Terra Antartica
1998, 5(3), 703-713

Magnetostratigraphy of Lower Miocene Strata from the CRP-1 Core, McMurdo Sound, Ross Sea, Antarctica

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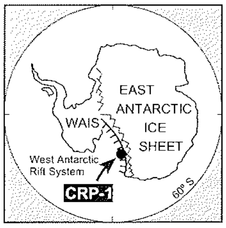
Received 17 July 1998; *accepted in revised form* 31 October 1998



Abstract - A lower Miocene glaciomarine sequence was recovered in the lowermost 90 m of the CRP-1 core from McMurdo Sound, Antarctica. Palaeomagnetic studies were conducted to constrain the chronology of the core and to enable comparison with other records from the Antarctic margin and the Southern Ocean. The palaeomagnetic behaviour is generally stable and magnetite appears to be the dominant remanence carrier. A clear polarity zonation has been obtained, although a zone of mixed polarity between 143 and 148 metres below sea floor (mbsf) is probably remagnetised. For the interval from 43 - 143 mbsf, diatom biostratigraphy, $^{40}Ar/^{39}Ar$ dating and $^{87}Sr/^{86}Sr$ ratios provide constraints on correlations of the magnetostratigraphy with the magnetic polarity timescale (MPTS). The constraints imposed by the relevant data sets are not mutually consistent, therefore several possibilities exist for correlation with the MPTS. Our preferred correlation indicates that the record from 43 - 143 mbsf ranges in age from 21.5 Ma at the base to 17.5 Ma immediately beneath an unconformity at *c.* 43 mbsf, with as much as 2 m.y. missing in an unconformity beneath lodgement diamictite at 124.2 mbsf.

INTRODUCTION

The transition from greenhouse conditions of the Cretaceous to "ice-house" conditions of the late Cenozoic was made possible by thermal isolation of the Antarctic continent (Kennett, 1977). Thermal isolation resulted from middle Eocene to Oligocene plate movements which enabled deep ocean circulation to develop around Antarctica through seaways south of Australia and South America (Lawver et al., 1992). Despite the importance of the events that led to the onset of Antarctic glaciation, and their impact on the subsequent development of Earth's present climate system, the precise timing and nature of Antarctic cryosphere development are still poorly understood (*e.g.*, Barrett, 1991). The aim of the Cape Roberts Project is to recover sedimentary records from the Ross Sea margin, Antarctica, in order to investigate the onset of Antarctic glaciation and the history of rifting in the Ross Sea (Cape Roberts Science Team, 1998a).

The first phase of drilling at Cape Roberts was carried out in the austral spring of 1997 (at 77°S, 163.8°E). Drilling of the CRP-1 core was prematurely terminated and core was recovered only to a depth of 147.69 metres below sea floor (mbsf). A thicker than expected sequence of Quaternary and Miocene glaciomarine sediments was recovered (Cape Roberts Science Team, 1998a), and, although strata were not recovered from the targetted 30 to 100 Ma age range, the core is useful for developing a more accurate picture of early Miocene Antarctic glacial activity.

In this paper, palaeomagnetic results are presented from the CRP-1 core which, together with biostratigraphy and radiometric dating, place Miocene glacial activity at the site within a temporal framework that enables comparison with other sites. Initial results (Cape Roberts Science Team, 1998b) were obtained during the drilling season in a palaeomagnetic laboratory that was established specifically for the Cape Roberts Project at McMurdo Station (Cape Roberts Science Team, 1998a). Some samples required the sensitivity of a cryogenic magnetometer or were mechanically unsuitable for analysis with a high speed spinner magnetometer, and were not fully analysed until after the drilling season. The additional palaeomagnetic data allow refinement of the polarity zonation, and new rock magnetic results provide additional constraints on the polarity zonation of part of the core. The results presented here supercede previous results (Cape Roberts Science Team, 1998b), which were inherently preliminary in nature.

METHODS

SAMPLING

The Quaternary interval of the CRP-1 core (19 - 43 mbsf) consists of dominantly coarse-grained lithofacies (including diamictons) which are poorly consolidated and highly fractured. This part of the core was not sampled for palaeomagnetic studies. Preliminary biostratigraphic analyses indicated that the remainder of the core (43 - 147.69 mbsf) is early Miocene (*c.* 17.5 - 22.3 Ma) in age (Cape Roberts Science Team, 1998b). The Miocene interval is more consolidated and less fractured than the Quaternary interval and is generally dominated by finer-grained lithofacies. All of the palaeomagnetic samples discussed in this paper are from the lower interval.

Standard palaeomagnetic samples (25 mm diameter x 22 mm height) were drilled from the working half of the CRP-1 core using a modified drill press. The cores were oriented with respect to vertical, but azimuthal orientation was not maintained because of frequent core breaks. The lack of azimuthal orientation does not pose a problem for magnetostratigraphic studies because the field has a steep inclination at the high latitude of the CRP-1 site, and palaeomagnetic inclination is sufficient to uniquely determine the polarity.

The CRP-1 core was sampled at 0.5 m intervals in order to minimise the possibility of not detecting short polarity intervals. As noted above, the time interval represented by CRP-1 was estimated to be 17.5 - 22.3 Ma. In this period, the shortest polarity intervals occur between 21.7 and 24.2 Ma and have a duration of 50 - 300 k.y. (Cande & Kent, 1995). For a uniform sedimentation rate, the above strategy would result in a spacing of 30 - 35 k.y. between samples. However, the sedimentation rate is not necessarily uniform and the desired sampling interval was not always achieved because the lithology was not always suitable. The lower sampling resolution in these intervals could cause problems if they correspond to portions of the magnetic polarity time scale (MPTS) that have high reversal frequency, such as the period from 21.7 to 24.2 Ma.

One hundred and sixty-six samples were collected from the interval between 58.80 and 147.65 mbsf. Fourteen pairs of samples, each separated stratigraphically by a few cm, were collected at regular intervals from varying lithofacies throughout the core. These samples were used for a pilot study, which was aimed at determining the most suitable demagnetisation technique for routine treatment of the samples, as discussed below.

Diamictites are common between 58.80 and 147.65 mbsf. Whenever possible, samples were selected from fine-grained horizons; however, there was often no alternative but to sample diamictites or sandstone-dominated lithofacies. The diamictite matrix is often silt-sized and is, therefore, potentially useful for palaeomagnetic study. However, very coarse sand grains, granules and pebbles within samples from diamictites pose a problem because the deposition of such large particles would be controlled by gravitational rather than magnetic forces. Thus, their orientation cannot be expected to represent the geomagnetic field at, or near, the time of deposition. This problem would be most severe for strongly magnetic basic igneous material, which is a common clast constituent in the core. The possible presence of such grains means that care should be taken in interpreting palaeomagnetic data from coarse-grained intervals.

During sampling, x-ray images of the CRP-1 core were used to identify clast-free intervals. However, this method was not ideal because acidic igneous clasts have the same x-ray density as the quartzo-feldspathic matrix. To deal with the possible presence of these clasts, a conservative interpretive approach was adopted and results from coarse-grained lithologies are considered reliable only if: 1) no clasts are visible within a sample, 2) the palaeomagnetic inclinations are consistently steep throughout a coarse-grained interval, and 3) the results from such intervals are consistent with those from surrounding finer-grained intervals.

MEASUREMENTS

At McMurdo Station, all measurements of natural remanent magnetisation (NRM), including measurements after each stepwise alternating field (AF) and thermal demagnetisation step, were performed with an AGICO JR-5A spinner magnetometer (Cape Roberts Science Team, 1998a). Approximately 20% of the samples were either too friable or too weakly magnetised to measure with this magnetometer. These samples were measured after the drilling season with a 2G Enterprises cryogenic magnetometer with in-line AF demagnetisation in Rome. An additional 15 samples were measured after the drilling season with a similar system at the University of California, Davis (UCD).

For the pilot study, one sample from each set of paired samples was subjected to stepwise AF demagnetisation at steps of 5, 10, 15, 20, 25, 30, 40, and 50 mT; for some samples, some of the following steps were added: 35, 45, 60, 70, 80, 90, and 100 mT. The corresponding sample was subjected to thermal demagnetisation in 40° increments from 80°C to 600°C. After each thermal demagnetisation step, the magnetic susceptibility was measured to monitor for thermal alteration. Further heating was abandoned if the susceptibility increased by more than about 30%, with concomitant loss of coherence in the palaeomagnetic signal.

Detailed rock magnetic studies were conducted on the AF-demagnetised samples. Some rock magnetic studies were conducted on chips or on powder samples from off-cuts that were taken during sampling. Magnetic properties are reported here insofar as they are relevant to understanding palaeomagnetic behaviour and the magnetostratigraphy. A more detailed presentation of the magnetic properties is given elsewhere (Sagnotti et al., this volume).

After AF demagnetisation, samples were routinely given an isothermal remanent magnetisation (IRM) with maximum inducing fields of 1 T. The IRM_{1T} was then demagnetised with back-fields of 5, 10, 20, 30, 40, 50, 60, 80, 100, and 300 mT. These measurements were performed to determine the coercivity of remanence (B_{cr}) and the S-ratio ($-IRM_{-0.3T}/IRM_{1T}$). These parameters provide information about the bulk coercivity of the magnetic assemblage and are therefore useful in understanding the magnetic mineralogy (*e.g.*, King & Channell, 1991; Verosub & Roberts, 1995). IRM_{1T} and the low-field magnetic susceptibility (κ) are useful indicators of magnetic mineral concentration. Thermomagnetic and hysteresis measurements were also made on bulk sediment samples using a variable field translation balance (up to 700°C in air with a relatively low applied field of 27 mT in order to avoid dominance by paramagnetic minerals) and on an alternating gradient magnetometer (up to maximum fields of 1 T), respectively, in order to determine the mineralogy and domain state of magnetic grains.

RESULTS

ROCK MAGNETISM

The magnetic characteristics of the recovered sediments vary with depth in the core (Fig. 1). In general, zones of high κ also have high IRM_{1T}, high S-ratios and low values of B_{cr}. This suggests that the high κ zones are dominated by low-coercivity ferrimagnetic grains. Conversely, zones of low κ have low IRM_{1T}, low S-ratios, and high values of B_{cr}. This suggests that the low κ zones are dominated by high-coercivity magnetic phases. The magnetic property variations (Fig. 1) may be partially controlled by fluctuations in the position of glacier termini, as suggested by Sagnotti et al. (this volume), although other factors are probably also important.

PALAEOMAGNETIC BEHAVIOUR

All samples from the CRP-1 core display a significant sub-vertical, drilling-induced magnetic overprint (Fig. 2). Such overprints are common in drill cores and were routinely observed in the nearby CIROS-1 core (Wilson et al., 1998). Overprints that are sufficiently strong to completely remagnetise sediments have compromised palaeomagnetic studies associated with the Ocean Drilling Program for many years (*e.g.*, Roberts et al., 1996; Fuller et al., 1998). On the other hand, if the drilling-induced overprint does not completely remagnetise the sample, then the consistently steep, upward orientation of the overprint provides unambiguous evidence that neither the core nor the samples have been mistakenly inverted at any stage.

The drilling-induced overprint is particularly strong in the high coercivity zones and usually comprises 75 - 85% of the NRM (Fig. 2a & k). This makes it difficult to isolate a stable characteristic remanence component, particularly with AF demagnetisation, and, in general, thermal demagnetisation appears to be more effective in determining the polarity of the characteristic remanence for these intervals (*e.g.*, Fig. 2a). Thermal demagnetisation was therefore used for many of the samples from these zones.

The magnetic behaviour of samples from the relatively low coercivity zones (Fig. 2b-d, h-j & m-o) indicates that the magnetic carriers are more stable than in the high coercivity zones, although the behaviour varies somewhat with lithology. For many of the paired samples from the low coercivity zones, there is close agreement between the characteristic remanence directions identified by AF and thermal demagnetisation (*e.g.*, Fig. 2i & j). Moreover, in most cases, AF demagnetisation at 5 or 10 mT is sufficient to remove the drilling-induced overprint. Given that the palaeomagnetic behaviour of these samples is usually straightforward, all other samples from these intervals were treated with AF demagnetisation. In a few cases, there is a relatively large drilling-induced overprint for

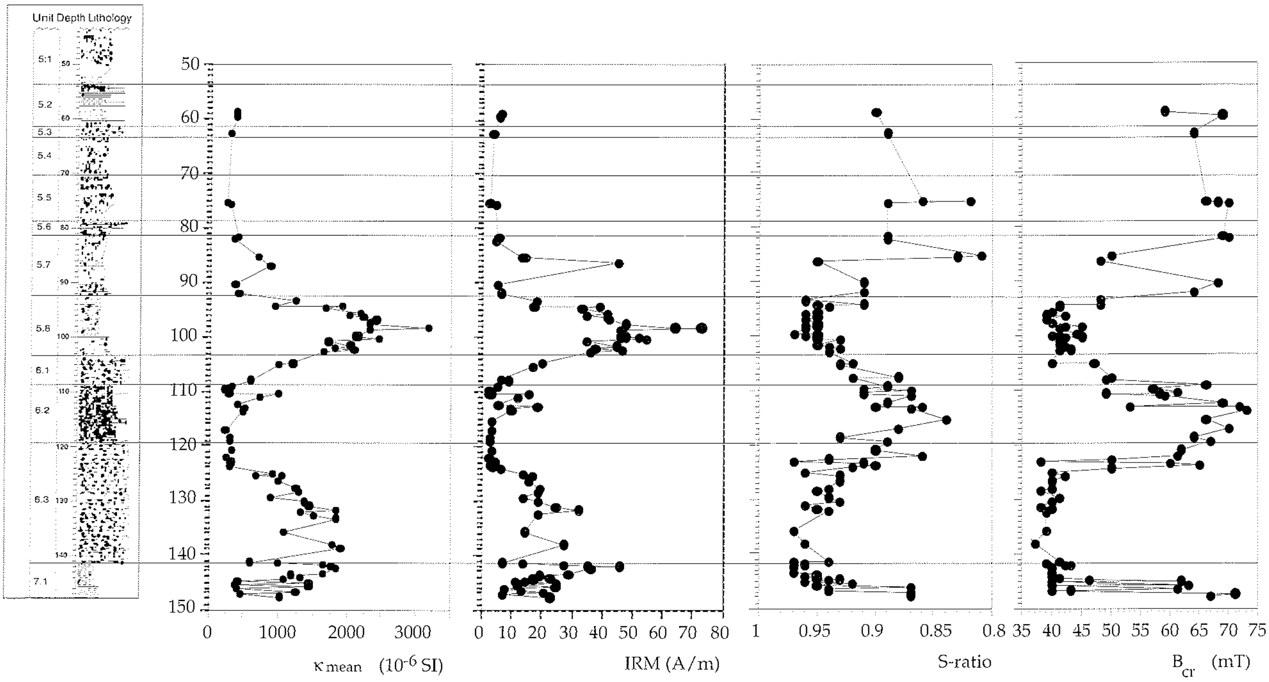


Fig. 1 - Lithological subdivision and down-core variations in magnetic properties for the CRP-1 core, including magnetic susceptibility (κ_{mean}), IRM (at 1 T), S-ratio, and coercivity of remanence (B_{cr}). See text for discussion.

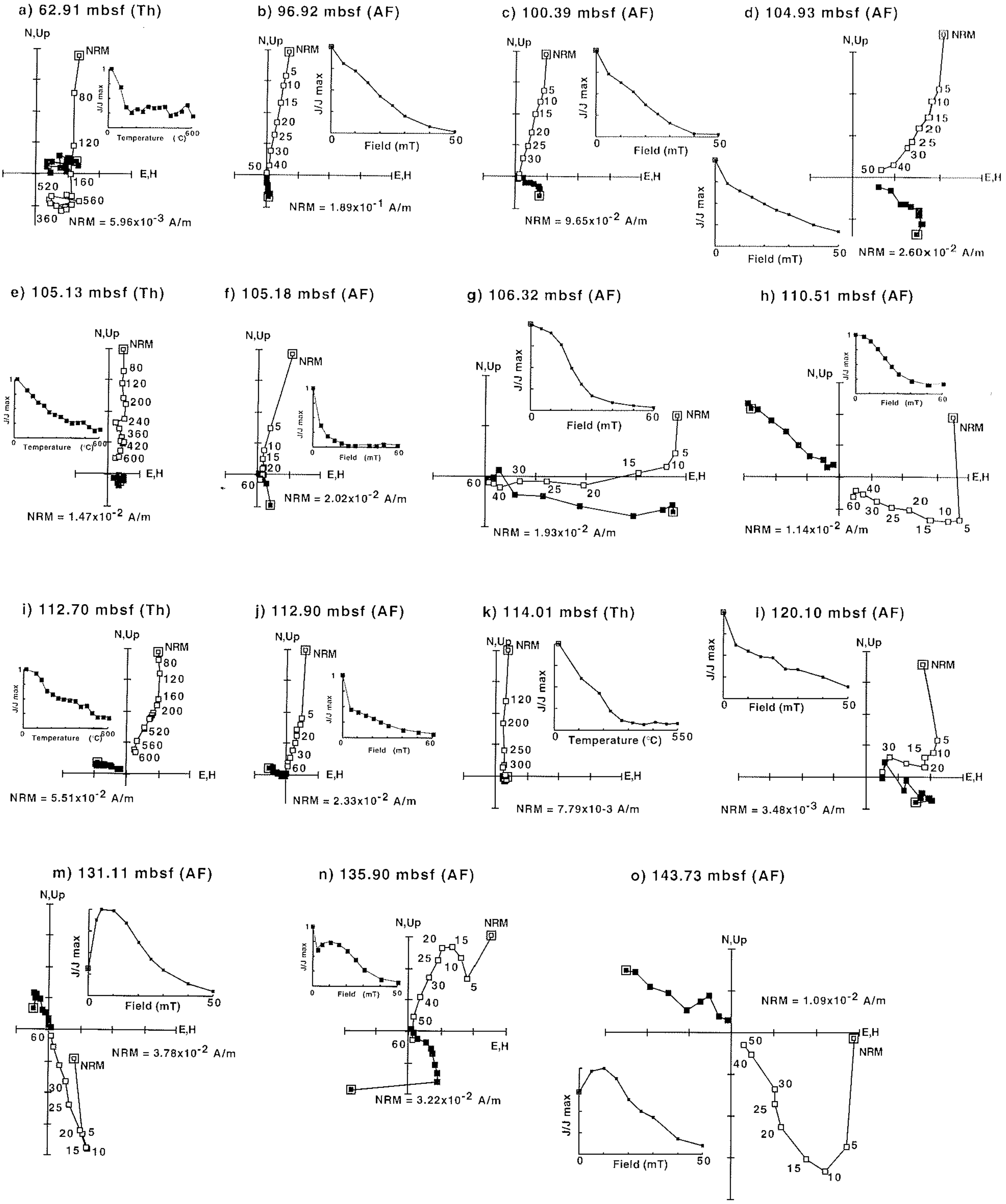


Fig. 2 - Vector component diagrams of demagnetisation behaviour of representative samples from the CRP-1 core: (*a*) thermal demagnetisation of a sample from 62.91 mbsf; AF demagnetisation of samples from (*b*) 96.92 mbsf, (*c*) 100.39 mbsf, and (*d*) 104.93 mbsf; comparison of thermal and AF demagnetisation of samples from (*e*) 105.13 and (*f*) 105.18 mbsf, respectively; AF demagnetisation of samples from (*g*) 106.32 mbsf and (*h*) 110.51 mbsf; comparison of thermal and AF demagnetisation of samples from (*i*) 112.70 and (*j*) 112.90 mbsf, respectively; thermal demagnetisation of a sample from (*k*) 114.01 mbsf; and AF demagnetisation of samples from (*l*) 120.10 mbsf, (*m*) 131.11 mbsf, (*n*) 135.90 mbsf, and (*o*) 143.73 mbsf.

samples from the low coercivity zones. Even though it is difficult to identify a characteristic remanence component in some of the AF-demagnetised data (Fig. 2f), it is not clear whether thermal demagnetisation enabled adequate removal of the drilling-induced overprint (Fig. 2e). In this case, the choice of AF demagnetisation seems justified because it is preferable to have data that are compromised by the drilling-induced overprint than to use the apparently stable, but possibly erroneous (*i.e.*, completely remagnetised), thermal demagnetisation data.

A few samples in the pilot study exhibited anomalous palaeomagnetic behaviour. For example, a sample from a diamictite unit at 135.90 mbsf (Fig. 2n) has a normal polarity drilling-induced overprint (0 - 5 mT), a reversed polarity component (5 - 15 mT) and a stable normal polarity component (20 - 60 mT). We interpret this three-component magnetisation as arising from the presence of one or more clasts within the sediment matrix. In particular, the reversed polarity component may be due to the presence of a coarse-grained (*i.e.*, low coercivity) igneous clast that is oriented with a downward magnetisation. This sample demonstrates the need to exercise caution in interpreting data from coarse-grained lithofacies.

Stable palaeomagnetic behaviour is evident from the vector component plots of 140 of the 166 samples. Characteristic remanence directions were determined using best-fit lines through the data points on vector component diagrams (Fig. 2). Steep normal polarity directions were observed for 75 stably magnetised samples (*e.g.*, Fig. 2b, c, i & j), and steep reversed polarity directions were observed for 49 samples (*e.g.*, Fig. 2a, m & o); remanence directions for 7 samples were neither steep nor clearly of reversed or normal polarity (*e.g.*, Fig. 2g & h). Most of the samples with abnormally low inclinations (*e.g.*, Fig. 2g) or with 3-component magnetisations (*e.g.*, Fig. 2l & n) are from diamictites and contain small dolerite clasts. The magnetisation of these samples is probably dominated by the clasts whose orientation was not controlled by the ambient magnetic field during deposition.

For 35 samples, useful characteristic remanence directions could not be obtained; however, the polarity of 9 of these samples could be inferred from the trend exhibited during demagnetisation (*e.g.*, Fig. 2a). It was not possible to determine the polarity for the remaining 26 samples. Eleven of these samples were from diamictites and were interpreted to be dominated by clasts. In most of the remaining samples, the drilling-induced overprint was the dominant component, and most of the magnetisation was lost during the first few demagnetisation steps (*e.g.*, Fig. 2f & k).

MAGNETIC POLARITY STRATIGRAPHY

A magnetic polarity zonation for the lower 90 m of the CRP-1 core is shown in figure 3. The polarity record can be divided into four magnetozones: an upper interval of predominantly reversed polarity (<81 mbsf, R1); a predominantly normal polarity interval from 81-124 mbsf (N1), with 2 thin reversed polarity intervals at *c.* 106 and 118 mbsf, respectively; a second interval of reversed polarity

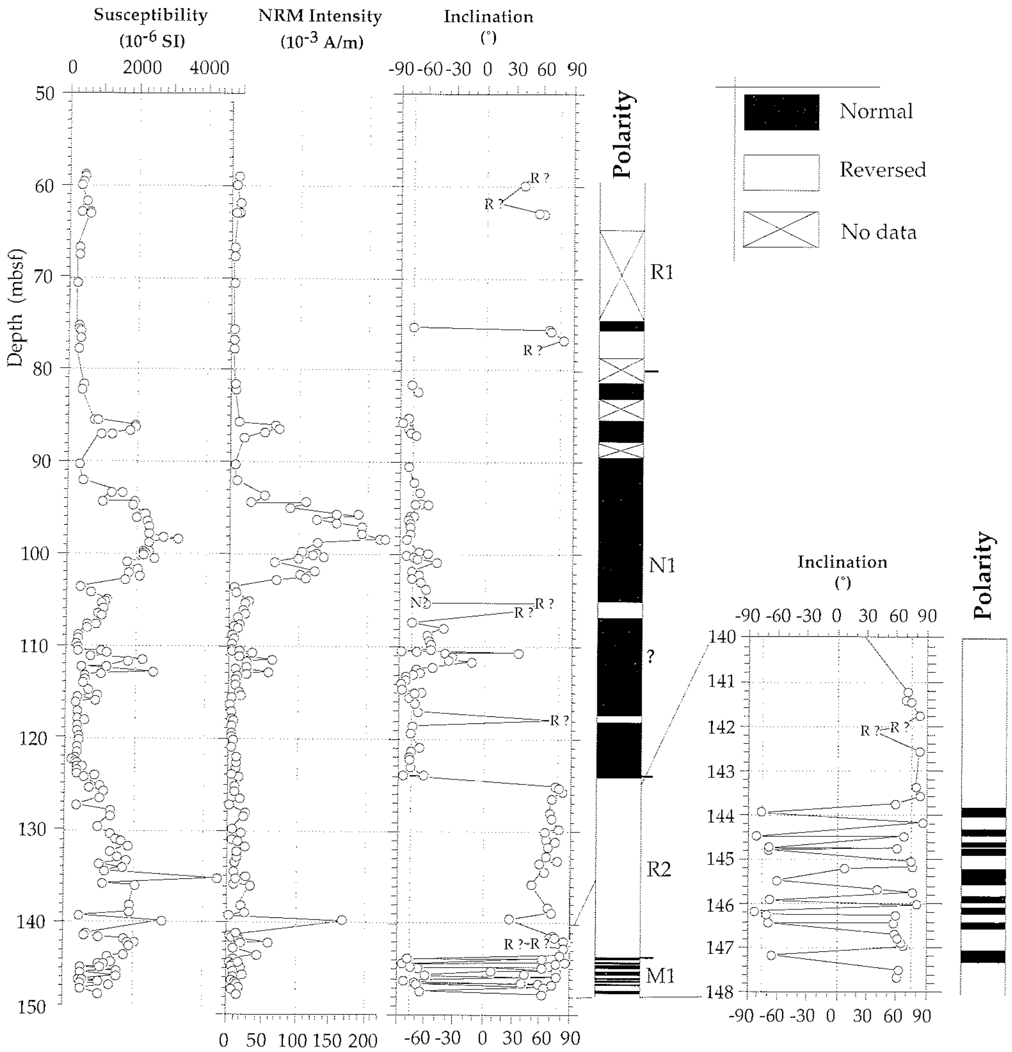


Fig. 3 - Down-core variations of magnetic susceptibility, natural remanent magnetisation (NRM) intensity, palaeomagnetic inclination and magnetic polarity zonation (black = normal polarity, white = reversed polarity) for the CRP-1 core. R? (N?) denotes samples that display a clear trend toward reversed (normal) polarity but for which a stable characteristic component was not isolated before the intensity of remanence became too weak to measure. An enlargement of the inclination data and polarity is shown on the right-hand side for the lower 8 m of the CRP-1 core.

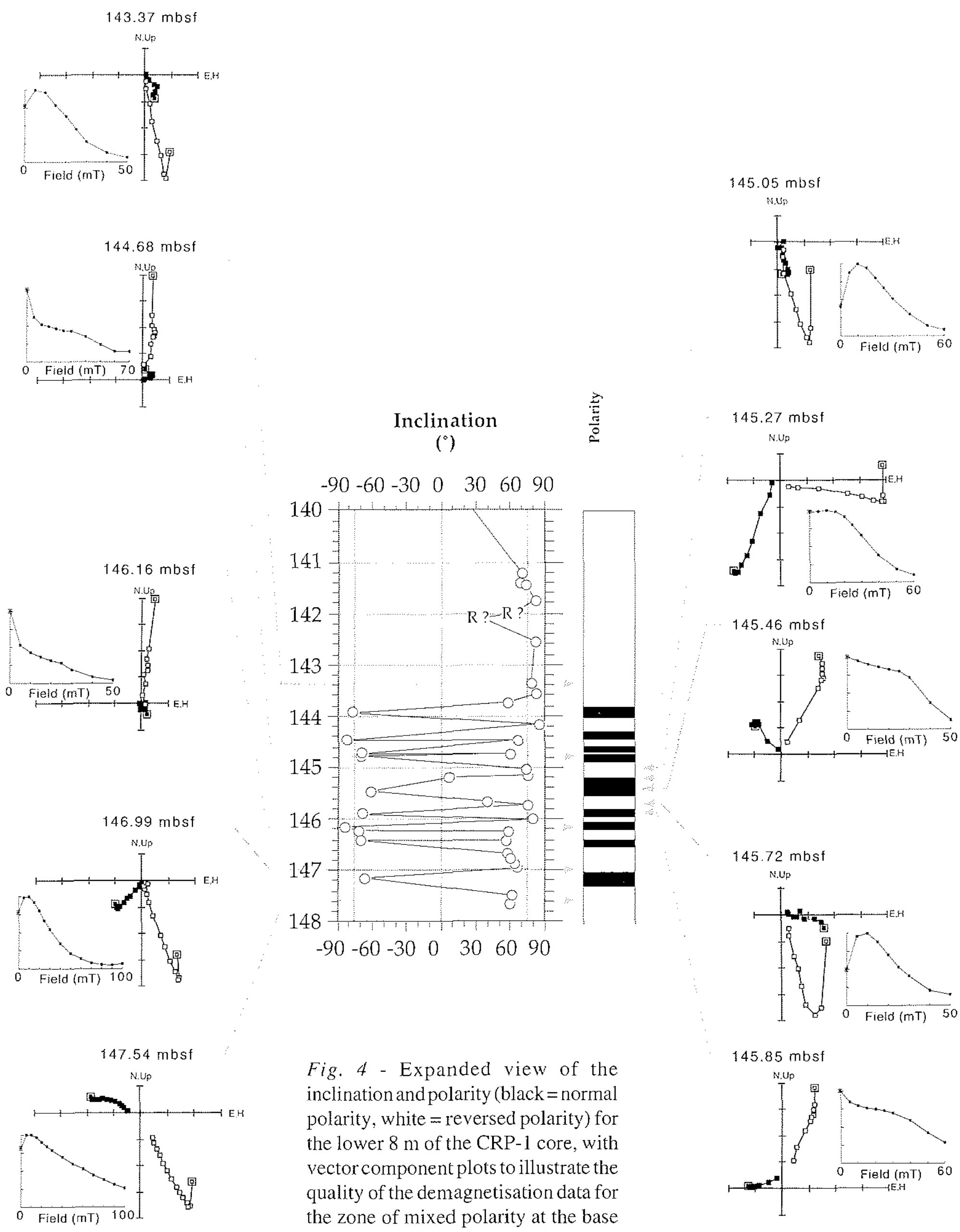


Fig. 4 - Expanded view of the inclination and polarity (black = normal polarity, white = reversed polarity) for the lower 8 m of the CRP-1 core, with vector component plots to illustrate the quality of the demagnetisation data for the zone of mixed polarity at the base of the core.

between 124 and 143.8 mbsf (R2); and an interval of mixed polarity at the base of the record, between 143.8 and 147.65 mbsf (M1). A single stable, but low inclination (30°), sample at 110.5 mbsf may indicate a thin reversed polarity interval. The interval around this sample from 110 to 112.5 mbsf also contains several stable intermediate to low angle normal polarity samples. This interval may represent a geomagnetic excursion. The question mark in figure 3 indicates uncertainty in the interpretation of this interval.

Initial results indicated that the reversal frequency was high in M1, and additional samples were collected to give an average sample spacing of 13 cm. Despite this close spacing, many polarity zones are represented by single samples. Almost all of the data for this interval are from stably magnetised samples with unambiguous vector endpoints (an expanded view is shown in Fig. 4). Possible interpretations of the polarity zonation are discussed below.

MAGNETIC PROPERTIES OF THE BASAL PART OF THE CRP-1 RECORD

Detailed rock magnetic investigations of the lower part of the CRP-1 record were undertaken to assist interpretation of the mixed polarity zone (M1). There is a marked alternation in magnetic properties that matches the polarity alternations (Fig. 5). In general, reversed polarity zones are characterised by relatively low coercivity (low B_{cr} and high S-ratios) as well as by high IRM and κ, while normal polarity zones are characterised by high coercivity (high B_{cr} and low S-ratios) as well as by low IRM and κ. This correspondence between polarity and magnetic properties is not observed in the polarity zones above 143.8 mbsf (*cf.* Figs. 1 & 3).

Thermomagnetic analyses were conducted to determine the magnetic mineralogy in the CRP-1 core; however,

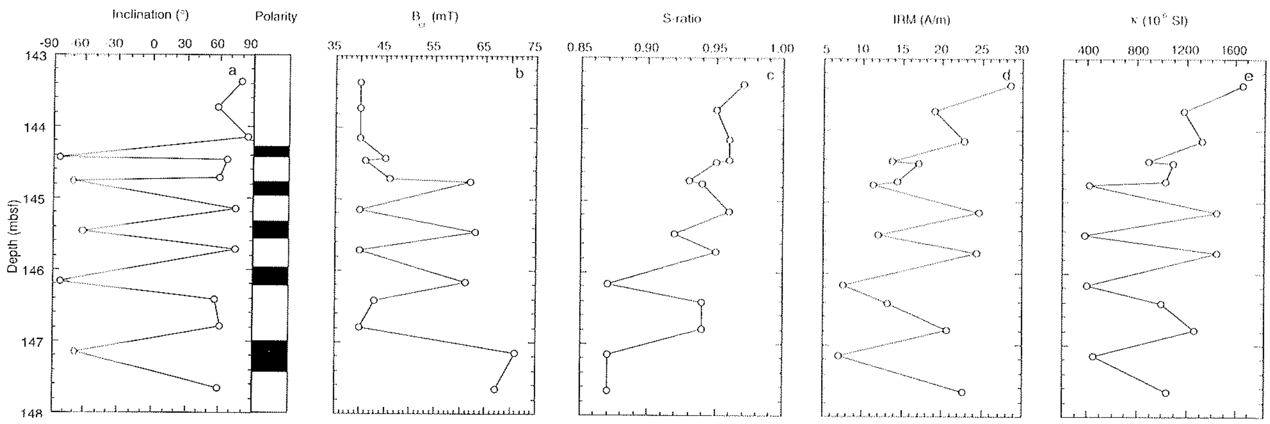


Fig. 5 - Down-core variations in magnetic properties for the lower 5 m of the CRP-1 core: (*a*) inclination, with polarity log (black = normal polarity, white = reversed polarity); (*b*) coercivity of remanence (B_{cr}); (*c*) S-ratio; (*d*) IRM at 1 T (IRM_{1T}); and (*e*) magnetic susceptibility (κ). Note that polarity data are only shown for the samples for which corresponding rock magnetic data were obtained. Not all of the samples were analysed for rock magnetic studies, therefore the polarity pattern is not as detailed as in figures 3 and 4.

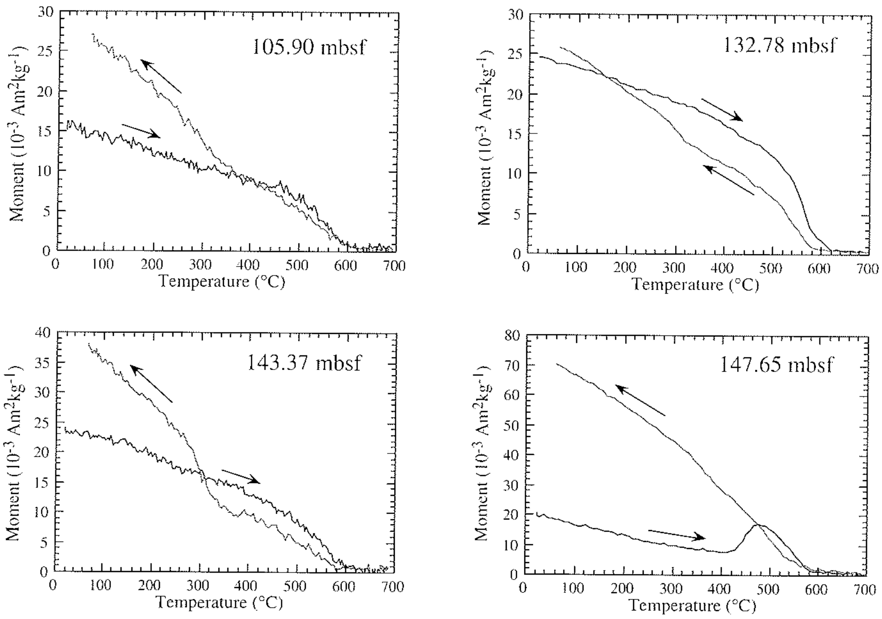


Fig. 6 - Thermomagnetic data for samples from 105.90 mbsf, 132.78 mbsf, 143.37 mbsf, and 147.65 mbsf. The data from 147.65 mbsf are dominated by paramagnetic phases which prevent identification of the magnetic carrier(s). Magnetite is the only magnetic mineral indicated for the other samples.

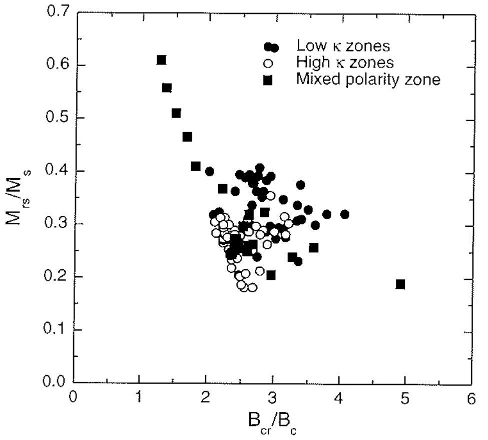


Fig. 7 - Plot of M_{rs}/M_s *versus* B_{cr}/B_c (*cf.* Day et al., 1977) for samples from the CRP-1 core. Data cluster together for the high κ and low κ zones, respectively, but are more variable for the mixed polarity zone at the base of the core. See text for discussion.

most of the samples display a 1/T decay in magnetisation (even at low applied fields of 27 mT), which indicates the dominance of paramagnetic material such as clay minerals (*e.g.*, 147.65 mbsf; Fig. 6). This makes it difficult to identify the main magnetic carrier. Unambiguous evidence concerning magnetic mineralogy was obtained only from the high κ zones of figure 1. In each case, the thermomagnetic behaviour is clearly consistent with that of magnetite, with a Curie temperature of *c.* 580°C (105.90, 132.78 and 143.37 mbsf; Fig. 6). The only interpretable sample from the mixed polarity interval (143.37 mbsf) has reversed polarity, low coercivity, high IRM_{1T} and high κ. We have been unable to identify the magnetic mineral that dominates the high coercivity normal polarity zones in magnetozone M1.

Hysteresis data are also variable for the lowermost part of the core. The hysteresis parameters do not vary as distinctly as the parameters shown in figure 5 and they do not correspond as clearly with polarity. However, they are markedly different and more variable than those of the rest of the CRP-1 core (Fig. 7). Above 143.8 mbsf, the hysteresis data from the high κ zones are dominated by magnetite which occurs in a fairly narrow grain size range (*cf.* Day et al., 1977). M_{rs}/M_s and B_{cr}/B_c values are higher in the low κ zones than in the high κ zones. These values may suggest a higher degree of oxidation in the low κ zones. In contrast, the hysteresis data from the lower part of the CRP-1 core indicate variation across a much larger range of domain states. Such large variations in domain state, and probably mineralogy, could have important implications for the polarity record of this part of the CRP-1 core.

DISCUSSION

The polarity zonation shown in figure 3 is based on interpretation of stepwise demagnetisation data that pass strict stability criteria. While no rigorous statistical analysis has been performed on the inclination-only data, the reversed and normal polarity data appear to be antipodal (*i.e.*, they probably pass a reversals test). Field tests for the age of magnetisation are difficult to apply to cored sequences, but the shallow inclinations observed in the diamictites could indicate a positive conglomerate test. The polarity intervals are not related to lithologic features: the boundaries between polarity zones occur almost exclusively within lithologic units rather than at lithostratigraphic breaks or at cycle boundaries (Fig. 8). Thus, the present study warrants a magnetostratigraphic quality ranking (*cf.* Opdyke & Channell, 1996) of 8 (and possibly 9 if the congomerate test is considered valid) out of 10, which is as high as can reasonably be expected.

Given the above factors, the palaeomagnetic data from the core can be interpreted in terms of geomagnetic polarity and an interpretation of the polarity of the CRP-1 core with respect to the MPTS is plotted in figure 8. For the purpose of correlation with the MPTS, the polarity record has been divided into the four magnetozones shown in figures 3 and 8. Due to the variable nature of the lithofacies, it is likely that there are large fluctuations in sedimentation rate. Therefore, the thicknesses of the identified magnetozones cannot be directly compared to the duration of polarity chrons.

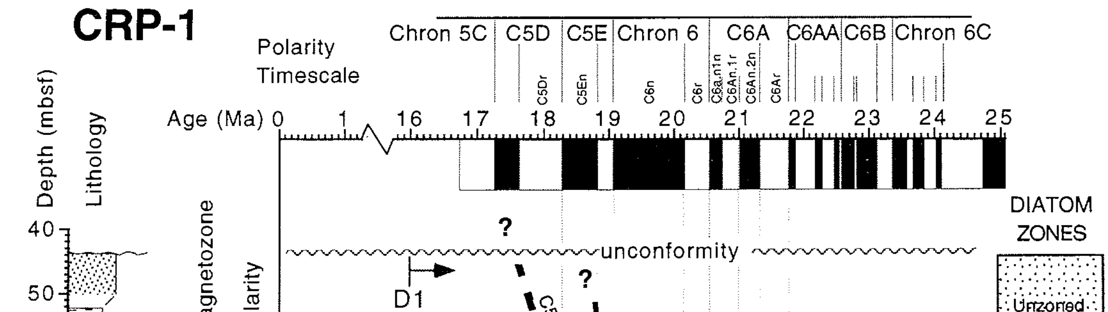


Fig. 8 - Correlation of the CRP-1 magnetic polarity zonation with the magnetic polarity timescale (MPTS) of Cande & Kent (1995) and Berggren et al. (1995). Black denotes normal polarity, white denotes reversed polarity and cross-hatching indicates no data. Correlation is constrained by $^{40}Ar/^{39}Ar$ dating (A1-A8), $^{87}Sr/^{86}Sr$ ratios (S1) and diatom datums (D1-D6): the main diatom zonations are shown on the right hand side of the figure (from Harwood et al., this volume). D1 = the absence of *A. ingens*, *D. marc*, and *F. grossep*; D2 = LO of *T. praefraga*; D3 = FCO of *T. praefraga*; D4 = LO of *S. spinossisima*; D5 = LO of *C. rectus*; and D6 = the absence of *L. ornata*, *P. anina*, and *R. gelida*. Several different correlations with the MPTS are considered (see text for discussion).

DIATOM BIOSTRATIGRAPHY

The diatom flora from the CRP-1 core include species from the *Thalassiosira praefraga* and *Stephanopyxis spinosissima* Zones, which suggests that the lower 104 m of the core is of early Miocene age (see Harwood et al., this volume). Several diatom datums more closely constrain a possible correlation to the MPTS. These include: the last occurrences (LO) of *Cavitatus rectus* (D5, Fig. 8) and *Stephanopyxis spinosissima* (D4, Fig. 8) at *c.* 145 and 141.5 mbsf, respectively, the first common occurrence (FCO) of *T. praefraga* (syn. *T. fraga*) at 102.2 - 103.4 mbsf (D3, Fig. 8) and the LO of *T. praefraga* at 58.8 - 60.0 mbsf (D2, Fig. 8). The LO of *S. spinosissima* is known from the nearby MSSTS-1 core (syn. S. sp. A, Harwood et al., 1989; see Harwood et al., this volume) to occur within Chrons C6AA and C6A and the LO of *C. rectus* occurs in C6An.1 or C6An.2. The FCO of *T. praefraga* is reported to occur in Chron C6An at ODP sites 747 and 748 from the Kerguelen Plateau (Harwood & Maruyama, 1992; Harwood et al., 1992; Harwood et al., this volume). Further constraints on the age of the base of the core (148 mbsf) and the top of the Miocene interval (43 mbsf) are available from the absence of diatom species that are relatively common in the Southern Ocean (Harwood et al., this volume). The absence of *L. ornata, P. anina*, and *R. gelida* suggests that the base of the core is no older than *c.* 25 Ma (D6, Fig. 8) and the absence of *A. ingens*, *D. marc*, and *F. grossep* from the uppermost Miocene interval of the core suggests that the strata immediately beneath the unconformity at 43 mbsf are no younger than *c.* 16 Ma (D1, Fig. 8) (Harwood et al., this volume).

$^{40}Ar/^{39}Ar$ DATING

Disseminated pumiceous material occurs from 116 to 117 mbsf in the CRP-1 core. It is reworked but is probably nearly *in situ* and a plateau $^{40}Ar/^{39}Ar$ date of 18.4 ± 1.2 Ma (A8, Fig. 8) on anorthoclase crystals (McIntosh et al., this volume) may provide a depositional age for this horizon. Although this date is imprecise, it constrains possible correlations to the MPTS (17.2 - 19.6 Ma) at 116 - 117 mbsf.

Seven further $^{40}Ar/^{39}Ar$ dates have been obtained from reworked volcanic clasts from four stratigraphic horizons in the Miocene interval of the CRP-1 core (McIntosh et al., this volume). While reworked clasts do not provide direct age constraints, they can provide maximum age estimates because the age of the horizon containing the reworked clasts must be younger than the clasts. Each date is based on several single crystal analyses and/or whole rock plateau determinations. At *c.* 114 mbsf, a single clast yielded a plateau $^{40}Ar/^{39}Ar$ date of 19.7 ± 0.9 Ma (A7, Fig. 8), which suggests that this horizon is younger than 20.6 Ma. At *c.* 104 mbsf, another single volcanic clast (most likely from the same source) yielded a precise $^{40}Ar/^{39}Ar$ date of 19.3 ± 0.1 Ma (A6, Fig. 8) on individual anorthoclase crystals, which suggests that this horizon is younger than 19.4 Ma. Three separate dates were obtained from a horizon at *c.* 90 mbsf. A precise $^{40}Ar/^{39}Ar$ date of 19.3 ± 0.3 Ma (A3, Fig. 8) was obtained from individual anorthoclase crystals, while two whole rock $^{40}Ar/^{39}Ar$ plateau determinations of 17.9 ± 0.4 Ma and 17.2 ± 0.8 Ma were obtained from clasts (A4 and A5, respectively, Fig. 8). Because whole rock analyses are less precise and less reliable than single crystal determinations, we infer that this horizon (90 mbsf) must be younger than 19.6 Ma and may be younger than 17.9 Ma. Two further $^{40}Ar/^{39}Ar$ plateau dates were obtained from clasts at *c.* 61 mbsf (17.3 ± 0.9 Ma and 18.1 ± 0.7 Ma; A1 and A2, respectively, Fig. 8). These dates are imprecise, but suggest that the horizon is younger than 18.2 Ma.

$^{87}Sr/^{86}Sr$ DATING

Several $^{87}Sr/^{86}Sr$ dates have been obtained from relatively unweathered and diagenetically unaltered pecten shells from *c.* 62 mbsf in the CRP-1 core (Lavelle, this volume). The mean age from four analyses is 18.7 ± 0.2 Ma (S1, Fig. 8). If the dated shell material was deposited soon after death, and if the waters of McMurdo Sound were in equilibrium with the world ocean, the strontium ratios should yield an *in situ* age for this horizon. However, if the shell material was reworked, the $^{87}Sr/^{86}Sr$ date must be considered a maximum age, and it is only possible to conclude that this horizon must be younger than 18.9 Ma.

CORRELATION TO THE MPTS

It is clear from figure 8 that there are discrepancies among the constraints imposed by the relevant data sets and that several possibilities must be considered when correlating the magnetic polarity stratigraphy of the CRP-1 core with the MPTS. In each case, compromises must be made because there is no unique correlation that satisfies all constraints. Several possible correlations are discussed below and are summarised in figure 8.

The solid black correlation line in figure 8 indicates a possible correlation to the MPTS in which it is assumed that all of the documented magnetozones in the CRP-1 core have correlatives in the MPTS: this correlation is constrained only by the diatom datums (producing average sedimentation rates of *c.* 20 m/m.y.). With these constraints, R1 can be correlated with Chrons C5Er through C5Dr, N1 can be correlated with Chrons C6An.2n through C6n, and R2 can be correlated with Chron C6Ar. This correlation does not take into account the $^{40}Ar/^{39}Ar$ and strontium isotope data.

The strontium isotope date (S1, Fig. 8) suggests that the upper part of the Miocene interval may be slightly older and that R1 may correlate with Chron C5Er. This interpretation is compatible with diatom datum D2, but it requires that the normal polarity sample at *c.* 75 mbsf does not represent a real polarity zone in the MPTS. The palaeomagnetic behaviour of this sample is good, and it may represent a short polarity excursion that was not resolvable on the marine magnetic anomaly profiles on which the MPTS of Cande & Kent (1995) is based.

Neither of the preceding correlations satisfy the maximum age constraints from the $^{40}Ar/^{39}Ar$ dating of reworked volcanic clasts or the *in situ* age of the disseminated pumice at 116 - 117 mbsf. These dates suggest that the core is up to *c.* 1.5 m.y. younger than was inferred from the other data sets and that it has a higher average sedimentation rate, perhaps as high as 70 m/m.y. (grey dashed correlation line in Fig. 8). In this correlation, the short normal polarity interval in R1 and both short reversed polarity intervals in N1 are assumed to be excursions that were not documented in the MPTS of Cande & Kent (1995), and N1 is correlated to Chron C5En. This correlation either requires that the shell material dated by strontium isotopes (S1) was reworked from older strata or that the waters of McMurdo Sound were not in equilibrium with the world ocean. It also requires that the FCO of *T. praefraga* occurs more than 1 m.y. later at the CRP-1 site than is expected from Southern Ocean observations. A more satisfying correlation, using the $^{40}Ar/^{39}Ar$ constraints, is depicted by a solid grey line in figure 8. Here, the reversed polarity interval at *c.* 106 mbsf, which is at least 2 m thick, is correlated with Chron C5Er, while the normal polarity of N1 above this level is correlated with Chron C5En and the normal polarity of N1 below this level is correlated with the upper part of Chron C6n. This interpretation also requires that the strontium isotope date is not reliable and that the FCO of *T. praefraga* is younger than in the Southern Ocean.

In both of the latter correlations, as constrained by $^{40}Ar/^{39}Ar$ dates, it is likely that R2 correlates with Chron C6Ar and that *c.* 2 m.y. is missing in an unconformity at *c.* 124.2 mbsf. However, it cannot be ruled out that some of the upper part of R2 might correlate with Chron C6r. In either case, an additional sequence boundary must be placed at the unconformity at *c.* 124.2 mbsf. Circumstantial evidence for a significant time gap at this unconformity includes an abrupt change in rock magnetic properties at 124.2 mbsf (Sagnotti et al., this volume) and evidence that the diamictite immediately above 124.2 mbsf was formed by lodgement beneath grounded ice (van der Meer & Heimstra, this volume).

If it is assumed that the mixed polarity zone in the lowermost 4 m of the CRP-1 core represents genuine geomagnetic field behaviour, then there appears to be a one-to-one reversal match with the 21 - 25 Ma interval of the MPTS (dark dotted correlation line in Fig. 8). The lower interval would therefore represent a condensed section with surprisingly low average sedimentation rates of *c.* 1 m/m.y. Despite the apparent one-to-one correlation of reversals with the MPTS in the mixed polarity zone, a sedimentation rate of 1 m/m.y. is as low as the lowest ever documented pelagic sedimentation rates (*e.g.*, Berger, 1974), which would be surprising in a glaciomarine environment.

Inspection of demagnetisation data from M1 (Fig. 4) indicates that for all of the reversed polarity samples, a clear delineation can be made between the normal polarity drilling-induced overprint and the reversed polarity characteristic component. The reversed polarity data therefore appear to be reliable. However, such a clear delineation between the overprint and the normal polarity "characteristic" component is not so obvious for many samples from M1 (*e.g.*, 144.68 and 146.16 mbsf). Furthermore, the observation that normal polarities occur only in zones of low susceptibility within M1 (Fig. 5) suggests that these zones may be more prone to remagnetisation. The probable variations in magnetic mineralogy, as suggested by the highly variable hysteresis data from M1 (Fig. 7), may account for the susceptibility to remagnetisation in parts of the mixed polarity zone. It should be noted, however, that not all of the samples from the low κ zones have ambiguous demagnetisation behaviour: there is clear evidence for an overprint and a stable characteristic component for a transitional sample at 145.27 mbsf and for a normal polarity sample at 145.46 mbsf (Fig. 4). It is therefore possible that the normal polarity zone at *c.* 145 mbsf may not have been remagnetised.

Given the observed correlation between polarity and magnetic properties, it is reasonable to conclude that parts of the mixed polarity zone (M1) are remagnetised (possibly due to drilling-induced effects). Furthermore, the one-to-one match of polarities with the 21 - 25 Ma interval of the MPTS (dark dotted correlation line in Fig. 8) indicates that the Oligocene-Miocene boundary should occur within M1 (*cf.* Berggren et al., 1995), but Harwood et al. (this volume) did not find an Oligocene flora from the base of the CRP-1 core. Because of the above-described uncertainties, we refrain from interpreting the magnetostratigraphy from this interval.

CONCLUSIONS

Samples from the Miocene interval of the CRP-1 core are generally stably magnetised and magnetite appears to be the dominant remanence carrier. A magnetic polarity stratigraphy has been established for the lower 90 m of the CRP-1 core, which can be used to constrain the chronology of glacial activity in the area. A zone of mixed polarity between 143.8 and 148 mbsf in the CRP-1 core is probably remagnetised and is not interpreted in terms of magnetostratigraphy.

Diatom biostratigraphy, $^{40}Ar/^{39}Ar$ dating and $^{87}Sr/^{86}Sr$ ratios provide constraints on correlating the magnetic polarity stratigraphy of the CRP-1 core with the MPTS. The constraints imposed by the relevant data sets are not mutually consistent, therefore several possibilities exist for correlation of the interval between 43 and 143 mbsf with the MPTS. Our preferred correlation indicates that this interval ranges in age from 21.5 Ma at the base to 17.5 Ma immediately beneath the unconformity at *c.* 43 m, with an average sedimentation rate of *c.* 50 m/m.y., and with as much as 2 m.y. missing in an unconformity beneath lodgement diamictite at *c.* 124.2 mbsf.

ACKNOWLEDGEMENTS

The palaeomagnetic component of the Cape Roberts Project was supported by grants from the U.S. National Science Foundation to KLV, APR, GSW and DMH and from the Italian *Programma Nazionale di Ricerche in Antartide* to LS and FF. We thank Brad Clement and Joe Stoner for helpful reviews of the ms, Fred Davey for editorial assistance, Rich Jarrard for use of samples for AF demagnetisation studies, John Foster for assistance with thermomagnetic analyses, Brendan McCarthy for assistance with hysteresis measurements and Glen Smith and the CSEC technical support staff and Jay Burnside and the science construction staff of Antarctic Support Associates for their patience, efficiency, and cooperation.

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