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High-resolution evidence for dynamic transitional geomagnetic field behaviour from a Miocene reversal, McMurdo Sound, Ross Sea, Antarctica

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We report a high-resolution record of a Miocene polarity transition (probably the Chron C6r-C6n transition) from glacimarine sediments in McMurdo Sound, Ross Sea, Antarctica, which is the first transition record reported from high southern latitudes. The transition is recorded in two parallel cores through a 10.7 m stratigraphic thickness. The sediments are interpreted as having been deposited in a marine environment under the influence of floating ice or seaward of a glacier terminus from which a large sediment load was delivered to the drill site. The core was recovered using rotary drilling, which precludes azimuthal orientation of the core and determination of a vector record of the field during the transition. However, constraints on transitional field behaviour are provided by the exceptional resolution of this record. Large-scale paleomagnetic inclination fluctuations in the two cores can be independently correlated with each other using magnetic susceptibility data, which suggests that the sediments are reliable recorders of geomagnetic field variations. Agreement between the two parallel transition records provides evidence for highly dynamic field behaviour, as suggested by numerous large-scale inclination changes ($\sim 90^\circ$) throughout the transition. These large-scale changes occur across stratigraphically narrow intervals, which is consistent with the suggestion of rapid field changes during transitions. In one intact portion of the core, where there is no apparent relative core rotation between samples, declinations and inclinations are consistent with the presence of a stable cluster of virtual geomagnetic poles within the transition (although the possibility that this cluster represents a rapid depositional event cannot be precluded). These observations are consistent with those from other high-resolution records and provide a rare detailed view of transitional field behaviour compared to most sedimentary records, which are not as thick and which appear to have been smoothed by sedimentary remanence acquisition processes.
Key words: Paleomagnetism, geomagnetic field behaviour, polarity reversal, glacial processes, Antarctica.

1. Introduction

Despite the fact that the geomagnetic field is known to have reversed polarity hundreds of times during earth history, the behaviour and geometry of the field while it reverses between stable polarity states is still not well known (Roberts, 1995). Over the last 15 years, debate concerning transitional field geometries has centered around interpretations of patterns observed in transitional virtual geomagnetic pole (VGP) paths. It has been suggested that transitional VGPs fall along two preferred longitudinal bands (Clement, 1991; Clement and Kent, 1991; Tric *et al.*, 1991; Laj *et al.*, 1991) or in clusters along these bands (Hoffman, 1991, 1992; Brown *et al.*, 1994). These interpretations imply that dipolar fields were dominant during polarity transitions, and the persistence of these inferred patterns of transitional VGP paths for many reversals over the last 10 million years might suggest deep-mantle control of the reversal process (e.g., Laj *et al.*, 1991).

A significant component of the debate concerning the nature of the transitional geomagnetic field has involved the reliability of transition records. For example, directional bias imposed by smoothing during remanence acquisition could have a significant effect on sedimentary transition records (e.g., Rochette, 1990; Langereis *et al.*, 1992; Løvlie, 1994; Quidelleur and Valet, 1994; Quidelleur *et al.*, 1995). The primary shortcoming of transition studies, however, is a lack of a robust global distribution of sites from which detailed records are available (McFadden *et al.*, 1993). In order to advance the state of knowledge concerning transitional geomagnetic field behaviour, it is important to obtain records from a wider distribution of sites, and, for sedimentary records, to provide evidence that sedimentary processes have not biased the paleomagnetic records.

In this study, we present a high-resolution early Miocene polarity transition record from glacimarine sediments deposited in McMurdo Sound, Antarctica. The transition record spans a stratigraphic thickness of 10.7 m, which should provide a detailed record of field behaviour without smoothing by sedimentary remanence acquisition processes. In addition, the fact that the transition is recorded in two immediately adjacent cores (see below) provides an important test of the fidelity of the paleomagnetic sig-

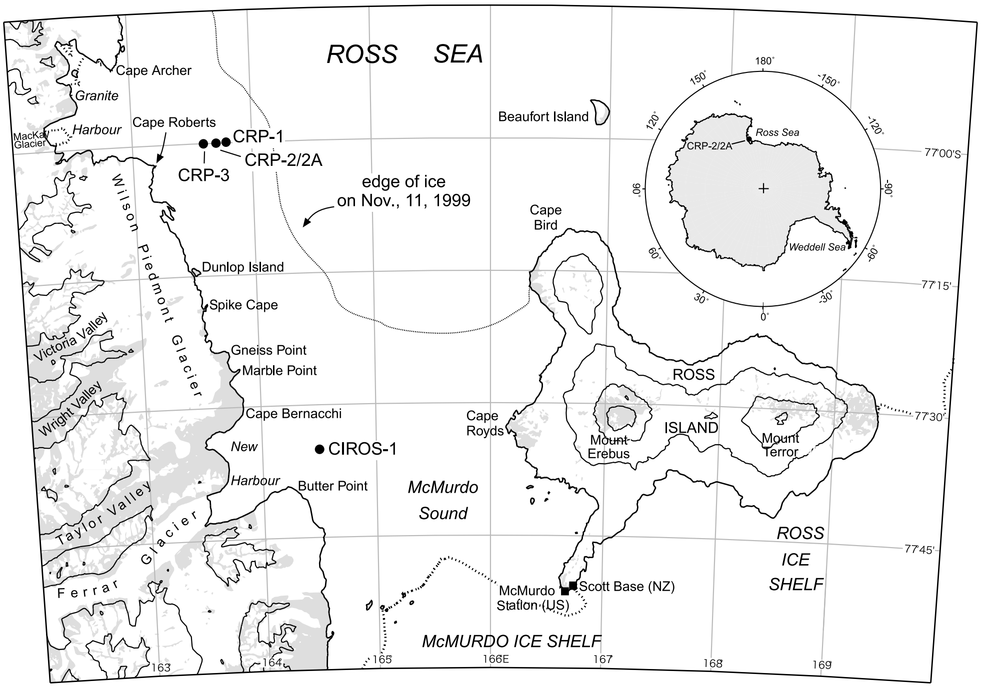

Fig. 1. Location map of the McMurdo Sound area of the Ross Sea with distribution of sea ice in November, 1999, and location of the Cape Roberts Project (CRP) drill sites, including the site studied here (CRP-2/2A).

nal for this transition. Finally, this record represents the first from high southern latitudes, which helps to broaden the geographic distribution of sites with available transition records.

2. Geological Setting

The polarity transition discussed in this study was recovered from cores drilled for the Cape Roberts Project (CRP) in Victoria Land Basin, McMurdo Sound, western Ross Sea, Antarctica (Fig. 1). A primary aim of the Cape Roberts Project was to drill a series of holes through landward dipping seismic reflectors on the Antarctic continental margin to study fluctuations of the East Antarctic Ice Sheet through its early history prior to 30 Ma (Cape Roberts Science Team, 1999). An additional goal was to elucidate the history of rifting in the western Ross Sea in association with the break-up of Gondwana. Three holes were drilled offshore of Cape Roberts from 1997 to 1999 (Fig. 1), with drilling technology that uses a seasonal sea-ice platform. In the austral spring of 1998, a 624-m early Oligocene to Quaternary sequence was cored from the second of three sites (CRP-2). In the uppermost part of the hole, difficulties with drilling required the CRP-2 hole to be offset, and the remainder of the core was recovered from the CRP-2A hole. Parts of the upper 60 m of the composite CRP-2/2A record were recovered in both the CRP-2 and CRP-2A holes.

Below 27 metres below sea floor (mbsf), the CRP-2/2A drill hole contains a sedimentary record that spans the early Oligocene to the early Miocene, and which largely represents cyclic glacimarine nearshore to offshore sedimentation. Sequence stratigraphic analysis indicates that 22 unconformity-bounded, vertically stacked depositional packages were recovered between 27 and 624 mbsf (Cape Roberts Science Team, 1999; Fielding *et al.*, 2000; Powell *et al.*, 2000). When completely preserved (i.e., not top-truncated by erosion at the overlying sequence boundary), these sediment packages typically comprise a four-part architecture involving, in ascending order: 1) a sharp-based, coarse-grained unit, 2) a fining-upward succession of sandstones, 3) a mudstone interval, which in some cases coarsens upward to muddy sandstones, and 4) a sharp-based, sandstone-dominated succession (Cape Roberts Science Team, 1999; Fielding *et al.*, 2000). The sedimentary cyclicity is interpreted in terms of retreat and advance of a glacier terminus to the west (Fig. 1), with concomitant rises and falls in relative sea level (Cape Roberts Science Team, 1999; Fielding *et al.*, 2000; Naish *et al.*, 2001).

Magnetostratigraphic studies were conducted for all CRP cores in order to constrain the chronology of the recovered sequences (Roberts *et al.*, 1998; Wilson *et al.*, 2000a, 2002; Florindo *et al.*, 2001), a summary of which is provided by Florindo *et al.* (2005). Thick intervals of the recovered sequences comprise coarse-grained lithologies, which would not normally be considered to be well suited to paleomagnetic investigations because they are more likely to contain coarse magnetic particles that are incapable of carrying a long-term paleomagnetic record. In the Cape Roberts Project cores, however, these intervals have proved suitable for paleomagnetic analysis because they have polymodal particle-size distributions with a significant mud component. Paleomagnetic sampling of the CRP cores was restricted to the fine-grained sedimentary matrix and pebbly and deformed intervals were avoided. Based on our investigations of a number of cores from the Victoria Land Basin, it is evident that the paleomagnetic signal is carried by fine-grained (pseudo-single domain) magnetite in the sediment matrix even in dominantly coarse-grained lithologies (Roberts *et al.*, 1998; Wilson *et al.*, 1998, 2000a; Verosub *et al.*, 2000; Florindo *et al.*, 2001; Sagnotti *et al.*, 1998a, b, 2001). The characteristic remanence directions identified in these studies have consistently steep inclinations with bimodal normal and reversed polarity distributions that pass paleomagnetic field tests for stability, including a conglomerate test and an inclination-only reversal test. It is therefore possible to sample the fine-grained sedimentary matrix and identify reliable paleomagnetic directions even in diamictites.

Wilson *et al.* (2000a) recognised an interval with a significant thickness of intermediate paleomagnetic directions that separates underlying reversed polarity strata from overlying normal polarity strata in an interval within lithostratigraphic units 4.1 and 3.1 in the CRP-2/2A core (see Fig. 2 for lithostratigraphy). The age of this interval is constrained by diatom biostratigraphy as well as by ^{87}Sr/^{86}Sr dates on calcareous macrofossils (Lavelle, 2000) and ^{40}Ar/^{39}Ar dates (McIntosh, 2000) from volcanic ashes and clasts (Wilson *et al.*, 2000a, b; Florindo *et al.*, 2005). The polarity transition studied here most likely represents the early Miocene reversed-normal polarity transition from C6r to C6n (Florindo *et al.*, 2005), which corresponds to an age of 20.13 Ma on the timescale of Cande and Kent (1995).

The upper part of lithostratigraphic unit 5.1 (Fig. 2) consists of poorly sorted fine sandy mudstone and muddy very fine sandstone, which is interpreted to have been deposited in an inner shelf environment with iceberg influence (Cape Roberts Science Team, 1999). The contact between units 5.1 and 4.1 is interpreted to represent an erosional sequence-bounding unconformity, with unit 4.1 being a massive, poorly sorted sandy diamicton deposited in an ice proximal environment (possibly subglacial, but possibly resulting from rain-out processes below floating ice) (Cape Roberts Science Team, 1999). The overlying sand of unit 3.1, up to the next sequence-bounding unconformity at 37.8 mbsf, was probably deposited near a stream discharge from a glacier terminus into a shallow marine environment.

From the perspective of using glacimarine deposits as a high-resolution archive of geomagnetic field behaviour, the possibility of subglacial deformation is an obvious concern. Identifying the glacial environment can be difficult because the physical characteristics of a diamictite usually provide insufficient information to allow clear interpretation of the precise mode of glacial deposition (e.g., Domack and Lawson, 1985; Dowdeswell *et al.*, 1985). Passchier (2000) reported brecciation between 44 and 46 mbsf in CRP-2A and concluded that the lower part of unit 3.1 (Fig. 2) was deformed in a proglacial ice-push environment. However, brecciation observed in the CRP-2 core (Passchier, 2000) was not observed in the same stratigraphic interval in the immediately adjacent CRP-2A core (the two cores are estimated to lie within 1 m of each other). It is therefore possible that the observed brecciation resulted from core recovery and handling. Microfabric evidence from unit 4.1 may be indicative of subglacial deposition (Van der Meer, 2000); however, this inference is inconsistent with clast macrofabric data (Cape Roberts Science Team, 1999). On the basis of sedimentary grading, stratification and lamination in units 4.1 and 3.1, sedimentary facies analysis (Cape Roberts Science Team, 1999; Powell *et al.*, 2000) suggests that these units probably represent both waterlain ice-proximal rain-out and sediment gravity flow deposits, most likely near a glacier terminus ending in the sea. Thus, the fine-grained matrix of these rocks should be capable of carrying a paleomagnetic record that has not been mechanically disturbed by glacial processes. These units were therefore sampled in detail for the present study to provide a detailed record of the polarity transition, with the exception of the interval of brecciation described by Passchier (2000).

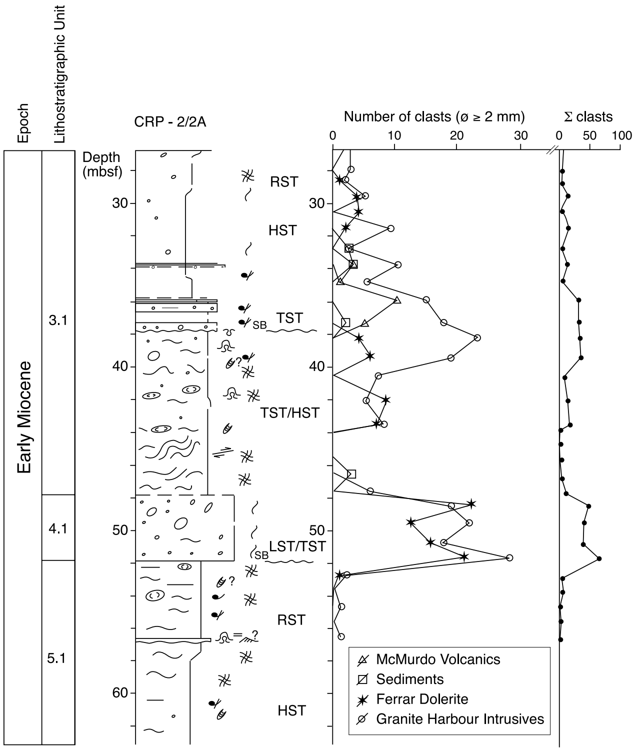

Fig. 2. Lithological column of the CRP-2/2A core in the stratigraphic interval studied in this paper, with lithostratigraphic subdivision, and clast counts for different parent lithologies. The sequence stratigraphic subdivision is that of Fielding *et al.* (2000): RST=regressive systems tract; HST is high-stand systems tract; TST is transgressive systems tract; LST is low-stand systems tract; SB is sequence boundary.

3. Methods

Two hundred fifty five samples were collected in 6.6 cm^3 plastic boxes from the working half of the two cores, either during initial sampling at the Crary Science and Engineering Center, McMurdo Station, Antarctica, or at the Alfred Wegener Institute for Polar Research, Bremerhaven, Germany, where the core is now curated. All of the samples are from the stratigraphic interval containing and bounding the polarity transition. One hundred sixty seven samples were taken from the CRP-2 core between 31.03 and 56.28 mbsf, and 88 samples were taken from the CRP-2A core between 39.09 and 55.60 mbsf. For both cores, lithostratigraphic units 5.1 through 3.1 were sampled at 10-cm intervals, where possible, while avoiding pebbles and intervals where the core was deformed (see Fig. 2). In particular, it should be noted that the lithological log shown in Fig. 2 is based on a description of the CRP-2A core and the interval of brecciation shown between 44 and 46 mbsf (Passchier, 2000) was not sampled. This interval is not brecciated in

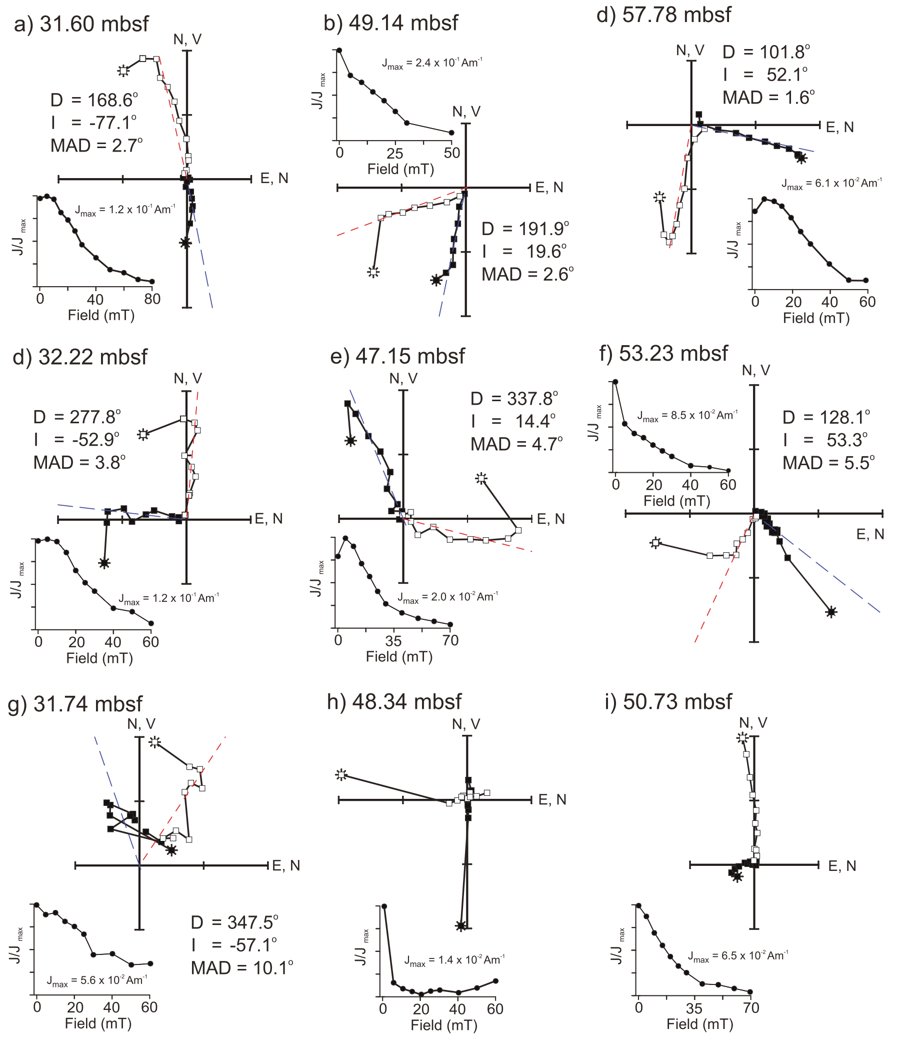

Fig. 3. Vector component diagrams (with normalized intensity decay plots) for selected samples from the CRP-2/2A cores. Class A: (a) a normal polarity sample from above the polarity transition (31.60 mbsf), (b) a sample from within the polarity transition (49.14 mbsf), (c) a reversed polarity sample from below the polarity transition (57.78 mbsf). Class B: (d) a normal polarity sample from above the polarity transition (32.22 mbsf), (e) a sample from within the polarity transition (47.15 mbsf), (f) a reversed polarity sample from below the polarity transition (53.23 mbsf). Class C: (g) a stable, but noisy, normal polarity sample from above the polarity transition (31.74 mbsf), Class D: (h) a sample with behaviour that is impossible to interpret (48.34 mbsf). Illustration of a sample with (i) a dominant drilling-induced overprint (50.73 mbsf). All samples are from CRP-2, except (h), which is from CRP-2A.

the CRP-2 core and was therefore sampled. The samples were oriented only with respect to vertical. Although parts of the core were azimuthally oriented using borehole televiewer (BHTV) imagery (Paulsen *et al.*, 2000), it was not possible to scan the interval studied here with the BHTV tool, therefore absolute paleomagnetic declinations could not be recovered for the polarity transition. This prevents us from calculating VGP positions for the studied polarity transition; however, a high-resolution record of this type is unusual and inclination data alone can provide useful insights into transitional field behaviour.

Paleomagnetic measurements were made using a 2-G Enterprises cryogenic magnetometer in the paleomagnetic laboratory at the National Oceanography Centre, Southampton (NOCS), UK. After measurement of the natural remanent magnetization, the samples were routinely subjected to alternating field (AF) demagnetization at successive peak fields of 5, 10, 15, 20, 25, 30, 40, 50 and 60 mT. In some cases, it was necessary to apply higher peak fields of 70 and 80 mT. AF demagnetization was conducted using a Molspin tumbling AF demagnetizer. Bulk low-field magnetic susceptibility was measured using a Kappabridge KLY-2 magnetic susceptibility meter. Rock magnetic measurements were made using a Princeton Measurements Corporation vibrating sample magnetometer at NOCS. First-order reversal curve (FORC) diagrams (Pike *et al.*, 1999; Roberts *et al.*, 2000) were measured for selected 1-cm^3 subsamples. For such samples, 140 FORCs were measured using an averaging time of 250 ms. All FORC diagrams were calculated using a smoothing factor (SF) of 5 (see Roberts *et al.*, 2000).

4. Results

4.1 Paleomagnetic behaviour

During polarity transitions, field intensities generally decay to between one-fifth and one-tenth of pre-transitional intensities (Bogue and Coe, 1984; Prévot *et al.*, 1985a; Roperch *et al.*, 1988; Lin *et al.*, 1994). As a result, remanence intensities are generally weaker within a transition than before or after a transition, and the quality of paleomagnetic data can vary throughout a transition. We have therefore classified samples according to their paleomagnetic behaviour in order to take into account any variations in data quality. The magnetizations from about two-thirds of the samples analysed in this study are stable and are characterized by univectorial decay to the origin of vector component plots after removal of a low-coercivity overprint (Fig. 3).

Many samples (29%) have a clearly defined, linear characteristic remanent magnetization (ChRM) component, for which the maximum angular deviation (MAD; see Kirschvink (1980)) is less than 3° (Category A; Fig. 3(a)–(c)). A similar proportion of samples (32%) have unambiguous paleomagnetic vectors, which are not as clearly defined (3°<MAD<10°) as those from Category A and are designated as Category B samples (Fig. 3(d)-(f)). A few samples (6%) have noisier demagnetization trajectories for which the ChRM direction can still be identified (Category C; Fig. 3(g)); these samples are included in our analysis. By contrast, the demagnetization data for 33% of samples give no coherent signal (Category D) due to the dominance of low coercivity overprints (Fig. 3(h)), or to noisy behaviour on demagnetization. Also included in this category are a small percentage of samples that are dominated by a steep remanence component (Fig. 3(i)) without the low-coercivity overprint that is observed in the majority of samples. Such samples are interpreted as being dominated by a drilling-induced overprint and are observed throughout our studies of sediments from the Victoria Land Basin (Roberts *et al.*, 1998; Wilson *et al.*, 2000a; Florindo *et al.*, 2001, 2005); these samples are not included in our analysis.

4.2 Magnetostratigraphy through the polarity transition

Paleomagnetic directions are shown in Fig. 4 for all Category A, B and C samples throughout the transitional interval for the CRP-2 and CRP-2A cores. As mentioned above, the cores are not azimuthally oriented, and, because of the use of rotary drilling, parts of the core have rotated with respect to others. The declinations are therefore not rigorously useful for interpreting transitional field behaviour. The transitional interval, defined on the basis of inclinations shallower than ±45°, appears to be 10.7 m in thickness (shaded in Fig. 4). The majority of samples (61%) have unambiguous paleomagnetic directions (Category A and B; closed and open circles, respectively) and most Category C samples (open squares) have directions that are similar to those of adjacent higher quality samples (Fig. 4). There does not, therefore, seem to be any objective reason to exclude the somewhat lower quality Category C samples.

The non-transitional paleomagnetic inclinations are generally shallower than expected for a geocentric axial dipole field (±83.4°) at the latitude of the drill site (77°S). The mean non-transitional inclinations in Fig. 4 are ±57.8°, which is indistinguishable from the mean inclinations for normal and reversed polarity data for the entire CRP-2/2A core (Wilson *et al.*, 2000a). This inclination shallowing can be largely attributed to stratal tilt (Wilson *et al.*, 2000a; Paulsen *et al.*, 2000). When cores are matched across core

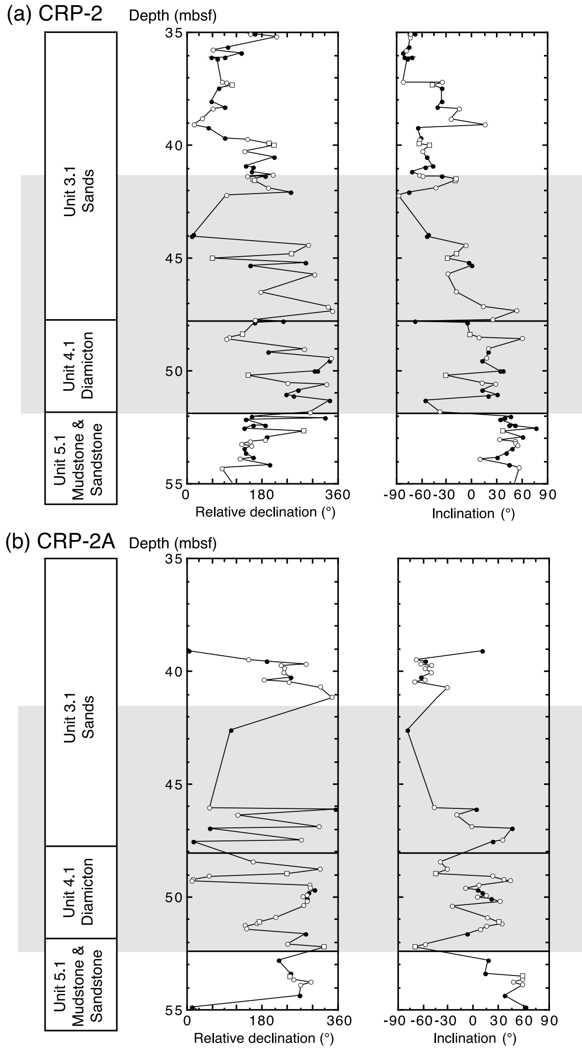

Fig. 4. Paleomagnetic declinations and inclinations for the polarity transition recorded in the (a) CRP-2 and (b) CRP-2A cores. The cores were not azimuthally oriented, therefore declinations are relative to laboratory coordinates only. Closed and open circles and open squares indicate data from categories A, B, and C, respectively. The interval with transitional inclinations (less than ±45°) is shaded and bold lines indicate the major lithostratigraphic boundaries in the cores (see Fig. 2 for a more detailed lithostratigraphic description).

breaks and reoriented using BHTV imagery (for intervals of the core below the studied polarity transition where such data are available), and reoriented back to horizontal using estimates of bedding tilt from Jarrard *et al.* (2000), the mean paleomagnetic inclination is ±81.6° (Paulsen *et al.*, 2000). This mean inclination is statistically indistinguishable from the expected inclination for a geocentric axial dipole field at the site latitude and provides evidence that pre- and post-transitional paleomagnetic data reliably record geomagnetic information and therefore that the studied polarity transition can be used for constraining transitional geomagnetic field behaviour.

4.3 Correlation of polarity transition records from CRP-2 and CRP-2A

Inspection of the paleomagnetic inclinations in Fig. 4 indicates that the two records are highly similar. To enable direct comparison of the records, an appropriate physical pa-

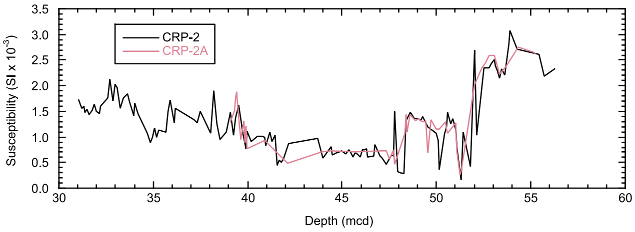

Fig. 5. Low-field magnetic susceptibility data for the CRP-2 and CRP-2A holes, with the CRP-2A data correlated to the CRP-2 depth scale (which is labelled as the metres common depth, or mcd, scale) in order to facilitate direct comparison of data between the two holes. This mcd scale for CRP-2A is used in Fig. 6 to directly compare paleomagnetic data for the two holes.

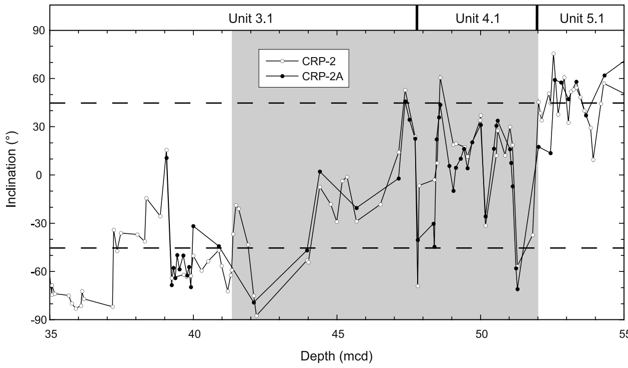

Fig. 6. Paleomagnetic inclination data for the CRP-2 and CRP-2A holes after the depths for samples from CRP-2A have been converted to depths in the CRP-2 hole (mcd scale), through correlation of magnetic susceptibility data from the two holes (see Fig. 5). Agreement between the two data sets indicates that the paleomagnetic data are reliable and that the dynamic variations in paleomagnetic directions result from field behaviour rather than noise in either data set. The shaded area represents the transitional interval defined in Fig. 4.

rameter, such as the low-field magnetic susceptibility, can be used to independently correlate the records and to plot the data onto the same depth scale. A common depth scale was derived for the two cores by matching magnetic susceptibility features using the software package "Analyseries" (Paillard *et al.*, 1996). The CRP-2 record is far more complete than the CRP-2A record through this interval, therefore data from the CRP-2A record were correlated to equivalent depths in CRP-2 to produce a common depth scale. Results of the magnetic susceptibility correlation are shown in Fig. 5. At some depths, there are spikes (e.g., 47.81 and 52.02 mbsf in CRP-2) or troughs (e.g., 50.17 mbsf in CRP-2 and 49.54 mbsf in CRP-2A) in the susceptibility curves that probably result from the presence of either highly magnetic or weakly magnetic clasts within the samples. If these features are ignored, the fit between the two susceptibility records is acceptable. The depth adjustment of correlative points from CRP-2A to CRP-2 is usually $<$0.5 m, with a maximum of $\sim$2 m. The necessity of depth adjustments within this range is visually evident when comparing the depths associated with the shaded transitional regions for the two cores in Fig. 4.

When comparing the inclination records using this common depth scale (or metres common depth, mcd), the agreement is also good (Fig. 6). The main features are reproduced at equivalent depths in both records. The largest discrepancies between the records occur for single samples at depths of about 40, 48, 52.5 and 54 mcd. In many of these cases, there are significant gaps between adjacent samples with stable magnetizations. Correlation between the records is dependent on matching equivalent depths in the cores and does not take into account aliasing of the signal due to incomplete sampling. Thus, the apparent discrepancies between the records may simply result from aliasing rather than real disagreement.

5. Discussion

5.1 Sedimentation rates in an ice-proximal environment

Based on astronomically calibrated paleomagnetic time series, Channell and Kleiven (2000) estimated the duration of the last few geomagnetic reversals to be about 5 k.y., where the polarity transition is defined as the interval where VGP latitudes are $<$45°. Clement (2004) estimated an average duration of about 7 k.y. for sedimentary records of the last 4 reversals, while Singer and Pringle (1996) estimated a 12 k.y. duration for the Matuyama-Brunhes transition based on ^{40}Ar/^{39}Ar dating of transitional lava flows. Both of these studies defined the transitional interval in the same way as Channell and Kleiven (2000). Based on an inclination cutoff of 45°, shown as the shaded interval in Fig. 6, the polarity transition in the CRP-2/2A record is 10.7 m in thickness. This is equivalent to the thickest reported polarity transition record, the 10-m-thick Po Valley record (upper Olduvai transition) of Tric *et al.* (1991). It should be noted that the magnetic signal for the record of Tric *et al.* (1991) is carried by several generations of the authigenic magnetic iron sulphide mineral, greigite, which grew during early diagenesis and which will have smoothed the Po Valley polarity transition record (Roberts *et al.*, 2005). Based on an estimated range of durations of 5–12 k.y. for a polarity transition, sedimentation rates in this part of the CRP-2/2A record must have ranged between about 0.8 and 2 m/k.y. This rate is a minimum estimate because the probable presence of two minor hiatuses, at sedimentary contacts spanned by the transition, suggests that the full transition was not recorded (see below). Furthermore, sedimentation rates in glacimarine environments are likely to be highly variable, so this is a minimum estimate of the mean sedimentation rate. This rate is higher than the average longer-term sedimentation rates recorded in the CRP-2/2A core, which seem to have fluctuated between 0.025 m/k.y. and 1 m/k.y., depending on lithology, sediment accommodation space and depositional environment (Wilson *et al.*, 2000a, b).

Quantitative estimates of sedimentation rates in such glacimarine environments are relatively sparse, which makes the CRP-2/2A polarity transition record useful for comparison. Powell *et al.* (1998, 2000) suggested that the Miocene glacimarine deposits recovered in the CRP-1 and CRP-2/2A cores are similar to modern polythermal glacial sequences, such as in parts of the Antarctic Peninsula or Svalbard today. In Svalbard, average rates of sediment accumulation during deglaciation in basinal settings within fjords were about 0.5 to 1 m/k.y. (Elverhøi *et al.*, 1983).

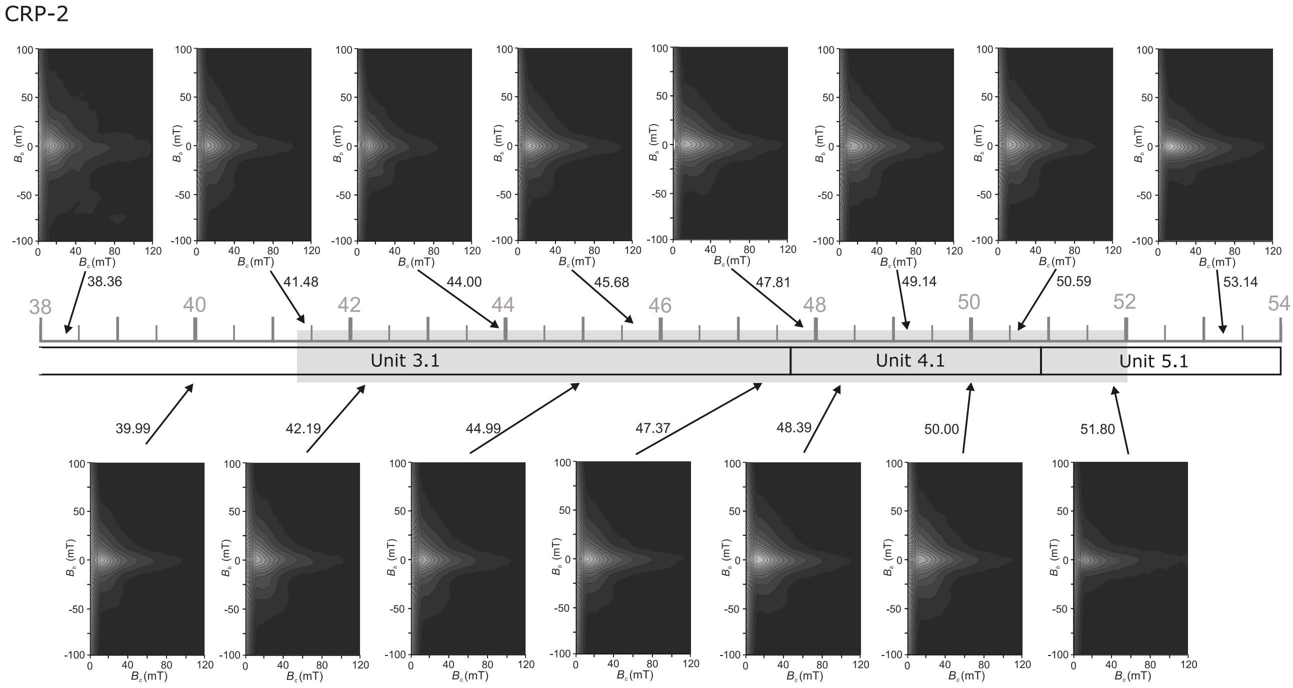

Fig. 7. FORC diagrams for selected samples through the studied polarity transition in CRP-2. The numbered scale in the middle represents the down-hole depth scale, for comparison with lithological variations shown in Fig. 2 and other magnetic variations in Figs. 5 and 6. The shading denotes the polarity transition interval. All FORC diagrams were calculated with SF=5. The FORC diagrams indicate relatively uniform magnetic grain size assemblages within the polarity transition interval despite significant variations in sediment grain size.

During the last glacial, average glacimarine accumulation rates on the continental shelf are estimated at 1.24 m/k.y. (Laberg and Vorren, 1996). This value overlaps with the lower end of the range of values estimated here. The high sedimentation rate preserved throughout the studied polarity transition supports the interpretation that lithostratigraphic units 3.1 and 4.1 were deposited near a meltwater stream discharge from a glacier terminus into the sea. This interpretation provides a mechanism for delivering large quantities of sediment to the drill site over a short period of time, which would be more difficult to achieve in a more distal marine depositional environment.

5.2 Are recording artefacts likely to have compromised the paleomagnetic record?

The question of directional bias imposed by smoothing during remanence acquisition is important when considering short-duration features within sedimentary transition records (e.g., Rochette, 1990; Langereis *et al.*, 1992; Løvlie, 1994; Quidelleur and Valet, 1994; Quidelleur *et al.*, 1995). The effects of remanence smoothing on paleomagnetic records can be constrained by numerical modelling of post-depositional remanent magnetization (PDRM) acquisition (e.g., Bleil and von Dobeneck, 1999; Roberts and Winklhofer, 2004). The PDRM lock-in depth would have to be unrealistically large to cause significant smoothing of paleomagnetic records at estimated sedimentation rates in the range from 0.8 to 2 m/k.y. (e.g., Roberts and Winklhofer, 2004). PDRM smoothing is therefore extremely unlikely in the present record. A more serious concern is that variations in sediment grain size or lithology could have also led to large variations in magnetic grain size, which can cause variable lock-in efficiency (e.g., Bleil and von Dobeneck, 1999). This possibility can be investigated with rock magnetic data, such as the FORC diagrams that are shown for the studied transition interval from CRP-2 in Fig. 7. Magnetite is consistently the dominant magnetic mineral in sediments from the Victoria Land Basin, which are partially sourced from basic igneous and metamorphic rocks that crop out in the nearby Transantarctic Mountains (Fig. 1) as well as volcanic rocks from the McMurdo Volcanic Province (Roberts *et al.*, 1998; Sagnotti *et al.*, 1998a, b, 2000; Wilson *et al.*, 1998, 2000a; Verosub *et al.*, 2000; Florindo *et al.*, 2001, 2005). Verosub *et al.* (2000) demonstrated that the magnetic mineralogy of the uppermost 270 m of the CRP-2/2A core, which includes the interval studied here, is dominated by magnetite sourced from volcanic glass from the McMurdo Volcanic Group. The FORC diagrams from throughout the studied interval are striking in their near-uniformity. They are indicative of coarse pseudo-single domain (PSD) magnetite (cf. Roberts *et al.*, 2000), except for the sample from 51.80 mbsf, which has a slightly finer-grained magnetic assemblage. Thus, despite significant variation in the overall sediment grain size, it is apparent that the detrital magnetite particles that carry the paleomagnetic signal are relatively homogeneous throughout the studied polarity transition. This provides strong evidence against the possibility of variable lock-in efficiency resulting from lithological variations.

Another possible concern is the apparent similarity between the low-field magnetic susceptibility profile (Fig. 5) for the studied interval compared to the paleomagnetic inclinations (Fig. 6). As shown in Fig. 7, there is no rock magnetic indication that this pattern is related to variations in magnetic mineralogy or grain size, and it is difficult to conceive of mechanisms whereby the geomagnetic field could cause such a pattern. The most likely explanation for this is simply a fortuitous variation in magnetic mineral concentration from high concentrations at the beginning of the polarity transition to low concentrations at the end of the transition. This variation in magnetic mineral concentration is consistent with the lithological variations indicated in Fig. 2. Overall, the rock magnetic evidence does not support the possibility that recording artefacts might have compromised the paleomagnetic record.

5.3 Geomagnetic field behaviour during a polarity transition

Overall, the consistency between the CRP-2 and CRP-2A polarity transition records (Fig. 6) indicates that the observed large-scale fluctuations are due to dynamic behaviour of the geomagnetic field during the transition rather than to noisy data or to recording artefacts associated with remanence acquisition processes in the sediments. Good serial correlation between the two records suggests that there is no significant problem with efficiency of sedimentary remanence lock-in at low transitional field intensities. The thickness of the studied transition therefore provides exceptional resolution of transitional field behaviour. The field appears to have undergone large-scale fluctuations during three periods between 52 and 47 mcd, a more gradual, but less well resolved, change from reversed to normal polarity between 47 and 41 mcd, and a period of post-transitional stability between 40 and 39 mcd. It should be noted that there are significant inclination changes across two lithological contacts at about 52 and 48 mcd, respectively. The lowermost boundary between lithostratigraphic units 5.1 and 4.1 is recognised as a sequence stratigraphic boundary that represents a disconformity surface where the sedimentary facies was dislocated toward a nearer-shore depositional environment or a more ice-proximal glacimarine environment. The early part of the transition record is therefore likely to be missing across this disconformity. The boundary between lithostratigraphic units 4.1 and 3.1 at about 48 mcd is not considered to represent a significant disconformity because it represents the gradual fining of grain size during a transgressive phase of sea level, rather than an abrupt facies change. Regardless, the paleomagnetic inclination shifts by about 60° across this contact, which makes it likely that a relatively small amount of time is also missing across this boundary. An additional sequence stratigraphic boundary is recognized at about 37.8 mcd (Fig. 2), which is considered to be a current-scoured surface in an ice-proximal, but fully marine, environment (Cape Roberts Science Team, 1999). In contrast to the two lithological changes discussed above (48 and 52 mcd), no significant inclination change is evident across this sequence boundary. We interpret the upper part of the polarity transition to occur just above the inclination anomaly at ∼41.3–42 mcd (Fig. 6). The directional fluctuations between 37 and 39 mcd, which span the sequence-bounding unconformity at 37.8 mcd, are interpreted to represent short-term fluctuations of the field (i.e., a geomagnetic excursion) that are not associated with the studied polarity transition.

High-resolution records of transitional geomagnetic field behaviour are rare. Some published high-resolution studies, such as those of Valet *et al.* (1986, 1988), where the transitions span stratigraphic intervals of ∼1.5 m, indicate a fairly smooth transition from one polarity to the other, whereas other high-resolution studies indicate that the field was more variable during polarity transitions (Laj *et al.*, 1988; Holt and Kirschvink, 1995). Channell and Lehman (1997) reported multiple transition records for the last few reversals from North Atlantic drift deposits with mean sedimentation rates of ∼12 cm/k.y., which are much higher than normal deep-sea rates that are pertinent to many studies of polarity transitions. These high-resolution records indicate complex VGP paths, rather than longitudinally confined trajectories (Clement, 1991; Clement and Kent, 1991; Tric *et al.*, 1991; Laj *et al.*, 1991), with two VGP clusters similar to those suggested from volcanic records (Hoffman, 1991, 1992; Brown *et al.*, 1994). This suggests that the longitudinally constrained VGP paths are highly smoothed representations of the transitional field. Channell and Lehman (1997) suggested that the marked changes in VGP position that punctuate their records may represent abrupt field changes similar to the stop-go impulses evident in the Miocene transition record from volcanic rocks on Steen's Mountain, Oregon (Prévot *et al.*, 1985a, b; Coe *et al.*, 1995).

Our high-resolution transition record from McMurdo Sound, Antarctica, also suggests that the overall trend from reversed to normal polarity is punctuated by several large-scale directional fluctuations. These fluctuations clearly do not represent noisy data because they are recorded by more than one data point and are present in both of the studied cores. The effects of differential core rotation on different parts of the core makes it difficult to assess whether the record contains VGP clusters. However, lack of variability in the declination data between 49.5 and 50.5 mbsf from CRP-2A (Fig. 4) indicates that this interval represents an intact piece of core. Both the declinations and inclinations are clustered with consistently similar directions at this point of the transition, which might indicate a relatively stable intermediate VGP cluster. Alternatively, the lack of paleomagnetic variability in this part of the record could represent a rapid pulse of sedimentation rather than a prolonged phase of stable transitional field behaviour. This possibility is supported by the coarser grain size and abundance of clasts with diameter >2 mm (Fig. 2), which would be consistent with greater depositional energy and more rapid sedimentation. This ambiguity reflects one disadvantage of ice-proximal environments for studying geomagnetic field behaviour.

Sedimentation rates are likely to have been variable in this ice-proximal depositional environment and the presence of two probable hiatuses within the transition record also means that the record is incomplete, which makes it difficult to make inferences about the speed at which the field changed. In each of the large-scale directional fluctuations between 47 and 52 mcd, however, the directional change appears to have been abrupt, which might be consistent with the suggestion of rapid impulses during a polarity transition (Prévot *et al.*, 1985a, b; Coe *et al.*, 1995). Regardless, the large-scale geomagnetic fluctuations observed in our record indicate that the transitional field is highly dynamic, which supports the conclusions of Channell and Lehman (1997) concerning the complexity of transitional field behaviour. Together, these studies indicate that lower resolution sedimentary polarity transition records must be substantially affected by smoothing during remanence acquisition, which is consistent with the modelling results of Roberts and Winklhofer (2004).

6. Conclusions

Paleomagnetic data from a Miocene polarity transition in the CRP-2/2A core, McMurdo Sound, Antarctica, provide the thickest (10.7-m) transition record ever obtained. This record is also the first from high southern latitudes and extends the global distribution of polarity transition records. Good serial correlation between transition data in the parallel CRP-2 and CRP-2A cores indicates that the sediments provide a reliable record of geomagnetic information. The presence of several large-scale directional fluctuations within the transition indicates highly dynamic transitional field behaviour; the narrowness of the stratigraphic intervals across which these large-scale changes are recorded suggests that they represent abrupt geomagnetic directional changes. This interpretation is consistent with observations from other high-resolution records. The exceptional resolution of the CRP-2/2A polarity transition, in conjunction with data from other high-resolution records, indicates a much more dynamic transitional field compared to most sedimentary transition records, which suggests that many lower resolution sedimentary polarity transition records may have been substantially smoothed.

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