Earth Planets Space, **59**, 807–814, 2007

Environmental magnetic record and paleosecular variation data for the last 40 kyrs from the Lake Biwa sediments, Central Japan

Akira Hayashida[1], Mohammed Ali[2*], Yoshiki Kuniko[3], Hiroyuki Kitagawa[4], Masayuki Torii[5], and Keiji Takemura[6]

[1]*Department of Environmental Systems Science, Doshisha University, Japan*
[2]*Department of Geology and Mineralogy, Kyoto University, Japan*
[3]*Graduate School of Human and Environmental Studies, Kyoto University, Japan*
[4]*Graduate School of Environmental Studies, Nagoya University, Japan*
[5]*Department of Biosphere-Geosphere System Science, Okayama University of Science, Japan*
[6]*Beppu Geothermal Research Laboratory, Kyoto University, Japan*

(Received September 29, 2006; Revised May 8, 2007; Accepted May 10, 2007; Online published July 20, 2007)

We have conducted paleomagnetic and environmental magnetic analysis of a sediment piston core recovered from Lake Biwa, central Japan. Tephrochronology and AMS radiocarbon dating showed that this core covers the time period since about 40 kyr BP. The variation of paleomagnetic direction shows a good agreement with the PSV record for the last 10 kyrs from the deeper water site (BIWA SV-3; Ali *et al.*, 1999), although the amplitudes are subdued probably due to the relatively lower accumulation rate at the shallower site. Inclination lows of the pre-Holocene interval are correlated to PSV records reported from the marine sediments off Shikoku and in the Japan Sea. In addition, the variation of magnetic mineral concentration reflects environmental changes during the last glacial period. It is suggested that the flux of fine-grained magnetite, probably associated with greater precipitation, was increased during interstadial periods. The variation of anhysteretic remanent magnetization is likely correlated to the Dansgaard-Oeschger (D-O) cycles recorded in Greenland ice cores. An apparent swing of the PSV curve is recognized at about 27 ka, but evidence for the Mono Lake excursion at 32 ka around the D-O events 6 and 7 is unclear. Combination of the detailed paleomagnetic record and the sub-Milankovitch climate cycles thus provides better resolution for understanding geomagnetic secular variation and polarity excursions in space and time.

Key words: Environmental magnetism, paleosecular variation, lake sediment, Dansgaard-Oeschger cycles.

1. Introduction

Lake sediments are often targeted to obtain records of environmental magnetic record and paleosecular variations (PSVs) of the geomagnetic field (e.g., Evans and Heller, 2003). Most lake basins, however, postdate the last glacial period, providing paleomagnetic records only for the last 10,000 years or a shorter interval in the Holocene. Lake Biwa, located in central Japan (Fig. 1), is a unique freshwater basin which contains continuous sediments at least since the Middle Pleistocene. Several attempts to recover sub-bottom sediments from Lake Biwa have been made, including epoch-making recovery of core samples totaling about 200 m long in 1971 (Horie, 1984) and drilling of the entire lake sediments through the basement rock in 1982 and 1983 (Takemura, 1990). These studies revealed that the lake basin contains a sedimentary sequence of about 900 m thick, which was deposited in lacustrine or fluvial environments during the Pliocene and the Pleistocene. The uppermost 250 m thick unit consists of continuous clay sediments with about 50 volcanic ash layers. Based on tephrochronological and paleo-climatological data, the 250-m clay unit is correlated to major glacial-interglacial cycles for the last 430,000 years (e.g., Meyers *et al.*, 1993). Hence, Lake Biwa sediment is expected to offer continuous records of past geomagnetic field and environmental changes since the Middle Pleistocene.

Kawai *et al.* (1972) found the occurrence of anomalous remanent magnetizations in the core samples from Lake Biwa, assigning them to the Blake event, the Biwa I and Biwa II excursions. Yaskawa *et al.* (1973) also reported records of short excursions, which were then dated at about 18,000 and 49,000 yr BP. After these pioneering works in the 1970's, many records of geomagnetic excursions have been reported from the eastern Asian region, including a Chinese loess/paleosol sequence (Fang *et al.*, 1997) and the sediments of Lake Baikal (Oda *et al.*, 2002). It is difficult, however, to investigate the possible correlation of these reported excursions because questions have been raised about the excursion records from Lake Biwa. These questions result from changes in the chronology of the earlier Lake Biwa studies and from unresolved issues about the reliability of the records of Lake Biwa excursions. The concerns about the older Lake Biwa paleomagnetic studies should be addressed using new cores and more rigorous modern techniques.

We have made a high-resolution studies of multiple pis-

---

[*] Now at Schlumberger Infomation Solutions, Calgary, Canada.

Table 1. Radiocarbon dates and tephra ages used for the age-model of core BIW95-4 from Lake Biwa.

Composite depth (m)	Sample code	Material	Lab number	^{14}C age (yr BP)	1 sigma	Calendar age (ka)	Calibration method*
1.65	BIW95-4A/102	leaf	HGr-995	2431	110	2.54	1
1.86	Kawagodaira	volcanic ash				2.95	2
2.81	BIW95-4A/218	leaf	HGr-1008	4910	120	5.67	1
3.21	Kikai-Akahoya (K-Ah)	volcanic ash		6300		7.25	1*
4.13	Ulreung-Oki (U-Oki)	volcanic ash				10.19	2
6.83	Sakate	volcanic ash				18.73	2
7.71	BIW-95-4-3A/203	leaf	HGr-1009	17770	150	21.15	1
9.98	BIW95-4-3B/175	TOC	HGr-1117	22200	400	25.80	2
10.90	BIW95-4-4A/15-20	TOC	HGr-1113	25200	500	28.60	2
11.76	Aira-Tn (AT)	volcanic ash				28.78	2
12.00	BIW95-4-4A/125-130	TOC	HGr-1114	27670	600	31.50	2
12.75	BIW95-4-4A/200-205	TOC	HGr-1115	30200	800	32.30	2
13.46	BIW95-4-4B/22	leaf	HGr-1010	29900	750	32.00	2
14.00	BIW95-4-4B/75	leaf	HGr-1001	32500	1400	33.90	2
14.66	BIW95-4-4B/141	leaf	HGr-1011	>37500			

*Calibration of radiocarbon age was made using 1: Stuiver *et al.* (1998) and 2: Kitagawa and van der Plicht (1998). The ^{14}C age of the K-Ah ash is after Machida and Arai (1978).

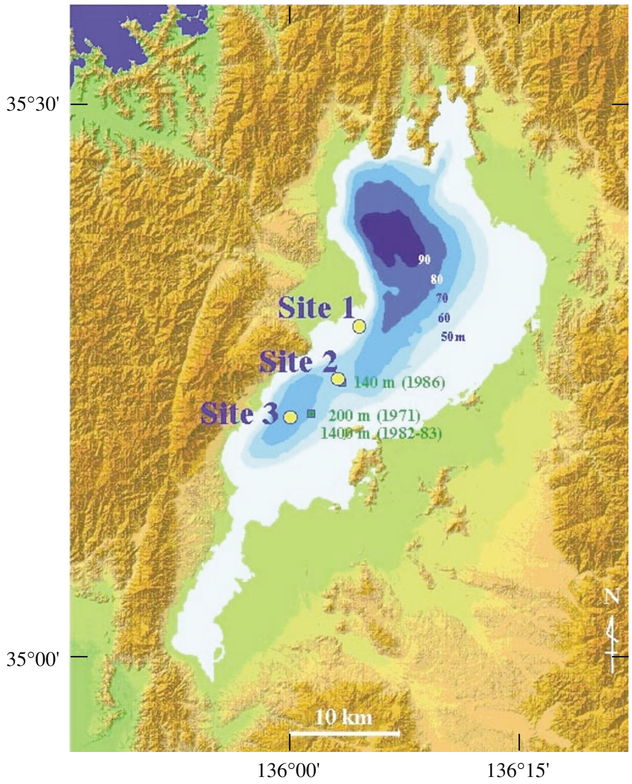

Fig. 1. Map showing location of piston coring sites in Lake Biwa. Locations of previous deep drillings in 1971 and 1982–83 are also shown.

ton cores obtained at three sites in the central part of Lake Biwa (Fig. 1), aiming to produce high-resolution records of PSVs and sub-Milankovitch paleoclimate changes (Takemura *et al.*, 2000). A composite PSV record for the Holocene was constructed by fine-scale adjustment and stacking of three piston cores obtained from Site 3 (35°13′N, 136°00′E; Ali *et al.*, 1999). Here we describe results of magnetic measurements on a 15-m long piston-core from Site 2 (35°15′N, 136°03′E), which spans the last 40 kyrs. The rock magnetic parameters provide high-resolution records of paleoclimate variability since 40 kyrs ago, including abrupt interstadial events during the last glacial period.

2. Age Model

Two piston cores of about 15 to 16 meters long, cores BIW95-4 and BIW95-5, were recovered at Site 2, off Shirahige Beach in a water depth of 67 m (Fig. 1). These cores were mainly composed of homogeneous bluish gray to gray clay and silty clay, intercalated with 10 volcanic ash layers. Based on lithological description and magnetic susceptibility profiles, we established a detailed core-to-core correlation and obtained the composite depth scale as described by Takemura *et al.* (2000). Among the 10 volcanic ashes, we found widespread tephra layers such as the Kawagodaira (Kg), Kikai-Akahoya (K-Ah), Ulreung-Oki (U-Oki), Sakate, Daisen-Higashi Daisen (DHg), Daisen-Sasaganaru (DSs; including both plinian and co-ignimbrite units) and Aira-Tn (AT) ashes.

In order to construct the age model for core BIW95-4, we adopted the published ^{14}C age of the K-Ah ash (Machida and Arai, 1978) and the varve counting data of the Kg, U-Oki, Sakate and AT ashes from Lake Suigetsu (Kitagawa and van der Plicht, 1998), as shown in Table 1. We also collected single pieces of terrestrial macrofossils such as leaves, small branches and insect wings from 9 horizons and additional mud samples from 5 horizons of core BIW95-4 for radiocarbon dating at the AMS facility of Nagoya University. Among them, 9 AMS ages were obtained and calibrated using INTCAL98 (Stuiver *et al.*, 1998) for the data younger than 22,000 calibrated year B.P., and using the Lake Suigetsu calibration curve (Kitagawa and van der Plicht, 1998) for the older interval (Table 1).

Our radiocarbon dates are generally consistent with the published ages of the widespread tephras, as shown in Fig. 2. However, some ages from bulk total organic carbon (TOC) samples are slightly older when compared with the

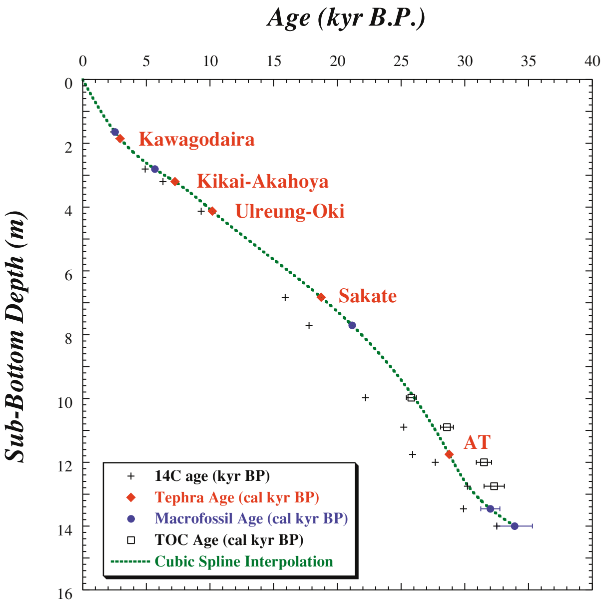

Fig. 2. Age model for Core BIW95-4 from Site 2 based on varve chronology of five widespread tephra layers and five calibrated AMS radiocarbon dates of macrofossils. Slightly older ages from TOC samples were not included for the age model construction.

age of the Aira-Tn (AT) tephra (25.9 kyr ^{14}C BP and 28.8 cal kyr BP; Kitagawa and van der Plicht, 1998). The AT tephra is one of the most important time markers of the last glacial period in Japan, which has yielded radiocarbon ages between 24 and 25 kyr ^{14}C BP (Matsumoto *et al.*, 1987; Murayama *et al.*, 1993; Miyairi *et al.*, 2004). Hence we discarded the four TOC samples and constructed an age model by cubic spline interpolation of the macrofossil data and the tephra ages (Fig. 2). The two cores from Site 2 cover the time interval for about 40 kyrs, providing an average sedimentation rate of about 40 cm/kyr.

3. Magnetic Measurements

We made magnetic measurements of 615 cubic samples of 7 cm^3, which were sampled at about 2.4 cm spacing from core BIW95-4. Low-field magnetic susceptibility of these samples, measured on a Bartington Instruments susceptibility meter with a MS1B sensor operating at a frequency of 0.47 kHz, were reported in Takemura *et al.* (2000).

Natural remanent magnetization (NRM) was measured on a cryogenic magnetometer (ScT C-112) at Kyoto University. Sixteen pilot samples were measured after stepwise alternating field (AF) demagnetization up to 60 mT at 5 mT intervals. Additionally, every fifteenth sample was measured after stepwise AF demagnetization at 15, 25, and 35 mT. Typical results of the stepwise AF demagnetization are shown in Fig. 3. All pilot samples selected for stepwise AF demagnetization exhibit a stable and well-defined single component. The AF demagnetization at 15 mT was found more than sufficient to remove the soft remanence that may be of viscous origin acquired in the laboratory. Samples that show anomalous direction were examined by additional treatment with 25 and 45 mT AF demagnetization and twelve samples were rejected which had possessed unstable remanence. The remaining samples show less than

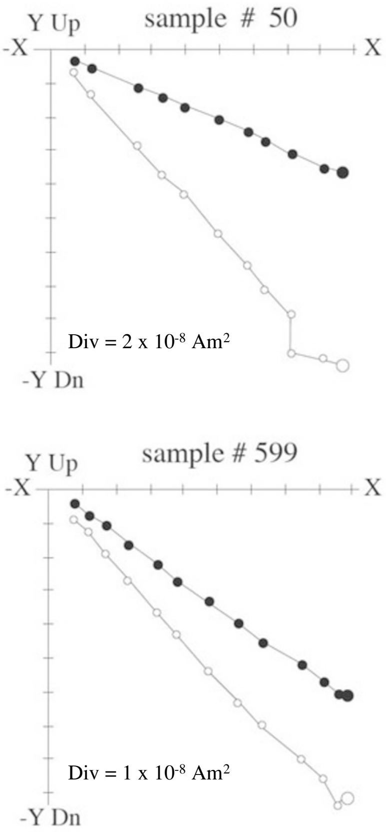

Fig. 3. Representative results of stepwise alternating field demagnetization for samples #50 from 2.47 m and #599 from 15.06 m core depth. Open and closed symbols indicate projection of vector end-points on the vertical and horizontal planes, respectively.

2° of scatter in direction and are believed to be free of secondary overprints. Low-coercivity ferrimagnetic minerals, such as magnetite of pseudo-single domain size, are assumed because the majority of pilot samples lost more than 90% of their initial remanence between 50 and 60 mT. The median destructive field (MDF) for the pilot samples ranged between 23 and 38 mT.

After the NRM measurements, we made acquisition experiments of anhysteretic remanent magnetization (ARM) for all the samples and isothermal remanent magnetization (IRM) for half of the samples at about 5 cm intervals. The ARM was imparted in a 100 mT peak AF with a 0.1 mT steady field, and the ARM susceptibility (k_{ARM}) was obtained by dividing the ARM intensity by the biased field. The IRM was given in a static field at 1 T produced by an electromagnet. We also obtained back-field IRMs at 0.3 T in order to calculate the S-ratio ($S_{-0.3\mathrm{T}}$) using the definition of Bloemendal *et al.* (1992): S = ((− back-field IRM / IRM) + 1) / 2. This ratio, ranging from 0 to 1, measures the proportion of low-coercivity magnetic minerals to higher coercivity grains.

4. Variation of Paleomagnetic Directions

The declination, inclination and intensity profiles plotted on our age model are shown in Fig. 4. The ash layers in the cores were found perpendicular to the core barrel liner suggesting that the corer penetrated vertically during the coring

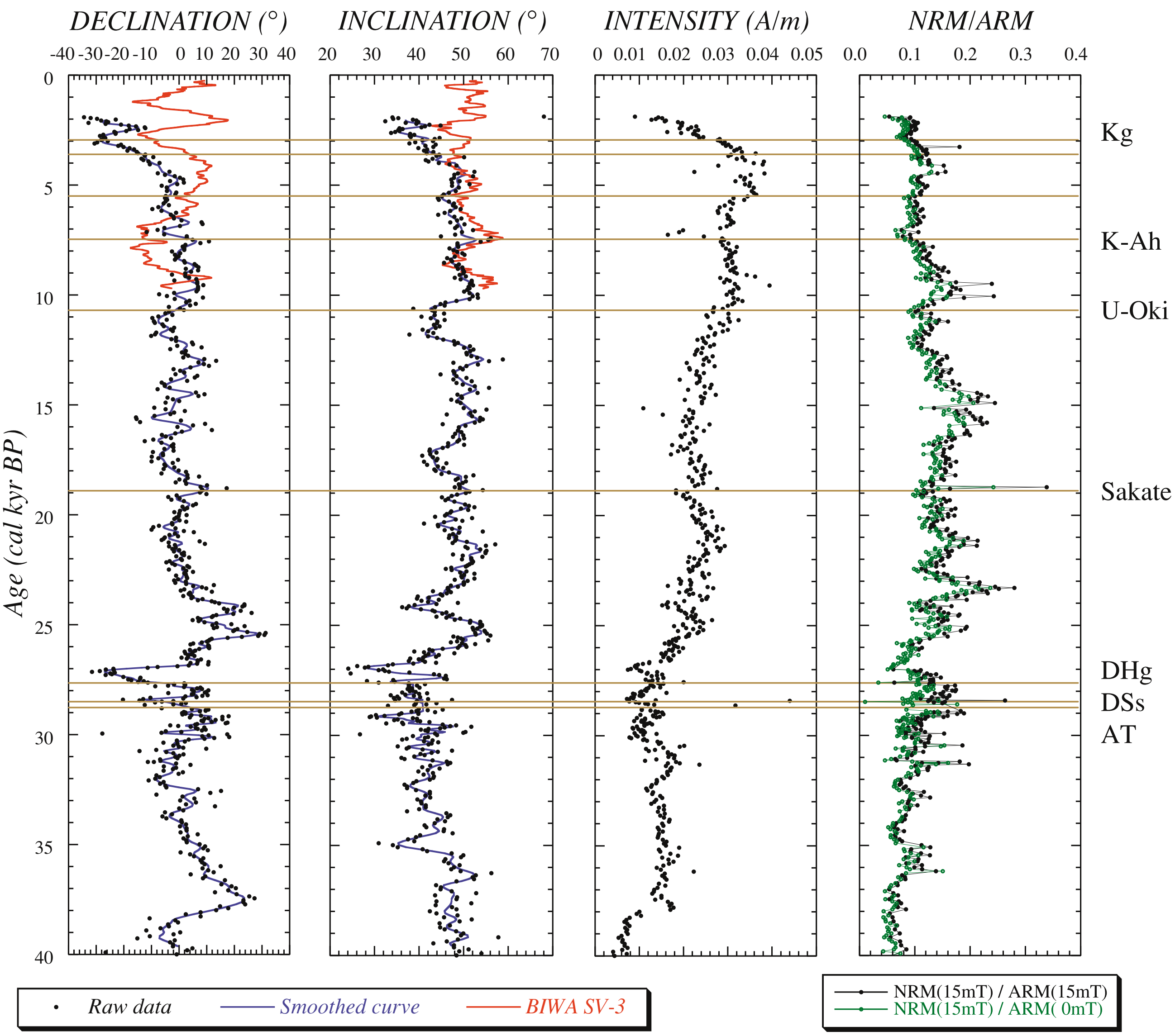

Fig. 4. Variation of declination, inclination and intensity of remanent magnetization observed in the BIW95-4 core after AF demagnetization at 15 mT. The Holocene PSV record obtained at Site 3 in Lake Biwa (BIWA SV-3; Ali *et al.*, 1999) is shown for the last 10 cal kyr. Also shown is variation of the NRM/ARM ratio. The horizontal lines show horizons of volcanic ash layers (See text for the abbreviations). The Daisen-Sasaganaru (DSs) tephra layer consists of the plinian and co-ignimbrite units.

procedure. Therefore inclinations observed relative to the axis of core barrel represent the true inclination relative to the bedding plane. Because the core was not azimuthally oriented, the zero-declination is set for the mean declination of the entire core. We then applied the filter function of seven-point weighted vector mean, the same technique used by Verosub *et al.* (1986) and Ali *et al.* (1999). The weighting factors for the filter are 0.037, 0.230, 0.693, 1.000, 0.693, 0.230 and 0.037.

A large fluctuation of both declination and inclination was observed in the topmost part younger than 4 cal kyr BP and is probably due to mechanical deformation of the sediments during the piston coring. The period between 4 and 23 cal kyr BP shows maximum peak to peak amplitudes of 23° for declination and 14° for inclination. The mean inclination calculated for the interval between 4 and 23 cal kyr BP is 48.8°, which is close to but slightly shallower than the expected value (54.7°) from the geocentric axial dipole field at the coring site.

The directional variations for the last 10 cal kyr show a good agreement in morphology with the Holocene PSV record from Site 3 of Lake Biwa (BIWA SV-3; Ali *et al.*, 1999), as shown in Fig. 4. However, the amplitudes of the BIW95-4 core record seem to be subdued compared to BIWA SV-3. An average sedimentation rate at Site 3 is about 110 cm/ky, which is almost 2.5 times higher than that of Site 2 (40 cm/ky). The smaller amplitude observed at Site 2 may be a result of filtering effect or lock-in delay of post depositional remanent magnetization (PDRM). The effect of the PDRM filtering may also attenuate amplitude of the geomagnetic excursion records, as suggested by Thouveny and Creer (1992), Lund and Keigwin (1994), and Roberts and Winklhofer (2004).

As mentioned before, Yaskawa *et al.* (1973) reported occurrence of negative inclinations at about 18,000 and 49,000 yr BP in the core samples of Lake Biwa. Based on recent

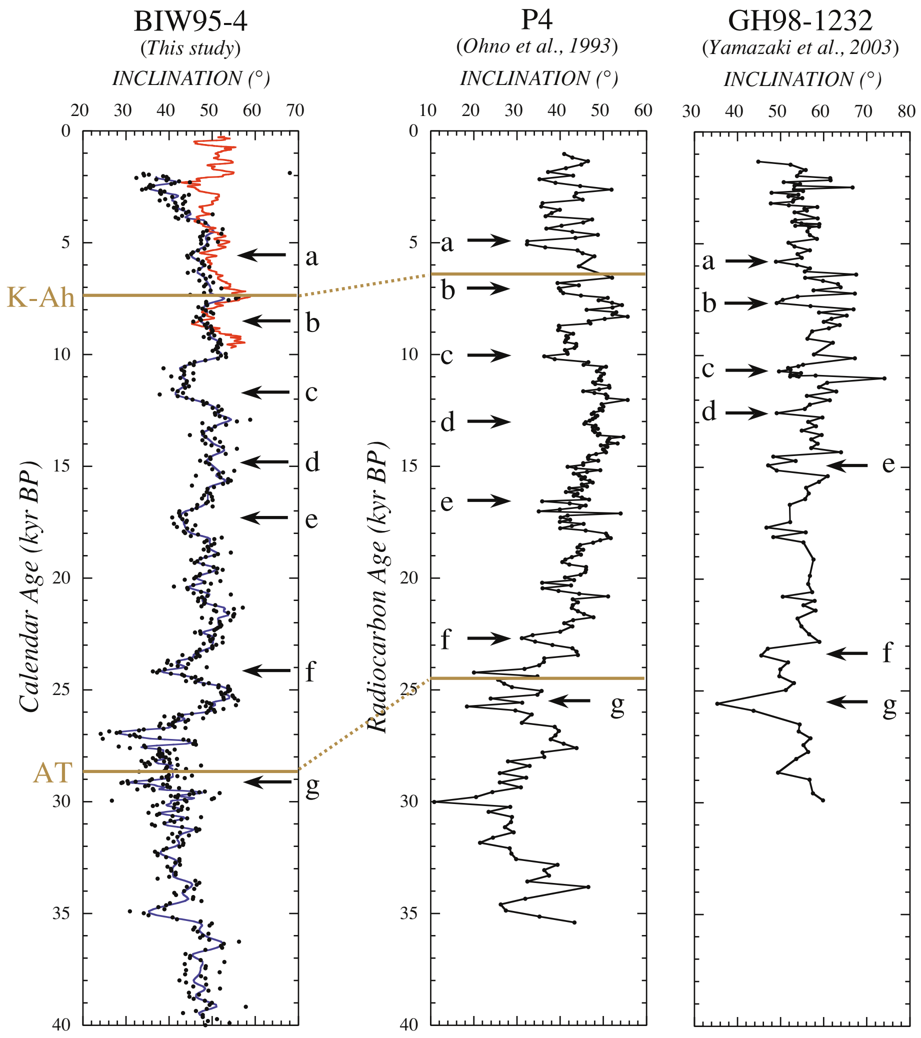

Fig. 5. Comparison of inclination profiles between the core from Lake Biwa (BIW95-4, this study), off Shikoku (Ohno *et al.*, 1993) and the Japan Sea (Yamazaki *et al.*, 2003). The inclination lows, shown by the arrows (a to g), can be correlated between sites, and is partly constrained by the occurrence of the K-Ah and AT tephras.

knowledge of tephrochronology (e.g. Machida *et al.*, 1991), these features correspond to the horizons below the K-Ah ash (7.3 cal kyr BP) and the AT tephra layer itself (28.8 cal kyr BP). While both ashes are found in the BIW95-4 core, we found no correlative anomalous PSV features. On the other hand, the horizon at about 27 cal kyr BP (10.4–10.9 m) in our core is characterized by relatively larger variation in paleomagnetic directions (Fig. 4). Considering the effect of the PDRM filtering, this record implies occurrence of a geomagnetic excursion. It is also noticeable that the NRM/ARM ratio shows a significant drop at this horizon (Fig. 4). Although it is not clear whether this core is suitable for relative paleointensity study, these results suggest a possibility that this interval represents a global geomagnetic feature of a millennial scale.

Our age model for the BIW95-4 core (Fig. 2) locates the excursional feature (27 cal kyr BP) close to estimated ages for the Mono Lake excursion at 24 to 25 ^{14}C kyr BP (Liddicoat and Coe, 1979) and about 28 ^{14}C kyr BP (Benson *et al.*, 1998). Recently, there is an intense debate about identification of the Mono Lake excursion at the original site, the Wilson Creek Formation in California. Kent *et al.* (2002) and Zimmerman *et al.* (2006) suggested that the anomalous paleomagnetic feature at Mono Lake is correlative with the Laschamp excursion at about 41 cal kyr BP. On the other hand, Benson *et al.* (2003) showed that the excursion is dated at about 32 cal kyr BP and correlated with a paleointensity low in the NAPIS-75 record (Laj *et al.*, 2000). It is therefore important to delineate the geomagnetic field variation corresponding to the excursion around 32 ka in widely distributed locations. However, the estimated age for the excursional feature in our core is 27 cal kyr BP, which is constrained from the AMS radiocarbon dates and published ages of the widespread tephra layers (Table 1 and Fig. 2). In particular, occurrence of the AT ash indicates that the horizon of our excursional feature is distinctively younger than 30 ka. We interpret that the large PSV swing in the BIW95-4 core represents a geomagnetic field variation associated with a paleointensity low younger than 30 ka.

When the inclination variation is compared to paleomagnetic records from marine sediments around the Japanese Islands (Ohno *et al.*, 1993; Yamazaki *et al.*, 2003), there is a good similarity between them. Yamazaki *et al.* (2003) pointed out that inclination lows found in the cores from

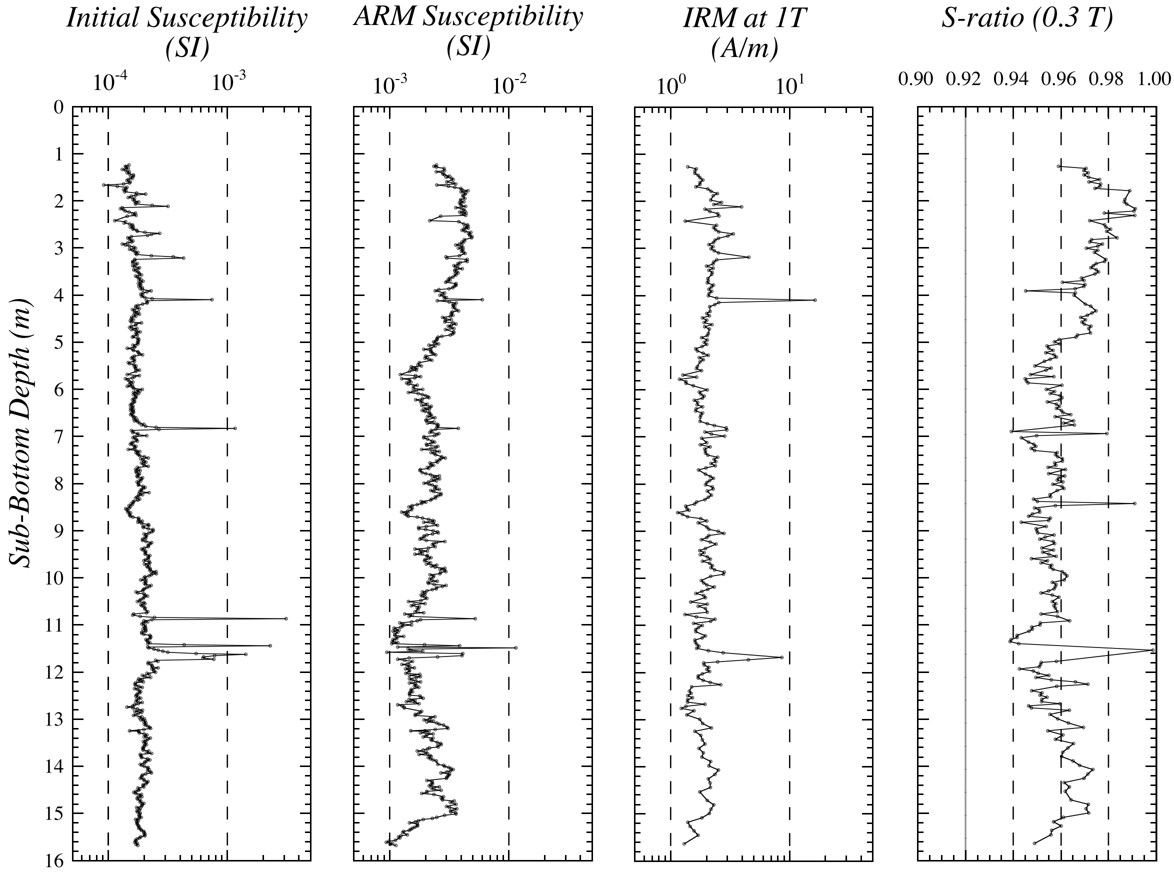

Fig. 6. Depth plots of initial susceptibility, k_{ARM}, isothermal remanent magnetization of 1 T and S-ratio at 0.3 T.

the Japan Sea (44°48′N, 139°42′E; Yamazaki *et al.*, 2003) and off Shikoku (32°09′N, 133°54′E; Ohno *et al.*, 1993) are well correlated each other, as shown in Fig. 5. Age models for both marine records are based on AMS radiocarbon dates of planktonic foraminifers, which were not converted to calendar ages. Nevertheless we can extend the inclination correlation to the Lake Biwa sediments, partly supported by common occurrence of the K-Ah and AT tephra deposits (Fig. 5). The regional similarity in inclination strongly suggests that these inclination features reflect variation of the geomagnetic field around Japan for the last 40 kyrs.

5. Environmental Magnetic Record

Figure 6 shows depth profiles of the low-field magnetic susceptibility, k_{ARM}, IRM of 1 T and S-ratio at 0.3 T. The variations of these parameters show outstanding peaks at several horizons, which correspond to volcanic ash layers. Except for these peaks, the three parameters covary with each other at some intervals, but the correlation is not so significant, in particular between the initial susceptibility and the k_{ARM}. Because the initial susceptibility is measured in a magnetic field, it may be controlled by diamagnetic and paramagnetic minerals rather than the remanence carriers. It is generally believed that the ARM is more sensitive to the presence of small magnetite grains compared to low-field susceptibility or saturation IRM (e.g., King *et al.*, 1983; Bloemendal *et al.*, 1993). The ARM results suggest that the abundance of fine-grained magnetite is increased at the interval above 5 m, which corresponds to the post-glacial period. The IRM and S-ratio data shows consistent variation with the ARM. The interval between 11 and 12 m deep seems to be characterized by relatively coarse-grained magnetite, which is probably explained by the presence of several volcanic ash layers at this interval.

Figure 7 shows the variation of total organic carbon (TOC) content (Yamada, 2004) and k_{ARM} from the BIW95-4 core. The TOC data shows increased value in the upper intervals, which correspond to the post-glacial period. The increased TOC values suggest that the post-glacial period is characterized by enhanced aquatic productivity and an increased flux of wash-in nutrients and organic matter, as described by Meyers *et al.* (1993). As shown in Fig. 7, the amount of magnetic minerals represented by the k_{ARM} shows a variation similar to the total organic carbon content. The k_{ARM} data suggest that the fine-grained magnetite flux was also increased during warm periods, probably associated with enhanced precipitation.

We also compared the magnetic concentration in the Lake Biwa sediments with the oxygen isotope records from the Greenland ice core, NGRIP (Johnsen *et al.*, 2001; North Greenland Ice Core project members, 2004) in Fig. 7. The k_{ARM} data is characterized by abrupt increases of fine-grained magnetite at several intervals during the last glacial period. These peaks may represent interstadial events, which were presumably linked with the Dansgaard-Oeschger (D-O) cycles (Dansgaard *et al.*, 1993). In particular, the k_{ARM} data between 30 and 40 cal kyr BP show similar variations with the ice core record of the D-O events 5

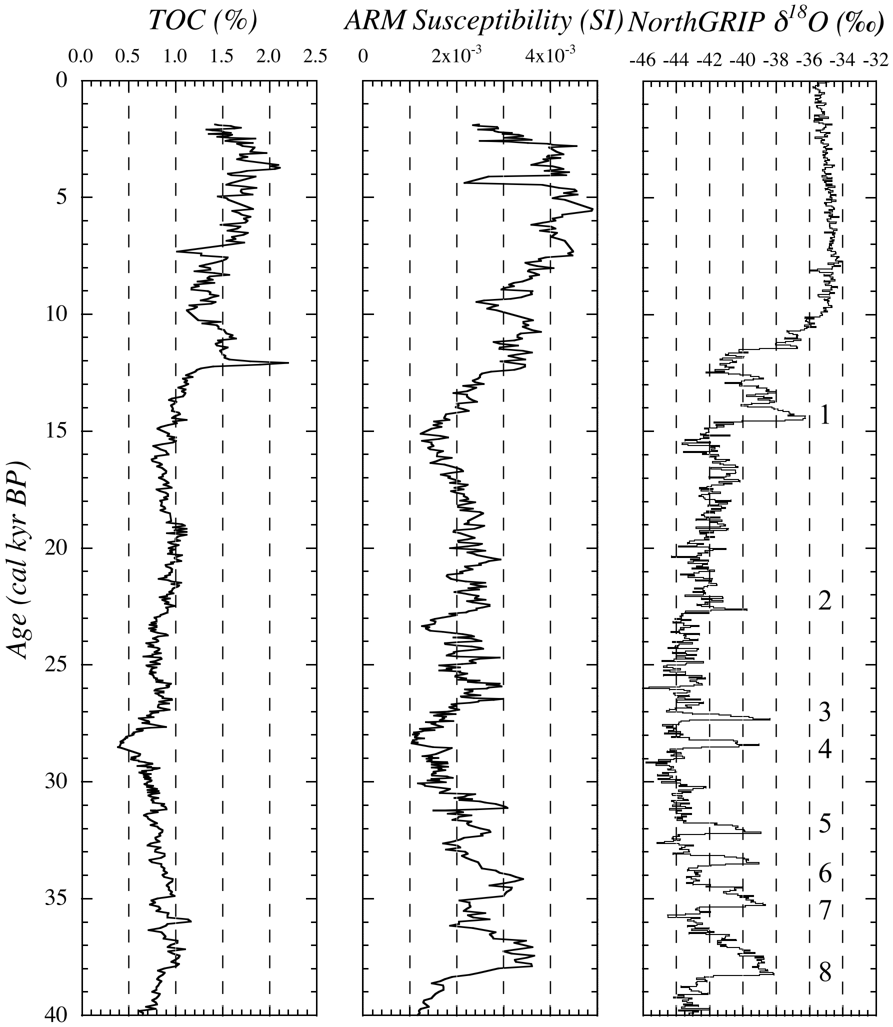

Fig. 7. Comparison of the total organic carbon (TOC) content (Yamada, 2004) and the magnetic concentration (k_{ARM}) of core BIW95-4 from Lake Biwa. The variation of k_{ARM} also shows good similarity with the oxygen isotope record from the Greenland ice core (NGRIP; North Greenland Ice Core Project members, 2004). The numbers (1 to 8) show the interstadial events in the Dansgaard-Oeschger cycles.

to 8, although the younger D-O events are not clearly identified. Evidence of the Younger Dryas cold event is not observed in the rock magnetic signature between 10 and 15 ka, where the k_{ARM} record shows a gradual increase contrasting to the Greenland ice core isotope record.

As mentioned before, the Mono Lake excursion was suggested to correspond to a paleointensity low at about 32 ka (Benson *et al.*, 2003). It was also reported that a peak of ^{36}Cl concentration occurs between the D-O events 6 and 7 at about 32 ka in the GRIP ice core (Wagner *et al.*, 2000). Our assignment of the k_{ARM} record with the D-O events 5 to 8 suggests that at least a directional feature of the Mono Lake excursion was not recorded at the corresponding interval in the Lake Biwa sediments. Significant directional features were also not observed in core samples from Lake Baikal (Peck *et al.*, 1996) and the western Equatorial Pacific (Blanchet *et al.*, 2006; Leduc *et al.*, 2006), although these cores show paleointensity lows which can be linked to the Mono Lake excursion. The Laschamp excursion is dated at 40.4 ± 2.0 ka (Guillou *et al.*, 2004) and assigned near the D-O event 10 (Kissel *et al.*, 1999). Unfortunately our core did not reach to the interval of the D-O event 10, where a record of the Laschamp excursion may be observed.

6. Conclusion

Detailed paleomagnetic analysis of Core BIW95-4 from Lake Biwa provided a record of geomagnetic field for the last 40 cal kyr, which is comparable to the Holocene PSV records obtained from the deeper site of Lake Biwa and also with the older inclination features reported from the Japan Sea and off Shikoku. In addition, this research suggests that rock magnetic properties of the sediment core form Lake Biwa provide an interpretable proxy of environmental change such as the Dansgaard-Oeschger cycles. We can expect to observe similar paleoclimatically sensitive mineral magnetic records from the older sediments in Lake Biwa. Combination of the detailed paleomagnetic record and the sub-Milankovitch climate cycles provides a clue to understand geomagnetic secular variation and polarity excursions in space and time. We therefore propose a future drilling project in Lake Biwa to obtain high-resolution paleomagnetic and mineral magnetic records of fine-grained sedimentary sequences in order to extend the records presented here further back in time.

Acknowledgments. We acknowledge Makoto Okamura and Hiromi Matsuoka for their support with the coring work in Lake

Biwa. We thank K. Yamada for providing the TOC data. This manuscript was greatly improved by the reviews of N. Thouveny and J. A. Peck. This work was partly supported by the Grant-in-Aid for Scientific Research from Japan Society for the Promotion of Science (19204050).

References

Ali, M., H. Oda, A. Hayashida, K. Takemura, and M. Torii, Holocene paleomagnetic secular variation at Lake Biwa, central Japan, *Geophys. J. Int.*, **136**, 218–228, 1999.

Benson, L. V., S. P. Lund, J. W. Burdett, M. Kashgarian, T. P. Rose, J. Smoot, and M. D. Schwartz, Correlation of Late-Pleistocene lake level oscillations in Mono Lake, California, with North Atlantic climate events, *Quaternary Research*, **49**, 1–10, 1998.

Benson, L., J. C. Liddicoat, J. Smoot, A. Sarna-Wojcicki, R. Negrini, and S. Lund, Age of the Mono Lake excursion and associated tephra, *Quaternary Science Reviews*, **22**, 135–140, 2003.

Blanchet, C. L., N. Thouveny, and T. de Garidel-Thoron, Evidence for multiple paleomagnetic intensity lows between 30 and 50 ka BP from a western Equatorial Pacific sedimentary sequence, *Quaternary Science Reviews*, **25**, 1039–1052, 2006.

Bloemendal, J., J. W. King, F. R. Hall, and 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**, 4361–4375, 1992.

Bloemendal, J., J. W. King, A. Hunt, P. B. deMenocal, and A. Hayashida, Origin of the sedimentary magnetic record at Ocean Drilling Program sites on the Owen Ridge, western Arabian Sea, *J. Geophys. Res.*, **98**, 4199–4219, 1993.

Dansgaard, W. *et al.*, Evidence for general instability of past climate from a 250-kyr ice core record, *Nature*, **364**, 218–220, 1993.

Evans, M. E. and F. Heller, *Environmental Magnetism—Principles and Applications of Enviromagnetics*, 293 pp., Academic Press, 2003.

Fang, X.-M., J.-J. Li, R. Van der Voo, C. M. Niocaill, X.-R. Dai, R. A. Kemp, E. Derbyshire, J.-X. Cao, J.-M. Wang, and G. Wang, A record of the Blake Event during the last interglacial paleosol in the western Loess Plateau of China, *Earth Planet. Sci. Lett.*, **146**, 73–82, 1997.

Guillou, H., B. S. Singer, C. Laj, C. Kissel, S. Scaillet, and B. R. Jicha, On the age of the Laschamp geomagnetic excursion, *Earth Planet. Sci. Lett.*, **227**, 331–343, 2004.

Horie, S. (ed.), *Lake Biwa*, 654 pp. Dr. W. Junk Publishers, Dordrecht, 1984.

Johnsen, J. S., D. Dahl-Jensen, N. Gundestrup, J. P. Steffensen, H. B. Clausen, H. Miller, V. Masson-Delmotte, A. E. Sveinbjörnsdottir, and J. White, Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRIP, *Journal of Quaternary Science*, **16**, 299–307, 2001.

Kawai, N., K. Yaskawa, T. Nakajima, M. Torii, and S. Horie, Oscillating geomagnetic field with a recurring reversal discovered from Lake Biwa, *Proc. Japan Acad.*, **48**, 186–190, 1972.

Kent, D. V., S. R. Hemming, and B. D. Turrin, Laschamp excursion at Mono Lake?, *Earth Planet. Sci. Lett.*, **197**, 151–164, 2002.

King, J. W., S. K. Banerjee, and J. Marvin, A new rock-magnetic approach to selecting sediments for geomagnetic paleointensity studies: application to paleointensity for the last 4000 years, *J. Geophys. Res.*, **88**, 5911–5921, 1983.

Kissel, C., C. Laj, L. Labeyrie, T. Dokken, A. Voelker, and D. Blamart, Rapid climatic variations during climatic stage 3: Magnetic analysis of North Atlantic sediments, *Earth Planet. Sci. Lett.*, **171**, 489–502, 1999.

Kitagawa, H. and J. van der Plicht, A 40,000-year varve chronology from Lake Suigetsu, Japan: Extension of the radiocarbon calibration curve, *Radiocarbon*, **40**, 505–516, 1998.

Laj, C., C. Kissel, A. Mazaud, J. E. T. Channell, and J. Beer, North Atlantic paleointensity stack since 75 ka (NAPSIS-75) and the duration of the Laschamp event, *Phil. Trans. R. Soc. London, A*, **358**, 1009–1025, 2000.

Leduc, G., N. Thouveny, D. L. Bourlès, C. L. Blanchet, and J. T. Carcaillet, Authigenic ^{10}Be/^{9}Be signature of the Laschamp excursion: A tool for global synchronisation of paleoclimatic archives, *Earth Planet. Sci. Lett.*, **245**, 19–28, 2006.

Liddicoat, J. C. and R. S. Coe, Mono Lake geomagnetic excursion, *J. Geophys. Res.*, **84**, 261–271, 1979.

Lund, S. and L. Keigwin, Measurement of the degree of smoothing in sediment paleomagnetic secular variation records: an example from late Quaternary deep-sea sediments of the Bermuda Rise, western North Atlantic Ocean, *Earth Planet. Sci. Lett.*, **122**, 317–330, 1994.

Machida, H. and F. Arai, Akahoya Ash—a Holocene widespread tephra erupted from the Kikai Caldera, south Kyushu, Japan, *The Quaternary Research (Japan)*, **17**, 143–163, 1978.

Machida, H., F. Arai, and T. Yokoyama, Re-examination of maker-tephra layers in the 200 m Biwa-lake core, *The Quaternary Research (Japan)*, **30**, 439–442, 1991.

Matsumoto, E., Y. Maeda, K. Takemura, and S. Nishida, New radiocarbon age of Aira-Tn ash (AT), *The Quaternary Research (Japan)*, **26**, 79–83, 1987.

Meyers, P. A., K. Takemura, and S. Horie, Reinterpretation of Late Quaternary sediment chronology of Lake Biwa, Japan, from correlation with marine glacial-interglacial cycles, *Quaternary Res.*, **39**, 154–162, 1993.

Miyairi, Y., K. Yoshida, Y. Miyazaki, H. Matsuzaki, and I. Kaneoka, Improved ^{14}C dating of a tephra layer (AT tephra, Japan) using AMS on selected organic fractions, *Nuclear Instruments and Methods in Physics Research B.*, **223–224**, 555–559, 2004.

Murayama, M., E. Matsumoto, T. Nakamura, M. Okamura, H. Yasuda, and A. Taira, Re-examination of the eruption age of Aira-Tn Ash (AT) obtained from a piston core off Shikoku—determined by AMS ^{14}C dating of planktonic foraminifera—, *J. Geol. Soc. Japan*, **99**, 787–798, 1993.

North Greenland Ice Core Project members, High-resolution record of Northern Hemisphere climate extending into the last interglacial period, *Nature*, **431**, 147–151, 2004.

Oda, H., K. Nakamura, K. Ikehara, T. Nakano, M. Nishimura, and O. Khlystov, Paleomagnetic record from Academician Ridge, Lake Baikal: a reversal excursion at the base of marine oxygen isotope stage 6., *Earth Planet. Sci. Lett.*, **202**, 117–132, 2002.

Ohno, M., Y. Hamano, M. Murayama, E. Matsumoto, H. Iwakura, T. Nakamura, and A. Taira, Paleomagnetic record over the past 35000 years of a sediment core from off Shikoku, Southwest Japan, *Geophys. Res. Lett.*, **20**, 1395–1398, 1993.

Peck, J. A., J. W. King, S. W. Colman, and V. A. Kravchinsky, An 84-kyr paleomagnetic record from the sediments of Lake Baikal, Siberia, *J. Geophys. Res.*, **101**, 11365–11385, 1996.

Roberts, A. P. and M. Winklhofer, Why are geomagnetic excursions not always recorded in sediments? Constraints from post-depositional remanent magnetization lock-in modeling, *Earth Planet. Sci. Lett.*, **227**, 345–359, 2004.

Stuiver, M., P. J. Reimer, E. Bard, J. W. Beck, G. S. Burr, K. A. Hughen, B. Kromer, G. McCormac, J. Van Der Plicht, and M. Spurk, INTCAL98 radiocarbon age calibration, 24,000-0 cal BP, *Radiocarbon*, **40**, 1041–1083, 1998.

Takemura, K., Tectonic and climatic record of the Lake Biwa, Japan, region provided by the sediments deposited since Pliocene times, *Palaeogeogr. Palaeoclimat. Palaeoecol.*, **78**, 185–193, 1990.

Takemura, K., A. Hayashida, M. Okamura, H. Matsuoka, M. Ali, Y. Kuniko, and M. Torii, Stratigraphy of multiple piston-core sediments for the last 30,000 years from Lake Biwa, Japan, *J. Paleolimnol.*, **23**, 185–199, 2000.

Thouveny, N. and K. M. Creer, Geomagnetic excursions in the last 60 thousand years: ephemeral secular variation features, *Geology*, **20**, 399–402, 1992.

Verosub, K. L., P. J. J. Mehringer, and P. Waterstraat, Holocene secular variation in western North America: Paleomagnetic record from Fish Lake, Harney County, Oregon, *J. Geophys. Res.*, **91**, 3609–3623, 1986.

Wagner, G., J. Beer, C. Laj, C. Kissel, J. Masarik, R. Muscheler, and H.-A. Synal, Chlorine-36 evidence for the Mono Lake event in the Summit GRIP ice core, *Earth Planet. Sci. Lett.*, **181**, 1–6, 2000.

Yamada, K., Last 40 ka climate changes as deduced from the lacustrine sediments of Lake Biwa, central Japan, *Quaternary Int.*, **123–125**, 43–50, 2004.

Yamazaki, T., A. L. Abdeldayem, and K. Ikehara, Rock-magnetic changes with reduction diagenesis in Japan Sea sediments and preservation of geomagnetic secular variation in inclination during the last 30,000 years, *Earth Planets Space*, **55**, 327–340, 2003.

Yaskawa, K., T. Nakajima, N. Kawai, M. Torii, N. Natsuhara, and S. Horie, Palaeomagnetism of a core from Lake Biwa (I), *J. Geomag. Geoelectr.*, **25**, 447–474, 1973.

Zimmerman, S. H., S. R. Hemming, D. V. Kent, and S. Y. Searle, Revised chronology for late Pleistocene Mono Lake sediments based on paleointensity correlation to the global reference curve, *Earth Planet. Sci. Lett.*, **252**, 94–106, 2006.

A. Hayashida (e-mail: ahay@mail.doshisha.ac.jp), M. Ali, Y. Kuniko, H. Kitagawa, M. Torii, and K. Takemura