Lake Baikal
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Paleomagnetic and Rock-magnetic studies on Lake Baikal sediments -BDP96 borehole at Academician Ridge-

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Abstract

Paleomagnetic and rock-magnetic studies were conducted on two sedimentary cores, BDP96-1 (length: 200 m) and BDP96-2 (100 m), drilled at the Academician Ridge of Lake Baikal.

Comparison of the paleomagnetic inclination records with the geomagnetic polarity time scale showed that the sedimentary sequence covers the age of the past 5 million years. The study was conducted on discrete samples and on quarter-core samples. Path-through measurement of the quarter core samples revealed detailed geomagnetic variation, such as the double polarity transitions around the B/M boundary.

The average sedimentation rate was estimated from the depth-age relation to be 3.8 cm/kyr, with a correlation coefficient of 0.997-0.999. This high correlation suggests that the sedimentation at Academician Ridge during the past 5 million years has been continuous in a quiet environment.

Magnetic susceptibility is closely related to changes in the content of biogenic silica and shows a clear correlation with glacial-interglacial change. Susceptibility measurement is relatively quick and nondestructive, making it a valuable means of paleoclimatic study of Lake Baikal sediment. Changes in magnetic minerals (species, size) should also be taken into consideration in these studies.

Introduction

Lake Baikal is located in eastern Siberia (104-110°E, 51-56°N) and is one of the deepest (1643 m), most voluminous (23,000 km^3), and oldest freshwater lakes in the world. It is an important and unique site for paleoclimatic studies because of its high-latitude, continent-interior setting, and its long, continuous stratigraphic record. Grosswald (1980) suggested that Lake Baikal was never completely glaciated during the glacial periods, so that a continuous sedimentary record can be obtained even during the glacial periods. The sedimentary sequence of Lake Baikal is more than 5,000 m thick and believed to cover the age since the middle Miocene. Paleoclimatic records from continental regions are much fewer in number than records from marine regions. This makes Lake Baikal sediment particularly valuable, and it may provide a source of continental climate information over a long period.

The Baikal Drilling Project (BDP), in progress since 1993, is an international investigation of the paleoclimatic history and tectonic evolution of the sedimentary basin. In this paper, we describe a paleomagnetic study of the BDP96 cores drilled at Academician Ridge in the central part of Lake Baikal (Fig. 1). The Angara River, situated in the southern basin, is the only river draining Lake Baikal. The Selenga River, in the southern central portion of Lake Baikal is the largest river draining into the lake and carries

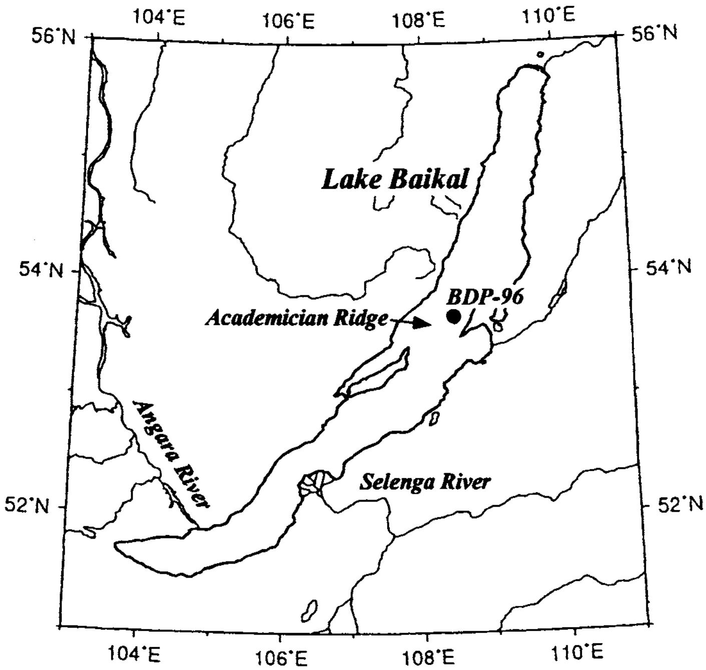


Fig. 1: BDP96 at Academician Ridge in the central part of Lake Baikal. The drilling site (53°41'38"N, 108°21'06"E) is at the depth of 382 m.

a large amount of sediment into it. Academician Ridge is away from these rivers and is a structual and bathmetric high that is isolated from direct fluvial and downslope sedimentation.

This study had two purposes. One was to examine the magnetostratigraphy and determine the age-scale of the sedimentary sequence, and the other was to study the history of paleoclimate based on the magnetic properties of the sediment.

Samples of BDP96 cores from Academician Ridge

BDP96 consists of two cores, BDP96-1 (length: 200 m) and BDP96-2 (100 m). The drilling was conducted by piston coring in the upper portion (depth <60 m), by percussion coring in the middle portion (60-120 m), and by rotary coring in the lower portion (120-200 m). Core recovery was 95% for BDP96-2, 90% for the upper 119 m of BDP96-1, and 70% for the rotary coring portion.

The BDP96 cores were divided into sub-cores 2 m in length, and each sub-core was cut in half lengthwise (split). The samples for the paleomagnetic study were discrete samples (DS) and quarter-core samples (QC) extracted from the half lengthwise core. The DS samples were divided into three groups. In this paper, we present the data obtained from the Japanese DS samples and the QC samples. Figure 2 is a schematic diagram of the paleomagnetic samples. The DS samples were collected from the core in 10 cm^3 plastic cube cases at 20-cm intervals. The QC samples were collected from the piston core portion, where the hardly disturbed cores at the drilling were not used.

Several short cores (~10m) were drilled around Academician ridge before BDP96. The rockmagnetic data of the St. 18 short core obtained near the BDP96 site (Sakai et al., 1997) is referred to in this paper.

Experimental methods and AF demagnetization

Remanent magnetization was measured by using a path-through-type cryogenic magnetometer (2G-760R), and magnetic cleaning was achieved by the AF demagnetization method. Magnetic susceptibility was assessed with a Bartington MS-2 meter, and the anisotropy of susceptibility (AMS) was measured with a Sapphire SI2B unit.

All of the discrete samples were AF demagnetized stepwise to 40 mT in 5 mT steps. Secondary magnetization was eliminated from most of the samples by demagnetization to 20 mT. The samples collected from the lower portion of the core had the weakest remanent magnetization and showed instability at high-field AF demagnetization.

The AF demagnetization experiment was conducted on the QC samples up to 40 mT in 10-mT steps. Stepwise AF demagnetization and measurement was performed at 1 cm intervals with a 2G-760R automatic demagnetization system. The results show that the main secondary component in the QC samples was also eliminated by demagnetization to 20 mT. The paleomagnetic data after 20 mT AF demagnetization are used below.

Paleomagnetic inclination

Variation of inclination with depth and magnetostratigraphy

Figure 3 shows the change in inclination with depth in the discrete samples. Since sedimentological study suggests that the BDP96-1 core lacks the surface sequence to a depth of 6.3 m, the inclination data have been

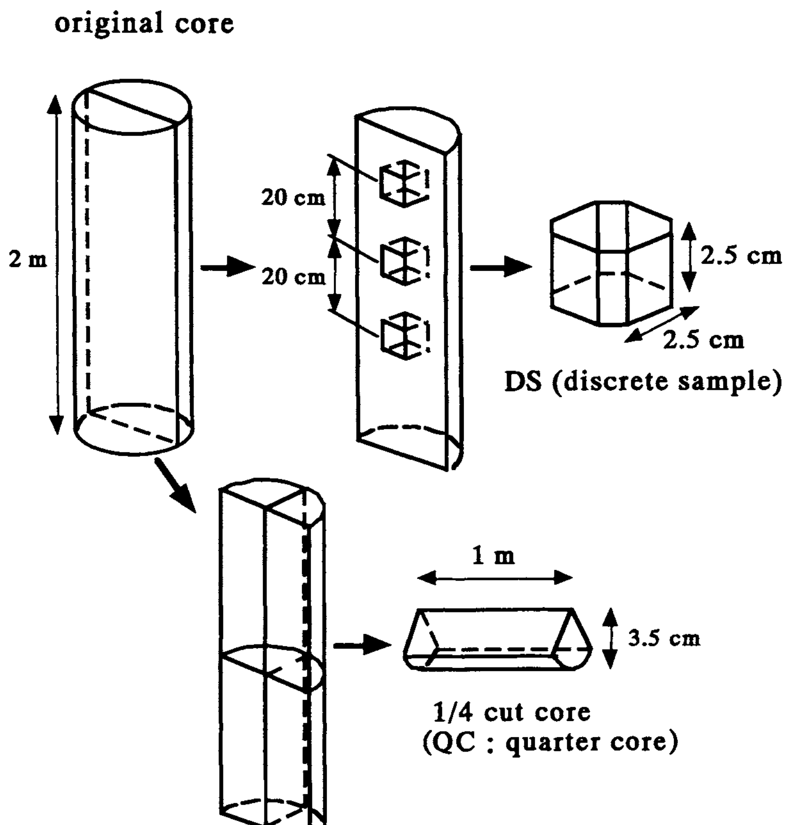


Fig. 2: Discrete samples and quarter-core samples were collected from the half lengthwise core for the paleomagnetic study.

plotted by taking its absence into account. The inclination changes with depth show a clear polarity reversal pattern, which is concordant with the preliminary data obtained by Baikal Drilling project II Members (1997).

Fig. 4 shows the inclination changes in the QC samples. The changes in inclination are almost perfectly consistent with the data from the DC samples. There are several abrupt inclination changes in Fig. 4. They may have been caused by regions of disturbance and/or core-breaks which we were unable to examine when making the measurements.

The DC samples during Matuyama reversed polarity in Fig. 3 show more scattered inclination than the other core portions, especially in the BDP96-1 core. Referring to the AF demagnetization results shows that these samples have larger unstable magnetization than other samples. One of the major reasons for the scattered inclination is a problem in the sampling, that is, the samples were collected from disturbed and/or mis-oriented areas. The thermal demagnetization experiment in chapter 5-4 suggests the presence of two different kinds of magnetic minerals in the sediments. Another possible reason for the scattered inclination is the existence of hard secondary magnetization against the AF demagnetization. This may be important, and further study is necessary.

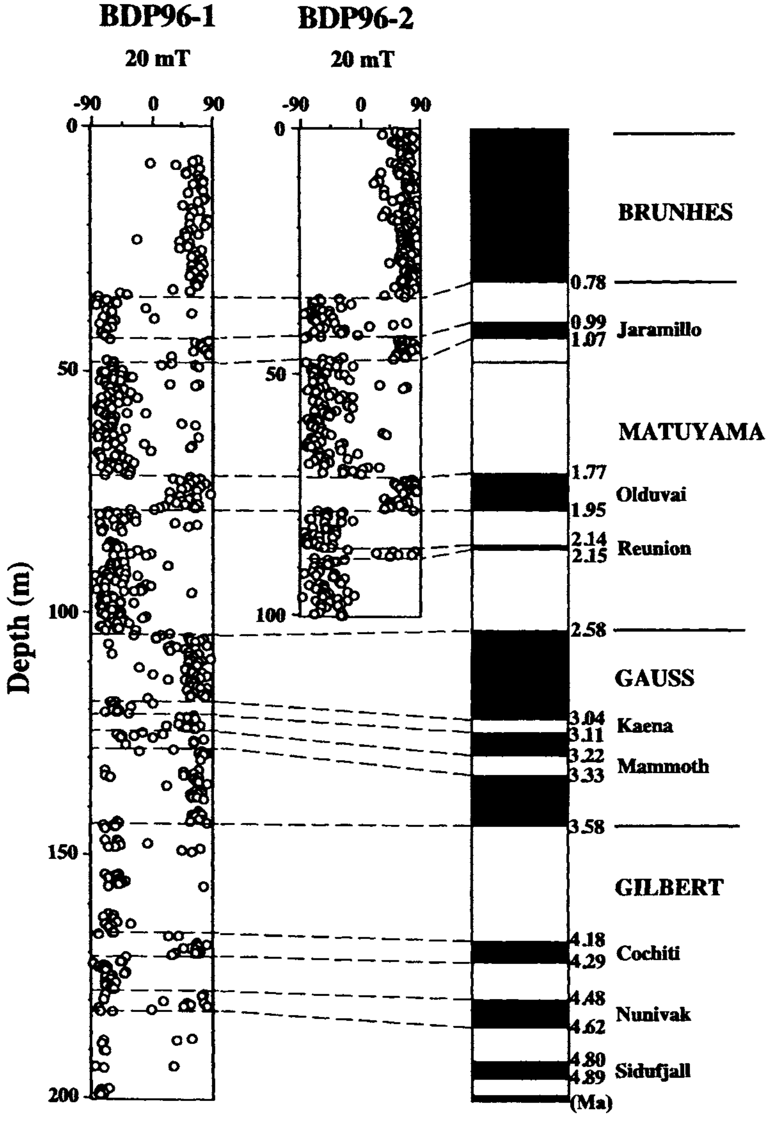
In Figs. 3 and 4, the inclination changes are compared with the geomagnetic polarity time scale of Cande and Kent (1995). BDP96-1 includes the geomagnetic polarity epochs of Brunhes normal polarity, Matuyama reversed polarity, Gauss normal polarity, and Gilbert reversed polarity. BDP96-2 includes the Brunhes and Matuyama polarity epochs. Most of the geomagnetic events during the above polarity epochs have been identified. The comparison shows that the BDP96 covers the age of the past 5 million years. Table 1 shows the geomagnetic polarity epochs, events, and the corresponding depth of the BDP96 cores.

Sedimentation rate

The graphs for BDP96-1 and BDP96-2 in Fig. 5 show the correlation between depth and age for the assigned geomagnetic polarity boundary in Table 1. Straight lines are produced by the least squares method on the plots in the diagram.

The average sedimentation rate at BDP96 was estimated from the linear relation in Fig. 5 to be 3.8 cm/kyr. The correlation coefficient of linearity is 0.997 for BDP96-1 and 0.999 for BDP96-2. The high correlation coefficient in the depth-age graph suggests that the sedimentation at Academician Ridge has not suffered any major disturbances, such as produced by crustal movement, during the past 5 million years, and this may be important in assessing the tectonic history of Lake Baikal.

The AMS (anisotropy of magnetic susceptibility) of the samples was



(Cande and Kent, 1995)

Fig. 3. Changes in inclination with the depth of discrete samples of BDP96 cores after 20 mT AF demagnetization. The geomagnetic polarity time scale of Cande and Kent (1995) is shown on the right for reference.

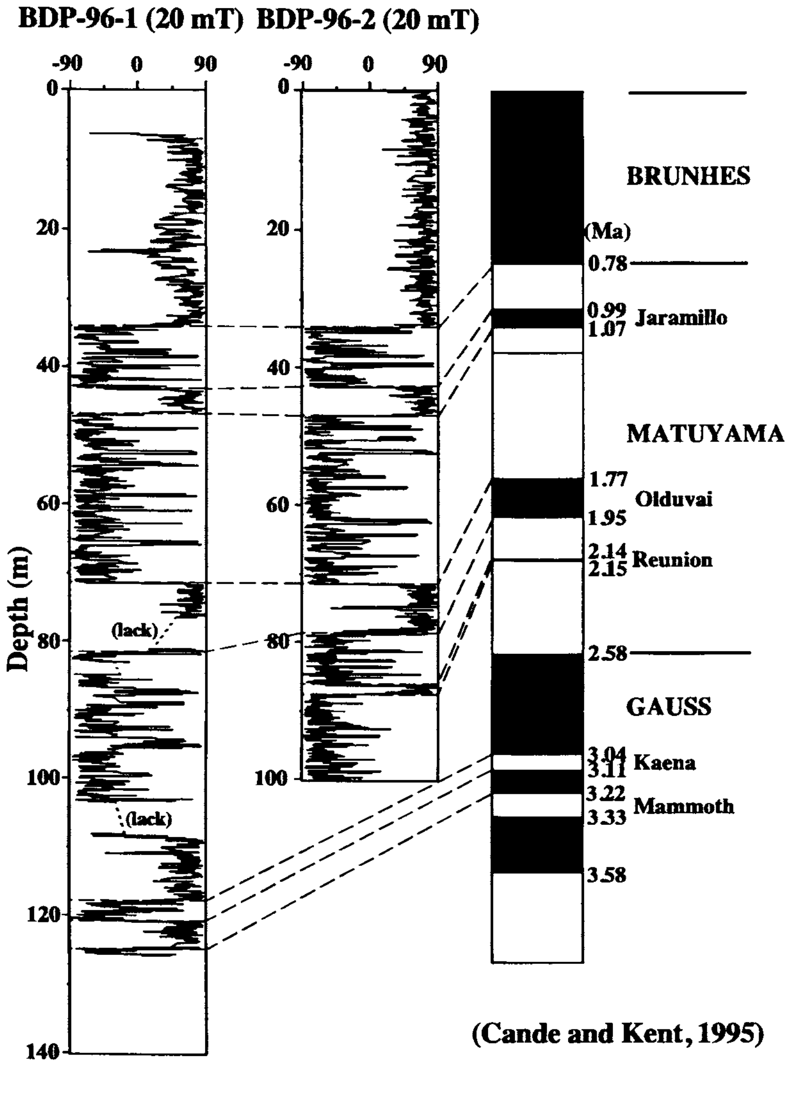


Fig. 4. Changes in inclination with depth of the QC samples of BDP96 after 20 mT AF demagnetization. The geomagnetic polarity time scale of Cande and Kent (1995) is shown on the right for reference.

also studied to investigate the sedimentary environment. The upper panel in Fig. 6 refers to the distribution of AMS in the St.18 short core near the BDP96 site. AMS revealed an oblate anisotropic fabric, that is, the maximum and intermediate axes are distributed in the horizontal plane, and the minimum axis lies in the vertical direction.

The lower panel shows the changes in the AMS parameter Max/Int-Int/Min in BDP96-2 with age, where the Max, Int, and Min values represent the degree of anisotropy of the maximum axis, intermediate axis, and minimum axis, respectively. This parameter is less than zero in most of the sequence, which means that the oblate AMS fabric is dominant. There does not seem to be any serious change in AMS features caused by the turbidite flow. The results of the AMS measurements corroborate the quiet sedimentary environment at Academician Ridge suggested by the constant sedimentation rate.

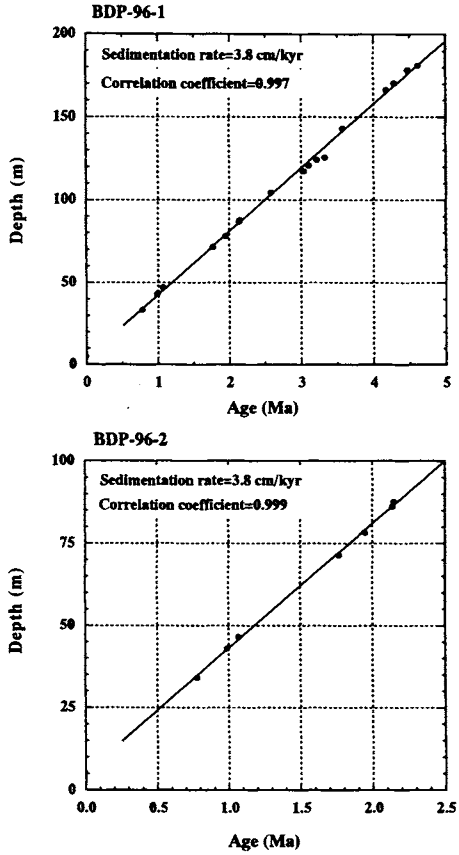


Fig. 5. Depth-age graphs of the polarity boundaries of geomagnetic events and epochs.

The upper graph is the diagram for BDP96-1, and the lower graph is for BDP96-2.

The geomagnetic polarity time scale by Cande and Kent (1995) has been used for reference.

Path-through measurement of QC samples

Path-through measurements were made on QC samples at 1 cm intervals and reveal its geomagnetic features in detail. We examined the QC data around the Brunhes/Matuyama (B/M) geomagnetic polarity boundary.

In Fig. 7, the inclination around the B/M boundary shows two normal/reverse transitions. That is, the polarity changes from Matuyama reverse to normal, then to reverse again, and finally back to Brunhes normal polarity. Such double transition phenomena at the B/M boundary

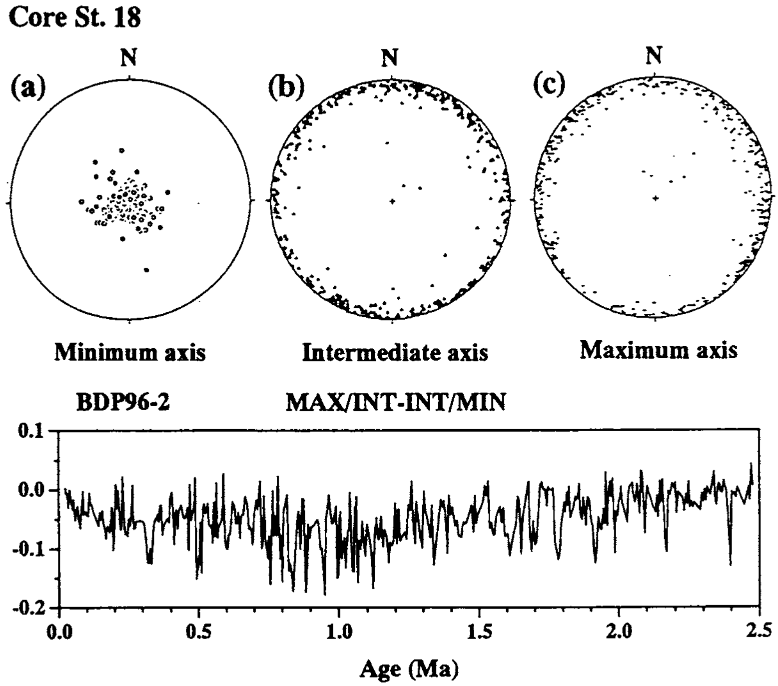


Fig. 6. The upper panel shows the distribution of the susceptibility anisotropy axes of the St. 18 sedimentary sequence. (a): minimum axis, (b): intermediate axis, (c): maximum axis. The lower panel shows the change in the AMS parameter (Max/Int-Int/Min) with age in BDP96-2.

have been reported in several studies (Jacobs, 1994). This QC study of BDP96 supports the existence of double polarity changes at the B/M boundary.

The greatest benefit of path-through long core measurements is that the data are continuous through minute measurement intervals, and further study will examine the possibility that QC data include formerly unknown geomagnetic events. However, when we analyzed the data around the region of core-breaks or disturbances, the path-through QC data yielded peculiar features. Therefore, path-through measurements on long cores should be used carefully by checking for disturbances in the core.

Changes in magnetic susceptibility as the environmental detector

Comparison with the content of diatom frustules and biogenic silica

Figure 8 shows the stratigraphic variation in magnetic susceptibility in short core St. 18 near BDP96. The figure also shows the fluctuations in the

Table 1 The age of geomagnetic polarity epochs, events, and the corresponding depth of BDP-96 cores. The geomagnetic polarity timescale of Cande and Kent (1995) is referred.

Polarity (Chron)	Boundary of Chron Subchron (Ma)		BDP-96-1 Discrete sample	BDP-96-2 Discrete sample
BRUNHES Normal			6.30m～	0.00m～
	B/M	(0.78)	33.48m/33.68m	33.96m/34.16m
MATUYAMA Reversed	Jaramillo	(0.99)	43.27m/43.47m	42.88m/43.08m
		(1.07)	47.03m/47.23m	46.45m/46.65m
	Olduvai	(1.77)	71.435m/71.615m	71.28m/71.48m
		(1.95)	78.025m/78.225m	78.20m/78.40m
	Reunion	(2.14)	86.955m/86.975m	86.07m/86.27m
		(2.15)	87.815m/87.835m	87.47m/87.87m
	Ma/Ga	(2.58)	104.27m/104.47m	
GAUSS Normal	Kaena	(3.04)	117.25m/117.45m	
		(3.11)	120.61m/121.13m	
	Mammoth	(3.22)	123.775m/124.525m	
		(3.33)	125.525m/126.04m	
	Ga/Gi	(3.58)	143.16m/143.36m	
GILBERT Reversed	Cochiti	(4.18)	166.14m/166.34m	
		(4.29)	170.40m/170.60m	
	Nunivak	(4.48)	178.48m/178.68m	
		(4.62)	181.14m/181.34m	

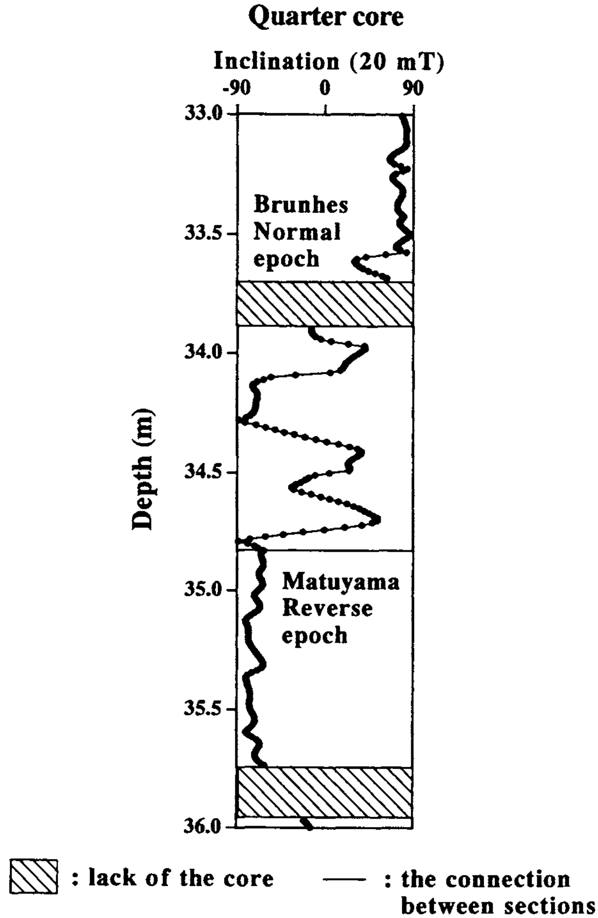


Fig. 7. Path-through inclination data of QC samples around the Brunhes/Matuyama boundary.

concentration of diatom frustules and fluctuations in the content of biogenic silica (bio-SiO_2), and the lithologic changes studied by Grachev et al. (1997) are also shown.

Magnetic susceptibility is low at depths where the sediment has high diatom frustule and bio-SiO_2 content. The fluctuations in diatom frustule and bio-SiO_2 content are an indicator of paleoclimatic change, and thus the fluctuations in magnetic susceptibility also serve as an indicator of paleoclimate. High susceptibility suggests a glacial (low diatom) period in Lake Baikal, and low susceptibility indicates an interglacial (high diatom) period.

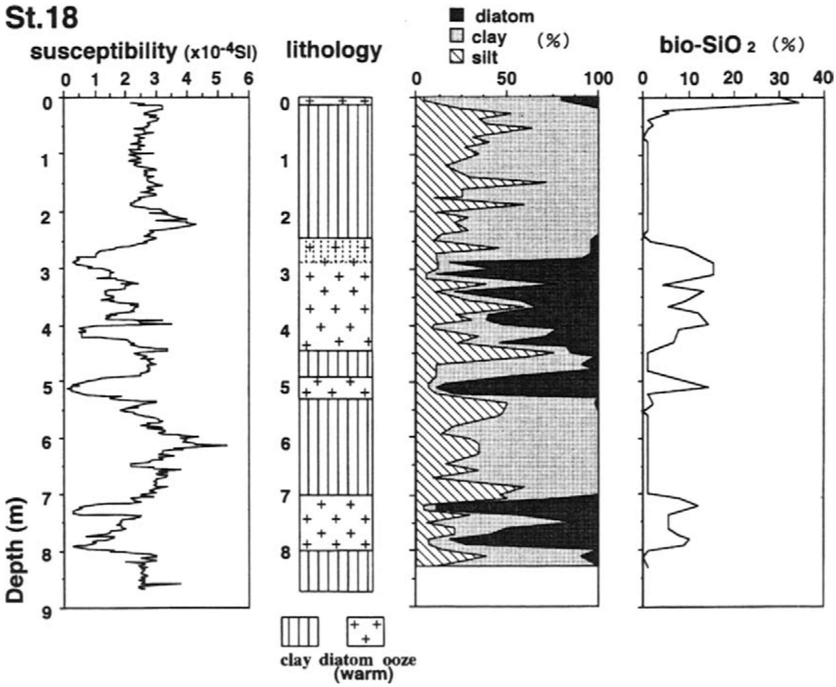


Fig. 8. Fluctuations in magnetic susceptibility, relative amount of diatom-clay-silt, and bio-SiO_2 content in core St.18 with depth at Academician ridge.

Comparison with iron content

Neutron activation analysis was conducted to study the fluctuations in iron content in the sediment of core St.18. Samples were collected at 10-cm intervals from 350 cm to 150 cm deep. In Fig. 9, the changes in iron content with depth are compared with the changes in magnetic susceptibility. There is a clear positive correlation between them, which suggests that the content of magnetic mineral is mainly responsible for the magnitude of susceptibility.

Around 280 cm deep (region-A), there was a distinct change in iron content, but the susceptibility changed little. Region-A corresponds to the boundary between glacial and interglacial sequences, and this may suggest intrusion of another mechanism on the correlation. Further study will be necessary to identify it.

Susceptibility change of BDP96

The upper panel in Fig. 10 shows the fluctuations in susceptibility with

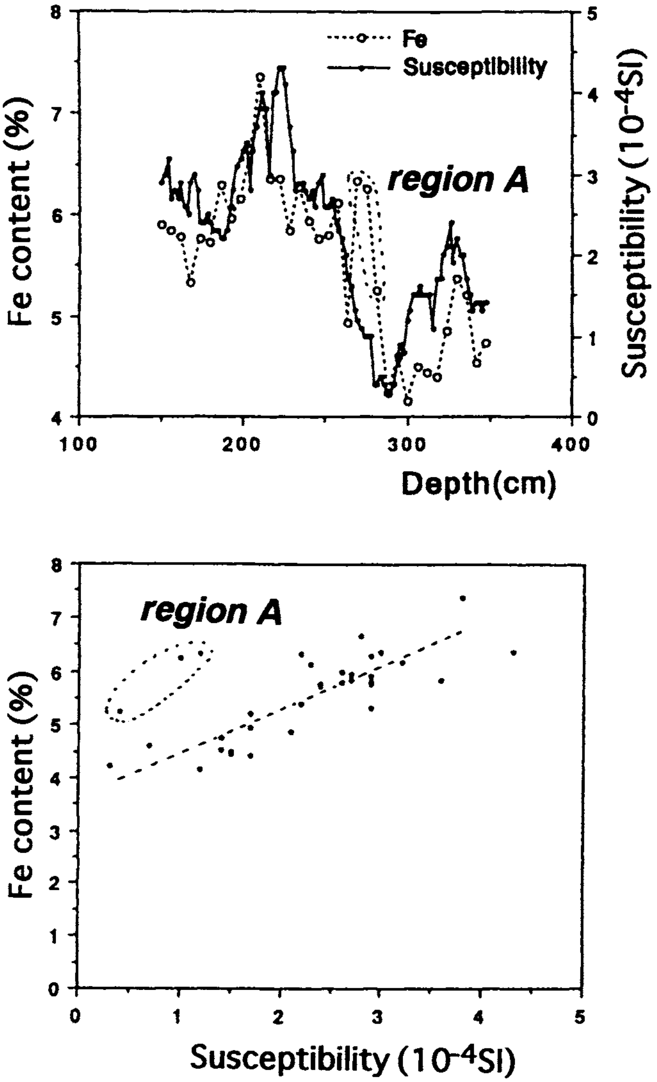


Fig. 9. Changes in the iron content and susceptibility of core St.18 from 350 cm to 150 cm deep. The lower figure shows the correlation between them (after Takamatsu, Sakai et al., 1997).

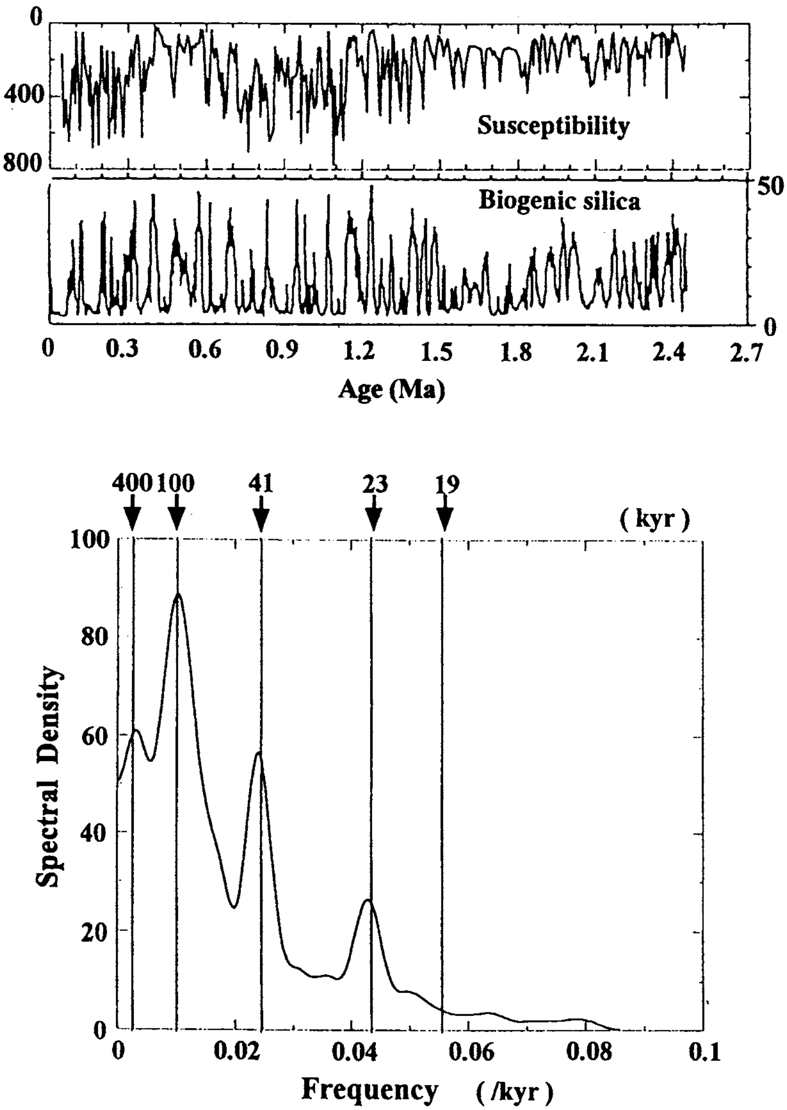


Fig. 10. Changes in susceptibility and biogenic silica with the depth of BDP96-2 (Williams et al., 1997) and the results of spectral analysis of susceptibility (Horii, 1999).

time of the BDP96-2 core (DC samples), and the middle figure shows the changes in the biogenic silica content of the sediment (Williams et al., 1997). An inverse correlation is seen between the two, similar to the correlation in Fig. 8. The lower panel shows the results of the spectral analysis of susceptibility, which reflects the distinct orbital Milankovitch cycle (Horii, 1999). These results indicate that the susceptibility changes in BDP96 are clearly related to global paleoclimatic changes.

The primary mechanism for the correlation between susceptibility and paleoclimate is thought to be as follows. The dilution of magnetic minerals during the interglacial period by the increase in biogenic mineral is responsible for the low susceptibility, and the increase in terrigenous flux with low biogenic mineral content during the glacial period causes the high susceptibility.

Susceptibility generally changes not only with fluctuations in the content of magnetic minerals, but with variations in species and the size of the magnetic minerals. The correlation between susceptibility and iron content in Fig. 9 suggests that the content of magnetic minerals is mainly responsible for the magnitude of susceptibility. We then examined the fluctuations in magnetic minerals with the changes in susceptibility by thermal demagnetization.

Thermal demagnetization

The thermal demagnetization analysis of isothermal remanent magnetization (IRM) was conducted on specimens prepared from the two regions: the specimens in group A taken from the interglacial period region where susceptibility was minimal, and the specimens in group B collected from the glacial period region with maximum susceptibility. The specimens in group A are specimen a (depth: 6.4 m), specimen c (14.19 m), and specimen e (19.71 m). The specimens in group B are specimen b (11.19 m), specimen d (16.41 m) and specimen f (42.93 m). These specimens were extracted from plastic cubes and coated with heat-resistant adhesives. After adequate drying for several days, IRM was achieved with a 0.2 T magnet. The thermal demagnetization experiment was carried out in a nitrogen atmosphere by stepwise heating from 100°C to 580°C in nine steps.

Figure 11 shows that the group A specimens with low susceptibility contain magnetic minerals whose magnetization drops at high temperatures (~580°C), whereas distinct decreases in the magnetization of the group B specimens with high susceptibility occurs at other temperatures around 350°C, in addition to 580°C. The same trend was observed in the experiments on the other specimens. These findings suggest that the differences in susceptibility between the glacial and interglacial periods may have been

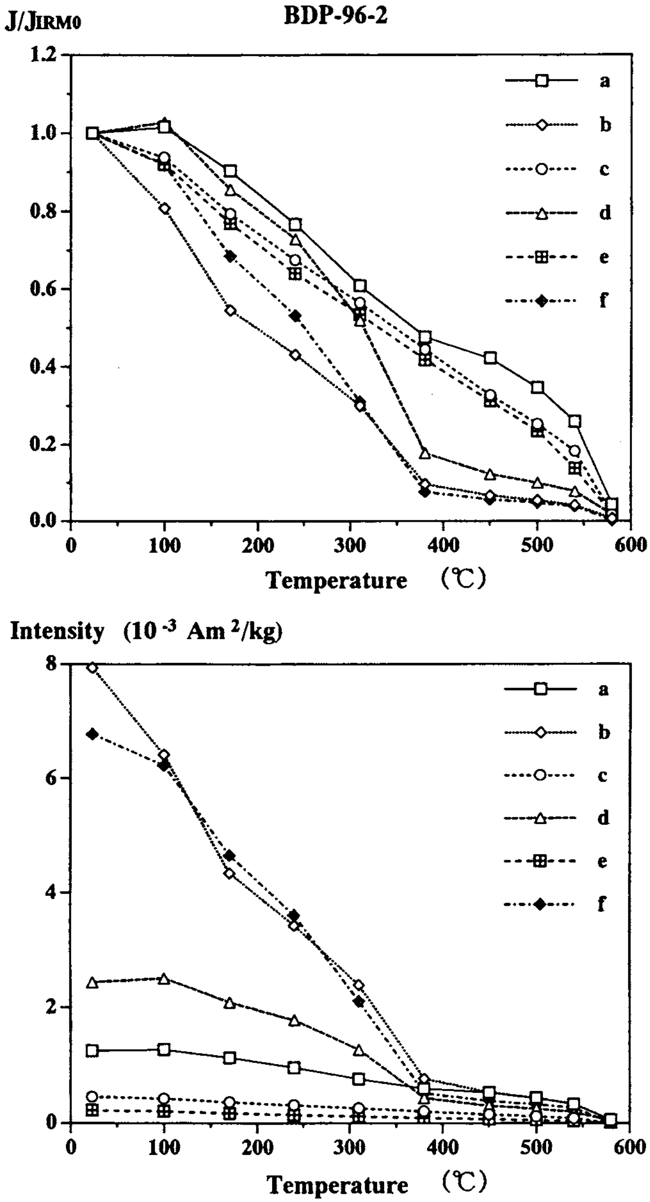


Fig. 11. Results of thermal demagnetization of BDP96 specimens. The lower panel shows the changes in intensity of remanent magnetization with temperature for each specimen. The upper panel shows the changes in relative remanent intensity normalized by the IRM intensities at 30°C (before heating).

associated with changes in the species and/or size of the magnetic minerals.

The supply of sediments in the lake may have two different origins, one being the terrigenous sediment from the river transportation system and the other being of biogenic origin. Since the Academician Ridge is of bathmetric high and away from the rivers, transpiration of terrigenous sediment brought by the river during the interglacial period is selected and limited. During the glacial period, the surface of the lake was covered with ice, and the terrigenous sediment may have been brought by the ice-rafting, giving rise to different magnetic minerals from the interglacial period.

Peck and King (1996) showed that the presence of magnetite could be traced to magnetotactic bacteria in Lake Baikal sediment. Magnetotactic bacteria have also been found in Antarctica (Funaki, private communication). The magnetotactic bacteria may be more active than other organisms (diatoms, etc.) in the glacial period, and magnetic minerals from the magnetotactic bacteria may be responsible for the remanent magnetization of sediment even in the glacial period. One interpretation of the differences between magnetic minerals in the glacial and interglacial periods is that sediment originated from ice-rafting contributes to magnetic mineral in the glacial period and that the magnetic minerals from magnetotactic bacteria are common to both periods.

Summary

Two BDP96 cores (BDP96-1 and BDP96-2) showed clear inclination reversals with depth. Comparison with the geomagnetic polarity timescale resulted in assignment of the sedimentary sequence of the 200 m long BDP96-1 core to the geomagnetic polarity epochs during the past 5 million years: the Brunhes, Matuyama, Gauss and Gilbert epochs. The sedimentation rate was estimated to be 3.8 cm/kyr by the least squares method based on the depth-age relationship. The fairly high correlation coefficient (0.997-0.999) of the depth-age relationship indicates that sedimentation at Academician ridge has been continuous in a quiet environment. This may be an important factor for the tectonic study of Lake Baikal.

Path-through measurements on quarter core samples around the B/M boundary showed the double polarity transitions. Path-through measurements are an effective means of investigating continuous magnetization of long cores, and it is necessary to examine disturbances in the core carefully.

The changes in magnetic susceptibility with time were inversely correlated with the changes in biogenic silica content, and spectrum analysis revealed clear Milankovitch orbital periodicities in the fluctuations in susceptibility. Susceptibility analysis makes it possible to study the paleoclimate, however, further study of the mechanism of the susceptibility changes in Lake Baikal associated with paleoclimate are needed.

Acknowledgements
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