A Geomagnetic Secular Variation Record for the Last Glacial Period, Reconstructed from Coastal Bog Sediments on the Inland Sea of Japan

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A paleomagnetic secular variation record of geomagnetic field direction for the time span from 25 to 16 ka was obtained from oriented bog sediment samples in a coastal area of the eastern Inland Sea, Japan. The plot of this secular variation record, combined with Holocene secular variation data, shows that a long-term westerly declination feature began after 16 ka and ended at 7.5 ka. This feature lasted more than 4,000 years and less than 8,500 years. The declinations at 25–16 ka are dominated by easterly values, and no westerly declination was observed in the time span of 24–19.5 ka. The inclinations at 25–16 ka are characterized by slightly shallow values with small amplitude changes, compared to those in the Holocene. Prior to 18 ka a large clockwise looping was dominant in the motion of the geomagnetic vector, while counter-clockwise rotations were dominant after it. Many features of secular variation in the last glacial period have the potential to yield good age constraints for use in paleomagnetic dating.

Key Words : Paleomagnetism, geomagnetic secular variation, the last glacial period, bog sediment

I. Introduction

Paleomagnetic study of sedimentary sequences yields continuous records of the geomagnetic field of the past, extending our knowledge of geomagnetic field behaviors and geodynamic processes. Most data on reversal transitions, excursions, and secular variations have been obtained from paleomagnetic records in marine and lacustrine sediments. Past geomagnetic field behavior can also be useful for dating. Recent paleomagnetic studies of lacustrine and shallow-marine sediment cores have yielded time scales based on geomagnetic secular variation (SV) in various

regions (e.g., Hyodo *et al.*, 1993 ; Lund, 1996).

In Japan, an SV record of geomagnetic field direction has been obtained by stacking data from large-diameter (20 cm) cores taken from lakes and the Inland Sea (Hyodo *et al.*, 1993 ; Hyodo and Minemoto, 1996). This study has extended the time span of the SV record back to 11.6 ka, about six times that for archeomagnetic SV (Hirooka, 1971 ; Maenaka, 1990). There is presently no SV record prior to 11.6 ka constructed by stacking data from several sites.

The Holocene SV record in Japan has many prominent features that may be used for dating. One of these is the large westerly dec-

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lination swing that started before 11.6 ka and persisted until 7.5 ka. The time when this westerly swing started is presently unknown. Large early Holocene westerly declinations have also been detected in homogeneous marine clay in Osaka Bay using hand-oriented samples (Muroi and Yaskawa, 1977; Hyodo and Yaskawa, 1986) and in a stalagmite from western Japan (Morinaga *et al.*, 1992). Based on this information, the westerly swing is not an artifact of core twisting and/or core tilting, but a true geomagnetic signal. Determining exactly when this westerly declination swing began is important for magnetochronologic studies.

In this study, paleomagnetic fields have been reconstructed from hand-oriented samples of bog sediments formed during the last glacial period, and an SV record has been obtained for a time span of about 9,000 years. Characteristic features of the SV are discussed, along with similar features in the Holocene. Bog sediments have never been used for SV studies, but they were sometimes used for magnetostratigraphic studies, and yielded good quality paleomagnetic data (e.g., Qing and Zhou, 1991; Biswas *et al.*, 1999).

II. Geological setting and sampling

The Ikari-iwa Lowland (Tanaka, 1997) near Mitsu Town, Hyogo Prefecture, is located about 2 km north from the shoreline of the Inland Sea of Japan (Fig. 1). It is bounded to the north and south by hills less than 200 m high, and to the east by the Ibo River. The basement rocks in the hills consist of late Cretaceous rhyolites. Marine terrace deposits along the shore of the Inland Sea near Mitsu Town, which intercalate with the Akahoya (K-Ah) tephra layer, show that sea level rose as much as 3.5–5 m higher than at present after 6.3 ka (Naruse *et al.*, 1985). This marine transgression did not reach the present study site ($34^{\circ} 47.5' \text{N}$, $134^{\circ} 32.8' \text{E}$), where bog sediments are exposed at an elevation of about 8 m.

Paleomagnetic samples were taken from a section of sediments, about 4 m thick, that were deposited in a bog and exposed by agricultural activities. The conformable sequence of sediments consists mainly of horizontally layered

Fig. 1 Map showing sampling location
The star shows the sample site.

Table 1 Results of radiocarbon dating

Level (m)	^{14}C dates (years BP)	Calibrated dates (calendar years)	Sample material	Laboratory* Code No.
1.00	16100 ± 300	18900	humus	KEEA-80
3.22	22500 ± 225	25800	peat	KEEA-81

*Kyushu Environmental Evaluation Association (KEEA)
Dating method: benzene synthesis - liquid scintillation counting
Calibration is based on the varying oceanic circulation model by Laj *et al.* (1996) (see text).

fine-grained, peaty clay, clay and silt (Fig. 3), with an amphibolite-rich tephra layer (Naruse *et al.*, 1995) in its upper part. We have determined two radiocarbon dates in this sequence (Table 1), the first being $16,100 \pm 300$ yr 1.00 m below the top of the section and just below the tephra layer, and the second being $22,500 \pm 40$ yr 3.22 m below the top. These dates suggest that the tephra layer correlates with the Sambe Ukinuno pumice fall deposit (U2, SUP: Miura and Hayashi, 1991) or the Sambe Ukinuno pyroclastic flow deposit (U1: Matsui and Inoue, 1971). The age of the U2 tephra has been estimated at 15–16 ka (Matsui and Inoue, 1971) and 15.8 ka (Nomura *et al.*, 1995), and the

age of the U1 tephra at 15.6 ka (Katoh *et al.*, 1996). Naruse *et al.* (1995) suggested that the Aira-Tn (AT) tephra of 24.3 ka age (Murayama *et al.*, 1993) should be present below the bottom of the section, and this tephra was found by trenching about 30 m to the north and about 1 m below the bottom of the main section we sampled.

The procedure for hand-sampling is as follows: First, an excavation was made to a depth of 10–20 cm below the outcrop surface, and a horizontal surface was made in fresh sediments with non-magnetic tools. Second, a brass guide was fixed to the flat surface, and the azimuth and plunge of the guide were measured. Third, titanium tubes 5 cm long and 2.5 cm wide were forced into the sediment along the guide by blows of a plastic hammer. The guide and tubes were then taken off and the sediment sample in the titanium tube was carefully transferred into a cubic polycarbonate capsule with a volume of 10 cm³, using a tool with a titanium piston. To prevent drying, the cubic capsules were immediately sealed with a plastic bonding agent.

A total of 135 paleomagnetic samples from 28 horizons were collected, mainly from fine-grained sediments. All samples were stored in hermetically sealed cases with wet tissue paper to keep them moist, and measured in three weeks.

III. Conversion to a time scale

The vertical scale for the section was converted to a time scale using the two radiocarbon dates. The dates of 16.1 and 22.5 ka were corrected to 18.9 and 25.8 ka, respectively, using a geomagnetic calibration that is based on geomagnetic intensity and assuming a varying oceanic circulation model (Laj *et al.*, 1996). At present, we consider the geomagnetic calibration of Laj *et al.* (1996) to be the best available for the last 50 kyr, especially for studies beyond the range of dendrochronology (Stuiver and Reimer, 1993; Kromer and Becker, 1994). These calibration data are generally consistent with those from tree-ring calibration (Stuiver and Reimer, 1993; Kromer and Becker, 1994), varve calibration (Goslar *et al.*, 1995) and U-Th calibration (Bard *et al.*, 1990,

1993; Edwards *et al.*, 1993).

Each sampling level was dated by liner interpolation between the dated levels at 1.00 and 3.22 m, and extrapolated above 1.00 m using the accumulation rate of 32 cm/kyr calculated for the sequence below 1.00 m. There is no clear evidence to support the assumption of constant sedimentation, but the absence of evidence for a hiatus, less sand, and the almost constant susceptibility (except for the tuff layer), may support this assumption. The average accumulation rate of 32 cm/kyr is much lower than the rates seen in Holocene lake and shallow-marine sediments in Japan, such as 130 cm/kyr in Lake Kizaki, 83 cm/kyr in Lake Yogo (Hyodo *et al.*, 1993), and 90–150 cm/kyr in Osaka Bay (Takatsugi and Hyodo, 1995). However, this rate is consistent with those from bog sediments of the last glacial period. For example, accumulation rates are estimated to be 26 cm/kyr at Hosoiike Moor, western Japan (Nomura *et al.*, 1995), and 25 cm/kyr in Fusedame Pond, central Japan (Matsushita and Maeda, 1996).

IV. Magnetic measurements and results

Natural remanent magnetization (NRM) was measured using a 2G super-conducting rock magnetometer, and a tumbler-type Natsuhara alternating field demagnetizer was used for demagnetization. Low-field magnetic susceptibility was measured using a Bartington susceptibility meter.

NRM intensities range from $0.54\text{--}4.61 \times 10^{-3}$ Am⁻¹, and susceptibility values range from $6.6\text{--}25 \times 10^{-5}$ SI except for samples from the tephra layer. The samples that contain tephra materials have an average NRM intensity of 8.3×10^{-3} Am⁻¹ and an average susceptibility of 61.2×10^{-5} SI. These measurements are listed in Table 2, together with other magnetic results.

All specimens were subjected to progressive demagnetization in alternating fields (AF). They were first demagnetized at levels of 2.5, 5, 7.5, and 10 mT, and subsequent demagnetization levels were then selected depending on the degree of intensity decrement. Usually we adopted four to ten steps at levels of 15, 20, 25, 30, 40, 50, 60, 80, 100, and 120 mT. Median destruc-

Table 2 Results of magnetic measurements

Sample	Level	n/N_0	D	I	α_{95}	k	J_0	MDF	χ	Lithology
	(m)		(°)	(°)	(°)		(mA/m)	(mT)	(E-SSI)	
IK01	0.14	4/5	6.5	47.3	10.0	85.5	2.82	21	11.9	silt
IK02	0.19	4/5	4.4	45.2	14.4	41.9	2.90	18	17.3	silt
IK03	0.20	4/5	4.0	44.4	3.3	795.5	3.05	24	17.6	silt
IK04	0.25	4/5	-3.7	43.2	6.4	205.3	3.69	33	12.6	silt
IK05	0.32	4/5	7.8	35.2	9.4	97.5	2.57	25	14.0	peaty clay
IK06	0.34	4/5	12.3	43.6	10.4	79.0	3.03	29	12.0	peaty clay
IK07	0.37	4/5	5.4	49.5	9.3	99.1	2.89	29	18.5	peaty clay
IK08	0.41	5/5	6.2	46.1	12.2	40.4	2.39	22	17.7	peaty clay
IK09*	0.44	2/5	13.3	38.6			2.99	29	23.9	peaty clay
IW01	0.62	5/5	-31.3	49.2	11.7	44.0	2.14	12	13.1	peaty clay
IW02*	0.72	2/3	-12.7	36.4			2.15	28	15.0	peaty clay
IW03	0.81	3/3	-8.8	44.5	15.1	68.0	1.67	11	12.2	peaty clay
IW04*	0.88	2/3	-17.2	50.0			8.70	7	58.3	peaty clay
IW05	1.00	5/6	-7.5	43.4	13.8	31.8	1.29	19	10.3	peaty clay
IW16	1.04	5/5	-12.8	41.6	10.2	57.6	2.25	19	18.9	peaty clay
IW06	1.10	4/5	-16.3	50.9	7.8	139.8	1.32	14	7.6	peaty clay
IW17	1.22	5/5	7.0	47.5	3.3	528.3	2.18	19	17.4	peaty clay
IW18	1.64	5/5	15.1	50.2	9.9	60.9	2.31	15	14.3	silt
IW19	1.71	4/5	2.3	44.6	14.1	43.6	2.03	10	16.0	silt
IW08	2.06	5/5	13.2	46.2	8.9	75.7	1.63	12	13.1	clay
IW21	2.16	4/5	19.4	41.1	13.9	45.0	1.52	8	13.0	clay
IW07	2.53	5/5	6.8	44.6	8.1	90.8	0.84	6	9.9	clay
IW23	2.61	4/5	8.3	38.3	11.0	70.7	1.17	4	14.0	clay
IW24	2.68	4/5	15.4	35.3	12.8	52.3	1.40	3	15.5	clay
IW09	2.86	5/5	-30.7	43.9	9.4	67.1	0.99	8	12.3	peaty clay
IW10	3.07	5/5	-8.4	55.2	12.0	41.6	1.51	5	15.7	peaty clay
IW11*	3.22	3/5	5.9	43.6	23.7	28.2	0.78	5	11.6	peaty clay

n/N_0 : number of specimens yielding a ChRM / total specimen number

D, I: declination and inclination of a horizon mean ChRM

α_{95} : radius of 95%-confidence circle k: precision parameter J_0 : mean

NRM intensity MDF: mean destructive field χ : mean susceptibility

*Excluded in the plots of field directions in Figs. 3 and 4 (see text)

tive fields (MDF), at which the NRM intensity decreases to half the original value, ranged from 3 to 33 mT and were 16 mT on average.

Most of the samples have stable NRMs, as shown in the results of AF demagnetization in Figure 2. A weak viscous magnetization component was removed by demagnetization at an AF level lower than 7.5 mT. Characteristic remanent magnetizations (ChRM) were calculated for 110 clay or silt samples by principal component analysis (Kirschvink, 1980). ChRMs were not calculated for 25 samples, most of which except five coarse silt ones have lower MDFs < 5 mT or lower NRM intensities compared with other samples in the same horizon. The sediment structure of these samples may have been disturbed during the sampling procedure. The unstable NRMs of coarse silt samples, from which no ChRM was isolated, may be caused by coarse magnetic grains. No ChRM was obtained at one horizon. We did

not observe any difference in magnetic properties between organic and inorganic sediments. However, we find that the MDF tends to increase upward, while the magnetic susceptibility shows relatively uniform values from the base to the top (Fig. 3). This MDF change may indicate the increase of fine-grained magnetic minerals, caused by a gradual climate change or some other factors of paleoenvironment during the last glacial period.

The mean paleomagnetic direction was calculated for each horizon based on the ChRMs. The mean declination and inclination at 23 horizons, excluding those with an asterisk in Table 2, are shown in Figure 3. Four horizons with an asterisk in Table 2 either show a large scattering or yielded no statistical parameters, but they are consistent with the plotted directions.

Both the declination and inclination exhibit small amplitudes of change (Fig. 3). A notable

Fig. 2 Representative results from progressive AF demagnetization of samples of peaty clay (a), clay (b), and silt (c)

Solid and open circles show projections on the horizontal and vertical planes, respectively.

feature is that easterly declination is dominant, especially in the 2.7–1.2 m interval. The declination also evidences a long-term sinusoidal change.

Declination and inclination for the mean of average directions at all horizons are 1.1° and 45.6° , respectively. The inclination is shallower than that expected from the geocentric axial dipole, which is 54.3° . This shallow inclination does not reflect the inclination-shallowing in magnetization process. Post-depositional detrital magnetization is acquired along with the ambient magnetic field (Irving and Major, 1964), as has been verified in many laboratory experiments (e.g., Tucker, 1980; Otofujii and Sasajima, 1981) and by numerous paleomagnetic observations. No systematic inclination error has been found in Holocene SV records that are comparable to the SV from archeomagnetism (Turner and Thompson, 1981; Hyodo *et al.*, 1993), or from lava flows

(Lund, 1985). Inclination-shallowing due to compaction during diagenesis (Blow and Hamilton, 1978; Anson and Kodama, 1987; Arson and Levi, 1990) is also implausible because the bog sediments in Ikari-iwa Lowland have scarcely acquired overlying deposits following the last glacial. A shallow inclination during the last glacial period has also been observed in Pacific deep-sea sediments off Shikoku Island (Ohno *et al.*, 1993).

V. Discussion

1. Geomagnetic secular variation

The paleomagnetic field directions obtained in this study range from 25 to 16 ka in calendar years. These data are plotted in Figure 4, together with the Holocene SV record obtained in an area from central to southwestern Japan (Hyodo *et al.*, 1993). The time scale in conventional radiocarbon years is also shown on the right in Figure 4.

Fig. 3 Lithology, paleomagnetic field directions, NRM intensity, susceptibility, and MDF from the Ikari-iwa Lowland near Mitsu Town, southwestern Japan

The two arrows in the lithology show horizons dated by the radiocarbon method. The calibrated age data are shown. In the declination and inclination plots, the solid circles show the mean of characteristic remanent magnetizations at each horizon, and the error bars represent limits of a 95%-confidence circle. The magnetic data in the right three plots show the horizon mean values listed in Table 2.

The declination plot represents a cluster of values of about 5° E at 17–16 ka. The easterly declination in this period suggests that the long-term westerly declination swing that persisted until 7.5 ka in the early Holocene began after 16 ka, and that the time span of this westerly swing was 8,500 years at most. Before 17 ka, the westerly declination period and easterly declination period seem to alternate, although the latter period is longer. The long interval of easterly declination at 24–19.5 ka (Fig. 5) may be a useful age constraint.

The inclinations during the time span 25–16 ka change within a narrow range from 35° – 55° , but mostly between 40° and 50° (Fig. 4). Another salient feature is that there are no incli-

nation data steeper than 60° . Thus, the inclinations of paleomagnetic fields during the last glacial period were characterized by slightly shallow values with small amplitude changes.

For comparison, the paleomagnetic field direction at the time of the AT ash fall, calculated from the paleomagnetic chart of Nakajima and Fujii (1995), is also plotted in Figure 4. An age of 27.8 ka in calendar years is used for the AT tephra data, calibrated in the same way. The paleomagnetic direction is consistent with the features of the SV at 25–16 ka.

2. Field vector motion

The motion of the geomagnetic field vector in the Bauer plot in Figure 5 is characterized by elongated fluctuations confined to an east-

Fig. 4 Combined plot of geomagnetic secular variation data for southwestern Japan since 28 ka

The data in this study are plotted for 25.5–16 ka. The error bars show limits of a 95%-confidence circle. SVJ 1 data (Hyodo *et al.*, 1993) are for the time span 11.6–0.5 ka. The dots show mean directions for each 50-yr interval, and the thin lines represent a 95%-confidence circle. The diamond shows a paleomagnetic direction at the time of the AT ash fall, calculated from the magnetic chart of Nakajima and Fujii (1995).

west direction throughout the time span of 25–16 ka. This is caused by high-amplitude changes in declination, relatively to the inclination values. There was clearly a change in the sense of rotational motion at about 18 ka. The field vector was dominated by clockwise motion before 18 ka, and by counter-clockwise motions after 18 ka. The large clockwise looping motion seen in Figure 5-a has a period of about 5,000 years, which is much longer than the period of 1,000–1,300 years, the estimate of dominant periodicity for clockwise rotation during Holocene time in Britain, North America, and Australia (Itota *et al.*, 1997). It is also longer than the period of 2,100–2,400 years, the estimate in Japan (Itota *et al.*, 1992) and

Fig. 5 Bauer plots of the paleomagnetic field directions from the Ikari-iwa Lowland at 25–18 ka (a) and 18–16 ka (b)

The ages are in calendar years. The arrows show forward direction in time.

Britain (Itota *et al.*, 1997). Only in North America has a period of clockwise field motions as long as 5,600 years been estimated for the Holocene (Itota *et al.*, 1997). This agreement in the sense of rotation and the similar periods may indicate a causal relationship.

According to Runcorn's rule (Runcorn, 1959; Skiles, 1970), clockwise vector motions are generated by westward drift of a non-dipole magnetic field. If this rule is applied to the clockwise rotational period of about 5,000 years obtained in this study, then there was an estimated westward drift of the non-dipole field of about $0.07^\circ/\text{yr}$. This rate is significantly slower than $0.36^\circ/\text{yr}$, the rate estimated by Yukutake (1967) from historical records of observation, and is about half of the $0.13^\circ/\text{yr}$ estimated from Holocene data (Hyodo *et al.*, 1993). Quite different sources may have caused such different rates for westward-drifting fields. Counter-clockwise rotations were dominant after 18 ka (Fig. 5), which may have been due to the eastward drifting of non-

dipole fields. Such a change in the sense of field vector rotation may become a useful age constraint, in addition to providing important geophysical insights.

A number of features in the geomagnetic SV of the last glacial period have the potential for yielding good age constraints in paleomagnetic dating. However, it will be necessary to accumulate more such data with reliable age constraints in order to develop the SV record into a dependable dating tool. In SV studies, using oriented sediment samples is superior to using bored cores that are easily affected by core-tilting and inaccurate horizontal orientation. In this regard, the data obtained in this study are particularly valuable. So far, reconstruction of paleomagnetic fields from oriented sediment samples is quite few (e.g., Turner *et al.*, 1982). This method will be important for future SV studies.

VI. Conclusions

Paleomagnetic measurements of oriented samples from coastal bog sediments in the eastern Inland Sea, Japan, yield a paleomagnetic SV record for the 25–16 ka time span. A plot of the SV data combined with published data for the Holocene shows that a long-term westerly declination swing began after 16 ka and ended at 7.5 ka. The time span of the westerly declination swing was longer than 4,000 years and shorter than 8,500 years. The following SV features useful for dating are found in the 25–16 ka time span: The declinations are dominated by easterly values; easterly declination was maintained, especially at 24–19.5 ka; the inclinations are characterized by slightly shallow values, with small amplitude changes, ranging mainly from 40 to 50°; the motion of the geomagnetic vector is elongated in an east-west direction; the sense of rotational motion clearly changed at about 18 ka. A large clockwise looping motion was dominant prior to 18 ka, while counter-clockwise rotations became dominant afterwards.

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瀬戸内海沿岸域の湿原堆積物から得られた 最終氷期の地磁気永年変化

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(要 旨)

瀬戸内海東部における湿原堆積物の定方位試料から25~16 kaの地磁気永年変化記録を得た。完新世の地磁気永年変化データと合わせてプロットすると、これまで報告されていた完新世以前から7.5 kaまで継続する長期の偏角西振りの開始時期は16 ka以降であること、およびその西振り期間は4,000年以上、8,500年以下であることがわかった。期間25~16 kaの偏角は、東振りが

卓越している。特に24~19.5 kaの間は、西振り偏角が観測されていない。期間25~16 kaの伏角は、完新世に比べやや低伏角で、変動幅が小さい。地磁気ベクトルの運動は、約18 ka以前は大きな時計回り回転が卓越し、それ以降は半時計回りが卓越する。最終氷期の地磁気永年変化の多くの特徴は、年代決定に使える可能性がある。

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