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Invited review article

Magnetostratigraphy of the Lake Baikal sediments: A unique record of 8.4 Ma of continuous sedimentation in the continental environment

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ABSTRACT

Lake Baikal sedimentary records in general and magnetostratigraphy in particular have already enormously contributed in the global context to evaluate environmental and climatic changes in the deep continental setting. The Baikal Drilling Project (BDP) has become a world leader in pioneering recovery of extremely long (several hundred meters) lacustrine sediment sequences from deep water. This has made it possible, for the first time, to obtain a continental archive with the same chronostratigraphic integrity as marine records to address critical questions of the last eight million years. It explains why the amount of publications on Lake Baikal sedimentary and magnetic records can be compared to the number of papers for the Oceanic Drilling Program.

The unique continuity of the Lake Baikal deep drilled cores — short piston cores and deep drilled cores — of 1993, 1996, and 1998 enables one to reconstruct reliably the geomagnetic polarity chrons and a number of the shorter geomagnetic events. Data from three very long cores allows a comparison to the geomagnetic polarity time scale (GPTS) and detailed records of geomagnetic events in the last 8.4 Ma. A refined age model, supported by ^{10}Be dates, provides constraints for the short geomagnetic events. Some geomagnetic events are correlated with geomagnetic excursions already discussed in the literature; others are identified for the first time and may need future confirmation.

1. Introduction

Lake Baikal is the largest lake in the world in terms of water volume. It contains 20% of the fresh surface water on Earth (23,615 km^3) with water depths up to 1642 m in the deepest part and a sedimentary infill up to 9 km. The lake occupies the central part of the largest tectonically active rift system in Eurasia, the Baikal rift (Ten Brink and Taylor, 2002). The Baikal rift system consists of a series of fault-bounded basins stretched along a ~1800 km S-W–N-E belt that frames the south-eastern margin of the Siberian craton (Logachev, 2003). The structure of the zone results from several stages of compression and extension that have affected the region from Early Paleozoic to Mesozoic times (Delvaux et al., 1995). After the final closure of the Mongol-Okhotsk Ocean in the Late Jurassic to Early Cretaceous (Kravchinsky et al., 2002), a period of relative tectonic dormancy existed from Cretaceous to Paleogene Periods (Kuzmin et al., 2010). After the Late Oligocene, the Baikal rift system reactivated forming a number of individual rift basins along the rift zone, including the south, central, and north Lake Baikal basins (Fig. 1). Smaller rift basins outside of the lake have developed north and south of Lake Baikal, mainly in E–W oriented deformation sectors defined by strike-slip faulting (Mats et al., 2000).

On the basis of the onshore geology analysis around the lake – including deep boreholes – and of multichannel reflection seismic profiles on the lake, it is generally assumed that Cenozoic rifting started by slow subsidence of the south and central Baikal basins sometime in the Late Oligocene (~30 Ma), and of the north Baikal basin in the Late Miocene (~8 Ma) (Logatchev and Florensov, 1978; Mats et al., 2000). For > 20 Ma, a series or lacustrine and fluvial sediments up to 4–5 km thick accumulated in slowly subsiding basins surrounded by subdued highlands. This period is referred to as the early rifting stage (Mats et al., 2000). From the Late Pliocene (~3.5 Ma) onward, a strong acceleration in basin subsidence and flank uplift took place. This late rifting stage resulted in an additional sedimentary infill of > 4 km, a Lake Baikal water depth of > 1 km, and flank uplifts of 1–2 km. Ongoing present day rift deformation is testified by numerous seismic events annually (Déverchère et al., 2001) and by a GPS-derived mean rate of extension of about 4 mm/yr (Calais et al., 2003).

Academician Ridge is a high ridge that separates two of Lake Baikal's three basins, the Central and North basins (Baikal Drilling Project group, 2000) (Fig. 1). The ridge is a submerged asymmetrical horst bounded by the Ushkan fault in the northwest and by the Olkhon fault in the southeast; the ridge rises for 500 m above the lake bottom in the northwest and is over 1000 m above the lake bottom in the southeast. The water depth over the ridge varies from 300 to 350 m.

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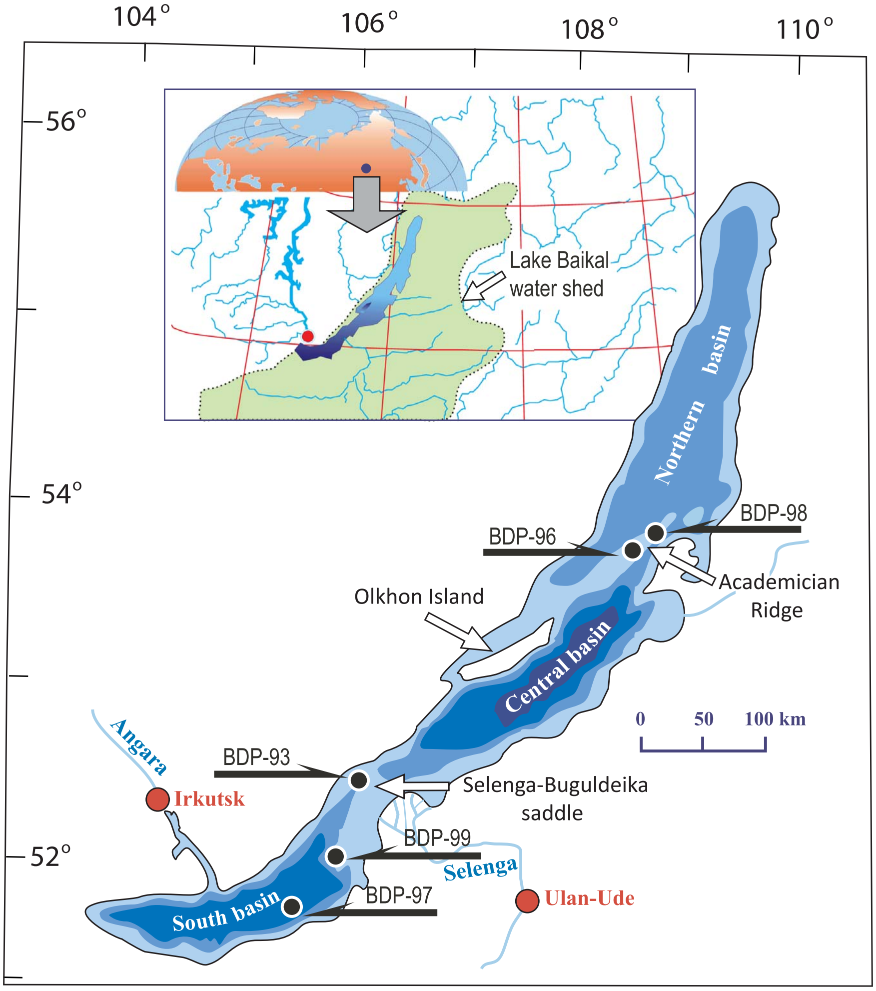

Fig. 1. Geographic position and bathimetric map of lake Baikal. Isobath interval is 500 m, and core sites are numbered. The location of the drilled sites in Lake Baikal is shown. (Modified from Kravchinsky et al. (2003).)

Table 1
Baikal Drilling Project borehole locations.

Borehole	Geographical location	Latitude, N	Longitude, E	Water depth (m)	Borehole depth/core length (m)
BDP-93	Buguldeyka isthmus	52°31′05″	106°09′11″	354	102/100
BDP-96-1	Academician Ridge	53°41′48″	108°21′06″	331/333	302/200
BDP-96-2	Academician Ridge	53°41′48″	108°21′06″	331/333	100/100
BDP-97	South basin	51°47′50″	105°29′13	1436	225/225
BDP-98	Academician Ridge	53°44′48″	108°24′34″	337	674/600
BDP-99	Posolsk Bank	52°05′23″	105°50′24″	201	350/350

Academician Ridge represents a unique sedimentary setting. The north and central basins of Lake Baikal, with depths of 900 m and 1600 m, respectively, isolate the ridge from coarse sediment input and turbidites. The Academician Ridge location is restricted to fine, continuous hemipelagic sedimentation with some coarse-grained particles deposited by ice rafting (Kuzmin et al., 2000); wind-blown sediments were also suggested to play some role in the deposition (Peck et al., 1994). Multichannel seismic profiling reveals two major seismic units in the section (Hutchinson et al., 1992; Mats et al., 2000; Colman et al., 2003). The upper unit is finely laminated and was deposited in relatively steady lacustrine conditions, whereas the lower unit contains wedge-like features indicating deposition in the river delta (Baikal Drilling Project group, 2000). Only the upper unit, which includes seismic boundaries B6–B10, was drilled and is discussed in this study.

The prolonged formation of the Lake Baikal sedimentary infill makes it possible to build a protracted magnetostratigraphic scale for the deposit of lake sediments. Although the drainage basin was glaciated during its geological past, the lake itself was never covered by permanent ice, so sedimentary input provides continues record of geomagnetic events (Peck et al., 1996; Kravchinsky et al., 2003; Prokopenko et al., 2006). Paleomagnetic investigations of Lake Baikal sediments were initiated and published in the 1970s and 1980s (Kravchinsky and Mats, 1982). This pioneering study demonstrates the feasibility of the paleomagnetic method to evaluate the age of shore sediments and deep bottom short piston cores, although little attention has been paid to the lake shore outcrops by the research community. The main purpose of the Kravchinsky and Mats (1982) study was to build a proper age model for the Pliocene and Pleistocene outcrops and to correlate them in order to shed light on the large and still undeveloped potential of the coastal geological sections for future magnetostratigraphic and geological studies. Presently, all of the magnetostratigraphy correlations on the shore need to be reevaluated. Step-wise detailed demagnetizations were not a standard procedure in the 1970s, therefore, the primary character of the magnetization is still in question.

Since the beginning of 1990s, large scale coring has been undertaken as a result of cooperation between Russian, American, Japanese,

Table 2
Dating overview of the Baikal short and deep drilling cores.

Baikal cores	Dating methods	Age range	Key references
Short piston cores, The Academician Ridge and Central Basin	AMS radiocarbon together with paleomagnetic data	Down to ~35 kyr	Peck et al. (1994) Colman et al. (1996)
The Vydrino Shoulder and Continent Ridge	AMS radiocarbon	Down to ~35 kyr	Piotrowska et al. (2004)
The Vydrino Shoulder, Posolsky Bank at distal part of the Selenga Delta, Academician and Continental Ridges	AMS radiocarbon together with paleomagnetic data; correlation of magnetic parameters to the isotope stages	Down to 200 kyr	Demory et al. (2005)
Academician Ridge	Correlation of X-ray CT values to the isotope stages together with paleomagnetic data	Down to ~230 kyr	Oda (2005)
BDP-93	U-Th	185 ± 9 kyr	Sandimirov and Pampura (1995)
	AMS radiocarbon; paleomagnetic dating	Down to ~25 kyr	BDP-93 Baikal Drilling Project Members (1997)
	Paleomagnetic dating; correlation of magnetic susceptibility and biogenic silica to the isotope stages	Down to 670 kyr	Kravchinsky et al. (2007)
BDP-96-1/2	Paleomagnetic dating; correlation of magnetic susceptibility and biogenic silica to the isotope stages	Down to 5 Myr	Antipin et al. (1997); Williams et al. (1997a); Antipin et al. (1998); Kuzmin et al. (2000); Kravchinsky et al. (2003)
BDP-96-1/2; BDP-98	Correlation of biogenic silica to the insolation, obliquity, precession and isotope stage aided by paleomagnetic dating	Down to 1.8 Myr	Prokopenko et al. (2006)
BDP-98	Paleomagnetic dating; correlation of magnetic susceptibility and biogenic silica to the isotope stages	Down to the bottom of the core (various age estimates)	Williams et al. (1997a); Baikal Drilling Project group (2000); Kashiwaya et al. (2002); BDP Members (2001); Krainov et al. (2001); Kashiwaya et al., 2002; Prokopenko et al. (2002); Kravchinsky et al. (2003); Sakai et al. (2003)
	^{10}Be	Down to 8.4 Ma	Horiuchi et al. (2003); Sapota et al. (2004)
	^{10}Be and paleomagnetic dating	Down to 8.4 Ma	Horiuchi et al. (2004)

and German scientific teams. Such unprecedented not-for-profit co-operation has led to numerous publications of paleomagnetic results from the Lake Baikal sediments. In 1993, 1996, 1997, 1998, and 1999 the international cooperation resulted in the Lake Baikal Drilling Project (BDP) which drilled seven boreholes: BDP-93-1 and BDP-93-2 at the Buguldeika isthmus, BDP-96-1, BDP-96-2, and BDP-98 at Academician Ridge, BDP-97 in the southern basin of Lake Baikal, and BDP-99 in the Selenga River isthmus (Fig. 1, Table 1).

At Academician Ridge, cores BDP-96-1 and BDP-96-2 (53°41′48″, 108°21′06″) and BDP-98 (53°44′48″, 108°24′34″) in water depths of 331 m and 333 m, respectively (Fig. 1, Table 1), were the most successful missions in terms of magnetostratigraphic profile recovery. Cores BDP-96-1 and BDP-96-2 were taken ~5 m apart from the same drilling platform. Core BDP-98 was drilled ~7 km away from the BDP-96 site. Sediments were obtained by piston coring from the level of the lake floor to 270 m in the deepest BDP-98 borehole. For more consolidated sediments between 270 m down to 601 m, rotary drilling was used. The BDP-98 borehole was then drilled down to 670 m without coring below 601 m. Average recovery of the cores was 95–98%. The 1998 drilling aimed to extend the Lake Baikal sampling

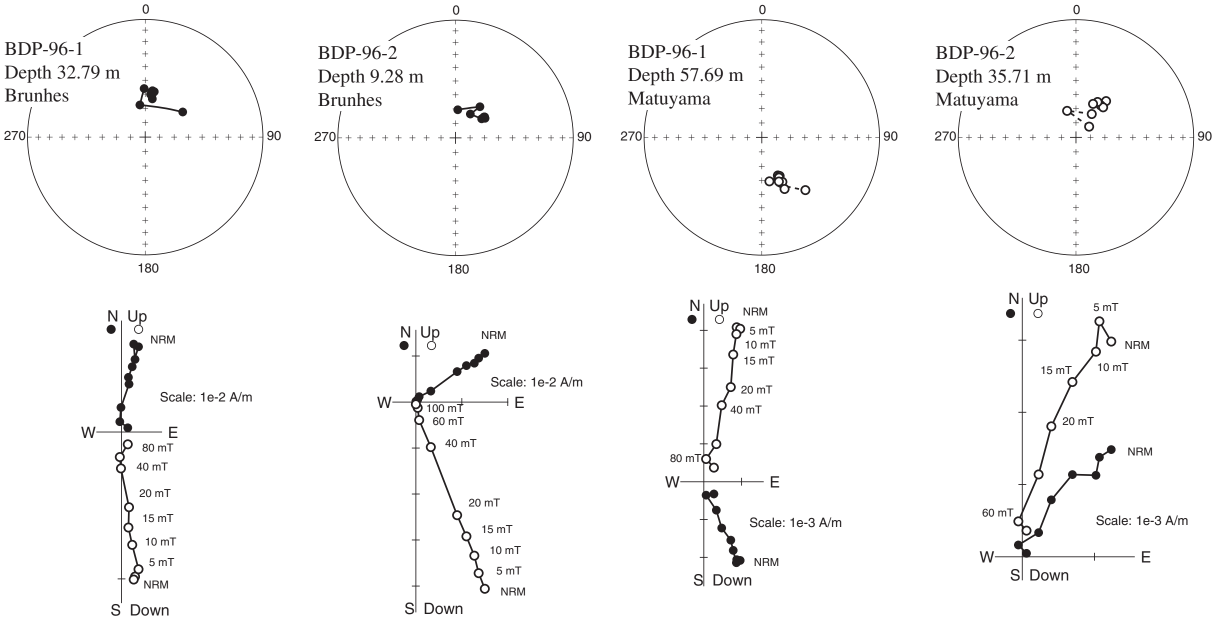

Fig. 2. Examples of demagnetization behaviour of pilot samples from BDP-96-1 and BDP-96-2 for Brunhes and Matuyama chrons. Closed (open) symbols in equal-area projections represent downward (upward) inclinations; closed (open) symbols in orthogonal plots represent projections onto the horizontal (vertical) plane. The core was not oriented azimuthally, so zero declination is arbitrary. Plotted with the PaleoMac software (Cogné, 2003).

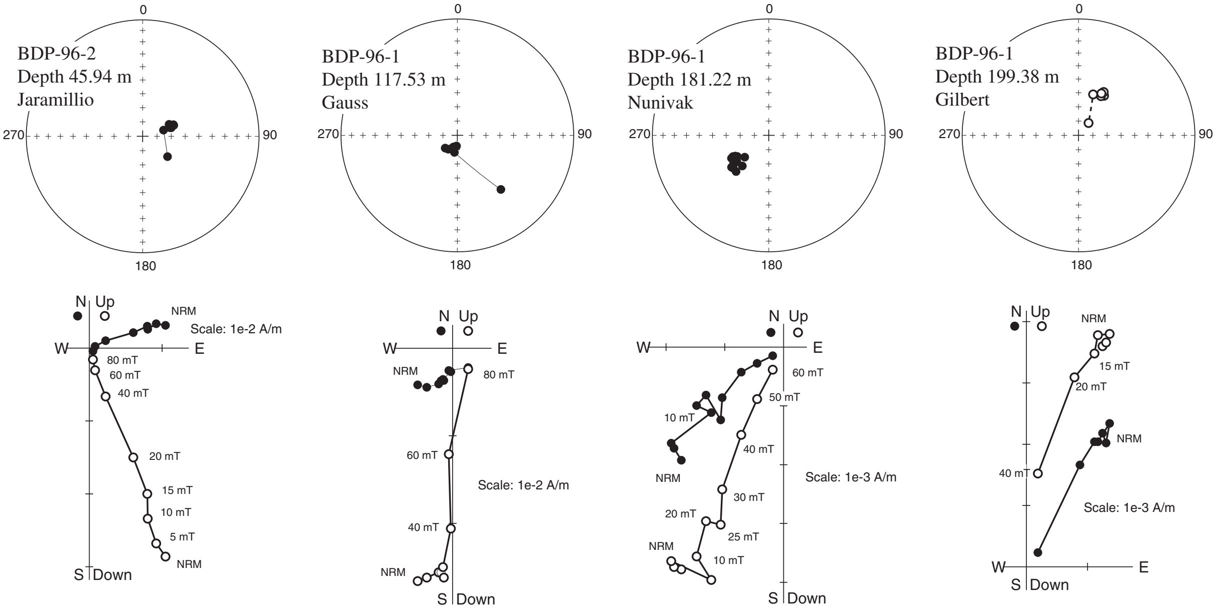

Fig. 3. Examples of demagnetization behaviour of pilot samples from BDP-96-1 and BDP-96-2 for Jaramillo, Gauss, Nunivak and Gilbert chrons. Closed (open) symbols in equal-area projections represent downward (upward) inclinations; closed (open) symbols in orthogonal plots represent projections onto the horizontal (vertical) plane. The core was not oriented azimuthally, so zero declination is arbitrary. Plotted with the PaleoMac software (Cogné, 2003).

deeper into the Miocene sediments than sampling in the BDP-96 drilling. The drilling site was chosen to be remote from coarse deltaic deposits identified in the seismic cross-section of the southeastern part of Academician Ridge (Hutchinson et al., 1992). Cores BDP-96-1, BDP-96-2, and BDP-98 provided an excellent regional paleoclimate archive based on biogenic silica and diatom records reaching back 5 million years (Antipin et al., 1998; Williams et al., 1997a, Williams et al., 1997b; Antipin et al., 1998; Kravchinsky et al., 1998; Kuzmin et al., 2000; Prokopenko et al., 2006). Age models below 5 Ma varied until reliable ^{10}Be ages were obtained in 2003 (Table 2), therefore, paleoclimate interpretations published earlier should be treated with caution (see section 2).

2. Magnetostratigraphy in the last 8.4 Ma

The unique continuity of the Lake Baikal deep drilled cores of 1996 and 1998 and a constant sedimentation rate, first demonstrated in Williams et al. (1997a) and in Baikal Drilling Project group (2000), makes it possible to reconstruct the geomagnetic polarity chrons and shorter events with exceptional resolution. Although there are a number of publications that cite drilled core ages, some of the age models became out-of-date after new ^{10}Be ages were obtained in 2003 and 2004 (Horiuchi et al., 2003, 2004; Sapota et al., 2004). The latest and now commonly accepted age model is used in our further analysis.

Kashiwaya et al. (2001) published an age model based on magnetostratigraphy only, i.e., visual correlation of the magnetostratigraphic

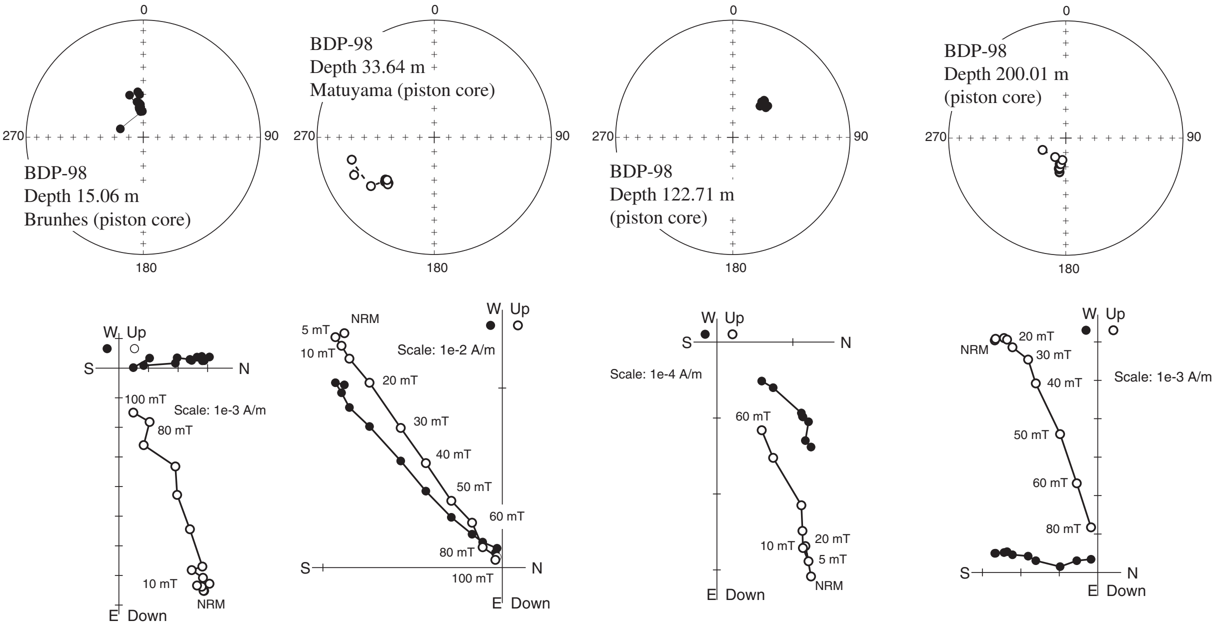

Fig. 4. Examples of demagnetization behaviour of pilot samples from piston cores of the drilled core BDP-98. Closed (open) symbols in equal-area projections represent downward (upward) inclinations; closed (open) symbols in orthogonal plots represent projections onto the horizontal (vertical) plane. The core was not oriented azimuthally, so zero declination is arbitrary. Plotted with the PaleoMac software (Cogné, 2003).

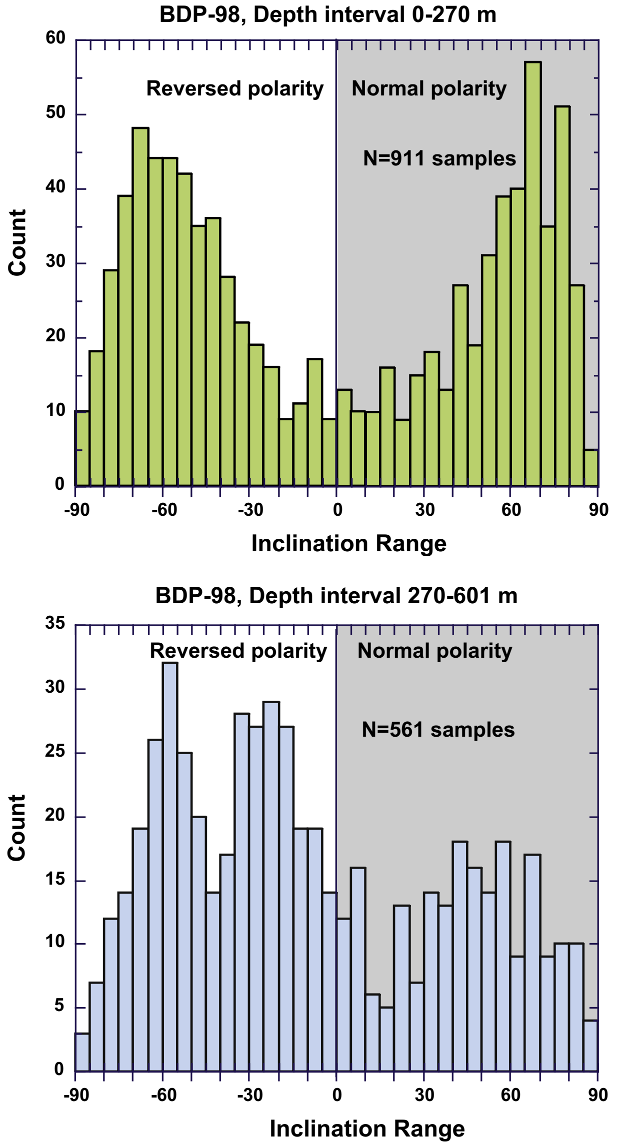

Fig. 5. Histograms of inclination values after 10 mT AF treatment for depth interval 0–270 m (top) and for 270–601 m (bottom).
(Modified from Kravchinsky et al. (2003).)

profile with the geomagnetic polarity time scale (GPTS) of Cande and Kent (1995). This age model assigns the age of 12 Ma to the 601 m deep core BDP-98. Kravchinsky et al. (2003) established an age model for the upper 270 m of BDP-98 considering a constant rate of sedimentation and suggested a temporary age model for the interval between 270 and 601 m. Other available age assignments of the Miocene section in the BDP-98 core demonstrated large discrepancies (Baikal Drilling Project group, 2000; BDP Members, 2001; Krainov et al., 2001; Kashiwaya et al. (2002); Prokopenko et al., 2002; Sakai et al., 2003; Horiuchi et al., 2003, 2004). In particular, the timing of the 600 m BDP-98 core base was assigned to 12 Ma (Kashiwaya et al., 2001, 2002; Sakai et al., 2003), 9.3 Ma (BDP Members, 2001; Prokopenko et al., 2002), 8.4 Ma (Horiuchi et al., 2003, 2004), and 8 Ma (Sapota et al., 2004). An age model based on ^{10}Be data removes discrepancies and provides the most integrated and accurate outcome (Horiuchi et al., 2003, 2004; Sapota et al., 2004).

2.1. *Paleomagnetic directions for the deep drilled piston cores*

Kravchinsky et al. (2003) described the results of a step-wise alternating field (AF) demagnetization of single samples of the BDP-98 cores, but such diagrams for the BDP-96 core have not been published. Samples from the three cores were taken in small plastic boxes (5 cm^3 or 8 cm^3) at $\sim$10 cm intervals throughout the cores. Single sample results were obtained after measurements in the Irkutsk Paleomagnetic Laboratory (Ministry of Natural Resources of Russia, Siberia) and in laboratories at the University of Alberta (Canada), the University of Rhode Island (USA), and the University of Toyama (Japan). In total, 1472 samples from the BDP-98 core, 565 samples from the BDP-96-1 core, and 394 samples from the BDP-96-2 core were measured. In this section we discuss magnetization directions in the piston cores: BDP-96-1 (100 m), BDP-96-2 (200 m), and the top 270 m of BDP-98. Rotary core data (BDP-98, 270–600 m) are discussed in section 2.1.1.

Pilot samples of BDP-96 cores 1 and 2 and the BDP-98 core that presented all lithological types were taken from different depths (25% of the sample collection) for detailed alternating field (AF) demagnetization measurements (8–10 AF steps between 2.5 mT and 80–100 mT). For single samples the principal component analysis was used (Kirschvink, 1980) to evaluate the magnetization directions. The results for the piston cores show that the sediments preserved a stable primary magnetic remanence with a relatively high intensity of magnetization (median = 2.2 mA/m), and a very small secondary viscous component which was easily removed by the 10 mT alternating field in all three cores (Figs. 2–4). The stable components had normal or reverse inclination allowing identification of the geomagnetic chrons. The remaining samples were demagnetized at 3–5 principal blanket fields and remeasured after each step (Kravchinsky et al., 2003).

In addition to single sample measurements, quarters of the BDP-96-1 and BDP-96-2 drilled cores were measured using a pass-through cryogenic magnetometer (2G Enterprise 760R) at Toyama University (Japan). The measurements were taken every 1 cm, with AF demagnetizations of 10, 20, 30, and 40 mT. The published dataset (Sakai et al., 2000) was based on a blanket AF treatment 20 mT for all samples. To assess the choice of a blanket field of 10 or 20 mT in previous publications, we compared the magnetic field inclination after 10 mT with characteristic remanent magnetization (ChRM) plots. The path-through data were reanalyzed using 5 step demagnetizations (natural remanent magnetization (NRM), 10, 20, 30, 40 mT) of samples from drilling hole BDP-96-1. Examples of single sample demagnetization shown in Figs. 2–4 confirmed that 10 mT was sufficient to determine the magnetic direction of the well-preserved characteristic component (ChRM). Very few samples ($<$ 4% of the total number of samples) had a maximum angular deviation (MAD) larger than 10°. Such samples usually had lower magnetic intensity values and corresponded to intervals of polarity transition when the magnetic intensity was lower than during the stable polarity intervals. It is therefore appropriate to use a blanket field of 10 mT to represent the inclination profile.

Kravchinsky et al. (2003) demonstrated that the 911 oriented samples from the upper piston core section (upper 270 m) of the deepest drilled hole (BDP-98) showed a clear bimodal distribution of magnetic inclination, with peaks near $+70^\circ$ and -70° (Fig. 5). A significant number of intermediate values presented transitional field vectors, excursions or secular variations.

2.1.1. *Geomagnetic polarity stratigraphy of deep drilled piston cores*

The magnetostratigraphy of drilled cores BDP-96-1 and BDP-96-2 was presented in Kravchinsky et al. (2003), where the results for the samples measured independently by three international teams (Russia, USA, Japan) were summarized. In the present review the magnetostratigraphic age model of the upper 270 m and the lower part (270–600 m) of the BDP-98 core is reevaluated after ^{10}Be dating and magnetostratigraphic measurements in Horiuchi et al. (2003, 2004) and Sapota et al. (2004) and the most recent reference geomagnetic polarity time scale (GPTS) of Ogg (2012). The age and depth of the geomagnetic chrons and events in the three drilled cores — BDP-96-1, BDP-96-2, and

Table 3
Geomagnetic chrons and events identified at in the deep drilling cores on Academician Ridge using the GPTS (Ogg, 2012).

Geomagnetic chron/event	Age (Ma)	BDP-98 Depth (m)	BDP-96-1 Depth (m)	BDP-96-2 Depth (m)
Piston cores (0–270 m)				
Brunhes/Matuyama	0.781	31.50	33.80	34.20
Kamikatsura	∼0.870/0.885	∼34/35.05	34.2/38.63	33.7/35.05
Santa Rosa	0.932/0.945	36.40/36.80	39.75/40.30	39.21/39.84
Jaramillo	0.988/1.072	39.55/43.10	43.34/46.50	42.82/46.95
Olduvai	1.778/1.945	60.6/70	71.5/78.3	71.6/78–79.4
Matuyama/Gauss	2.581	95	104.5–104.8	
Kaena	3.032–3.116	107.5/111.5	117.7–120.7	
Mammoth	3.207–3.330	116/122	124.0–127	
Gauss/Gilbert	3.596	140	143	
Cochiti	4.187–4.300	166/168.7	166.3–171	
Nunivak	4.493–4.631	202.12/215.06	180.5–181.7	
Sidufjall	4.799–4.896	229.62/238.13	192–196	
Thvera C3n.4n	4.997/5.235	245.95/267.67		
Bottom of BDP-96-1 core	5.300	270	200	
Rotary cores (270–600 m)				
C3An.1n	6.033/6.254	375.48/392.23		
C3An.2n	6.436/6.733	411.90/456.52		
C3Bn	7.140/7.212	489.65/495.01		
C3Br.1n	7.251/7.285	498.77/499.47		
C3Br.2n	7.454/7.489	511.45/512.91		
C4n.1n	7.528/7.642	517.87/526.28		
C4n.2n	7.695/8.108	530.67/568.30		
C4r.1n	8.254/8.300	582.49/586.53		
Bottom of BDP-98 core	∼8.400	600		

BDP-98 — are summarized in Table 3. Fig. 6 illustrates the correlation between the three cores using the ^{10}Be depth–age relationship in Table 3. The expected magnetic inclination is steep (∼70°), which makes differentiation between normal and reverse polarity intervals straightforward.

^{10}Be dated profiles of BDP-96-1, BDP-96-2, and the upper 270 m of BDP-98 were compared with the reference geomagnetic polarity time scale (GPTS) of Ogg (2012). A zero age for the top of the cores is consistent with radiocarbon data obtained from several short gravity cores (4–10 m) previously collected near the drilling sites (Colman et al., 1996). The Brunhes, Matuyama, Gauss, and Gilbert subchrons are identified further in Table 3. A number of short geomagnetic events (Jaramillo, Cobb Mtn., Gilsa, Olduvai, Reunion, Kaena, Mammoth, Cochiti, Nunivak, Sidufjall, and Thvera) can be identified reliably in the BDP-98 and BDP-96 cores. Thus the estimated age of the 200 m BDP-96-1 core is around 5 Ma as reported earlier (∼5 Ma, Williams et al., 1997a; Sakai et al., 2000; 4.97 Ma, Kravchinsky et al., 2003). The newer ^{10}Be dates require the inclusion of the Thvera geomagnetic event in the magnetostratigraphic model for the upper piston core interval of BDP-98 (Fig. 6) as demonstrated by Horiuchi et al. (2003, 2004). The age of the bottom of the BDP-98 piston core interval (0–270 m) is therefore reevaluated and is 8.4 Ma by interpolation, which is much younger that reported in (Kravchinsky et al., 2003).

2.1.2. *Geomagnetic polarity stratigraphy of BDP-98 rotary cores (270–601 m)*

After 10 mT demagnetization, samples from the lower part of the BDP-98 core (270–601 m) yielded a more complicated outcome. Fig. 7 shows that the normal and reverse polarity intervals in the magnetic inclination data are less clear than in the upper piston core. The polarity intervals are rather broad and weak, and the inclinations are slightly shifted toward shallower values, from −70° for some depth intervals. An adequate number of negative inclination intervals indicate that wholesale normal polarity overprinting is not the problem. Nor can one appeal to insufficient cleaning; > 99% of the inclination values after 20 mT and 40 mT AF treatment differed by < 15° from the inclination value after 10 mT AF treatment (Fig. 7). Pilot sample demagnetizations of the rotary core demonstrate that the drilling overprint exists but can be easily removed by AF demagnetization of 20 mT or higher (Fig. 8). All our rotary core samples came from the central part of the core to avoid deformations from the liner.

Fig. 7 illustrates the inclination pattern in the rotary drilling part of the BDP-98 core and its correlation to the GPTS of Ogg (2012). A magnetostratigraphic age model was built in Horiuchi et al. (2003, 2004) using ^{10}Be dating. The dating provides only a first order depth-age relationship. Horiuchi et al. (2003, 2004) used it as a starting point to compare polarity intervals with the GPTS more accurately. The age model in Table 3 was constructed by identifying the polarity chrons. A linear extrapolation of the chron C4r.1n shows that the age of the bottom of the rotary core is 8.4 Ma.

2.1.3. *The rate of sedimentation at Academician Ridge*

The rate of sedimentation in different magnetic epochs can be calculated based on magnetostratigraphy. The rate of sedimentation in the BDP-96 drilling hole was found to range from 3.7 cm/kyr at depths of 30–50 m to 3.9–4.1 cm/kyr at depths of 50–200 m, with an average sedimentation rate of 3.8 cm/kyr (Sakai et al., 2000). The difference in sedimentation rates might be explained by the lower density in upper sediment horizons compared to that in lower sediment horizons. Fig. 9 illustrates an age model for BDP-98. The upper part of the BDP-98 piston cores has an average sedimentation rate comparable to that of BDP-96 (3.79 cm/kyr) until 200 m depth. Multichannel seismic investigations of the sedimentary sequence of Academician Ridge (Moore et al., 1997 and references therein) have revealed two main seismic-–stratigraphic complexes. The thickness of the upper fine-layered sedimentary complex A in Academician Ridge is < 200 m whereas the lower complex B is over 1000 m thick. These sequence sets are separated by a pervasive acoustic boundary B10, which is associated with an angular erosional unconformity in the northern basin of Lake Baikal (Moore et al., 1997). At the BDP drilling site the sedimentary complex A has a thickness of 100 m, and complex B starts below the seismic reflector B10 (Fig. 9). Although the average sedimentation rate for the upper 200 m of BDP-98 is 3.79 cm/kyr, it could be split for the two segments in a different way, where one segment is above B10 with a sedimentation rate of 3.51 cm/kyr and another segment expands from B10 to B9 with a sedimentation rate of 5.01 cm/kyr.

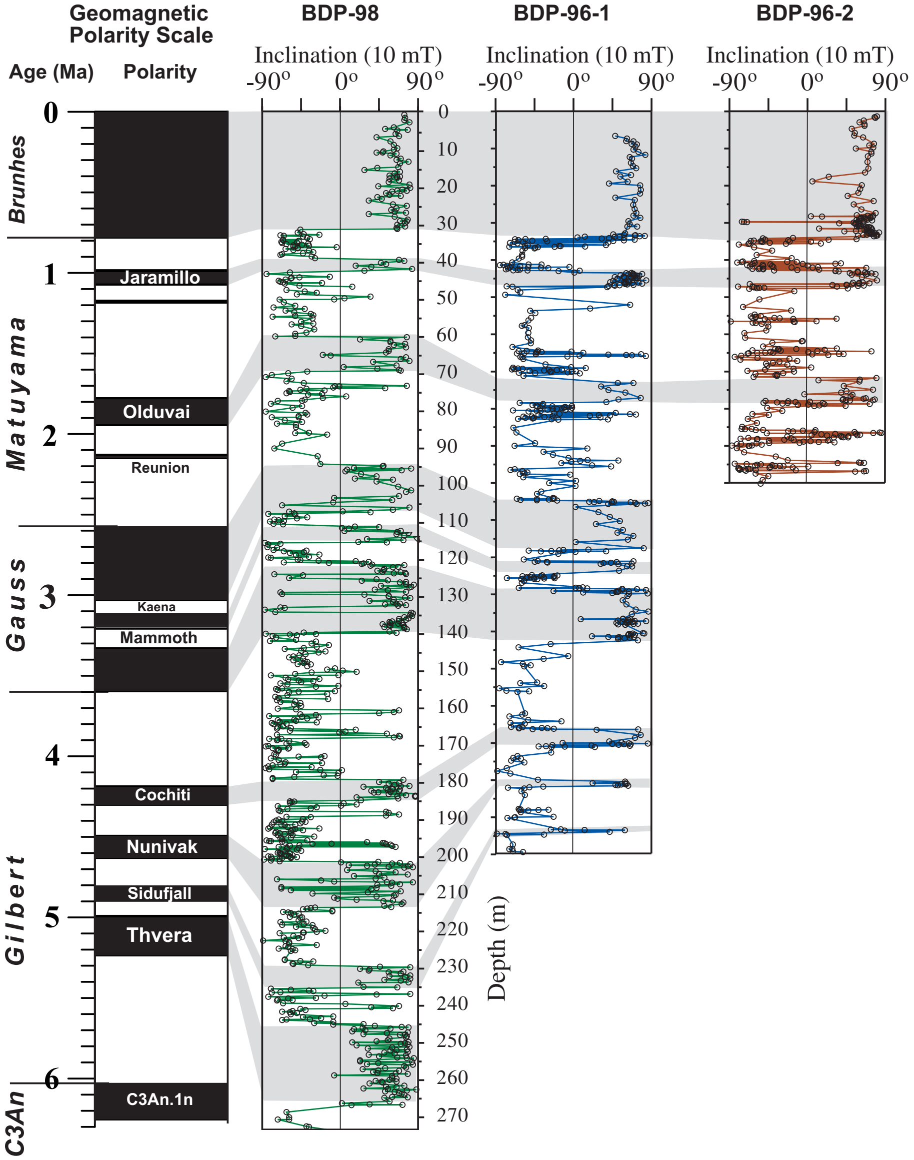

Fig. 6. Matching the inclination profiles for BDP-98 (0–270 m) and BDP-96 holes 1 and 2 to the reference geomagnetic polarity scale after Ogg (2012) for 6.5 Ma. All inclination values are after 10 mT AF demagnetization.

The sedimentary sequences above the B9 and B10 discontinuities defined by seismic studies are characterized by repetitive high-amplitude reflections and intervening low-amplitude discontinuous reflections as described in Moore et al. (1997). The sedimentary strata in the seismic boundaries B3 to B8, below the boundary B9, are of about regular thickness and can be traced as successive packages of reflectors. The top of B8 boundary is the most emphatic reflection in the entire cross-section.

The average sedimentation rate of the interval 200–600 m is 10.66 cm/kyr, however, if split in two sections, the rate of the interval would slightly vary (Fig. 9). In the depth range of 200–270 m the sedimentation rate is 9.56 cm/kyr and in the interval 270–600 m it is 8.34 cm/kyr. The major change in the sedimentation rate occurs at the seismic boundary B9. The average sedimentation rates above (from the surface to 200 m) and below this boundary (from 200 to 600 m) are respectively 3.79 and 10.66 cm/kyr. The change in the sedimentation rate occurs around 4.5 Ma. Prior to the sedimentation rate change at the seismic boundary B9, terrigenous sediments were deposited with a sedimentation rate two times higher than the sedimentation rate above this boundary. After the uplift of Academician Ridge, the influx of sediments decreased, which is recorded by the lower rate of sedimentation above seismic reflector B9. Ivanov and Demonterova (2009), following an idea in Logatchev and Zorin (1987), explained that this change in sedimentation rate could have been caused by a forceful tectonic event at 4.5 Ma which led to the rapid growth of Academician Ridge between the central and northern Baikal basins.

3. Short geomagnetic events in the Lake Baikal piston cores

Paleomagnetic investigations of the Lake Baikal piston core sediments were initiated in the late 1970s (Kravchinsky and Mats, 1982). The first results demonstrated that the bottom sediments in Lake Baikal are suitable for paleomagnetic study and passable intercore correlations using magnetic susceptibility and the intensity of remanent magnetization. After the age model of the sediments became considerably improved in the 1990s and later, a few studies could firmly identify geomagnetic excursions in the Brunhes epoch (Peck et al., 1996; Grachev et al., 1997; Oda et al., 2002; Demory et al., 2005; Kravchinsky et al., 2007). The geomagnetic excursions in the Brunhes chron are better resolved and described in the literature. These excursions are listed in Table 4 along with the excursions identified in the Lake Baikal cores.

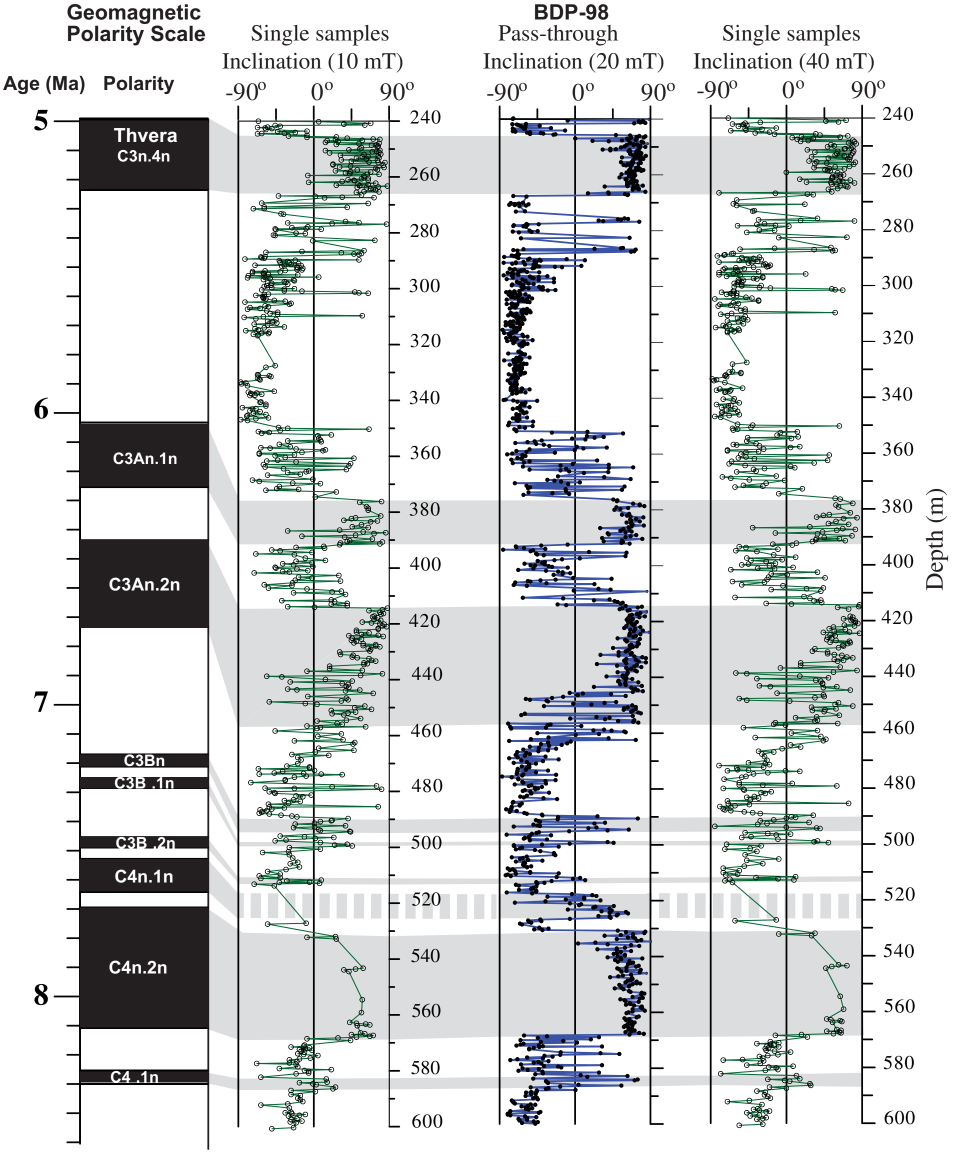

Fig. 7. Matching the inclination profiles for BDP-98 (240–600 m) to the reference geomagnetic polarity scale after Ogg (2012) for 6.5 Ma. All inclination values are after 10 mT AF demagnetization.

3.1. *Short geomagnetic events during the last 640 ka evident in the short piston cores and deep drilled BDP-93 core*

The first relative paleointensity record in the last 85 ka was built for Lake Baikal by Peck et al. (1996). Peck et al. (1996) were the first to demonstrate the presence of a geomagnetic excursion in the Lake Baikal sediments at 20 ka (Fig. 10). Three other geomagnetic events at 41, 61, and 67 ka were interpreted as large-amplitude secular variations registered in both geomagnetic directions and at 41 and 67 ka at lower values of paleointensity. It was considered that a sedimentation rate of 13 cm/ka creates considerable smoothing of the geomagnetic excursion behaviour in the studied piston cores. Nevertheless, the event at 41 ka appears to correspond to the Laschamp excursion, which was independently confirmed by similar findings in cores that were drilled later (Demory et al., 2005; Kravchinsky et al., 2007). Demory et al. (2005) expanded the paleointensity record and built a high resolution paleointensity stack for the last 200 ka (Fig. 11). The new stack corresponds well to the record published by Peck et al. (1996) and to the global compilation SINT-2000 (Valet et al., 2005). Although the global compilation is a smoothed record, the major features could be traced among all three records.

Kravchinsky et al. (2007) published the paleointensity and inclination record from the BDP-93 drilled cores (holes 1 and 2) with average sedimentation rates of 14 and 19 cm/ka in different segments of the core, i.e. above and below the seismic reflector at 58 m (Fig. 12). The BDP-93 core paleomagnetic record corresponds to the paleointensity low in the global paleointensity compilations SINT-2000 (Valet et al., 2005) and PISO-1500 (Channell et al., 2009). We also compared our directional and paleointensity BDP-93 records with the recently published geomagnetic dipole moment variation in the Brunhes chron, which was derived from the cosmogenic nuclide ratio ^{10}Be/^{9}Be (Simon et al., 2016). The record is similar in part with SINT-2000 and PISO-1500, although some intervals differ, which makes some features more or less pronounced (Supplementary Fig. 1).

Demory et al. (2005) documented the Laschamp geomagnetic excursion in the Lake Baikal at ~42 ka. Plenier et al. (2007) reported K-Ar and Ar-Ar ages that suggest that the Laschamp excursion spans between 33.3 and 39.8 ka 35.2 and 39.7 ka, which fits well with our dating (Supplementary Fig. 2). Krainov et al. (2013) confirmed the presence of the Laschamp excursion in the drill core BDP-99 from the southern basin of Lake Baikal, where the sedimentation rate is estimated to be 16.15 cm/ka in the upper 132 m of the core. Supple-

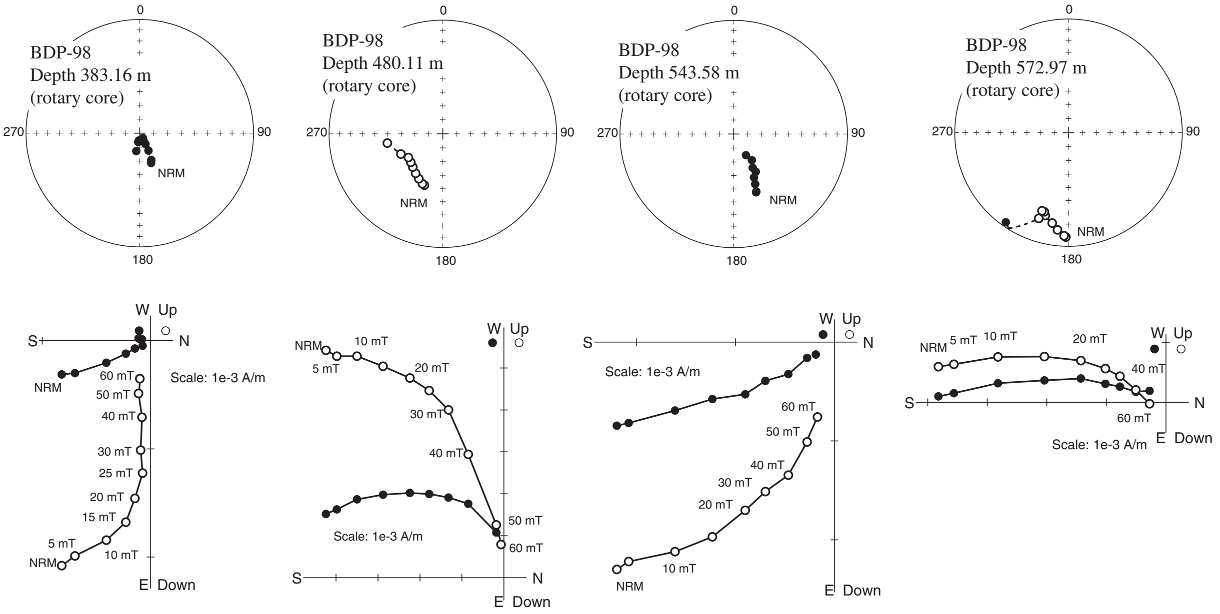

Fig. 8. Examples of demagnetization behaviour of pilot samples from rotary cores of the drilled core BDP-98. Closed (open) symbols in equal-area projections represent downward (upward) inclinations; closed (open) symbols in orthogonal plots represent projections onto the horizontal (vertical) plane. The core was not oriented azimuthally, so zero declination is arbitrary. Plotted with the PaleoMac software (Cogné, 2003).

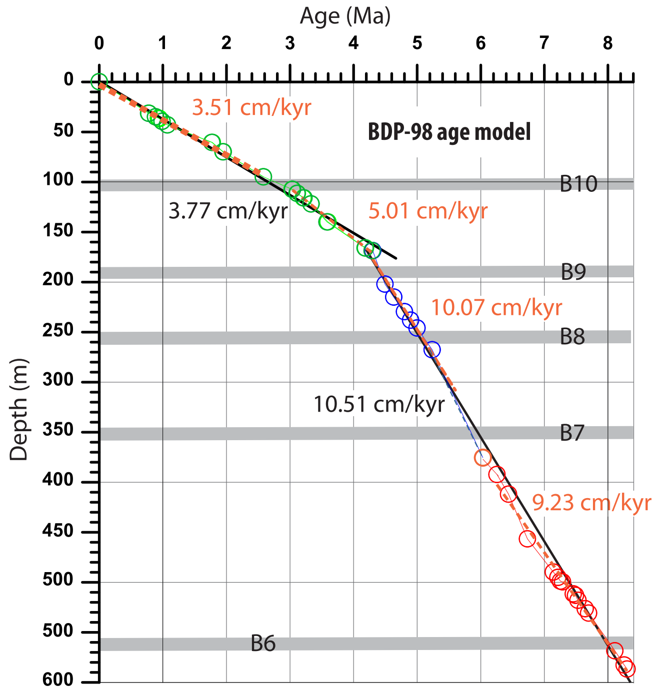

Fig. 9. Age-depth relationships for the drilled hole BDP-98 based on magnetostratigraphy adjusted for ^{10}Be ages. Major seismic reflectors are shown as B6–B10 horizontal lines.

mentary Fig. 2 shows detailed morphology (inclination and relative declination) of the Laschamp excursion in the BDP-93-2 record (BDP-93-1 was sampled with low resolution and is not illustrative to demonstrate excursion behaviour). The age model for the BDP-93 core is highly reliable as it was built by comparing several independent approaches (Kravchinsky et al., 2007): (1) correlation of magnetic susceptibility with the oxygen isotope curve, (2) correlation of biogenic silica with the oxygen isotope curve, (3) correlation of relative paleointensity with the global reference curve SINT-800 from Guyodo and Valet (1999), and (4) U-Th dating. An average deposition rate for the BDP-93 core is 15 cm/ka. Spectral analysis of the magnetic susceptibility and biogenic silica profiles indicate the presence of all fundamental Milankovitch periodicities, which confirms the accuracy of the age model. In any case, the geomagnetic excursion may slightly deviate from accepted ages in the literature because the age model for the BDP-93 core was built assuming a linear interpolation between age control points.

The Norwegian-Greenland Sea excursion was initially reported in Peck et al. (1996) as a large-amplitude secular variation at 67 ka, and is confirmed in the BDP-93 records in Kravchinsky et al. (2007) at 65–66 ka. Supplementary Fig. 3 illustrates that an excellent match between both records is obtained by shifting the Peck et al. (1996) curve 1.5 ka higher on the age axis. The shape and width of the inclination plot are exactly the same in both records. The amplitude of the declination anomaly is greater in the BDP-93 record because the sedimentation rate at the BDP-93 Buguldeika drilling site was higher than the sedimentation rate at the Academician Ridge coring sites.

Most published studies concluded that there is no Blake geomagnetic excursion in the Lake Baikal record, except Grachev et al. (1997) where it is suggested that very low and negative inclinations at the depth interval of 925–960 cm in piston core 15 of the Vereschagin research vessel trip in 1994 might correspond to the Blake event. However, no further published studies confirmed this suggestion. The BDP-93 record shows one negative inclination sample at 88 ka and another one at 99 ka (Kravchinsky et al., 2007; Supplementary Fig. 4). Although, these are around post-Blake/Fram Strait (91–100 ka) time interval (Worm, 1997; Thouveny et al., 2004; Jensen et al., 2016), there is not enough evidence to conclude that the post-Blake event is well resolved in the Lake Baikal record.

Another geomagnetic event, possibly Albuquerque, is registered at ~ 145–146 ka (140 ± 10: Westgate et al., 1990; 141 ± 15: Takai et al., 2002). Oda (2005) determined the age of this excursion to be 140–160 ka. The inclination and declination profiles are shown in Supplementary Fig. 5 after Kravchinsky et al. (2007). There is no correlation of the Albuquerque excursion in terms of a paleointensity low with the global paleointensity compilations SINT-2000 (Valet et al., 2005) as there is no strong minimum at 145–146 ka (Fig. 12).

Inclinations and relative declinations were reconstructed from three different core segments at ~ 190 ka and demonstrate geomagnetic

Table 4
Geomagnetic excursions in the Brunhes chron.

Geomagnetic excursion	Age (Ka)	Marine Isotope Stage	Principal references	Present (+)/absent (−) in Lake Baikal
Mono Lake	27–33	2/3	Laj and Channell (2007); Thouveny et al. (2008); Simon et al. (2016)	−
Laschamp	41	3		+
Norwegian-Greenland Sea	60–62	4		+
Post-Blake/Fram Strait I	94.1 ± 7.8/98	5.3	Thouveny et al. (2004); Jensen et al. (2016)	+
Blake	117–120	5.5	Laj and Channell (2007); Thouveny et al. (2008); Simon et al. (2016)	−
Iceland Basin	188–190	6/7		+
Pringle Falls	211–217	7		−
Calabrian Ridge 0/Fram Strait	258–260	8		−
Portuguese margin	286	8		−
Calabrian Ridge I	309–325	9		−
Levantine	378	10/11		−
Unnamed	406–412	11		−
Emperor	438–447	12		−
Baikal/Galapagos (?)	491	13	Thouveny et al. (2008); this study	+
Calabrian Ridge II	523–530	13	Simon et al. (2016)	−
	538	13/14		−
Big Lost	550	14		−
Calabrian Ridge III/Los Tilos	583	15		−
La Palma	615	15/16		−
Delta	700	17		−
West Eifel 1	715	18		−

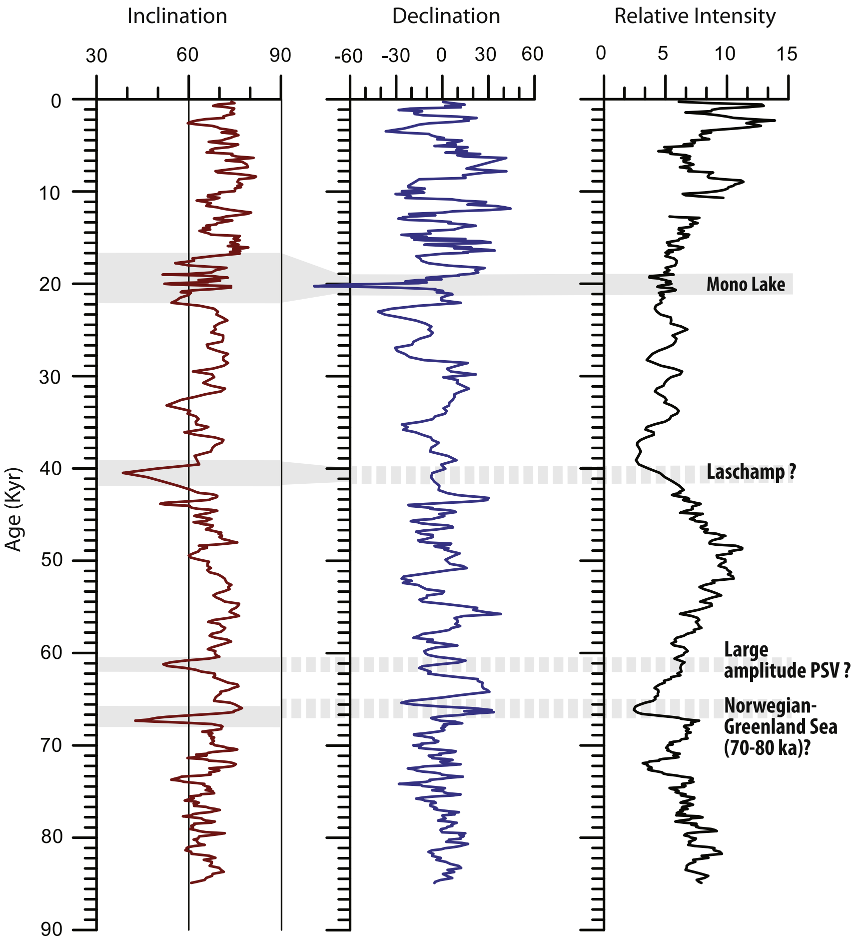

Fig. 10. Stacked inclination and declination profiles (10 mT) and relative intensity profile for 84 ka at the Buguldeika saddle of Lake Baikal (Peck et al., 1996). Grey correlation lines indicate geomagnetic events described in the text.

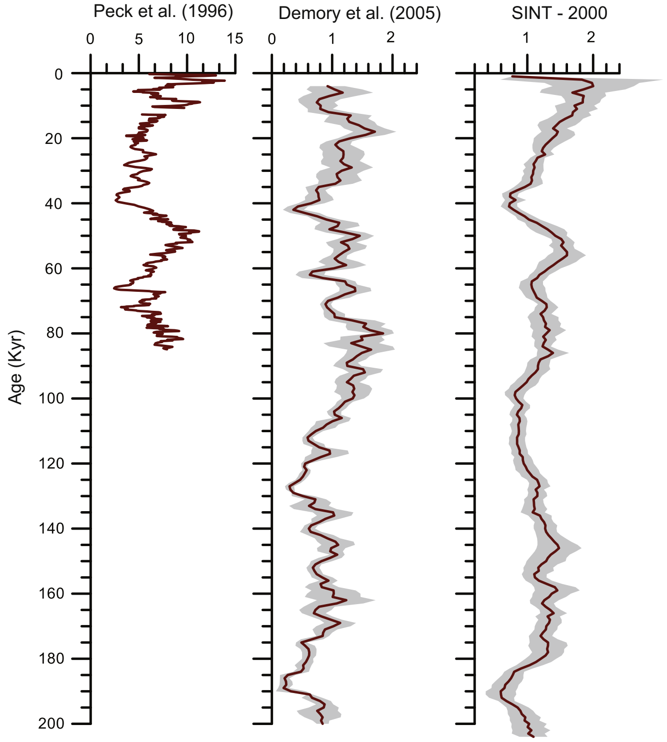

Fig. 11. Comparison of the relative paleointensity for the Buguldeika saddle of Lake Baikal 84 ka record (Peck et al., 1996) and 200 ka record (Demory et al., 2005) with the global stack SINT-2000 (Valet et al., 2005). One standard deviation error is shown by shaded lines.

excursional behaviour (Kravchinsky et al., 2007; Supplementary Fig. 6). This excursion correlates well with the relative paleointensity minimum in the BDP-93 record (Fig. 12). The main part of this geomagnetic excursion lasted ~5 ka, although the slow recovery to typical normal polarity inclinations (60–70°) may double this time. The authors of Kravchinsky et al. (2007) concluded that this was an Iceland Basin geomagnetic excursion that occurred near the base of oxygen isotope stage 6 (180–190 ka). Laj and Channell (2007) defined the Iceland Basin excursion's age at ~188 ka. Additionally, we note that the actual shape of the excursion shown in Supplementary Fig. 6 closely resembles that of the excursion reported by Oda et al. (2002) in the Lake Baikal record. Demory et al. (2005) discussed the mismatch between dating of Iceland Basin events with Oda et al. (2002). Oda et al. (2002) determined the age of the Iceland Basin excursion at 186–189 ka using the correlation with the marine records. Demory et al. (2005) estimated the age as 185 ka suggesting a possibility of a time-lag between Central Eurasia climatic change and global ice volume change at transition MIS6/7 which could be responsible for the dating discrepancy. Alternatively, authors suggest that different lock-in of the geomagnetic field variations in the different sediments could also contribute to the mismatch. Later, Thouveny et al. (2008) demonstrated that the Iceland Basin event corresponds to the end of the marine isotope stage MIS-7 using both paleomagnetic and cosmonuclide geochemistry results. Their dating fits accurately with the dating of the excursion from the BDP-93 core with the higher sedimentation rate (Kravchinsky et al., 2007), which suggests that the Central Eurasia area climate does not lag with the global ice volume change.

One more geomagnetic event of complex shape is revealed in both drilling holes (Supplementary Fig. 7). The age of this event is ~480–495 ka, which could correspond to the wide minimum between

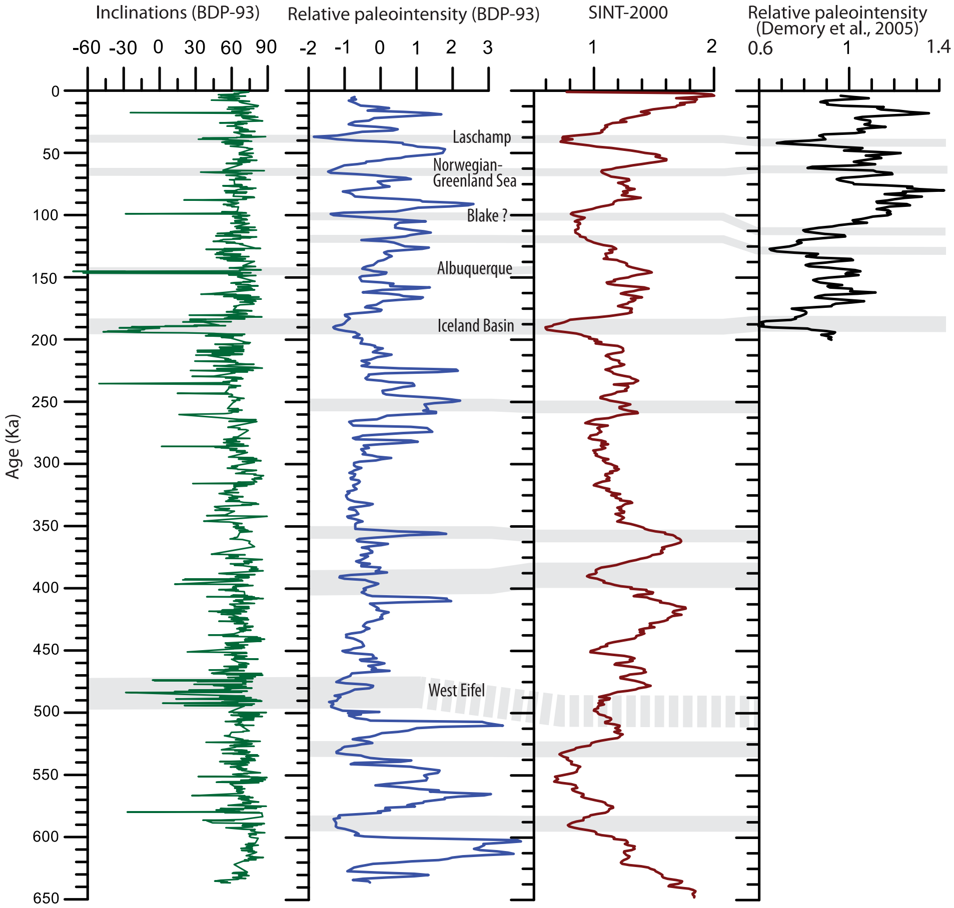

Fig. 12. Comparison of the inclination and relative paleointensity for the Buguldeika saddle of Lake Baikal 640 ka record (Kravchinsky et al., 2007), SINT-2000 (Valet et al., 2005), and the Buguldeika saddle 200 ka record (Demory et al., 2005). Grey correlation lines indicate geomagnetic events described in the text.

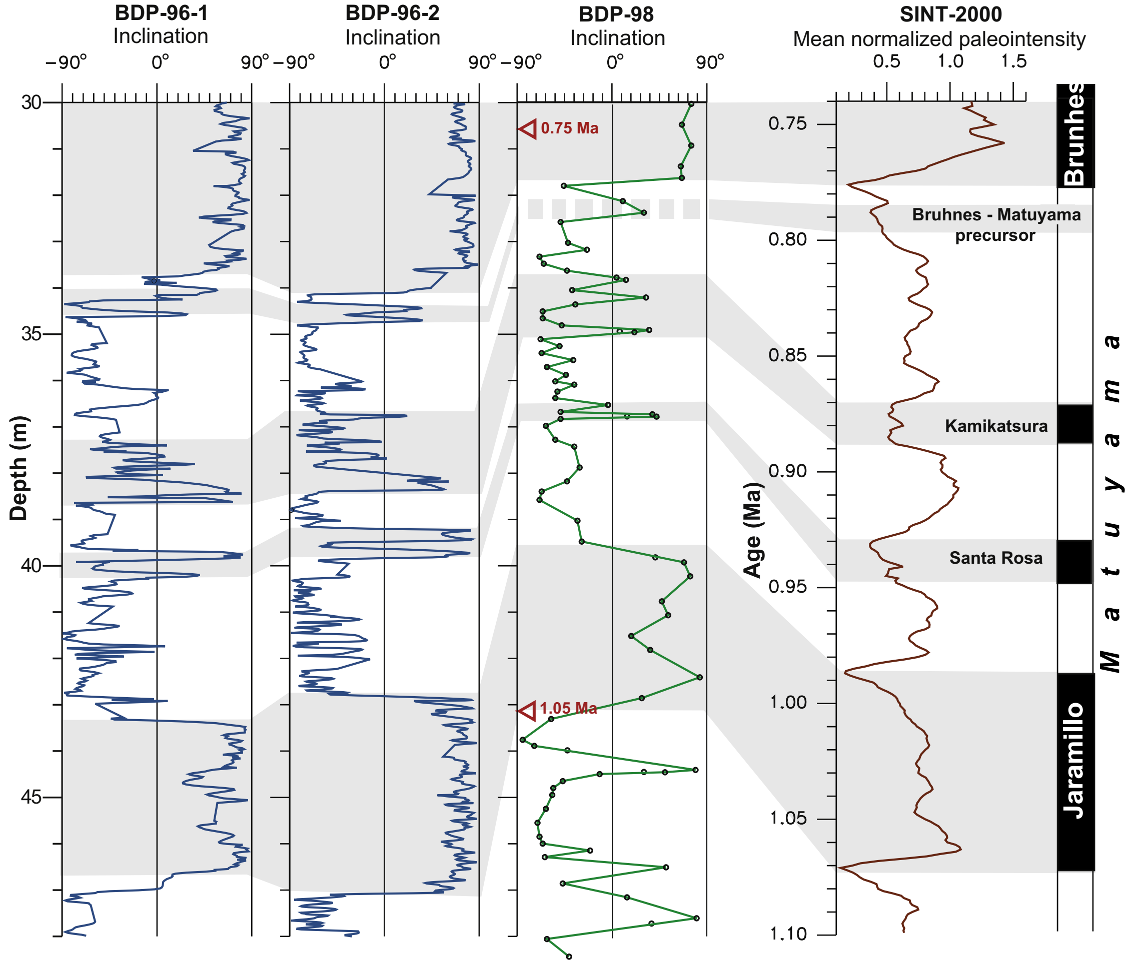

Fig. 13. Inclination profiles for the cores BDP-96-1, BDP-96-2 and BDP-98 at the interval 0.75–1.1 Ma (data from Sakai et al. (2000) and Kravchinsky et al. (2003), figure is modified from (Rohraff, 2012)) matched to the paleointensity reference curve SINT-2000 (Valet et al., 2005). Grey correlation lines correspond to the known geomagnetic normal polarity reversals. Red triangles correspond to ^{10}Be ages from Horiuchi et al. (2003) (number besides in the age in Ma).

480 and 500 ka in the SINT-2000 compilation (Valet et al., 2005). This geomagnetic excursion could be the West Eifel excursion, originally dated in Schnepp and Hradetzkyl (1994) as 510 ± 30. An age of ~ 510 ka was proposed in Lund et al. (2001) based their magnetic susceptibility correlation to SPECMAP in the western North Atlantic Ocean.

3.2. Short geomagnetic events in the deep drilled cores of BDP-96 and 98

Geomagnetic excursions in drilled cores BDP-96-1 and 2 and the upper part of BDP-98 (piston coring) should be identified with caution because the sedimentation rate is relatively low (on average ~ 4 cm/ka). Transitional behaviour of geomagnetic reversals cannot be properly registered with sedimentation rates lower than 5 cm/ka, as recently confirmed in Valet et al. (2016). However, when the same event can be identified in three different cores, the short geomagnetic occurrence may be considered the more credible. Fig. 13 illustrates a comparison of upper Matuyama chron inclination profiles for the three deep drilled cores BDP-96-1, BDP-96-2, and BDP-98 using the datasets in Sakai et al. (2000) for BDP-96 and in Kravchinsky et al. (2003) for BDP-98. Depth is converted to age based on the BDP-98 age model described above. Linear interpolation is used between the normal/reverse polarity chron boundaries. More accurate dating of the Jaramillio event and the Brunhes/Matuyama boundary (BMB) is performed by matching the top and bottom of the events to the SINT-2000 paleointensity record (Valet et al., 2005) and PISO-1500 (Channell et al., 2009) (only SINT is shown in Fig. 13). Lower values of paleointensity correspond to transition zones where polarity changes (Valet et al., 2005), therefore, the middle of the inclination transition can be correlated to the paleointensity minimum. Fig. 13 demonstrates that such correlation is straightforward for the top and bottom of the Jaramillio event. Identification of the BMB is more delicate because the inclination changes from positive to negative more than once during this time interval. The uppermost transition from positive to negative inclinations is at ~ 33.8 m for BDP-96-1, 34.2 m for BDP-96-2, and 31.5 m for BDP-98, which corresponds to ~ 0.78 Ma (0.776 Ma) of the SINT-2000 (Valet et al., 2005) minimum.

The double peak event at a depth of 34–35 m of BDP-96-1 and 2 and the single peak event at a depth of 32–32.5 m is interpreted here as the BMB precursor. Such precursor is extensively described in Coe et al. (2004), Macrì et al. (2010), Valet et al. (2012), and the references therein. Kravchinsky et al. (2003) estimated the depth of the BMB in the middle of the whole transition interval including the precursor. This study assigns the BMB to the uppermost transition (Fig. 13). The BDP-98 core also demonstrates the presence of a BMB precursor, however, single sample data have larger spacing (every 30 cm) and do not resolve the double peak with the clarity of the 1 cm spacing between measurements of the quarters of the cores taken with the 2-G cryogenic magnetometer. It is necessary to take into account that the pass-through cryogenic measurements always smooth the out-coming record, averaging the measurements of the ~ 5 cm length core interval. Our choice of the BMB position is additionally validated by the beryllium date of

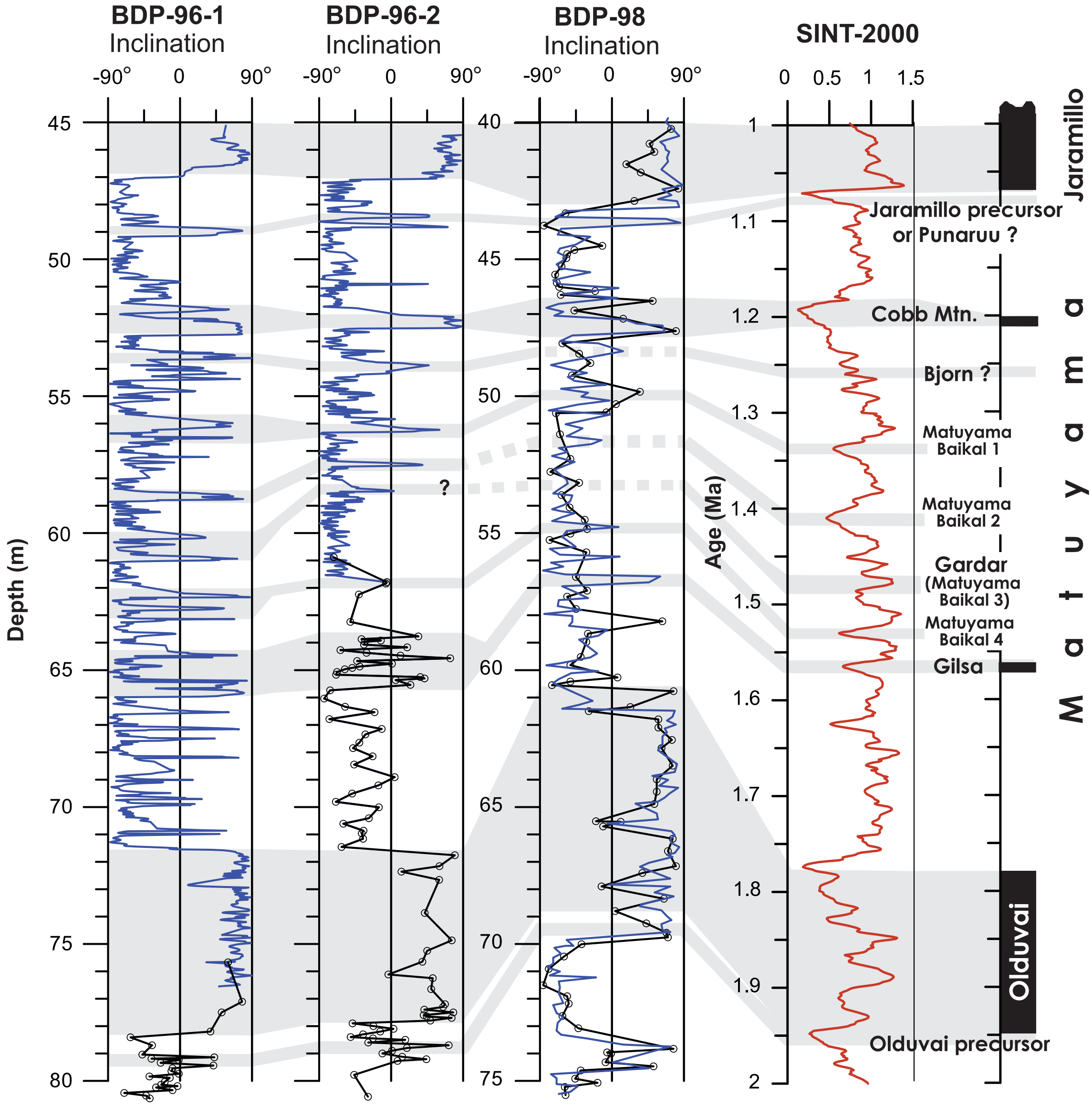

Fig. 14. Inclination profiles for the cores BDP-96-1, BDP-96-2 and BDP-98 at the interval 1–2 Ma (data from Sakai et al. (2000) and Kravchinsky et al. (2003)) matched to the paleointensity reference curve SINT-2000 (Valet et al., 2005). Grey correlation lines correspond to the geomagnetic events described in text. Blue line corresponds to the inclinations obtained with the pass-through measurements; black line corresponds to the inclinations obtained with the single samples.

~0.75 Ma at the depth 30.5 m (just above the boundary). The position of the top of the Matuyama chron is independently confirmed by the occurrence of magnetic susceptibility minima and the maximum of biogenic silica at the BMB in all three BDP records: BDP-96-1, BDP-96-2, and BDP-98 (Fig. 7 in Kravchinsky et al., 2003). Ochiai and Kashiwaya (2005) indicate the BMB for the BDP-98 core at 32 m, however, they do not explain that choice.

Further assessment of the inclination record allows the identification of shorter geomagnetic events — Jaramillio, Kamikatsura, Santa Rosa — which correspond to minima on the SINT-2000 (Valet et al., 2005) reference curve. The SINT-2000 minimum suggests that Kamikatsura spans from ~0.87–0.89 Ma, which is very close to the ^{40}Ar/^{39}Ar ages for Kamikatsura at ~0.9 ± 0.05 Ma reported by Coe et al. (2004). The top of Kamikatsura has multiple features, which are very short in time and may appear to be a noisy record generated by secular variations. One may observe a group of peaks with complex shapes below the Kamikatsura event; the peaks are interpreted here as Santa Rosa geomagnetic excursion. The event is reported as a single peak at ~0.936 Ma by Singer and Brown (2002).

Although the longer geomagnetic events listed in Table 3 can be reliably identified in the drilled cores BDP-96-1 and 2 and BDP-98, an interpretation of short geomagnetic events that resemble geomagnetic excursion behaviour is problematic for ages older than 1 Ma. Previous publications have not interpreted any geomagnetic excursions in these cores. Although geomagnetic excursions in these cores have been registered, they were not discussed in the literature because the global database for short geomagnetic events older than 1 Ma is incomplete. Using a computational model, Roberts and Winklhofer (2004) demonstrated that geomagnetic excursions could be smoothed out in sediments with sedimentation rates of < 10 cm/ka. The sedimentation rate in the upper ~170 m portion of the BDP-96 and 98 record is ~4 cm/ka. At the same time, the high latitude position of Lake Baikal would produce sharper changes in the inclination profile as the average field inclination moves closer to the vertical orientation. In this paper, the occurrence of geomagnetic excursions is discussed for the first time, regardless of the low sedimentation rate, because the short geomagnetic events in the Lake Baikal drilled cores match well with time intervals available from other publications (Lanphere et al. (2002); Channell and

Table 5
Geomagnetic excursions in the Matuyama, Gauss and Gilbert chrons.

Geomagnetic event	Age (Ma)	Principal references
Matuyama		
Jaramillo precursor or Punaruu	∼1.07	Channell et al. (2002); this study
Cobb Mnt.	1.173–1.185	Ogg (2012); this study
Bjorn	1.25–1.27	Laj and Channell (2007); this study
Matuyama Baikal 1	1.36–1.38	This study
Matuyama Baikal 2	1.40–1.42	
Matuyama Baikal 3/Gardar	1.46–1.48	Laj and Channell (2007); Channell and Guyodo (2004); this study
Matuyama Baikal 4	1.53–1.54	This study
Gilsa	1.567–1.575	Laj and Channell (2007); this study
Pre-Olduvai	1.96–1.98	
HRT (Huckleberry ridge tuff)	2.06–2.08	Lanphere et al. (2002); this study
Reunion	2.11–2.15	Laj and Channell (2007); Yang et al. (2007); this study
Matuyama Baikal 5	2.23	Yang et al. (2007); Ohno et al. (2012); this study
Matuyama Baikal 6	2.32–2.35	
Matuyama Baikal 7	2.44–2.45	
Matuyama Baikal 8	2.53–2.57	
Gauss		
Gauss Baikal 1	2.62–2.65	Ohno et al. (2012); this study
Gauss Baikal 2	2.71–2.75	
Gauss Baikal 3	2.91–2.94	This study
Gauss Baikal 4	3.07–3.09	
Gauss Baikal 5	3.39–3.43	
Gauss Baikal 6	3.46–3.49	
Gilbert (preliminary estimate, all need confirmation)		
Gilbert Baikal 1	3.71–3.78	This study
Gilbert Baikal 2	3.89–3.96	
Gilbert Baikal 3	4.00–4.50	
Gilbert Baikal 4	4.08–4.13	
Gilbert Baikal 5	4.14–4.19	
Gilbert Baikal 6	4.33–4.35	
Gilbert Baikal 7	4.38–4.41	
Gilbert Baikal 8	4.43–4.46	

Guyodo (2004); Ohno et al. (2012)). Such interpretation should be treated with caution until events are further confirmed.

Roberts and Winklhofer (2004) showed that in some cases the age offset of a geomagnetic event could be due to the lock-in process of magnetic particles, because the depth at which the sediments acquire magnetization is a sum of the surface mixing layer depth and the magnetic particle lock-in depth. Channell and Guyodo (2004) established that the surface mixing layer produces an apparent age offset for the magnetic polarity transition, while the particle lock-in depth controls the apparent length of the transition. What is certain, however, is that the lock-in process of magnetic particles did not play a significant role in creating the age offset in the Lake Baikal sediments, because all the geomagnetic polarity ages known from events in the literature are well matched with ^{10}Be dates in the cores (see Table 2 and the age model discussion above).

Fig. 14 illustrates the geomagnetic events in the inclination profiles for BDP-96-1, BDP-96-2, and BDP-98. Jaramillo, Cobb Mountain, Gilza, and Olduvai could be identified with certainty and traced among all three cores. Other short geomagnetic event records are relatively noisy; they may appear to be large secular variations and some are found in all three cores (solid grey correlation line) or in only two cores (dashed grey correlation line, where the common presence is not found or is doubtful). Short geomagnetic events in the Matuyama chron are highlighted and numbered as Matuyama Baikal 1, Matuyama Baikal 2, etc. (Table 5). Further proof from different parts of the world is necessary to confirm these events to be actual geomagnetic events in Lake Baikal. The Bjorn and Gardar events are marked based on an apparent fit with events reported by Laj and Channell (2007) and Channell and Guyodo (2004) in the Oceanic Drilling Program (ODP), Sites 980–984.

Fig. 15 illustrates the time interval between 1.8 and 3.3 Ma. The pre-Olduvai excursion is shown just below the Olduvai event. This excursion is well documented in the ODP, Sites 980–984, at 1977 ka (Channell and Guyodo, 2004). Two other geomagnetic events, the Huckleberry Ridge Tuff (HRT) and the Reunion, are documented in the Lake Baikal record below pre-Olduvai. Lanphere et al. (2002) concluded that these two events occurred between 2.2 and 2.0 Ma. Four more events between 2.2 Ma and the top of the Gauss chron (∼2.6 Ma) match reasonably well with the detailed geomagnetic field record between 2.1 and 2.75 Ma from a sediment core IODP Site U1314 which has a high sedimentation rate (≥10 cm/ka) and good age control (Ohno et al., 2012). Four events in Matuyama (Matuyama Baikal 5–Matuyama Baikal 8) correlate with four events, L1–L4, of the IODP Site U1314 (Table 5). Yang et al. (2007) reported a few excursions in early and middle Matuyama from the Chinese loess. Reunion and Matuyama Baikal events 5–7 match their findings well.

Further, four reverse polarity events can be resolved between 2.6 and 3.2 Ma (Fig. 15, Table 5). The event Gauss Baikal 1 appears to correspond to two events of U1314 — L5 and L6 — in the terms of age, although the Gauss Baikal 1 event cannot be resolved as a double event because of the smoothing effect of the low sedimentation rate. The event Gauss Baikal 2 corresponds to U1314 events L7 and L8 and appears as a double event as well. The Lake Baikal record demonstrates a presence of other short geomagnetic events below 2.75 Ma. Events have not yet been reported in this time interval. The event Gauss Baikal 3 appears at ∼2.93 Ma and Gauss Baikal 4 is an intra-Kaena event at ∼3.7 Ma.

Fig. 16 shows short geomagnetic events between 3.2 and 4.7 Ma. The geomagnetic chrons Mammoth, Cochiti, and Nunivak can be confidently resolved in the BDP-96-1 and BDP-98 records. The sampling resolution of BDP-96-1, however, does not allow the identification of short geomagnetic events, therefore, the short geomagnetic events are identified only in the BDP-98 core, both in the single sample profile and in the pass-through record. These events are hypothetical until they are confirmed in the literature. At the moment the low Gauss and Gilbert chrons have not been studied in sufficient detail to confirm the Lake Baikal events. Here we report two probable events (Gauss Baikal 5 and Gauss Baikal 6) in the earliest Gauss between 3.4 and 3.5 Ma. The other 8 events, from Gilbert Baikal 1 to Gilbert Baikal 8, are registered between 3.7 and 4.5 Ma (Fig. 16, Table 5).

4. Conclusions

Lake Baikal shore and lake sediments have been investigated paleomagnetically since the late 1970s, during which publications describing the region's magnetostratigraphy have provided a unique continuous sedimentary archive of millions of years, an archive that is studied by a large international community. This review focuses on the short piston and long drilled cores which contain a detailed record of geomagnetic events during last 8.4 Ma.

The age model for drilled cores BDP-93-1 and BDP-93-2 is based on magnetic susceptibility and a biogenic silica record correlation with the reference oxygen isotope ^{18}O curve, relative paleointensity, and U-Th dating. The relatively high sedimentation rate (∼15 cm/ka) shown in the BDP-93 core enabled us to establish a detailed relative paleointensity and geomagnetic excursion record for the last 640 ka. A few well-known geomagnetic excursions in the Brunhes chron (Laschamp, Norwegian-Greenland Sea, Albuquerque, Iceland Basin, West Eifel) were identified in the record.

Sedimentation rates in deep drilled cores BDP-96-1, BDP-96-2, and BDP-98 are relatively low, from 4 to ∼10 cm/ka. Geomagnetic chrons and numerous short geomagnetic events can be observed in all three cores. The geomagnetic chrons can be reliably established using ^{10}Be dating. The top 2.5 Ma geomagnetic events were traced between all

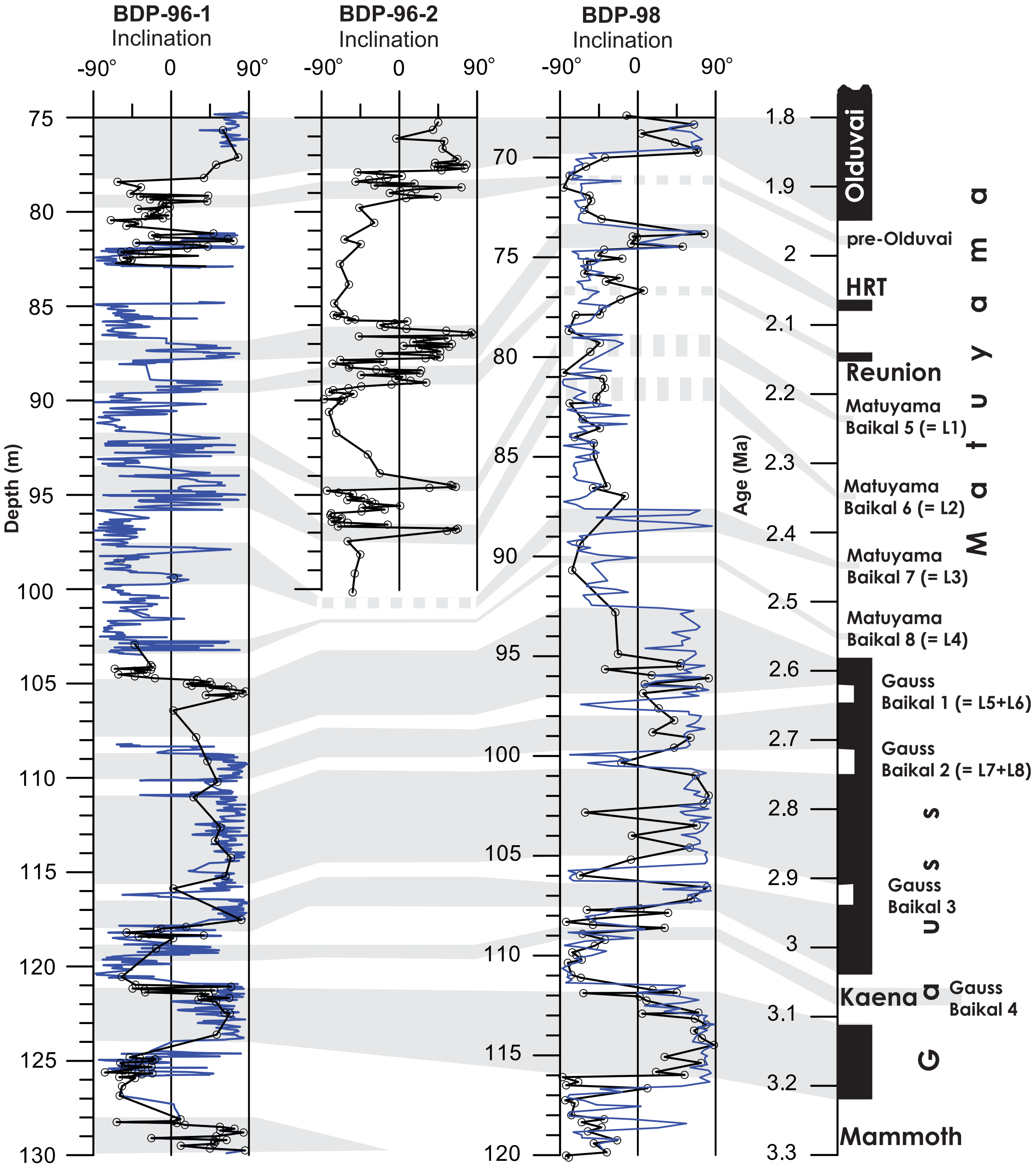

Fig. 15. Inclination profiles for the cores BDP-96-1, BDP-96-2 and BDP-98 at the interval 1.8–3.3 Ma (data from Sakai et al. (2000) and Kravchinsky et al. (2003)) matched to the paleointensity reference curve SINT-2000 (Valet et al., 2005). Grey correlation lines correspond to the geomagnetic events described in text. Blue line corresponds to the inclinations obtained with the pass-through measurements; black line corresponds to the inclinations obtained with the single samples.

three drilling cores and between the two deeper drilled cores (BDP-96-1 and BDP-98) until 3.2 Ma. Geomagnetic events between 3.2 and 4.7 Ma were established only from the more detailed record in the BDP-98 core, although geomagnetic chrons are well correlated between BDP-96-1 and BDP-98. The short geomagnetic events in the Lake Baikal drilling cores match well with time intervals available in recent publications. The Lake Baikal magnetostratigraphy record shed light on the 2.75–4.7 Ma interval, which was not previously documented in the literature. A few events within normal and reverse polarity chrons are described (Gauss Baikal 3 to 6 at Fig. 15 and Gilbert Baikal 1 to 8 at Fig. 16).

A continuous BDP drill core magnetostratigraphy record is crucial for refining the geomagnetic excursion record. Data from the Lake Baikal drill cores can be used to identify geomagnetic events in other parts of the world. An accurate age model is necessary to interpret various climate proxies in the drilled cores of Lake Baikal and to perform accurate climate and environment change reconstructions during the Neogene–Quaternary periods in continental Asia.

5. Data availability

Excel files containing the datasets from this study can be downloaded from http://ualberta.ca/~vadim/Data_Repository.htm.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gloplacha.2017.04.002.

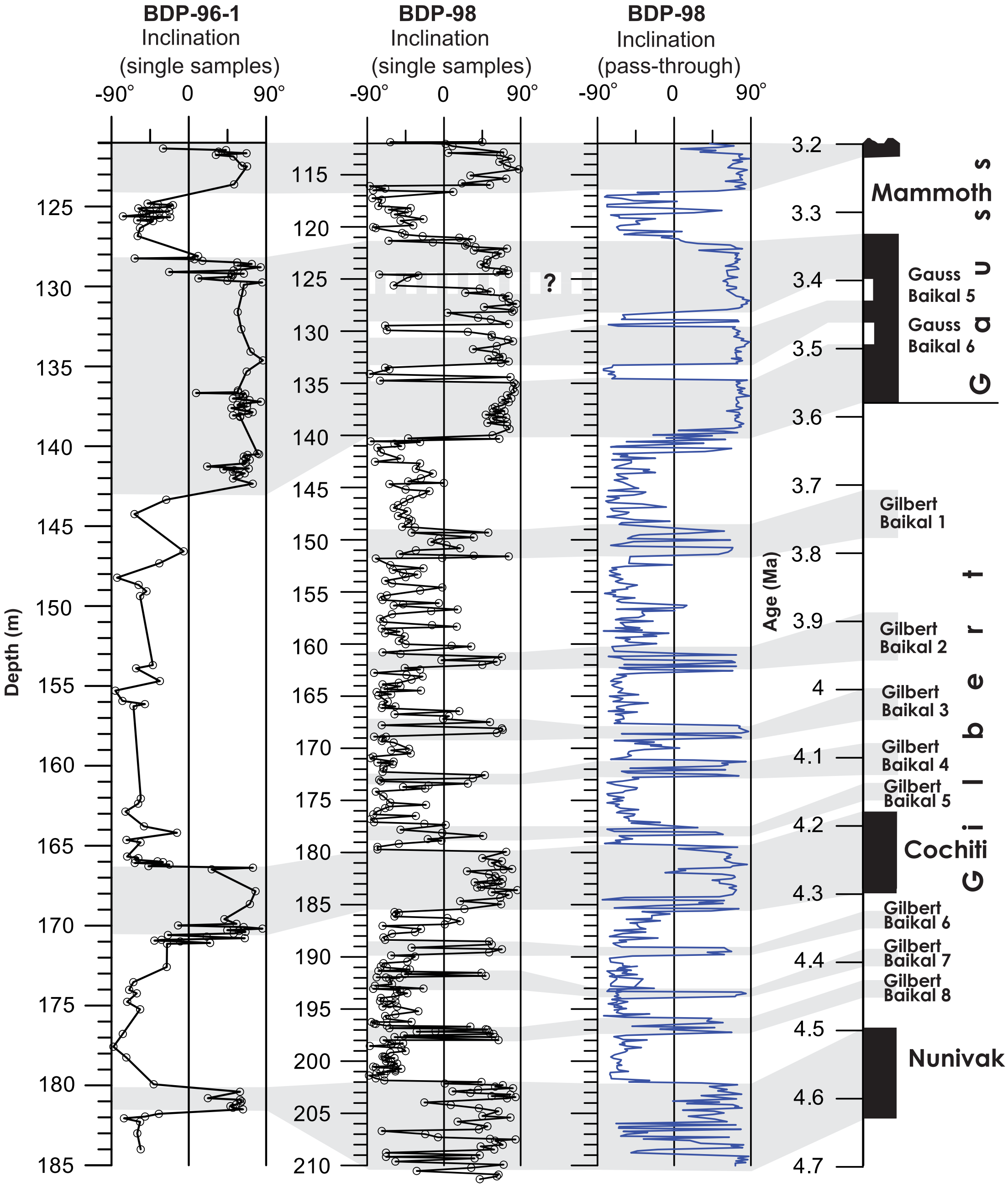

Fig. 16. Inclination profiles for the cores BDP-96-1 and BDP-98 at the interval 3.2–4.7 Ma (data from Sakai et al. (2000) and Kravchinsky et al. (2003)) matched to the paleointensity reference curve SINT-2000 (Valet et al., 2005). Grey correlation lines correspond to the geomagnetic events described in text. Blue line corresponds to the inclinations obtained with the pass-through measurements; black line corresponds to the inclinations obtained with the single samples.

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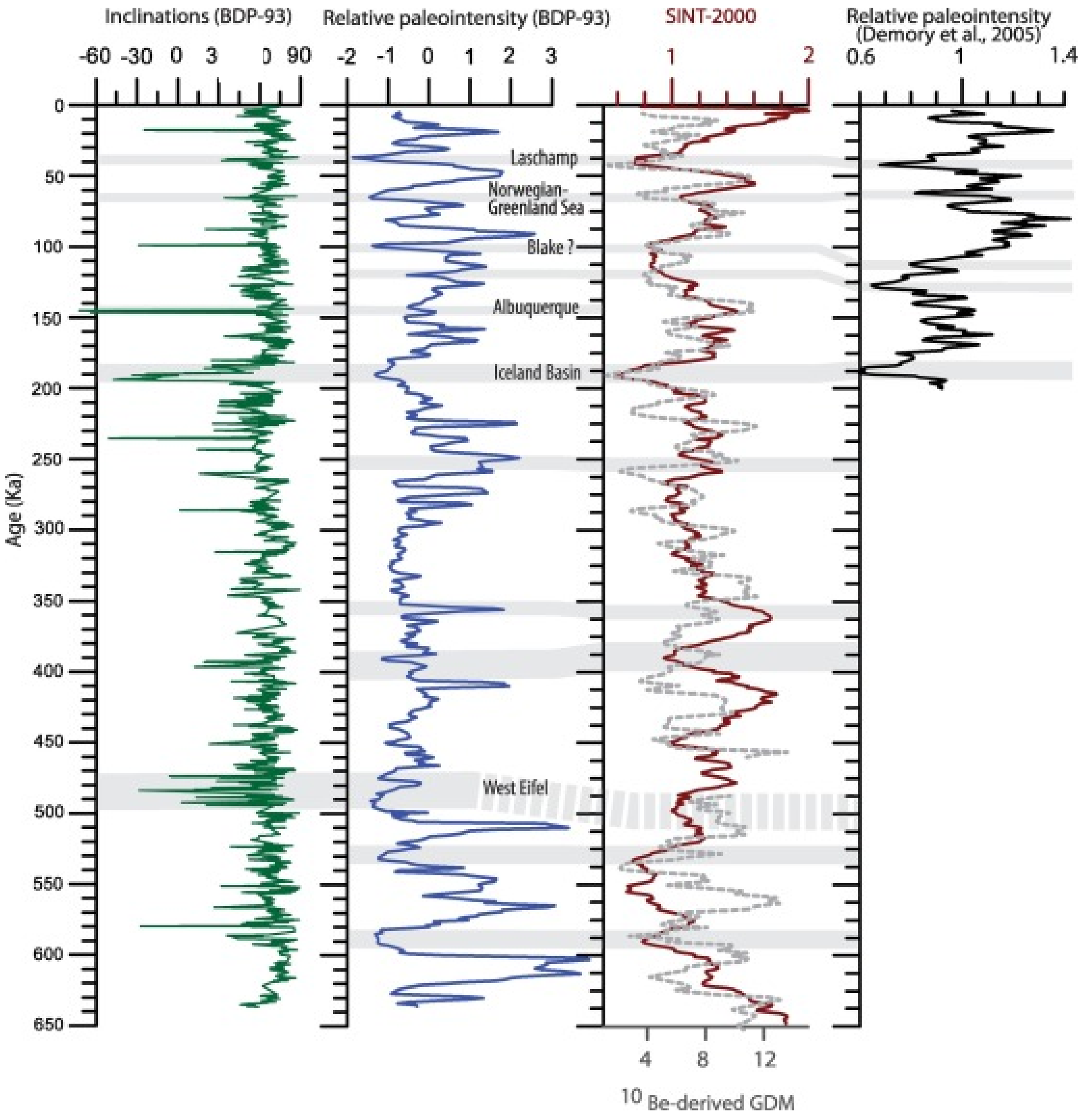
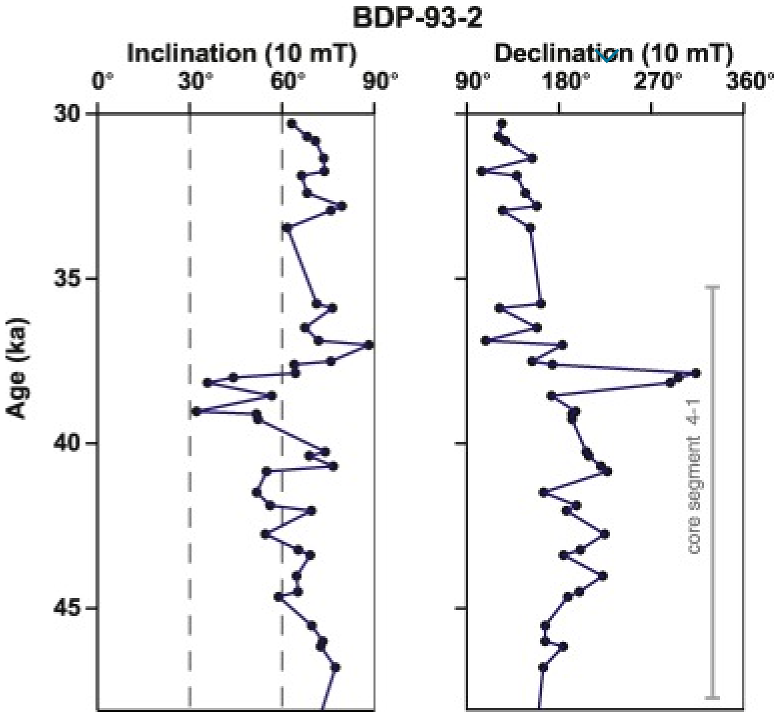
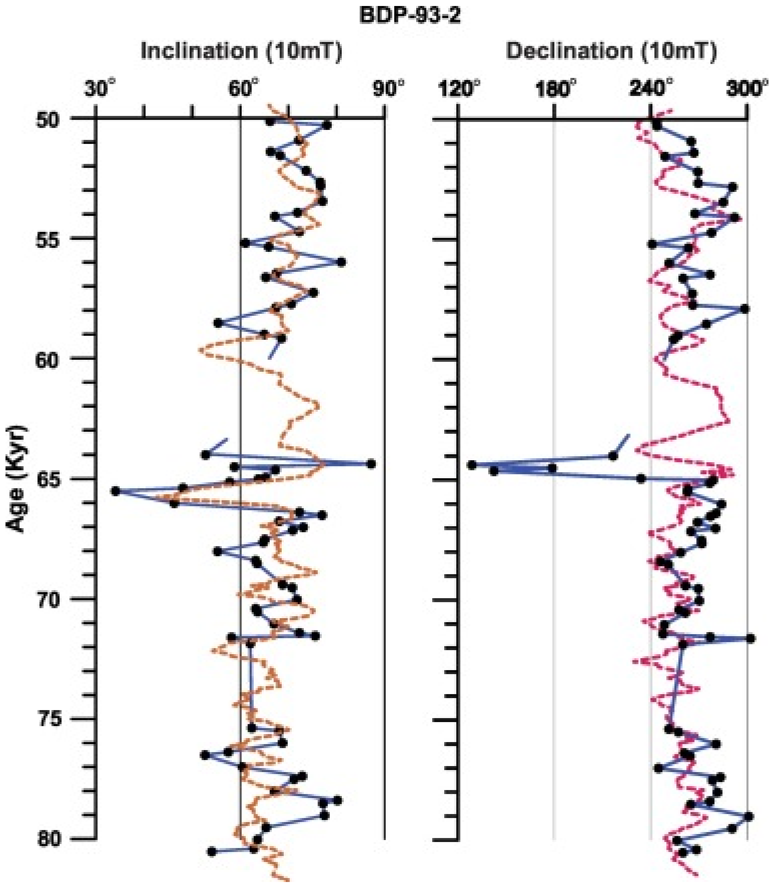
The following are the supplementary data related to this article.



Supplementary Fig. 1. Comparison of the inclination and relative paleointensity for the Buguldeika saddle of Lake Baikal 640 ka record (Kravchinsky et al., 2007), SINT-2000 (Valet et al., 2005), ^{10}Be-derived geomagnetic dipole moment GDM (Simon et al., 2016) and the Buguldeika saddle 200 ka record (Demory et al., 2005). Grey correlation lines indicate geomagnetic events described in the text.

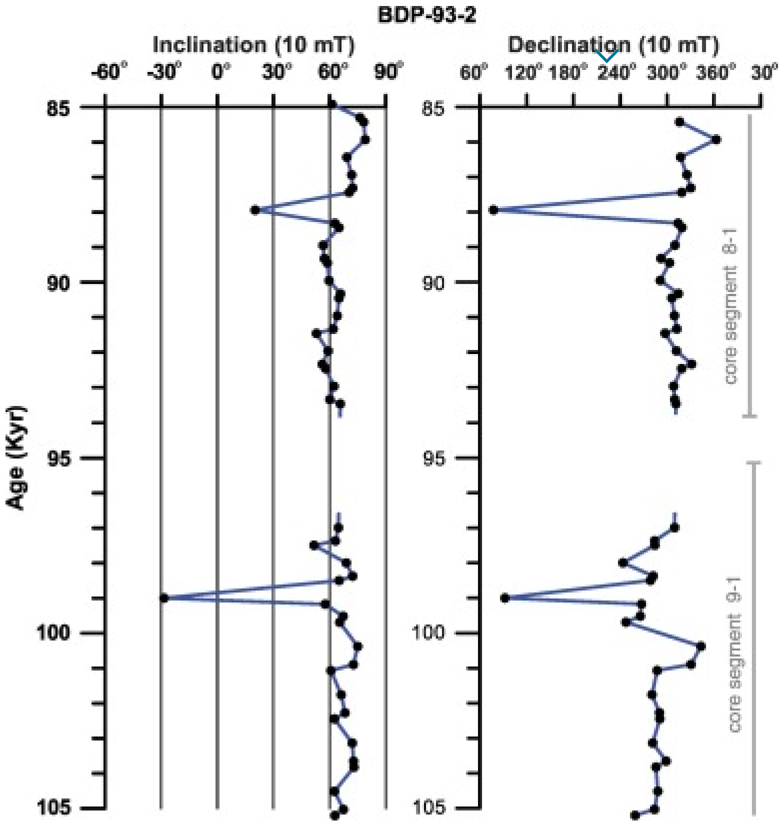


Supplementary Fig. 2. Inclination and relative declination patterns from core BDP-93-2 which is interpreted to correspond to the Laschamp geomagnetic excursion. All inclinations and declinations are after 10 mT AF demagnetization. The extent of the core segment 4-1 is indicated. Replotted using the data from Kravchinsky et al. (2007).



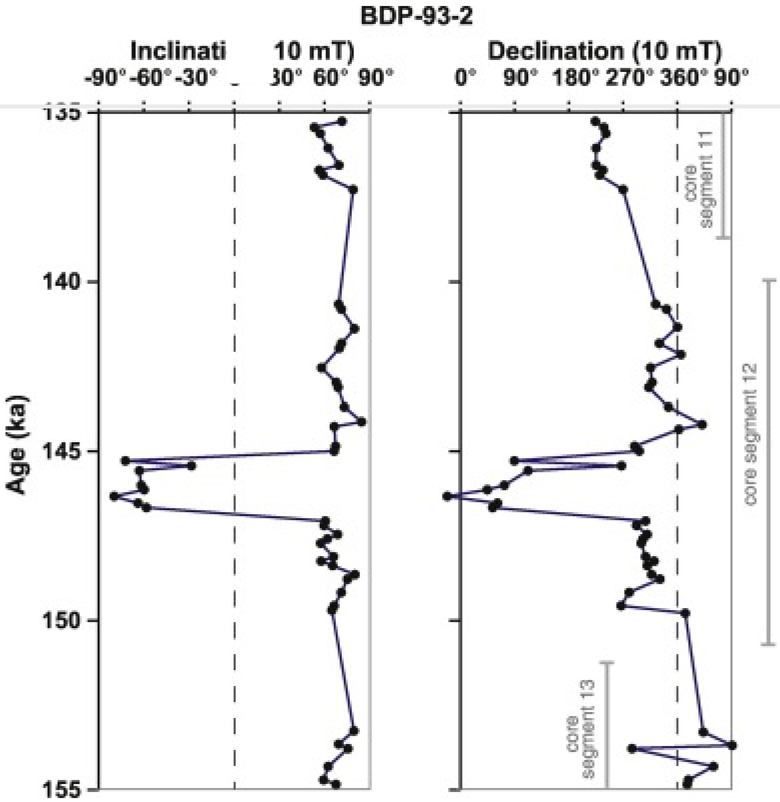
Supplementary Fig. 3. Inclination and relative declination patterns from core BDP-93-2 which is interpreted to correspond to the Norwegian-Greenland Sea geomagnetic excursion. All inclinations and declinations are after 10 mT AF demagnetization.

(Blue solid line is replotted using the data from Kravchinsky et al. (2007), dashed line is replotted using the data from Peck et al. (1994).)



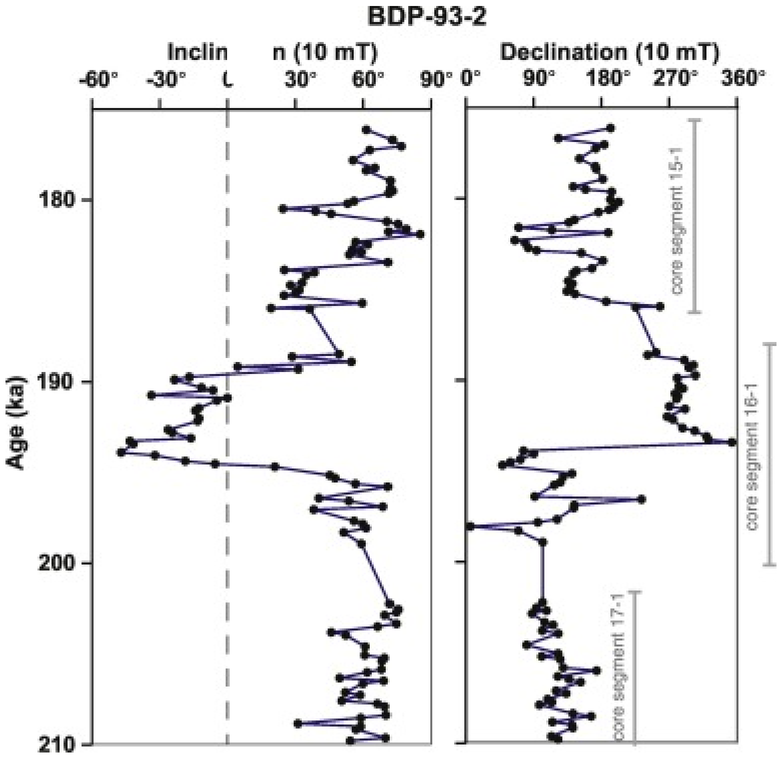
Supplementary Fig. 4. Inclination and relative declination patterns from core BDP-93-2 which is interpreted as a possible post-Blake geomagnetic excursion, although, the sample resolution does not allow one to demonstrate it firmly. All inclinations and declinations are after 10 mT AF demagnetization. The extent of the core segments 8-1 and 9-1 are indicated.

(Replotted using the data from Kravchinsky et al. (2007).)



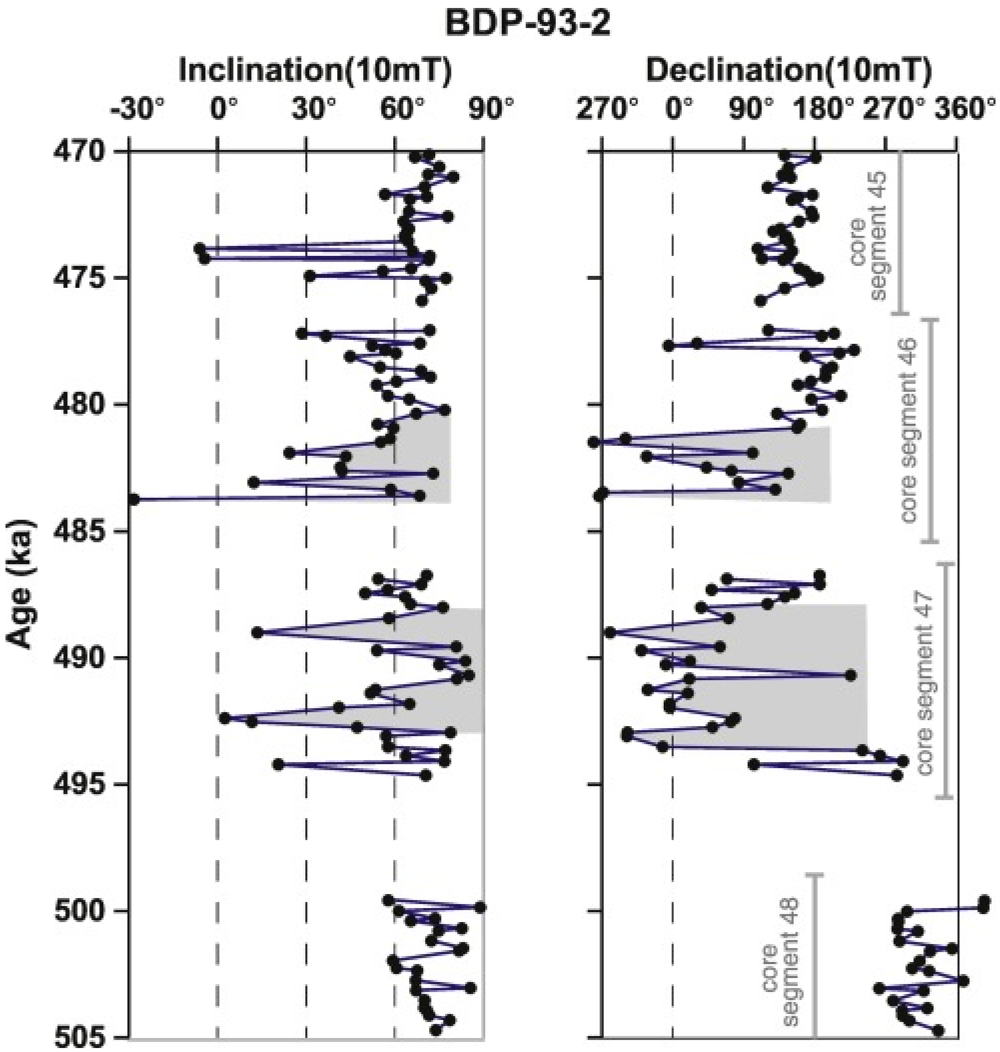
Supplementary Fig. 5. Inclination and relative declination patterns from core BDP-93-2 which is interpreted to correspond to the Albuquerque geomagnetic excursion. All inclinations and declinations are after 10 mT AF demagnetization. The extent of the core segments 11, 12 and 13 are indicated.

(Replotted using the data from Kravchinsky et al. (2007)).



Supplementary Fig. 6. Inclination and relative declination patterns from core BDP-93-2 which is interpreted to correspond to the Iceland Basin geomagnetic excursion. All inclinations and declinations are after 10 mT AF demagnetization. Core segments 15-1, 16-1 and 17-1 are indicated.

(Replotted using the data from Kravchinsky et al. (2007).)



Supplementary Fig. 7. Inclination and relative declination patterns from core BDP-93-2 which is interpreted to correspond to the West Eifel geomagnetic excursion. All inclinations and declinations are after 10 mT AF demagnetization. Core segments from 45 to 48 are indicated. Shaded areas indicate the excursion.

(Replotted using the data from Kravchinsky et al. (2007)).