Paleomagnetic directions of the Gauss-Matuyama polarity transition recorded in drift sediments (IODP Site U1314) in the North Atlantic

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(Received April 4, 2008; Revised August 23, 2008; Accepted August 25, 2008; Online published September 26, 2008)

The geomagnetic field direction during the Gauss-Matuyama (G-M) polarity transition was investigated from a high-accumulation-rate ($\geq$10 cm/kyr) sediment core drilled in the Gardar drift in the North Atlantic at Site U1314 during Expedition 306 of the Integrated Ocean Drilling Program (IODP). A well-defined characteristic remanent magnetization was generally obtained by alternating field demagnetization. The consistency of the results with records from Icelandic lavas confirms that the North Atlantic drift sediments contain a high-fidelity record of the geomagnetic field change. During the G-M transition, the virtual geomagnetic pole (VGP) latitude shows north-south-north-south rebounding, with the three VGP paths falling within different longitudinal bands. Two of the three paths are close to or within the preferred bands in which transitional VGPs are suggested to be longitudinally confined. Three additional loops occur that approach mid-to-low latitudes from the North or South pole regions. In addition, the VGPs show rapid movement (directional jumps) between VGP clusters.

Key words: Geomagnetism, polarity transition, Integrated Ocean Drilling Program, Expedition 306, Site U1314.

1. Introduction

Geomagnetic reversals illustrate the dynamic nature of the Earth's magnetic field and provide important clues about how the geodynamo works. The behavior of the geomagnetic field during polarity transitions, i.e., transitional fields, has therefore been a focus of paleomagnetic studies. Transitional fields have been investigated mainly on lava flows and sediments. Relative to records from lava flows, sedimentary records have the advantage that they yield continuous records of field behavior and the disadvantage that they filter (smooth) the temporal variation of the ambient field (e.g. Hyodo, 1984), with the degree of smoothing dependent primarily on sedimentation rate, although magnetization acquisition rate and depth (lock-in depth) also play a role. Sediments that accumulate rapidly ($\geq$10 cm/kyr) are expected to provide high-resolution records of geomagnetic field behavior that approach the temporal resolution of rapidly extruded sequence of lava flows while also providing continuous observations (e.g., Merrill and McFadden, 1999). Drift sediments in the North Atlantic are characterized by high-accumulation rates and stable remanent magnetizations, which have been used to study geomagnetic field behavior of polarity transitions back to the Réunion subchron (Channell and Lehman, 1997; Mazaud and Channell, 1999; Channell and Raymo, 2003; Channell *et al.*, 2003, 2004). In this paper, we extend the coverage back to the Gauss-Matuyama (G-M) transition at 2.58 Ma (ages are based on the geomagnetic polarity timescale of Cande and Kent (1995)). Only three sedimentary records have depicted the path of the virtual geomagnetic pole (VGP) in the G-M transition; one from Turkmenian sediments (Burakov *et al.*, 1976), one from lake sediments from California (Liddicoat, 1982; Glen *et al.*, 1999), and one from Chinese loess (Zhu *et al.*, 2000). Yang *et al.* (2005) recently reported that the paleomagnetic record of Chinese loess showed high-frequency polarity fluctuations accompanying the G-M transition.

2. Sampling and Magnetic Measurement

Integrated Ocean Drilling Program (IODP) Site U1314 was drilled in the Gardar Drift at 56°21.9′N, 27°53.3′W at a water depth of 2800 m (Fig. 1). Three holes were drilled with the advanced piston corer (APC) using non-magnetic core barrels; the core recovery was over 100% at each hole. Sedimentation rates based on onboard microfossil data and polarity reversals indicate a mostly constant sedimentation rate of approximately 11 cm/kyr between the G-M boundary and the Olduvai Subchron (Expedition 306 Scientists, 2006). Among the three holes, the G-M transition was recovered only in Hole U1314A in Core U1314A-25H, with the transitional directions spanning from about

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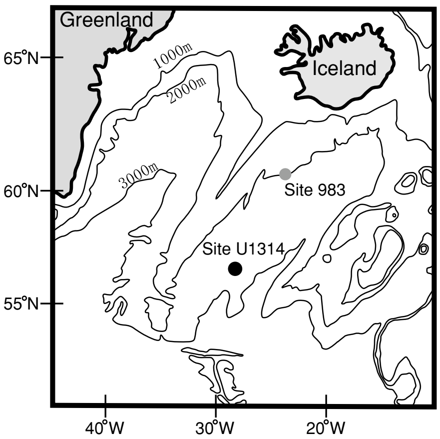

Fig. 1. Location map for IODP Site U1314, which is about 500 km from ODP Site 983 downstream the Gardar Drift. Bathymetric contours are given in meters.

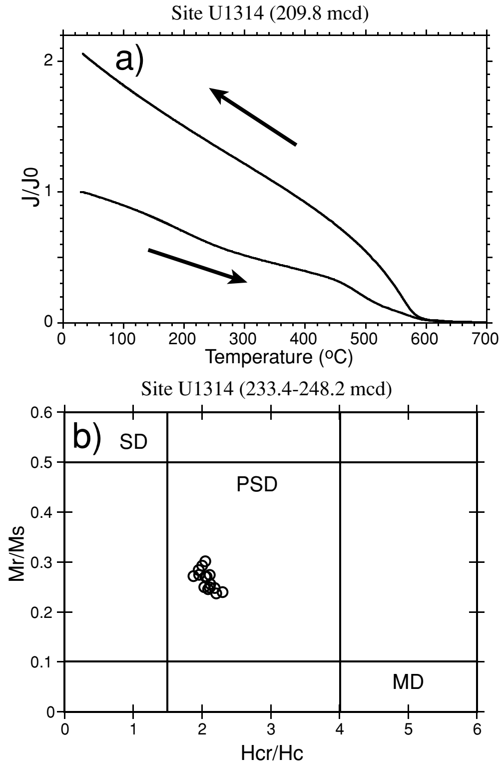

Fig. 2. (a) Typical result of thermomagnetic analysis. (b) Hysteresis ratio plot for 15 samples. SD, PSD, and MD indicate single domain, pseudo-single domain, and multidomain fields, respectively (see Day *et al.*, 1977).

240.3 to 241.3 m composite depth (mcd). Unfortunately, the G-M transition was not cored in Hole U1314C, which only extended down to 222.3 mcd, and was not recovered in Hole U1314B because it occurred entirely between cores U1313B-24H and 25H.

U-channel samples of 1.5 m in length with a 2×2-cm square cross section were sampled from the central part of the 'archive' half cores. Remanent magnetizations and hysteresis parameters were measured at the Center for Advanced Marine Core Research in Kochi University. The natural remanent magnetization (NRM) of the u-channel samples were measured at every 1-cm interval using a high-resolution small-access pass-through magnetometer (2G Enterprises, 755SRM) after alternating field (AF) demagnetization in ten steps in the 20- to 80-mT peak field interval, because archive halves of the cores were demagnetized at peak fields of 20 mT on board the ship. Most of the drill-string overprint, which was downward in direction, was removed at around 10 mT at the onboard treatment (Expedition 306 Scientists, 2006). Thermomagnetic curve and hysteresis parameters were obtained using a vibrating sample magnetometer (Princeton Measurements, Micromag 3900).

3. Results

In Fig. 2, the thermomagnetic analyses indicate (titano)magnetite and hysteresis ratios lie in the pseudo-single domain (PSD) field. The results are consistent with the mineralogy at nearby Ocean Drilling Program (ODP) Site 983 (see Fig. 1), which indicated PSD magnetite as the dominant magnetic mineral (Channell *et al.*, 1998; Mazaud and Channell, 1999; Channell and Kleiven, 2000).

Typical results of AF demagnetization are shown in Fig. 3; a well-defined characteristic magnetization component extending straight to the origin of the plot was generally obtained for the 20- to 80-mT demagnetization intervals. In Fig. 4, the component direction was determined using principal component analysis (PCA; Kirschvink, 1980) for each measurement point using a computer program by Mazaud (2005). Generally, data from all ten AF demagnetization steps were used in the PCA. The maximum angular dispersion (MAD) values are low ($<1°$) in the interval of pre- and post-reversal, indicating that the component directions are well defined. The MAD values are larger at the interval of the polarity transition partly because of the low intensity of the remanent magnetization (relatively high noise). Overprinting of rapidly changing geomagnetic field may also increase the MAD values (Channell *et al.*, 2002). When the MAD value exceeded 10°, the orthogonal plots were examined individually, and the principal component was determined using at least seven of the ten measurement steps. The declination values were corrected according to the shipboard 'Tensor Multishot' orientation tool.

4. Discussion

The VGPs calculated from each direction illustrate the movement of the north magnetic pole (Fig. 5(a)). Following the stable Gauss polarity interval, the VGPs draw a precursory loop over the North Atlantic (P1 in Fig. 5(a)) and go to the Antarctic through eastern Asia and west off Australia (P2). After a fluctuation towards the east coast of South America (P3), the VGPs pass along a nearly great circle path through the eastern Pacific on their way back to the Arctic (P4). On their final trip to the southern hemisphere, the VGPs pass through Asia, the Middle East, and South Africa (P5), settling around the Antarctic after a fluctuation towards Australia (P6). The characteristics of the VGP path can be summarized by a north-south-north-south (N-S-N-S) rebounding (P2, P4, and P5) associated with fluctuations in which the VGPs approach mid-to-low latitudes (P1, P3 and P6) before returning to a polar position. One of these loops encircles the drill site (P1), and another is nearly antipodal

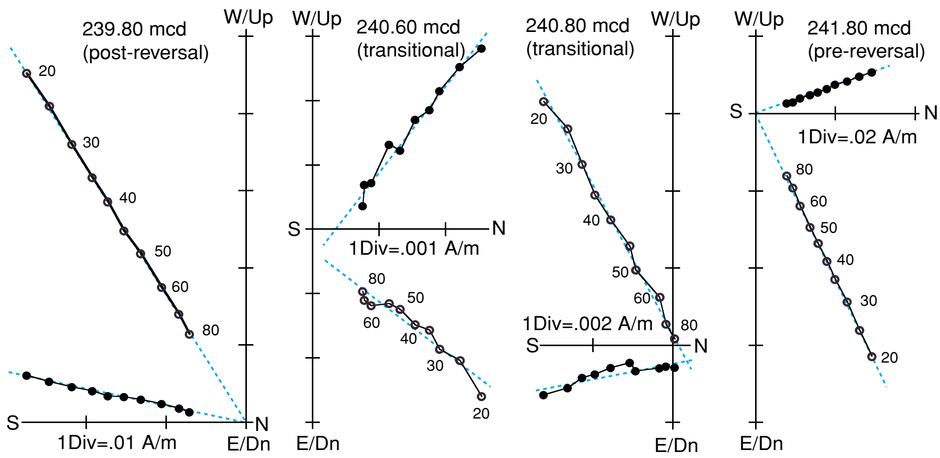

Fig. 3. Examples of orthogonal projections of alternating field demagnetization. Solid circles represent the horizontal projection, and open circles represent the vertical projection. The peak alternating field (mT) for each demagnetization step is indicated. Dotted lines indicate calculated component directions.

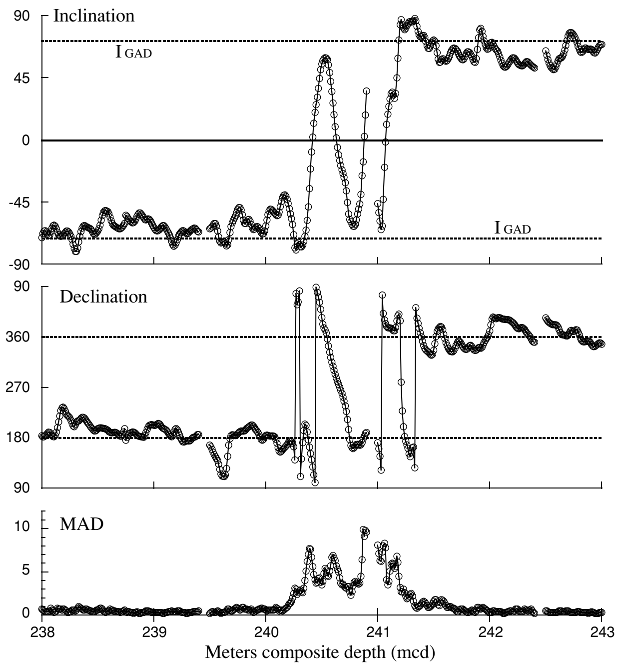

Fig. 4. Principal components (declination and inclination) and maximum angular dispersion (MAD). Inclination expected from geocentric axial dipole at the sampling site is indicated as I_{GAD}.

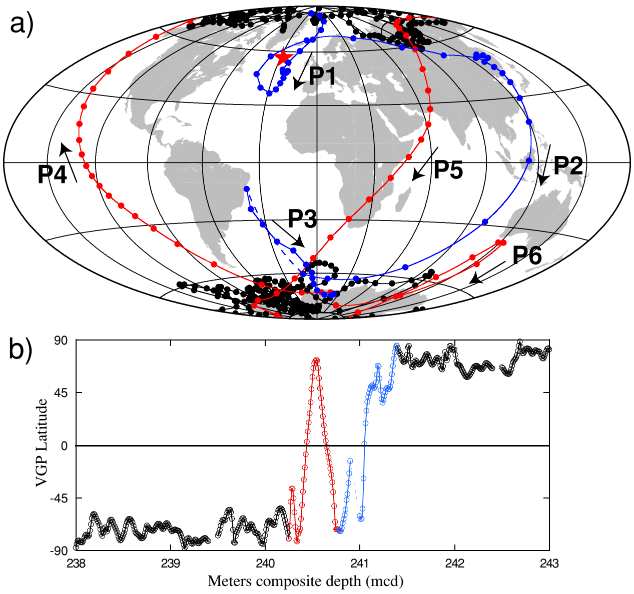

Fig. 5. Virtual geomagnetic poles (VGPs) during the G-M transition. (a) Path plotted on Hammer projection. The arrows indicate the movement of VGPs, and P1 to P6 represent the temporal order. Star indicates the drilling site. (b) VGP latitudes as a function of depth.

to the drill site (P6). The VGPs traverse different latitudinal bands for each of the three pole-to-pole paths (P2, P4, and P5).

We compare the results at Site U1314 with the volcanic records in Iceland. The two sites are only about 1000 km ($\sim 10^\circ$ in angular distance) apart. Transitional directions across the G-M boundary have been reported from Icelandic lava flows by many authors (Sigurgeirsson, 1957; Wilson *et al.*, 1972; Kristjansson *et al.*, 1980; Kristjansson and Sigurgeirsson, 1993; Tanaka *et al.*, 1995; Goguitchaichvili *et al.*, 1999). Kristjansson and Sigurgeirsson (1993) compiled preceding records, and based on their results (see their figure 5) we can group the VGPs into four regions: Japan-Australia, in and off South America, the Middle East, and equatorial Indian Ocean. It is remarkable that three of these regions are located on the VGP paths in our record: VGPs in the Japan-Australia region are on P2 in Fig. 5, those in and off South America are on P4, and those in the Middle East are on P5. In addition, the temporal order (stratigraphic order) in Kristjansson (1980) is consistent with our P4 and P5. We do not observe VGPs in the equatorial Indian Ocean: perhaps the volcanic sections have recorded short-term fluctuations that were smoothed out in our sedimentary record or short-wavelength anomaly predominates in the transitional field.

Glen *et al.* (1999) pointed out that the difference between VGPs from different locations may indicate the predominance of non-dipole fields during the G-M transition. Our VGP paths also have features different from others (Burakov *et al.*, 1976; Glen *et al.*, 1999; Zhu *et al.*, 2000) as well as some common characteristics. The change in the VGP latitude of the record in China (Zhu *et al.*, 2000) shows N-S-N-S rebounding as seen in the Site U1314 record. The VGPs from China go from the Arctic to the Antarctic through Americas and then go back to the Arctic through eastern Asia; these paths are located close to our paths P2 and P4, but they are opposite in direction to ours. These paths are within or close to the 'preferred bands' in which transitional VGPs are suggested to be longitudinally confined within two antipodal longitude bands (see, for example, Merrill and McFadden, 1999). The VGPs from Turkmenia (Burakov *et al.*, 1976) are also confined in eastern Asia and in the preferred bands. It is notable that in the three records of the G-M transition (this study, those from California, and those from China), the VGPs lie outside the preferred longitudinal bands as they pass over Africa before they go to and settle around the Antarctic.

One of the characteristics of the G-M transitional record from California (Glen *et al.*, 1999) is the presence of intervals of a quasi-stationary state (VGP clusters) and intervals of rapid movement of VGPs. We also find a similar feature in the present record. In Fig. 5(a) the VGPs cluster in the North Atlantic in the beginning of transition, move to eastern Asia rapidly, cluster there again, and then rapidly move to the Antarctic. It is also notable that the movement of VGPs slows down at the equatorial region off South America in the path from Antarctic to the Arctic (P4 in Fig. 5). These 'directional jumps' have been demonstrated in both volcanic records (e.g., Prévot *et al.*, 1985; Acton *et al.*, 2000) and sedimentary records (e.g. Channel and Lehman, 1997; Mazaud and Channell, 1999). The present record also supports the feature of 'directional jumps' in the G-M transition.

Acknowledgments. This research project used samples provided by the Integrated Ocean Drilling Program (IODP) and was partly supported by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). The research was performed within the framework of the cooperative research program of Center for Advanced Marine Core Research (CMCR), Kochi University (Accept No. 05B010, 06A010 and 06B010). We are indebted to the staff of the RV JOIDES Resolution, the IODP Bremen Core Repository, and CMCR for their support. Funding for G. Acton and H. Evans was provided by the U.S. Science Support Program of the Joint Oceanographic Institutions, which is funded by the Ocean Science Division of the National Science Foundation. We thank Tianshui Yang and Johnathan Glen for reviewing the manuscript.

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