Terra Antartica
2000, 7(4), 599-608

TERRA ANTARTICA

Environmental Magnetism of Oligocene - Miocene Glaciomarine Strata from CRP-2/2A, Victoria Land Basin, Antarctica

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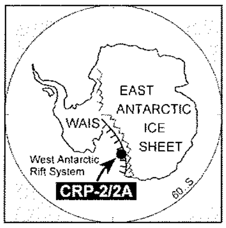
Received 24 December 1999; *accepted in revised form* 31 May 2000



Abstract - Analysis of the environmental magnetic properties of the 624.15-m CRP-2/2A core, from McMurdo Sound, Antarctica, suggests that the core can be divided into three intervals, based on the nature and abundance of the magnetic minerals in the sedimentary sequence. These variations in magnetic parameters do not appear to be directly related to lithological variations in the core. Above 270 metres below sea floor (mbsf), magnetite is the dominant magnetic mineral and variations in magnetic properties coincide with fluctuations in the input of volcanic glass from the McMurdo Volcanic Group. The two lowermost intervals (270 – 413 mbsf, and 413 – 624 mbsf) are marked by alternations between zones that are relatively enriched in magnetite and hematite, respectively. The two intervals are differentiated on the basis of their mean coercivity values. It is unlikely that the alternations in magnetic properties reflect fluctuations in sediment provenance. More probably they reflect changes in palaeoenvironmental conditions related to climate and weathering regime.

INTRODUCTION

One of the main goals of the Cape Roberts Project (CRP) is to study cores from the Victoria Land Basin, Antarctica, to determine the climatic history of the Ross Sea region and the tectonic history of the Ross Sea rift and the Transantarctic Mountains. The second phase of CRP drilling was completed in November, 1998. Technical problems led to the recovery of only 57 m of sediment in the CRP-2 hole. Subsequently, drilling was resumed at the same location, and the new drillhole was designated as CRP-2A. The composite CRP-2/2A record comprises 624.15 m and terminates in early Oligocene strata (Cape Roberts Project Science Team, 1999; Wilson, Florindo et al., this volume; Wilson, Bohaty et al., this volume). The composite record consists of an Oligocene - early Miocene glaciomarine sequence that is overlain by a thin cover of Pliocene - Pleistocene strata. The Oligocene - Miocene strata are primarily massive, bioturbated mudstones and coarse, poorly-sorted diamictites and conglomerates.

In this paper, we present an initial environmental magnetic study of samples from the Oligocene - Miocene interval of CRP-2/2A (27 - 624.15 metres below sea floor (mbsf)). Environmental magnetic methods are commonly used to document variations in the concentration, mineralogy and grain-size of magnetic particles in sedimentary rocks. These variations can provide information about changes in palaeoenvironmental conditions in a sedimentary basin and its surrounding region (Thompson & Oldfield, 1986; Verosub & Roberts, 1995). Sagnotti et al. (1998a) found alternations between zones of high and low ferrimagnetic mineral concentration in the lower Miocene strata from CRP-1. Alternating intervals of high and low magnetic mineral concentration have also been found in strata that span the Eocene - Oligocene boundary in the CIROS-1 core (Sagnotti et al., 1998b). CRP-2/2A spans the Oligocene - Miocene interval that is missing across an unconformity at about 366 mbsf in CIROS-1 and partially overlaps the lower Miocene strata that were recovered in CRP-1.

METHODS

One thousand eleven samples were collected from CRP-2/2A. Samples were taken at 0.5-m intervals if possible, but where the lithology was coarse or where the material was unconsolidated, the sampling density was lower. Diamictites and other coarse-grained sediments are common in CRP-2/2A, so, whenever possible, samples were collected from fine-grained horizons within intervals of coarse-grained sediment. In the diamictite units, we tried to select samples that were representative of the matrix alone, but if discrete samples showed evidence that they contained extra-formational pebbles, they were excluded from further analysis. In most of the upper 100 m of CRP-2/2A, and in two sandy intervals (185.96 - 193.69 mbsf and 280.75 - 286.80 mbsf), the sediments are poorly consolidated and were sampled with 6.25 cm^3 plastic cubes (12% of the samples). The lithologies in the remainder of the core are consolidated enough to allow drilling of conventional cylindrical palaeomagnetic samples using a modified drill press (88% of samples). Sub-samples were also collected from each sampling horizon in the form of chips or loose material (from the sandy intervals).

During the drilling season, low-field magnetic susceptibility (κ) of all samples was routinely measured at the Crary Science and Engineering Center, McMurdo Station, Antarctica, using a Bartington Instruments magnetic susceptibility meter with an MS-2B probe. Susceptibility was measured at low and high frequencies (470 Hz and 4.7 kHz, respectively) to enable determination of the frequency dependence of the magnetic susceptibility (*e.g.* Bloemendal et al., 1985). The frequency dependence of magnetic susceptibility is the ratio of the low frequency susceptibility minus the high frequency susceptibility to the low frequency susceptibility, expressed as a percentage. Samples that were treated with alternating field (AF) demagnetization for a magnetostratigraphic study (Wilson, Florindo et al., this volume) were subsequently used for the environmental magnetic study presented here. Anhysteretic remanent magnetizations (ARMs) were measured for 647 samples at the *Istituto Nazionale di Geofisica* (Italy). ARMs were imparted with a DC bias field of 100 μT and a peak AF of 100 mT. The ARM was then subjected to AF demagnetization, using an automated pass-through cryogenic magnetometer with an in-line, three-axis AF demagnetizer. From these measurements, a determination was made of the median destructive field (MDF_{ARM}). Acquisition of isothermal remanent magnetization (IRM) was studied on 18 selected samples, in fields up to 1 T (Cape Roberts Project Science Team, 1999). A progressively increasing back-field was then applied to the same samples, to determine the coercivity of remanence (B_{cr}) and the S-ratio, which is the absolute value of the IRM remaining after exposure to a back-field of 300 mT divided by the IRM acquired in a forward field of 1 T (*e.g.* Verosub & Roberts, 1995). Hysteresis parameters for sub-samples from the same stratigraphic levels were determined (up to peak fields of 1 T) at the University of California, Davis (USA), using a Princeton Measurements Corporation alternating gradient magnetometer (Micromag). The measured parameters include saturation magnetization (M_s), saturation remanent magnetization (M_r), coercive force (B_c) and B_{cr}. The high-temperature behaviour of the magnetic susceptibility of selected sampled was studied at the University of Oxford (UK) using an AGICO KLY-2 Kappabridge magnetic susceptibility meter coupled with a CS-2 furnace.

Magnetic parameters reflect the contribution of all magnetic minerals to the magnetization of a sample. When a sedimentary sequence contains a single magnetic mineral, it is possible to interpret magnetic parameters in terms of magnetic mineral concentration (using κ, ARM intensity, M_s, and M_r), magnetic grain size (using frequency-dependent magnetic susceptibility and inter-parametric ratios such as ARM/κ, B_{cr}/B_c, and M_r/M_s), and magnetic mineralogy (using B_c, B_{cr}, and MDF_{ARM}). The meaning of the above parameters can become ambiguous in sequences containing mixtures of magnetic minerals. However, when dealing with mixtures of magnetite (a low coercivity ferrimagnetic mineral) and hematite (a high coercivity canted antiferromagnetic mineral), the joint analysis of concentration-dependent and mineralogy-dependent parameters can be extremely useful. For example, hematite has a low magnetization compared to magnetite, and high values of concentration-dependent parameters in a sediment are likely to indicate a dominance of magnetite or similar ferrimagnetic phases. In contrast, when significant concentrations of high coercivity phases such as hematite are present, the coercivity of the sediment will be higher. Inter-parametric ratios have a much more limited use when mixtures of magnetic minerals are present, and inferences concerning magnetic grain size should be made with caution in such situations. For these reasons, we describe down-core mineral magnetic variations in CRP-2/2A in terms of magnetic concentration-dependent parameters and magnetic mineralogy-dependent parameters. We restrict the use of grain size-dependent parameters to samples that are clearly dominated by a single magnetic mineral.

RESULTS

Three intervals with distinct magnetic properties are evident in CRP-2/2A. Identification of these intervals requires information from magnetic concentration-dependent parameters, as well as from mineralogy-dependent parameters. In the following treatment, we present these results separately, but the three intervals are shown on figures 1 and 2 to facilitate comparison.

MAGNETIC MINERAL CONCENTRATION

Down-core variations in κ, ARM intensity, M_s, and M_r are shown in figure 1. The highest values are recorded in the upper 140 m of the core, and, in general, the values of these parameters decrease down-core until about 270 mbsf. At this depth, the concentration-dependent parameters reach background values that are lower than any values in the overlying 270 m of the core. Below 270 mbsf, the concentration-dependent parameters alternate between relatively high values and low background values. Using the concentration-dependent parameters alone, it is difficult to discriminate between different types of magnetic behaviour for the interval between 270 mbsf and the base of the core, apart from the marked alternations between high and low values.

Variations in concentration-dependent magnetic parameters show little or no correlation with lithological variations. High and low values of these parameters are both found in the same lithofacies; magnetic parameters

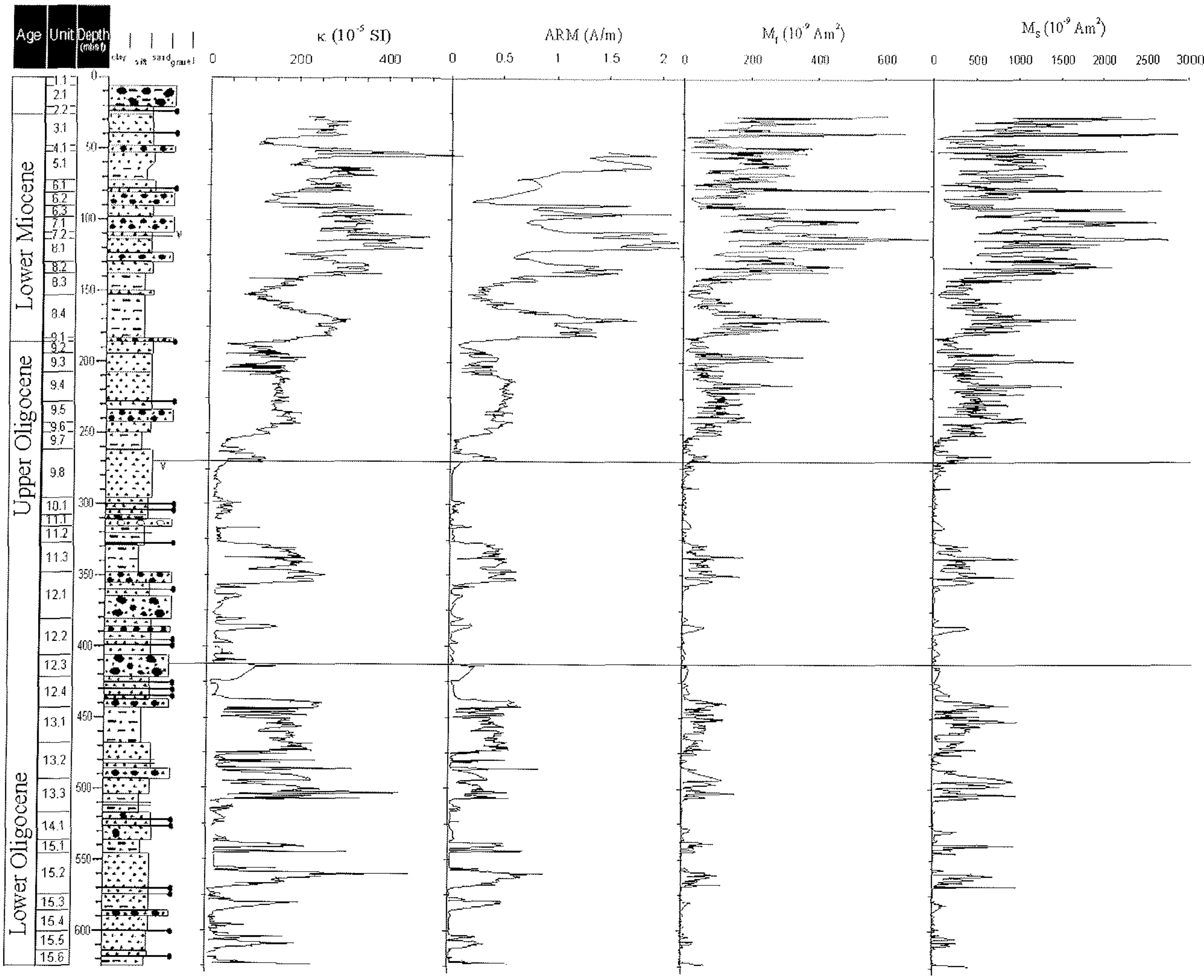


Fig. 1 – Down-core variation of ferrimagnetic concentration-dependent parameters (κ, ARM, M_r and M_s) in CRP-2/2A. The lines at 270 and 413 mbsf indicate the boundaries between intervals with different magnetic properties (see discussion in text, Fig. 2 & Tab. 1).

are constant across many lithostratigraphic boundaries; and transitions between high and low values often occur within lithological units.

MAGNETIC MINERALOGY

Magnetic mineralogy-dependent parameters (*e.g.* B_c and B_{cr}) vary within a relatively narrow range of values in the upper 270 m of CRP-2/2A (Fig. 2). These parameters are generally higher and are far more variable between 270 and 413 mbsf than in the upper interval. Below 413 mbsf, the coercivity parameters are still variable, but generally they have values that are lower than those observed between 270 and 413 mbsf and are closer to those observed in the upper 270 m. These differences can be quantified by applying a statistical *t*-test to the hysteresis parameters from the three intervals (Tab. 1). This analysis indicates that the mean coercivities are significantly different (at the 95% confidence level) for the three intervals (Tab. 2). It also indicates that only in the upper interval (27-270 mbsf) is the mean value of the concentration-dependent parameter, M_r, significantly different from the mean values in the other two intervals (Tab. 2). Thus, the mineralogy-dependent parameters, in conjunction with the concentration-dependent parameters, allow us to define three intervals with distinctive magnetic properties in CRP-2/2A (27-270 mbsf, 270-413 mbsf, and 413-624 mbsf).

When the coercivity parameters (Fig. 2) are compared with the concentration-dependent parameters (Fig. 1), it is evident that the high coercivity values occur in intervals where the concentration of ferrimagnetic minerals is low. Similarly, lower coercivities are evident in intervals where ferrimagnetic mineral concentrations are high.

To better understand the relationship between this pattern and the magnetic mineralogy, we looked at the behavior of the magnetic susceptibility during heating and cooling. Examples of temperature-dependent susceptibility curves are shown in figure 3. The first sample is from 83.68 mbsf and comes from a zone with low coercivity and a high concentration of ferrimagnetic grains. This sample (Fig. 3a) is clearly dominated by magnetite, with a major decrease in susceptibility at about 580 °C. The susceptibility then drops to zero at about 640 °C which indicates the possible presence of maghemite (Özdemir, 1990). The maghemite may occur as surficial oxidation of magnetite

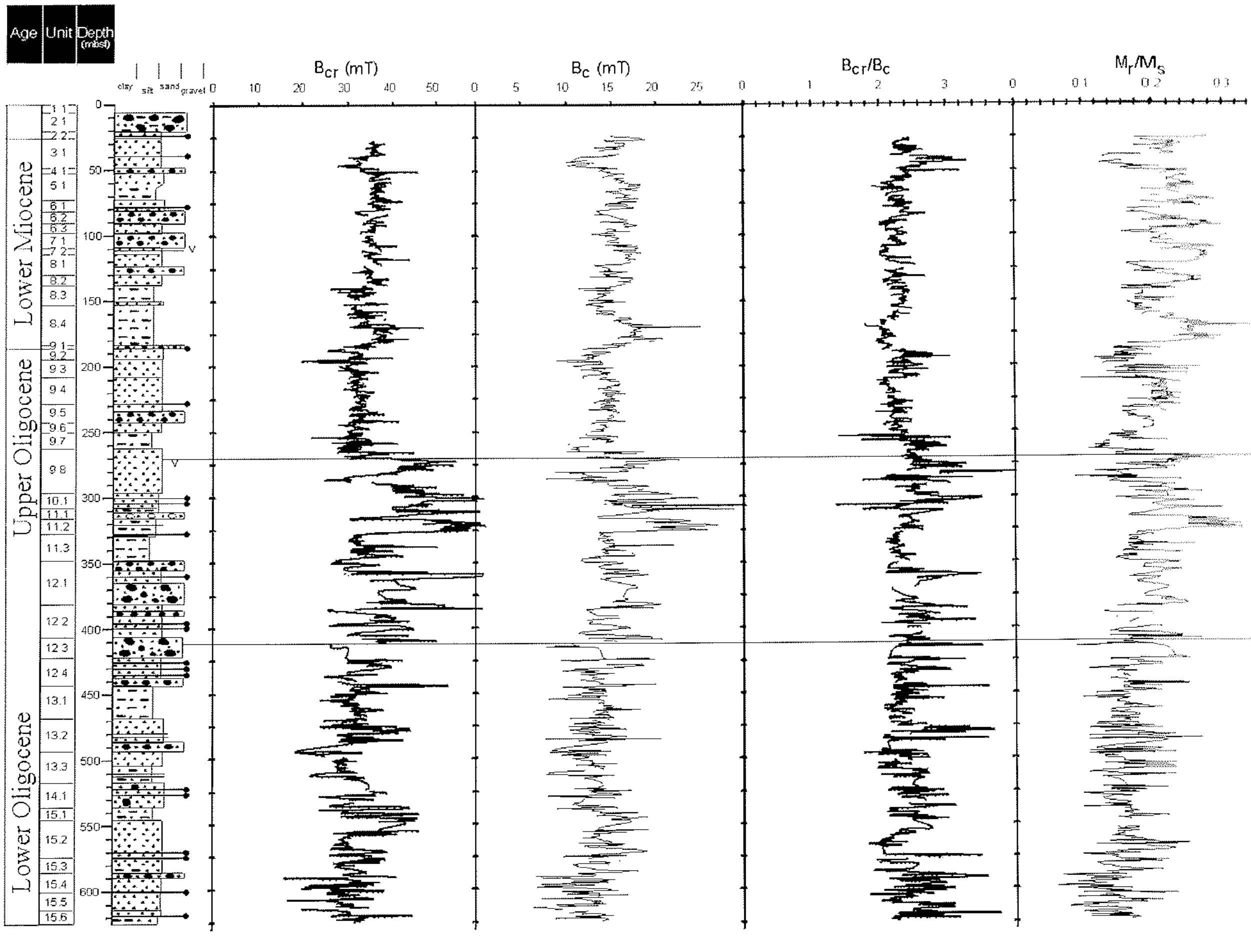


Fig. 2 – Down-core variation of the coercivity-dependent magnetic parameters (B_{cr} and B_c) and the inter-parametric hysteresis ratios B_{cr}/B_c and M_r/M_s for CRP-2/2A. The lines at 270 and 413 mbsf indicate the boundaries between intervals with different magnetic properties (see discussion in text, Fig. 1 & Tab. 1).

grains. Thus, the temperature-dependent susceptibility data support the conclusion that magnetite is the dominant ferrimagnetic mineral in the upper 270 m of CRP-2/2A.

The second sample is from 270.90 mbsf and comes from a zone with high coercivity and a low concentration of ferrimagnetic grains. The susceptibility drops to low values at about 500 °C (Fig. 3b), which is indicative of the presence of (low titanium) magnetite. However, instead of decreasing to near zero values at the Curie temperature of magnetite (580 °C), the susceptibility remains above zero until approximately 680 °C, the Néel temperature of hematite. The cooling curve is reversible at high temperatures, which is evidence that the hematite is primary and did not form as a result of heating. At about 640 °C, the cooling curve becomes irreversible, which could result from the formation of new magnetic minerals due to alteration of matrix minerals during heating. The data from this sample support the conclusion that hematite is the high coercivity mineral that is important in the zones with low magnetic mineral content. The drop in susceptibility at 500 °C indicates that a significant portion of the susceptibility is due to (low titanium) magnetite.

Tab. 1 - Hysteresis properties of CRP-2/2A core.

Interval	B_{cr} (mT)	B_c (mT)	M_r ($\times10^{-9}$ Am^2)	M_s ($\times10^{-9}$ Am^2)	M_r/M_s	B_{cr}/B_c
27 - 270 mbsf						
Mean	34.4	15.0	153.3	702.9	0.21	2.29
St dev.	3.3	1.9	139.5	580.7	0.04	0.21
270 - 413 mbsf						
Mean	40.9	16.4	20.0	107.2	0.20	2.51
St dev	9.7	3.7	28.4	160.2	0.04	0.36
413 - 624 mbsf						
Mean	31.6	13.2	23.9	153.5	0.16	2.43
St dev	5.1	2.3	29.8	202.3	0.03	0.34

Tab. 2 - Statistical significance (t-test) of Bcr and Mr.

Interval	N	Mean (variance)	Populations	t value	p value	Significantly different (at 95% level)
B_{cr}						
27 – 270 mbsf	416	34.2 (10.6)	27-270 mbsf and 270–413 mbsf	12.3	5.3×10^{-31}	Yes
270 – 413 mbsf	156	40.9 (94.7)	27–270 mbsf and 413–624 mbsf	-8.3	4.1×10^{-16}	Yes
413 – 624 mbsf	281	31.6 (26.3)	270–413 mbsf and 413–624 mbsf	-13.1	2.1×10^{-33}	Yes
M_r						
27 – 270 mbsf	416	153.3 (19451.8)	27-270 mbsf and 270–413 mbsf	-11.8	4.5×10^{-29}	Yes
270 – 413 mbsf	156	20.0 (804.1)	27–270 mbsf and 413–624 mbsf	-15.3	7.9×10^{-46}	Yes
413 – 624 mbsf	281	23.9 (888.5)	270–413 mbsf and 413–624 mbsf	1.34	0.18	No

However, the magnetic susceptibility of magnetite is at least three orders of magnitude greater than that of hematite. Thus, the presence of a detectable contribution to the magnetic susceptibility from hematite suggests that hematite occurs in much higher abundances than magnetite in the zones with low magnetic mineral concentration. Temperature-dependent susceptibility analyses of other samples from CRP-2/2A are consistent with this conclusion.

MAGNETIC GRAIN-SIZE

In the lower two intervals, where there are significant mineralogical variations, it is difficult to use inter-parametric ratios, such as B_{cr}/B_c and M_r/M_s (Fig. 2), to determine domain state and to make inferences concerning grain size variations. However, in the upper 270 m, coercivity variations are relatively minor, and, based on temperature-dependent susceptibility data, magnetite is likely to be the dominant magnetic mineral in this interval. It is therefore appropriate to use the ratios B_{cr}/B_c and M_r/M_s to examine grain size variations in this interval. In general, low values of M_r/M_s and high values of B_{cr}/B_c are indicative of coarse grains, while high values of M_r/M_s and low values of B_{cr}/B_c are indicative of fine grains (*cf.* Day et al., 1977). The range of M_r/M_s and B_{cr}/B_c values in the upper 270 m indicates considerable variation in magnetite grain size; however, there is no apparent relationship between grain size and sedimentary facies (Fig. 2). The presence of fine-grained magnetite can be inferred in both fine-grained lithofacies and in diamictites and the same is true for coarse-grained magnetite. Thus, lithology does not appear to exert a primary control on magnetic grain size.

None of the hysteresis loops is wasp-waisted, which suggests that neither hematite (high coercivity) nor superparamagnetic particles (zero coercivity) have a major influence on the hysteresis properties (Roberts et al., 1995). The hysteresis results for the interval above 270 mbsf are therefore consistent with the dominance of magnetite.

Strictly speaking, the method of Day et al. (1977) for determining magnetic grain sizes should only be used for samples that are dominated by magnetite, which is not the case for much of CRP-2/2A. However, displaying hysteresis data on Day plots can be useful for comparing the CRP-2/2A data with hysteresis data from other cores in the Victoria Land Basin (Sagnotti et al. 1998a, b) and can be used to identify general trends in the data. In

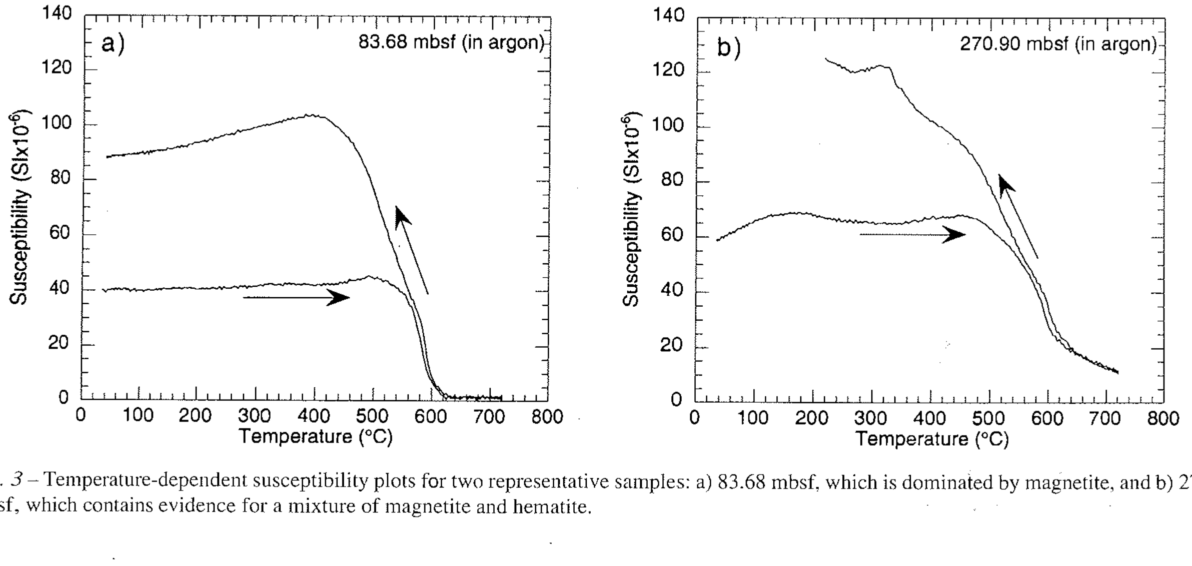


Fig. 3 – Temperature-dependent susceptibility plots for two representative samples: a) 83.68 mbsf, which is dominated by magnetite, and b) 270.90 mbsf, which contains evidence for a mixture of magnetite and hematite.

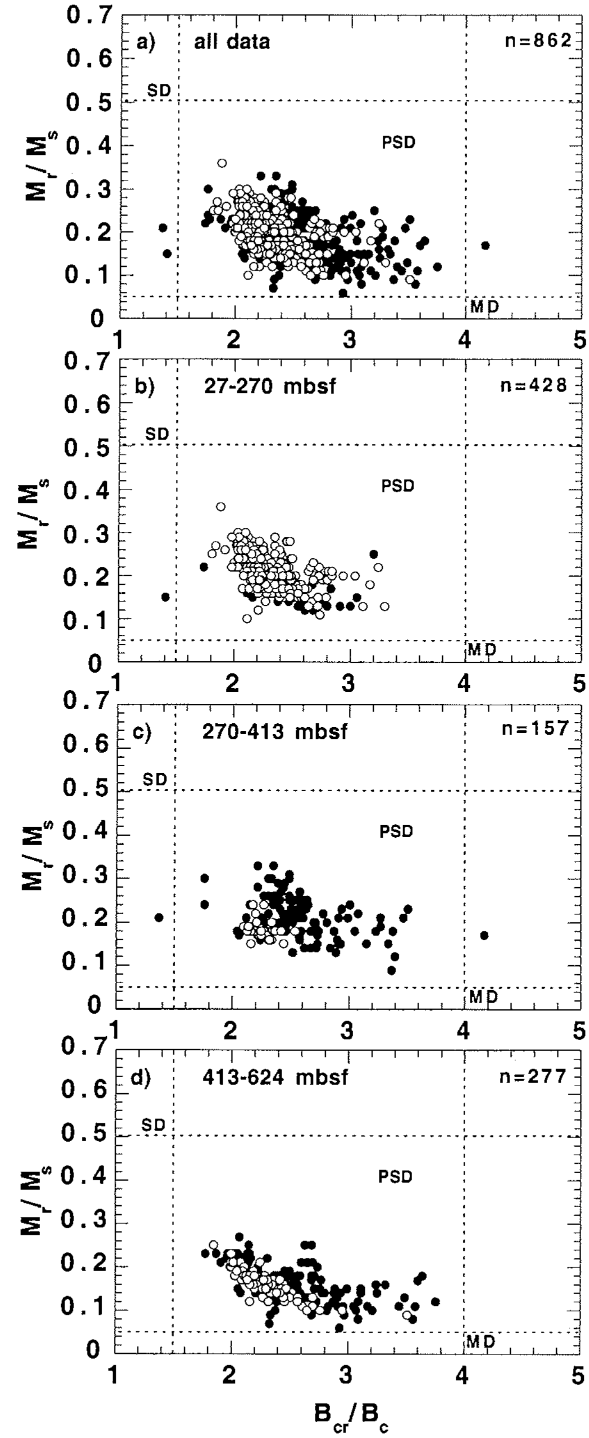


Fig. 4 – Plots of M_r/M_s versus B_{cr}/B_c for: a) all data from CRP-2/2A, b) the interval between 27 and 270 mbsf, c) the interval between 270 and 413 mbsf, and d) the interval between 413 and 624 mbsf. Open symbols correspond to points with high magnetic mineral concentration; closed symbols correspond to points with low magnetic mineral concentration. The fields marked for SD = single-domain, PSD = pseudo-single-domain, and MD = multi-domain, correspond to the ranges of values expected for crushed (titano)magnetite grains (Day et al., 1977).

figure 4, we show plots of M_r/M_s versus B_{cr}/B_c for different intervals in CRP-2/2A. It is clear that for the upper interval (27 - 270 mbsf; Fig. 4b), which is dominated by magnetite, the magnetic grains all fall within the pseudo-single-domain (PSD) field, as defined by Day et al. (1977). As noted above, there is considerable variation in grain size in this interval, and this is seen in the scatter of points in the PSD field (Fig. 4b) and in the stratigraphic fluctuations in these parameters (Fig. 2). In the interval between 270 and 413 mbsf, the samples from zones of high magnetic concentration fall on the same trend as the samples from the upper interval, but samples from zones of low magnetic concentration lie above and to the right of this trend. The displacement of this second group of samples is consistent with the presence of a higher coercivity phase, such as hematite. The hysteresis ratios for the interval between 413 and 624 mbsf are more tightly clustered with less difference between samples with high and low magnetic concentration.

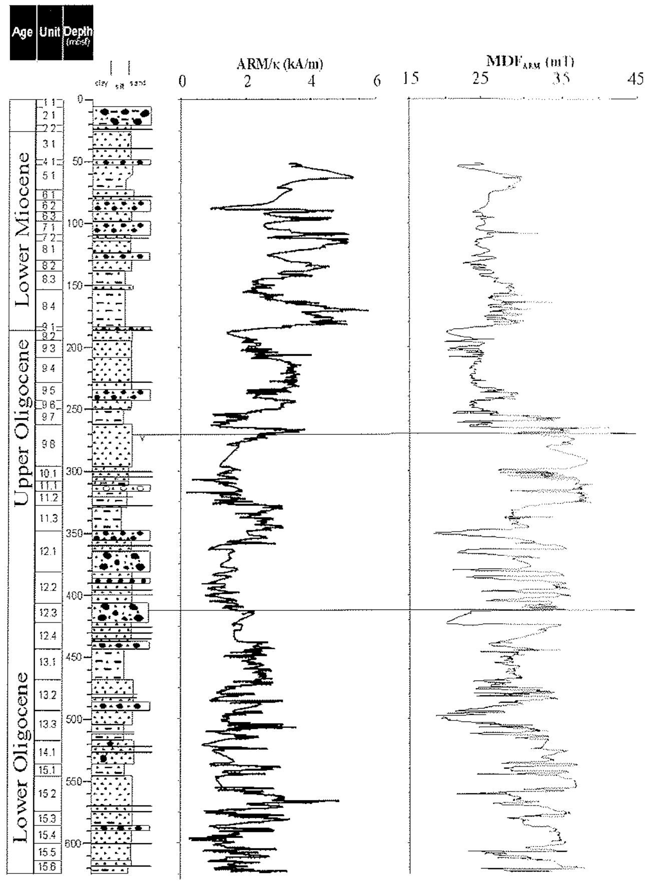


Fig. 5 – Down-core variations of ARM/κ and MDF_{ARM} for CRP-2/2A. The lines at 270 and 413 mbsf indicate the boundaries between intervals with different magnetic properties.

When magnetite is the dominant magnetic mineral, the ARM/k ratio is also indicative of magnetic grain size because, compared to magnetic susceptibility, ARM acquisition is more effective in activating finer magnetite grains (King et al., 1983). On a plot of ARM versus κ, changes in slope correspond to changes in magnetic grain size while variations along a line of constant slope are indicative of variations in the concentration of magnetic grains. In CRP-2/2A, ARM/κ is variable (Fig. 5), but different ranges of variability are evident in the three distinct magnetic intervals (Fig. 6). In the upper interval (where measurements of ARM were made only for samples between 50 and 270 mbsf), the data are scattered along a

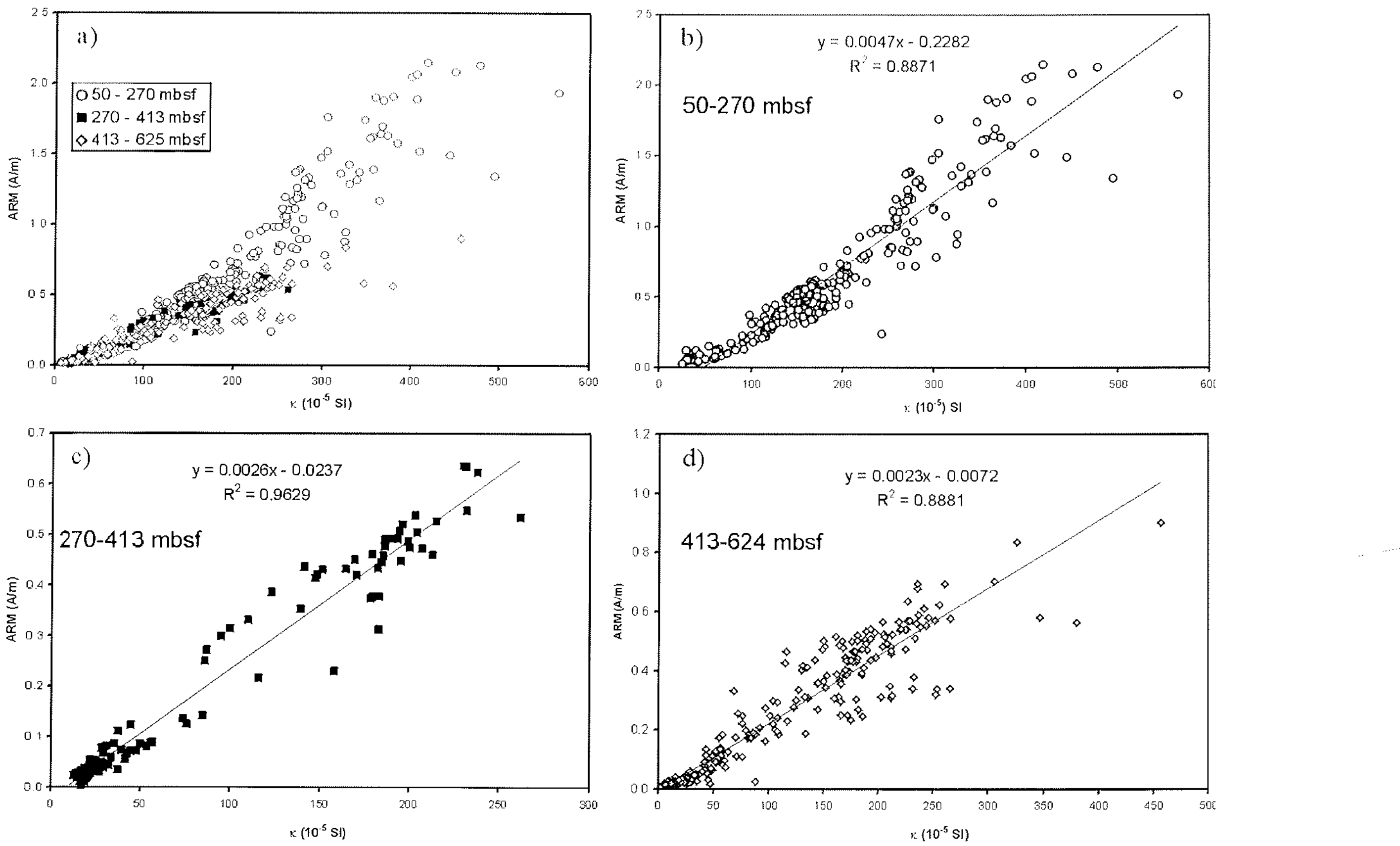


Fig. 6 – Plots of ARM versus κ for: a) all data from CRP-2/2A, b) the interval between 50 and 270 mbsf, c) the interval between 270 and 413 mbsf, and d) the interval between 413 and 624 mbsf (see discussion in text). Note that the scales on the axes and hence the slopes of the lines are different in each plot.

line with fairly constant slope (Fig. 6b), indicating considerable variation in the concentration of magnetic grains. The relatively low R^2 value of 0.89 is consistent with a range of magnetic grain sizes, as indicated in figures 2, 4 and 5. For the interval between 270 and 413 mbsf (Fig. 6c), the data are more linear (R^2 = 0.96) and are bimodally distributed between high and low magnetic mineral concentrations, with few intermediate points between the two clusters. A similar bimodal distribution is evident for the interval between 413 and 624 mbsf (Fig. 6d). This bimodality is a manifestation of the presence of zones with relatively high concentrations of magnetite (high magnetizations) and relatively high concentrations of hematite (low magnetizations).

The slopes of the lines in figure 6 are also quite different in the three intervals. In particular, the slope for the interval above 270 mbsf is considerably steeper which indicates that the magnetite in the upper interval is finer-grained than in the lower intervals. Despite the fact that the lower intervals contain mixtures of magnetite and hematite, the slopes of the lines in figures 6c and 6d are determined primarily by the clusters that contain magnetite. Hence, the comparison of relative grain sizes between the lower intervals and the upper interval is probably robust.

Frequency dependence of the magnetic susceptibility is a useful parameter for detecting the presence of ultra-fine grained (superparamagnetic) magnetite. In the zones of high magnetic mineral concentration, the frequency dependence varies between 0 and 6%, with most values falling between 2 and 4%. These values indicate that some superparamagnetic material is present in these zones, but not in significant quantities. In the zones of low magnetic mineral concentration, the susceptibility values were too low to permit reliable determination of the frequency dependence of magnetic susceptibility.

DISCRIMINATING BETWEEN SAMPLES THAT ARE RELATIVELY ENRICHED IN MAGNETITE AND HEMATITE

As noted above, the plots of ARM versus κ define clusters of points that represent samples containing different magnetic minerals (*i.e.* magnetite and hematite). In figure 7, we make use of a mineralogy-dependent parameter (MDF_{ARM}) and a concentration dependent parameter (ARM) to improve our ability to discriminate between the magnetite- and hematite-enriched intervals (see also Fig. 5). The wide scatter of points for the upper interval (50 – 270 mbsf) shows that the grain size and concentration of magnetite is highly variable here (Fig. 7). Despite this variability, the magnetite data fall into a distinct cluster (which has low coercivities and high magnetizations) that can easily be discriminated from the other samples in this interval (which have either higher coercivities and/or lower magnetizations). Below 270 mbsf, the magnetite-enriched and hematite-enriched samples are each represented by distinct clusters, with intermediate points between the two clusters probably representing mixtures of magnetite and hematite.

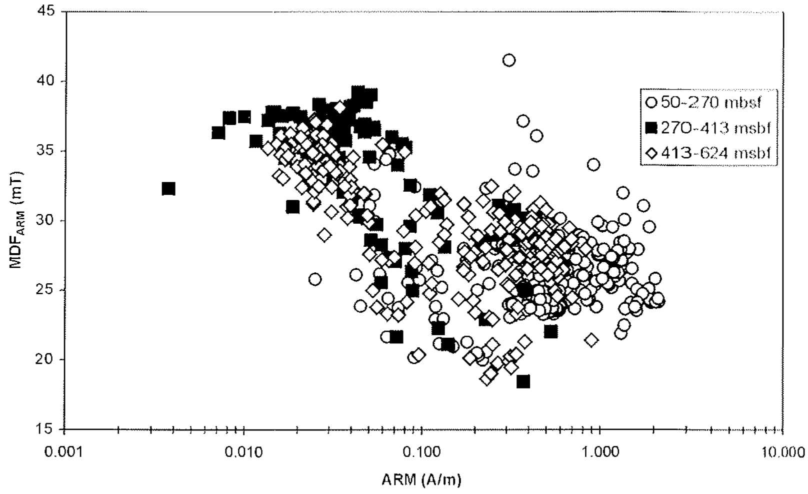


Fig. 7 – Plots of MDF$_{ARM}$ versus ARM for all data from CRP-2/2A. Two clusters of samples can be distinguished: one with low ARM intensities and relatively high MDF$_{ARM}$ values corresponds to hematite-enriched samples: the other with high ARM intensities and low MDF$_{ARM}$ values corresponds to magnetite-enriched samples. The points scattered between these clusters represent samples with a mixture of magnetite and hematite.

DISCUSSION

The results presented above indicate that CRP-2/2A contains three intervals with distinct magnetic properties. In the lowermost interval (413 - 624 mbsf), there is a marked alternation between zones with high and low magnetic mineral concentration, which are relatively enriched in magnetite and hematite, respectively. The alternations in this lower interval have a higher stratigraphic frequency than those in the middle interval (270 - 413 mbsf) and there are more zones with high magnetite concentration (Fig. 1). The middle interval is characterized by lower-frequency alternations between magnetite- and hematite-enriched zones (Fig. 1); the latter stand out by virtue of their high coercivities (Fig. 2). The uppermost interval is dominated by magnetite with variable grain sizes (Figs. 1 & 2).

A possible explanation for the alternations in magnetic mineral concentration below 270 mbsf is that the zones of low magnetic mineral concentration reflect cycles of increased magnetic mineral dissolution due to reductive diagenesis. Enhanced concentrations of superparamagnetic particles have also been reported from sediments that have been affected by reductive diagenesis (Tarduno, 1995). In the zones of high magnetic mineral concentration in the CRP-2/2A core, frequency dependence of magnetic susceptibility is relatively low (generally 2 – 4%), which suggests that there has not been significant enhancement of superparamagnetic particles. In zones of low magnetic mineral concentration, it is difficult to determine the frequency dependence of magnetic susceptibility because susceptibilities are low, and robust determinations of frequency dependence are not possible. However, reductive diagenesis usually requires moderate to high concentrations of organic material (*e.g.* Karlin & Levi, 1983, 1985; Canfield & Berner, 1987), and the total organic carbon content in the CRP-2/2A core is low (< 0.5%) and shows no systematic differences between zones of high and low magnetic mineral concentration (Cape Roberts Project Science Team, 1999). We therefore conclude that the environmental magnetic properties of CRP-2/2A primarily reflect a detrital rather than a diagenetic signature.

CRP-2/2A ENVIRONMENTAL MAGNETISM: 27-270 mbsf

The CRP-2/2A core contains evidence for the onset of activity associated with the McMurdo Volcanic Group, and volcanic detritus increases in frequency above about 280 mbsf (Cape Roberts Project Science Team, 1999). This depth corresponds to an age of about 24 Ma (Wilson et al., this volume a, b). The dominance of magnetite in the uppermost magnetic interval of CRP-2/2A (27-270 mbsf) can clearly be related to the influx of vesicular basalt, volcanic glass and pumice from the McMurdo Volcanic Group. There is generally good agreement between high and low concentrations of volcanic glass (Fig. 4.7; Cape Roberts Project Science Team, 1999) and high and low magnetic susceptibility values (Fig. 1). Thus, the environmental magnetic signal in this portion of CRP-2/2A provides a record of variations in the supply of fine-grained volcanic particles from the McMurdo Volcanic Group. Grain size-dependent magnetic parameters indicate that these magnetite grains are, on average, finer than those from lower parts of the core (Fig. 6). In the lower parts of CRP-2/2A, the dominant source of magnetite is likely to be the Jurassic Ferrar Dolerite. The magnetic grain-size parameters indicate that there are detectable differences in the magnetite populations from the McMurdo volcanics and the Ferrar Dolerite (Figs. 6 & 7), at least in this part of the Victoria Land Basin.

Evidence from CRP-2/2A indicates that the onset of volcanism associated with the McMurdo Volcanic Group is considerably older than was suggested by evidence from CRP-1 (24 Ma compared to about 18 – 19 Ma; *cf.* Cape Roberts Project Science Team, 1999; Roberts et al., 1998; Wilson, Florindo et al., this volume; Wilson, Bohaty et al., this volume). Thus, the environmental magnetic signal from CRP-1 could also have a significant contribution from the McMurdo Volcanic Group. This point was not considered by Sagnotti et al. (1998a) because petrological studies indicated that the McMurdo volcanics did not become significant in CRP-1 until above 62 mbsf (Armienti et al., 1998).

CRP-2/2A ENVIRONMENTAL MAGNETISM: below 270 mbsf

The alternations between magnetite- and hematite-enriched intervals below 270 mbsf are interpreted to indicate variations in detrital input that reflect environmental changes which are apparently independent of lithological variations. It is clear from the environmental magnetic data that the concentration of magnetite varied considerably during the time interval represented by CRP-2/2A. It is unclear, however, whether the concentration of hematite was constant or if it was also variable. As stated above, hematite has a much weaker magnetic moment than magnetite so that when it co-occurs with magnetite, it is difficult to quantify its concentration. Therefore, we present two alternative interpretations for the environmental magnetic alternations below 270 mbsf, and, with the present data, we cannot distinguish between them. In one interpretation, hematite concentrations remained roughly uniform, and variations in magnetite concentrations are primarily responsible for the alternations. In the other interpretation, both hematite and magnetite varied, and as the concentration of one of these magnetic minerals increased, the concentration of the other decreased. According to either interpretation, the variations in magnetite concentration must have had a palaeoenvironmental origin.

Periodic alternations of magnetite concentrations were also noted in the CIROS-1 core in an interval which predated the onset of volcanism associated with the McMurdo Volcanic Group (Sagnotti et al., 1998b). These cyclic variations in magnetite concentration occurred in the late Eocene and coincided with variations in clay mineralogy that reflected changes in climate and weathering styles on the Antarctic craton. These cycles in magnetite concentration had a periodicity of more than 1 m.y. However, in the CIROS-1 core, Sagnotti et al. (1998b) did not observe intervals where hematite concentrations are as strongly evident as those observed below 270 mbsf in CRP-2/2A. Furthermore, the period of time represented by this interval in CRP-2/2A is not recorded in CIROS-1 (Wilson et al., 1998; Wilson, Florindo et al., this volume; Wilson, Bohaty et al., this volume). One possibility is that the Palaeozoic Beacon Supergroup is the dominant source of the hematite and the Jurassic Ferrar Dolerite is the dominant source of the magnetite. However, the Beacon Supergroup is pervasively intruded by the Ferrar Dolerite, and the two units occupy similar stratigraphic positions in the Transantarctic Mountains, which is a significant source area for the detritus deposited in the Victoria Land Basin. Thus, it is difficult to see how provenance fluctuations from these two units could produce the observed magnetic variations.

Based on weathering indicators from clay mineralogy (Ehrmann, 1997), Sagnotti et al. (1998b) suggested that the increased concentrations of magnetite in the CIROS-1 core were produced by increased chemical weathering of the Ferrar Dolerite during periods when the climate was relatively warmer. However, there is no evidence from clay mineralogy to support this interpretation for CRP-2/2A (Ehrmann, this volume). At present, the most plausible interpretation of the mineral magnetic variations observed below 270 mbsf in CRP-2/2A is the one given by Sagnotti et al. (1998a) for CRP-1, namely that the environmental magnetic signal reflects climate variations that occur below the threshold required to change the style of weathering as recorded by clay mineralogy.

An important remaining question concerns the lack of correspondence between magnetic fluctuations, which may reflect climatic variations, and the lithological record of glacial fluctuations in the Victoria Land basin. The magnetic minerals in CRP-2/2A are almost certainly detrital in origin. They were deposited in the Victoria Land Basin as a result of erosion in the Transantarctic Mountains and are therefore likely to reflect regional-scale or continental-scale processes. On the other hand, sedimentary facies will be dominated by changes in local environmental processes, such as water depth, relative position with respect to the glacial termination, currents, etc. (Powell et al., this volume). Our working hypothesis, therefore, is that environmental magnetic parameters might provide important information concerning Antarctic climate. This hypothesis can be tested by analysis of the deeper, and older, record provided by the CRP-3 core from the Victoria Land Basin.

CONCLUSIONS

The CRP-2/2A record can be divided into three intervals on the basis of magnetic properties (27 - 270 mbsf, 270 - 413 mbsf, and 413 - 624 mbsf). Variations in magnetic properties in the uppermost interval coincide with fluctuations in volcanic glass contributions from the McMurdo Volcanic Group (Cape Roberts Project Science Team, 1999). Magnetic properties in this interval therefore provide a useful proxy for variations in fine-grained volcanic detritus from the McMurdo Volcanic Group. The two lowermost intervals (270 - 413 mbsf, 413 - 624 mbsf) are marked by alternations between zones that are relatively enriched in magnetite and hematite, respectively. The magnetite and hematite grains are almost certainly detrital in origin, and the alternations in magnetic properties probably reflect fluctuations in palaeoenvironmental conditions. Late Eocene - early Oligocene sediments from the Victoria Land Basin also reveal large alternations in magnetic properties, which are strongly linked to climatically-driven fluctuations in the weathering regime on the Antarctic craton (Sagnotti et al., 1998b). While there is no compelling evidence for similar fluctuations in the weathering regime from clay mineral evidence in CRP-2/2A, it is possible that the magnetic property variations reflect climate variability below the threshold required to detect changes in clay mineral assemblages.

ACKNOWLEDGEMENTS

The palaeomagnetic component of the Cape Roberts Project was supported by grants from the U.S. National Science Foundation to KLV, APR, and GSW and from the Italian *Programma Nazionale di Richerche in Antartide* to LS and FF. We are grateful to Betty Trummel for her help in the laboratory at McMurdo Station and to John Tarduno and Ken Kodama for their reviews of the manuscript. Cristina McFadden, Aaron Gomez and Alex Roth assisted with the Micromag measurements at UC-Davis.

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