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GEOCHEMISTRY

Oxygen Isotopic Composition in Diatom Algae Frustules from Lake Baikal Sediments: Annual Mean Temperature Variations during the Last 40 Ka

G. V. Kalmychkov[a], Academician of the RAS M. I. Kuz'min[a], B. G. Pokrovskii[b], and S. S. Kostrova[a]

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The oxygen isotopic compositions of ice sheets in Antarctica and Greenland and biogenic carbonates from deep-sea oceanic sediments represent a source of reliable information on global climate changes.

During glaciations, the ^{16}O-rich isotope is largely accumulated in polar ice sheets, while seawater becomes enriched in ^{18}O. Warming promotes glacier melting and concentration of the oxygen light isotope in atmospheric moisture and seawater. This is recorded in remains of biogenic carbonate organisms, for example, shells of fossil foraminifers.

The isotopic composition of biogenic carbonates from deep-water sediments of seas and oceans is sufficiently well known. Studies of them provided data for compiling the continuous high-resolution marine oxygen isotope curve (SPECMAP), which reflects alternating warm and cold periods since the late Miocene to recent times, and allowed definition of the periodicity (19–23, 41, and 100 ka) in global climate fluctuations. The data obtained are consistent with calculations by M. Milankovitch. In 1913, he proposed a theory that explains climate cyclicity as a response of the Earth's climatic system to insolation variations related to changes in orbital parameters of the planet [1].

In addition to marine and ice climatic records, long-term continental paleoclimatic records, which may be derived from lacustrine sediments, are also important. In this respect, Lake Baikal is most promising. For example, study of the biogenic silica distribution in lake sediments made it possible to compile a continuous climatic record, which comprises the period up to 8 Ma [2]. The SiO_{2bio} distribution through the section reflects the distinct climate cyclicity with periods of 19, 21, 41, and 100 ka. They accord well with the marine isotopic curve and data derived from the study of ices cores from Greenland and Antarctica.

Sediments of Lake Baikal lack biogenic carbonates. Therefore, diatom algae frustules composed of amorphous silica are the only material suitable for oxygen isotope studies. Recent studies confirmed the possibility of their application to paleoclimatic reconstructions [3, 4].

This communication presents the results of the $\delta^{18}O$ study in fossil diatom frustules from Lake Baikal. The frustules were extracted from bottom sediments recovered by gravity corers at two stations on the underwater Akademicheskii Ridge (Station 03-01, 53°44.838′ N, 108°24.559′ E, water depth 348 m) and in the Maloe More Strait (Station 04-02, 53°23.646′ N, 107°31.903′ E, water depth 233 m).

Diatom algae frustules were extracted from sediments using a special technique [5], which provides preparations suitable for isotopic measurements even in the case of low SiO_2 contents in sediments (no more than 2–3%). Study of the obtained sediments by the methods of scanning electron microscopy failed to find a terrigenous admixture (Fig. 1).

For isotopic analyses, the frustules were decomposed using ClF_3 at 400°C after preliminary training in vacuum for 2 h at 400°C. The $\delta^{18}O$ values were determined using an MI-1201V mass spectrometer with an accuracy of ±0.3 ‰ relative to SMOW.

Although no age determinations of sediments from cores 03-01 and 04-02 by the AMS^{14}C method were carried out, the data on the SiO_{2bio} in them (Fig. 2) allow us to reconstruct a substantially reliable age model. According to [2], the biogenic silica content in Baikal sediments accumulated during the interglacial period amounts to 40%, while its concentration in glacial periods rarely exceeds 2–3%.

The SiO_{2bio} content in cores 03-01 and 04-02 increases sharply beginning from the depth of 44 cm

[a] Vinogradov Institute of Geochemistry, Siberian Division, Russian Academy of Sciences, ul. Favorskogo 1-A, Irkutsk, 664033 Russia; e-mail: gkalm@igc.irk.ru
[b] Geological Institute, Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 119017 Russia

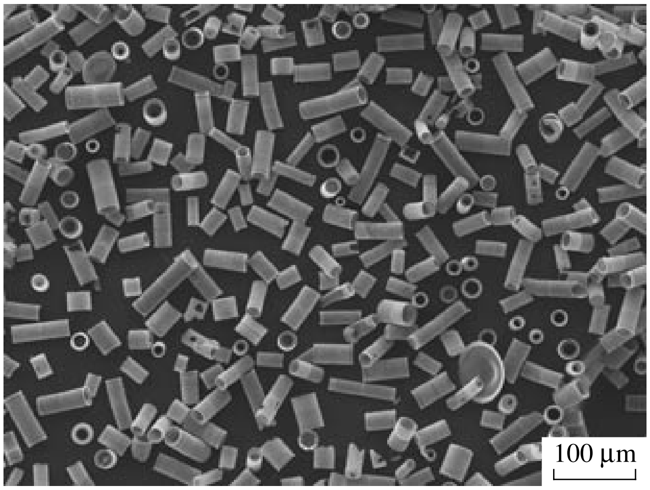

Fig. 1. SEM image of shells of diatom algae extracted from Core 04-02 (interval 219–220 cm, BC = 15.8%, $\delta^{18}O$ = 25.2‰).

and 66 cm, respectively, which corresponds to the onset of the Holocene (11 ka ago). Thus, the sedimentation rate at stations 03-01 and 04-02 is estimated at 4 and 6 cm/ka, respectively. Hence, the age of recovered sediments is 17 and 47 ka, respectively. The sedimentation rate determined for Station 03-01 accords well with that obtained for cores from deep holes BDP-96 and BDP-98 drilled on Akademicheskii Ridge [2]. It is conceivable that the sedimentation rate at Station 04-02 during cold periods was higher than in warm periods. Therefore, the average sedimentation rate for the entire section should be higher than in the Holocene and the age of sediments of Core 04-02 probably does not exceed 40 ka.

The interval of 85–175 cm in Core 04-02 is characterized by a low biogenic silica content (Fig. 2). Therefore, one can affirm with a high degree of confidence that these sediments correspond to the Sartanian stage of the Late Pleistocene glaciation. Downward into the section (interval 175–250 cm), the SiO_{2bio} content in sediments increases to 37 ± 17%. Hence, the interval under consideration corresponds to the Karginian Interstadial. Thus, Core 04-02 from the Maloe More area characterizes analogues of three marine isotopic stages: Karginian Interstadial (MIS-3), Sartanian Glaciation (MIS-2), and Holocene (MIS-1).

The $\delta^{18}O_{frust}$ value in Core 03-01 varies from 20.2 to 27.5‰. The gradual enrichment of frustules in ^{18}O upward through the section is generally contemporaneous with the growth of SiO_{2bio} contents in sediments (Fig. 2), but the curve of the $\delta^{18}O_{frust}$ distribution is characterized by more complicated patterns. The maximal $\delta^{18}O$ value (27.5‰) is registered at a depth of 4–5 cm. Toward the surface, frustules become depleted in ^{18}O by ~2‰. Minimums in the $\delta^{18}O$ values are registered at 58–61 and 72–73 cm (20.2–21.0 and 20.4‰, respec-

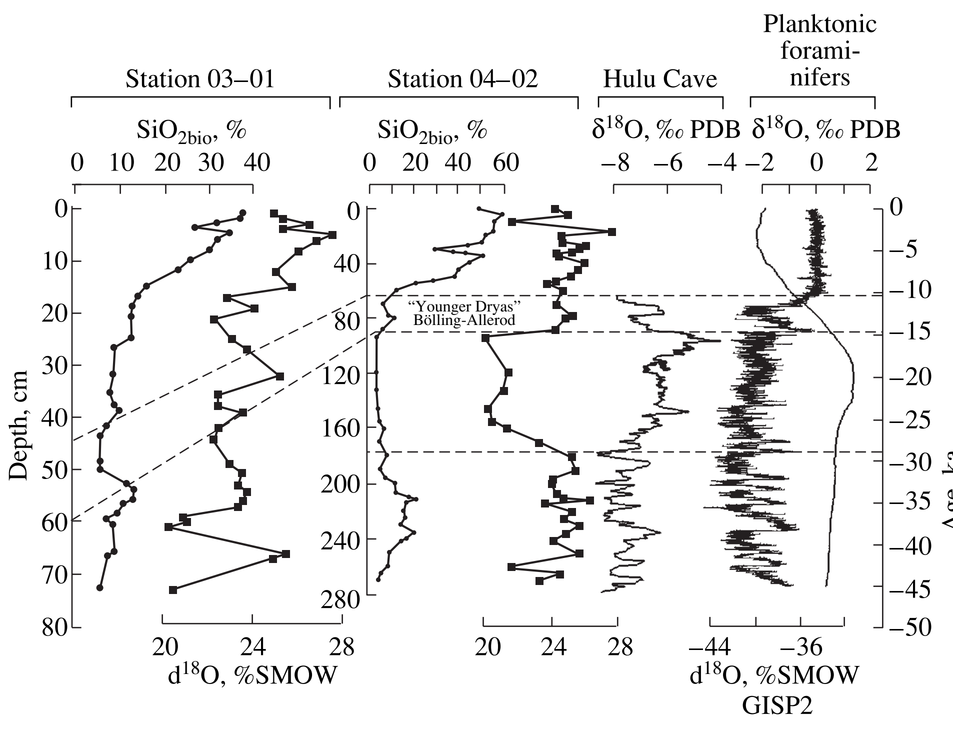

Fig. 2. The biogenic SiO_2 content and $\delta^{18}O$ in shells of diatoms from cores 03-01 and 04-02; $\delta^{18}O$ in planktonic foraminifers from oceanic sediments, stalactites of the Hulu Cave, southern China [8]; $\delta^{18}O$ in ice from Core GISP26, Greenland [7]. The sedimentation rate in Core 04-02 is accepted at 6 cm/ka.

Oxygen isotopic composition in glaciers and lacustrine diatoms during the Early Holocene (EH) and last glaciation maximum (LGM)

Object	$\delta^{18}O$ (EH)	$\delta^{18}O$ (LGM)	$\Delta^{18}O$ |EH–LGM|
Glaciers			
Greenland [7]	–39.7	–34.6	5.1
Antarctica [11]	–61.1	–55.7	5.4
Peru [12]	–22.9	–16.6	6.3
Tibet [13]	–18.5	–13.3	5.4
Lacustrine diatoms			
Alaska [14]	23.9	19.0	4.9
Baikal (this work)	25.2	20.0	5.2

tively). They are divided by the positive peak ($\delta^{18}O$ = 24.9–25.5‰), which is indistinguishable in the SiO_{2bio} distribution curve. It is conceivable that the last peak corresponds to the Bölling–Allerod warming event.

As in case of SiO_{2bio}, the $\delta^{18}O$ distribution curve shows the interval 0–90 cm with high values of this parameter (24.8±1.1‰). This interval comprises both the Holocene (Fig. 2) and Bölling–Allerod episodes. The interval of 0–90 cm, which is characterized by low $\delta^{18}O$ values (20.7±0.6‰), corresponds to the Sartanian Glaciation. At the lower interval of 179–250 cm, the $\delta^{18}O$ values are similar to those observed in diatoms from the Holocene sediments. This core interval corresponds to the Karginian Interstadial.

Positive peaks of $\delta^{18}O$ values at a depth of 5 cm (Core 03-01) and 15–16 cm (Core 04-02) are remarkable. These peaks correspond to ages of approximately 2.5–2 ka and likely mark the minor climatic optimum for Siberia, which is also evident from palynological data (Bezrukova, private communication).

In contrast to SiO_{2bio}, the scatter in the distribution of $\delta^{18}O$ values in frustules from the Akademicheskii Ridge and Maloe More is similar (20.0–27.5‰). This is quite natural, since the SiO_{2bio} content in sediments depends on the lake productivity, which is different in its various parts, while the $\delta^{18}O_{frust}$ value is governed by the isotopic composition of water, which is uniform, at least now, for all of Lake Baikal [4].

Taking the age model accepted for Core 04-02 into consideration, we can assume that the transition to the Sartanian Glaciation (Fig. 2) commenced in the Baikal region approximately 30 ka ago. Cooling is also registered in oxygen isotope curves based on the $\delta^{18}O$ values in planktonic foraminifers from oceanic sediments [6], GISP2 ice cores from Greenland [7], and stalactites from the Hulu Cave of South China [8].

Both Baikal cores record the short-term Bölling-Allerod climatic excursion approximately 15–16 ka ago, which was followed by the brief Younger Dryas cooling episode. Both episodes coincide with oxygen records based on marine foraminifers and cave carbonates from South China (Fig. 2). The Younger Dryas cooling in Siberia was probably less significant when compared with polar (primarily, Arctic) areas (Fig. 2).

Thus, the curves of $\delta^{18}O_{frust}$ distribution in cores 03-01 and 04-02, as well as oxygen isotope records from other regions, record distinct global climatic changes. Moreover, the isotopic data provide higher resolution of environmental changes as compared with that derived from biogenic silica records.

The oxygen isotopic composition of diatom frustules, which form in equilibrium with water, is controlled by its two main parameters (temperature and isotopic composition).

Most diatom algae in Lake Baikal develop during the cold season [9], when the water temperature does not exceed 3°C. It cannot be ruled out that diatom reproduction during cold and warm periods occurred under similar temperatures. It means that the $\delta^{18}O$ value in frustules of Baikal diatoms is determined only by changes in the isotopic composition of water, which depends, in the first approximation, on the isotopic composition of atmospheric precipitation in the lake basin. The decrease in the $\delta^{18}O$ value in atmospheric precipitation of Europe and the North Atlantic from the south to north is proportional to the annual mean temperature with a gradient of ≈0.7 ‰/1°C [10]. A similar correlation with the annual mean and summer temperatures is also established for $\delta^{18}O$ values in the atmospheric precipitation of Siberia.

The difference in the oxygen isotopic compositions in Baikal diatoms from the bottom sediments accumulated during cold and warm periods is 5–6‰ (Fig. 2). In this case, the maximal increase in the annual mean temperature during the Holocene as compared with the Sartanian Glaciation can be estimated at 8–10°C (average 5 or 6°C). It should be noted that the calculated temperatures represent typical changes in the mean weighted temperature of atmospheric precipitation feeding the Baikal region.

According to the isotope data obtained, the temperature regime of the Karginian Interstadial in the Baikal region was fairly similar to that in the Holocene.

It is remarkable that in ice cores from Greenland [7], Antarctica [11], low-latitude mountainous glaciers of Tibet and Peru [12, 13], and diatoms from Lake Grandfather in Alaska [14], transition from the glacial period (MIS-2, Sartanian Glaciation of Siberia) to the Holocene was accompanied by a $\delta^{18}O$ variation from 4.9 to 6.3‰ (average 5.4‰), which accords well with the values (from 5 to 6‰) obtained for Baikal diatoms (table).

Thus, this value represents a general parameter, which characterizes changes in the temperature regime of the Earth's atmosphere at transitions from cold to warm periods.

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