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Magnetostratigraphy of Late Eocene - Early Oligocene Strata from the CRP-3 Core, Victoria Land Basin, Antarctica

F. FLORINDO[1,2*], G.S. WILSON[3], A.P. ROBERTS[2], L. SAGNOTTI[1] & K.L. VEROSUB[4]

[1]Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata, 605, I-00143 Rome - Italy
[2]School of Ocean and Earth Science, University of Southampton, Southampton Oceanography Centre, European Way, Southampton SO14 3ZH - UK
[3]Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR - UK
[4]Department of Geology, University of California, Davis, California 95616 - USA

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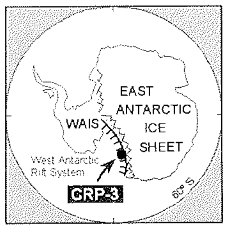
Abstract - The Cape Roberts Project was successfully completed in the austral spring of 1999 with drilling of the 939.42-m CRP-3 drillhole, located 2-km west of the CRP-2/2A drillhole. The CRP-3 core comprises a 790-m Cenozoic (glacio-) marine sequence separated from underlying Devonian basement rocks by a *c*. 30-m-thick dolerite conglomerate of undetermined age. Here, we present the results of a palaeomagnetic study, including correlation to the magnetic polarity time scale (MPTS) and an age model for the Cenozoic sequence recovered in CRP-3. The palaeomagnetic behaviour of the Cenozoic sedimentary sequence is generally stable, and magnetite is the main magnetic carrier. The magnetic polarity stratigraphy of the Cenozoic sequence in the CRP-3 core is subdivided into four magnetozones: R1 is an upper interval of dominantly reversed polarity (0-340.8 mbsf), N1 has dominantly normal polarity (340.8-627.3 mbsf), R2 has dominantly reversed polarity (627.3-760.2 mbsf), and N2 has normal polarity (760.2-788.8 mbsf). Magnetozones R1, N1, and R2 also contain thin intervals with opposite polarity, which are interpreted as representing either short polarity intervals (corresponding to "tiny wiggles" identified on marine magnetic anomaly records) or geomagnetic excursions. Above 340 mbsf, diatom and calcareous nannofossil biostratigraphy and $^{87}Sr/^{86}Sr$ ages suggest that magnetozone R1 correlates with Chron C12r of the MPTS. Below 340 mbsf, we tentatively correlate magnetozones N1 and R2 with chrons C13n and C13r of the MPTS, respectively. However, below R1, the magnetic polarity record is not constrained by biostratigraphy or $^{87}Sr/^{86}Sr$ ages. Our correlation implies that the Eocene-Oligocene boundary (33.7 Ma) in the CRP-3 core should lie within lithostratigraphic sub-Unit 13.1, at about 718 mbsf. Lack of independent chronostratigraphic constraints makes it difficult to interpret the age of the basal part of the CRP-3 Cenozoic sequence, but the magnetostratigraphy suggests a minimum age of Chron C13r (*c*. 34 Ma).



INTRODUCTION

Considerable progress has been made in deciphering the onset and development of the Antarctic ice sheets as a result of drilling the thick sedimentary sequences on the Antarctic continental margin. Most recently, the Cape Roberts Project (CRP) has demonstrated that cores can be successfully recovered from deep boreholes at inshore sites, using a sea-ice-based drilling system (Cape Roberts Science Team, 1998, 1999, 2000). The goals of CRP were to recover and analyse sedimentary records from the Ross Sea margin in order to investigate the onset of Antarctic glaciation and to date the onset of the West Antarctic Rift and uplift of the associated rift shoulder (the Transantarctic Mountains). The drilling plan was to recover a complete sequence through 1500-m of strata offshore from Cape Roberts (Barrett et al., 1995), by coring at 3 separate locations, in three successive years (1997, CRP-1, Cape Roberts Science Team 1998; 1998, CRP-2/2A, Cape Roberts Science Team, 1999; 1999, CRP-3, Cape Roberts Science Team, 2000).

The oldest Cenozoic strata in the Granite Harbour region of the Victoria Land Basin were recovered in CRP-3 (77.006°S, 163.719°E) during the austral spring of 1999. At the CRP-3 site, located just 2-km west of CRP-2/2A, core was recovered down to 939.42 mbsf with 97% recovery. A 790-m-thick Cenozoic sequence of sandstones (about 80% of the CRP-3 sequence) with minor diamictites, conglomerates and mudstones, was recovered in the upper part of the CRP-3 drillcore. Below this, a *c*. 30-m-thick (790-823.11 mbsf) interval of dolerite conglomerate of undetermined age was recovered. The basal 119 m (823.11-939 mbsf) of the CRP-3 sequence comprises Devonian sandstones of the Beacon Supergroup, which form the basement of the Victoria Land Basin in the vicinity of Granite Harbour (Cape Roberts Science Team, 2000).

**Corresponding author* (florindo@ingv.it)

In this paper, we present palaeomagnetic analyses for the CRP-3 core, including correlation of the identified magnetozones to the magnetic polarity time scale (MPTS) of Cande & Kent (1992a, 1995) and Berggren et al. (1995). A preliminary assessment of all data available for the upper 350 mbsf of CRP-3 was presented at the end of the drilling season (Cape Roberts Science Team, 2000). Here, we incorporate new data from additional samples that were measured after the drilling season. These data allow us to refine the magnetic polarity zonation and to improve the correlation to the MPTS. We restrict our analysis to the Cenozoic sequence and do not discuss the palaeomagnetism of the Devonian Beacon Supergroup strata recovered in the lower *c.* 116 m of the CRP-3 core.

METHODS

SAMPLING

Details about the palaeomagnetic sampling techniques, laboratory facilities and equipment installed at the Crary Science and Engineering Center (CSEC) at McMurdo Station, Antarctica, are given in Florindo et al. (1997) and Cape Roberts Science Team (1998a).

Where possible, samples were collected from CRP-3 at 0.5-m intervals in fine-grained horizons, avoiding intervals with drilling-related deformation. The sampling density was lower in coarse-grained intervals because mechanical energy and gravity may have outweighed the aligning influence of the geomagnetic field during deposition of these intervals. Similarly, multi-domain behaviour will occur in particles with larger grain sizes, which are less likely to retain a long-term magnetization. Thus, coarse-grained sediments are far from ideal for recording a reliable detrital remanent magnetization (DRM). Such sediments usually display distinctive palaeomagnetic behaviour upon demagnetization, which indicates that they are unsuitable for magnetostratigraphic analyses (*e.g.* Roberts et al., 1998; Wilson et al., 2000b).

A total of 1012 oriented discrete samples were collected from the centre of the working half of the Cenozoic sequence in the CRP-3 core. Ninety-two pairs of samples were taken at regular intervals (*c.* 10 m) for a pilot study to assess the most suitable demagnetization technique for routine treatment of the remaining samples. Each sample pair was separated stratigraphically by a few centimetres, and the pairs were selected from varying lithofacies throughout the sequence.

We sampled unconsolidated sediments (from 3.08 to 35.73 mbsf) with standard 6.25 cm^3 plastic cubes (30 samples) and consolidated sediments (below 35.73 mbsf) by drilling conventional cylindrical (25 mm diameter x 22 mm height) palaeomagnetic samples (982 samples) using a modified drill press. Cores and cubes were oriented with respect to vertical and were marked with a fiducial arrow pointing in the up-core direction. We also recorded the orientation of the core in the vertical plane with respect to a core-recovery-scribe-line. The scribe-line was not always continuous across core breaks, hence samples are not azimuthally oriented. The lack of azimuthal orientation of palaeomagnetic samples does not pose a problem for magnetostratigraphic studies of the CRP-3 core. The geomagnetic field at the latitude of the drill-site (77°S) has a steep inclination (83.4° assuming a geocentric axial dipole field) and, therefore, palaeomagnetic inclinations are sufficient to uniquely determine polarity.

Samples were not collected from several stratigraphic intervals where there was no core-recovery or where sediments were too coarse-grained to allow sampling (144.67-152.84, 259.0-264.33, 293.43-306.26, 344.89-351.22, 371.23-374.19, 378.91-381.93, 414.24-417.24, 441.27-444.71, 445.72-448.07, 470.86-473.65, 493.40-499.52, 509.34-512.02, 523.10-526.43, 526.99-533.88, 536.06-539.63, 560.46-564.89, 564.94-568.22, 638.30-640.30, and 772.31-776.68 mbsf).

PILOT STUDY

Before performing routine demagnetization of all samples from the CRP-3 core, a pilot study was conducted at McMurdo Station (using an AGICO JR-5A spinner magnetometer; Florindo et al., 1997; Cape Roberts Science Team, 1998a) to determine the most appropriate demagnetization technique for isolating the characteristic remanent magnetization (ChRM). One sample from each of the 92 pairs of pilot samples was subjected to alternating-field (AF) demagnetization at successive peak fields of 5, 10, 15, 20, 25, 30, 40, and 50 mT. The other sample was subjected to progressive thermal demagnetization, using a magnetically shielded oven, from room temperature up to 650°C at steps of 120, 180, 240, 300, 350, 400, 450, 500, 550, 600 and 650°C. The low-field magnetic susceptibility (κ) was monitored after each heating step, in order to detect possible thermally-induced changes in the magnetic mineralogy. Further demagnetization was abandoned if we observed a susceptibility increase of more than 30%, with a concomitant loss of coherence in the palaeomagnetic signal.

MEASUREMENTS

Time constraints limited the number of samples that could be measured at McMurdo Station during the drilling season. The on-ice analyses were limited to the measurement of the natural remanent magnetization (NRM) of all samples, and a pilot demagnetization of the 92 paired samples. During the drilling season, the remaining samples were divided and transported to the respective palaeomagnetic laboratories at the Istituto Nazionale di Geofisica e Vulcanologia, Rome (INGV) and the University of California, Davis (UCD) for routine demagnetization measurements. In both laboratories, samples were analysed within a magnetically shielded room using a 2-G Enterprises automated, pass-through cryogenic magnetometer with in-line AF demagnetization capability. The samples were routinely AF demagnetized up to peak fields of either 60 or 70 mT, because the pilot study indicated that, for samples with stable magnetizations, the ChRM is already isolated at 10-20 mT and totally removed at 60-70 mT (see below). By the end of the drilling season, results of palaeomagnetic measurements made at INGV and UCD were available for samples from the uppermost *c.* 350 mbsf and were reported in the Initial Report for the CRP-3 drillcore (Cape Roberts Science Team, 2000).

Low-field magnetic susceptibility was routinely measured at two frequencies (κ_{low}, κ_{high}) at McMurdo Station using a Bartington Instruments MS-2 susceptibility meter, with a dual-frequency sensor, which operates at 0.470 and 4.70 kHz. These data, obtained from discrete samples, were subsequently compared with the whole-core susceptibility log (Cape Roberts Science Team, 2000). The frequency-dependence of magnetic susceptibility ($\kappa_{fd}\% = [(\kappa_{low} - \kappa_{high})/\kappa_{low} \times 100\%]$) (*e.g.* Bloemendal et al., 1985) was used to estimate the contribution from magnetic grains near the superparamagnetic-stable single domain boundary.

Following the drilling season, additional rock magnetic studies were carried out at the INGV, UCD, and the Southampton Oceanography Centre (SOC), on AF demagnetized samples or on chips or powders collected during sampling. Analyses included acquisition and demagnetization of anhysteretic remanent magnetization (ARM), thermomagnetic and hysteresis measurements (including measurement of the saturation remanence, M_{rs}; saturation magnetization, M_s; coercivity of remanence H_{cr}; and coercive force, H_c). ARMs were imparted using an AF of 100 mT and a DC bias field of 100 μT, and were subsequently stepwise demagnetized, using the in-line system on the 2-G cryogenic magnetometer at the INGV. Hysteresis loops were measured using a Princeton Measurements Corporation Micromag alternating gradient magnetometer (maximum fields of 1.4 T) at UCD. Thermomagnetic analyses were conducted at the SOC using a variable field translation balance, with a field of 76 mT at a heating rate of 10°C/minute in air. Rock magnetic results are presented here if they are useful for understanding the palaeomagnetic behaviour. A more detailed presentation of the magnetic properties is given in Sagnotti et al. (this volume).

RESULTS

DOWN-CORE ROCK MAGNETIC PROPERTIES

Significant down-core fluctuations are evident in the low-field magnetic susceptibility and the NRM intensity (Fig. 1). These parameters have similar patterns of variation, particularly below 243 mbsf. Based on these magnetic properties, the Cenozoic portion of the CRP-3 core can be divided into four main rock magnetic intervals that are not directly related to lithological variations in the core. In rock magnetic interval I (down to 243 mbsf), κ and NRM are variable (κ = 16-586 x 10^{-5} SI, mean = 269.6 x 10^{-5} SI; NRM = 1.9-296 mA/m, mean = 67 mA/m) but they generally have higher values than in the underlying rock magnetic interval II (between 243 and 440 mbsf). The range of κ and NRM values is larger in rock magnetic interval II (κ = 8-747 x 10^{-5} SI, mean = 132.3 x 10^{-5} SI; NRM = 0.1-389 mA/m, mean = 29 mA/m) than in rock magnetic interval I. Between 440 and 628 mbsf (rock magnetic interval III), κ and NRM values are consistently low (κ = 1-226 x 10^{-5} SI, mean = 39.5 x 10^{-5} SI; NRM = 0.1-45 mA/m, mean = 6.7 mA/m), with the exception of high values between 539 and 560 mbsf. Rock magnetic interval III coincides with the part of the core that is dominated by clean sands. In rock magnetic interval IV (628-790 mbsf), the values and range of variability of κ and NRM are similar to those observed in rock magnetic interval I (κ = 45-432 x 10^{-5} SI, mean = 223.4 x 10^{-5} SI; NRM = 11.4-448 mA/m, mean = 70.2 mA/m). This subdivision of the Cenozoic portion of the CRP-3 sequence is consistent with low-resolution petrological results that indicate a higher relative input of detritus from the Ferrar Dolerite relative to Granite Harbour Intrusives and sedimentary clasts in intervals I and IV (Cape Roberts Science Team, 2000).

The four intervals with contrasting magnetic properties also correspond to different types of palaeomagnetic behaviour. Changes in κ during thermal demagnetization of pilot samples indicates that, when present, thermal alteration was limited to temperatures above about 400°C (Fig. 2). For samples with high κ (rock magnetic intervals I, IV and a few segments of rock magnetic intervals II and III), there is generally no evidence for the formation of new mineral phases during heating. In these intervals, κ clearly decreased when samples were heated above 500°C, possibly as a result of partial oxidation of magnetite to hematite. The lack of evidence for thermal alteration below 500°C suggests that thermal demagnetization is an appropriate method for treating such samples. For samples with low magnetic susceptibility (most of rock magnetic intervals II and III), κ generally increased when samples were heated above 400°C, indicating thermogenic production of new magnetic minerals during heating. This behaviour

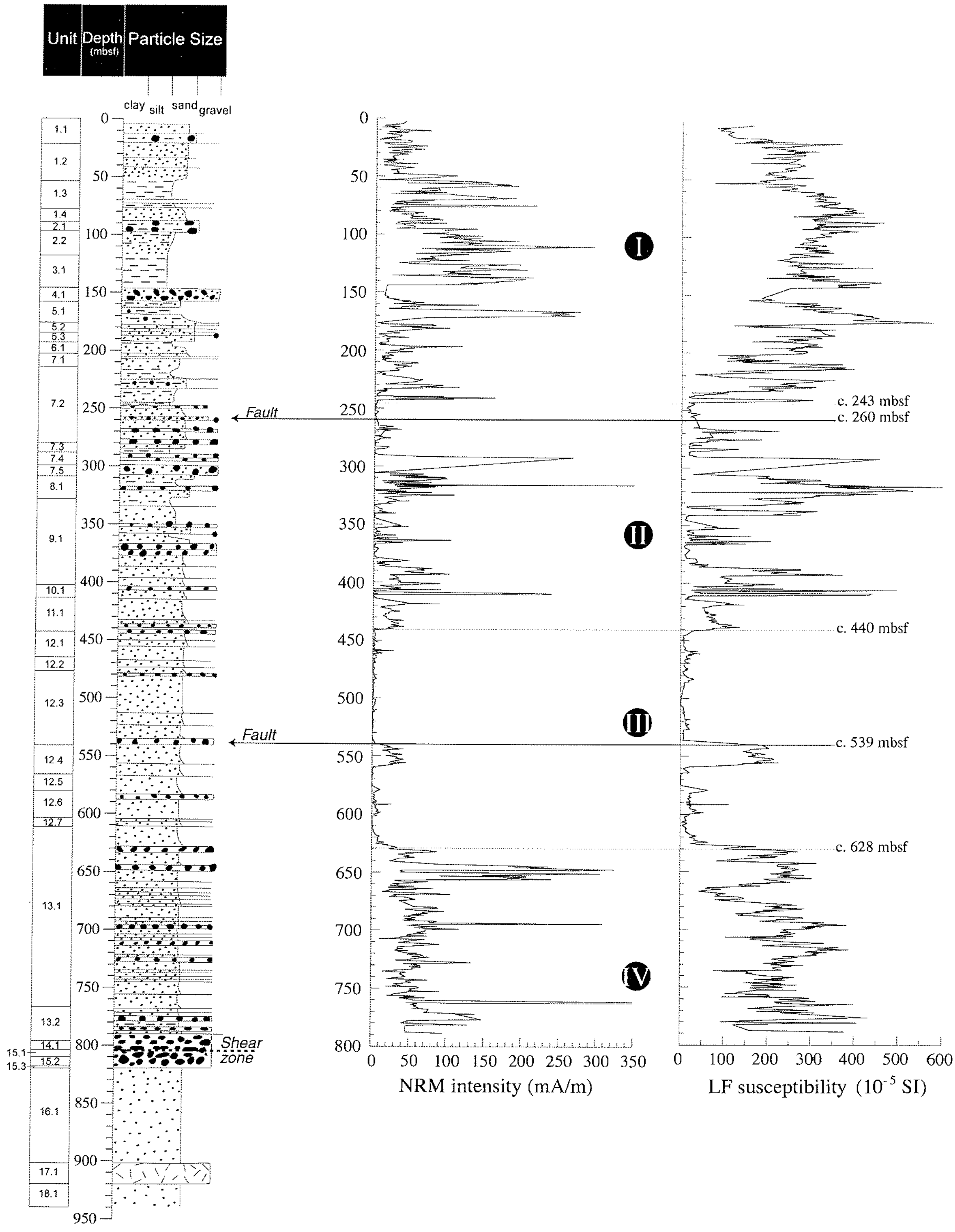


Fig. 1 - Lithostratigraphic column (after Cape Roberts Science Team, 2000), and down-core variations in the natural remanent magnetization (NRM) intensity and the low-field magnetic susceptibility (κ). Based on these parameters, the Cenozoic portion of the CRP-3 core has been divided into four main rock magnetic intervals (see text and Sagnotti et al., this volume).

suggests that thermal demagnetization is less useful in rock magnetic intervals with low κ (II and III) than in rock magnetic intervals with high κ (I and IV).

PALAEOMAGNETIC BEHAVIOUR

Demagnetization results were examined using orthogonal vector component diagrams, stereographic projections and intensity decay curves. ChRM components were determined from multiple demagnetization steps using principal component analysis (Kirschvink, 1980) (Fig. 3). Most of the analysed samples have a low-coercivity, nearly vertical, normal polarity component that is interpreted as representing a drilling-induced overprint (Fig. 3). This overprint has been observed in all of the cores

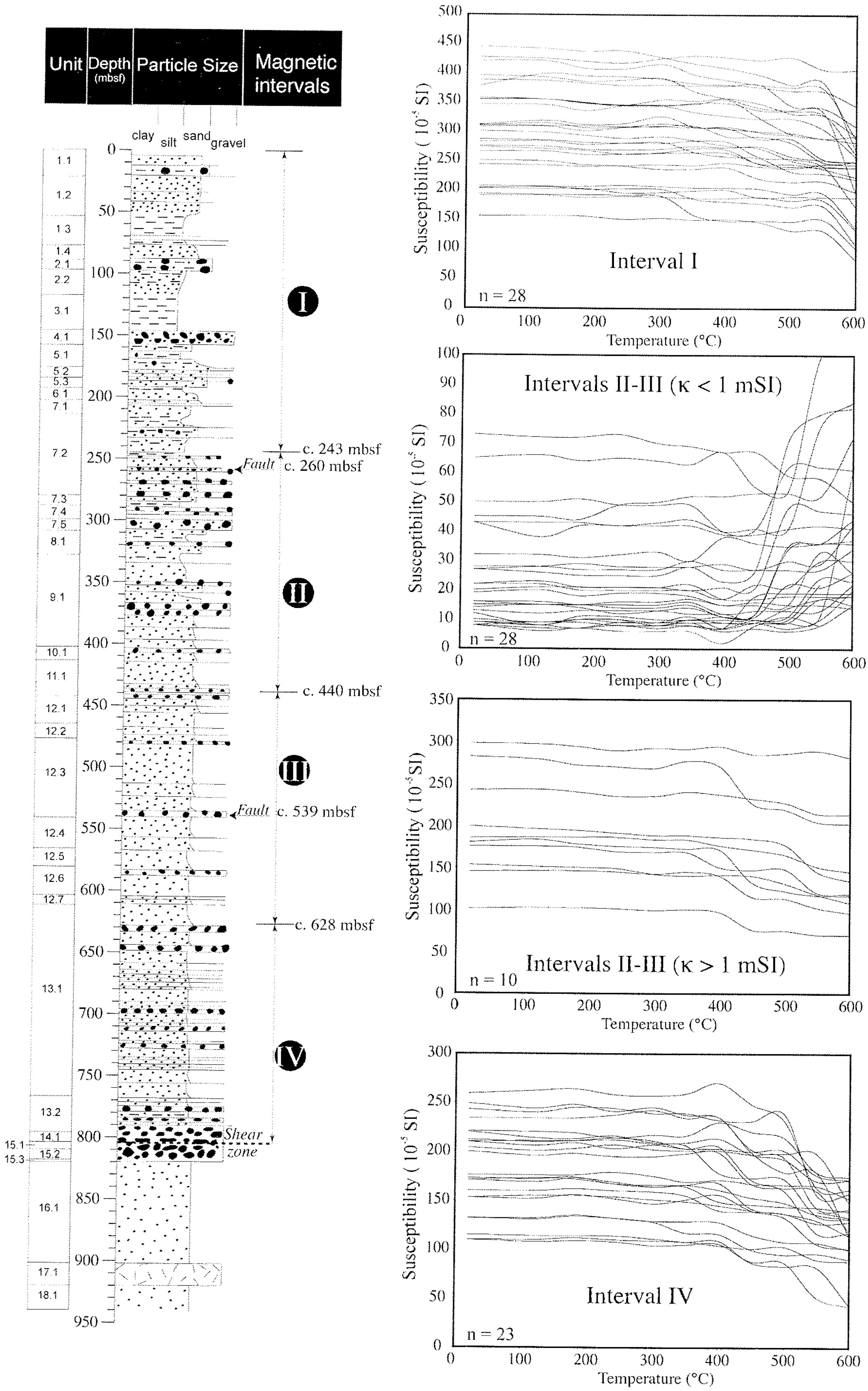


Fig. 2 - Changes in the low-field magnetic susceptibility (κ) during thermal demagnetization for pilot samples from different stratigraphic intervals in CRP-3.

that we have studied from the Victoria Land Basin (Roberts et al., 1998; Wilson et al., 1998, 2000b) and is generally removed without difficulty with peak alternating fields of < 20 mT.

For most samples from the intervals with high κ, thermal and AF demagnetization were equally effective in removing secondary magnetization components and in isolating identical ChRM components for both normal and reversed polarity (Fig. 3c-h, o & p). In some cases, however, AF demagnetization was more efficient in removing secondary remanence components (Fig. 3a & b, k-n). Despite the fact that thermal demagnetization revealed a high-temperature ChRM component similar to that revealed by AF demagnetization (Fig. 3a & b, m & n), AF demagnetization was preferred to thermal treatment because it is faster and because the samples do not undergo thermal alteration and can therefore be used for additional rock magnetic investigations.

In the thick interval dominated by well-sorted and clean sandstones, from 380 to 580 mbsf (corresponding roughly to rock magnetic interval III), the pilot AF demagnetization study revealed a dominance of low-coercivity phases, consistent with the presence of coarse-grained magnetic minerals (Fig. 3i). Thermal demagnetization usually revealed a steep normal polarity component, which is gradually removed up to 400-500°C (Fig. 3j). Usually, this steep component, with apparently stable remanence during thermal demagnetization corresponds to a low-coercivity component in the AF demagnetization data. We interpret this component as a viscous remanent magnetization (VRM) that is relatively resistant to thermal demagnetization. For such samples, neither AF nor thermal demagnetization enabled identification of a stable ChRM component. For such samples, we preferred AF demagnetization for routine treatment because it was more likely to give a clearer indication that the data were unreliable. For some pilot study samples, a steep, normal polarity component was indicated by thermal demagnetization, and a clear reversed polarity ChRM is revealed by AF demagnetization (Fig. 3k, l). In such cases, we interpret the thermal demagnetization data as being dominated by a viscous overprint, and AF demagnetization is apparently more successful in removing this secondary component.

In a few cases (*c.* 1% of the collected samples), particularly in predominantly sandy lithologies, we found another overprint, which is more resistant to AF demagnetization than the nearly vertical drilling-induced overprint. This overprint has a nearly horizontal inclination and is always perpendicular to the split plane of the core, *i.e.*, in sample coordinates, the overprint is entirely in the x-z plane, with y = 0 (Fig. 4). In other drillcores, two different mechanisms have been suggested to explain this spurious component: 1) a radial overprint, as documented by Fuller et al. (1997, 1998), which is related to cutting-shoe and/or core barrel magnetic fields, and 2) a core-splitting overprint (Roberts et al., 1998; Wilson et al., 1998, 2000b). At this stage, it has not been possible to determine which of the two suggested mechanisms is responsible for the overprint. Dominantly vertical and dominantly horizontal magnetic overprints are evident in histograms of the NRM directions. The horizontal overprint is illustrated by a distinct statistical mode around 180° in the NRM declination histogram (Fig. 5a). The nearly vertical, normal polarity overprint is illustrated by a statistical mode at around -80° in the NRM inclination histogram (Fig. 5b). These secondary components were successfully removed by the demagnetization treatment, as shown in the ChRM declination and inclination histograms (Fig. 5c, d). The ChRM declinations appear to be randomly distributed, as would be expected for an azimuthally unoriented drillcore, and the ChRM inclinations have a clear bimodal distribution that demonstrates the presence of two stable polarity states. Steep normal and reversed polarity directions are clearly dominant, as would be expected at high latitudes. In conjunction with evidence from vector component diagrams, this indicates that our demagnetization procedures have successfully removed the secondary remanence components.

Stable palaeomagnetic behaviour was identified by the presence of ChRM directions that have linear trends toward the origin of vector component diagrams (Fig. 3) for 63% (635) of the samples from the Cenozoic CRP-3 sequence. In some cases, the best-fit lines were not constrained through the origin of the plots. In addition to the dominantly steep normal and reversed polarity ChRM directions, a significant number of samples have ChRM inclinations that are indicative of transitional field states. It is not surprising that transitional directions are recorded because rapidly deposited sediments, such as those recovered in the CRP drill holes, have a higher probability of recording geomagnetic polarity transitions.

The normal and reversed polarity ChRM directions from the stable polarity intervals are grouped in two nearly antipodal clusters, as expected for reliable ChRM directions, with I = 56.6° (standard deviation, σ = 17.7) for 464 reversed polarity samples and I = -58.9° (standard deviation, σ = 21.3) for 177 normal polarity samples. These inclinations are shallower than would be expected (±83.4°) for the 77°S latitude at the CRP-3 site (assuming a geocentric axial dipole field). The discrepancy between the expected and observed palaeomagnetic inclinations could be related to the dip of the sedimentary sequence sampled by CRP-3. Dip-meter data indicate that the structural dip is constant at 21°, toward 65°E, throughout the Tertiary section, except for the top 100-m of the borehole, where dips appear to be about 5-10° shallower (Jarrard et al., this volume). Palaeomagnetic

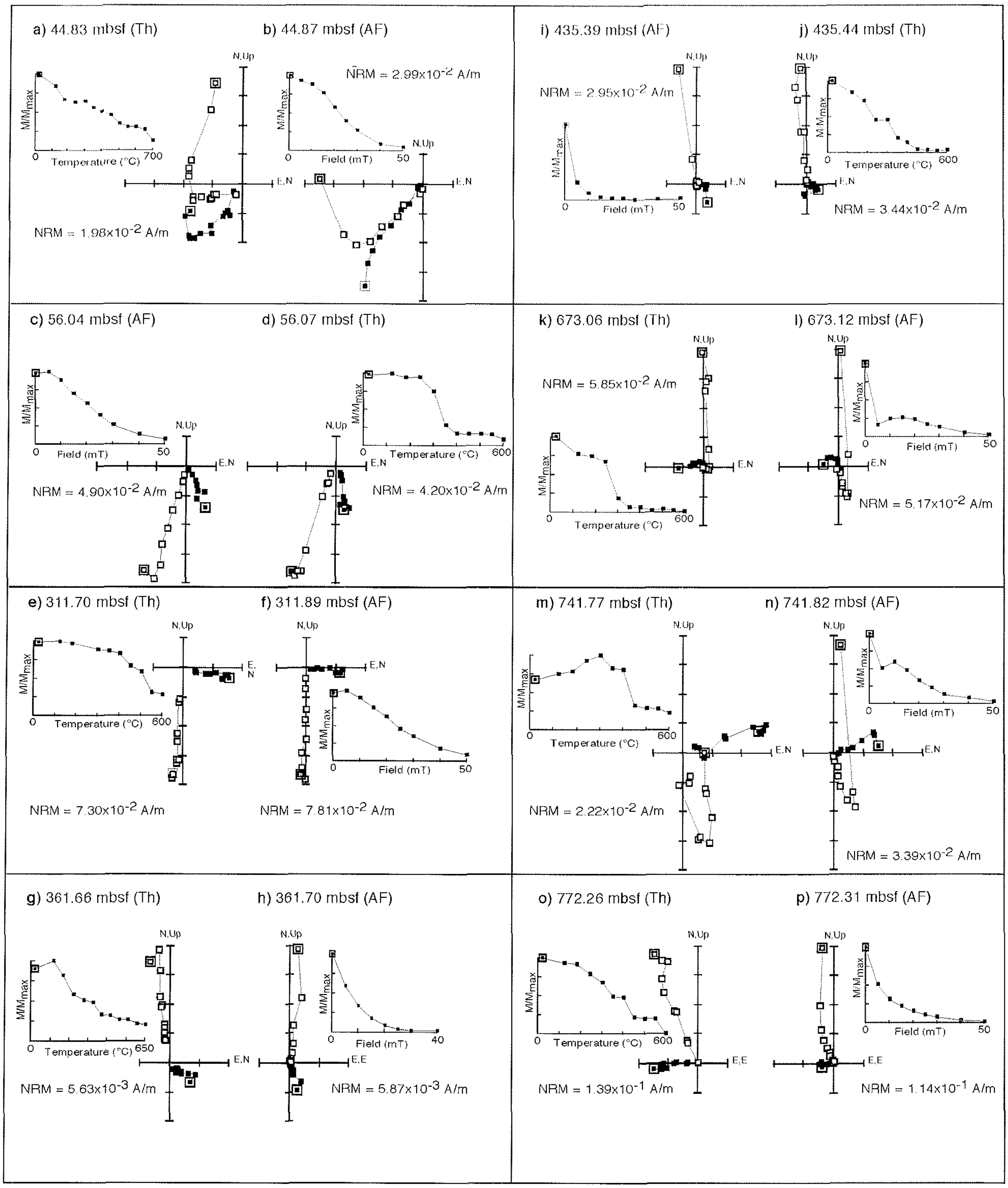


Fig. 3 - Vector component diagrams for selected pairs of pilot samples from CRP-3. Sample pairs were subjected to AF and thermal demagnetization. Samples are not azimuthally oriented and declinations are reported in the laboratory coordinate system with respect to the split face of the drillcore. a) and b) comparison of thermal and AF demagnetization from samples at 44.83 and 44.87 mbsf, respectively. c) and d) Comparison of AF and thermal demagnetization from samples at 56.04 mbsf and 56.07 mbsf, respectively (both reversed polarity). Comparison of thermal and AF demagnetization from samples at: e) 311.70 mbsf and f) 311.89 mbsf, respectively (both reversed polarity); g) 361.66 mbsf, and h) 361.70 mbsf, respectively (both normal polarity). Comparison of AF and thermal demagnetization from samples at: i) 435.39 mbsf and j) 435.44 mbsf, respectively. Comparison of thermal and AF demagnetization from samples at: k) 673.06 mbsf and l) 673.12 mbsf, respectively; m) 741.77 mbsf and n) 741.82 mbsf, respectively; and o) 772.26 mbsf and p) 772.31 mbsf, respectively. Projections onto the vertical (horizontal) plane are represented by open (solid) symbols, respectively. See text for discussion of each diagram.

data reported here are not corrected for stratal tilt because of the lack of azimuthal orientation data for the complete CRP-3 sequence. Alternatively, the inclination shallowing could also be related to inclination error that arises from the physical rotation of detrital grains toward the bedding plane of the

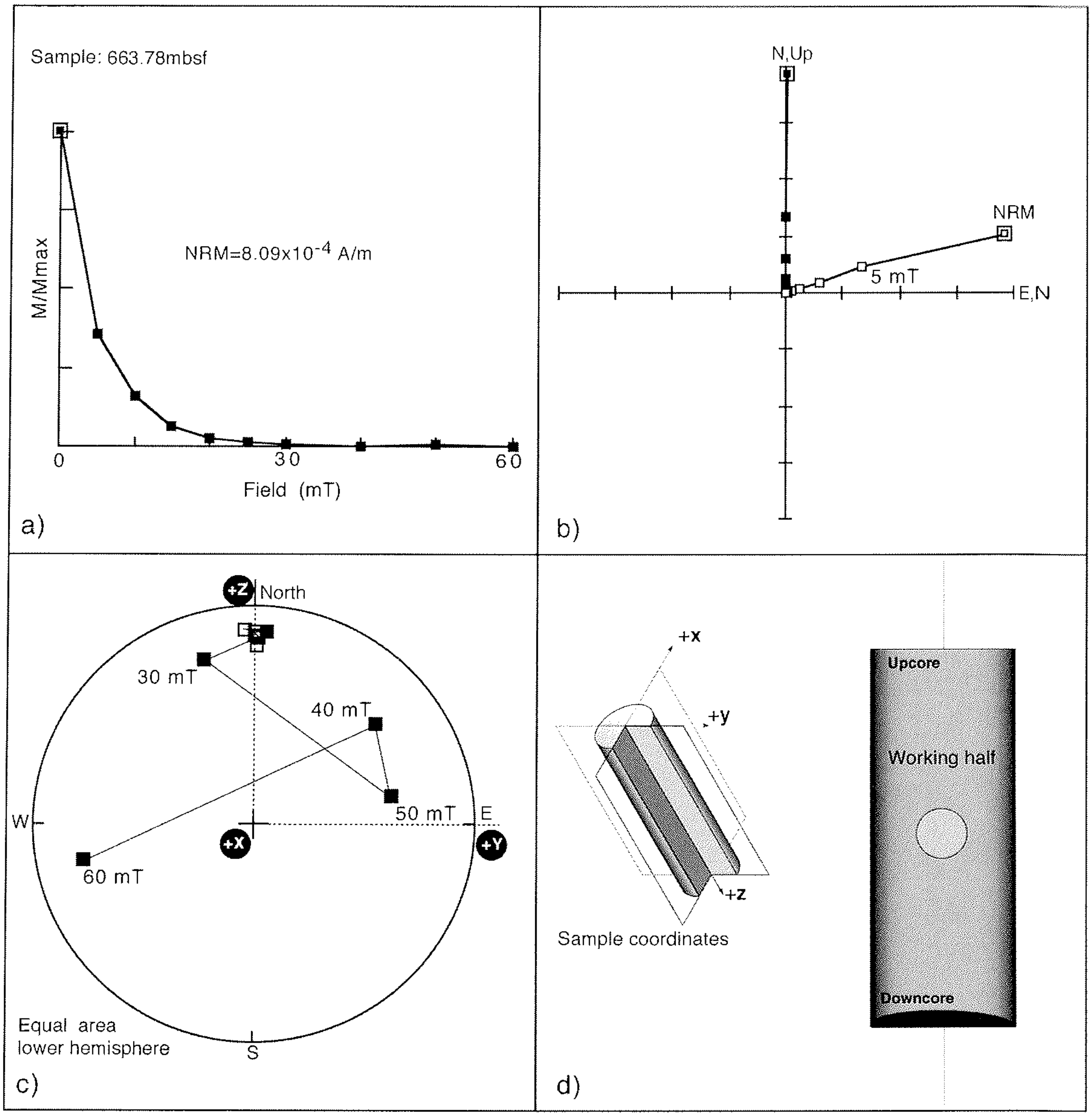


Fig. 4 - Demagnetization data for a representative sample with a nearly horizontal overprint. a) Normalized intensity decay plot, b) vector component diagram (solid squares refer to the projection onto the horizontal plane, and open squares refer to the projection onto the vertical plane), c) equal area stereographic projection and d) palaeomagnetic sample coordinates.

sediment due to gravitational forces. This phenomenon is commonly observed in sediments that have undergone significant compaction after deposition (*e.g.* Anson & Kodama, 1987; Arason & Levi, 1990) and where bioturbation is limited or absent (Verosub, 1977), which seems to be the case for some lithostratigraphic units in CRP-3.

A detailed rock magnetic study has been carried out on the AF demagnetized samples used for this study and on additional powdered samples (Sagnotti et al., this volume). Relatively low coercivities and thermomagnetic behaviour imply that magnetite and/or low-Ti titanomagnetite is the primary remanence carrier. Hysteresis parameters are consistent with the presence of pseudo-single domain magnetite in a narrow grain size range (*cf.* Day et al., 1977). No evidence of "wasp-waisted" characteristics was detected, which is consistent with a uniform mineralogy and a narrow range of grain sizes (*cf.* Roberts et al., 1995). The down-core variation of ARM, IRM and M_s confirms the subdivision of the Cenozoic portion of the CRP-3 core into four main rock magnetic intervals, as proposed at the end of the drilling season (Cape Roberts Science Team, 2000).

MAGNETIC POLARITY STRATIGRAPHY OF THE CRP-3 CORE

In this study, we update the preliminary magnetic polarity stratigraphy for the Cenozoic sequence in the CRP-3 core (Cape Roberts Science Team, 2000) by including data from 340-790 mbsf (Fig. 6). The magnetic polarity signal recorded in this interval is considered primary because the samples are stably magnetized and the normal and reversed polarity samples define two antipodal clusters (based on

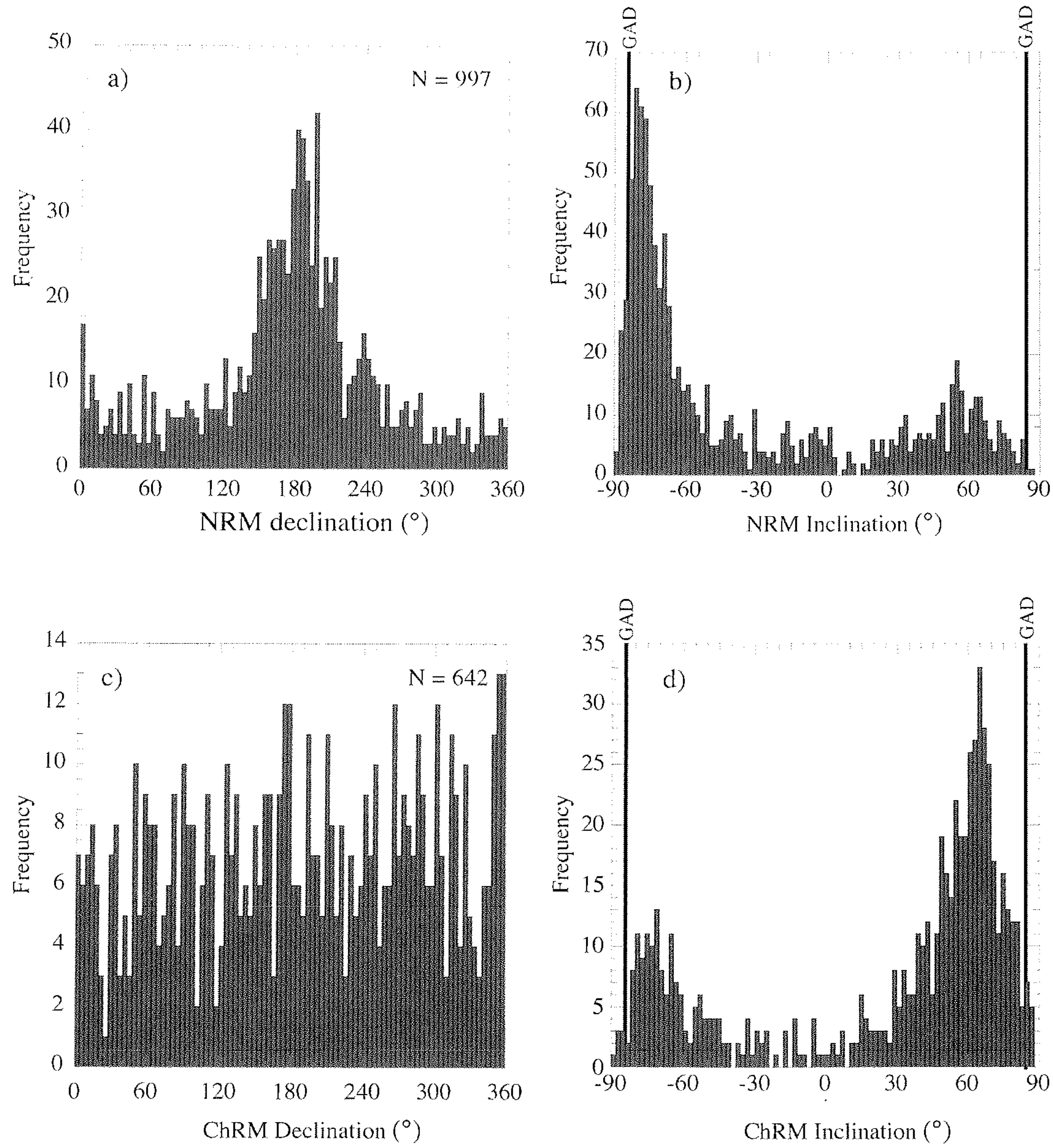


Fig. 5 - Frequency histograms of a) NRM declination, b) NRM inclination, c) ChRM declination and d) ChRM inclination. The expected inclinations for the 77°S latitude at the CRP-3 site (assuming a geocentric axial dipole field) are shown at ±83.4°. See text for discussion.

inclinations only). The CRP-3 polarity record is complex and contains multiple thin normal and reversed polarity intervals within thicker intervals of dominantly reversed or normal polarity, respectively. For convenience, we have subdivided the record into four main magnetozones, two of dominantly reversed polarity and two of dominantly normal polarity. Boundaries between polarity intervals are placed either at the midpoint between successive samples of opposite polarity or at a lithological contact or disconformity that separates such samples. Within some polarity intervals, samples display opposing polarities to those of the rest of the polarity interval. In each case, the palaeomagnetic behaviour is stable, and the presence of a steep, low-coercivity, normal polarity secondary component, attributable to a viscous or drilling-induced magnetic overprint, suggests that the samples have not been inadvertently inverted during sampling and/or measurement. These samples were not included in development of the overall magnetic polarity zonation of the CRP-3 core (Fig. 6), which is defined strictly on the basis of multiple consecutive stably magnetized samples.

The upper 340.8-m of the magnetic polarity record is dominated by reversed polarity (magnetozone R1; Fig. 6). However, the inclination record contains some thin intervals with shallow reversed or normal polarity inclinations. A polarity transition is recorded by five successive samples between the top of the drillcore and 7 mbsf. Between 41.72 and 44.40 mbsf, transitional and shallow normal polarity inclinations are also recorded. The boundaries of this thin polarity interval do not occur at lithostratigraphic breaks or disconformities but, rather, within a single lithostratigraphic sub-unit (LSU 1.2). Four other intervals with normal polarity or shallow inclinations were encountered at 70.40-72.40 (70.40 mbsf marks the boundary between LSU 1.3, a sandy mudstone, and LSU 1.4, a very fine-grained sandstone and mudstone), 214.1-227.12, 232.7 -240.14, and 269.02-288.73 mbsf, respectively. The polarity record between 242 and 266 mbsf also contains transitional directions, but is poorly defined because the sediment was too coarse-grained to allow detailed sampling and the demagnetization behaviour is less stable than for other intervals of the drillcore. Moreover, the presence of a fault zone between 257 and 261 mbsf contributes to interpretational difficulties in this interval.

Magnetozone N1 (340.8-627.3 mbsf) is a thick zone of normal polarity that encompasses most of the low magnetic intensity interval from 440 to 628 mbsf (rock magnetic interval III). Intermediate

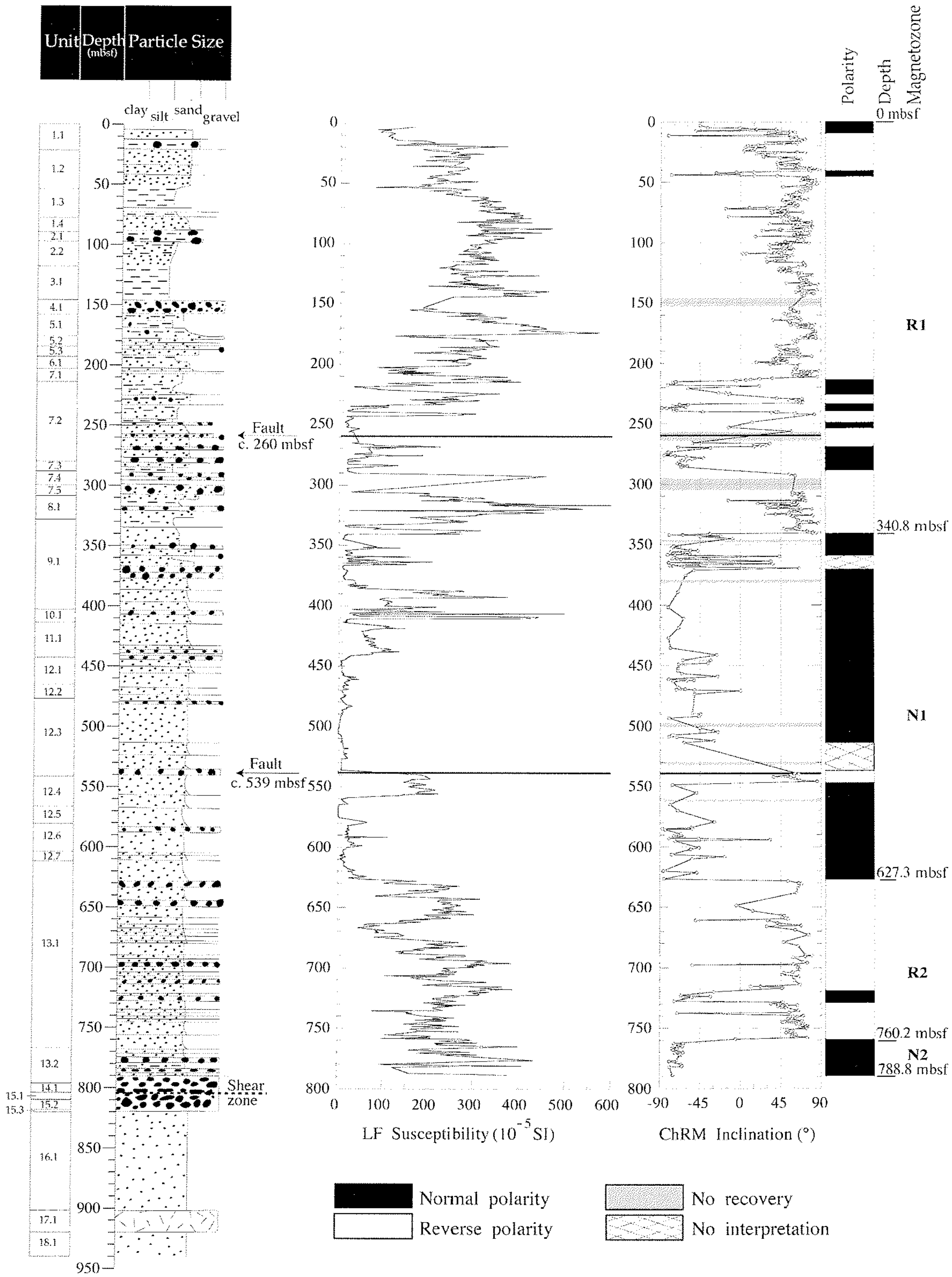


Fig. 6 - Lithostratigraphic column (after Cape Roberts Science Team, 2000), down-core variations of magnetic susceptibility and ChRM inclination. The magnetic polarity zonation is shown on the log to the right. Black (white) represents normal (reversed) polarity intervals.

palaeomagnetic inclinations were not observed at the boundary between magnetozones R1 and N1; the boundary occurs within a muddy fine-grained sandstone with dispersed clasts (LSU 9.1). In the upper part of magnetozone N1, from 359.3 to 370.4 mbsf, the inclination record has mixed polarity with most of the fluctuations represented by single samples. These fluctuations are mirrored by changes in κ and NRM intensity, which suggests that they might be related to non-geomagnetic factors such as variations in diagenetic redox conditions. No polarity interpretation is made for this interval. From 513.49 to 539.63 mbsf, the magnetizations are weak and the sediments are coarse-grained; no reliable ChRM inclinations were obtained for this 26-m-thick interval. A normal fault occurs at 539.31 mbsf (Wilson, this volume). This fault marks the upper boundary of an 8-m-thick interval of reversed polarity within magnetozone N1, and also the upper boundary of a peak in κ values (Fig. 6). The lower boundary of this interval of reversed polarity does not correspond with a change in κ. ChRM inclinations are variable for the lowermost part of magnetozone N1 (547.18-627.26 mbsf), but are predominantly normal in polarity.

Reversed polarity dominates the interval from 627.26 to 760.2 mbsf (magnetozone R2). The boundary between magnetozones N1 and R2 lacks intermediate palaeomagnetic directions and corresponds to a sharp increase in κ (at the boundary between rock magnetic intervals III and IV). The presence of a sharp, planar lithological boundary at 627 mbsf in the upper part of LSU 13.1 (Cape Roberts Science Team, 2000) may indicate a time gap between magnetozones N1 and R2.

From 718.64 to 728.68 mbsf, there is a normal polarity interval that is defined by six samples. Its upper limit is defined by a series of samples with transitional inclinations. Its lower limit is not defined by intermediate palaeomagnetic inclinations, but corresponds to a sharp lithological boundary. Low inclinations are recorded by two samples at 648.21 and 653.12 mbsf, which could represent part of another thin normal polarity interval. However, this interval cannot be more clearly resolved because other samples near this level did not yield stable magnetizations.

The lower 31-m of the CRP-3 Cenozoic sequence comprises stable normal polarity (magnetozone N2). The boundary between magnetozones R2 and N2 is defined by a single sample with intermediate palaeomagnetic inclination (759.15 mbsf; I = -5°) and occurs within a fine-grained, muddy grey/blue sandstone (LSU 13.1). The lower boundary of magnetozone N2 was not reached above the dolerite conglomerate at 790 mbsf. The lowermost sample with stable palaeomagnetic behaviour in the Cenozoic sequence was collected at 788.82 mbsf.

CORRELATION TO THE MPTS

"Tiny wiggles" and their importance in the Eocene - Oligocene

Before any attempt is made to correlate the CRP-3 magnetic polarity zonation with the MPTS, it is necessary to discuss a chronostratigraphic issue that is particularly important in sediments of Eocene - Oligocene age. The MPTS is defined using marine magnetic anomaly records (*e.g.* Cande & Kent, 1992a); beside the large-amplitude features that are observed in these anomaly profiles, additional short-wavelength variations have been identified in profiles across fast-spreading ridges. These short-period fluctuations have durations of less than 30 k.y. and are referred to as "tiny wiggles". Their origin has been debated for over 30 years and two possible explanations have been proposed: "tiny wiggles" represent either 1) short-period polarity intervals (Blakely & Cox, 1972; Blakely, 1974), or 2) large-scale fluctuations in the intensity of the dipole component of the geomagnetic field (Cande & Labreque, 1974; Cande & Kent, 1992b). Uncertainty concerning the origin and the concomitant magnetostratigraphic manifestation of "tiny wiggles" has resulted in use of the term "cryptochron" to refer to these global geomagnetic features with durations of less than 30 k.y.

"Tiny wiggles" are particularly common in Eocene-Oligocene marine magnetic anomaly records. Several investigations have tested the origin of Eocene-Oligocene "tiny wiggles". Lowrie & Lanci (1994) and Lanci & Lowrie (1997) analysed Italian pelagic limestone sequences of Eocene-Oligocene age, but they did not observe short polarity zones in the stratigraphic positions corresponding to the expected positions of "tiny wiggles" on marine magnetic anomaly records. Hartl et al. (1993) and Tauxe & Hartl (1997) studied nearly continuous sedimentary palaeomagnetic records for an 11 m.y. period in the Oligocene, for which a number of "tiny wiggles" have been reported from marine magnetic anomaly studies. They concluded that "tiny wiggles" resulted from periods of low geomagnetic palaeointensity that were sometimes accompanied by directional excursions. In all of these studies, however, sedimentation rates were low (~1 cm/k.y.), and it is possible that short polarity events were smoothed out of the palaeomagnetic records as a result of sediment remanence acquisition processes (*i.e.* bioturbation and delays in DRM lock-in). Roberts & Lewin-Harris (2000) recently reported evidence for short polarity intervals in Miocene sediments (sedimentation rates of ~2-3 cm/k.y.) in a period where "tiny wiggles" have also been reported from marine magnetic anomaly profiles. They therefore concluded that at least some cryptochrons represent real short-period polarity intervals. If this conclusion is correct, it would be expected to record such short-period polarity intervals in rapidly deposited sediments of Eocene-Oligocene age, such as those recovered in the CRP cores (accumulation rates were as high as 1000 m/m.y. in the CRP-2/2A drill core; Wilson et al., 2000 a, b). This possibility should be considered when interpreting the magnetostratigraphic record from CRP-3.

A more detailed discussion of the short polarity intervals we have documented within the Late Eocene and Oligocene, will be presented elsewhere in a dedicated paper.

Independent age constraints for CRP-3

Siliceous microfossils were recovered only between 3 and 193 mbsf and their preservation is poor below 85 mbsf (Cape Roberts Science Team, 2000; Harwood & Bohaty, this volume). The diatom *Cavitatus jouseanus* first occurs between 48.44 and 49.68 mbsf in CRP-3 and marks the base of the *C. jouseanus* zone of Scherer et al. (2000). In ODP Hole 748B, this biostratigraphic datum occurs within the lower part of the calcareous nannofossil *Chiasmolithus altus* zone, within Chron C12n. In ODP Hole 744B, the first occurrence of *C. jouseanus* spans the boundary between chrons C12n and C12r (Baldauf & Barron, 1991; Barron et al., 1991; Harwood et al., 1992; Wei & Wise, 1992). The diatom *Rhizosolenia antarctica* first occurs between 68.60 and 70.61 mbsf in CRP-3 and marks the base of the *R. antarctica* zone (Harwood & Bohaty, this volume). In DSDP Hole 511, the base of this zone occurs within the uppermost part of the calcareous nannofossil *Blackites spinosus* zone, within Chron C12r (Wise, 1983).

Traces of poorly-preserved assemblages of siliceous microfossils were found between about 70 and 195 mbsf in CRP-3 (Harwood & Bohaty, this volume). Despite their poor preservation, these assemblages are distinctly different from the lowermost Oligocene assemblages reported from CIROS-1 (Harwood, 1989). Several diatom taxa that are documented below the major unconformity in the CIROS-1 hole (at *c.* 366 mbsf) are absent in the upper 200 mbsf of CRP-3 (Harwood & Bohaty, this volume). The calcareous nannofossil *Transveropontis pulcheroides*, which occurs at the midpoint of the *Blackites spinosus* zone (Wise, 1983), last occurs at 94 mbsf in the CRP-3 core (Watkins et al., this volume).

Strontium isotope ratios from molluscan shell fragments provide age information at four stratigraphic horizons that, within the relevant statistical uncertainties, are in close agreement with the biostratigraphic constraints discussed above (Lavelle, this volume). These observations suggest that the upper 200 m of the CRP-3 core is younger than *c.* 32 Ma (Chron C12r), and represents, at least in part, a stratigraphic interval that is missing within the main unconformity (RSU6) in CIROS-1. Below about 200 mbsf, CRP-3 is barren of diatoms and calcareous nannofossils (Harwood et al., this volume; Watkins et al., this volume). Furthermore, this interval lacks the *in situ* dinocysts of the Transantarctic flora (Hannah et al., this volume) and terrestrial palynomorphs (Askin & Raine, this volume), which are indicative of mid-Eocene warm conditions. These forms are documented in late Eocene sediments from the base of CIROS-1 (Mildenhall, 1989; Hannah, 1997; Hannah et al., 1997; Wilson et al., 1998) and in mid-Eocene glacial erratics from the southern McMurdo Sound area (Levy & Harwood, 2000; Askin, 2000), which suggests that the base of CRP-3 is latest Eocene or younger in age.

Magnetostratigraphic interpretation for CRP-3

Biostratigraphic and $^{87}Sr/^{86}Sr$ age constraints indicate that the top of CRP-3 should lie within Chron C12r, which is consistent with the dominance of reversed polarity in the upper 340 m of the core (Fig. 7). If it is assumed that the top of magnetozone R1 corresponds to Chron C12r and that the four normal polarity intervals that occur between 214 mbsf and 289 mbsf correspond to successive subchrons in the MPTS, then the lowermost of these polarity intervals would have to be of Eocene age. Available biostratigraphic constraints make such an interpretation highly unlikely. Furthermore, this interpretation would imply average sediment accumulation rates on the order of 50 m/m.y. Average sediment accumulation rates in CRP-2/2A were considerably higher than this (up to 1000 m/m.y.; Wilson et al., 2000 a, b), and the lithofacies indicate similarly high sedimentation rates in CRP-3 (Cape Roberts Science Team, 2000). Our preferred interpretation, based on biostratigraphic datums and the likelihood of high average sediment accumulation rates, is that the sequence of four short normal polarity intervals recognised in magnetozone R1 represent some of the "tiny wiggles" identified in marine magnetic anomaly profiles in the lower part of C12r (Cande & Kent, 1992a). This interpretation is consistent with the conclusion of Roberts & Lewin-Harris (2000) that "tiny wiggles" represent short polarity intervals. Available biostratigraphic constraints do not allow precise correlation of the CRP-3 polarity zonation to specific "tiny wiggles" within Chron C12r.

Below 200 mbsf, correlation of the magnetic polarity stratigraphy to the MPTS is not well constrained by palaeontological data. However, assuming uniform average sediment accumulation rates (as suggested by the continuity of sedimentary lithofacies; Cape Roberts Science Team, 2000), we propose a tentative correlation of the remaining CRP-3 Cenozoic sequence to the MPTS. Starting from the lower boundary of Chron C12r, magnetozone N1 (340.8-627.3 mbsf) is correlated with Chron C13n, which implies an average sediment accumulation rate

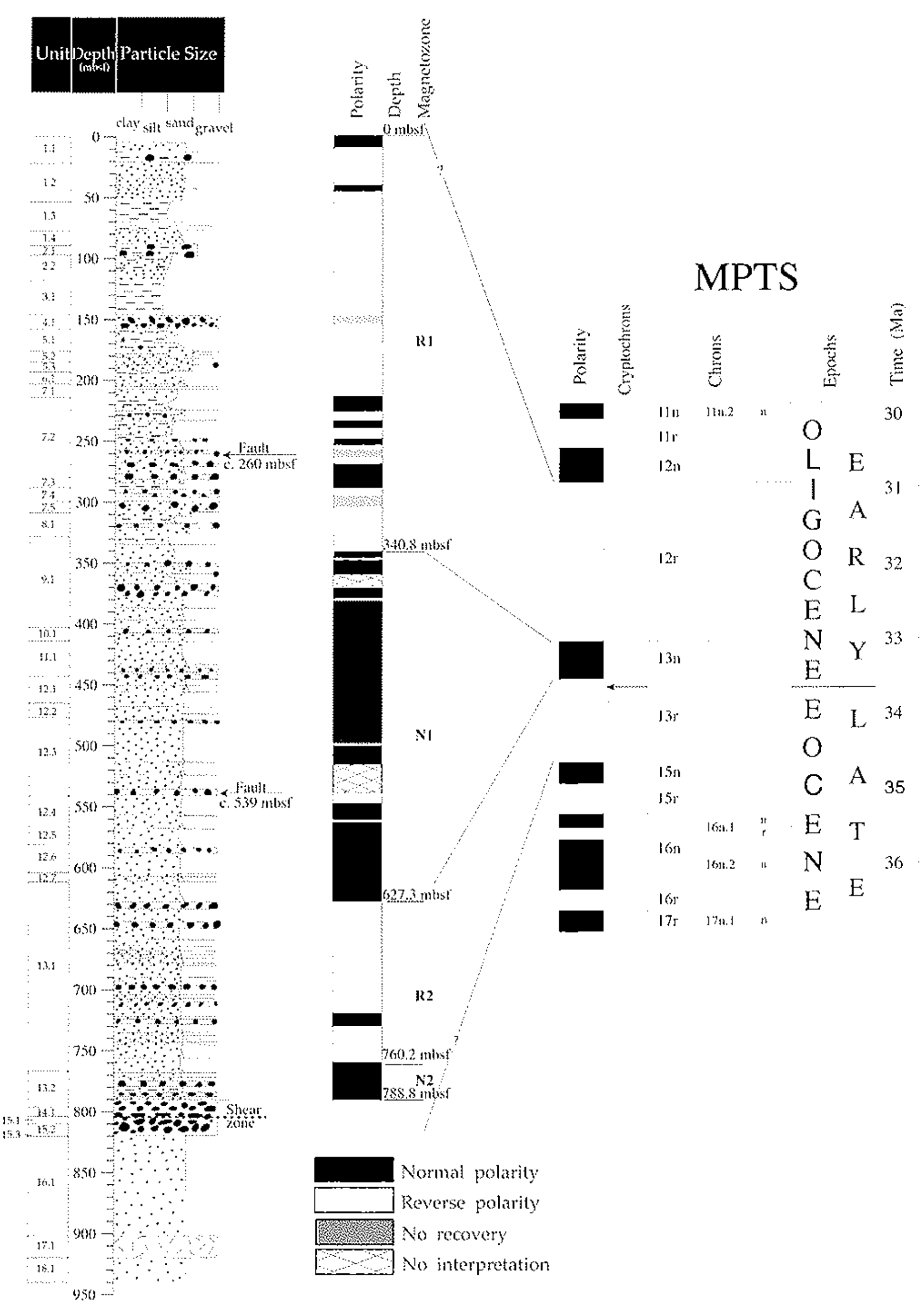


Fig. 7 - Correlation of the CRP-3 magnetic polarity zonation with the magnetic polarity time scale (MPTS) of Cande & Kent (1995) and Berggren et al. (1995). Correlation of the dominantly reversed polarity magnetozone R1 (0 to ~340 mbsf) to the MPTS is well constrained by diatom assemblages, with additional data from calcareous nannofossils and $^{87}Sr/^{86}Sr$ age determinations (see text for discussion).

of about 590 m/m.y. for this magnetozone. The 8-m-thick interval of reversed polarity within magnetozone N1 (this is a minimum thickness because of uncertainty concerning its upper boundary) is interpreted as cryptochron C13n-1 (Cande & Kent, 1992a; 1995). Considering that cryptochron C13n-1 is estimated to have had a duration of 17 k.y., the average sediment accumulation rate of this interval is consistent with the overall rate for magnetozone N1. Proceeding down-core, magnetozone R2 (627.3 to 760.2 mbsf) could correlate with Chron C13r of the MPTS. This implies that the Eocene - Oligocene boundary occurs between 650 and 700 mbsf within the upper part of lithostratigraphic unit 13.1. The normal polarity interval within magnetozone R2 (718.64-728.68 mbsf) and all of magnetozone N2 (760.2 to 788.82 mbsf) might then correlate with the upper two of the four cryptochrons (C13r-1, C13r-2, C13r-3, C13r-4) identified within Chron C13r (Cande & Kent, 1992a; 1995). If the sedimentation rate for magnetozone N1 is then applied to this section of the core it would place the Eocene-Oligocene boundary at about 718 mbsf. A slower rate would, of course, make it shallower and a faster rate would make it deeper in the core. The correlation of magnetozone N2 with C13r-2 would imply an age of 33.9 Ma at 760 mbsf, the top of N2 (Cande & Kent, 1995). Alternatively, magnetozone N2 might correlate with the upper part of Chron C15n of the MPTS. A more robust correlation of the CRP-3 polarity record with the MPTS below 340 mbsf is not possible without additional age constraints. However, with the available biostratigraphic datums, a minimum age approach suggests that magnetozone R2 cannot be younger than Chron C13r, and the bottom of the Cenozoic sequence in CRP-3 must be at least as old as the upper part of Chron C13r (*c.* 34 Ma). If magnetozone R2 represents the whole of Chron C13r, and magnetozone N2 represents part of Chron C15n, then the bottom of the sequence would have an age of *c.* 35 Ma. This interpretation would imply an average sediment accumulation rate of 119 m/m.y. for magnetozone R2. The absence of mid-Eocene terrestrial and marine palynomorphs suggests that it is unlikely that magnetozones R2 and N2 correlate with older polarity chrons in the MPTS.

CONCLUSIONS

Most of the palaeomagnetic samples from the Cenozoic strata of the CRP-3 drillcore display stable palaeomagnetic behaviour, and magnetite appears to be the primary remanence carrier. A magnetic polarity stratigraphy has been established, and four main magnetozones are defined. Short polarity intervals were also identified and are interpreted as corresponding to "tiny wiggles" observed on marine magnetic anomaly profiles.

Above 340 mbsf, correlation of the magnetic polarity zonation to the MPTS is well constrained by siliceous microfossils, calcareous nannoplankton biostratigraphy and by $^{87}Sr/^{86}Sr$ ages. These data imply that magnetozone R1 represents part of Chron C12r. Between 340 mbsf and the bottom of the Cenozoic (glacio-)marine sequence (790 mbsf), correlation of the magnetic polarity zonation is not well constrained by biostratigraphic or $^{87}Sr/^{86}Sr$ age data, and the sequence of normal and reversed polarity intervals can only be tentatively correlated with the MPTS. This tentative correlation predicts that the Eocene-Oligocene boundary (33.7 Ma) occurs at about 718 mbsf within lithostratigraphic unit 13.1 and that the basal part of the Cenozoic sequence is at least as old as the upper part of Chron C13r (*c.* 34 Ma) in age. The CRP-3 core, therefore, represents a new high latitude site from the Antarctic margin, together with the CIROS-1 core (McMurdo Sound) (Barrett, 1989) and ODP Leg 188, Site 1166 (Prydz Bay) (O'Brien et al., 2001), from which the Eocene - Oligocene boundary has been recovered.

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REFERENCES

Anson G.L. & Kodama K.P., 1987. Compaction-induced shallowing of the post-depositional remanent magnetization in a synthetic sediment. *Geophysical Journal of the Royal Astronomical Society*, **88**, 673-692.

Arason P. & Levi S., 1990. Compaction and inclination shallowing in deep sea sediments from the Pacific Ocean. *Journal of Geophysical Research*, **95**, 4501-4510.

Askin R.A., 2000. Spores and pollen from the McMurdo Sound erratics, Antarctica. In: Stilwell J.D. & Feldman R.M. (eds.), *Palaeobiology and palaeoenvironments of Eocene rocks, McMurdo Sound, East Antarctica*, American Geophysical Union Antarctic Research Series, **76**, 161-181.

Baldauf J.G. & Barron J.A., 1991. Diatom biostratigraphy: Kerguelen Plateau and Prydz Bay regions of the Southern Ocean. In: Barron J.A., Larsen B. et al. (eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, College Station, TX (Ocean Drilling Program), **119**, 547-598.

Barrett P.J. (ed.), 1989. *Antarctic Cenozoic history from CIROS-1 drillhole, McMurdo Sound, Antarctica. DSIR Bulletin*, **245**, Science Information Publishing Centre, Wellington, 254 p.

Barrett P.J., Henrys S.A., Bartek L.R., Brancolini G., Busetti M., Davey F.J., Hannah M.J. & Pyne A.R., 1995. Geology of the margin of the Victoria Land Basin off Cape Roberts, southwestern Ross Sea. In: Cooper A.K., Barker P.F. & Brancolini G. (eds.), *Geology and seismic stratigraphy of the Antarctic margin*, American Geophysical Union Antarctic Research Series, **68**, 183-207.

Barron J.A., Baldauf J.G., Barrera E., Caulet J.-P., Huber B.T., Keating B.H., Lazarus D., Sakai H., Thierstein H.R. & Wei W., 1991. Biochronologic and magnetochronologic synthesis of Leg 119 sediments from the Kerguelen Plateau and Prydz Bay, Antarctica. In: Barron J.A., Larsen B. et al. (eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, College Station, TX (Ocean Drilling Program), **119**, 813-847.

Berggren W.A., Kent D.V., Swisher III C.C. & Aubrey M.P., 1995. A revised Cenozoic geochronology and biostratigraphy. In: Berggren W.A., Kent D.V., Aubrey M.P. & Hardenbol J. (eds.), *Geochronology, Time Scales, and Stratigraphic Correlation*, Society of Economic Palaeontologists and Mineralogists, Special Publication, **54**, 129-212.

Blakely R.J., 1974. Geomagnetic reversals and crustal spreading rates during the Miocene. *Journal of Geophysical Research*, **79**, 2979-2985.

Blakely R.J. & Cox A., 1972. Evidence for short geomagnetic polarity intervals in the early Cenozoic. *Journal of Geophysical Research*, **77**, 7065-7072.

Bloemendal J., Barton C.E. & Radhakrishnamurthy C., 1985. Correlation between Rayleigh loops and frequency-dependent and quadrature susceptibility: Application to magnetic granulometry of rocks. *Journal of Geophysical Research*, **90**, 8789-8792.

Cande S.C. & Kent D.V., 1992a. A new geomagnetic polarity time scale for the late Cretaceous and Cenozoic. *Journal of Geophysical Research*, **97**, 13917-13951.

Cande S.C. & Kent D.V., 1992b. Ultrahigh resolution marine magnetic anomaly profiles: A record of continuous palaeointensity variations? *Journal of Geophysical Research*, **97**, 15075-15083.

Cande S.C. & Kent D.V., 1995. Revised calibration of the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research*, **100**, 6093-6095.

Cande S.C. & LaBrecque J.L., 1974. Behaviour of the Earth's palaeomagnetic field from small scale marine magnetic anomalies. *Nature*, **247**, 26-28.

Cape Roberts Science Team, 1998a. Background to CRP-1, Cape Roberts Project, Antarctica. *Terra Antartica*, **5**, 1-30.

Cape Roberts Science Team, 1998b. Miocene Strata in CRP-1, Cape Roberts Project, Antarctica. *Terra Antartica*, **5**, 63-124.

Cape Roberts Science Team, 1998c. Summary of Results from CRP-1, Cape Roberts Project, Antarctica. *Terra Antartica*, **5**, 125-137.

Cape Roberts Science Team, 1999. Studies from the Cape Roberts Project, Ross Sea, Antarctica. Initial Report on CRP-2/2A. *Terra Antartica*, **6**, 1-173. With Supplement, 245 p.

Cape Roberts Science Team, 2000. Studies from the Cape Roberts Project, Ross Sea, Antarctica. Initial Report on CRP-3. *Terra Antartica*, **7**, 1-209. With Supplement, 305 p.

Day R., Fuller M. & Schmidt V.A., 1977. Hysteresis properties of titanomagnetites: Grain-size and compositional dependence. *Physics of the Earth and Planetary Interiors*, **13**, 260-267.

Florindo F., Sagnotti L., Roberts A.P., Verosub K.L. & Wilson G.S., 1997. The world's southernmost palaeomagnetic laboratory is established in McMurdo Station (166°40'10"E, 77°50'18"S), Antarctica. *EOS, Transactions of the American Geophysical Union*, **78**, 603.

Fuller M., Herrero-Bervera E., Frost G., Herr B., Hastedt M. & Garrett E., 1997. Magnetic contamination acquired during APC coring. *EOS, Transactions of the American Geophysical Union*, **78**, F186.

Fuller M., Hastedt M. & Herr B., 1998. Coring-induced magnetization of recovered sediment. In: Weaver P.P.E., Schmincke H.-U., Firth J.V. & Duffield W. (eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, **157**, College Station, TX, 47-56.

Hannah M.J., 1997. Climate Controlled Dinoflagellate Distribution in Late Eocene-Earliest Oligocene Strata from CIROS-1 Drillhole, McMurdo Sound, Antarctica. *Terra Antartica*, **4**, 73-78.

Hannah M.J., Cita M.B., Coccioni R. & Monechi S., 1997. The Eocene/Oligocene Boundary at 70° South, McMurdo Sound, Antarctica. *Terra Antartica*, **4**, 79-87.

Hannah M.J., Florindo F., Harwood D.M., Fielding C.R. & CRP Science Team, 2001. Chronostratigraphy of the CRP-3 drillhole, Victoria Land Basin, Antarctica. This volume.

Hartl P., Tauxe L. & Constable C.G., 1993. Early Oligocene geomagnetic field behaviour from Deep Sea Drilling Project Site 522. *Journal of Geophysical Research*, **98**, 19649-19665.

Harwood D.M., 1989. Siliceous microfossils. In: Barrett P.J. (ed.), *Antarctic Cenozoic history from CIROS-1 drillhole, McMurdo Sound, Antarctica. DSIR Bulletin*, **245**, Science Information Publishing Centre, Wellington, 67-97.

Harwood D.M., Lazarus D., Abelmann A., Aubry M.P., Berggren W.A., Heider F., Inokuchi H., Maruyama T., McCartney K., Wei W. & Wise S.W. Jr., 1992. Neogene integrated magnetobiostratigraphy of the Southern Kerguelen Plateau, ODP Leg 120. *Proceedings of the Ocean Drilling Program, Scientific Results*, **120**, College Station, TX, 1031-1052.

Harwood D.M. & Bohaty S., 2001. Early Oligocene siliceous microfossil biostratigraphy of Cape Roberts Project core CRP-3, Victoria Land Basin, Antarctica. This volume.

Kirschvink J.L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data. *Geophysical Journal of the Royal Astronomy Society*. **62**, 699-718.

Lanci L. & Lowrie W., 1997. Magnetostratigraphic evidence that 'tiny wiggles' in the oceanic magnetic anomaly record represent geomagnetic palaeointensity variations. *Earth and Planetary Science Letters*, **148**, 581-592.

Lavelle M.A., 2001. Strontium isotope stratigraphy for CRP-3, Victoria Land Basin, Antarctica. This volume.

Levy R.H. & Harwood D.M., 2000. Marine palynomorph biostratigraphy and age(s) of the McMurdo Sound erratics. In: Stillwell J.D. & Feldmann R.M. (eds.), *Palaeobiology and palaeoenvironments of Eocene rocks, McMurdo Sound, East Antarctica*. American Geophysical Union, Antarctic Research Series, **76**, 183-242.

Lowrie W. & Lanci L., 1994. Magnetostratigraphy of Eocene-Oligocene boundary sections in Umbria, Italy: No evidence for short subchrons within chron 13r. *Earth and Planetary Science Letters*, **126**, 247-258.

Mildenhall D.C., 1989. Terrestrial palynology. In: Barrett P.J. (ed.), *Antarctic Cenozoic history from CIROS-1 drillhole, McMurdo Sound, Antarctica. DSIR Bulletin*, **245**, Science Information Publishing Centre, Wellington, 119-127.

O'Brien P.E., Cooper A.K., Richter C., et al., Proc. ODP, Initial Reports, 188 (Online), Available from World Wide Web: *http://www-odp.tamu.edu/publications/188_IR/188ir.htm*, 2001.

Raine J.I. & Askin R.A., 2001.Terrestrial palynology of Cape Roberts Project Drillhole CRP-3, Victoria Land Basin, Antarctica. This volume.

Roberts A.P. & Lewin-Harris J.C., 2000. Marine magnetic anomalies: Evidence that "tiny wiggles" represent short-period geomagnetic polarity intervals. *Earth and Planetary Science Letters*, **183**, 375-388.

Roberts A.P., Cui Y.L. & Verosub K.L., 1995. Wasp-waisted hysteresis loops: Mineral magnetic characteristics and discrimination of components in mixed magnetic systems. *Journal of Geophysical Research*, **100**, 17909-17924.

Roberts A.P., Wilson G.S., Florindo F., Sagnotti L., Verosub K.L. & Harwood D.M., 1998. Magnetostratigraphy of Lower Miocene Strata from the CRP-1 Core, McMurdo Sound, Ross Sea, Antarctica. *Terra Antartica*, **5**, 703-713.

Sagnotti L., Verosub K.L., Roberts A.P., Florindo F. & Wilson G.S., 2001. Environmental magnetic record of the Eocene-Oligocene transition in CRP-3 drillcore, Victoria Land Basin, Antarctica. This volume.

Scherer R.P., Bohaty S.M. & Harwood D.M., 2000. Oligocene and Lower Miocene Siliceous Microfossil Biostratigraphy of Cape Roberts Project Core CRP-2/2A, Victoria Land Basin, Antarctica. *Terra Antartica*, **7**, 417-442.

Tauxe L. & Hartl P., 1997. 11 million years of Oligocene geomagnetic field behaviour. *Geophysical Journal International*, **128**, 217-229.

Verosub K.L., 1977. Depositional and postdepositional processes in the magnetization of sediments. *Reviews of Geophysics and Space Physics*, **15**, 129-143.

Wei W. & Wise S.W. Jr., 1992. Oligocene-Pleistocene calcareous nannofossils from Southern Ocean sites 747, 748, and 751. *Proceedings of the Ocean Drilling Program, Scientific Results*, **120**, College Station, TX, 509-522.

Watkins D.K., Wise S.W., Jr. & Villa G., 2001. Calcareous nannofossils from Cape Roberts Project drillhole CRP-3, Victoria Land Basin, Antarctica. This volume.

Wilson G.S., Roberts A.P., Verosub K.L., Florindo F. & Sagnotti L., 1998. Magnetobiostratigraphic chronology of the Eocene-Oligocene transition in the CIROS-1 core, Victoria Land Margin, Antarctica: Implications for Antarctic glacial history. *Geological Society of America Bulletin*, **110**, 35-47.

Wilson G.S., Bohaty S.M., Fielding C.R., Florindo F., Hannah M.J., Harwood D.M., McIntosh W.C., Naish T.R., Roberts A.P., Sagnotti L., Scherer R.P., Verosub K.L., Villa G., Watkins D.K. & Woolfe K.J., 2000a. Chronostratigraphy of the CRP-2/2A Drillhole, Ross Sea, Antarctica. *Terra Antartica*, **7**, 647-654.

Wilson G.S., Florindo F., Sagnotti L., Verosub K.L. & Roberts A.P., 2000b. Magnetostratigraphy of Oligocene - Miocene Glaciomarine Strata from the CRP-2/2A Core, McMurdo Sound, Ross Sea, Antarctica. *Terra Antartica*, **7**, 631-646.

Wise S.W. Jr., 1983. Mesozoic and Cenozoic calcareous nannofossils. *Initial Reports of the Deep-Sea Drilling Project*, **71**, 481-550.