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

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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, 40Ar/39Ar dating and 87Sr/86Sr 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 targeted 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
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, 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 stepwise AF 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 magnetostatigraphy. 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 $\text{IRM}_{1T}$ 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 ($B_c$) and the S-ratio ($\text{S}_{\text{IRM}} = \text{IRM}_{0.1T}/\text{IRM}_{1T}$). 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). $\text{IRM}_{1T}$ 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 IRM₁ⱽ, high S-ratios and low values of Bcr. This suggests that the high κ zones are dominated by low-coercivity ferrimagnetic grains. Conversely, zones of low κ have low IRM₁ⱽ, low S-ratios, and high values of Bcr. 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 samples

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 (Bcr). See text for discussion.
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

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.
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 between 124 and 143.8 mbsf (R2); and an interval of mixed polarity at the base of the record, between 143.8 mbsf and 150 mbsf (M1).

![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.](image-url)
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 $B_c$ and high S-ratios) as well as by high IRM and $\kappa$, while normal polarity zones are characterised by high coercivity (high $B_c$ and low S-ratios) as well as by low IRM and $\kappa$. 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,
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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.

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 \( \kappa \) zones of figure 1. In each case, the thermo-magnetic behaviour is clearly consistent with that of magnetite, with a Curie temperature of \( c_\text{c} \approx 580^\circ \text{C} \) (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 \( \kappa \). 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). $M_r/M_s$ and $B_{cr}/B_s$ 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 diamicrites 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 conglomerate 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 chron.

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**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 Cavittatus 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. grosea 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 19.4 Ma. At c. 103 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 ^Ar/^Ar dating and qSr/^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.

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