Complexity in Matuyama-Brunhes polarity transitions from North Atlantic
IODP/ODP deep-sea sites

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Abstract.

Integrated Ocean Drilling Program (IODP) Expedition 303 to the North Atlantic provided 16 records of the Matuyama-Brunhes polarity transition (MBT), based on u-channel and discrete samples, from holes drilled at three sites (Sites U1304, U1305 and U1306) that have mean Brunhes sedimentation rates of 16-18 cm/kyr. The MBT occurs during the transition from marine isotope stage (MIS) 19c to MIS 18e, with mid-point at ~773 ka, and a transition duration of ~8 kyr. Combining the new MBT records, including one new record for the top Jaramillo, with previously published North Atlantic MBT records (ODP Sites 983, 984 and 1063) yields a total of more than 20 high-sedimentation-rate polarity transition records. The MBT yields a repetitive pattern of transitional field states as virtual geomagnetic poles (VGPs) move from high southern latitudes to loop over the Pacific, group in NE Asia, and transit into the mid-latitude South Atlantic before reaching high latitudes in the Northern Hemisphere. The VGPs for the top Jaramillo transition feature a loop over the Pacific, then a NE Asia group before transit over the Indian Ocean to high southerly latitudes. The North Atlantic MBT records described here contrast with longitudinally-constrained VGP paths for the MBT, indicating that relatively low sedimentation rate (~4 cm/kyr) records of the MBT are heavily smoothed by the remanence acquisition process and do not adequately represent the MBT field. The VGPs at the MBT and top Jaramillo, as measured in the North Atlantic, have similarities with excursion (Iceland Basin) VGP paths, and were apparently guided by maxima in downward vertical flux similar to those seen in the modern non-dipole (ND) field, implying longevity in ND features through time.

Keywords: North Atlantic, Matuyama-Brunhes transition, relative paleointensity

1. Introduction

The conventional age of Matuyama-Brunhes polarity transition (MBT) in modern versions of the geomagnetic polarity timescale (GPTS) (Lourens et al., 2004; Ogg, 2012) is 780 or 781 ka, ages stemming from Shackleton et al. (1990). On the other hand, more recent correlations of $\delta^{18}\text{O}$ to the MBT have resulted in a mid-point age for the MBT of 773 ka (e.g., Channell and Kleiven, 2000; Channell et al., 2010; Valet et al., 2014). The 773 ka estimate is broadly consistent with a recent U-Pb age from a marine-deposited tephra that lies ~80 cm stratigraphically below the MBT in sediments of the Boso Peninsula (Japan), leading to a MBT age of 770.2 ± 7.3 ka (Suganuma et al., 2015). The $^{40}\text{Ar}/^{39}\text{Ar}$ age for the MBT from the Hawaiian Haleakala lavas of 776 ka (Coe et al., 2004; Singer et al., 2005), using a Fish Canyon sanidine (FCs) standard age of 28.02 Ma, translates to 781 ka or 784 ka for currently popular FCs ages of 28.201 Ma (Kuiper et al., 2008) and 28.305 Ma (Renne et al., 2010), respectively. Singer (2014) cited new ages from the Haleakala lavas, with exceptionally low and stable analytical blanks and FCs age of 28.201 Ma, that are consistent with the astrochronological ages (773 ka). On the other hand, a MBT age of 786 ± 1.5 ka has recently been obtained from $^{40}\text{Ar}/^{39}\text{Ar}$ ages of tephras in lacustrine sediments from the Sulmona Basin of central Italy (Sagnotti et al., 2014, 2016) using an Alder Creek Rhyolite (ACR) standard age of 1.194 Ma. The ACR standard age has been revised to 1.2061 Ma (Renne et al., 2010), leading to a MBT age at Sulmona of 794.4 ± 1.5 ka. This result has important implications as a MBT age of 794 ka coincides with abrupt increase in mid-summer insolation at 65°N (Laskar et al., 2004; Supplemental Fig. 1), that is conventionally considered to have triggered deglaciation at the end of marine isotope stage (MIS) 20 and the onset of MIS 19. Based on numerous studies in marine sediments (e.g., Channell and Kleiven, 2000; Channell et al., 2010; Valet et al., 2014), the MBT postdates the peak interglacial, referred to as MIS 19c in the terminology of Railsback et al. (2015). The

age of the MBT can only coincide with the insolation change if an important tenet of Milankovitch theory of climate, that abrupt increases in Northern Hemisphere insolation forced deglaciations, is incorrect.

The precise age of the MBT may be a moot point in view of the conclusions of Leonhardt and Fabian (2007) who used four MBT records, three from the North Atlantic, as the basis for Bayesian modeling of the MBT field and concluded that the age of the MBT is site dependent being ~10 kyr older in the Pacific Ocean than in the Atlantic Ocean. This paper has been regularly cited to explain discrepancies between the $^{40}\text{Ar}/^{39}\text{Ar}$ ages for the MBT from Hawaii (784 ka), using the most recent FCs age, and the MBT age from astrochronology of North Atlantic sediments (773 ka). The implications for stratigraphy, and for the mechanisms of the geodynamo, of global diachroneity of the MBT are far-reaching. Here we report new MBT records that test whether the North Atlantic MBT records used in the Leonhardt and Fabian (2007) analysis (Valet et al., 1989; Clement and Kent, 1986) are faithful representations of the MBT field.

Records of field structure at the MBT (or at other polarity reversals) have been elusive in lavas due to irregular and unresolvable rates of volcanic eruption, and in sediments due to the inadequate sedimentation rates and magnetization smoothing associated with remanence acquisition. The most detailed volcanic record of a polarity reversal is that from Steens Mountain, Oregon (Prévot et al., 1985; Jarboe et al., 2011) that indicates a polarity transition field, for this early Miocene reversal, that is considerably more complex than implied by data from the vast majority of sedimentary and volcanic reversal transition records (Clement, 1991; Laj et al., 1991). Hoffman and Singer (2004) emphasized the recurrence of transitional VGPs off western Australia associated with reversals and excursions during the last 3 Myr recorded in the Society Islands, and noted the coincidence of this Australasian VGP cluster with the *south* VGP of the modern non-axial dipole (NAD) field.

“Complexity” in MBT and top Jaramillo records, using terminology of Coe and Glen (2004), involves VGP paths featuring loops and transits, and has come from Ocean Drilling Program (ODP) Sites 983 and 984 (Fig. 1) located on sediment drifts south of Iceland (Channell and Lehman, 1997; Channell et al., 2004). Similar

complexity has been observed for the boundaries of the Jaramillo Subchronozone at IODP Sites U1304, U1305 and U1306 (Mazaud et al., 2009). The North Atlantic MBT and Jaramillo records indicate several intermediate virtual geomagnetic pole (VGP) clusters (groups), notably in the South Atlantic, NE Asia, and the northern Pacific, as the VGPs transit from high southerly latitudes to high northerly latitudes, or vice versa for the top of the Jaramillo (Channell and Lehman, 1997; Channell et al., 2004; Mazaud et al., 2009).

2. Studied deep-sea cores

Here, we describe paleomagnetic and RPI records for the MBT, and one top Jaramillo record, at three North Atlantic sites drilled during IODP Expedition 303 (Sites U1304, U1305 and U1306, Fig. 1). During IODP Expedition 303, the Advanced Piston Corer (APC) was used exclusively in order to optimize core quality, and drilling of multiple holes at each site minimized gaps in core recovery (Channell et al., 2006). Physical properties, such as magnetic susceptibility, reflectance, and gamma-ray porosity, measured on recovered core sections during occupation of the site, were used to set coring offsets among holes, and ensure complete recovery of the sedimentary section. Lithologies in the vicinity of the MBT comprise silty clay nannofossil ooze with diatoms (Site U1304), silty clay with nannofossils (Site U1305) and silty clay (Site U1306). These sites provide records from multiple holes drilled at each site, that augment the North Atlantic MBT records available from ODP Sites 983, 984 and 1063 (Channell and Lehman, 1997; Channell et al., 2004; Channell et al., 2010). The new data bear on the age and duration of the MBT, and the provide constraints on the structure of the geomagnetic field during the polarity transition.

The natural remanent magnetization (NRM), RPI proxies, and rock magnetic properties, derived from the composite sections at Sites U1304, U1305, and U1306 are reported elsewhere (Xuan et al., 2016; Mazaud et al., 2012; Channell et al., 2014). These studies were based largely on u-channel samples (2x2x150 cm³ samples encased in plastic) collected from each ~150 cm core section included in the composite splice. Additional rock magnetic data for Sites U1305 and U1306,

indicating fine-grained magnetite as the principal remanence carrier, can be found in Kawamura et al. (2012). Age models in the vicinity of the MBT involved planktic oxygen isotope and RPI data at Site U1306 (Channell et al., 2014), planktic oxygen isotope data at Site U1305 (Hillaire-Marcel et al., 2011), and benthic oxygen isotope data at Site U1304 (Xuan et al., 2016). For this study, the MBT was sampled from core sections outside the composite splice, and the consensus from multiple records of the MBT is the subject of this paper. Identification of core sections that record the MBT was based on initial shipboard paleomagnetic measurement of core sections from all holes, shipboard determination of hole-to-hole correlations and composite depths (Channell et al., 2006), and results from u-channel samples collected from the composite splice at each site (Xuan et al., 2016; Mazaud et al., 2012; Channell et al., 2014).

3. Methods

U-channel measurements were carried out at 1-cm spacing, with a 10-cm leader and trailer, on a 2G Enterprises cryogenic magnetometer at the University of Florida. Two u-channel samples recording the MBT, from core sections U1305B-13H-2/3 of the Site U1305 composite splice, were measured using similar instrumentation at Gif-sur-Yvette (Mazaud et al., 2012). As the archive halves of core sections were demagnetized shipboard at peak fields of 15-20 mT, the measurement protocol for u-channels from archive halves comprised NRM measurement prior to demagnetization, then measurement after demagnetization at peak fields of 20-60 mT, applied in 5 mT increments, followed by peak fields of 60-100 mT applied at 10 mT increments. Magnetization components were computed for 20-80 mT peak fields without anchoring to the origin of the orthogonal projections using standard methods (Kirschvink, 1980) and the UPmag software (Xuan and Channell, 2009). The component magnetizations, computed at 1-cm intervals, are associated with maximum angular deviation (MAD) values that gauge the quality of individual component directions. Examples of orthogonal projections of AF demagnetization for the three sites, chosen to display data associated with both high and low MAD values, are provided (Supplementary Figs. 2-7).

Ten discrete, 2 cm x 2 cm x 2 cm, samples were collected from one core section (U1304B-14H-2) and 133 back-to-back 1 cm x 1 cm x 1 cm discrete samples were collected from two core sections (U1306D-13H-2 and 3) in order to compare discrete and u-channel data. After initial NRM measurements, discrete samples were AF demagnetized in 5 mT peak-field steps from 15-60 mT and 10 mT peak-field steps from 60-90 mT. Component magnetization directions were calculated using the standard technique (Kirschvink, 1980) for a uniform 20-80 mT peak field range using software based on the UPMAG software of Xuan and Channell (2009).

After measurement of NRM, volume magnetic susceptibility was measured at 1-cm spacing for all u-channel samples on a susceptibility track designed for u-channels with a Gaussian-shaped response function similar to that for the u-channel magnetometer (Thomas et al., 2003).

Comparison of u-channel and discrete sample data from Hole 1306D was facilitated by deconvolution of u-channel data, after detailed measurement of the response function of the 2G u-channel magnetometer at the University of Florida, using methods described by Oda and Xuan (2014) and Xuan and Oda (2015).

The intensity of a sedimentary detrital (or depositional) remanent magnetization (DRM) depends on the intensity of the geomagnetic field, and the concentration and alignment efficiency of remanence-carrying grains. The relative strength of the magnetizing field can be estimated by using the intensity of anhysteretic remanent magnetization (ARM) to normalize the NRM intensity for changes in concentration of NRM-carrying grains. The resulting normalized remanence can be a proxy for relative paleointensity (RPI) variations in cases where fine-grained magnetite is the sole remanence carrier and magnetic concentration parameters do not vary by more than about an order of magnitude (e.g., Tauxe, 1993). Our procedure for determining RPI proxies is to use the same demagnetizing fields for ARM as for NRM demagnetization. We then calculate slopes of NRM-lost versus ARM-lost over a specific demagnetization interval (20-60 mT). ARMs were acquired using a 50 μ T DC field and a peak alternating fields of 100 mT. For some u-channels we also measured ARMAQ (ARM acquisition), and determined the slopes of NRM-lost versus ARM-acquired. These slopes are

analogous to NRM/ARM, and NRM/ARMAQ ratios, and are accompanied by linear correlation coefficients (r) that provide estimates of the linearity of each slope, calculated at 1-cm intervals down-core. For all u-channel samples, we measured isothermal remanent magnetization (IRM) intensities acquired in a 1T DC field using a pulse magnetizer and then demagnetized at the same peak fields as NRM and ARM. Although the NRM/IRM slopes are similar to the NRM/ARM slopes, the linear correlation coefficients (r) indicate that the NRM/IRM slopes are less well defined compared to NRM/ARM slopes, consistent with earlier findings at these sites (Mazaud et al., 2012, Channell et al., 2014, Xuan et al., 2016).

The studied cores were not adequately oriented in azimuth, although the Tensor orientation device was utilized during the cruise (Channell et al., 2006), and therefore the orientation of cores was reconstructed by rotating each (~ 10 m) core such that mean component magnetization declinations within the Brunhes and Matuyama chrons are oriented North and South, respectively. The orientation process is less problematic when most of the core, or the entire core, has been measured, as is often the case for cores incorporated in the composite splice. For individual sections from outside the composite splice, the process must be carried out for single sections or several adjacent sections, thereby introducing more uncertainty into the orientation process.

The alignment of magnetic records from individual holes at a site follows the shipboard determination of meters composite depth (mcd) (Channell et al., 2006). The construction of the composite splice, and the assignment of composite depths, is based on correlation among holes at each site, that is in turn based on shipboard core scans for magnetic susceptibility, natural gamma radiation (NGR) and reflectance (Channell et al., 2006). Aboard ship, individual cores, up to about 10-m long, are cut into (up to seven) 150-cm lengths, and then split into archive and working halves. The working and archive halves of the composite splice were the focus of post-cruise sampling, with the archive halves designated for u-channel sampling and working halves for sampling by other shipboard scientists. In critical intervals such as the MBT, we were permitted to sample working halves within the composite splice (and then surrender these samples for sub-sampling for other

purposes), as well as working and archive halves from other holes that were outside the composite splice and outside the designated permanent archive. The results from this sampling have yielded multiple records of NRM directions and RPI proxies for the MBT. The data are from sediments with mean Brunhes sedimentation rates exceeding 15 cm/kyr, and test of the fidelity of u-channel measurements in an interval where magnetization directions are rapidly changing. The u-channel data are accompanied by discrete sample data from Sites U1304 and U1306. As expected, the new magnetic data across the MBT reveal misalignments from hole-to-hole that imply decimeter-scale errors in composite depths (Figs. 2, 4 and 6). In Figures 5 and 7, we modified the shipboard composite depths for Holes U1304D and U1306B at the MBT by a uniform adjustment of 12 cm and 15 cm, respectively, although uniform adjustment does not compensate entirely for the offsets at the two holes, presumably due to relative stretching/compaction between holes.

4. Results

4.1 Site U1304

IODP Site U1304 (53.06° N, 33.53° W) is located at the southern limit of the Gardar Drift, north of the Charlie-Gibbs fracture zone (Fig. 1), at a water depth of 3024 m. The MBT occurs at a depth of ~139 mcd at Site U1304 indicating a mean Brunhes sedimentation rate of ~18 cm/kyr (Xuan et al., 2016). The elevated sedimentation rates at Site U1304 are due to the sporadic occurrence of diatom oozes and mats (Channell et al., 2006; Xuan et al., 2016). In the vicinity of the MBT at Site U1304, the lithology comprises dark-gray to gray nannofossil ooze and silty clay, with thin intercalations of greenish gray diatom ooze (Channell et al., 2006). Thick diatom mats occur elsewhere in the Quaternary section but are absent in the MBT interval. The composite splice in the vicinity of the MBT comprises core sections U1304A-13H-2 to 6, and the archive halves of these core sections were therefore included in the sampling of the composite section (Xuan et al., 2016). In addition to the archive half of Hole U1304A, we were permitted to sample, using u-channels, the working half of core section U1304A-13H-5, working and archive halves of core sections U1304B-14H-1 to 2, and the working half of core sections

U1304D-8H-4 to 5. Nine discrete (8-cm³) cubic samples were collected from the archive half of core section U1304B-14H-2, alongside the u-channel sample.

Component magnetization directions across the MBT at Site U1304 are represented in Figure 2, where they are color coded such that greens represent Hole U1304A (archive and working halves), blues represent Hole U1304B (archive and working halves) and red represents Hole U1304D (working half). When working and archive halves of the same core section were sampled, the lighter (darker) shades represent archive (working) halves. Results from discrete (8-cm³) samples from the archive half of U1304B-14H-2 are displayed as purple triangles (Fig. 2). The component magnetizations were determined for a uniform (20-80 mT) peak field demagnetization interval for both u-channel and discrete samples. Magnetization components are well-defined based on maximum angular deviation (MAD) values that are largely <5°. The data from Hole U1304D (red in Fig. 2) are clearly offset up-section, by ~12 cm, compared to data from other holes, as a result of imprecise hole-to-hole correlation and composite depths for Hole U1304D in the MBT interval.

Orthogonal projections of AF demagnetization data at specific depths (cm) in core sections U1304A-13H-5 and U1304B-14H-2 (Supplemental Fig. 2) and U1304D-8H-4 (Supplemental Fig. 3) indicate that the component magnetizations are very often, but not always, well defined. The MAD values associated with the component magnetization, computed in the 20-80 mT demagnetization range, are indicated with each projection. Declinations in the orthogonal projections are not corrected for core rotation, as in Fig. 2. The orthogonal projections were chosen in order to display not only the good quality (low MAD value) data but also the low quality (high MAD value) data. For example, the orthogonal projections associated with high MAD values at 139.0-139.2 mcd for core section U1304A-13H-5 (dark green symbols in Fig. 2) are shown in Supplemental Figure 2.

Apart from anomalous declinations in the 139.5-140.0 mcd interval of Hole U1304D (red symbols in Fig. 2), when inclinations are steep and therefore declinations poorly constrained, component directions are similar but not identical for working and archive halves from the same hole, and for different holes from the

site (Fig. 2). Even when shipboard hole-to-hole correlations are carried out precisely, relative stretching or compaction between hole-to-hole ties are not accounted for, and therefore hole-to-hole alignment cannot be expected to be perfect using current shipboard methods. In addition, other contributors to hole-to-hole discrepancies may include: hole-to-hole differences in depositional and/or bioturbation history, as well unrecognized sediment disturbance during coring, core splitting, and sampling. From repeated u-channel sample measurements, sample positioning in the magnetometer during NRM measurement, and inherent asymmetries in the magnetometer response functions, are considered to be of secondary importance.

The component magnetization directions can be represented as virtual geomagnetic pole (VGP) latitudes, as a means of viewing directions without implication that the magnetizing field was dipolar. This representation shows a number of common features in the polarity transition records from Site U1304 (Fig. 3). In Figure 3, the record from Hole U1304D (red in Figs. 2 and 3) has been shifted down-section by a uniform 12 cm to account for the offset noted in Figure 2. An initial shift in VGP latitudes at ~139.2 mcd from high southern latitudes, followed by a rather coherent pattern of mid-latitude VGPs, is followed by VGPs arriving at high northern latitudes at ~138.6 mcd (Fig. 3). The M-B polarity transition, where the transition interval is defined as being bounded by VGPs between 40°N and 40°S, occupies ~60 cm of core section at Site U1304 (138.60-139.18 mcd). The transition zone (shaded in Fig. 3) spans the 766-774 ka interval with mid-point of the reversal at 770 ka. The polarity transition lies within an interval of low RPI, and linear correlation (r) coefficients close to unity imply well-defined RPI proxies (Fig. 3). The benthic oxygen isotope data based on *Cibicidoides wuellerstorfi* (Xuan et al., 2016) indicate that the polarity transition occurs post MIS 19c (peak interglacial), possibly prior to MIS 19b, although MIS 19a and 19b (terminology of Railsback et al., 2015) are poorly defined at Site U1304.

4.2 Site U1305

The location (57° 28.51 N, 48° 31.81 W) and water depth (3460 m) at IODP Site U1305 (Fig. 1), on the southwestern toe of Eirik Drift, leads to sedimentation rates that are relatively elevated in interglacial stages, when the Western Boundary Undercurrent (WBUC) was believed to have been most active, leading to enhanced sediment supply to the site (Hillaire-Marcel et al., 1994, 2011; Channell et al., 2006; Mazaud et al., 2012). The MBT at Site U1305 occurs at ~127.4-128.3 mcd indicating a mean sedimentation rate in the Brunhes Chron of 16.5 cm/kyr. In the MBT interval, the lithology comprises dark-gray silty clay with nannofossils, and the composite splice comprises the archive halves of core sections U1305B-13H-2/3 (Channell et al., 2006; Mazaud et al., 2012). In addition to the MBT record from the composite splice, we report the MBT records from the working halves of core sections U1305B-13H-2/3, the working and archive halves of core sections U1305A-12H-6/7, and the working halves of core sections U1305C-13H-4/6.

The NRM directions from the working and archive halves from Hole U1305B (blues in Fig. 4) are very similar, in spite of the fact that magnetic measurements for the archive half were carried out at Gif-sur-Yvette (Mazaud et al., 2012) and for the working half at the University of Florida (UF). The susceptibility calibration is, however, different for the working and archive halves of Hole U1305B (Fig. 4), reflecting calibration discrepancies at the two laboratories. The results from the archive and working halves of Hole U1305A, both measured at UF, are similar but not identical (greens in Fig. 4). Magnetization components are determined for a uniform (20-80 mT peak field) demagnetization interval. MAD values are largely below 5° although values exceed 10° for some measurement intervals (Fig. 4). Note that the alignment of magnetic susceptibility amongst the u-channels is no better than for NRM directions.

Orthogonal projections of AF demagnetization data at specific depths (cm) in core sections U1305A-12H-6 (Supplemental Fig. 4) and U1305B-13H-2/3 and U1305C-13H-5 (Supplemental Fig. 5) indicate that the component magnetizations are very often, but not always, well defined. The displayed orthogonal projections were chosen to illustrate not only the good quality (low MAD value) data but also the low quality (high MAD value) data. For example, orthogonal projections

associated with MAD values $>15^\circ$ in core section U1305A-12H-6 at ~ 128.2 mcd (dark green symbols in Fig. 4) are shown in Supplemental Figure 4. Declinations in the orthogonal projections are not corrected for core rotation as in Fig. 4.

At Site U1305, the MBT transition interval, defined by VGP latitudes between 40°N and 40°S , apparently spans the 762-777 ka (Fig. 5) interval based on the age model of Hillaire-Marcel et al. (2011). The isotopic age of the MBT is poorly constrained at this site due to the low abundance of *Neogloboquadrina pachyderma*, particularly in the latter part of MIS 19 (Hillaire-Marcel et al., 2011). The MBT clearly postdates the $\delta^{18}\text{O}$ minimum associated with the MIS 19c peak interglacial. The representation of NRM directions as VGP latitudes (Fig. 5) indicates an initial shift from high southerly VGP latitudes to mid-latitude VGPs at ~ 128.1 mcd followed by a shift to northerly latitudes at ~ 127.47 mcd, similar to those observed at Site U1304 (Fig. 3). Data from archive and working halves of Hole U1305A (greens in Figs. 4 and 5) show a perturbation in VGP latitude below the MBT at ~ 128.25 mcd, although this feature is absent in the records from the other holes. The RPI record indicates minima at the boundaries of the transition interval, with evidence for recovery of RPI during the transition interval. No adjustments to the shipboard mcd-scale have been made for this site, and depth offsets among holes can be attributed to decimeter or cm-scale errors in the shipboard composite depths and/or relative hole-to-hole compaction and stretching.

4.3 Site U1306

IODP Site U1306 (58.23°N , 45.64°W) is close to the crest of the Eirik Drift (Fig. 1) at 2272 m water depth, considerably shallower than Site U1305. The age model at Site U1306, based on a combination of RPI and $\delta^{18}\text{O}$, indicates enhanced sedimentation rates in glacial intervals particularly in the transitions from interglacials to glacials (Channell et al., 2014). The MBT lies at 122.6 to 124.0 mcd (Fig. 6) indicating a mean Brunhes sedimentation rate of 16 cm/kyr. In the MBT interval, the lithology comprises dark-gray silty clay, and the MBT is recorded in core sections U1306C-13H-3 to 5 within the composite section (orange in Fig. 6 and

7). U-channel samples recording the MBT were also collected from the working halves of these same sections (red in Fig. 6 and 7), and from archive and working halves of core sections U1306B-13H-5 to 7 (blues in Fig. 6 and 7).

Orthogonal projections of AF demagnetization data at specific depths (cm) of u-channel samples from core sections U1306C-13H-3/4 (Supplemental Fig. 6) and U1306D-13H-2/3 (Supplemental Fig. 7) indicate that the component magnetizations are very often, but not always, well defined. The orthogonal projections were chosen in order to display not only the good quality data (low MAD values) but also the low quality (high MAD value) data. For example, orthogonal projections associated with MAD values $>20^\circ$ at ~ 123.5 mcd in core section U1306D-13H-2 (dark green symbols in Fig. 6) are displayed in Supplemental Figure 7. Declinations in the orthogonal projections are not corrected for core rotation, as in Fig. 6.

The working half of core sections U1306D-13H-2 and 3 were sampled using u-channels and 133 back-to-back 1-cm³ discrete cubes collected alongside the u-channel trough. Samples from Hole U1306D are shown in green colors in Figure 6, with discrete samples as triangular symbols. The shipboard-derived composite depths at the MBT for Hole U1306B (blues in Fig. 6) are lower relative to other holes from the site by ~ 15 cm. In the representation of VGP latitudes and RPI (Fig. 7), we have made a uniform adjustment of depths (mcd) for Hole U1306B by 15 cm. Note that a uniform mcd-adjustment improves but does not eliminate the offsets, reflecting the inadequacy of a single uniform adjustment for reconciling hole-to-hole relative compaction and/or stretching.

Following Oda and Xuan (2014), the response functions of the u-channel magnetometer at the University of Florida were carefully measured, and the u-channel data from Hole U1306D deconvolved to compensate for the averaging effect of Gaussian-shaped magnetometer response functions, that are not identical for the three orthogonal axes of the magnetometer, and are narrower than the response functions of the Oregon State University magnetometer depicted in Oda and Xuan (2014). The deconvolved data from Hole U1306D were then recombined to determine component magnetization directions for 20-80 mT peak field demagnetization interval, for comparison with original (undeconvolved) u-channel

component magnetizations computed over the same demagnetization interval, and with component magnetizations from 1-cm³ discrete samples (Fig. 8). The consistency of u-channel data (deconvolved and undeconvolved) and discrete sample data (Fig. 8) implies that differences in component magnetization directions among holes (Figs. 2, 4, 6) are due to hole-to-hole differences in sedimentation/bioturbation, sampling and drilling disturbance, rather than issues related to the u-channel measurement procedure.

For Site U1306, the pattern of VGP latitudes (Fig. 7) indicates a similar pattern to that seen at Sites U1304 and U1305 (Figs. 3 and 5). Abrupt change from southerly VGP latitudes to mid-latitude VGPs at 123.45 mcd is followed by undulations of VGPs at mid-latitudes followed by an abrupt shift to high northerly latitudes at ~122.73 mcd (Fig. 7). The RPI records reveal minima at the VGP latitude shifts to/from high latitudes, and recovery of RPI between these two VGP shifts. The recovery of RPI during the transition at Site U1306 is, however, not clearly observed at Sites U1304 and U1305 (Figs. 3 and 5). A perturbation in VGP latitude below the MBT at ~124 mcd is recorded in both archive and working halves from Hole U1306C, and in discrete and u-channel samples from Hole U1306D (Fig. 6 and 7). The MBT interval, defined by VGP latitudes between 40°N and 40°S, corresponds to the 768-776 ka based on the published age model (Channell et al., 2014). The MBT clearly postdates the peak interglacial (MIS 19c) and appears to predate MIS 19a/b, although the planktic $\delta^{18}\text{O}$ record at Site U1306 is again affected by low abundance of *N. pachyderma* (Fig. 7).

5. Virtual geomagnetic poles (VGPs)

The similarities in MBT component magnetization directions can be displayed by plotting VGPs on a global projection. The color-coding of VGPs in Figure 9 are the same as in Figures 2-7. The MBT is characterized by three intermediate field states as VGPs migrate from high southerly to high northerly latitudes. We observe sequentially, a VGP loop in the Pacific (Group 1 in Fig. 9), a VGP grouping in NE Asia (Group 2 in Fig. 9) and a VGP grouping in the mid-latitude South Atlantic (Group 3 in

Fig. 9). At Site U1306, similar but not identical VGP groups are observed for both u-channel samples and back-to-back 1-cm³ discrete samples (Fig. 9). At this site, VGPs are scattered at high southerly latitudes in the South Atlantic realm, then transit to the NW Pacific with a broad loop over the Pacific (Group 1 in Fig. 9), and a grouping in the mid-latitude South Atlantic (Group 3 in Fig. 9) before transit to high northerly latitudes. Group 2 in NE Asia observed at Sites U1304, U1305, 983 and 984 (Fig. 9) is less prominent at Site U1306 although a NE Asian grouping appears prior to the Pacific loop for both u-channel and discrete samples at this site (Fig. 9). The Site U1306 discrete sample VGPs displayed in Figure 9 comprises 115 samples (out of a total of 133 samples) for which the MAD values associated with the magnetization component directions are <10°.

Comparison with MBT records from ODP Site 983 and 984 (Channell and Lehman, 1997; Channell et al., 2004) indicates similar VGP features at the MBT (Fig. 9). Note that the “precursor” observed at Site 984, located within MIS 19c (see Fig. 14 of Channell et al., 2004), is not observed at any of the sites discussed here. If the VGPs associated with this “precursor” at Site 984 are removed from the Site 984 VGP plot, we observe more clearly the repetition of the VGP Groups 1-3 (Fig. 9). The MBT record from ODP Site 1063 (Fig. 1, Channell et al., 2010) also yields VGPs with similar locations, although the NE Asia Group 2 is apparently missing (Supplemental Fig. 8).

6. Discussion

Although repetitive features are observed in NRM component directions, RPI proxies, and VGP records, at Sites U1304, U1305 and U1306, the directional and RPI records from separate holes are certainly not identical. Misalignments in depth may be attributed to errors in shipboard-derived composite depths (Channell et al., 2006) that are based on hole-to-hole correlation of core scanning data (such as magnetic susceptibility and reflectance) and do not compensate for any relative expansion or contraction of the sedimentary section between holes. In addition, hole-to-hole differences in depositional and bioturbation history, coring and sampling disturbance, including undulations in the core-splitting plane, may

contribute to differences in magnetization directions among holes at a site. Finally, the u-channel measurement procedure introduces distortions/smoothing due to the shape of the magnetometer response function (Weeks et al., 1993). We have endeavored to assess these u-channel distortions/smoothing by using back-to-back 1-cm³ plastic cubes collected alongside the u-channel trough in core sections U1306D-13H-2 and 3. The results from the back-to-back cubes are broadly compatible with the u-channel data from the same core sections (U1306-D-13H-2 and 3), both before and after deconvolution of u-channel data (Fig. 8). This implies that the positioning of u-channel samples in the magnetometer and asymmetries in the magnetometer response functions are not the sources of hole-to-hole (and archive to working) differences in component magnetization directions. From inspection of Figure 8, u-channel results are clearly smoothed relative to the data from the 1-cm³ plastic cubes although the deconvolution of the u-channel data succeeds in replicating most features in the 1-cm³ discrete sample data. The sampling of back-to-back 1-cm³ plastic cubes involves sampling disturbance at cube walls that is likely to be more disruptive than the disturbance associated with u-channel sampling. Provided the resolution (sedimentation rate and continuity) of the sedimentary record is sufficient, u-channel samples can provide useful and important data from polarity transitions, in contrast with the conclusions of Valet et al. (2016) and Valet and Fournier (2016) who have advised: “we should exclude transitions measured using u-channels”.

Based on analysis of 10 volcanic polarity transition records dating back to 180 Ma, Valet et al. (2012) concluded that “precursors” and “rebounds” are a characteristic of polarity transitions including the MBT. We recognize a possible “precursor”, defined here as low or mid-latitude (<40°) VGPs bounded by high-latitude VGPs, at ODP Site 984 that occurs in MIS 19c (see Fig. 14 in Channell et al., 2004) and muted “precursors” at Site U1305 (Fig. 5) and U1306 (Fig. 7), also within MIS 19c. A weakly manifest directional “precursor” associated with the MBT, occurring apparently in late MIS 20 and associated with a RPI minimum, has been observed at IODP Site U1308 (Channell et al., 2010). The “precursor” observed in the Indian Ocean correlates to MIS 20 (Valet et al., 2014), and is not correlative to

the precursor at ODP Site 984 as it lies in a different isotopic stage. In conclusion, we do not see evidence from the North Atlantic sediment records that “precursors” and “rebounds” are general features of the MBT. On the other hand, the sedimentary records described may be interpreted as smoothed renditions of the pattern of “precursors” and “rebounds” observed in volcanic rocks (Valet et al., 2012).

Until recently, the MBT records from ODP Sites 983 and 984 (Channell and Lehman, 1997; Channell et al., 2004) and records of the top Olduvai at Site 983 (Mazaud and Channell, 1999) were rather unique, exhibiting “complexity” in transitional VGP paths. On the other hand, these complex VGP paths have common features with VGP paths from the boundaries of the Jaramillo Subchronozone at IODP Site U1304, U1305 and U1306 (Mazaud et al., 2009), VGPs from numerical simulations of polarity transitions (Coe and Glen, 2004; Olson et al., 2011), and VGPs from the Steens Mountain volcanic record of a Miocene polarity transition (Jarboe et al., 2011). The new North Atlantic MBT records, described here, yield VGP paths that are similar but not identical from site-to-site and hole-to-hole, and compatible with previously published data from ODP Sites 983 and 984 (Fig. 9). At Steens Mountain, two VGP groups, one over South America and one over the western Pacific (see Fig. 16a of Jarboe et al., 2011), are similar to the VGP groups for the MBT from North Atlantic sediments.

Analogous but different VGP groups are observed at the boundaries of the Jaramillo Chronozone at IODP Sites U1304, U1305 and U1306 (Mazaud et al., 2009). A single published record of the top Jaramillo from Hole U1306D (see Figs. 5 and 7e of Mazaud et al., 2009) can now be augmented by an additional record of top Jaramillo from Hole U1306C measured for this paper (Fig. 10), and compared with the top Jaramillo records from three holes at Site 983 from Channell and Lehman (1997). The top Jaramillo transitional VGP paths are strikingly similar (Fig. 10) but different from the VGP paths for the MBT (Fig. 9). The NE Asia group of VGPs and the VGP loop in the eastern Pacific appear to be partially common for the MBT and for the top Jaramillo transition.

7. Conclusions

The new data from Sites U1304, U1305 and U1306 serves to bring “complexity” at the MBT (and top Jaramillo) out of the shadows, and ratifies “complexity” in MBT records observed at ODP Sites 983 and 984 (Channell and Lehman, 1997; Channell et al., 2004). This MBT behavior is distinctly different from the vast majority of polarity transition records that contributed to compilations of longitudinally constrained VGP paths in the early 1990s (Clement, 1991; Laj et al., 1991). We conclude that polarity transitions are not adequately captured by the vast majority of sedimentary and volcanic sequences because of insufficient or sporadic sedimentation rates or eruption rates, augmented by smoothing of magnetization directions due to non-instantaneous remanence acquisition in sediments, and cooling/terrain artifacts in lava flows.

A Bayesian inversion of the MBT field (Leonhardt and Fabian, 2007) was based on four MBT records, three of which comes from the North Atlantic, two sedimentary records (Valet et al., 1989; Clement and Kent, 1986) and one volcanic record from La Palma (Valet et al., 1999). The estimated mean sedimentation rates in the two North Atlantic sedimentary records used in the Bayesian simulation are ~4-5 cm/kyr, about 25% of the sedimentation rates for the records presented here. One of the North Atlantic sedimentary records used in the Bayesian inversion is from Deep Sea Drilling Project (DSDP) Site 609 (Clement and Kent, 1986), reoccupied as Site U1308 during IODP Expedition 303 (Channell et al., 2006). The Site U1308 MBT record (Channell et al., 2010) is not part of the present paper because of the relatively low sedimentation rates at this site (mean Brunhes sedimentation rate is 6 cm/kyr). It is worth noting that the VGP distribution for the MBT at Site U1308 (Supplemental Fig. 9) is very similar to the VGP path determined from Site 609 by Clement and Kent (1986) with VGPs passing over the Americas (compare Supplemental Fig. 9 with Fig. 4γ of Leonhardt and Fabian, 2007). We interpret these observations to indicate that polarity transitions are generally not adequately recorded at sedimentation rates <10 cm/kyr, due to rapidly directional change combined with smoothing associated with NRM acquisition in sediments.

We conclude that the sedimentary records, on which the MBT Bayesian inversion of Leonhardt and Fabian (2007) is based, have not adequately recorded the MBT field. These inferences are consistent with recent conclusions of Valet et al. (2016) and Valet and Fournier (2016).

The geographical distribution of the sites studied here, limited to the North Atlantic, does not allow definitive conclusions regarding the MBT field. It is noteworthy that the distribution of VGP groups at the MBT (Fig. 9) resembles features of the modern non-dipole (ND) geomagnetic field. Maxima in vertical intensity of the modern ND field at the Earth's surface occur in NE Asia and in the South Atlantic (see Fig. 9 in Channell, 2014). The preference of VGPs during the MBT for these locations may imply that the ND field influenced the MBT field, as the dipole fields declined, and that modern ND field characteristics have longevity that influence not only the MBT, but also Matuyama polarity reversals (Channell and Lehman, 1997; Mazaud et al., 2009), and Brunhes-aged magnetic excursions (Channell, 2014). The top Jaramillo VGP distribution has common features with the VGP distribution at the MBT (Figs. 9 and 10). Similarities of VGP groups with the distribution of maxima in vertical intensity of the modern ND field are more apparent for the MBT than the top Jaramillo, possibly implying long-term drift of ND features on 10^5 - 10^6 year timescales.

Acknowledgements: Research supported by US National Science Foundation grants 0850413 and 1014506. Data archived at the Pangaea Database (www.pangaea.de). I thank Joe Stoner, Alain Mazaud and Helen Evans for help with the initial u-channel sampling, Chaug Xuan for help with the deconvolution procedure, Kainian Huang for help in the paleomagnetic laboratory, Jean-Pierre Valet for a critical review, Bruce Buffett for editorial guidance, the curatorial staff at the IODP core repository in Bremen for sampling assistance, and the Captain and crew of the Joides Resolution for their support during IODP Expedition 303.

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Figure Captions

Fig. 1. Location of IODP Sites U1304, U1305, U1306 and U1308; and ODP Sites 983, 984 and 1063.

Fig. 2. Site U1304 Matuyama-Brunhes transition: Component declination, inclination and associated maximum angular deviation (MAD) values determined for a uniform 20-80 mT demagnetization interval for u-channel and discrete samples, with volume magnetic susceptibility. Depths are in meters composite depth (mcd). Hole U1304A (light green, archive half; dark green, working half), Hole U1304B (light blue, archive half; dark blue, working half), Hole U1304D (red, working half). All data from u-channel samples other than data depicted as purple triangles that are from Hole U1304B cubic (8-cm³) discrete samples.

Fig. 3. Site U1304 Matuyama-Brunhes transition (MBT): Benthic oxygen isotope data, virtual geomagnetic pole (VGP) latitudes, relative paleointensity (RPI) proxies (slopes of NRM/ARM and NRM/ARMAQ determined for the 20-60 mT demagnetization/acquisition interval) with linear correlation coefficients (r) associated with each slope. Color codes as for Figure 2 with circular and triangular symbols in RPI plot indicating NRM/ARM and NRM/ARMAQ slopes, respectively. Coding of symbols for linear correlation coefficients (r) is the same as for RPI. The shaded intervals represents the MBT as defined by VGP latitudes between 40°N and 40°S, transferred from depth to age plots using the age model of Xuan et al. (2016).

Fig. 4. Site U1305 Matuyama-Brunhes transition: Component declination, inclination and associated maximum angular deviation (MAD) values determined for a uniform 20-80 mT demagnetization interval, with volume susceptibility. Depths are in meters composite depth (mcd). Hole U1305A (light green, archive half; dark green, working half), Hole U1305B (light blue, archive half; dark blue,

working half), Hole U1305C (red, working half). All data are from u-channel samples.

Fig. 5. Site U1305 Matuyama-Brunhes transition: Planktic oxygen isotope data (Hillaire-Marcel et al., 2011), virtual geomagnetic pole (VGP) latitudes, relative paleointensity (RPI) proxies (slopes of NRM/ARM and NRM/ARMAQ determined for the 20-60 mT demagnetization/acquisition interval) with linear correlation coefficients (r) associated with each slope. Color codes as for Figure 4 with circular and triangular symbols in RPI plot indicating NRM/ARM and NRM/ARMAQ slopes, respectively. Coding of symbols for linear correlation coefficients (r) is the same as for RPI. The shaded intervals represents the MBT as defined by VGP latitudes between 40°N and 40°S, transferred from depth to age plots using the age model of Hillaire-Marcel et al. (2011).

Fig. 6. Site U1306 Matuyama-Brunhes transition: Component declination, inclination and associated maximum angular deviation (MAD) values determined for a uniform 20-80 mT demagnetization interval for u-channel and discrete samples, with volume susceptibility. Depths are in meters composite depth (mcd). Hole U1306B (light blue, archive half; dark blue, working half), Hole U1306C (orange, archive half; red, working half), Hole U1306D (green, working half). Data are from u-channel samples other than data depicted as green triangles that are back-to-back discrete cubic samples (1-cm³) from Hole U1306D.

Fig. 7. Site U1306 Matuyama-Brunhes transition: Planktic oxygen isotope data (Channell et al., 2014), virtual geomagnetic pole (VGP) latitudes, relative paleointensity (RPI) proxies (slopes of NRM/ARM and NRM/ARMAQ determined for the 20-60 mT demagnetization/acquisition interval) with linear correlation coefficients (r) associated with each slope. Color codes as for Figure 6 with circular and triangular symbols in RPI plot indicating NRM/ARM and NRM/ARMAQ slopes, respectively. Coding of symbols for linear correlation coefficients (r) is the same as for RPI. The shaded intervals represents the MBT

as defined by VGP latitudes between 40°S and 40°N, transferred from depth to age plots using the age model of Channell et al. (2014).

Fig. 8. Hole U1306D Matuyama-Brunhes transition: component magnetization directions determined for the 20-80 mT peak field range for u-channel samples (dark green circles), 1-cm³ discrete samples (light green triangles) and deconvolved u-channel data (open black squares).

Fig. 9. Virtual geomagnetic poles (VGPs) for the Matuyama-Brunhes transition (MBT) at ODP/IODP Sites U1304, U1305, U1306, 983 and 984. Site U1304 u-channel data: Hole U1304A (light green, archive half; dark green, working half), Hole U1304B (light blue, archive half; dark blue, working half), Hole U1304D (red, working half). All are data from u-channel samples other than data depicted as purple triangles that are from Hole U1304B (8-cm³) cubic discrete samples. Site U1305 u-channel data: Hole U1305A (light green, archive half; dark green, working half), Hole U1305B (light blue, archive half; dark blue, working half), Hole U1305C (red, working half). Site U1306 u-channel data: Hole U1306B (light blue, archive half; dark blue, working half), Hole U1306C (orange, archive half; red, working half), Hole U1306D (green, working half). Site U1306 discrete samples: green triangles represent back-to-back discrete cubic samples (1-cm³) from Hole U1306D. ODP Hole 983B (red) and Hole 983C (blue). Hole 984A (green), Hole 984B (red), Hole 984C (blue) (see Channell et al., 2004). Sequential VGP groupings common to all sites are labeled 1, 2, and 3.

Fig. 10. (a) Virtual geomagnetic poles (VGPs) for the top Jaramillo transition for IODP Hole U1306C (blue symbols, this paper), and Hole U1306D (red symbols from Mazaud et al., 2009). (b) VGPs for the top Jaramillo transition for ODP Hole 983A (blue), 983B (red) and 983C (green) from Channell and Lehman (1997). All data are from u-channel samples. The VGP loop over the eastern Pacific (labeled 1) precedes the VGP group in NE Asia (2), that is followed by the VGP transit into the Southern Hemisphere.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10