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6 - Palaeomagnetism

INTRODUCTION

Palaeomagnetic investigations of CRP-3 were aimed at developing a magnetic polarity zonation for the core. We only expected to encounter Cenozoic sediments in CRP-3, therefore, the main focus of this chapter is on the Cenozoic rocks encountered in the upper *c.* 790 mbsf of the CRP-3 record. Sedimentary rocks that are inferred to represent the Beacon Supergroup (823.11-939.42 mbsf) will be the subject of future studies. CRP-3 consists mainly of sandstones with minor diamictites, conglomerates and mudstones (see Lithostratigraphy and Sedimentology chapter). Coarse-grained sediments are usually not suitable for palaeomagnetic analysis. However, in previous palaeomagnetic studies of sedimentary units from the Victoria Land Basin, strong and stable magnetizations have been recorded and even coarse-grained units have proved suitable for palaeomagnetic analysis (Wilson et al., 1998, in press a; Roberts et al., 1998). We attribute the stability of the magnetizations to the presence of fine magnetic particles within the fine-grained sediment matrix in these otherwise coarse-grained units (*cf.* Sagnotti et al., 1998a, b; Wilson et al., 1998, in press a; Roberts et al., 1998; Verosub et al., in press).

The goal of developing a magnetic polarity zonation is to enable correlation to the magnetic polarity time scale (MPTS) of Cande & Kent (1995) and Berggren et al. (1995) to help constrain an age model for CRP-3. Polarity is a binary signal that is difficult to interpret uniquely in glaciomarine environments where the lithostratigraphical record is incomplete and where sedimentation rates are variable. Additional chronostratigraphical constraints are required from biostratigraphy or numerical dating techniques.

METHODS

We sampled unconsolidated sediments (from 3.08 to 35.73 mbsf) with plastic cubes (6.25 cm^3) and consolidated sediments (below 35.73 mbsf) by drilling conventional cylindrical palaeomagnetic samples with a modified drill press. The palaeomagnetic sampling techniques, laboratory facilities and equipment installed at the Crary Science and Engineering Center, McMurdo Station, Antarctica, were described by the Cape Roberts Science Team (1998a). We used a modified sample measurement scheme this season, in contrast to previous CRP drilling seasons. In previous seasons, the majority of samples were measured at McMurdo Station. However, 1 011 samples were collected from CRP-2/2A, and time constraints precluded measurement of many of these samples during the drilling season. We expected a similar number of samples would be obtained from CRP-3. Palaeomagnetic measurements for CRP-3 at McMurdo Station were, therefore, restricted to the measurement of the natural remanent magnetization (NRM) and low-field magnetic susceptibility of all samples, along with a pilot demagnetization study of paired samples from *c.* 10-m intervals. The remaining samples were analysed in the palaeomagnetic laboratories at the *Istituto Nazionale di Geofisica*, Rome, and at the University of California, Davis. At both laboratories, the samples were measured on an automated, pass-through cryogenic magnetometer and were subjected to in-line, stepwise, alternating field (AF) demagnetization up to peak fields of either 60 or 70 mT.

Information was collected at the drill site to enable azimuthal orientation of the core. However, these constraints were not available at the time of data analysis and no effort has been made to re-orient the core. Lack of azimuthal orientation does not pose a problem for magnetostratigraphical studies because the geomagnetic field has a steep inclination at the latitude of the CRP-3 site (77°S). As a consequence, the palaeomagnetic inclinations, which were determined from principal component analysis (Kirschvink, 1980) of characteristic remanence components on vector demagnetization plots, are sufficient to uniquely determine polarity (*i.e.* negative (upward) magnetizations correspond to normal polarity; positive (downward) magnetizations correspond to reversed polarity).

Where possible, CRP-3 was sampled at 0.5-m intervals. This strategy was adopted to avoid missing any short polarity intervals due to inadequate sampling. Lower sampling resolution was achieved in intervals where the lithology was unsuitable for sampling. Sediment-accumulation rates in the CRP-1 and CRP-2/2A cores were consistently high (about 20 m/m.y. in CRP-1 (Roberts et al., 1998) and between 25 and 1000 m/m.y. in CRP-2/2A (Wilson et al., in press a). If sedimentation rates in CRP-3 were similar to those of CRP-1 and CRP-2/2A, it is unlikely that short polarity intervals were missed due to inadequate sampling resolution.

Most of the CRP-3 succession consists of sandstones (*c.* 80%) and diamictites and conglomerates (*c.* 10%) (see Lithostratigraphy and Sedimentology chapter). Whenever possible, samples were selected from fine-grained horizons. However, most samples were taken from sandstone-dominated lithofacies. Above *c.* 380 mbsf, the sandstones are muddy and are therefore potentially useful for palaeomagnetic study. However, between *c.* 380 and 580 mbsf, the sandstones are well sorted and clean (*i.e.* they have little or no fine-grained matrix).

Below *c*. 580 mbsf, sandstone is still the major lithofacies but with a possible authigenic mud matrix. Primary mud increases down to the top of a shear zone at *c*. 790 mbsf (see Depositional History section). However, coarse sand grains, granules and pebbles are dispersed throughout the CRP-3 succession. Samples from coarse-grained intervals pose a problem because the deposition of such large particles would be controlled by gravitational rather than magnetic forces. Thus, their orientation could not 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 CRP-3 (see Petrology chapter). The presence of such grains means that care should be taken in interpreting palaeomagnetic data from coarse-grained intervals. The possible presence of clasts was taken into account by adopting a conservative interpretive approach within coarse-grained lithologies. After magnetic measurements were completed, such samples were examined to determine the presence of clasts. Results from such samples are considered reliable only if no clasts were visible, if the palaeomagnetic inclinations are consistently steep throughout coarse-grained intervals, and if the results from these intervals are consistent with results from surrounding finer-grained intervals.

Eleven hundred seventeen samples were collected from CRP-3 (105 of these are from the inferred Beacon Supergroup strata in the lower part of the core; pilot results from these samples are discussed at the end of this chapter). For the pilot studies, 92 pairs of samples, each separated stratigraphically by a few cm, were collected at *c*. 10-m intervals from varying lithofacies throughout the Cenozoic succession. The pilot study was aimed at determining the most suitable demagnetization technique for routine treatment of the samples. The pilot study was conducted by subjecting one sample from each pair to stepwise AF demagnetization, while the corresponding sample was subjected to thermal demagnetization. After measurement of the NRM, AF demagnetization was conducted at successive peak fields of 5, 10, 15, 20, 25, 30, 40 and 50 mT. Thermal demagnetization was conducted on the paired samples at temperatures of 120, 180, 240, 300, 350, 400, 450, 500, 550, 600 and 650°C. Magnetic susceptibility was measured after each step to monitor for thermal alteration.

A total of 617 samples were subjected to detailed stepwise demagnetization (including the 92 pairs of samples from the pilot study). Time constraints limited the number of samples that could be measured, but all samples have been measured to 376.48 mbsf. In this report, we present detailed palaeomagnetic results down to *c*. 350 mbsf. Below this level, we only present results of the pilot studies.

Attempts have been made to study magnetic mineralogy by continuous monitoring of low-field magnetic susceptibility of selected samples during heating. The temperature dependence of susceptibility, up to a maximum temperature of 700°C, was measured with a CS-2 furnace attached to a Kappabridge KLY-2 (AGICO) magnetic susceptibility meter (Hrouda, 1994). The KLY-2 meter has an operating frequency of 920 Hz and a magnetic induction of 0.4 mT. These analyses were conducted at the *Istituto Nazionale di Geofisica*, Rome.

RESULTS

DOWN-CORE MAGNETIC PROPERTIES

Prior to demagnetization, we measured the low-field magnetic susceptibility and the NRM intensity for all samples. These parameters generally vary in phase with each other and significant down-core variations are evident (Fig. 6.1). It is possible to subdivide the CRP-3 record into four intervals on the basis of these magnetic properties. In the upper part of the record (magnetic-intensity interval I down to *c*. 243 mbsf), susceptibility and NRM are variable but generally have higher values than in the underlying magnetic-intensity interval II (between *c*. 243 and 440 mbsf). The range of susceptibility and NRM values is larger in magnetic-intensity interval II than in magnetic-intensity interval I. Magnetic-intensity interval III (*c*. 440-628 mbsf) coincides with part of the core that is dominated by clean sands and susceptibility, and NRM values are consistently low (with the exception of a marked peak from *c*. 539 to 560 mbsf). In magnetic-intensity interval IV (*c*. 628-790 mbsf), the values and range of variability of susceptibility and NRM are more similar to those observed in magnetic-intensity interval I. This subdivision on the basis of magnetic susceptibility and NRM intensity is consistent with low-resolution petrological results that indicate a higher relative input of detritus from the Ferrar Dolerite in magnetic-intensity intervals I and IV. As will be seen below, these intervals also generally correspond to different types of palaeomagnetic behaviour.

Magnetic susceptibility was measured after each heating step for pilot samples treated with thermal demagnetization (Fig. 6.2). These results indicate that thermal alteration was limited. For samples with high magnetic susceptibility (magnetic-intensity intervals I, IV and parts of magnetic-intensity intervals II and III), there is no evidence for the formation of new magnetic minerals as a result of heating. At temperatures above 500°C, the existing magnetic minerals generally lose susceptibility, possibly as a result of oxidation to hematite. The lack of evidence for thermal alteration suggests that thermal demagnetization is an appropriate method for treating such samples. Different behaviour is evident in the low susceptibility samples in magnetic-intensity intervals II and III. For these samples, susceptibility generally increases above 400°C, which indicates thermogenic production of new magnetic minerals. This

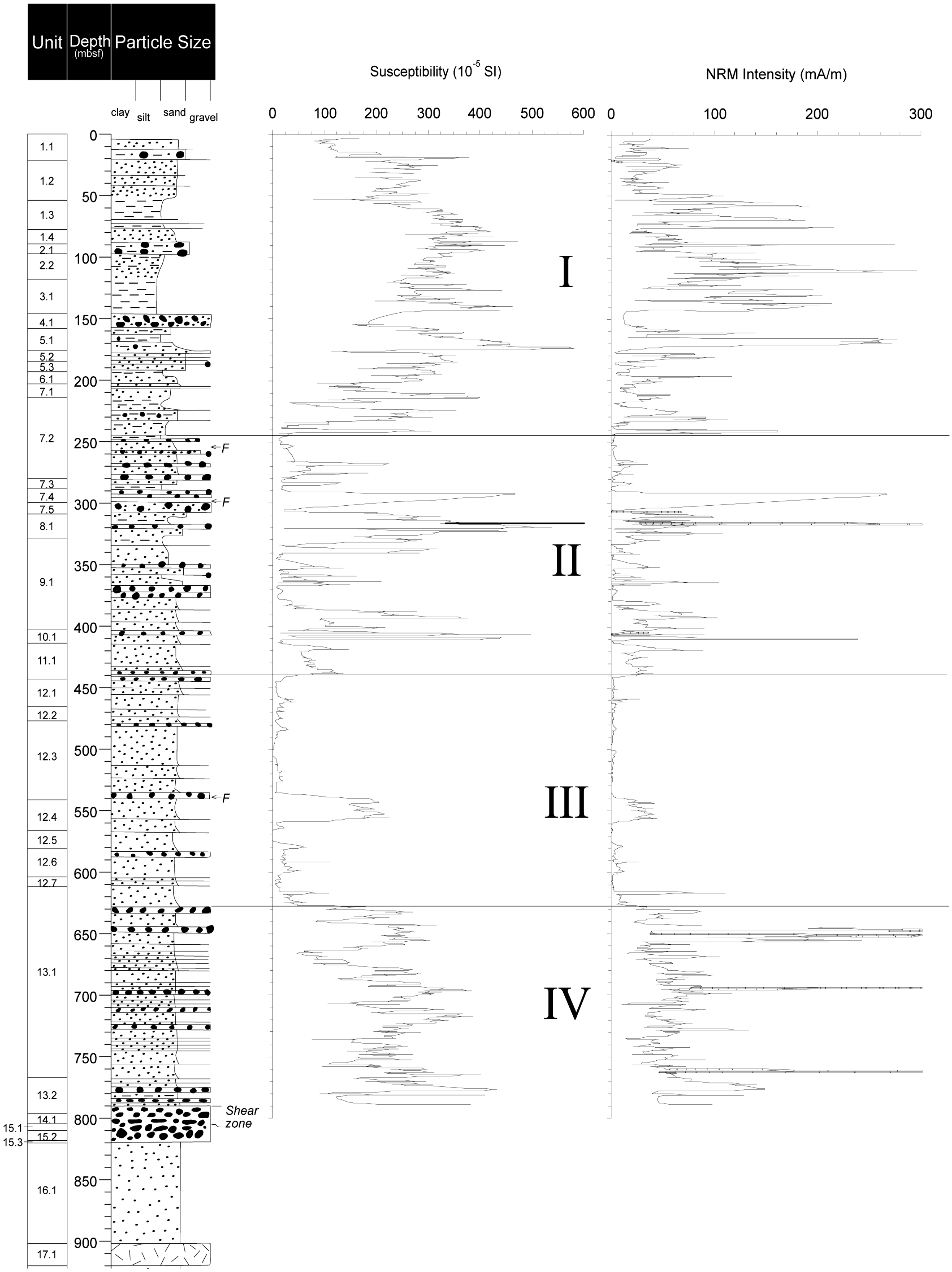

Fig. 6.1 - Plot of down-core variations in low-field magnetic susceptibility and NRM intensity. On the basis of these data, the CRP-3 record can be subdivided into four intervals with different magnetic intensities (see text for description).

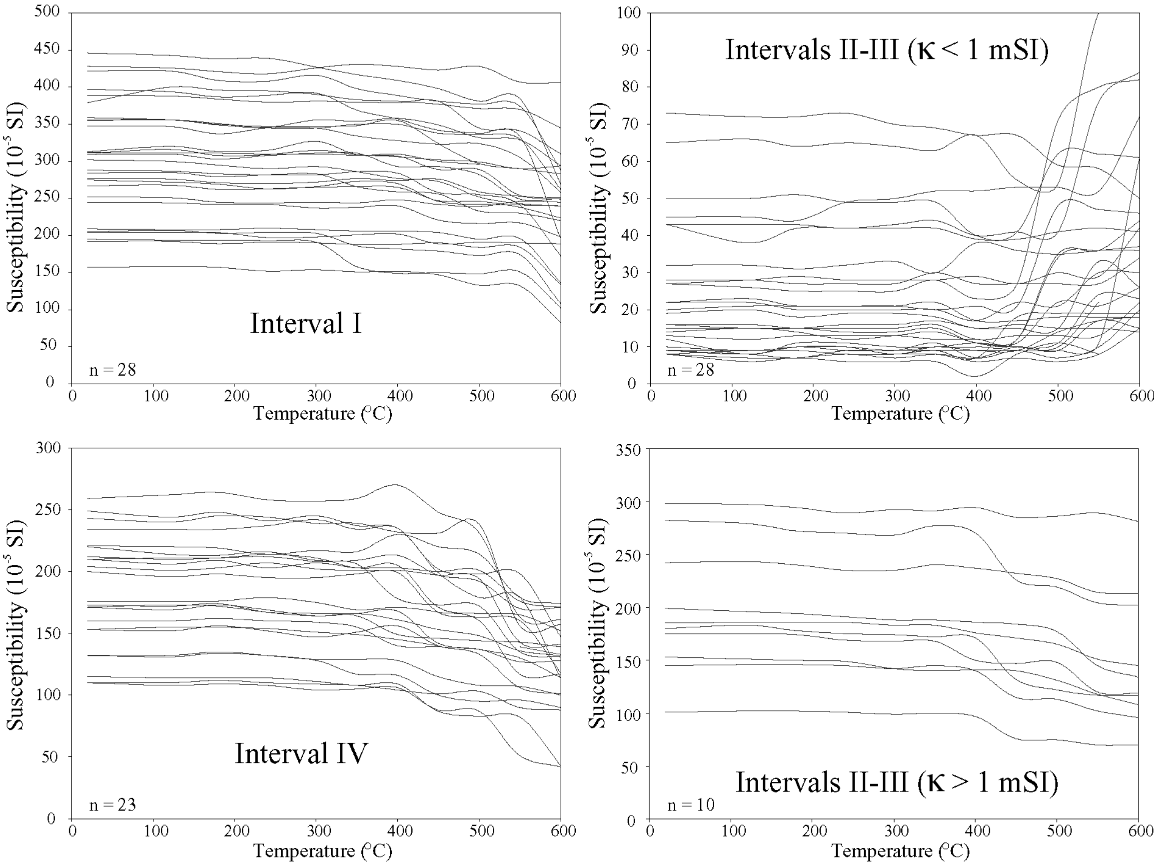

Fig. 6.2 - Magnetic susceptibility (κ), as measured after each thermal demagnetization step, for pilot samples from different intervals in CRP-3. The intervals are based on magnetic susceptibility and NRM intensity variations, as shown in figure 6.1.

probably indicates a difference in matrix mineralogy between high and low susceptibility samples. It also suggests that thermal demagnetization will be less useful in low susceptibility intervals than in high susceptibility intervals.

PILOT STUDY

Results of the pilot study indicate that thermal and AF demagnetization have variable efficiency in removing secondary remanence components and in isolating characteristic remanent magnetization (ChRM) components. For many samples, particularly those from the intervals with high magnetic susceptibility, the two techniques were comparable and identical ChRM components were identified for both normal and reversed polarity samples (Fig. 6.3 c-h, o & p). However, in many cases, AF demagnetization was clearly more efficient in removing secondary remanence components (Fig. 6.3 a, b, k-n). In some of these cases, thermal demagnetization at higher temperatures reveals a ChRM component that is similar to that revealed by AF demagnetization (Fig. 6.3 a & b, m & n). However, in such cases it is clear that the ChRM component is more clearly revealed at lower demagnetization levels using AF demagnetization. In the interval dominated by clean sands (magnetic-intensity interval III), AF demagnetization indicates that the samples have extremely low coercivity, which is consistent with a dominance by multi-domain magnetic particles (Fig. 6.3i). The thermal demagnetization behaviour of samples from these intervals is in marked contrast to the AF demagnetization behaviour (Fig. 6.3 i & j). With thermal demagnetization, a steep normal polarity component is gradually removed up to between 400 and 500°C. The fact that samples from this interval have low coercivity suggests that the steep and apparently stable remanence component revealed by thermal demagnetization is a viscous remanent magnetization (VRM) that has completely remagnetized the samples. Also, these samples are more prone to thermal alteration during heating (Fig. 6.2). For such samples, it is apparent that neither AF nor thermal demagnetization enables identification of a stable ChRM component: thermal demagnetization reveals a spurious VRM component, and AF demagnetization produces data from which no meaningful polarity interpretation can be made. This suggests that it will be difficult to extract useful polarity information for much of the interval containing clean

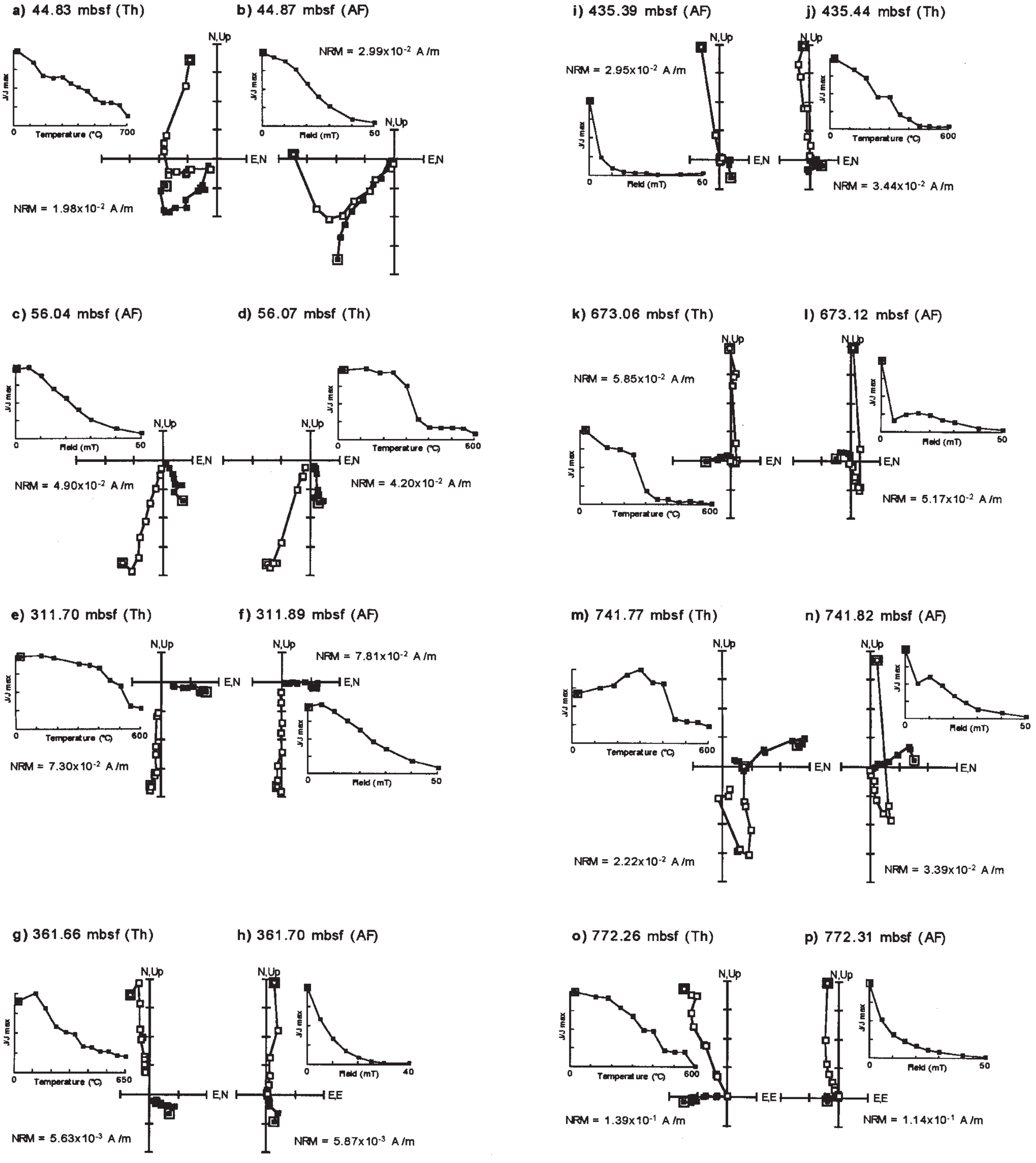

Fig. 6.3 - Vector component diagrams for selected pairs of pilot samples from CRP-3 that were subjected to AF and thermal demagnetization, respectively. Projections onto the vertical (horizontal) plane are represented by open (solid) symbols, respectively. Samples are not azimuthally oriented and declination projections are given in the laboratory component system, samples are oriented with respect to vertical. a) and b) comparison of thermal and AF demagnetization from samples at 44.83 and 44.87 mbsf, respectively. These data indicate that AF demagnetization is more efficient in isolating the reversed polarity ChRM direction. AF and thermal demagnetization seem to be equally efficient for samples from: c) 56.04 mbsf, d) 56.07 mbsf (both reversed polarity), e) 311.70 mbsf, f) 311.89 mbsf (both reversed polarity), g) 361.66 mbsf, and h) 361.70 mbsf (both normal polarity). For samples from i) 435.39 mbsf and j) 435.44 mbsf, AF demagnetization indicates low-coercivity behaviour while thermal demagnetization isolates a steep normal polarity component. The thermal demagnetization data from such intervals are interpreted to be dominated by a VRM. The thermal demagnetization data from k) 673.06 mbsf are also interpreted to represent a VRM, while the AF demagnetization data from the paired sample from l) 673.12 mbsf indicate a reversed polarity ChRM after removal of a VRM component. Reversed polarity directions are isolated by both demagnetization methods at m) 741.77 mbsf and n) 741.82 mbsf, although AF demagnetization data are less noisy. Consistent normal polarity data were obtained by both techniques at o) 772.26 mbsf and p) 772.31 mbsf.

sands. Finally, for some samples, a steep, normal polarity remanence component is indicated by thermal demagnetization, and a clear reversed polarity ChRM is indicated by AF demagnetization (Fig. 6.3 k, l). In such cases, we interpret the thermal demagnetization data to be dominated by a VRM, and AF demagnetization is apparently more successful in removing this secondary component.

For all of the above cases, AF demagnetization appears to be the preferable technique for routine sample treatment. In cases where the results from both techniques are identical, AF demagnetization is preferable because it is less time-consuming than thermal demagnetization and because it avoids thermal alteration, which means that the samples can be used for subsequent environmental magnetic studies. In other cases, AF demagnetization is preferable because it is more efficient in isolating ChRM components than thermal demagnetization. In cases where thermal demagnetization data are dominated by a VRM component, AF demagnetization is preferable because it is better not to interpret polarity due to the dominance of low coercivities than to be misled by thermal demagnetization data that are dominated by an apparently stable VRM.

Except for intervals where thermal demagnetization was less efficient in removing secondary magnetic overprints and intervals where the magnetization was unstable, the results from pairs of pilot samples are in excellent agreement. A summary of polarity results from paired pilot samples is shown for the Cenozoic interval of CRP-3 in figure 6.4. Several features are immediately evident in this figure. First, for the upper *c.* 243 mbsf (magnetic-intensity interval I), the pilot samples are stably magnetized, with a dominance of reversed polarity. Second, the frequency of stably magnetized samples is lower for magnetic-intensity interval II (*c.* 243 to 440 mbsf), although significant parts of the interval contain stable magnetizations. Third, in magnetic-intensity interval III (*c.* 440 to 628 mbsf), many thermally-demagnetized samples are dominated by a VRM, and many AF-demagnetized samples have such low coercivity that no stable ChRM can be identified. It is, therefore, impossible to define palaeomagnetic polarity for large parts of magnetic-intensity interval III with the current data. Fourth, magnetic-intensity interval IV has a high proportion of stably magnetized samples. Reversed polarity is dominant between *c.* 660 and 760 mbsf, and normal polarity is dominant from *c.* 760 to 790 mbsf. The potential for obtaining useful magnetostratigraphical results from magnetic-intensity interval IV is therefore good.

On the basis of the pilot studies, all remaining samples from magnetic-intensity intervals I and II were sent to the palaeomagnetic laboratories in Rome and Davis for detailed stepwise AF demagnetization analysis. These results are presented and discussed below. Magnetic-intensity interval III is palaeomagnetically problematical, and the remaining samples from this interval will be analysed after the drilling season. Magnetic polarity data from magnetic-intensity interval IV are difficult to interpret in terms of chronology because of the lack of data from the overlying magnetic-intensity interval III. As a result, most of the samples from magnetic-intensity interval IV were also reserved for analysis after the drilling season.

PALAEOMAGNETIC BEHAVIOUR

Many of the analysed samples display a low-coercivity (or low-temperature), near-vertical, normal-polarity remanence component that is interpreted to represent a drilling-induced overprint (Fig. 6.3). This type of overprint has been observed in all other cores that we have studied from the McMurdo Sound area (Wilson et al., 1998, in press a; Roberts et al., 1998) and is generally removed without difficulty at peak AFs of less than 20 mT. In cases where the drilling-induced overprint and the ChRM had completely overlapping coercivity spectra, it was not possible to isolate the two components, and such samples were excluded from subsequent magnetostratigraphical interpretations. In some cases, particularly in dominantly sandy lithologies, another overprint is present. This overprint has a nearly horizontal inclination and a southward-directed declination, as described by Wilson et al. (in press a). We attribute this overprint to contamination introduced by cutting the samples (after drilling) because the overprint is always perpendicular to the cut face of the sample (*i.e.* in sample coordinates, the overprint is entirely in the x-z plane, with y = 0). Rotation of the saw blade produces a measurable magnetic induction perpendicular to the blade (Wilson et al., in press a). In most cases, the overprint produced by this field was easily removed by application of peak AFs of 10 mT. Where present, this overprint is usually stronger than the drilling-induced overprint. The saw-overprint is only sporadically present in CRP-3.

Many of the samples are from intervals where clasts may dominate the magnetic properties of the sample and produce a magnetization that does not represent the geomagnetic field orientation at or near the time of deposition. Samples that contain such clasts usually display abnormal palaeomagnetic behaviour and are readily detected (*e.g.* Roberts et al., 1998; Wilson et al., in press a). Such samples were rare in CRP-3 and were excluded from subsequent magnetostratigraphical interpretations.

Stable palaeomagnetic behaviour was evident from the vector component plots of 518 of the 617 demagnetized samples (84%). In most cases, the ChRM direction was determined using a best-fit line that was constrained, using principal component analysis, through the origin of the vector component diagram (*e.g.* Fig. 6.3). In some cases, the best-fit lines were not constrained through the origin of the plots. In other cases, the polarity of the ChRM component was clear, but because of a low signal/noise

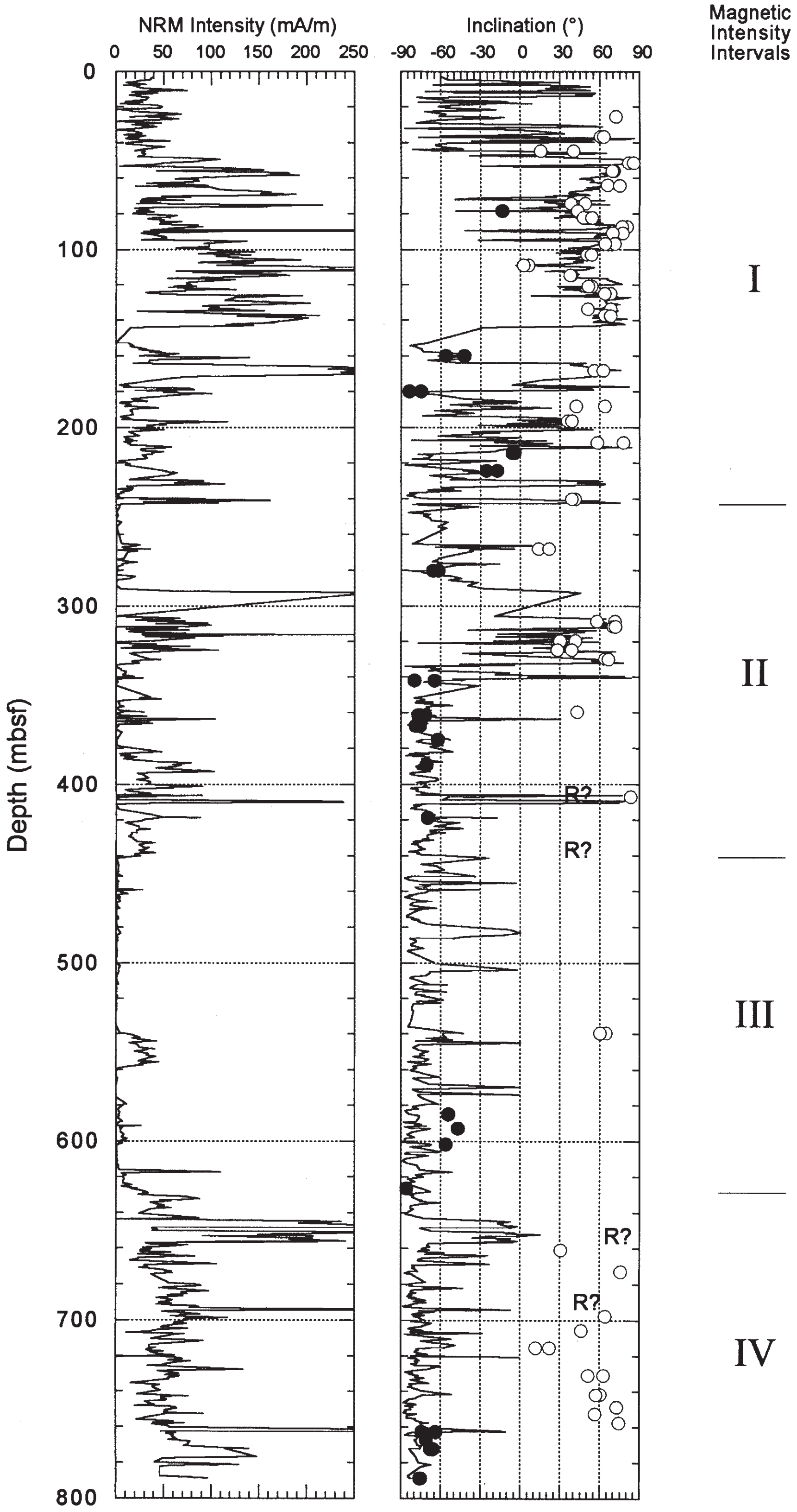

Fig. 6.4 - Summary of NRM intensity (left-hand side), palaeomagnetic inclination before demagnetization (solid line) and inclinations from pilot samples after demagnetization (right-hand side) for CRP-3. For the pilot samples, solid symbols indicate normal polarity and open symbols indicate reversed polarity. Pilot samples from the upper 350 mbsf and between *c*. 650 and 790 mbsf generally have stable magnetizations. The data are of poorer quality between *c*. 350 and 650 mbsf, and few pilot samples from Interval III (*cf.* Fig. 6.1) yielded useful palaeomagnetic data.

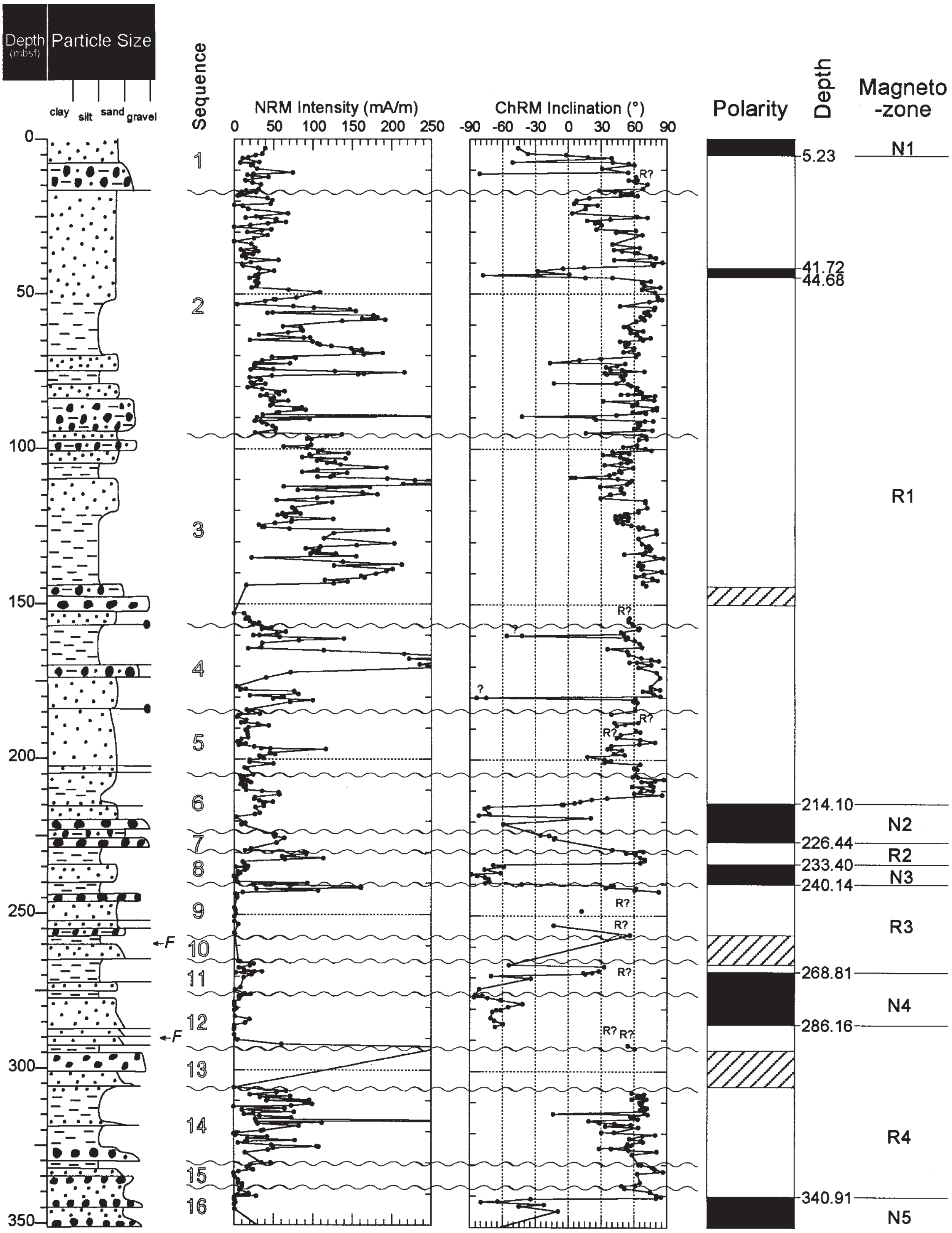

Fig. 6.5 - Interpretation of the polarity zonation for CRP-3. Characteristic remanent magnetizations (ChRMs) were determined by principal component analysis of data from multiple demagnetization steps. Polarity intervals are interpreted from the stratigraphical variations in ChRM inclination (black = normal polarity; white = reversed polarity). The polarity zonation for the upper 350 mbsf of CRP-3 is subdivided into 9 magnetozones (N1 to N5). The boundaries of the magnetozones do not correspond to sequence stratigraphical boundaries.

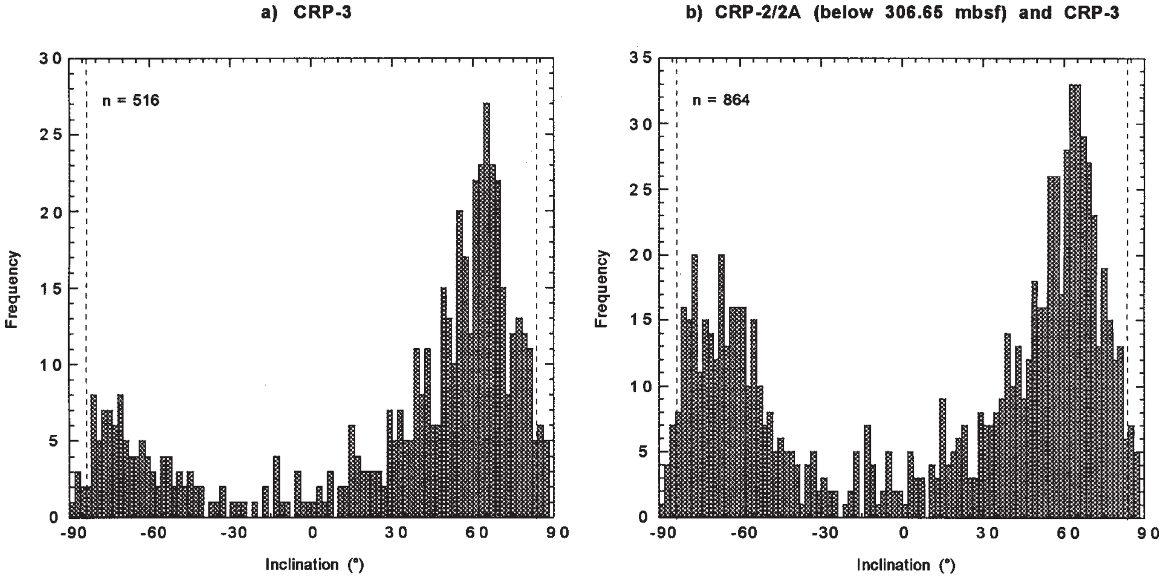

Fig. 6.6 - Frequency histogram of ChRM inclinations from stepwise-demagnetized samples from a) CRP-3 and b) CRP-2/2A (below the prominent unconformity at 306.65 mbsf) and CRP-3. There is a clear bimodal distribution of polarities, with a bias to reversed polarity that results from the rapid sedimentation rates during a long period of reversed polarity in CRP-3 (see discussion in text). The expected inclinations are shown as dashed lines at ±83.4°. The palaeomagnetic inclinations are shallower than expected (see text).

ratio or incomplete removal of secondary remanence components, the final direction of magnetization could not be precisely determined. In these cases, which were most evident for reversed polarity samples, the sample is represented on figure 6.5 by an "R?".

The inclinations of the ChRM directions have a clear bimodal distribution that demonstrates the dominance of the two stable polarity states (Fig. 6.6a). Steep normal and reversed polarity directions, as would be expected at high latitudes, are clearly dominant. In conjunction with evidence from vector component diagrams (*e.g.* Fig. 6.3), this indicates that secondary remanence components have been successfully removed. The distribution of inclinations is strongly biased toward reversed polarity (in contrast to CRP-2/2A, which was dominated by normal polarity; Wilson et al., in press a). The dominance of a single polarity results from a combination of factors, including relatively high sedimentation rates, high measurement density and the predominance of reversed polarity in this part of the polarity time scale (see magnetostratigraphical interpretation below).

There are insufficient normal polarity data to test whether there is a statistically significant difference between the modes of the two polarity states. For similar reasons given above for the dominance of reversed polarity in CRP-3, there was a dominance of normal polarity in CRP-2/2A. By combining the data sets from CRP-2/2A (below the angular unconformity at 306.65 mbsf) and CRP-3, it is possible to test whether there is a significant difference between the modes of the two polarity states (Fig. 6.6b). The normal polarity distribution is not as tightly peaked as the reversed polarity distribution, although the modes for the two polarity states appear to be *c.* –66° and 64° for normal and reversed polarity, respectively. On the basis of these data, it appears that the normal and reversed polarity data are antipodal as would be expected for reliable ChRM directions.

The palaeomagnetic inclinations in figure 6.6 are up to 18° shallower than expected (±83.4°) for the site latitude (77°S). The sedimentary succession dips at an angle of *c.* 21±5° to the east (see Core Properties and Downhole Geophysics chapter). Because the magnetization of the sediment lies in the N-S plane, an eastward stratal tilt is likely to have a limited effect in producing the discrepant palaeomagnetic inclinations. The 18° maximum discrepancy between the expected and observed palaeomagnetic inclinations may partially result from inclination error. This phenomenon is commonly observed in sedimentary environments where bioturbation is not widespread, such as seems to be the case for some lithostratigraphical units in CRP-3. In environments where bioturbation is widespread, magnetic particles have freedom to rotate and to follow the geomagnetic field in water-saturated shallow sediments. Thus, when the remanence is locked in during shallow burial, the magnetization of bioturbated sediments can provide an accurate record of the geomagnetic field. On the other hand, in sediments where bioturbation is absent, magnetic grains can roll as they settle onto the substrate and the resultant inclination can be retained in the absence of bioturbation (Verosub, 1977). Sediment compaction has also been interpreted to be responsible for inclination errors (*e.g.* Anson & Kodama, 1987; Arason & Levi, 1990).

In addition to the dominantly steep normal and reversed polarity directions, a significant number of samples display a ChRM that is transitional between normal and reversed polarity (*e.g.* Figs. 6.5 & 6.6). Most of these samples display stable palaeomagnetic behaviour and are not obviously affected by the presence of clasts. It is not surprising that transitional directions are recorded because there is a higher probability of recording deposition during geomagnetic polarity transitions in rapidly deposited sediments such as those recovered in the CRP drill holes.

MAGNETIC MINERALOGY

Different magnetic minerals display different behaviour during heating. The temperatures at which the susceptibility falls to zero on heating (Curie or Néel temperatures) are diagnostic of mineralogy. Two temperature-dependent susceptibility curves (from 80.77 and 193.52 mbsf) are shown in figure 6.7. Both samples are from magnetic-intensity interval I, but they display different behaviour. The sample from 80.77 mbsf has a clear Curie temperature at *c.* 580°C (Fig. 6.7a), which indicates that magnetite (Hunt et al., 1995) is the dominant magnetic mineral. The sample from 193.52 mbsf also shows a clear Curie temperature at *c.* 580°C, but it does not completely lose its susceptibility at this temperature (Fig. 6.7b). The susceptibility continues to decrease to *c.* 700°C. The Néel temperature of hematite is *c.* 680°C (Hunt et al., 1995), and the high-temperature behaviour is indicative of the presence of hematite. The fact that the cooling curve is reversible might indicate that the hematite is primary. Thermal demagnetization data can provide additional information concerning magnetic mineralogy. For many of the thermally-demagnetized samples, the magnetization drops to near-zero values between 550 and 600°C, which is consistent with the presence of magnetite (Fig. 6.3 d, e, j, k, o). However, in many samples, the magnetization persists to between 650 and 700°C (Fig. 6.3 a, g), which indicates that hematite is also present. These results are consistent with the thermomagnetic data shown in figure 6.7.

In addition to the presence of magnetite and hematite, some of the thermal demagnetization data indicate a significant unblocking at *c.* 300°C (Fig. 6.3 d, k). Several magnetic minerals undergo thermal unblocking at these temperatures, including iron sulphide minerals such as greigite (Roberts, 1995) and pyrrhotite (Dekkers, 1989), and iron oxide minerals such as maghemite and titanomagnetite (Hunt et al., 1995). At present, we have insufficient evidence to distinguish between these possibilities. However, it should be noted that if magnetic iron sulphides are present, they would almost certainly be authigenic in origin. This could cause complications in polarity interpretation if the authigenic phases formed a long time after deposition. In many cases, however, such iron sulphide minerals form during early burial, and there is little time-lag in acquisition of magnetization between detrital and authigenic magnetic phases, particularly in rapidly-deposited sediments (*e.g.* Roberts & Turner, 1993). This interpretation is preferred in the case of the CRP-3 samples because the component that unblocks at *c.* 300°C (possible magnetic iron sulphide) carries the same palaeomagnetic direction as the component that unblocks between 550 and 600°C (probable magnetite) (Fig. 6.3 d, k). We, therefore, conclude that the magnetizations recorded by the CRP-3 sediments can be interpreted to have been acquired at, or close to, the time of deposition.

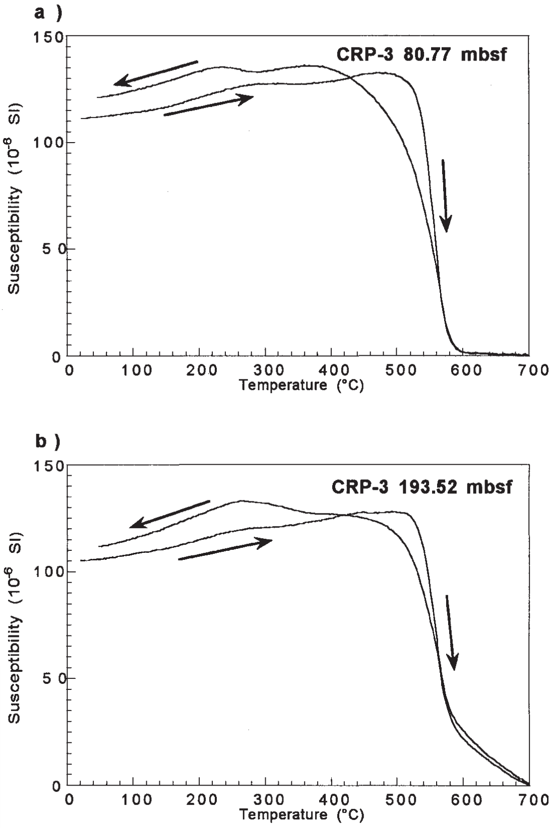

Fig. 6.7 - Temperature-dependence of magnetic susceptibility for samples from a) 80.77 mbsf and b) 193.52 mbsf. Both samples are dominated by magnetite (Curie temperature at *c.* 580°C), although the sample from 193.52 mbsf probably also contains significant hematite (Néel temperature at *c.* 680°C).

MAGNETIC POLARITY STRATIGRAPHY

In the following treatment, we describe only the magnetic polarity stratigraphy for the upper 350 mbsf of the CRP-3 record. There are three intervals from which no palaeomagnetic samples were taken, because the lithologies were too coarse-grained to allow sampling (144.67-152.84, 259.0-264.33 and 293.43-306.26 mbsf, respectively). The magnetic polarity zonation described below is preliminary and awaits refinement after measurement of further samples from the lower part of the record.

The magnetic polarity stratigraphy shown in figure 6.5 is tentatively divided into 9 magnetozones: 5 of dominantly normal polarity and 4 of dominantly reversed polarity. In many of the magnetozones, there are samples with opposite polarities to those of the surrounding rocks. In each case, the palaeomagnetic behaviour is stable, and the presence of a steep, normal polarity drill-string overprint suggests that the samples have not been inadvertently inverted. In the following discussion, no interpretations are based on results from single samples. In two cases (at *c*. 160 and 180 mbsf, respectively), pairs of pilot samples display clear normal polarity behaviour that stands out from the surrounding stratigraphical intervals (that are dominated by reversed polarity). In both of these cases, the pilot samples were taken from thin carbonate-cemented intervals because they are harder than the surrounding lithology, and it was therefore possible to measure the samples on the high-speed spinner magnetometer at McMurdo Station. Samples from the surrounding intervals were sandy and would have disintegrated during measurement on the high-speed spinner magnetometer. The contrast in polarity between the carbonate concretions and the surrounding lithology raises questions about whether this material was remagnetized during the diagenetic event that gave rise to the carbonate-cemented intervals. Thus, despite the fact that these two intervals represent polarity zones that are defined by two samples, we refrain from treating them as separate polarity zones in our interpretation. This approach is supported by the likelihood that sedimentation rates are high in this interval and that true polarity zones would normally be recorded across a wide stratigraphical interval rather than only in carbonate concretions that have been more strongly affected by diagenesis than the surrounding sediments.

Reversed polarity dominates the interval from 5.25 to 340.91 mbsf. In the upper part of magnetozone R1, there is a short interval from 41.72 to 44.68 mbsf where samples have transitional and shallow normal polarity inclinations. This interval is indicated as having normal polarity (Fig. 6.5), but it is not treated as a separate magnetozone because there is only one sample with fully normal polarity behaviour (*i.e.* inclination is steeper than -50°). Other thin normal polarity intervals are treated as distinct magnetozones because they contain at least three samples with full normal polarity behaviour.

The transitions from magnetozones R2 to N2 and from magnetozones N2 to R1 are gradual, and transitional palaeomagnetic directions are recorded over a stratigraphical interval of several metres (Fig. 6.5). It is well known that the process of polarity reversal occurs over periods of about 5-10 k.y. (Jacobs, 1994). If sedimentation rates were roughly uniform through these polarity transitions and through the intervening polarity interval, it can be inferred that magnetozone N2 represents a short-period polarity interval on the order of tens of thousands of years in duration.

Between *c*. 245 and 306 mbsf, magnetizations are weak, and there are two gaps in sampling (Fig. 6.5). The palaeomagnetic behaviour from this interval is not ideal, and it is difficult to construct a clear magnetic polarity stratigraphy. However, this interval appears to contain three magnetozones (R3, N4 and R4). Between 306 and 350 mbsf, the magnetization intensities are higher, palaeomagnetic behaviour is more stable, and magnetozones R4 and N5 are well defined (Fig. 6.5).

Unlike the CRP-2/2A record, it appears that there are no sequence stratigraphical boundaries that coincide with polarity boundaries in the CRP-3 record (Fig. 6.5). The only magnetozone boundary that lies close to a sequence stratigraphical boundary is the one between magnetozones R3 and N3. The first normal polarity sample that defines magnetozone N3 lies at 239.93 mbsf, which is immediately below the sequence boundary at 239.89 mbsf. However, without additional chronological constraints, it is impossible to determine whether significant amounts of time are missing in sequence stratigraphical boundaries in CRP-3.

DISCUSSION

"TINY WIGGLES" AND THEIR SIGNIFICANCE IN EOCENE - OLIGOCENE MAGNETOSTRATIGRAPHY

Before presenting possible interpretations of the CRP-3 magnetic polarity zonation, it is necessary to discuss a chronostratigraphical issue that is particularly important in sediments of Eocene - Oligocene age. The standard MPTS was constructed by identifying the positions of magnetic reversals on marine magnetic anomaly records. In order to make this process robust, numerous records from different ocean basins were stacked, and the resultant anomaly pattern was superimposed on an age/distance template from the South Atlantic Ocean (Cande & Kent, 1992a). In many marine magnetic anomaly profiles from fast-spreading oceanic crust, additional short-period, low-amplitude anomalies are evident (with durations <30 k.y.). These anomalies have been named "tiny wiggles". It is difficult to resolve magnetic anomalies when their spatial wavelength represents less than 0.5 km of seafloor and, as a result, the origin of "tiny wiggles" has been debated for the last 30 years. Two possibilities have been suggested: "tiny wiggles" represent either short-period polarity intervals (Blakely & Cox, 1972; Blakely, 1974) or large-scale fluctuations in the ancient field intensity (Cande & LaBrecque, 1974; Cande & Kent, 1992b). The dominant view has been that "tiny wiggles" represent fluctuations in intensity of the geomagnetic field (Cande & Kent, 1992b). However, the possibility that they may represent short polarity intervals is implicitly recognised in the designation of the term "cryptochron", which is used in cases where magnetostratigraphical evidence exists for short polarity intervals. "Tiny wiggles" are particularly common in Eocene - Oligocene marine magnetic anomaly records. The uncertainty concerning the origin of "tiny wiggles" led Cande & Kent (1992a) to label the positions of cryptochrons as dashes on the side of the polarity log on their MPTS (Fig. 6.8).

Several tests of the origin of Eocene - Oligocene cryptochrons have been made. Lowrie & Lanci (1994) and Lanci & Lowrie (1997) analysed Italian pelagic limestone successions of Eocene - Oligocene age and did not observe short polarity zones that coincided with the positions of expected "tiny wiggles". Hartl et al. (1993) and Tauxe & Hartl (1997) also reported nearly continuous sedimentary palaeomagnetic records for an 11 m.y. period in the Oligocene, in which a number of "tiny wiggles" have been reported. They concluded that "tiny wiggles" resulted from periods of low palaeointensity that were sometimes accompanied by directional excursions. In all of these examples, however, the sedimentation rates were low (~1 cm/k.y.), and it is possible that such short polarity events were smoothed out of the records as a result of sediment remanence acquisition processes (*i.e.* bioturbation and delays in remanence lock-in).

Although the origin of "tiny wiggles" is not yet settled, cryptochrons should be clearly evident in rapidly deposited sedimentary successions, such as those recovered in the Cape Roberts Project, if they represent short polarity intervals. This possibility should, therefore, be taken into account when interpreting magnetostratigraphical records from CRP holes.

INTERPRETATION OF THE CRP-3 MAGNETIC POLARITY ZONATION

A preliminary correlation of the CRP-3 polarity zonation to the MPTS is plotted in figure 6.9, and includes constraints from available biostratigraphical data (see Palaeontology chapter). Diatom preservation above 67 mbsf is excellent, and the first occurrence (FO) of *Cavitatus jouseanus* (which represents the base of the *C. jouseanus* Zone of Scherer et al., in press) is recorded at 48.44-49.69 mbsf. This datum occurs within the lower part of the *Chiasmolithus altus* Zone, which is expected to lie in Chron 12n, although it spans the boundary between C12n and C12r in ODP hole 744B (Baldauf & Barron, 1991; Barron et al., 1991; Harwood et al., 1992; Wei & Wise, 1992). The FO of the diatom *Rhizosolenia antarctica*, which occurs within the *Blackites spinosus* (calcareous nannofossil) Zone (Chron 12r in DSDP hole 511; Wise, 1983), is recorded at 68.60-70.61 mbsf. The last occurrence (LO) of the calcareous nannofossil *Transveropontis pulcheroides*, which occurs in the midpoint of the lowest Oligocene *Blackites spinosus* Zone (Wise, 1983), lies at 114.3 mbsf. This suggests an age of *c.* 32 Ma at 114 mbsf (see Calcareous Nannofossil section). Furthermore, diatom taxa that are documented below the prominent unconformity in the CIROS-1 hole (at

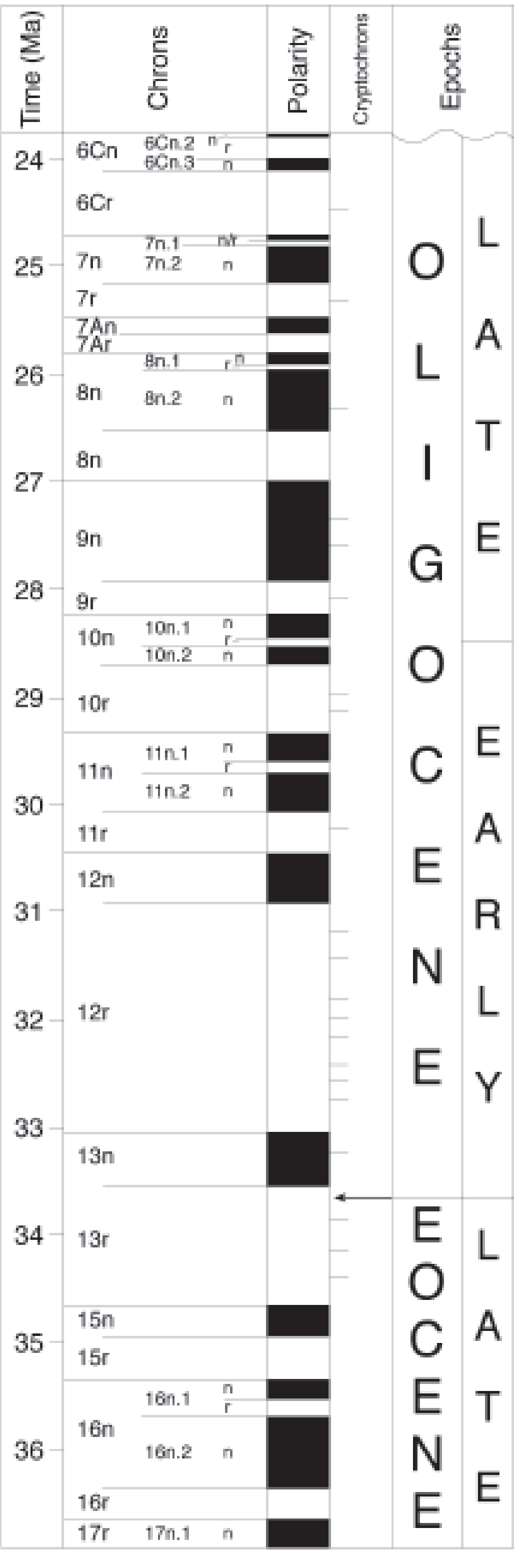

Fig. 6.8 - Magnetic polarity time scale (MPTS) for the late Eocene and for much of the Oligocene, from Cande & Kent (1992a). Beside the standard succession of polarity zones observed from marine magnetic anomalies, Cande & Kent (1992a) indicate the possibility of short-period polarity intervals, called cryptochrons, as dashes on the side of the polarity log. When dealing with rapidly-deposited sediments of this age, as is the case with the Cape Roberts Project, the possibility of encountering cryptochrons must be considered.

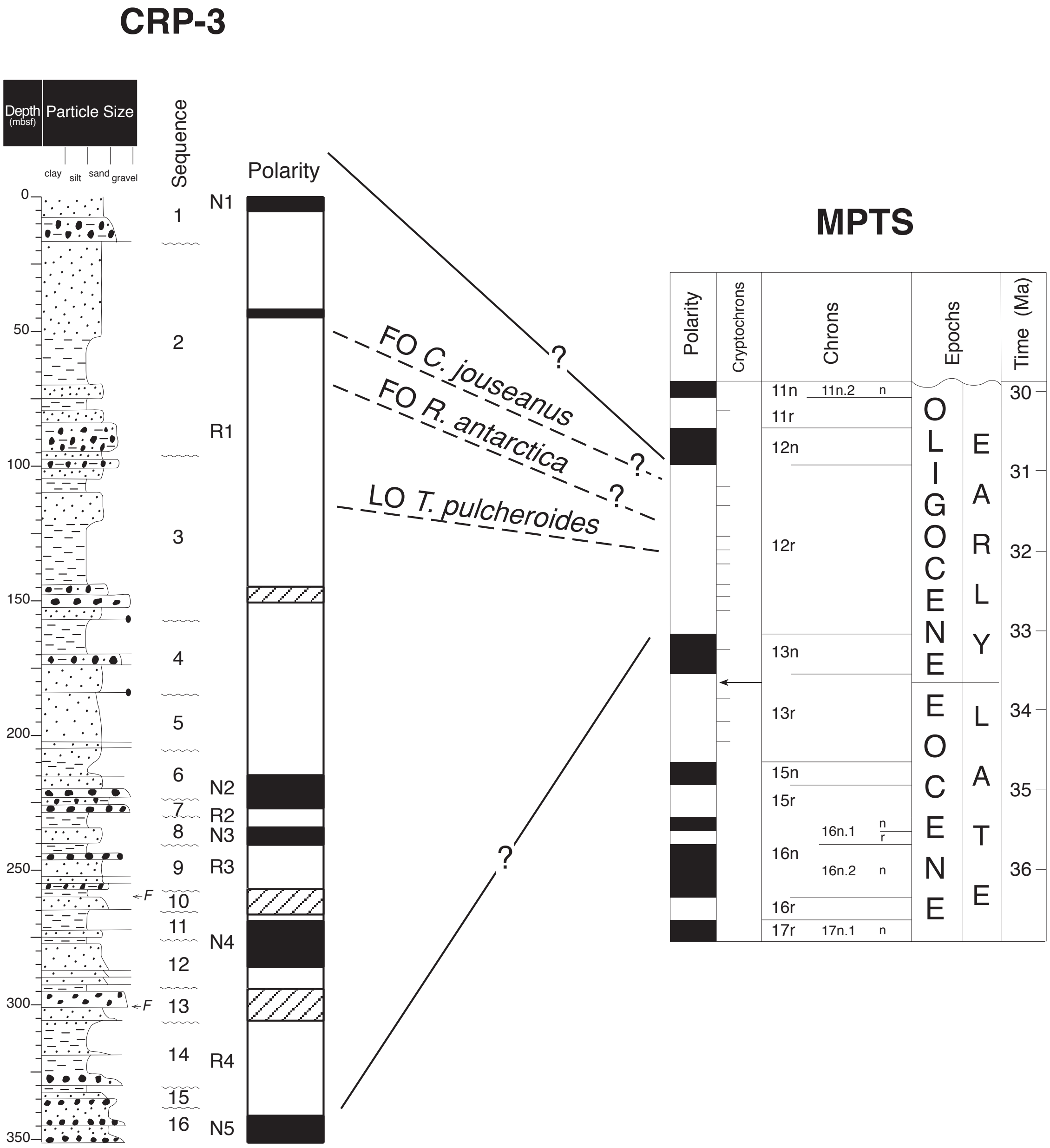

Fig. 6.9 - Tentative correlation of the polarity zonation for the upper 350 mbsf of CRP-3 with the MPTS of Cande & Kent (1992a, 1995). The dominance of reversed polarity in CRP-3 is consistent with biostratigraphical datums (the FO of the diatom *Cavitatus jouseanus* and the LO of the calcareous nannofossil *Transveropontis pulcheroides*) which are expected to lie in Chron 12r. It is likely that most of the normal polarity magnetozones in CRP-3 correspond to cryptochrons rather than to normal polarity subchrons. However, age constraints are insufficiently precise to allow correlation of individual cryptochrons to those on the MPTS.

c. 366 mbsf) are absent in the upper 200 mbsf of CRP-3. This suggests that the upper 200 mbsf of CRP-3 is younger than late Eocene to earliest Oligocene in age.

Below 200 mbsf, CRP-3 is barren of diatoms and calcareous nannofossils. Marine palynology provides the primary biostratigraphical age constraint for the lower part of CRP-3. Dinoflagellate cysts are present to the base of the Cenozoic succession (*c.* 812 mbsf). These assemblages are similar to those found in CRP-2/2A. The Transantarctic assemblage seen in sediments from the base of CIROS-1 (Hannah, 1997) and in Eocene glacial erratics from the southern McMurdo Sound area (Levy & Harwood, in press), is not seen in CRP-3 (see Palynology section). This suggests that the base of CRP-3 is younger than mid-late Eocene in age (Hannah et al., 1997; Wilson et al., 1998).

In summary, the biostratigraphical constraints suggest that the top of CRP-3 should lie in Chron 12r. This is consistent with the dominance of reversed polarity in the upper 350 mbsf in CRP-3. If it is assumed that the top of CRP-3 corresponds to C12r and that each of the magnetozones documented in CRP-3 has a correlative in the MPTS, this would suggest that magnetozones N2 to N5 represent normal polarity zones in the Eocene. Based on the biostratigraphical constraints, this interpretation is 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 1 000 m/m.y.; Wilson et al., in press a, b), and the lithofacies indicate similarly high sedimentation rates in CRP-3 (see Lithostratigraphy and Sedimentology chapter). Also, the upper and lower boundaries of magnetozone N2 are defined by transitional palaeomagnetic directions which suggest that this magnetozone is brief (< 30 k.y. in duration) and that sediment accumulation rates are closer to ~600 m/m.y. in this part of CRP-3. It is, therefore, more likely that the short normal polarity interval at 41.72-44.68 mbsf and magnetozones N2, N3 and N4 represent cryptochrons in the lower part of C12r. The biostratigraphical age constraints are not sufficiently precise to enable correlation of the polarity zonation to specific cryptochrons within C12r. The correlation lines on figure 6.9 are therefore shown with question marks. It is possible that magnetozone N5 correlates with Chron 13n, however, it could also represent a cryptochron within Chron 12r. Regardless, the magnetic polarity zonation and the biostratigraphical constraints indicate that the entire upper *c*. 350 mbsf of CRP-3 is early Oligocene in age.

CORRELATION OF CRP-3 WITH CRP-2/2A

Wilson et al. (in press a) presented three possible correlations with the MPTS for the lower 200 m of CRP-2/2A. Correlation C predicts that strata at the base of CRP-2/2A are latest Eocene in age. Correlations A and B suggest that strata at the base of CRP-2/2A are early Oligocene in age (C11r and C12r, respectively). Interpretations of seismic reflection data that were used to choose the CRP-3 drill site predicted that it would have a small amount of overlap (*c*. 50 m) with the base of CRP-2/2A. The C12r age assignment for the uppermost strata from CRP-3 confirm that correlations A or B are more likely to be correct, which implies that strata from the base of CRP-2/2A are early Oligocene in age (C12). Furthermore, initial biostratigraphical examination of CRP-3 (see Palaeontology chapter) suggests that the uppermost strata from CRP-3 were deposited during the middle of Chron 12r and that as much as 1 m.y. could be missing between the base of CRP-2/2A and the top of CRP-3.

Short polarity intervals were also recognised in the Oligocene strata of CRP-2/2A (Wilson et al., in press a). These had no correlative in the MPTS and probably also represent cryptochrons in chrons C9 - C11.

PALAEOMAGNETIC RESULTS FROM BELOW 790 MBSF IN CRP-3

A breccia with dolerite clasts was encountered between 789.77 and 822.87 mbsf. This interval was unsuitable for palaeomagnetic sampling. Beneath a major unconformity, from 823.11 mbsf to the bottom of the CRP-3 hole, a lithified medium-grained light red/brown quartz sandstone was recovered. This unit may represent the Arena Sandstone of the Beacon Supergroup (Devonian). Most outcrops of Beacon Supergroup strata were thermally overprinted by intrusion of the Jurassic Ferrar Dolerite, and the apparent polar wander path for Antarctica has no palaeomagnetic constraints from the Devonian to the Triassic (Grunow, 1999). Because the strata appear fresh and unaltered, it was decided to sample this interval for palaeomagnetic study. Because of previous problems with magnetic overprinting and poor palaeomagnetic behaviour of Beacon Supergroup strata, a pilot study was conducted at McMurdo Station before routine sampling was undertaken. Four closely-spaced samples were collected from three horizons. One sample from each horizon was subjected to AF demagnetization, and the remaining 3 samples were subjected to thermal demagnetization. Results of the pilot study indicate that thermal demagnetization is more efficient than AF demagnetization. The thermal demagnetization data indicate the presence of a reversed polarity overprint with a consistent normal polarity ChRM. Future thermal demagnetization studies will be conducted to determine the nature of this magnetization and whether it can be used to identify a reliable palaeomagnetic pole for this unit.

ADDITIONAL WORK

The above-reported initial characterization studies indicate several areas that warrant additional work. The magnetostratigraphy of CRP-3 clearly needs to be refined, particularly in the lower part of the record. This could have significant implications for the chronostratigraphical interpretation. The present interpretation is preliminary and should be used with caution. Although high-quality palaeomagnetic results have been obtained from the majority of the CRP-3 samples, it is still important to characterize the mineral magnetic properties of different parts of the core. The mineral magnetic measurements will provide the basis for studies of the environmental magnetic record of CRP-3. A suite of samples will also be analysed from the inferred Beacon Supergroup strata (below 823.11 mbsf) in an attempt to determine a palaeomagnetic pole.