland in the wake of the initiation of the Bølling–Allerød warm phase at ca. 15 cal kyr BP was followed after a few decades by a dramatic increase in the concentration of methane in the atmosphere of the Earth resulting from an increase in humidity in the tropics [J.P. Severinghaus, E.J. Brook, Science 286 (1999) 930–934]. Analysis of a sediment core from Lake Baikal (East Siberia), spanning the end of the last glacial period and the Holocene, revealed an abrupt, stepwise, 1.3–3.4-fold decrease in the concentration of several 'soluble' elements such as Na, K, Mg, Ca and Si in hot nitric acid extracts of small intervals (3 cm). This chemical change appears to have occurred over the same time span, based on similarities in the profiles of silica and diatoms found in other ^{14}C-dated cores. This suggests that the calcium-rich 'mammoth steppe' landscape [R.D. Guthrie, Quat. Sci. Rev. 20 (2001) 549–573] of Siberia created during the last glaciation underwent a dramatic transformation at the end of this period (at the beginning of the Bølling–Allerød warm phase) due to an increase in precipitation within a time interval of less than 300 yr.

Keywords: Lake Baikal; paleolimnology; paleoclimatology; rainfall; soils; weathering; diatoms; climate change

1. Introduction

One of the most important and challenging tasks of natural sciences is to understand the reasons for abrupt climate oscillations. This lack of understanding makes it hard to elaborate reliable models of climate change in the near future. A possible approach to verify such models is to identify and ascertain as precisely as possible the timing of all the abrupt climate change events that have occurred in the past throughout the world.

During the last decade, international studies of the sediments of Lake Baikal have revealed that they contain a unique, continuous record of the

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past climates of the largest continent [3]. The analysis of sediments deposited over the last 5 Myr showed that the content of diatoms in these sediments has varied cyclically according to Milankovich time periods of 100, 41, 23 and 19 kyr [4]. Diatoms are highly abundant in layers associated with interglacial, but absent from those associated with glacial periods. The diatom signal, as well as other climate proxies in Baikal sediments, should reflect geochemical changes that occurred in the huge (500 000 km^2) catchment basin of Lake Baikal. However, until recently, the connection was not clear – the signals were not calibrated with respect to particular climate variables such as temperature or humidity. Only a few papers have discussed the relationship between high-frequency millennial-scale (1500–2500 yr) climate oscillations and geochemical changes in the sediments of Lake Baikal (e.g. [5]). Data on the paleoclimate records on different time scales stored in the sediments of Lake Baikal are presented in many publications, the most recent examples are [6–9].

In a search for new signatures of abrupt climate change, we studied a sediment core (VER-99-2 St6 GC) from Lake Baikal collected using a gravity corer from a site on the underwater high Posolskaya Bank south of the delta of the Selenga River, the major tributary to Lake Baikal. This high is surrounded on all sides by troughs (from 400 to 1400 m deep). The sediments on the relatively flat top of Posolskaya Bank have, for Lake Baikal, a relatively high sediment accumulation rate (ca. 10 cm/kyr), and are not disturbed by turbidites.

2. Field sampling and methods

The core VER-99-2 St6 GC was taken at E 52°05′20″, N 105°50′26″, water depth of 200 m. Its length was 3.6 m. The core was sampled at 3 cm intervals, which, according to our age model (vide infra), yields a temporal resolution of approximately 300 yr. Every slice was homogenized and stored in a plastic bag at 4°C until time of analysis.

Sub-samples of wet sediment (3 g) were weighed, dried at 60°C to constant weight, and ground in a mortar; 50 mg samples of dry sediments were leached with 0.5 ml of 72% nitric acid using mechanical shaking for 2 h at 80°C. These suspensions were diluted with water to 15 ml, 150 ng of In standard added, centrifuged and aliquot portions of the supernatants removed. This method of extraction provides a solution of elements from two sources: pore water, and easily leachable components of the sediment. The nature of the residual fraction was not studied.

The solutions were pumped (30 ml/min) into an inductively coupled plasma–mass spectrometry (ICP–MS) machine (PlasmaQuad II, VG Instruments). Measurements were made in the scanning mode at a rate of 3 min/sample over an interval covering mass numbers from 4 to 240. After measuring sample #1, the tube of the pump was immediately transferred into sample tube #2, and so on, without any intermediate washing. The stability of the response function of the instrument was checked after every 20 samples by pumping a mixture of equal volumes of aliquot portions of all samples. The bell-shaped dependence of sensitivity on mass was measured using a solution of a mixture of known concentrations of a few elements having widely different masses (Be, Mg, Co, Ni, In, Ce, Pb, Bi, U) and used for a calibration of the response of the instrument. The precision of analysis was ±5% with elements present at concentrations >35 ppb (μg per kg of dry sediment). Diatom analysis was performed as described by Grachev et al. [10].

3. Results and discussion

The results of the ICP–MS analyses are compared with those from diatom counting in Fig. 1. Total diatom content is used as the basis for a stratigraphic correlation by comparison with its distribution in other cores studied earlier in order to develop an age–depth model to provide an estimate of time associated with each depth interval. No diatoms were present in the lower part of the core, below 170 cm. Approximately 20 cm above this depth a small peak of diatoms (labeled #1) appears. Above this peak, there is another interval

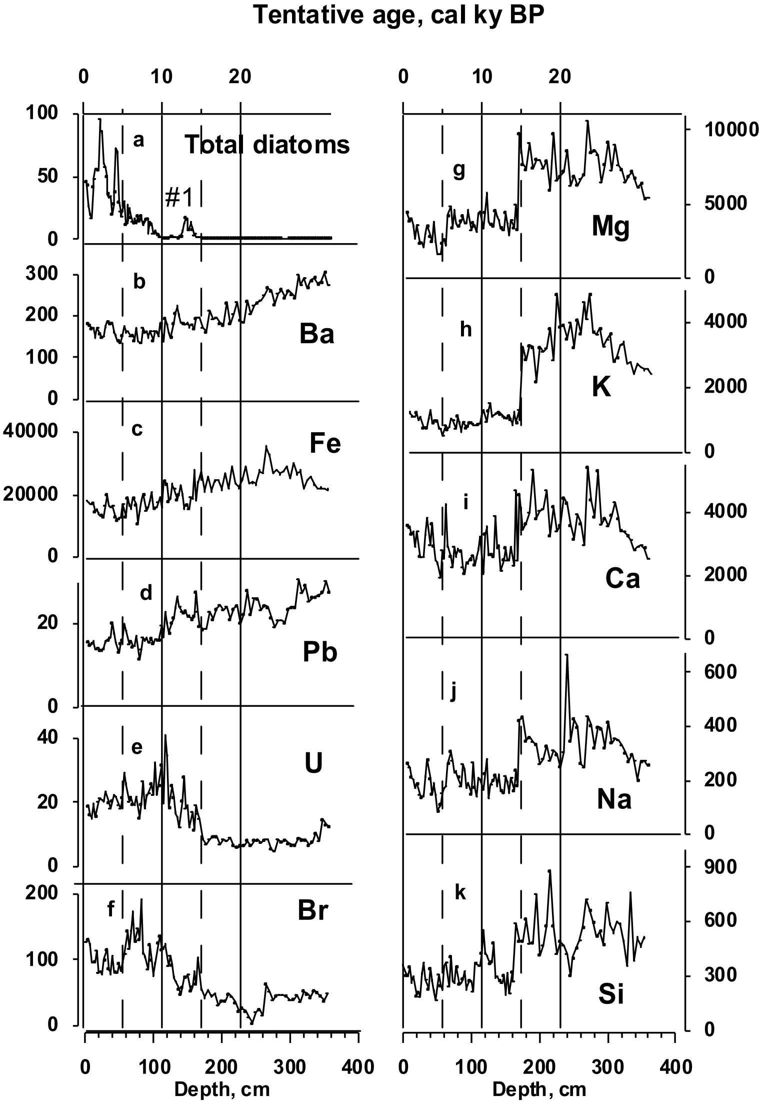

Fig. 1. Profiles of (a) total diatoms content in sediments of Posolskaya Bank, Lake Baikal, number g^{-1}, and (b–k) different elements (ppm in dry matter) in extracts of these sediments obtained by treatment with hot nitric acid determined by ICP–MS. The tentative age shown in the upper horizontal axes is from the age–depth model described in the text. Peak #1 of diatoms in (a) is ascribed to the Bølling–Allerød warming (cf. [12]), and the diatom-barren interval between 12 and 10 kyr BP to the Younger Dryas cooling.

with a very low content of diatoms. Finally, from a depth of approximately 110 cm to the core top, there is a regular increase in diatoms concentration with a maximum at a depth of approximately 20 cm. The distribution of total diatoms (Fig. 1a) and of diatom species (Fig. 2) in this core is similar to those found in other cores with widely differing sedimentation rates. Peak #1 (Fig. 1a) in the present core contains the species *Stephanodiscus flabellatus* (Fig. 2). This diatom, which is found nowhere else within the uppermost Pleistocene and Holocene, has been detected in the corresponding small peak of biogenic silica in all other sediment cores of similar age collected

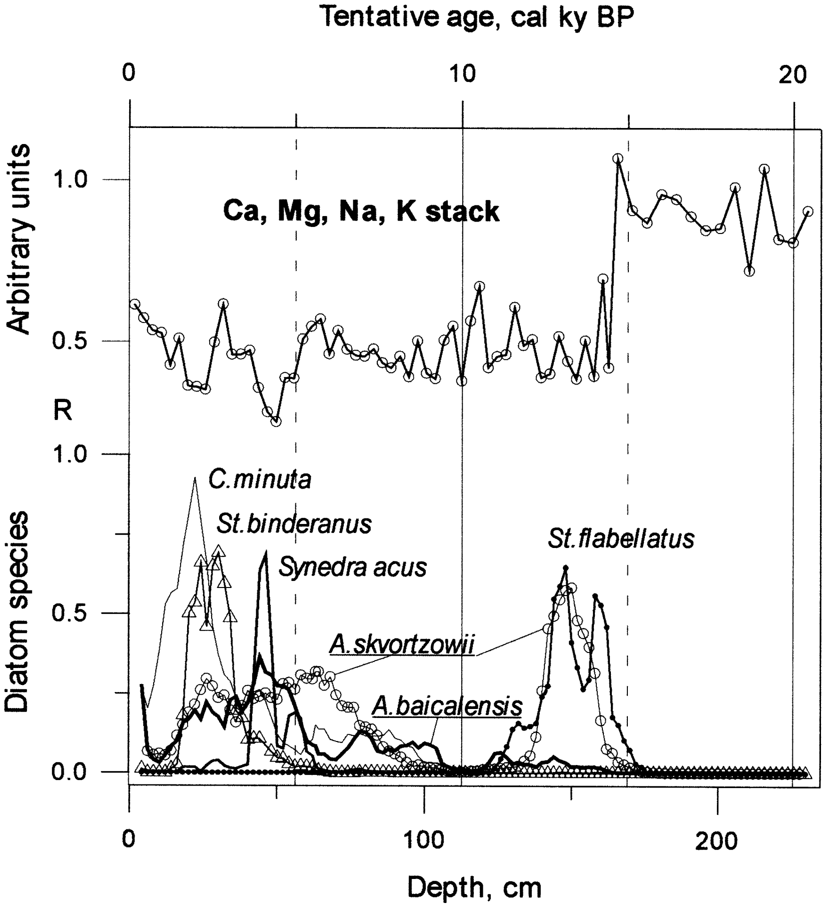

Fig. 2. Stack of leachable light cations (upper panel) and diatom species (lower panel) in sediments of Posolskaya Bank, Lake Baikal. The depth (z) profiles of Na, Ca and K ($f_i(z)$) were transformed into profiles of $f_{i,t}(z) = a + bf_i(z)$; coefficients a and b were selected in such a way that the difference between the areas under the profile of Mg and that of each $f_{i,t}(z)$ was minimal. An average of the four profiles obtained was calculated and normalized by division by the maximum amplitude. The function obtained is presented as the Ca, Mg, Na, K stack. Individual diatom species contents are presented as relative abundances R = (abundance of given diatom species at given depth)/(maximum abundance of the same species); the profiles shown are three-point running averages, and for this reason the maximum R values are always less than 1.

from Baikal dated using ^{14}C [10,11]. Colman et al. [12] measured the ages of samples from other cores, bracketing this small peak (labeled #1 in our core), and concluded that it occurred shortly after 15 cal kyr BP (calibration according to [13]), that is, approximately during the Bølling–Allerød warm phase or Greenland Interstadial, GI-1. Further, since Colman et al. [12] concluded that the sediment accumulation rate in Lake Baikal remained approximately constant throughout the Holocene and uppermost Pleistocene, it is reasonable to infer the tentative age–depth model for our core presented as the upper horizontal axes in Figs. 1–3. This and other studies suggest that climate changes at Baikal are similar in timing and magnitude as those seen in Europe (Bølling–Allerød, Younger Dryas, etc.). According to Velichko et al. [14], temperatures of January and July in the forest zone of Siberia in Younger Dryas were equal to −31°C and +13°C, respectively, whereas at present they are equal to −28°C and +17°C.

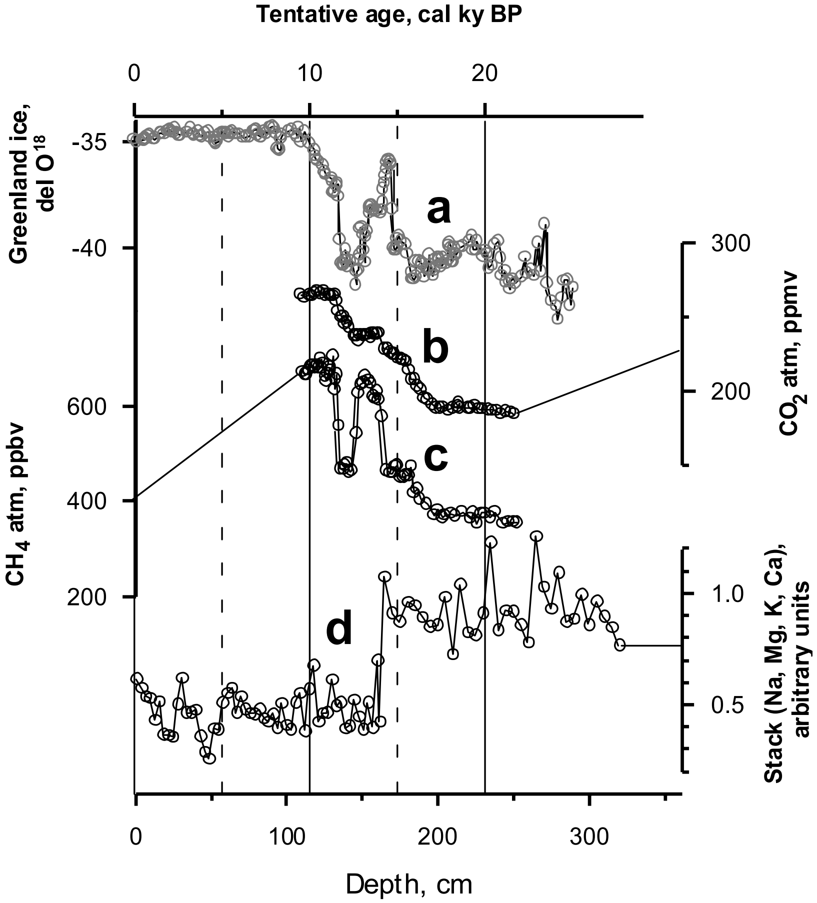

Fig. 3. Comparison of the Baikal sedimentary record with global climate records. (a) $\delta^{18}O$ in Greenland ice [20]. (b and c) CO_2 and CH_4 in Antarctic ice [21]; profiles b and c are arbitrarily shifted – ca. 800 yr to match the Greenland profile in the way proposed by Monnin et al. [21]. (d) Stack of Ca, Mg, Na, K (see legend to Fig. 2).

Recently, Soma (personal communication, 2001) analyzed few intervals of the same core as studied here by AMS radiocarbon dating, yielding a radiocarbon age at a depth of 160 cm of 12.8 ^{14}C kyr, which, according to the calibration used earlier by Colman et al. [12], corresponds to a calendar age of 15.2 cal kyr. This is in good agreement with our proposed depth–age model within the error of radiocarbon measurement.

Profiles of concentrations of elements extracted from the sediment with hot nitric acid are presented in Fig. 1b–k (profiles in a digital form can be requested at info@lin.irk.ru). The concentration of Ba (Fig. 1b) gradually decreases from bottom to top, and reaches a plateau in the Holocene. Profiles of Fe and Pb (Fig. 1c,d) are very similar to that for Ba, as are those of Sn, Co, Ni, Cu, Zn, Ga, Rb, Cs, La, Ce, Tl, Bi, and Th, which are not shown. Some of the latter profiles are somewhat confused by minor steps and peaks. These elements are placed in Class 1. Variation within Class 1 elements may be due to a change in the source of terrigenic matter. In the Pleistocene, vast amounts of suspended solids were delivered into the lake by glaciers. These mountain glaciers mostly disappeared in the Holocene.

The profile for uranium (Fig. 1e) shows that at ages older than before 15 kyr BP the concentration of U is low. Above this boundary, the concentration of U gradually increases. The profile is complicated by the presence of narrow peaks. Remarkably, the increase in the concentration of U begins much earlier than the growth of total diatoms (cf. Fig. 1a). Similar profiles were obtained for Br (Fig. 1f), Nb and W (data not shown). Uranium was first identified by Edgington et al. [15] as a proxy for wetter/warmer climates in extracts of sediments of Lake Baikal leached with hot HNO_3. This was confirmed for bulk sediments in subsequent publications, e.g. [10]. Bromine as a proxy for wetter/warmer climates in bulk sediments of Lake Baikal was identified by means of X-ray fluorescent analysis with synchrotron radiation [16]. According to Edgington et al. [15], the increase in concentration of uranium in the sediments could result from enhanced delivery of the element in run-off from soils and rocks in the catchment basin drained by the Selenga River under the wetter and warmer climates during the Holocene. Uranium thus was delivered into the lake in a dissolved form, and was subsequently absorbed on settling sediment particles. During the cold climates, this leaching was suppressed, and U was mostly delivered with suspended solids which we now believe to be of glacial and/or eolian origin [15,10]. The elements U, Br, W, Nb are placed into Class 2.

The most dramatic changes are exemplified by a widely distributed set of elements which we place into Class 3. These are Na, K, Mg, Ca and Si (see Fig. 1g–k) which show the inverse of the behavior of uranium. These elements exhibit an abrupt decrease at the end of the last glacial period, at the 15 cal kyr BP boundary. This transition is extremely sharp and occurs within a period of less than 300 yr (our sampling interval). High potassium content in sediments had been identified earlier by Gavshin et al. [17] as an indicator of cold climates in the sediments of Lake Baikal on a low temporal resolution Milankovich time scale from the distribution of ^{40}K. However this finding refers to total sediments, rather than to nitric acid extracts. An increase in Ca in a few samples of the Pleistocene sediments from Lake Baikal has been ascribed by Qiu et al. [18] to be of pedogenic origin. Several of the profiles shown in Fig. 1 are complicated by peaks that can be related to abrupt climate change events. In particular, the observed small peak for Si at a depth of 105 cm is consistent with the timing of the Younger Dryas cooling (Fig. 1k).

Along with elements of Classes 1–3, we analyzed a few other leachable elements, such as P, Mn and Mo, which exhibit a complex series of extremely narrow peaks in the core (data not shown). We believe that these peaks are of diagenetic origin, i.e. that they formed long after the deposition of the sediments. However, a discussion of diagenesis is beyond the scope of the present paper.

The comparison of the Baikal record of the concentrations of leachable light cations with the global records of climate proxies such as $\delta^{18}O$, CO_2 and CH_4 [19,20] is shown in Fig. 3. The accuracy of our depth–age correlation is sufficiently good to suggest that the stepwise drop of the Na, K, Mg and Ca stack in the sediments (Fig. 3d) occurred immediately after the end of the last glaciation because of its close apparent timing with the abrupt change in $\delta^{18}O$. Severinghaus and Brook [1] established that the temperature gradient following the Bølling–Allerød warming in Greenland was steepest ca. 14.7 cal kyr BP, and was followed in 20–80 yr 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 atmospheric circulation, i.e. that of the storm tracks, induced by a change in the circulation of waters in the North Atlantic. The similarity in the timing of the transitions of $\delta^{18}O$ and CH_4 in the ice cores and the distribution of Class 3 elements in the Baikal sedimentary record strongly suggests that these changes may have been driven by the same mechanism, even though Siberia is many thousands of kilometers to the east of Greenland.

The very sharp transition in the Class 3 elements and in the sediments of Lake Baikal (Fig. 3d), and $\delta^{18}O$ in the Greenland ice core (Fig. 3a), contrasts with the slightly slower transition for CH_4 and with the considerably slower transition for CO_2 recorded in the ice cores (Fig. 3b,c). The slow response of carbon dioxide is due to the high inertia of the carbon cycle, i.e. interaction of atmosphere with the oceanic CO_2. The response of $\delta^{18}O$ in Greenland ice is fast because it is a proxy of the difference in temperature between the North Atlantic surface water and on top of the Greenland ice dome (as reflected also by snow accumulation rate). Methane is, according to Severinghaus and Brook [1], almost immediately delivered into the atmosphere from the tropics as soon as the land becomes wet.

It is well known that the climate of East Siberia during the last glacial was not only cold, but also dry: atmospheric precipitation has been estimated to be 200 mm per year then, whereas at present it is ca. 400 mm per year [21,22]. However, previous studies have not addressed how fast this increase in precipitation occurred. The lowland landscapes of Siberia during the last glacial period were dominated by the so-called 'mammoth steppe' which was characterized by uniquely fertile calcium-rich soils [2]. These landscapes have no modern analogs. Evidently, the terrigenous solids that were delivered to Lake Baikal from the catchment basin by rivers and from the air at that time inherited the geochemical properties of the soils of the 'mammoth steppe', and for this reason contained high concentrations of labile Na, K, Mg, Ca and Si. According to our hypothesis, sediments deposited in Lake Baikal did not lose these soluble elements during or after sedimentation. The change in concentration of the Class 3 elements found in the sediments requires percolation of water that could only occur prior to delivery of the sediment to the lake in a sub-aerial environment. At the start of the Bølling–Allerød warm phase, the pattern of atmospheric circulation must have abruptly changed in such a manner that storm tracks began to reach Northern Mongolia and Trans-Baikalia regularly. Increase in precipitation immediately leached the soluble components from the 'mammoth steppe' soils with the concomitant change in the geochemistry of the sediment particles delivered to the lake.

Remembering that we only measured the nitric acid leachable fraction of the sediment, the composition of the altered state found after the Bølling–Allerød warm transition suggests that rain-induced leaching of the 'mammoth steppe' soils removed only the most labile portion of these elements. It is highly improbable, from our understanding of the present-day aquatic chemistry of the lake, that the concentration of any of these inorganic ions in the water could have approached equilibrium with an insoluble species or compound (i.e. $CaCO_3$) [23]. It also seems unlikely that a major cause for the geochemical changes could have been the discontinued delivery of finely dispersed rocks and soils from the mountain glaciers around Lake Baikal – their melting must have taken a relatively long time, and relict mountain glaciers currently exist in the region.

An alternative explanation for the abrupt change in Class 3 elements could be that the change in weather to a wetter climate reduced the deposition of the eolian dust component, which is rich in exchangeable base cations such as Ca^{2+} and Mg^{2+}, to the lake and its watershed. The basis for the formation of the 'mammoth steppe' proposed by Walker et al. [24,25] is that the continual influx of base cations and carbonate-rich dust produces these non-acidic cation-rich soils and associated steppe-like vegetation. To support this mechanism requires a further analysis of our data, but, at present, it would be very difficult to distinguish between the two possible mechanisms: (1) leaching of soluble cations already present on the land surface or (2) diminution of eolian fluxes of base cation/carbonate-rich particles to land or lake because of the wetter climate.

In any case, no matter what the source of sediment, an increase in precipitation seems to be the most probable mechanism for the abrupt transformation in the geochemistry of light cations in the sediments. Cations such as Na^+, K^+, Mg^{2+}, Ca^{2+}, and Si are also found in the crystal lattices of non-weathered minerals (clay precursors). The behavior of light cations, as revealed by the profiles shown in Fig. 1g–j, is in accordance with our simple hypothesis, suggesting that a two-fold increase in precipitation [21,22] resulted in an approximately two-fold decrease of the cations in the leachable fraction in the soils as parent material to the sediments. Indeed, before and after the transition at ca. 15 cal kyr BP the concentrations of leachable Na^+, K^+, Mg^{2+} and Ca^{2+} dropped

1.7, 3.4, 2.1 and 1.3 times, respectively, with an average of 2.1 times. In the presence of water, elements that are an integral part of host mineral lattices are weathered or exchanged with protons at a rate too slow to provide the dramatic changes seen in this core (i.e. the minerals are thermodynamically unstable in a moist surficial environment).

The stepwise decrease in the concentration of leachable elements of Class 3 in the sediments of Lake Baikal occurred exactly at the same time as the abrupt increase in the concentration of diatoms (Fig. 2). This suggests that diatoms which survived in Lake Baikal in near-shore refugia during the glacial interval received a pulse of dissolved nutrients released by the degraded mammoth steppes following the Bølling–Allerød transition. After this, diatoms occupied the open water. Later, the flux of nutrients, e.g. soluble silica (see Fig. 1k), decreased during Younger Dryas (∼10 kyr BP) which resulted in a decline in abundance of diatoms. A subsequent increase in the concentration of diatoms was slow; it reached a maximum only 8000 yr after the onset of the Holocene. Remarkably, this natural eutrophication of Lake Baikal manifested itself in a succession of individual diatom species (Fig. 2), similar to that which happens on a much faster time scale in small lakes resulting from anthropogenic impact or insult. Presumably, the rate of increase in the abundance of diatoms was governed by the slow process of formation of new soils and weathering of rocks in the catchment basin. This slow recovery may be a direct consequence of either the reduction in eolian inputs or from the gradual weathering of Holocene soils as may be seen in the profiles of elements of Classes 1 and 2 (Fig. 1).

4. Conclusion

The data presented in this paper shed new light on the nature of the geochemical signals of changing climates in the sedimentary record and thus in the ecological structure of Lake Baikal. They also suggest that extremely abrupt climate changes in the middle of Asia had much in common with those observed in other locations around the world.

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