ELSEVIER

Earth and Planetary Science Letters 202 (2002) 117–132

EPSL

www.elsevier.com/locate/epsl

Paleomagnetic record from Academician Ridge, Lake Baikal: a reversal excursion at the base of marine oxygen isotope stage 6

H. Oda [a,*], K. Nakamura [a], K. Ikehara [a], T. Nakano [b], M. Nishimura [c], O. Khlystov [d]

[a] *Institute for Marine Resources and Environment, Geological Survey of Japan, AIST, Tsukuba 305-8567, Japan*
[b] *Public Relations Department, Geological Survey of Japan, AIST, Tsukuba 305-8567, Japan*
[c] *School of Marine Sciences and Technology, Tokai University, 3-20-1 Orido, Shimizu 424-0902, Japan*
[d] *Limnological Institute of the Siberian Branch, Russian Academy of Sciences, Ulan-Batorskaya Str. 3, 664033 Irkutsk, Russia*

Received 5 March 2002; received in revised form 6 June 2002; accepted 6 June 2002

Abstract

Paleomagnetic and rock-magnetic studies on a hydraulic piston core (Ver98-1, St.6) from Academician Ridge, Lake Baikal showed the occurrence of a reversal excursion at 670–696 cm depth, which is at the base of marine oxygen isotope stage 6. A correlation of X-ray CT values, as a proxy of relative density, to the marine oxygen isotope record provides an age of 177–183 ka for this reversal excursion. It can be correlated with other excursion records from Lake Baikal, found in Core 287-K2 from Academician Ridge [King et al., Russ. Geol. Geophys. 34 (1993) 148–162] and in core BDP93-1 drilled on the Buguldeika saddle [BDP-93, Quat. Int. 37 (1997) 3–17]. We correlate the Lake Baikal reversal excursion with a well documented excursion in the Brunhes Chron, the Iceland Basin event (186–189 ka) from ODP Sites 983 and 984 in the North Atlantic [Channell, J. Geophys. Res. 104 (1999) 22937–22951]. Also the relative paleointensity record agrees well with that from ODP Site 983 [Channell, J. Geophys. Res. 104 (1999) 22937–22951]. The Lake Baikal excursion and the Iceland Basin event correspond to the minimum of relative intensity at 188 ka in Sint-800 [Guyodo and Valet, Nature 399 (1999) 249–252]. We argue that it is distinct from the Jamaica/Pringle Falls excursion, estimated at 205–215 ka [Langereis et al., Geophys. J. Int. 129 (1997) 75–94]. This is supported by the recalibration of the age of another excursion found in Core St.16 in Lake Baikal [Sakai et al., Bull. Nagoya Univ. Furukawa Mus. 13 (1997) 11–22] with an age of ∼223 ka, which is close to the age of the Jamaica/Pringle Falls excursion, as suggested earlier [King et al., Russ. Geol. Geophys. 34 (1993) 148–162]. The VGP path of the reversal excursion (177–183 ka) consists of a southward swing through the North Atlantic, followed by a loop through Africa and the Indian Ocean. The path morphology is similar to that of the Iceland Basin event from the North Atlantic [Channell, J. Geophys. Res. 104 (1999) 22937–22951]. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Lake Baikal; reversals; Brunhes Chron

* Corresponding author. Present address: Paleomagnetic Laboratory 'Fort Hoofddijk', Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands. Tel.: +31-30-2531361; Fax: +31-30-2531677.
E-mail addresses: h.oda@geo.uu.nl (H. Oda), hirokuni-oda@aist.go.jp (H. Oda).

PII: S0012-821X(02)00755-0

1. Introduction

Lake Baikal is the world's deepest and most voluminous lake. The lake is located in the central part of the Baikal Rift system and has been subsiding since the early Miocene [7]. The sediment thickness reaches a maximum of approximately 8000 m. The lake can be divided into three subbasins: north, central and south. Since 1989, an international research program has conducted extensive studies using both short hydraulic piston cores and deep drilling from a platform [8].

There have been several paleomagnetic and rock-magnetic studies on piston cores from Lake Baikal. Peck et al. [9] conducted a rock-magnetic study on cores from Academician Ridge. Peck et al. [10] reported a 84 kyr secular variation record including relative paleointensity on cores from the Buguldeika saddle in front of the Selenga delta, located between the central and south basins. King et al. [1] reported two excursions from a piston core taken from Academician Ridge with estimated ages of approximately 180 ka and 215 ka.

The relative paleointensity stack Sint-800 [4] has a prominent minimum at 188 ka, which was labeled as Jamaica/Pringle Falls. However, Langereis et al. [5] argue that the Jamaica/Pringle Falls excursion has an age of 205–215 ka. On the other hand, a fully documented 'Iceland Basin event' was reported from ODP Sites 983 and 984 at 186–189 ka [3]. Therefore, the Iceland Basin event seems to better correspond to the paleointensity minimum at 188 ka in Sint-800. In addition, records of excursions with age estimates around 180–190 ka are accumulating [11–15].

We intend to clarify the existence and age of distinct geomagnetic excursions around 185 and 215 ka. From the Lake Baikal piston core taken on Academician Ridge, a paleomagnetic record, including a relative paleointensity record and a reversal excursion, was obtained. Details of the reversal excursion were investigated, and compared with other globally reported excursions.

2. Geological setting, samples and measurements

Piston core Ver98-1, St.6 (53°41′39″N, 108°21′01″E) was taken from Academician Ridge at a water depth of 335 m (Fig. 1); the total core length is 1096 cm. Academician Ridge is a topographic high, which divides the north and central basins of Lake Baikal. Sediments consist of an alternation of diatom-rich olive-colored silt and diatom-poor greenish silt or silty clay (Fig. 2) [16]. For the interval 32–84.5 cm, the sediments are disturbed, probably as a result of the slow trigger of the piston corer which was also reported for other Lake Baikal cores [9,10]. Also the deepest interval (897.5–1096 cm) was disturbed due to flow-in during coring. This was recognized both by visual inspection and by the X-ray CT scan image which represents a wet bulk density proxy, obtained from the tomography of X-ray attenuation.

On core Ver98-1, St.6, CT scanning at 1 mm intervals was conducted with 0.33 mm pixel resolution before splitting the core [17], using an X-ray CT scanner (Hitachi Medico CT-W2000) at the Geological Survey of Japan (GSJ). Subsequently, oriented cubic samples (7 cm^3) were taken, excluding the interval of flow-in. The cube samples were stored at a temperature of 2°C. The anisotropy of magnetic susceptibility (AMS) was measured on a AGICO Kappabridge KLY-3S at GSJ, to assess any physical disturbance during sedimentation or coring. Directions of the principal axes of AMS and susceptibilities along the axes (K_{max}, K_{int} and K_{min}) were obtained, and the degree of anisotropy (P_J) and the shape parameter (T) were calculated [18].

The natural remanent magnetization (NRM) was measured on a 2G Enterprises DC SQUID magnetometer (SRM Model 760) at GSJ. All samples were subjected to stepwise alternating field (AF) demagnetization using eight steps up to 80 mT with a demagnetizer in line with the SRM.

After the measurement of NRM, an anhysteretic remanent magnetization (ARM) was imparted along the z-axis with a constant DC magnetic field of 100 μT parallel to the AC demagnetizing field. Every tenth sample was used for stepwise ARM acquisition and subsequent stepwise AF demagnetization. After demagnetization of the NRM at 80 mT, an ARM was imparted in AC

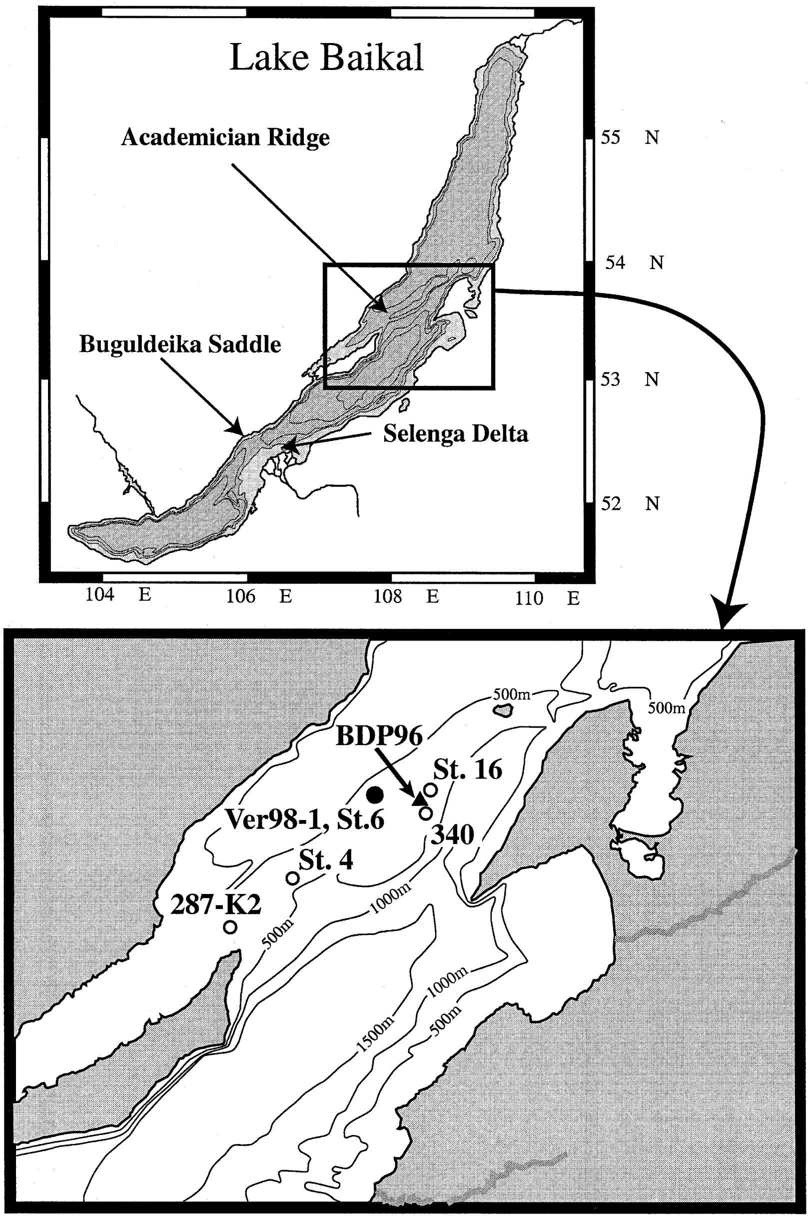

Fig. 1. Location map of coring site Ver98-1, St.6 (solid circle) and positions of other cores referred to in the text (open circles and a triangle).

fields from 5 up to 100 mT, in nine steps. Subsequently, the samples were AF demagnetized at the same nine steps. For the other samples, an ARM was imparted with an AC field of 100 mT, and demagnetized at AC fields of 10, 15, 20, 25, 30, and 40 mT.

A saturation isothermal remanent magnetization (SIRM) was acquired using a pulse magnetizer (2G model 660) at 2.5 T. The S_{ratio} was calculated [19] according to:

$$S_{ratio} = (-IRM_{-0.3T}/SIRM + 1)/2 \quad (1)$$

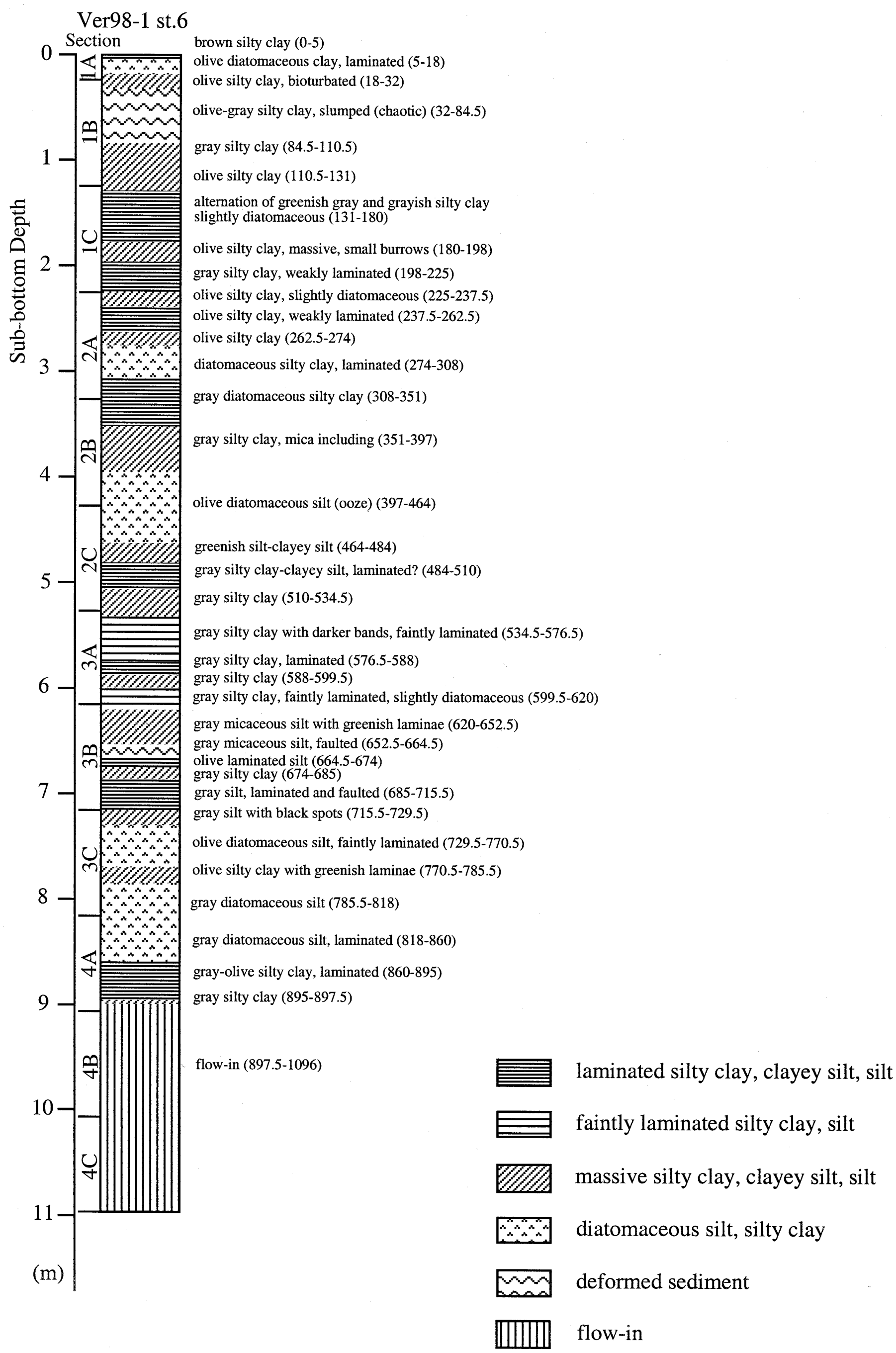

Fig. 2. Schematic stratigraphic column and lithology of the core.

where $IRM_{-0.3T}$ is the magnetization acquired after applying a reverse pulse magnetic field of 0.3 T.

Small amounts of sediment were taken from selected paleomagnetic specimens and subjected to low temperature magnetic measurement with a Quantum Design Magnetic Property Measurement System (MPMS-XL5) at GSJ. Samples were cooled in zero field from room temperature to 6 K, at which temperature a 2.5 T DC field was applied for 60 s. Upon warming up to 300 K, the IRM was measured at 2° steps.

3. Results

Typical examples of vector endpoint diagrams during progressive AF demagnetization show a stable primary remanence pointing toward the origin after demagnetization up to 20 mT (Fig. 3). Paleomagnetic directions were calculated by fitting a linear regression line to minimize maximum angular deviation (MAD) [20].

Zero field warming of IRM acquired at 6 K on samples from four selected horizons (Fig. 4) show a sharp drop at around 116 K, suggesting that the dominant magnetic mineral is nearly pure magnetite. The median destructive field of ARM ranges from 24 to 38 mT, except for a few horizons. The χ_{ARM}/SIRM ratio ranges from 10×10^{-5} to 30×10^{-5} m/A. According to the criteria by Maher [21], the magnetic grain size range is between 0.2 and 5.0 μm, which is in the single domain to pseudo-single domain range.

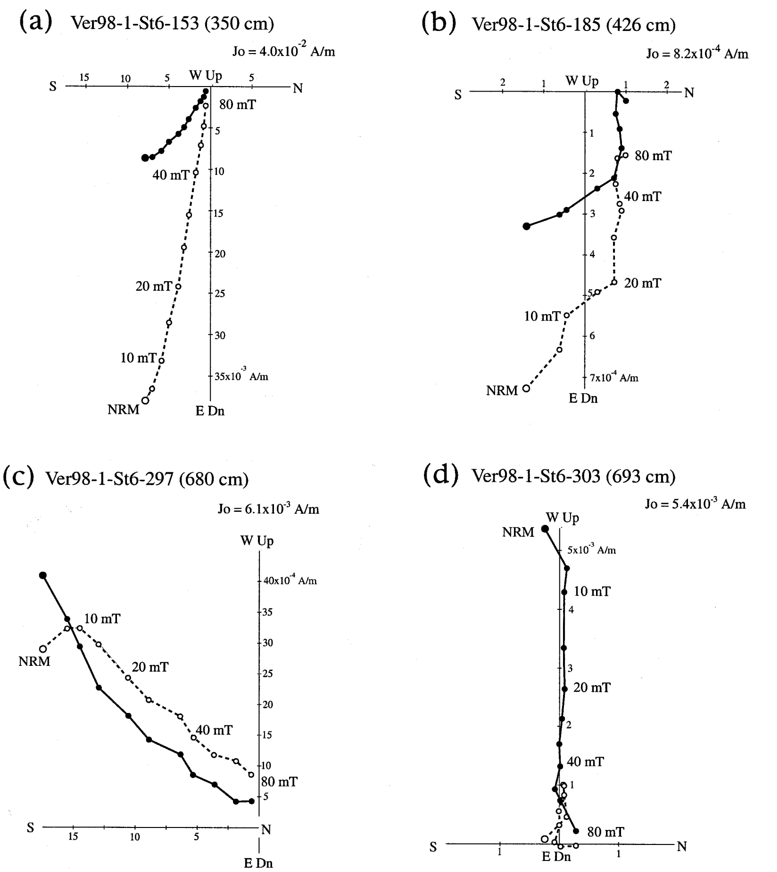

Fig. 3. Typical examples of vector endpoint diagrams. Solid (open) symbols represent projection of the vector onto a horizontal (vertical) plane. (a,b) Diagrams for samples outside the reversal excursion interval. (c,d) Samples within the reversal excursion interval.

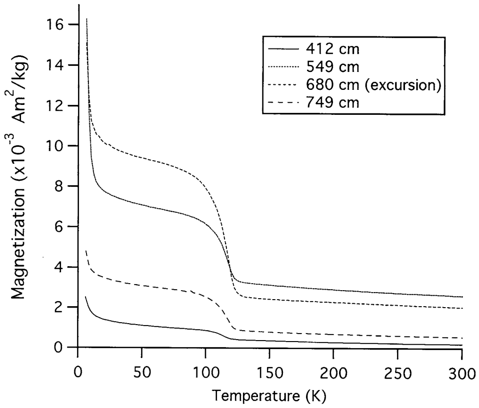

Fig. 4. Zero field warming from 6 K to 300 K after cooling from 300 K and imparting a 2.5 T DC magnetic field for 60 s at 6 K. The magnetizations were normalized with the dry weights of the samples to obtain mass specific magnetization.

A number of paleomagnetic and rock-magnetic parameters plotted downcore (Fig. 5), as well as the raw CT values by X-ray CT scan, as a measure of wet bulk density. Except for samples with very low intensity, MAD values are generally smaller than 5, suggesting that the paleomagnetic directions are stable and well determined. The NRM intensity after 20 mT AF demagnetization, magnetic susceptibility and ARM intensity all show a positive correlation with CT values. Low CT value (low density) corresponds to layers rich in porous and low density diatoms, leading to lower values of magnetic concentration parameters caused by dilution of magnetic minerals by diamagnetic diatom silica and water. A higher content of diatoms corresponds to warm interglacial periods, whereas a lower content corresponds to cold glacial periods [16]. Earlier, Peck et al. [9] found the same correlation between magnetic con-

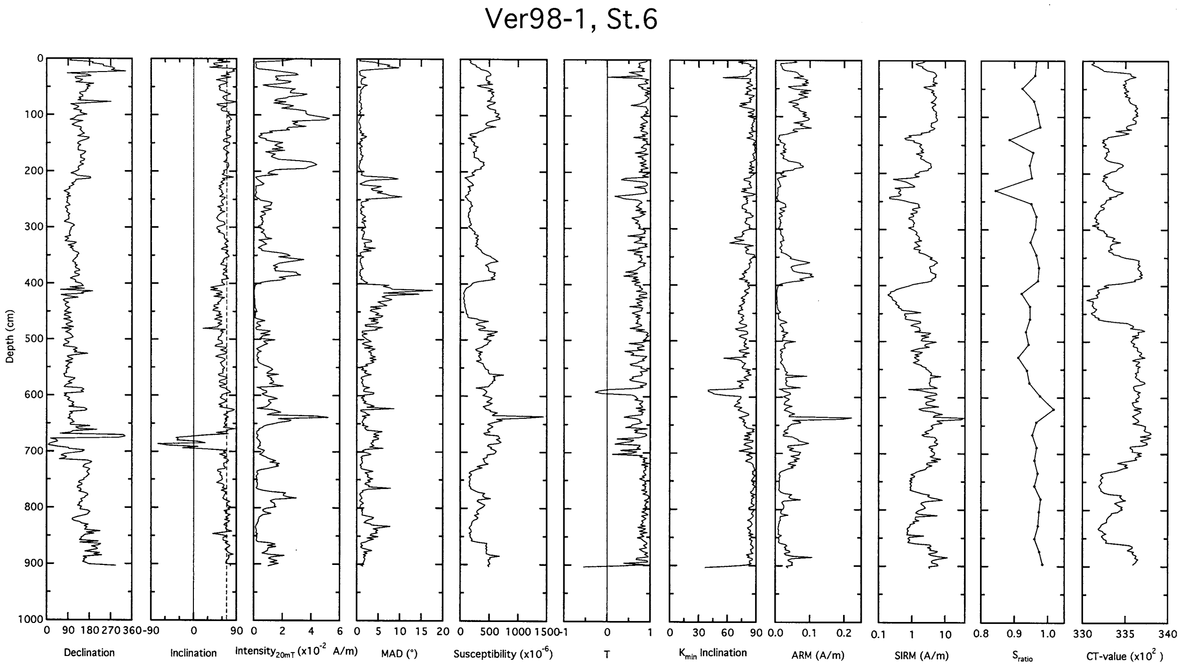

Fig. 5. Downhole plot of paleomagnetic and rock-magnetic parameters for core Ver98-1, St.6. Paleomagnetic directions were determined by fitting linear regression lines and MAD is the maximum angular deviation [20]. Intensity is after AF demagnetization at 20 mT. The vertical dashed line marks the expected inclination for a geocentric axial dipole at the site. T is the shape parameter [18], where a positive (negative) value means that the anisotropy ellipsoid is oblate (prolate); χ_{ARM}/SIRM is a proxy of grain size for magnetite, this ratio is higher for smaller grain sizes [21]. S_{ratio} is a remanence ratio that reflects magnetic mineralogy (see Eq. 1) [19]. The CT value of X-ray CT scan is a mean of 361 pixel values at the center of each 1 mm slice averaged for the depth interval corresponding to each paleomagnetic cube.

centration and wet bulk density for Baikal sediments.

The interval between 670 and 696 cm shows strongly negative inclinations and deviating declinations (Fig. 5). Since no physical disturbance was recognized at this depth by X-ray CT imaging nor by visual inspection, we interpret this as a reversal excursion. AMS parameters also show the primary fabric of sediments, since T is positive and the inclination of K_{min} is larger than 67°. The excursion is characterized by two successive fluctuations with negative values in inclination. The MAD is around 5° and the intensity at 20 mT is in the order of 10^{-2} A/m.

K_{max} and K_{min} axes of AMS were plotted on a equal area plot after setting a common North direction by using the average declination of NRM (Fig. 6). The distribution of K_{max} axes forms a crescent in the southeast quadrant, and K_{min} shows a slight shift toward the northwest quadrant. This evidence suggests that imbrication was formed by the bottom current which was flowing toward the northwest at the time of deposition.

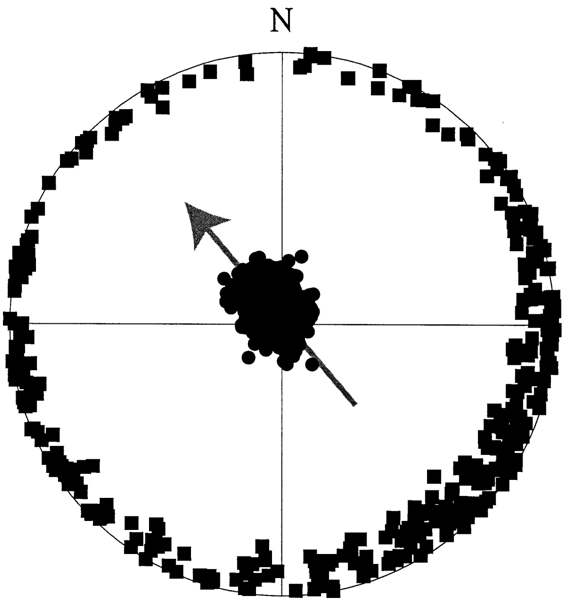

Fig. 6. Equal area plot of K_{max} (solid rectangles) and K_{min} (solid circles) axes of AMS projected onto the lower hemisphere. Gray arrow indicates the inferred direction of bottom currents.

4. Discussion

4.1. Age model

The alternating abundance of diatoms is correlated with warm and cold periods. During interglacial periods, a high concentration of diatoms leads to high biogenic silica content and low sediment density. Conversely, during cold glacial periods, a low concentration of diatoms corresponds to low biogenic silica and high sediment density. For our age model, we assume that the marine oxygen isotope stages (OIS) are correlative with the biogenic silica record from Lake Baikal, with a possible time difference of a few thousand years. This assumption was shown to be applicable to the drill core BDP96-2 on Academician Ridge [22], where the biogenic silica record of BDP96-2 could be correlated with the oxygen isotope record from ODP Site 677 [23]. The correlation included one anchor point: the Brunhes/Matuyama boundary.

Instead of biogenic silica content, we used a record of X-ray CT values, which provides a proxy of density that is inversely correlative with the biogenic silica content (Fig. 7). The correlation between mean X-ray CT value and the biogenic silica content of BDP96-2 [22] is relatively straightforward, and stages and substages are recognized (Fig. 7c). Triple peaks, with a small shoulder at the base, spanning substages 5.1 to 5.3 can be correlated with each other, and low and high values during substages 5.4 and 5.5 can be recognized. Finally, a wide low during stage 6 and the double peaks spanning substages 7.1 and 7.3 can be reliably correlated.

An age–depth plot was produced based on this correlation to major isotopic events (Fig. 8), using the age model by Martinson et al. [24] (Table 1). The susceptibility record based on this age model is consistent with the susceptibility record by Peck et al. [9]. Average sedimentation rates were estimated to be 4.3 cm/kyr around the reversal excursion. The age of the reversal excursion interval was estimated to be 177–183 ka.

4.2. Relative paleointensity

A relative paleointensity record was derived from the ARM acquisition data, and from AF demagnetization of ARM and NRM. Samples from above 84.5 cm were not used for the further analysis of relative paleointensity because the interval 32–84.5 cm is disturbed (Fig. 2). The slope of the best fit line was calculated on the diagram of NRM remaining versus ARM gained, according to the pseudo-Thellier method [25] (Fig. 7e, open circles). The best fit slope of NRM remaining versus ARM remaining between 10 and 40 mT is also shown (Fig. 7e, solid lines). Furthermore, another relative paleointensity estimate was determined as NRM_{20mT}/SIRM (Fig. 7e, broken line). These three values show nearly identical patterns of fluctuations.

Our paleointensity record meets the criteria for a reliable relative paleointensity record [26], even though the variation in magnetic concentration is quite large (Fig. 5). The magnetic concentration parameters (SIRM etc.) shows a large peak at 636–640 cm, which was not used for the relative paleointensity analysis. In general, SIRM varies between 0.2 and 12 A/m (Fig. 5). The large variations of the magnetic concentration might be caused by variations in the dilution by diatoms

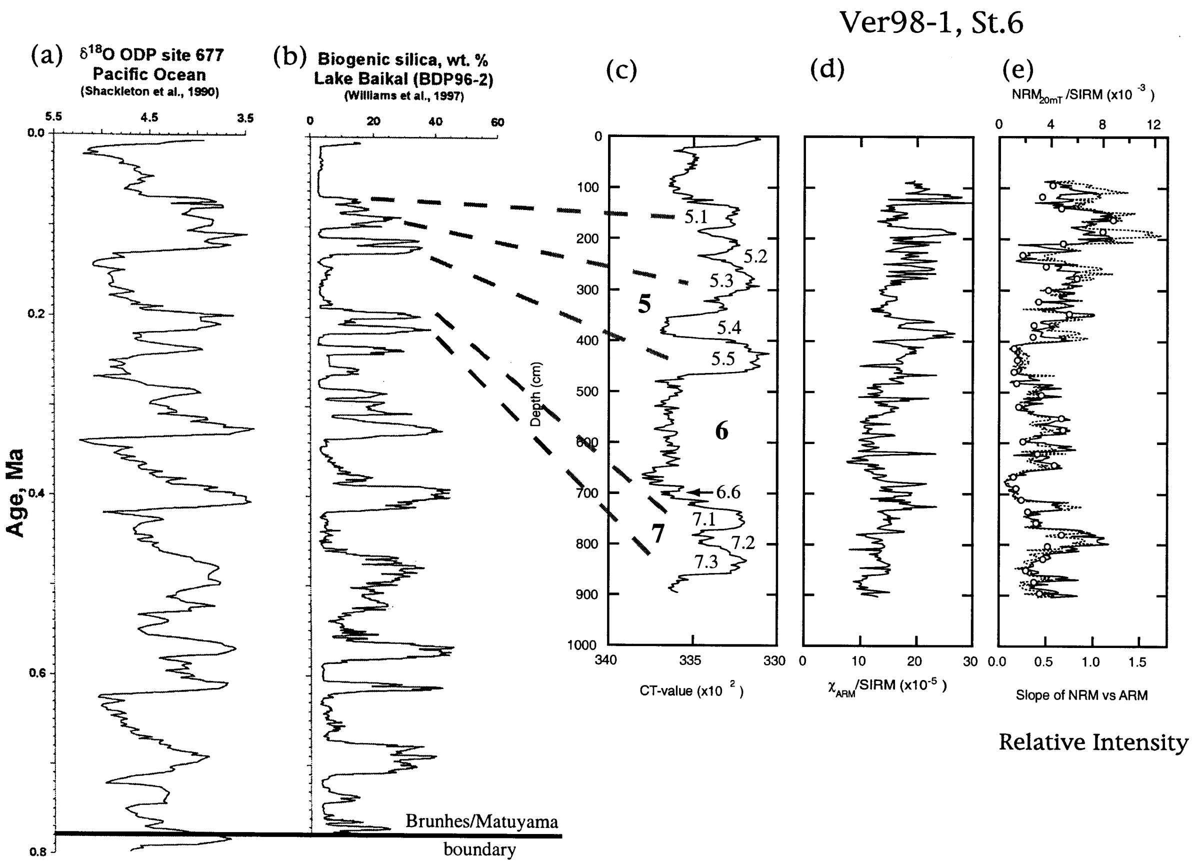

Fig. 7. Stratigraphic correlation of (c) the CT value (inverted scale) of core Ver98-1, St.6 with (b) the biogenic silica record from BDP96-2, which are located close to each other (Fig. 1). (a) The $\delta^{18}O$ record from ODP Site 677 [23] is also shown for comparison. (d) The rock-magnetic grain size proxy (χ_{ARM}/SIRM) shows that there are high frequency fluctuations superimposed on a gradually fining trend. (e) Relative paleointensity records from core Ver98-1, St.6. Open circles and solid lines (bottom axis) denote relative paleointensities calculated by the pseudo-Thellier method, and best fit on a plot of NRM decay versus ARM decay between 10 and 40 mT. Dotted lines are NRM at 20 mT divided by SIRM (top axis). Note that these three relative paleointensities are very consistent with each other.

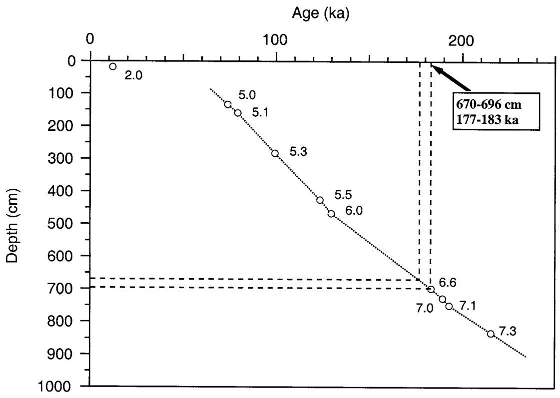

Fig. 8. Age–depth plot of core Ver98-2, St.6 used for the age model of this study. Dotted lines denote linear interpolation connecting the control points (open circles; see Table 1). The horizon of the excursion is shown by broken lines.

and in the magnetic mineral supply, related to the glacial–interglacial cycle.

The relative paleointensity record of Ver98-1, St.6 (Fig. 9d) and that from the Buguldeika saddle of Lake Baikal [10] (Fig. 9c) can be correlated, although the overlap is short. Our relative paleointensity record can be correlated well with that from ODP Site 983 [3] (Fig. 9b). The relative paleointensity stack Sint-800 [4] (Fig. 9a) is also shown for comparison. The minima of our relative paleointensity record correlate well with those from ODP Site 983. The reversal excursion found at 670–696 cm (177–183 ka) falls within the intensity minima from 670 to 710 cm (175–186 ka). Another prominent minimum at 122 ka (412 cm) in our record may correspond to the Blake event.

4.3. Excursion records from Lake Baikal

King et al. [1] reported two excursions for Core 287-K2 on Academician Ridge with ages of approximately 180 ka and 215 ka (Fig. 10). They estimated these ages on the basis of correlation between rock-magnetic parameters and the SPECMAP stack. Also Sakai et al. [6] reported an almost identical inclination record including two excursions for Core St.4 from Academician Ridge (Fig. 10). The susceptibility records from these cores show discrepancy, which may partly be introduced by fluctuation in density used for the calculation of mass susceptibility for Core 287-K2.

In the paleomagnetic record from the BDP93-1 core drilled on the Buguldeika saddle, two excursions are recognized [2]. The depth intervals of the excursions are 25.5–27 m and 67–71 m. Based on the correlation of the biogenic silica records of BDP93-1 with the marine OISs [24,27] (Table 1), the upper excursion at 25.5–27 m was assigned an age of 177–186 ka (Table 2).

Sakai et al. [6] also reported an excursion, which they inferred to be the Blake event, from Core St.16 taken on Academician Ridge. However, their age estimate was based on the extrapolation of ^{14}C ages downcore. Colman et al. [28] pointed out that ^{14}C ages based on low concentration organic carbon from glacial sediments in Lake Baikal can easily be contaminated by young carbon. Thus, we reinvestigated their record in terms of the age of the excursion. Core St.16 is close to Core 340 [9], our core and the drill core BDP96-2 (Fig. 1). Core St.16 and Core 340 show quite similar features in magnetic susceptibility (Fig. 11). Peck et al. [9] successfully correlated their susceptibility and HIRM (concentration of high coercivity magnetic mineral) with the SPECMAP stack and concluded that the bottom of their core has an age of 245 ka. The biogenic silica record of BDP96-2 can be inversely correlated with the magnetic susceptibility record and hence with that of Core St.16 (Fig. 11, thick broken lines). According to this correlation, we recalibrated the excursion of Sakai et al. [6] to be

Table 1
Control points for the age model

Stage	Age (ka)	Depth (cm)
2.0	12.1	18
5.0	73.9	133
5.1	79.3	160
5.3	99.4	283
5.5	123.8	425
6.0	129.8	467
6.6	183.3	698
7.0	189.6	728
7.1	193.1	750
7.3	215.5	833

Stage annotation and ages are from Martinson et al. [24].

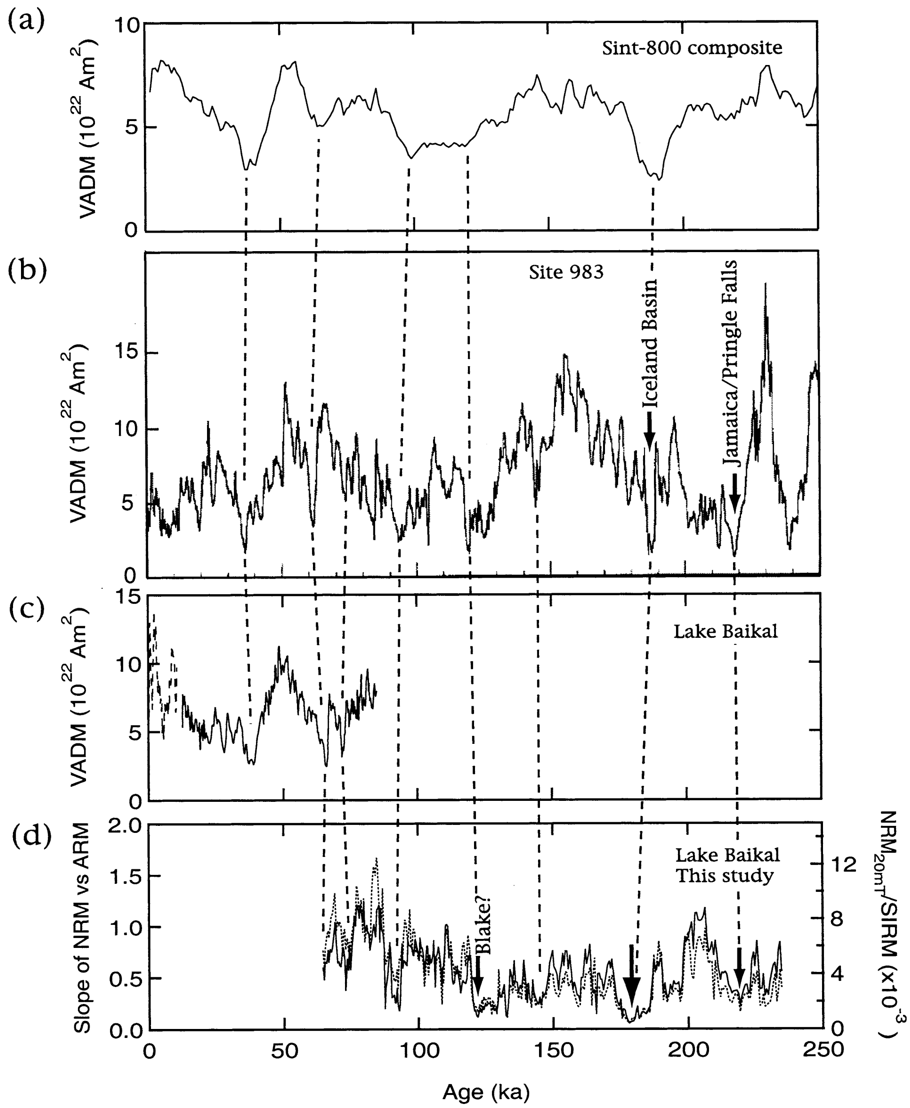

Fig. 9. Plot of relative paleointensities versus age for (a) Sint-800 [4], (b) ODP Site 983 [3], (c) the Buguldeika saddle of Lake Baikal [10], and (d) this study. The large arrow in panel d indicates the reversal excursion reported in this study. VADM is virtual dipole moment.

during marine OIS 7.4, which is approximately 223 ka. This correlates well with the older excursion (∼215 ka) of King et al. [1].

4.4. *Comparison of the excursion with those around OIS 6/7*

Quite a few excursion records have been reported from other sites on the globe, whose estimated ages are around OIS 6/7 (Table 2). Nowaczyk and Antonow [11] reported an excursion record from Greenland Basin with an age estimate of 179–189 ka. In addition, Channell [3] reported a well documented reversal excursion from multiple cores of ODP Sites 983 and 984 drilled in the Iceland Basin with mean sedimentation rates of

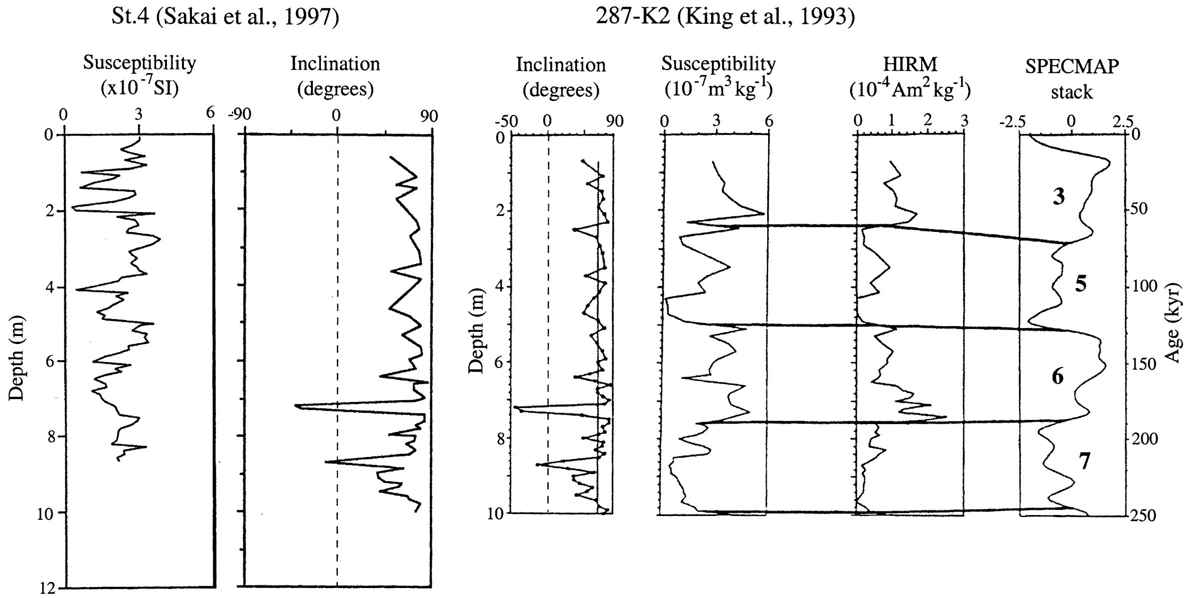

Fig. 10. Comparison of inclination and susceptibility records from Core 287-K2 [1] and Core St.4 [6]. Redrawn from the original figures.

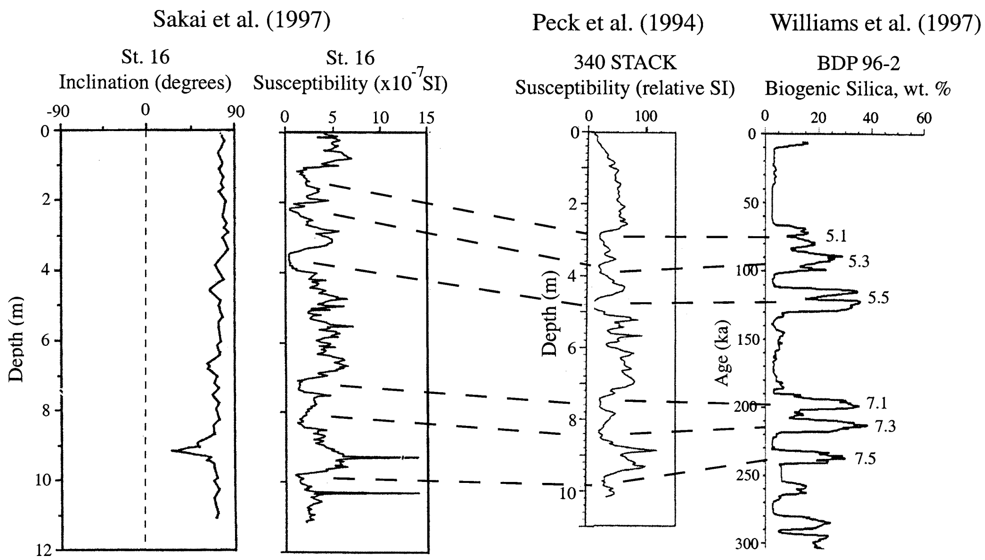

Fig. 11. Age recalibration of the record of inclination and susceptibility of Core St.16 from Academician Ridge [6] is shown. The susceptibility record of Core St.16 is correlated to that of nearby Core 340 [9]. The nearly identical pattern made it possible to make an unambiguous correlation between these two cores. It is clear that the top of Core St.16 is missing. The age model of Core 340 is determined by correlation of susceptibility with the SPECMAP stack [9]. The inferred OISs of the biogenic silica record from BDP96-2 [22] are also shown and correlated.

12–15 cm/kyr. He estimated the age of the excursion as 186–189 ka by correlation of the oxygen isotope record to the SPECMAP stack. These age estimates are close to the estimated age of our excursion (177–183 ka), and we consider them to represent the same excursion. The age discrepancy may come from time differences between the marine oxygen isotope record and the diatom record in the continental lake, error in age models, and/or differences in lock-in depths of postdepositional remanence. There are also reports of the excursion from the Pacific [14,15] and from the North Atlantic [12,13], which have similar ages (Table 2).

The excursions with older ages are shown together with the records from Lake Baikal in the lower part of Table 2. Langereis et al. [5] estimated the age of Jamaica/Pringle Falls excursion at 205–215 ka based on the original records. The volcanic excursion record 'event C' from the Hawaii Scientific Drilling Project was dated by $^{40}Ar/^{39}Ar$ on lavas above and below the excursion as between 200 ± 9 and 232 ± 4 [29]. The New Zealand Mamaku ignimbrite was also dated by $^{40}Ar/^{39}Ar$ as 210 ± 10 ka [30]. The excursion record from Pringle Falls occurs just above an ash layer, which was dated by $^{40}Ar/^{39}Ar$ on plagioclase as 218 ± 10 ka, and it was correlated with the excursions in Summer Lake and Long Valley [31]. They are also consistent with the excursion records

Table 2
Excursion records around marine oxygen isotopic stages 6/7

Age (ka)	Dating	Core etc.	Area	References/Notes
Iceland Basin event sediments				
177–183	X-ray CT tuned to $\delta^{18}O$	Ver98-1, St.6, Academician Ridge	Lake Baikal	This study
~180	HIRM tuned to $\delta^{18}O$	287-K2, Academician Ridge	Lake Baikal	[1]
~180	Inclination correlative with 287-K2 [1]	St.4, Academician Ridge	Lake Baikal	[6]
177–186	Bio-Si tuned to $\delta^{18}O$	BDP93-1, Buguldeika saddle	Lake Baikal	[2] recalibrated with the age model [27]
179–189	$\delta^{18}O$ and δ^{13} tuning	PS 1892-3 KAL	Greenland Sea	[11]
186–189	$\delta^{18}O$ tuning	ODP Sites 983 and 984	North Atlantic	[3]
180–190	$\delta^{18}O$ tuning	SU9008	Central North Atlantic	[12]
180–190	$\delta^{18}O$ tuning	SU9218 and SU9219	Central North Atlantic	[13]
~190	$\delta^{18}O$ tuning	ODP Hole 884D	North Pacific	[14]
~190	$\delta^{18}O$ tuning and susceptibility correlation	NP7, West Caroline Basin	Western Equatorial Pacific	[15]
Jamaica/Pringle Falls excursion sediments				
~215	HIRM tuned to $\delta^{18}O$	287-K2, Academician Ridge	Lake Baikal	[1]
~215	Inclination correlative with 287-K2 [1]	St.4, Academician Ridge	Lake Baikal	[6]
~223	Bio-Si tuned to $\delta^{18}O$	St.16, Academician Ridge	Lake Baikal	[6] recalibrated in this study
~200+	$\delta^{18}O$ tuning	V12-122, Jamaica Ridge	Caribbean Sea	[32] recalibrated [5]
~217−	sapropel layer tuned to $\delta^{18}O$	RC9–181	Mediterranean Sea	[32] recalibrated [5]
218 ± 10	$^{40}Ar/^{39}Ar$ on underlying ash	Pringle Falls (Summer Lake, Long Valley)	North America	[31]
Jamaica/Pringle Falls volcanic rocks				
200 ± 9–232 ± 4	$^{40}Ar/^{39}Ar$ on lavas above and below	Hawaii drill core (event C)	Hawaii	[29]
220 ± 10	$^{40}Ar/^{39}Ar$	Mamaku ignimbrite	New Zealand	[30]

Bio-Si: biogenic-silica; HIRM: concentration of high coercivity magnetic mineral.

from the recalibrated [5] cores in the Caribbean and the Mediterranean [32] and those from Lake Baikal [1,6].

According to the discussion above, our records might be the same as the younger excursions of Core 287-K2 [1] and Core St.4 [6] from Academician Ridge, the younger excursion of BDP93-1 from the Buguldeika saddle [2], and the Iceland Basin event from the North Atlantic [3]. Other records listed in the upper part of Table 2 are thought to represent the same excursion. We conclude that our excursion is correlative with the Iceland Basin event, which is reliably dated and has detailed paleomagnetic records from three holes. On the other hand, the older excursions of Core 287-K2 [1] and Core St.4 [6], and the excursion of Core St.16 [6] in Lake Baikal are older, and are correlative with the Jamaica/Pringle Falls excursion. Therefore, the intensity minimum at 188 ka labeled as Jamaica/Pringle Falls in Sint-800 [4] most likely represents the Iceland Basin event.

4.5. Detailed character of the reversal excursion

The detailed character of the reversal excursion is shown in terms of VGP latitude, relative paleointensity, SIRM and χ_{ARM}/SIRM (Fig. 12). Relative intensity is less than 20–25% of the values before and after the excursion from 186 ka to 175 ka (662–710 cm), whereas VGP latitude is lower than 45°N between 183 ka and 177 ka. The ratio χ_{ARM}/SIRM shows that the grain size of the magnetic mineral does not change significantly. The SIRM shows that the concentration of magnetic mineral does not change, except for the large peak around 170 ka, which was not used for paleointensity estimates, implying that the relative paleointensity low of the reversal excursion is a real feature of the geomagnetic field. It is obvious that there are two states, one with low intensity during the reversal excursion and one with higher intensity before and after the transition.

The VGP path during the reversal excursion (Fig. 13) consists of a southward swing through the North Atlantic followed by a loop through Africa and the Indian Ocean. The VGP path of the Iceland Basin event [3] shows a similar feature; that is a southward swing and a path through Africa followed by a loop through the Indian Ocean and Australia over the northwest Pacific.

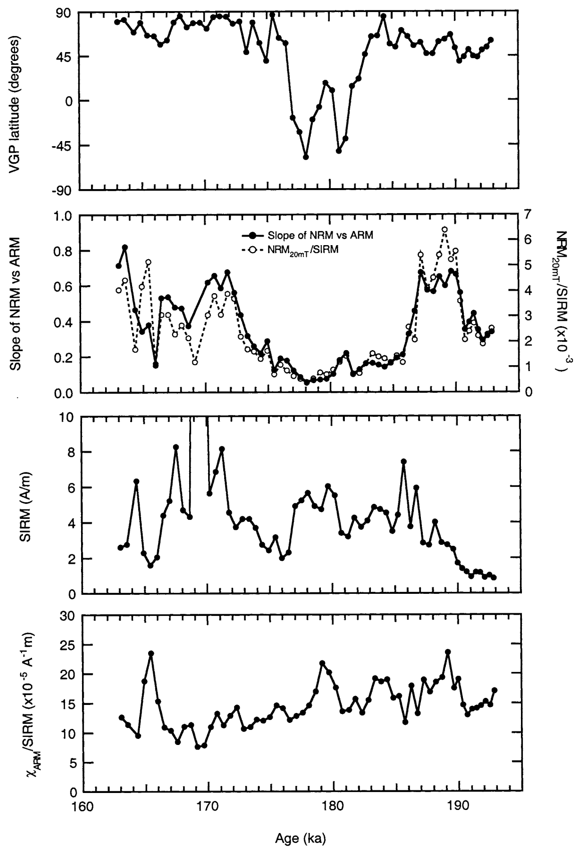

Fig. 12. Paleomagnetic record of the reversal excursion at the base of OIS 6. VGP latitude, relative paleointensity, SIRM and χ_{ARM}/SIRM are plotted versus age.

5. Conclusions

A good quality paleomagnetic record was obtained for piston core Ver98-1, St.6 from Academician Ridge, Lake Baikal. The relative paleointensity was estimated and was successfully correlated with the relative paleointensity record from ODP Site 983 [3] and Sint-800 [4]. There are two prominent minima at 662–710 cm (175–186 ka) and at 412 cm (122 ka).

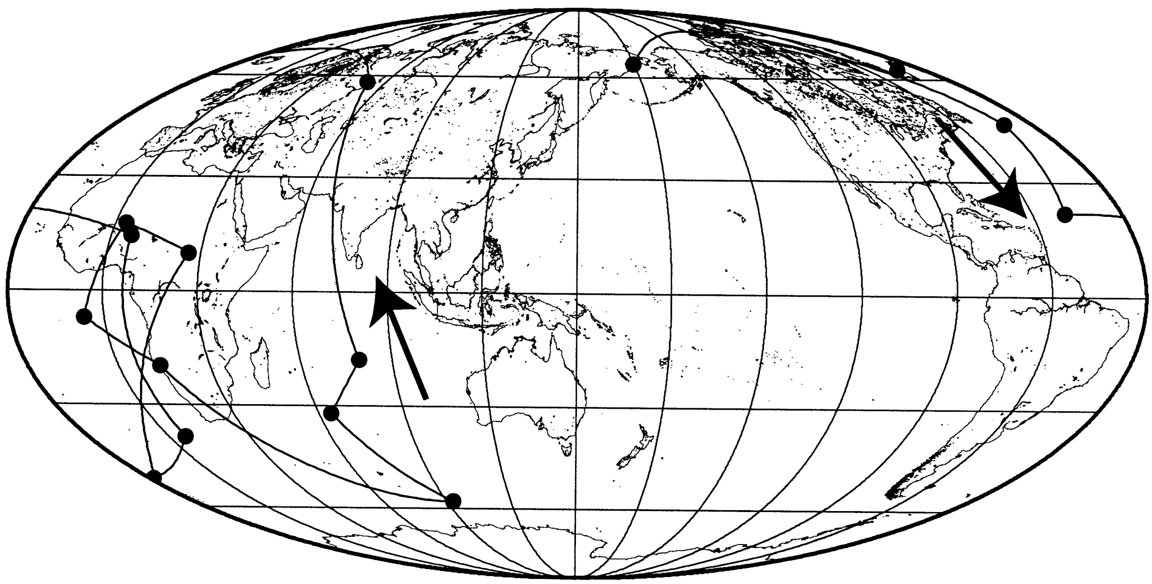

Fig. 13. VGP path for the reversal excursion at the base of OIS 6. A southward swing through the Atlantic is followed by a loop through Africa and back again through the Indian Ocean.

A reversal excursion was found at the base of OIS 6 (177–183 ka), in the interval of very low relative intensity. We correlated the Lake Baikal excursion to the well documented Iceland Basin event (186–189 ka) reported from ODP Sites 983 and 984 [3]. Reinvestigation of an excursion for the BDP93-1 core from the Buguldeika saddle in Lake Baikal has revised the age to be 177–186 ka; it thus represent the same excursion.

The recalibration of the record of an older excursion from core St.4 from Academician Ridge [6], originally assumed to be the Blake event, has yielded an age around 223 ka. The older excursion is therefore correlative with the Jamaica/Pringle Falls excursion (205–215 ka) [5]. The presence of two excursions is also consistent with the two excursions reported from Core 287-K2 from Academician Ridge in Lake Baikal with ages of 180 ka and 215 ka [1]. We conclude therefore that there are two distinct and now well documented excursions in this time interval.

The VGP path of the excursion from core Ver98-1, St.6 consists of a southward swing, followed by a loop through Africa and the Indian Ocean. The path morphology of the first southward swing is similar to that of the Iceland Basin event from the North Atlantic [3].

Acknowledgements

The authors are grateful to T. Kawai, M. Kuzumin and M. Grachev for promoting the Baikal Drilling Project. The authors thank T. Yamazaki and C. Langereis for improvements of the manuscript, and J. Channell and J. Peck for their critical reviews. H.O. appreciates the help on measurements by E. Usuda. Y. Guyodo and J. Peck kindly supplied their data. The hydraulic piston core was taken with a German piston corer on S/V *Vereschagin* of the Limnological Institute, Russia. This study was funded by the Lake Baikal Drilling Project of the Science and Technology Agency of Japan. H.O. is partly supported by the Japan Society for the Promotion of Science.***[RV]***

References

[1] J.W. King, J. Peck, P. Gangemi, V.A. Kravchinsky, Pa-

leomagnetic and rock-magnetic studies of Lake Baikal sediments, Russ. Geol. Geophys. 34 (1993) 148–162.

[2] BDP-93 Baikal Drilling Project Members, Preliminary results of the first scientific drilling on Lake Baikal, Buguldeika site, southeastern Siberia, Quat. Int. 37 (1997) 3–17.

[3] J.E.T. Channell, Geomagnetic paleointensity and directional secular variation at Ocean Drilling Program (ODP) Site 984 (Bjorn Drift) since 500 ka: Comparisons with ODP Site 983 (Gardar Drift), J. Geophys. Res. 104 (1999) 22937–22951.

[4] Y. Guyodo, J.P. Valet, Global changes in intensity of the Earth's magnetic field during the past 800 kyr, Nature 399 (1999) 249–252.

[5] C.G. Langereis, M.J. Dekkers, G.D. deLange, M. Paterne, P.J.M. vanSantvoort, Magnetostratigraphy and astronomical calibration of the last 1.1 Myr from an eastern Mediterranean piston core and dating of short events in the Brunhes, Geophys. J. Int. 129 (1997) 75–94.

[6] H. Sakai, T. Nakamura, M. Horii, K. Kashiwaya, S. Fujii, T. Takamatsu, T. Kawai, Paleomagnetic study with ^{14}C dating analysis on three short cores from Lake Baikal, Bull. Nagoya Univ. Furukawa Mus. 13 (1997) 11–22.

[7] T.C. Moore Jr., J.D. Klitgord, A.J. Golmshtok, E. Weber, Sedimentation and subsidence patterns in the central and north basins of Lake Baikal from seismic stratigraphy, GSA Bull. 109 (1997) 746–766.

[8] D.F. Williams, M.I. Kuzumin, A.A. Prokopenko, E.B. Karabanov, G.K. Khursevich, E.V. Bezrukova, The Lake Baikal drilling project in the context of a global lake drilling initiative, Quat. Int. 80–81 (2001) 3–18.

[9] J.A. Peck, J.W. King, S.M. Colman, V.A. Kravchinsky, A rock-magnetic record from Lake Baikal, Siberia: Evidence for late Quaternary climatic change, Earth Planet. Sci. Lett. 122 (1994) 221–238.

[10] J.A. Peck, J.W. King, S.M. Colman, V.A. Kravchinsky, An 84-kyr paleomagnetic record from the sediments of Lake Baikal, Siberia, J. Geophys. Res. 101 (1996) 11365–11386.

[11] N.R. Nowaczyk, M. Antonow, High-resolution magnetostratigraphy of four sediment cores from the Greenland Sea-I. Identification of the Mono Lake excursion, Laschamp and Biwa I/Jamaica geomagnetic polarity events, Geophys. J. Int. 131 (1997) 310–324.

[12] R.J. Weeks, C. Laj, L. Endignoux, A. Mazaud, L. Labeyrie, A.P. Roberts, C. Kissel, E. Blanchard, Normalised natural remanent magnetisation intensity during the last 240 000 years in piston cores from the central North Atlantic Ocean: geomagnetic field intensity or environmental signal?, Phys. Earth Planet. Inter. 87 (1995) 213–229.

[13] B. Lehman, C. Laj, C. Kissel, A. Mazaud, M. Paterne, L. Labeyrie, Relative changes of the geomagnetic field intensity during the last 280 kyear from piston cores in the Açores area, Phys. Earth Planet. Inter. 93 (1996) 269–284.

[14] A.P. Roberts, B. Lehman, R.J. Weeks, K.L. Verosub, C. Laj, Relative paleointensity of the geomagnetic field over the last 200,000 years from ODP Sites 883 and 884, North Pacific Ocean, Earth Planet. Sci. Lett. 152 (1997) 11–23.

[15] T. Yamazaki, N. Ioka, Long-term secular variation of the geomagnetic field during the last 200 kyr recorded in sediment cores from the western equatorial Pacific, Earth Planet. Sci. Lett. 128 (1994) 527–544.

[16] M.A. Grachev, S.S. Vorobyova, Y.V. Likhoshway, E.L. Goldberg, G.A. Ziborova, O.V. Levina, O.M. Khlystov, A high-resolution diatom record of the paleoclimates of East Siberia for the last 2.5 My from Lake Baikal, Quat. Sci. Rev. 17 (1998) 1101–1106.

[17] T. Nakano, Y. Nakajima, K. Nakamura, S. Ikeda, Observation and analysis of internal structure of rock using X-ray CT (in Japanese with English abstract), J. Geol. Soc. Japan 106 (2000) 363–378.

[18] V. Jelinek, Characterization of the magnetic fabric of rocks, Tectonophysics 79 (1981) 63–67.

[19] J. Bloemendal, J.W. King, F.R. Hall, S.-J. Doh, Rock magnetism of Late Neogene and Pleistocene deep-sea sediments: relationship to sediment source, diagenetic processes and sediment lithology, J. Geophys. Res. 97 (1992) 43612–43775.

[20] J.L. Kirschvink, The least-squares line and plane and the analysis of palaeomagnetic data, Geophys. J. R. Astron. Soc. 62 (1980) 699–718.

[21] B.A. Maher, Magnetic properties of some synthetic submicron magnetites, Geophys. J. 94 (1988) 83–96.

[22] D.F. Williams, J. Peck, E.B. Karabanov, A.A. Prokopenko, V. Kravchinsky, J. King, I. Kuzmin, Lake Baikal record of continental climate response to orbital insolation during the past 5 million years, Science 278 (1997) 1114–1117.

[23] N.J. Shackleton, A. Berger, W.R. Peltier, An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677, R. Soc. Edinburgh Trans. Earth Sci. 81 (1990) 251–261.

[24] D.G. Martinson, N.G. Pisian, J.D. Hays, J. Imbrie, T.C. Moore Jr., N.J. Shackleton, Age dating and the orbital theory of the ice ages development of a high-resolution 0 to 300,000-year chronostratigraphy, Quat. Res. 27 (1987) 1–29.

[25] L. Tauxe, T. Pick, Y.S. Kok, Relative paleointensity in sediments: A psuedo-Thellier approach, Geophys. Res. Lett. 22 (1995) 2885–2888.

[26] L. Tauxe, Sedimentary records of relative paleointensity of the geomagnetic field: theory and practice, Rev. Geophys. 31 (1993) 319–354.

[27] E.B. Karabanov, A.A. Prokopenko, D.F. Williams, S.M. Colman, Evidence from Lake Baikal for Siberian glaciation during oxygen-isotope substage 5d, Quat. Res. 50 (1998) 46–55.

[28] S.M. Colman, G.A. Jones, M. Rubin, J.W. King, J.A. Peck, W.H. Orem, AMS radiocabon analyses from Lake Baikal, Siberia: challenges of dating sediments from a large oligotrophic lake, Quat. Sci. Rev. 15 (1996) 669–684.

[29] J.W. Holt, J.L. Kirschvink, F. Garnier, Geomagnetic field inclinations for the past 400 kyr from the 1 km core of the Hawaii Scientific Drilling Project, J. Geophys. Res. 101 (1996) 11655–11663.

[30] H. Tanaka, G.M. Turner, B.F. Houghton, T. Tachibana, M. Kono, M.O. McWilliams, Palaeomagnetism and chronology of the central Taupo Volcanic Zone, New Zealand, Geophys. J. Int. 124 (1996) 919–934.

[31] E. Herrero-Bervera, C.E. Helsley, A.M. Sarna-Wojcicki, K.R. Lojoie, C.E. Meyer, M.O. McWilliams, R.M. Negrini, B.D. Turrin, J.M. Donnellly-Nolan, J.C. Liddicoat, Age and correlation of a paleomagnetic episode in the western United States by $^{40}Ar/^{39}Ar$ dating and tephrochronology: the Jamaica, Blake, or a new polarity episode?, J. Geophys. Res. 99 (1994) 24091–24103.

[32] W.B.F. Ryan, Stratigraphy of late Quaternary sediments in the Eastern Mediterranean, in: D.J. Stanley (Ed.), The Mediterranean Sea: A Natural Sedimentation Laboratory, Dowden, Hutchinson and Ross, Stroudsberg, PA, 1972, pp. 149–169.