Relative paleointensity and environmental magnetism since 1.2 Ma at IODP site U1305 (Eirik Drift, NW Atlantic)

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ABSTRACT

Integrated Ocean Drilling Program (IODP) Expedition 303 to the North Atlantic in 2004 recovered rapidly deposited deep-sea sediments at IODP Site U1305 on Eirik Drift, located south of Greenland at 3460 m water depth, along the path of the Western Boundary Under Current (WBUC). About 200 m of sediment was sampled with u-channels from the composite section, providing a continuous record of paleomagnetic field directions and relative paleointensity (RPI) variations covering the past 1.2 Myr. The age model, based on an oxygen isotope record, is consistent with the fit of the RPI record to a calibrated template, and indicates higher sedimentation rates during interglacials relative to glacial epochs. Magnetite grain-size and concentration proxies indicate higher concentrations of magnetite with larger grain sizes during interglacials. Enhanced interglacial deposition can be attributed to a combination of elevated entrainment of terrigenous detritus into the WBUC due to glacial retreat on continents flanking the upstream path of the WBUC (east Greenland and Iceland), and of increased bottom current (WBUC) vigor leading to elevated transport and deposition at the site during interglacials. This pattern is opposite to observations of flow of the Antarctic circum polar current (ACC) in the south Indian Ocean, which suggests an inter-hemispheric antiphase in marine circulation at the Milankovitch scale, with strong circulation in the deep North Atlantic when the ACC is weak, and vice versa.

1. Introduction

Expedition 303 of the Integrated Ocean Drilling Program (IODP) took place during September to November 2004 in the North Atlantic Ocean. One of the aims was to explore Quaternary millennial-scale climatic and hydrographic, as well as obtain records of past geomagnetic field variations. IODP Site U1305 is located close to the southwestern extremity of Eirik Drift, off southern Greenland (57°28.5 N, 48°31.8 W) (Fig. 1). The water depth of the site is 3460 m, which is below the present-day main axis of the Western Boundary Undercurrent (WBUC).

The WBUC is principally fed by Denmark Strait Overflow Water (DSOW), which flows west of Iceland, and by Iceland–Scotland Overflow Water (ISOW) flowing east of Iceland, which forms North East Atlantic Deep Water (NEADW) (Fig. 1). DSOW and NEADW currents join to form the WBUC, which flows south of Greenland and deposits sediments on Eirik drift (Fig. 1). After passing over Site U1305, the WBUC encounters the Davis Strait

Overflow Water (DSO) and the Labrador Seawater (LSW) currents, to form North Atlantic Deep Water (NADW), which flows southward into the deep Atlantic as a major component of the global thermohaline circulation. Site U1305 records detrital deposition events related to Greenland ice sheet dynamics, and, to a lesser extent, Labrador sea dynamics associated with the Laurentide ice sheet. WBUC is a major component of the NADW. IODP Site U1305 is, therefore, also ideally placed for investigations of North Atlantic deep current system evolution during successive glacial–interglacial periods, in response to Milankovich climate forcing. Magnetic methods applied to sediments are particularly useful in this region as sensitive indicators of past variability of the WBUC (Kissel et al., 1999, 2009; Stanford et al., 2006) and surrounding ice sheets (Stoner et al., 1995a, 1996; Evans et al., 2007). However, previous studies are limited to the last 400 kyr, with only a single record extending beyond 200 ka. Site U1305 provides an opportunity to extend the record back through the Brunhes Chron and beyond, providing a longer term understanding of the dynamics of the WBUC/NADW system and how it evolved under changing climate conditions. Site U1305 record is compared to a record of Antarctic circum current (ACC) vigor in the south Indian Ocean, allowing to investigate for the first time

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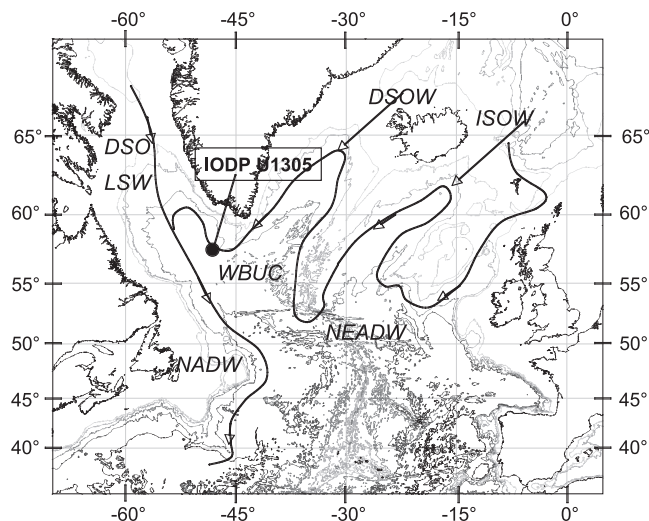 E-mail address: alain.mazaud@lsce.ipsl.fr (A. Mazaud).

Fig. 1. Location of IODP Site U1305 (solid circle) on Eirik drift in the North Atlantic Ocean, south of Greenland. Main currents are indicated by arrows: Denmark Strait Overflow Water (DSOW), Iceland–Scotland Overflow Water (ISOW), North East Atlantic Deep Water (NEADW), Western Boundary Undercurrent (WBUC), Davis Straight Overflow Water (DSO), North Atlantic Deep Water (NADW).

the concomitant evolution of these components of the global oceanic circulation have over several glacial–interglacial cycles.

IODP Site U1305 also provides a new detailed record of past geomagnetic field variations during the past 1.2 kyr, which includes the Matuyama–Brunhes boundary, the boundaries of the Jaramillo Subchron, and several geomagnetic excursions. Relative paleointensity (RPI) is compared to the PISO-1500 paleointensity stack, which was obtained from several sites distributed around the world (Channell et al., 2009).

2. Shipboard paleomagnetic results

Sediments recovered at Site U1305 were deposited over the past 2 Myr (Shipboard Scientific Party, 2006). Shipboard measurements and site characteristics are described in detail by Channell et al. (2006). Sediments at Site U1305 are dominated by varying mixtures of terrigenous components and biogenic material, primarily clay minerals, quartz, detrital carbonate, and nannofossils. The most common lithologies are dark gray to very dark gray silty clays with nannofossils (Channell et al., 2006). Three holes were drilled using the Advanced Piston Corer (APC), with non-magnetic core barrels that limit magnetic overprinting during coring (Lund et al., 2003). A continuous stratigraphic composite section was constructed to ~295 m composite depth (mcd), which corresponds to a basal age of 2 Ma according to the preliminary shipboard stratigraphy (Shipboard Scientific Party, 2006). Paleomagnetic measurements were conducted shipboard on archive-half core sections using the shipboard pass-through cryogenic magnetometer. The spatial resolution of the shipboard magnetometer is about 15 cm for each of the three orthogonal sensors. Aboard ship, the natural remanent magnetization (NRM) intensities and directions were measured on half-core sections before any demagnetization was performed, and then after alternating field (AF) demagnetization, restricted to peak fields of 10 mT, or occasionally 20 mT, to ensure that archive halves remained useful for shore-based high-resolution u-channel measurements.

NRM intensities before demagnetization ranged from $\sim 10^{-1}$ A/m to more than 1 A/m. After AF demagnetization at peak fields of 10–20 mT, NRM intensities drop to $\sim 10^{-1}$ A/m. Despite limited AF demagnetization, shipboard measurements

clearly enabled identification of the Brunhes chronozone and part of the Matuyama Chronozone, including the Jaramillo, Cobb and Olduvai Subchronozones (Shipboard Scientific Party, 2006). The mean sedimentation rate calculated using these magneto-statigraphic and biostratigraphic markers was estimated to be 17.5 cm/kyr (Channell et al., 2006).

3. High-resolution measurements: sampling and laboratory methods

Site 1305 composite section was sampled with u-channels at the IODP core depository in Bremen (Germany) down to a depth of 193 mcd, which corresponds to a basal age of 1.2 Ma. U-channel samples, which are "continuous" $2 \times 2 \times 150$ cm samples encased in plastic with a clip-on lid constituting one of the sides, were collected from each 150 cm core section. The NRM was then measured at the LSCE paleomagnetic laboratory, Gif-sur-Yvette (France), using small-diameter pass-through cryogenic magnetometers designed for u-channel measurements (Weeks et al., 1993). U-channel samples measured using these magnetometers allow a measurement resolution of ~4.5 cm, which is a marked improvement over the shipboard magnetometer. Stepwise AF demagnetization of the NRM was conducted up to peak fields of 100 mT using the 3-axis AF demagnetization coils system that is arranged in-line with the magnetometer sample track. Component magnetization directions and maximum angular deviation (MAD) values, which monitor the quality of the magnetization directions, were determined for the 20–60 mT or 20–80 mT demagnetization intervals, by using the standard "principal component" method of Kirschvink (1980) through an Excel spreadsheet software developed at Gif-sur-Yvette (Mazaud, 2005). Site U1305 sediments have well-defined NRM magnetization components. Declinations of the component magnetizations were then adjusted according to the shipboard "Tensor Multishot" orientation measurements, where available, or by uniform rotation of each individual core, such that the core mean declination for intervals outside polarity transitions equals 0° or 180°.

After measurement of the NRM, low-field volume magnetic susceptibility (κ), anhysteretic remanent magnetization (ARM), and the isothermal remanent magnetization (IRM) were measured. Susceptibility is controlled by the mineralogy, concentration, and grain size of ferromagnetic (s.l.) minerals. In these sediments, which have an extremely high concentration of ferromagnetic minerals, paramagnetic (and diamagnetic) contributions to susceptibility are negligible. Measurements of the low-field bulk susceptibility (κ) were performed at Gif-sur-Yvette using a small diameter Bartington instrument loop sensor mounted in line with a track system designed for u-channels, and a Sapphire loop with susceptibility track designed for u-channels at the University of Florida (Thomas et al., 2003). ARM and IRM are remanent magnetizations, and are therefore entirely controlled by the ferromagnetic (s.l.) fraction. ARM is principally linked to small magnetic grains, with sizes around 0.1–5 μm, while IRM is sensitive to a wider spectrum of grain sizes, up to several tens of microns (Maher, 1988; Dunlop and Özdemir, 1997). ARM was acquired along the axis of the u-channel using a 100 mT AF field and a 50 μT direct current (DC) bias field. Anhysteretic susceptibility (κ_{ARM}) can be then determined by normalizing ARM values by the DC field value (King et al., 1983). ARM was also demagnetized, using the same steps as those used for the NRM. An IRM was acquired in 6 steps up to 1 T using a 2G Enterprises pulse IRM solenoid. $IRM_{1\,T}$ was stepwise demagnetized. Then, after re-acquisition of an IRM at 1 T, a backfield of 0.3 T was applied to calculate the S-ratio where $S_{-0.3\,T} = -IRM_{-0.3\,T}/IRM_{1\,T}$ (King and Channell, 1991), and $S_{-0.3\,T}$

provides a measure of the magnetic coercivity, which, in turn, provides information on magnetic mineralogy.

4. Magnetic mineralogy

κ_{ARM} versus κ diagram indicates an elongated data distribution starting from the origin of the graph, with some dispersion in slope (Fig. 2a). This distribution indicates that magnetite has grain-size variations mainly in the 1–20 μm range according to the calibration of King et al. (1983). Limited mineralogical variations are indicated by the S-ratio, which varies around 0.95 (Fig. 2b), which implies a magnetic mineralogy dominated by low coercivity minerals (e.g. magnetite). The Day et al. (1977) diagram of magnetic hysteresis ratios (Fig. 2c) has a distribution typical of magnetite with variable grain size in the pseudo-single domain (PSD) range. Results are consistent with those from previous cores collected in the same area (Stoner et al., 1995a, b; 1996; Evans et al., 2007), which indicates that the magnetic
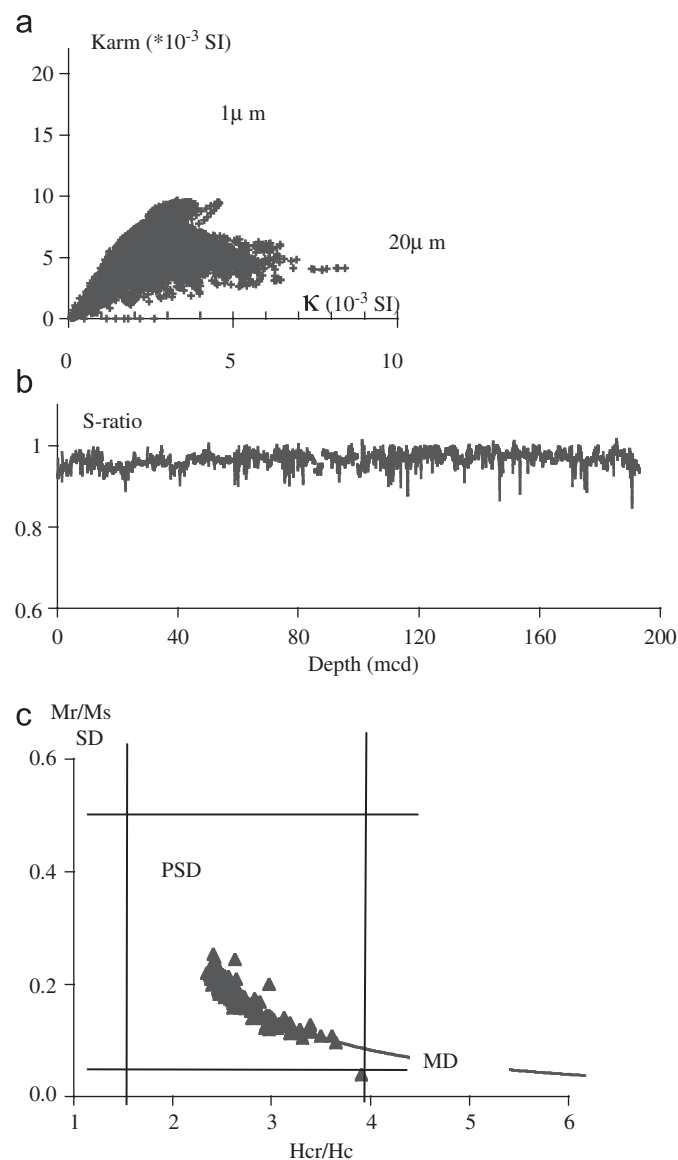
Fig. 2. Karm versus κ diagram. (a) Dotted lines indicate grain size of 1 μm (upper slope) and of 20 μm (lower slope), as estimated by King et al. (1983), (b) S-ratio obtained along the composite section, (c) Day et al. (1977) diagram (MD: multi-domain grains, PSD: pseudo-single domain, S: single domain).
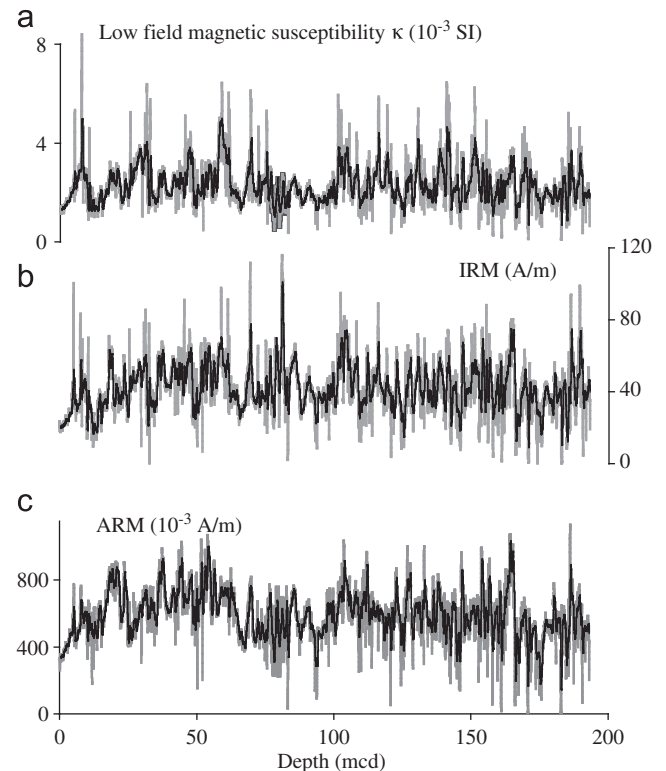
Fig. 3. Records of three bulk magnetic parameters, κ, ARM and IRM versus composite depth (mcd). Gray curve, unsmoothed record; dark curve, after smoothing with a 50 cm sliding window.

mineralogy is dominated by (titano)-magnetite with variable grain size primarily in the PSD range.

Records of the three bulk magnetic parameters (κ, ARM and IRM) versus composite depth are shown in Fig. 3. In general, these concentration dependent parameters co-vary, but with important differences. The high-frequency signal appears to be more pronounced below 100 mcd than in the upper part of the composite section. Overall, variations in amplitude do not exceed a factor of 5 for each parameter, so that Site U1305 sediments fit criteria for obtaining a reliable record of relative paleointensity (King et al., 1983; Tauxe, 1993). The close similarity of the κ and IRM records indicates a negligible contribution from paramagnetic minerals to the susceptibility signal.

5. Paleomagnetic record

5.1. Paleodirections

AF demagnetization of the NRM along the composite section indicates a progressive down-hole decrease of NRM intensity, with a stable characteristic magnetization direction obtained after demagnetization at peak fields greater than 20 mT. The u-channel record of component magnetization directions (declinations and inclinations) and MAD values calculated for the 20–60 mT peak field demagnetization interval are shown in Fig. 4a–c. The age model is that of Hillaire-Marcel et al. (2011), where depth-age tie-points were obtained from isotope stratigraphy derived from the planktic foraminifer *Neogloboquadrina pachyderma* (sinistral), due to the paucity of benthic foraminifera at this site, which was augmented by identification of polarity reversals at the Matuyama–Brunhes boundary and the boundaries of the Jaramillo Subchron from shipboard data (Channell et al., 2006). Component inclination varies around the expected value (72.5°) for an
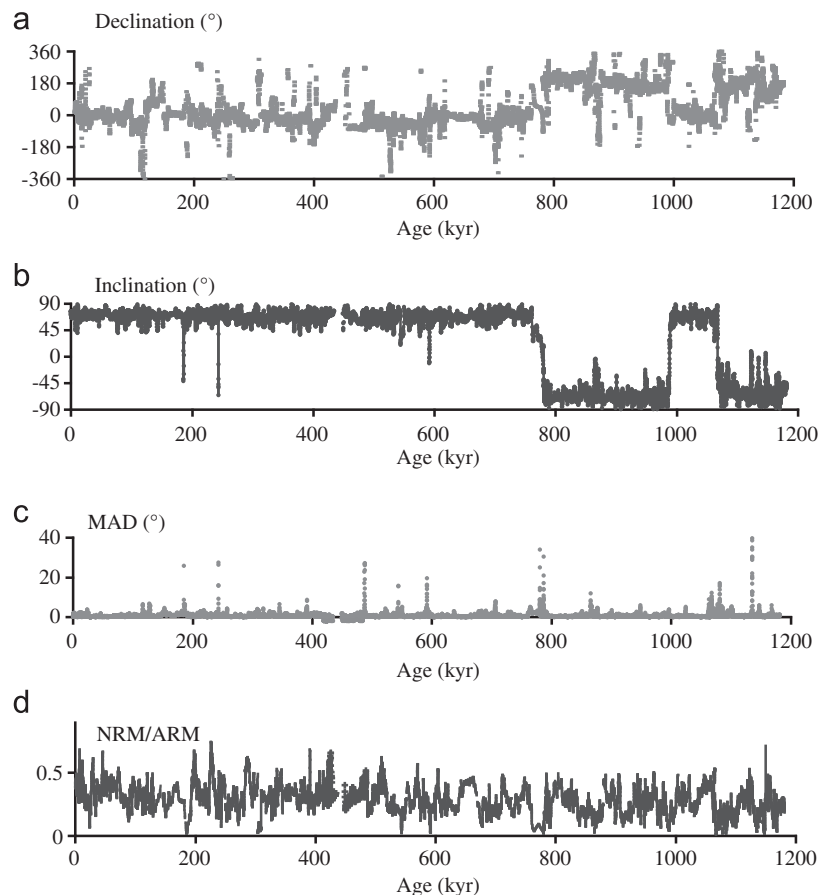
Fig. 4. NRM component declinations (a), inclinations (b), and MAD values (c), versus age (see text for details) and (d) paleointensity record obtained using ARM as a normalizer of the NRM intensity.

geocentric axial dipole field at the site latitude, for both polarities. The Matuyama–Brunhes boundary, and the boundaries of the Jaramillo Subchron are clearly recorded in the u-channel record (Fig. 4b), at locations consistent with shipboard measurements. The Iceland Basin geomagnetic excursion (Channell et al., 1997; Channell, 1999; Laj and Channell, 2007) is recorded at ∼190 ka, with two other apparent excursions in the Brunhes Chronozone (Fig. 4b). The excursion at ∼230 ka may correspond to the Pringle Falls excursion, which was first recorded in Oregon (Herrero-Bervera et al., 1989, 1994; Negrini et al., 1994). Regional tephro-chronology in the western USA yields age estimates close to 220 ka for the Pringle Falls excursion (Herrero-Bervera et al., 1994; Liddicoat et al., 1998). McWilliams (2001) reported an ^{40}Ar/^{39}Ar age of 223 ± 4 ka for the Mamaku ignimbrite in New Zealand that carries excursional magnetization directions (Shane et al., 1994). The Pringle Falls excursion has been associated with an excursion recorded in the Albuquerque Volcanics that has an ^{40}Ar/^{39}Ar age of 211 ± 13 ka (Singer et al., 2008a). On the other hand, a recent study at ODP Site 1063 yields an age of 238 ka for an excursion labeled as the Pringle Falls excursion (Channell et al., 2012). The excursion at ∼590 ka at Site U1305 (Fig. 3b), which occurred during marine isotope stage (MIS) 15 according to the Hillaire-Marcel et al. (2011) isotope stratigraphy, could corre-spond to the La Palma excursion (Quidelleur et al., 1999; Channell et al., 2004), and/or to one of several excursions observed in the 500–600 ka interval in the West Eifel volcanics (Singer et al., 2008b). Detailed records of geomagnetic polarity transitions during the Jaramillo Subchronozone at Site U1305, and from other sites occupied during IODP Expedition 303, have been published by Mazaud et al. (2009).

5.2. Paleointensity

NRM intensity depends on the intensity of the geomagnetic field that oriented the magnetic grains at time of deposition, but also on the mineralogy, concentration, and size of the magnetic grains and the characteristics of the non-magnetic matrix that influence alignment efficiency. RPI studies should be carried out on sediments in which magnetite is the sole magnetic mineral, with minimal variations in grain size and concentration (King et al., 1983; Tauxe, 1993). Once these conditions are met, it is necessary to normalize the NRM intensity by a parameter that represents the variation in magnetite concentration. ARM is sensitive to magnetite grains with size around 0.1–5 µm, which are the grains most likely to carry the NRM. For this reason, ARM is commonly used as a normalizer for the NRM intensity, and the NRM/ARM ratio (Fig. 4d) is used as a proxy for past geomagnetic field intensity changes, or relative paleointensity (RPI) (Banerjee and Mellema, 1974; Levi and Banerjee, 1976; King et al., 1983; Tauxe, 1993). Here, we determine the RPI proxy by calculating the NRM–ARM regression (slope) in the 20–60 mT peak AF interval (Channell et al., 2002). The linear correlation coefficient (r) is used to indicate the quality of definition of the NRM–ARM slopes. At Site U1305, correlation coefficients close to unity (around 0.99) predominate, with values lower than 0.95 obtained during polar-ity reversals and geomagnetic excursions. The RPI record has marked fluctuations, with broad minima at the time of polarity transitions and excursions. RPI proxies obtained by normalizing NRM by IRM, or κ, do not differ markedly from the record obtained using ARM (Fig. 4), thereby adding confidence to the RPI record. Overall, the Site U1305 RPI record is similar to
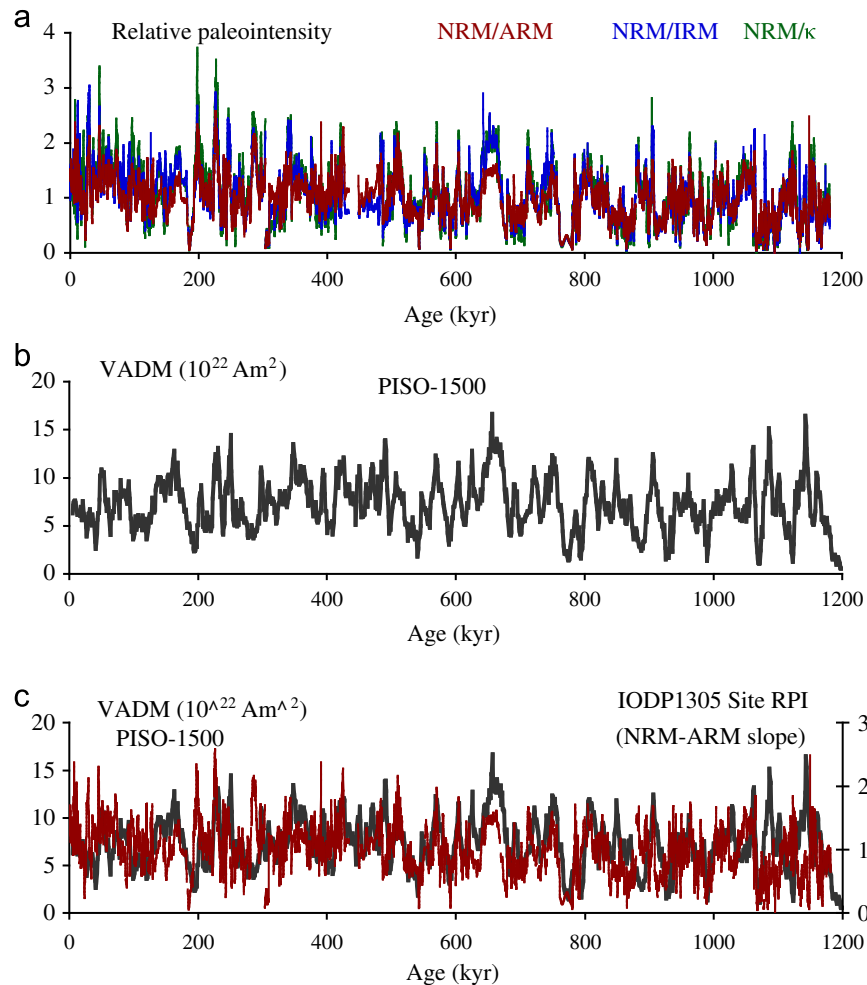
Fig. 5. (a) Paleointensity records obtained using κ, ARM and IRM as normalizers of the NRM intensity, (b) PISO 1500 paleointensity reference stack, (c) comparison between PISO 1500 and IODP Site U1305 RPI record, obtained with ARM normalization.

published results from Eirik Drift (e.g., Stoner et al., 1995b, 1998; Evans et al., 2007) and resembles the "PISO-1500" paleointensity stack (Channell et al., 2009), computed by stacking 13 paleointensity records from around the world (Fig. 5). The PISO-1500 stack was placed on an age model based on the Lisiecki and Raymo (2005) benthic oxygen isotope stack (Channell et al., 2009). There is, however, some differences between the Site 1305 record and PISO-1500, in particular around 500, 850 and 1100 kyr B.P. (Fig. 5c).

6. Magnetite grain-size and concentration

6.1. Magnetite concentration changes

Low field susceptibility (κ) variations trace changes in concentration of the dominant magnetic mineral, low-Ti titanomagnetite. κ values are consistently elevated during interglacial stages relative to glacial stages (Fig. 6). Magnetite concentration changes may reflect variations in sedimentation rate versus time (flux) of magnetic material, changes in detrital provenance, changes in the transport/deposition process, and/or changes in the dilution of the magnetic fraction by other, non-magnetic, materials. To further investigate this point, we calculated the magnetite flux using the Site U1305 age model. A value of $5 \times 10^{-4} \, m^3 \, kg^{-1}$ was used for the specific mass susceptibility of magnetite (Thompson and Oldfield 1986), in order to calculate
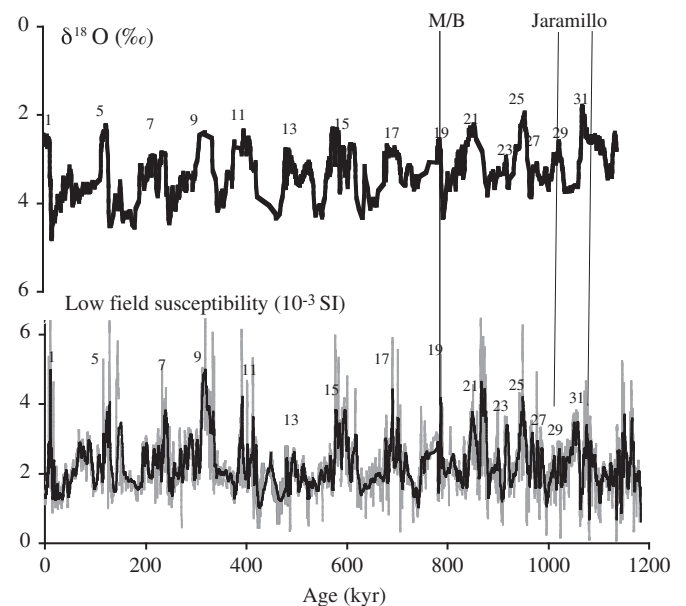

Fig. 6. (a) Isotope oxygen stratigraphy (Hillaire-Marcel et al., 2011), (b) Low field susceptibility versus ages (gray: unsmoothed record, dark: after smoothing with a 50 cm sliding window). Dashed lines indicate the Matuyama–Brunhes polarity transition and the Jaramillo subchronozone. Numbers refer to Marine Isotopic Stages as identified by Hillaire-Marcel et al. (2011).
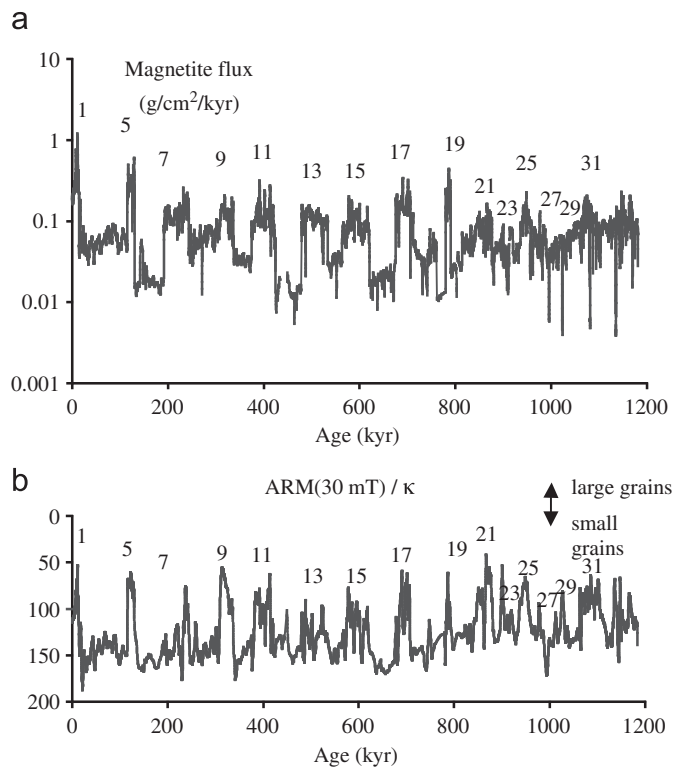
a

b

Fig. 7. (a) Calculated magnetite flux versus age (see text for details), (b) magnetite grain size variations versus age as traced by ARM/κ, Numbers refer to marine isotope stages as identified by Hillaire-Marcel et al. (2011).

the magnetite mass deposited per surface unit per kyr (g/cm²/kyr). Despite uncertainties due to the limited number of tie points in the age model, the calculated magnetite flux has higher values during interglacial stages than during glacial stages (Fig. 7a).

6.2. Magnetite grain size changes

The ARM/κ ratio is a measure of magnetite grain-size variations (King et al., 1983; Maher, 1988; Verosub and Roberts, 1995; Dunlop and Özdemir, 1997). Low values of ARM/k indicate larger grains, while higher values correspond to smaller grains, due to the sensitivity of ARM and k to smaller and larger grains, respectively. Grain size variations versus age, as traced by ARM/κ are shown in Fig. 7b. As previously observed from Eirik Drift sediments (Hall et al., 2004; Stoner et al., 1994; 1995a; Stanford et al., 2006, 2011; Evans et al., 2007), smaller grains were deposited during glacial epochs, when the magnetite flux was low, while larger grains were deposited during interglacials, when flux was high (Fig. 7b).

7. Discussion

IODP Site U1305 sediments provide high-resolution records of the geomagnetic field and of the sedimentation history at Eirik Drift since 1.2 Ma. The Matuyama–Brunhes boundary, and the boundaries of the Jaramillo Subchronozone, are clearly recorded in the u-channel data (Fig. 4). In addition, three apparent geomagnetic excursions, which are brief millennial-scale deviations of the paleomagnetic field direction (see Laj and Channell, 2007), are recorded in the Brunhes Chronozone (Fig. 4). Based on planktic oxygen isotope age model (Hillaire-Marcel et al., 2011), the ages of these excursions are 190 ka, 230 ka and 590 ka. These ages correspond to excursions recorded elsewhere: the Iceland

Basin (190 ka), Pringle Falls (∼220 ka) and La Palma (∼590 ka) excursions. RPI proxies, placed on the isotope oxygen age model, resemble the PISO-1500 paleointensity stack (Channell et al., 2009) (Fig. 5), which indicates that the RPI proxies represent past changes of geomagnetic field intensity.

Site U1305, which is located along the flow-path of the WBUC, appears to have recorded past variations in the vigor of this bottom-current as previously documented by glacial–interglacial variations in sedimentation rates of piston cores collected at different locations and water depths on Eirik Drift (e.g., Hillaire-Marcel et al., 1994, 2001, 2011; Stoner et al., 1996; Evans et al., 2007, Hunter et al., 2007). Deeper sites located in the vicinity of Site U1305 are known to be characterized by expanded inter-glacial stages, at least for the last two interglacials, whereas shallower sites located closer to the crest of Eirik Drift are characterized by relatively expanded glacial stages. It has also been shown that Greenland-derived detritus was an important depositional constituent on Eirik Drift during the last two inter-glacial stages. Evidence for this comes from a variety of sources, including sedimentary magnetic data (Stoner et al., 1995a; Stanford et al., 2006, 2011; Evans et al., 2007), changes in Ti and Fe concentrations from X-ray fluorescence data (Carlson et al., 2008), as well as Sr–Nd–Pb isotopic matching of Eirik Drift sediments to Greenland outcrops (Colville et al., 2011).

Variations of magnetite abundance and grain-size, at the Milankovitch scale, recorded at Site U1305 likely document changes in: (1) the capacity of the WBUC and upstream currents to transport and possibly erode silt-sized magnetite particles, (2) the location and depth of the WBUC relative to the sampling site, and, (3) the enhanced erosion and entrainment in the WBUC of detritus produced during times of glacial retreat on Greenland. Our results indicate that, during the past 1.2 Myr, transport and erosion capacity was consistently lower during glacial epochs (low amounts of magnetite and small grains) than during interglacial periods (large amount of magnetite and large grains). In the southern Indian Ocean, the abundance and size of magnetic grains east of the Kerguelen–Crozet Plateau document a stronger Antarctic Circumpolar Current (ACC) during glacial epochs than during interglacials (Mazaud et al., 2010). This situation is opposite to that observed at Site IODP U1305 for the WBUC, which suggests an antiphase global ocean circulation at Milankovitch scale with strong deep circulation in the North Atlantic when the ACC is weak, and vice versa.

8. Conclusion

IODP Site U1305 sediments provide new high-resolution geomagnetic and environmental records at Eirik Drift since 1.2 Ma. Relative paleointensity record extends published results from Eirik Drift, and exibits strong similarities with the"PISO-1500" paleointensity stack. Magnetite grain-size and concentration proxies extend over the past 1.2 Myr observations for the last climatic cycle that the marine circulation system changes in the North Atlantic, and particularly WBUC, were closely associated with the glacial–interglacial climatic changes (Labeyrie et al., 1992; Hillaire-Marcel et al., 2001; Kissel et al., 1999, 2009). Results indicate elevated terrigenous inputs into the WBUC due to ice retreat on nearby lands and increased bottom current (WBUC) vigor during interglacials. which is opposite to the ACC evolution in the south Indian Ocean.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.epsl.2012.09.037.

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