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PALEOCLIMATE RECORD IN THE BOTTOM SEDIMENTS OF LAKE BAIKAL FROM MAGNETIC SUSCEPTIBILITY DATA

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Two boreholes on the Akademichesky Ridge, 100 and 200 m deep (BDP-96-1 and BDP-96-2), were drilled and cored continuously under the Baikal Drilling Project. Results of low-frequency magnetic susceptibility measurements of the two cores were correlated with the SPECMAP oceanic oxygen isotope curve, and a composite section was compiled. The SPECMAP curve and the magnetic susceptibility of the BDP-96 cores showed a good fit. Frequency analysis of time variations in magnetic susceptibility showed a periodicity of the paleoclimate signal with intervals of 23, 35, 41, 52, 68, 85, 106, and 164 ka. The periods of 23, 41, 52, and 106 ka correspond to cycles of precession, inclination of the Earth's axis, an eccentricity harmonic overlapped with inclination, and the Earth's orbit eccentricity, respectively. The periods of 35, 68, and 164 ka, distinguished for the first time in magnetic susceptibility studies, though observed earlier in biogenic silica analysis, reflect different eccentricity harmonics, and the period of 68 ka is affected by precession. The period of 85 ka has never been revealed before in the climate record and is most likely related to regional periodicity rather than to any astronomic cycles.

Paleomagnetism, paleoclimate, rock magnetism, magnetic susceptibility, magnetostratigraphic scale, Milankovitch cycles, Baikal

INTRODUCTION

In 1996, two boreholes, BDP-96-1 and BDP-96-2, were drilled in the axial zone of the Akademichesky Ridge in the framework of the Baikal Drilling Project. Sediments were exposed to a depth of 200 m [1, 2]. Figure 1 demonstrates the geographic position of the drilling site.

The lithology of both boreholes displays their entity and neither discordance nor breaks in sediments. Uniformity of the composition and textures of the entire section suggests steady deposition and, therefore, relatively deep-water conditions of the lake [1, 2].

The petromagnetic and paleomagnetic records were used to date sediments. The age of 200 m thick sediment core of BDP-96-1 was estimated at 5 Ma [4, 5].

Continuous sedimentation for 5 Ma on the Akademichesky Ridge is a unique opportunity for continental paleoclimate study. The existing paleoclimatic models have been obtained basically either from cores of oceanic drilling or from loess-soil sections [6, 7]. Lacustrine sediments contain a geological record to hundreds of thousands of years [8]. In the Baikal sediment, it has become feasible to obtain a long and intact sediment core, thus giving a chance to use various parameters in examining the paleoclimate record.

Different methods have been developed to investigate paleoclimate using bottom sediments [9]. The most common one is aimed at obtaining biogenic silica record, its amount increasing in warm and decreasing in cold periods. The method of geochemical profiles proves to be highly effective. Measurements of magnetic susceptibility of sediments, i.e., the petromagnetic method, is discussed in this paper. Its advantage is that a

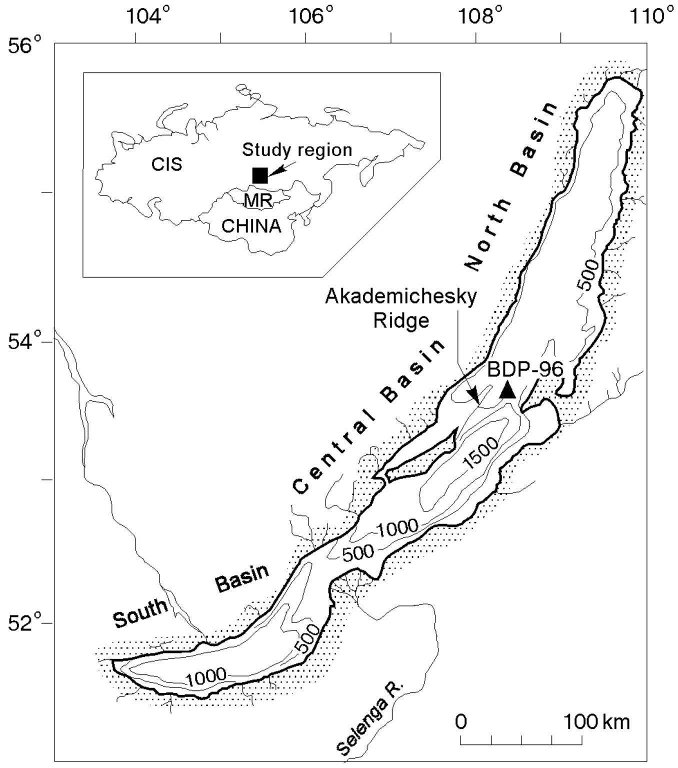

Fig. 1. Geographic position of BDP-96 drill site. Isobaths run 500 m apart from one another. Triangle stands for the borehole location. This scheme is based on the map from [3].

detailed continuous petromagnetic signal can be obtained without core destruction. Also, this method provides independent evaluation of paleoclimatic variations.

At least two mechanisms can be employed for evaluating climatic changes of the past epochs, based on magnetic susceptibility variations: (i) for oceanic bottom sediments, and (ii) loess-soil series of China.

In oceanic sediments, the climatic signal is analyzed through correlation of magnetic susceptibility variations and variations in oxygen isotope $\delta^{18}O$ abundance defined in the Ocean Drilling Project (ODP). These climate-dependent variations are explained by the fact that carbonates reflect the isotope $^{18}O/^{16}O$ ratio in water. It is remarkable that as temperature decreases, this value increases because, when ice is forming, primarily isotope ^{16}O passes into the solid phase, and ^{18}O is retained in the liquid phase. This change in isotope composition was used for building paleoclimatic curve in oceans [6]. The oceanic plankton is organisms, which utilize carbonate and oxygen for constructing their skeletons, bring the oxygen component into the carbonate sediment when dying. A detailed oxygen curve was plotted ob analyzing carbonate in oceanic drill core. The value characterizing ^{18}O content is expressed as $\delta = (R - R_0)/(R_0 \cdot 1000)$, where $R = C^{16}O^{18}O/C^{16}O_2$ in the sample studied and R_0, the same in the reference carbonate. The relationship between the change in magnetic susceptibility of bottom sediments and climate changes was found through magnetic-mineralogical investigations of the Late Pleistocene oceanic sediments in the northern Atlantic Ocean [8]. The high concentration of magnetic minerals and high values of magnetic susceptibility were shown to occur in the horizons representing the glacial periods, when carbonate accumulation drastically decreased and ice rafting of clastic material took place, which was caused by migration of the North Atlantic polar front to the south. The interglacial horizons, on the contrary, have a low concentration of magnetic minerals and abundant carbonate in the sediment, both responsible for the low values of magnetic susceptibility. Marked differences in the concentration of magnetic minerals are caused by climate-controlled variations in the source and volume of clastic material supplied [6]. Given that the composition and concentration of magnetic minerals in bottom sediments depend on climate variations, the magnetic susceptibility changes can be correlated with oxygen isotope curve [10].

The loess-soil deposits of China show a reverse dependence. In this case, the value of magnetic susceptibility was proved to be a reflection of climatic signal: In soils of China it is more than twice higher than that in loess [11, 12]. This is related to different ratios of clastic and pedogenic magnetic material in loess and soils [13]. Reverse correlation of magnetic susceptibility is revealed in loess-soil deposits of China with variations in contents of oxygen isotopes $\delta^{18}O$ [14]: High values of magnetic susceptibility are in the horizons corresponding to interglacial periods, and low values are in glacial horizons.

Obvious compatibility between the changes of logarithm of magnetic susceptibility through BDP-96-1 and BDP-96-2 cores and the isotope oxygen curve $\delta^{18}O$ was observed earlier [1–4]. The relationship between magnetic susceptibility and climate is explained by the fact that in warmer periods the productivity of diatoms was higher. That is why the biogenic silica (nonmagnetic) abundance increased, which resulted in reduction in the total magnetic susceptibility [15, 16].

The goal of work was:

1. To determine coefficients of correlation between the values of oxygen isotope $\delta^{18}O$ contents in the ocean and the values of magnetic susceptibility for both BDP-96 cores, so that reasoning to use such a correlation in building the age model of sedimentation on the Akademichesky Ridge could be checked. Such a comparison was made for sedimentary subsurface cores (3–10 m) and the borehole drilled in 1993 [3, 15, 16]. For BDP-96 it was a pioneer work.

2. To compile a composite column of magnetic susceptibility from the cores of BDP-96-1 and BDP-96-2.

3. To perform spectral analyses of magnetic susceptibility data for the last 5 Ma and to recognize the periods of basic climatic variations.

TECHNIQUE

In the core, magnetic susceptibility (K) was measured every 3 cm by a Bartington MS-1 magnetic susceptibility meter (recorder MS2C Core Logging Sensor) without exposing core to the low-frequency (0.565 kHz) field [1]. The advantages of this method are: (i) rapid performance and (ii) preservation of sediment after measurement [1, 15].

The correspondence of the contents of oxygen isotope and magnetic susceptibility for a particular age was found from the assumption on regular accumulation of bottom sediments and from data on magnetic polarity of core which were reported in [1, 4, 5]. The scale of magnetic polarity for columns BDP-96-2 and BDP-96-1 was based on measurements of natural remanent magnetization and stepwise demagnetization in the variable magnetic field of oriented core samples (sampling spacing 10 cm) [4]. Measurements were performed in paleomagnetic laboratories in Irkutsk, Russia, and Rhode Island, USA.

In order to decrease the errors arising from local fluctuations of magnetic susceptibility and those caused by sediment loss, a composite column from two boreholes was compiled. Because the upper part of BDP-96-1 core lacks 6.3 m sediment, the column BDP-96-2 was selected as a reference.

Reference points were set to identify the age dependence of magnetic susceptibility. The sedimentation rate between the reference points was accepted to be constant. In the sediments younger than 1.354 Ma (~ 60 m thick), the points were selected by visual comparison of charts of ODP and BDP-96-1 and BDP-96-2 (Fig. 2). This method turned out to be inapplicable for older sediments because of decreasing amplitude of magnetic susceptibility variations and visible merging of peaks (similar phenomenon was marked in the Chinese loess [18]). That is why we applied the correlation from the magnetic polarity scale, constructed by us earlier [1, 4, 5], for sediments located below 60 m (Fig. 3). For example, the position of Brunhes-Matuyama Chron (780 ka) was taken as a reference point. In BDP-96-2 core, this boundary lies at a depth of 33.9± 0.25 m, and in BDP-96-1 core, 33.5± 0.2 m.

When calculating the coefficient of correlation between the value of magnetic susceptibility (K) and the content of oxygen isotope $\delta^{18}O$ the following formula was applied:

$$r = \frac{\sum_{i=1}^{n} x_i y_i - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} y_i\right)}{\sqrt{\left[\sum_{i=1}^{n} x_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)^2\right]\left[\sum_{i=1}^{n} y_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} y_i\right)^2\right]}},$$

where x_i and y_i are the values $\delta^{18}O$ and ln K for the i-th value of the age [21].

Frequency analysis was performed by the fast Fourier transform (FFT) [22] using software Microcal Origin 6.0 (composite core was utilized for calculations). Prior to calculations, the data were filtered by the

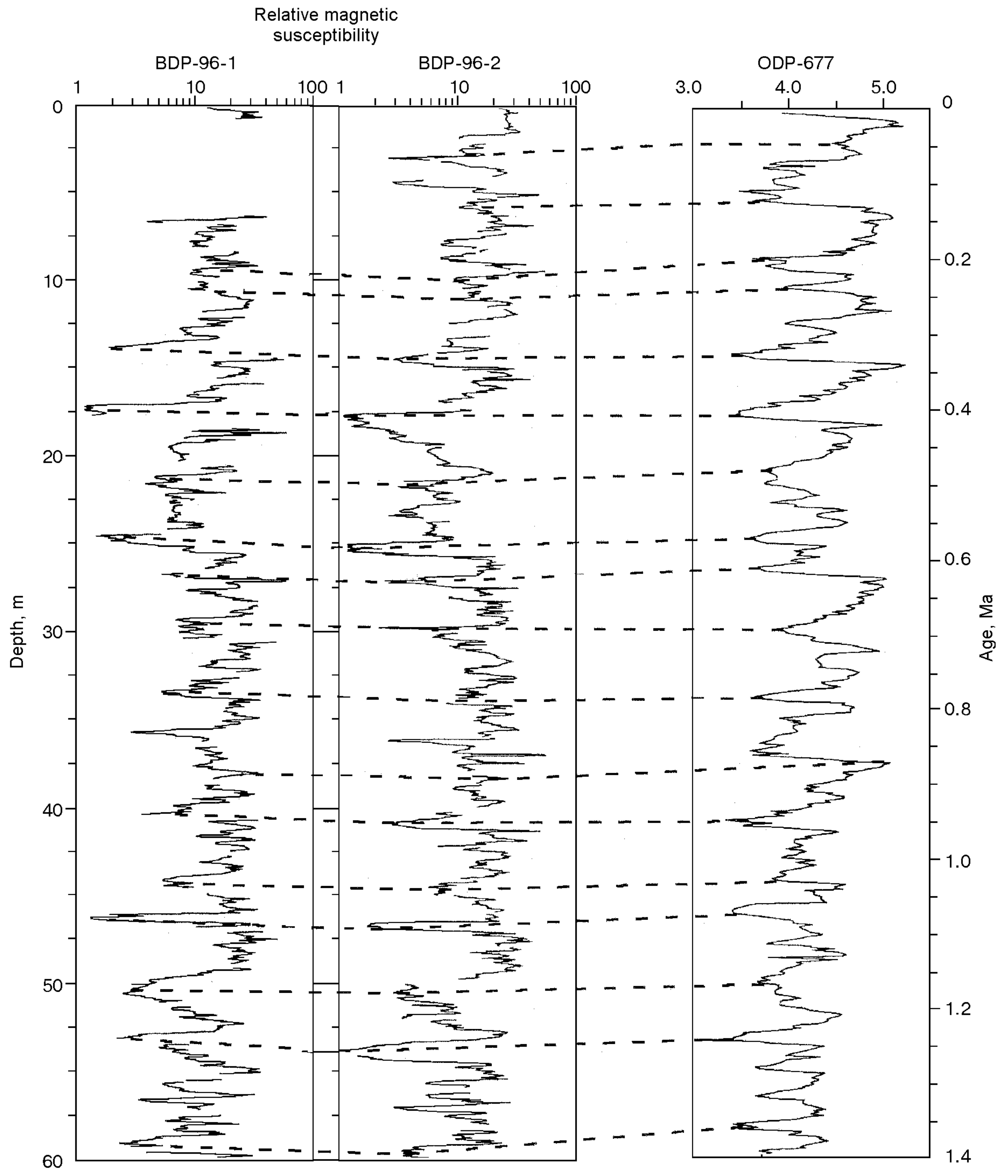

Fig. 2. Correlation of magnetic susceptibility of BDP-96-1 and BDP-96-2 cores with variations of $\delta^{18}O$ identified by ODP-677. Correlation of magnetic susceptibility profiles in deep boreholes BDP-96-1 and BDP-95-2 at the Akademichesky Ridge (left and center) and curve of oxygen isotope $\delta^{18}O$ (right) of ODP-677 [17] for upper 60 m. The correlation lines (dotted) connect characteristic points of curves. The charts illustrate the possibility [15, 16] of employing magnetic susceptibility profiles for analysis of climatic signal on Baikal.

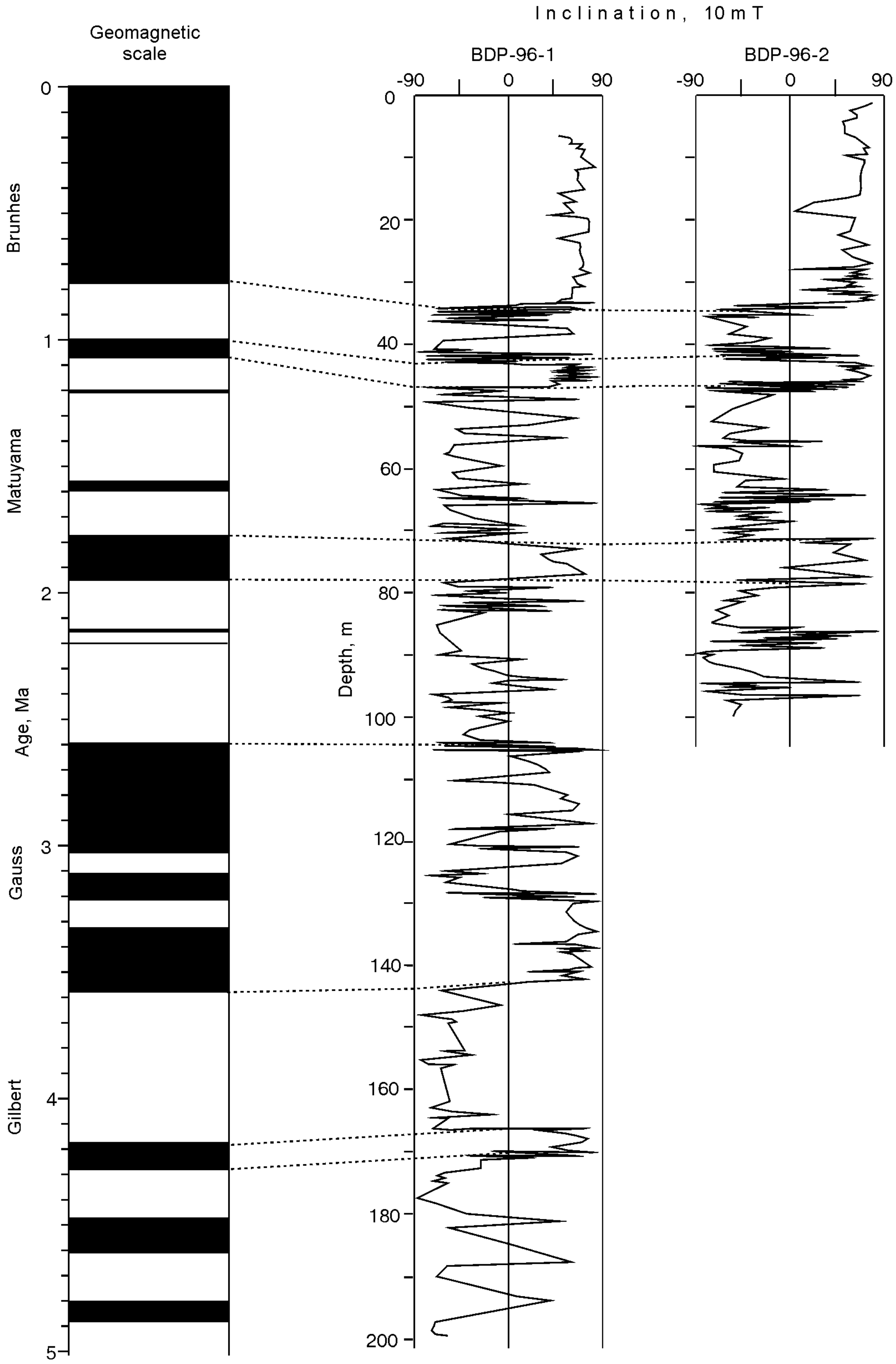

Fig. 3. Magnetostratigraphic scale for the last 5 Ma, based on the study of deep drill cores of bottom sediments from the Akademichesky Ridge. Baikal Drilling Project, 1996. The scale of geomagnetic polarity is given after [19, 20]. Profiles of inclination of BDP-96-1 and BDP-96-2 cores are given after demagnetization by variable magnetic field (10 mT). The correlation (dotted) lines show agreement of data in both cores.

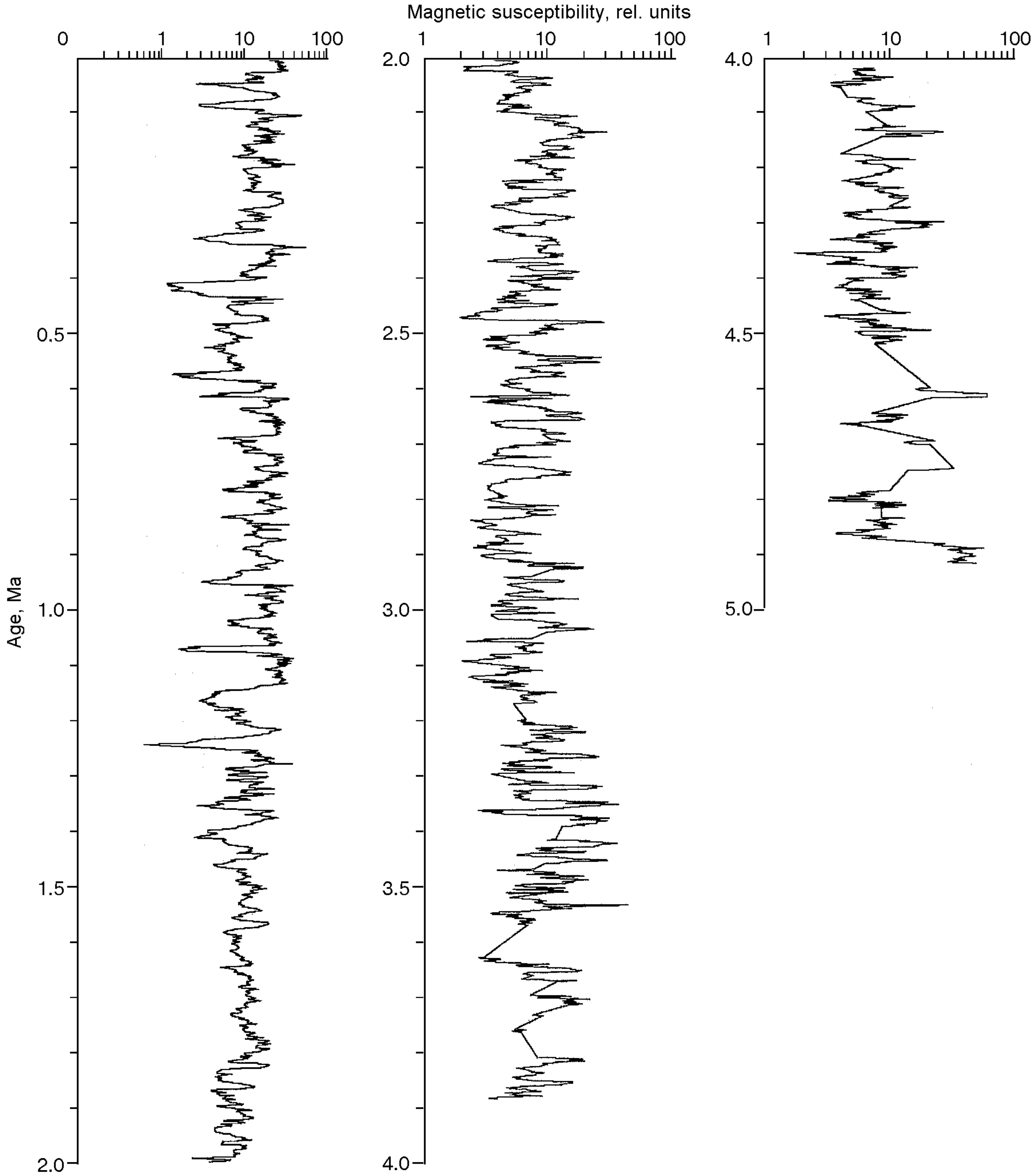

Fig. 4. Composite magnetic susceptibility profile for the age interval 0–5 Ma. Compiled after particular variations in magnetic susceptibility of BDP-96-1 and BDP-96-2 cores.

FFT method within the range from 6 to 60 Hz to depress high- and low-frequency noise. The latter was suppressed to avoid the peak at a frequency of 0 Hz, arising from a combination of errors. The high-frequency noise was suppressed because the available data are insufficient for reliable recognition of high-frequency periods.

RESULTS

Changes in magnetic susceptibility versus age of sediments are given in Fig. 4. For the age of 2.6 Ma, the data for BDP-96-1 and BDP-96-2 cores were synthesized, and for the age interval from 2.6 to 4.9 Ma, only the data for BDP-96-1 core were applied, because 100 m long BDP-96-2 did not penetrate sediments younger than 2.6 Ma.

We have correlated 419 values of $\delta^{18}O$ and ln *K* for BDP-96-2 and 325 values for BDP-96-1. In both cores, the correlation coefficient *r* was found to be the same and equal to 0.41 (to the second decimal place). The reliability of result was checked through Table 9 from [23], serving for determination of correlation coefficient reliability. With probability over 99.99% we can state the existence of a direct relationship between values $\delta^{18}O$ and logarithm of magnetic susceptibility. The much smaller value of the coefficient, compared with that calculated for Chinese loess (0.7) [18], may be explained by:

— Technical losses of sediment (significant losses in the upper and lower parts of cores, frequent small losses of sediment between cores because of slam);

— Uneven sedimentation at different sites of borehole [4];

— Difference in techniques for measuring magnetic susceptibility. When measuring magnetic susceptibility of Chinese loess, we used standard-size cubes; when studying Baikal sediment, the magnetic susceptibility was measured throughout the core without exposure, its filling being often irregular because of pressure difference while recovering the core.

Nevertheless, the values of correlation coefficient ln *K* and $\delta^{18}O$ for 1996 cores are much higher than those for gravitational cores of 1993 (coefficient *r* for the upper part of the borehole is 0.2268 [16]). The reason is that the upper part of the sediment core displays a less even sedimentation with its density being always smaller than that in the lower part.

Thus, we may reliably discuss the correlation of magnetic susceptibility of Baikal sediments with $\delta^{18}O$ (as shown above, the probability of relationship between magnetic susceptibility and SPECMAP curve is 99.9%) and, hence, with climate.

The frequency analysis was carried out in three stages:

— in the upper part of composite core, within the interval 0–1.35 Ma, where a visual correlation between $\delta^{18}O$ and ln *K* has been established;

— in the entire composite core, within the interval 0–2.6 Ma;

— in BDP-96-1 core, within the interval 2.6–5 Ma.

0–1.35 Ma. Figure 5, *a* provides results of frequency analysis for the first stage (ODP-677 data are also given here), where five peaks of great amplitude are observed, two of them showing distinct paleoclimatic interpretation. Peak 2 (see Fig. 5, marked by number), corresponds to the period 106 ka; peak 5 represents the period 41 ka (Milankovitch cycle corresponds to the inclination of the Earth's axis). These two cycles are widely known and registered in many deposits of Chinese loess and ODP boreholes [17, 18]. Peak 1 might correspond to one of the eccentricity harmonics described in [24, 25]. Peak 4 represents the period 68 ka. The same periodicity is reported in the study of geochemical profiles of Baikal bottom sediments [26]. Following papers [24, 25], the periods close to the detected frequency (72, 75, and 76 ka), may be interpreted as harmonics of the periods of eccentricity and precession. Peak 3, corresponding to a frequency of 85 ka, cannot be explained easily. Poorly expressed peak 6 near a frequency of 0.041 may be attributed to 23 ka (one of Milankovitch cycles, corresponding to precession). These results confirm that sediments of Lake Baikal contain an original record of paleoclimatic signal.

0–2.6 Ma. The periods recognized at the second stage of frequency analysis (to the lower part of BDP-96-2 core (0–2.6 Ma)) cannot be interpreted unambiguously (see Fig. 5, *b*). In this interval, the maximum values correspond to the periods 130, 87, and 47 ka (peaks 7, 8 and 9). With a certain probability, peak 7 may be assumed to represent the period 106 ka; the period 87 ka looks very similar to the period 85 ka, established at the first stage of frequency analysis for the interval 0–1.35 Ma. The period 47 ka is most difficult to be interpreted properly. This, probably, results from superposition of two variations (41 and 53 ka). This explanation cannot be considered satisfactory because in the other cases the periods, differing from each other by 25%, were easily separated.

2.6–5 Ma. Figure 5, *c* shows results of the third stage of frequency analysis (i.e., only for core BDP-96-1 within the interval 2.6–5 Ma). The period 106 ka, represented by peak 11, is well distinguished. Three more periods have been recognized: 142, 89, and 66 ka (peaks 10, 12, and 13, respectively). Note that in the two last cases we had to apply smoothening by the FFT method, otherwise the pattern seemed fairly unclear (much noise created a "saw"). The peak corresponding to the period 66 ka is more significant for this interval and, possibly, corresponds to the period 68 ka, established at the first stage of frequency analysis and is provisionally interpreted as harmonics of the periods of eccentricity and precession changes. The period ~ 85– 89 ka is established at all stages of frequency analysis and thus might indicate the existence of a new cyclic change

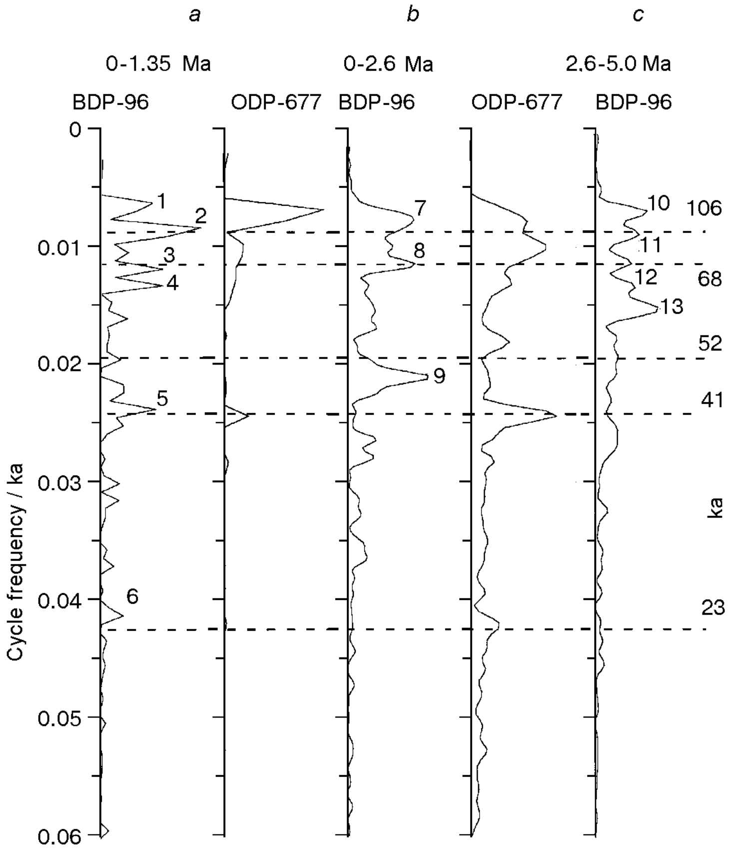

Fig. 5. Results of frequency analysis of magnetic susceptibility for composite core BDP-96 versus ODP-677 core. Intervals: *a* — 0–1.35 Ma; *b* — 0–2.6 Ma, *c* — 2.6–5.0 Ma. Horizontal dotted lines mark the periods of change in orbital parameters of the Earth, given in thousands of years. The amplitude of frequency curve is given in conventional units.

with this period. As far as we know, climatic variations with period 85–89 ka have never been described in literature before.

Stepwise frequency analysis. To analyze changes in frequency characteristics in different age intervals, we calculated frequency for the entire interval 0–5 Ma through 500 ka step. The results are given in Fig. 6:

a — results obtained without preliminary processing of data,

b — after smoothening by the FFT method.

For all age intervals the charts were constructed on the same scale, except for the interval 1–2 Ma, for which the vertical scale is reduced by a factor of 2.5, because maximum values for this interval were too high to plot on the figure. Table 1 lists the periods for every time interval. Thus, if we define the maximum values for the periods 41, 44, 42, 45, 42, and 45 ka, we assume that this was one period rather than four periods (within the assumed error of calculations, accepted to be ± 10%). In such cases we calculated the arithmetic mean of the periods (43 ka). With this error, we can state that this is a 41-year period of the Earth's axis inclination. Table 1 shows that nearly all intervals display the periods corresponding to the Milankovitch cycles 106 and 41 ka, which meets variations of eccentricity and inclination of the Earth's axis, respectively. The period 23 ka, preceding the precession cycle of Milankovitch, was found for interval 0–1 Ma [24, 27]. These periods are well known, and their climatic interpretation is beyond question. The cycle 52 ka was found to be a harmonic causing a change of eccentricity. It is remarkable that this period is due to fluctuation predicted by Berger (54 ka) [28] and fluctuation detected by paleomagnetic measurements of lacustrine sediments in Oregon (58 ka) [29].

Also, some more periods similar to those described above have been detected from the geochemical profiles [26]. These are:

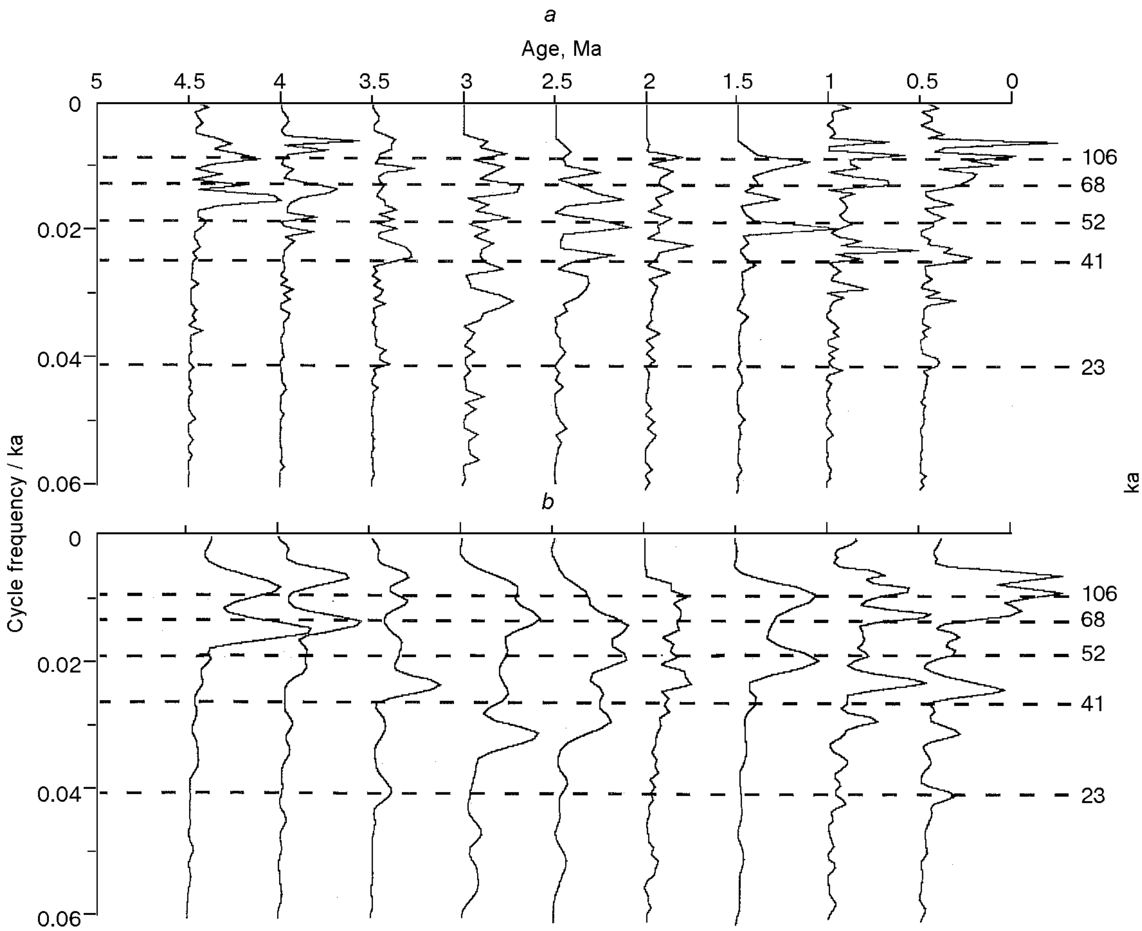

Fig. 6. Frequency analysis of magnetic susceptibility of composite core BDP-96 within the age range 0–5 Ma, with 500 ka spacing. *a* — Without smoothening, *b* — with smoothening. Horizontal dotted lines mark the periods of changes in orbital parameters of the Earth, in thousand years (ka). The amplitude of frequency is given in conventional units.

— 164 ka. It occurs four times, and several times it exceeds in amplitude the period 106 ka. According to [30], this period corresponds to a harmonic of eccentricity;

— 35 ka. It occurs four times and corresponds to a harmonic of eccentricity [24].

Two more periods have been established: 85 ka (twice) and 68 ka (four times).

A distinctive feature of these variations is that the presence of both these periods has never been recorded in magnetic profiles. The period of about 68 ka is mentioned in [26], whereas the period 85 ka has been found for the first time. Because these periods are not revealed simultaneously, we suppose that they characterize the same phenomenon with a period changing in time. The reason for this supposition was a greater scatter of periods for different intervals as compared to other fluctuations. We think it might be an integrated result of both astronomic cycles and regional fluctuations.

It is remarkable that the period corresponding to the 19 ka precession cycle was not revealed in bottom sediments. It was not found in biogenic silica profiles either [5]. This phenomenon has not been explained so far. However, we cannot state that the periodicity corresponding to the precession cycle is not typical of Baikal sediments. This period was found in analysis of geochemical profiles [26] and in analysis of the sediment obtained from short cores in 1993 [31].

CONCLUSIONS

On the basis of significant correlation between magnetic susceptibility of bottom sediments in BDP-96 and abundance of oxygen isotope $\delta^{18}O$ in ODP-677 core, we may conclude that sediments of Lake Baikal

Table 1

Distribution of Periods Reflecting Milankovitch Astronomic Cycles, after Magnetic Susceptibility Measurements in Sediments of BDP-96 Core

Frequency analysis calculated interval, Ma	Peak of eccentricity harmonics, ka	Eccentricity, ka	One of eccentricity harmonics			Inclination of Earth axis, ka	Poor harmonic of eccentricity, ka	Precession of the Earth axis, ka
			with superposition of precession cycle, ka	with superposition of precession cycle, ka	inclination reflection, ka			
0.0–1.0	160	112	89*	—	—	41	32	24
0.5–1.5	164	122	81*	—	—	44	35	—
1.0–2.0	—	106	—	67	51	—	—	—
1.5–2.5	—	118	—	—	—	45	—	—
2.0–3.0	—	95	—	67	52	42	35	—
2.5–3.5	—	—	—	—	—	45	39	—
3.0–4.0	164	97	—	—	—	42	—	—
3.5–4.5	166	—	—	71	52	—	—	—
4.0–5.0	—	114	—	65	—	—	—	—
Average	164	109	85	68	52	43	35	24

*** This period is probably the same as in the next column, but with regional variations superimposed (see explanations in the text).**

contain a continuous magnetic record of continental paleoclimatic signal acquired from the biogenic silica study [5]. Magnetic susceptibility decreased in warm periods and increased in cold periods, which is related to an increasing amount of biogenic nonmagnetic material (diatoms) in warm periods [5, 15].

The frequency analysis of magnetic susceptibility varying in time has shown correlation of arbitrary variations in magnetic susceptibility with Milankovitch cycles. We conclude that in certain times, climate depended largely on variations of both excentricity (0–1 Ma) and inclination of the Earth's axis (1–2 Ma) (in the other times, the amplitudes of peaks representing eccentricity and inclination are approximately equal), but it depended insignificantly on precession (in most cases the maximum corresponding to precession can never be determined).

Also, period 85 ka, which is not directly correlated with Milankovitch cycles, has been recognized. It appears to reflect some regional features of climatic variations.

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REFERENCES

[1] The Baikal Drilling Project Group, *A continuous record of climate changes for the late five million years from the bottom sediment of Lake Baikal*, Geologiya i Geofizika (Russian Geology and Geophysics), vol. 39, no. 2, p. 139(135), 1998.

[2] M. I. Kuz'min, E. M. Karabanov, V. F. Geletii, et al. in: *Global changes of the environment* [in Russian], Novosibirsk, p. 58, 1998.

[3] J. A. Peck, J. W. King, S. M. Colman, and V. A. Kravchinsky, *J. Geophys. Res.*, vol. 101, no. B5, p. 11356, 1996.

[4] V. A. Kravchinsky, J. A. Peck, H. Sakai, et al. in: *Global changes of the environment* [in Russian], Novosibirsk, p. 73, 1998.

[5] D. P. Williams, J. A. Peck, E. B. Karabanov, et al., *Science*, vol. 278, p. 1114, 1997.

[6] J. Imbrie, J. D. Hays, D. G. Martinson, et al., in: *Milankovitch and Climate*, Dordrecht, Netherlands. Part 1, p. 269, 1998.

[7] F. Heller and M. E. Evans, *Rev. Geophys.*, vol. 33, p. 211, 1995.

[8] J. W. King and J. E. T. Channel, in: *Rev. Geophys. Supplement, U.S. National Report to International Union of Geodesy and Geophysics, 1987–90: Contribution in Geomagnetism and Paleomagnetism*, New York, p. 358, 1991.

[9] M.I. Kuz'min, D. Williams, and T. Kawai, in: *Global changes of the environment and climate (selected scientific papers)* [in Russian], Moscow, p. 255, 1997.

[10] S. G. Robinson, *Phys. Earth Planet. Inter.*, vol. 42, p. 22, 1986.

[11] F. Heller and T. S. Liu, *Geoph. J. Roy. Astron Soc.*, vol. 77, p. 125, 1984.

[12] H. Zheng, G. Oldfield, L. Yu, et al., *Phys. Earth Planet. Inter.*, vol. 68, p. 250, 1991.

[13] B. A. Maher and R. Thompson, *Quart. Res.*, vol. 37, p. 155, 1992.

[14] G. N. Petrova and G. A. Pospelova, *Phys. Earth Planet. Inter.*, vol. 63, p. 35, 1990.

[15] J. W. King, J. A. Peck, P. Gangemi, and V. A. Kravchinsky, *Paleomagnetic and rock-magnetic studies of Lake Baikal sediments*, Geologiya i Geofizika (Russian Geology and Geophysics), vol. 34, nos. 10–11, p. 174(148), 1993.

[16] J. A. Peck, J. W. King, S. M. Colman, and V. A. Kravchinsky, *Earth Planet. Sci. Lett.*, vol. 122, p. 221, 1994.

[17] N. J. Shackleton, A. Berger, and W. R. Peltier, *Trans. Roy. Soc. Edinburgh: Earth Sciences*, vol. 81, p. 251, 1990.

[18] J. Bloemendal, X. M. Liu, and T. C. Rolph, *Earth Planet. Sci. Lett.*, vol. 131, p. 371, 1995.

[19] S. C. Cande and D. V. Kent, *J. Geophys. Res.*, vol. 100, p. 6093, 1995.

[20] J. E. T. Channel, *Review. Geophys., Supplement*, p. 161, 1995.

[21] I. P. Sharapov, *Application of mathematical statistics to geology* [in Russian], Moscow, 1970.

[22] P. Bloomfield, *Fourier Analysis of Time Series: An Introduction*, New York, 1976.

[23] B. L. Van-der-Varden, *Mathematical statistics* [Russian translation], Moscow, 1960.

[24] A. L. Berger, *J. Atmospheric Sciences*, vol. 35, no. 12, 1978.

[25] A. Berger and M. F. Loutre, *Quatern. Sci. Rev.*, vol. 10, p. 297, 1991.

[26] E. L. Goldberg, M. A. Phedorin, M. A. Grachev, et al., in: *International conference "Baikal as a world natural heritage site"*, Novosibirsk, p. 167, 1999.

[27] M. Milankovitch, *Roy. Serb. Acad. Spec. Publ.*, vol. 133, p. 1, 1941. (English version published by the Israel Program for Scientific Translations, Jerusalem, 1969).

[28] A. Berger, *Nature*, vol. 268, p. 44, 1977.

[29] R. M. Nergini, K. L. Verosub, and J. O. Davis, *Earth Planet. Sci. Lett.*, vol. 87, p. 173, 1988.

[30] M. R. House, in: *Orbital forcing timescales and cyclo-stratigraphy*, London, p. 1, 1995.

[31] S. M. Colman, J. A. Peck, E. B. Karabanov, et al., *Nature*, vol. 378, no. 6559, p. 769, 1995.

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