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Environmental Magnetism of Lower Miocene Strata from the CRP-1 Core, McMurdo Sound, Antarctica

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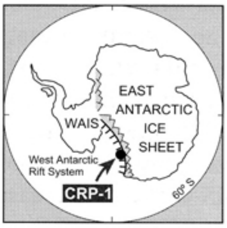
Abstract - Environmental magnetic data from the early Miocene sequence of the CRP-1 core, from McMurdo Sound, Antarctica, reveal an alternation between zones of high and low ferrimagnetic mineral concentrations. Although magnetite is the main magnetic mineral throughout the sequence, coercivity variations mirror the zonation in magnetic concentration, with high coercivities corresponding to zones of low concentration of ferrimagnetic grains and vice versa. High concentrations of ferrimagnetic grains (unoxidised magnetite) were found in fine-grained sediments that were deposited in a distal position with respect to the ice front, and in the lower part of one diamictite (Unit 6.3). Low concentrations of ferrimagnetic minerals occur in sandstones. We suggest that environmental changes that produced the variations in the amount of magnetite being eroded and transported to the CRP-1 site are best explained by a climatically-driven variation in the physical weathering regime on the Antarctic craton. Such fluctuations must have occurred in a relatively cold climate, below the threshold that would induce a change in the overall weathering regime. However, this interpretation is non-unique and rigorous interpretation of the sediment magnetic record requires validation from other data.



INTRODUCTION

Environmental magnetism involves the study of spatial and temporal trends in the magnetic properties of sediments that result from palaeoclimatic and other environmental processes (Thompson & Oldfield, 1986; Verosub & Roberts, 1995). In environmental magnetism, standard mineral magnetic methods are used to determine the concentration, mineralogy and grain-size of the magnetic particles in a sedimentary sequence, and variations in these parameters can often be used as proxies of palaeo-environmental changes that have taken place in a sedimentary basin and its surrounding catchment.

A recent environmental magnetic study of the CIROS-1 core, drilled in 1986 in the Victoria Land Basin, Antarctica (Barrett, 1989), revealed an alternation in magnetic properties that reflects variations between warm and cold periods during the late Eocene/early Oligocene (Sagnotti et al., 1998). This study confirmed that development of the Antarctic cryosphere was episodic in nature.

The Cape Roberts Project (CRP) is aimed at understanding the development of the Antarctic ice sheet and cryosphere and the coincident development of the Ross Sea Rift which resulted in uplift of the Transantarctic Mountains. CRP drilling aims to extend the stratigraphic record already recovered by CIROS drilling. The CRP-1 core was drilled in October, 1997, in 150 m of water, from a drill-rig situated on annual sea-ice, 16 km east of Cape Roberts, and 125 km northwest of McMurdo Station and Scott Base, Ross Island. The recovered sediments include a Quaternary sequence between 16 and 43.55 mbsf and a lower Miocene sequence between 43.55 mbsf and the bottom of the hole at 147.69 mbsf (Cape Roberts Science Team, 1998a, b, c, d). In the present paper, environmental magnetic results are reported from the lower Miocene portion of the CRP-1 core.

METHOD

Palaeomagnetic samples were collected at an average interval of 0.5 m, wherever sediment texture was suitable, in the consolidated lower Miocene sediments from the CRP-1 core (Cape Roberts Science Team, 1998a; Roberts et al., this volume). Mineral magnetic analyses were carried out on both standard cylindrical palaeomagnetic samples (25 mm diameter x 22 mm height) and on chips and powders from the same samples. These analyses were conducted after stepwise alternating field (AF) demagnetisation, which was performed to enable development of a magnetic polarity stratigraphy (Roberts et al., this volume).

Preliminary rock magnetic analysis of 18 samples was undertaken at McMurdo Station, Antarctica, during the 1997 drilling season (Cape Roberts Science Team, 1998a, c), and detailed studies were carried out later at the *Istituto*

Nazionale di Geofisica (Rome, Italy), the University of California-Davis (California, USA) and the Southampton Oceanography Centre (Southampton, United Kingdom).

Mineral magnetic measurements on cylindrical samples include: low-field magnetic susceptibility (κ) and its anisotropy (AMS), acquisition of an anhysteretic remanent magnetisation (ARM) in a peak AF of 100 mT with a superimposed 0.1 mT bias field, stepwise acquisition of an isothermal remanent magnetisation (IRM) up to 1 T and back-field demagnetisation of the IRM up to -0.3 T, with determination of coercivity of remanence (B_{cr}) and the S-ratio ($-IRM_{-0.3T}/IRM_{1T}$), and stepwise AF demagnetisation of the ARM and IRM, up to 100 mT, with determination of median destructive field (MDF). Samples that clearly contained large granules and pebbles were not included in the mineral magnetic analyses. Chip samples were used to determine hysteresis parameters (up to peak fields of 1 T), including saturation magnetisation (M_s), saturation remanent magnetisation (M_r), coercive force (B_c), and B_{cr}, and powder samples were used to measure high temperature magnetisation curves (in air with an applied field of 27 mT to minimise the contribution from paramagnetic phases).

AMS and k were measured with an AGICO KLY-2 Kappabridge susceptibility meter. ARM and IRM were measured with a 2G Enterprises cryogenic magnetometer with DC SQUID sensors when intensities were less than 10 A/m and with an AGICO JR-5A spinner magnetometer when intensities were higher than 10 A/m. AF demagnetisation was conducted with a 2G Enterprises AF demagnetizer that is in-line with the cryogenic magnetometer. Hysteresis loops were measured with a Princeton Measurements Corporation Micromag alternating gradient magnetometer and high temperature measurements were made with a Magnetic Measurements variable field translation balance.

Magnetic susceptibility (κ) and the intensities of the natural remanent magnetisation (NRM) and artificial remanences (ARM, IRM, M_s and M_r) are generally indicative of the concentration of ferrimagnetic minerals in a sample, whereas coercivity parameters (B_c, B_{cr}, S-ratio and MDF) and thermomagnetic curves are more diagnostic of magnetic mineralogy. Hysteresis ratios (M_r/M_s and B_{cr}/B_c) generally provide information on magnetic domain state (grain size), and AMS is particularly sensitive to the magnetic fabric of a sediment.

RESULTS

MAGNETIC MINERAL CONCENTRATION

For the Miocene portion of the CRP-1 core, all concentration-dependent magnetic parameters (κ, ARM, SIRM, M_s and M_r) have similar patterns of variation. In particular, high concentrations of ferrimagnetic minerals occur in two main intervals (Fig. 1). The first encompasses the whole of Unit 5.8 (a mudstone which extends from 92.2 to 103.4 mbsf) and the upper 2.5 metres of Unit 6.1 (a diamictite). The second interval of high ferrimagnetic concentration (from 124.2 to 143.8 mbsf) spans the lower two-thirds of Unit 6.3 (a diamictite) and the uppermost 2.2 m of the basal claystones (Unit 7.1). The lower part of Unit 6.3 has reversed magnetic polarity and a strong normal polarity overprint (Roberts et al., this volume) which combine to produce the relatively low NRM intensities shown in figure 1. Two other thin intervals of fine-grained sediment have relatively high concentrations of ferrimagnetic minerals: a silty fine sandstone (85 - 87 mbsf) in Unit 5.7 and a combination of siltstone and claystone (110.5 - 112.5 mbsf) in Unit 6.2 (Fig. 1). Low concentrations of ferrimagnetic minerals occur elsewhere, generally in sandy units.

The highest value for each of the parameters in figure 1 is found in Unit 5.8 at *c.* 98 mbsf. The range of values for the

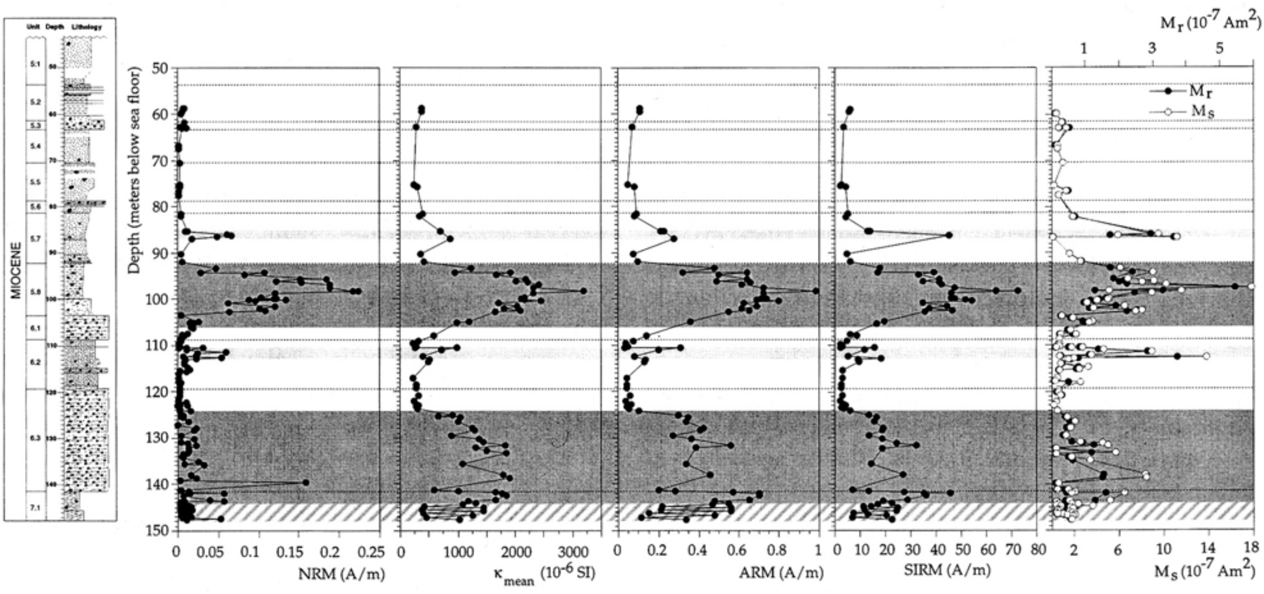


Fig. 1 - Downcore variation of ferrimagnetic concentration-dependent parameters (NRM, $κ_{mean}$, ARM, SIRM, M_r and M_s) in the CRP-1 core. The thin dashed lines indicate the lithostratigraphic boundaries. The dark shaded areas indicate the two main intervals with high concentrations of ferrimagnetic minerals. The light shaded areas indicate the two thin intervals with moderately high concentrations of ferrimagnetic minerals. The striped area at the bottom of the core indicates an interval with highly variable magnetic parameters (see also Figs. 2 & 6).

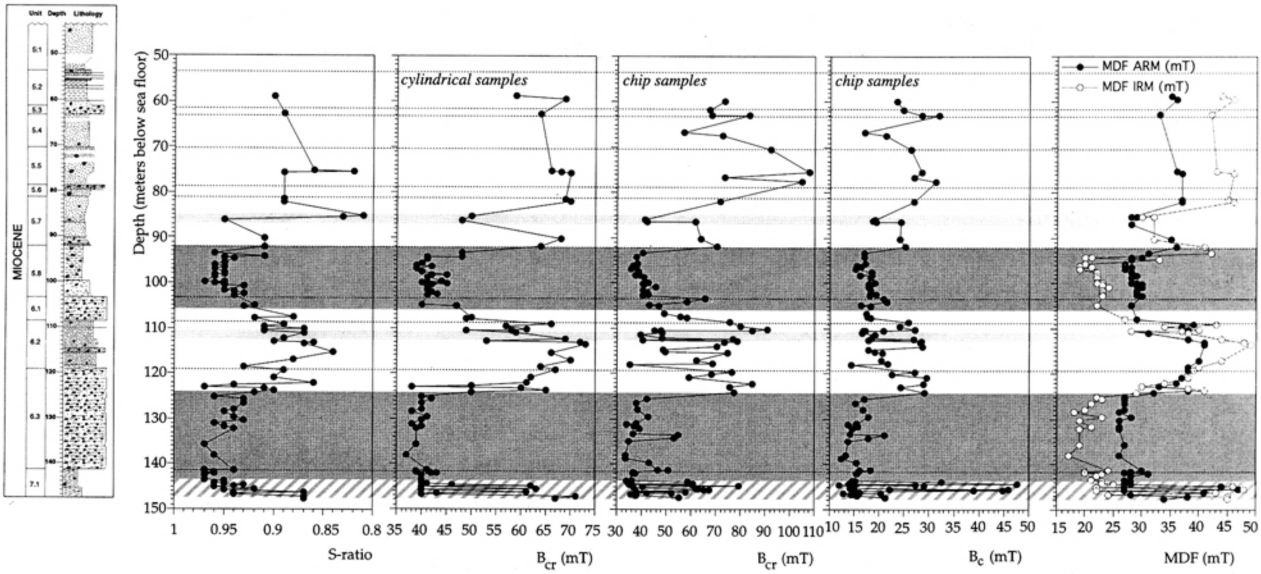


Fig. 2 - Downcore variation of the coercivity-dependent rock magnetic parameters (S-ratio, B_{cr} (from cylindrical samples), B_{cr} (from rock chips), B_c (from rock chips), MDF_{ARM} and MDF_{IRM}) in the CRP-1 core. The zonation is the same as in figure 1 (see also Fig. 6).

concentration-dependent magnetic parameters is comparable with that observed in the late Eocene/early Oligocene interval of the CIROS-1 core (Sagnotti et al., 1998).

In this study, samples that obviously contain pebbles have not been included, which results in elimination of several susceptibility peaks shown in figure 28e of the Initial Report of the Cape Roberts Science Team (1998c). The magnetic measurements from the diamictite units are now probably free from the influence of pebbles and can be considered representative of the rock matrix. Magnetostratigraphic work (Roberts et al., this volume) indicates that the lower 4 m of the recovered record has mixed magnetic polarity and that there are large variations in magnetic properties over short stratigraphic intervals. It is difficult to satisfactorily explain the observed magnetic behaviour of these sediments, and results from the basal part of Unit 7.1, from 143.8 to 147.69 mbsf, are not discussed in detail here.

DETERMINATION OF THE MAGNETIC MINERALOGY

The magnetic zonation indicated by the ferrimagnetic concentration-dependent parameters is also evident in the coercivity-dependent parameters (B_{cr}, B_c, MDF_{ARM}, MDF_{IRM}, S-ratio). Low concentrations of ferrimagnetic minerals occur in zones of relatively high coercivities and high concentrations of ferrimagnetic minerals occur in zones of relatively low coercivities (Fig. 2). Relatively high coercivities (*i.e.*, $B_{cr} > 50$ mT) are widespread in the upper part of the studied sequence, from 58 to 92 mbsf, and in the interval from 106 to 124 mbsf. The highest coercivities were found at *c.* 76 mbsf, with a peak in B_{cr} of more than 100 mT. In general, coercivities measured on cylindrical samples were slightly lower than corresponding measurements on chip samples (Fig. 2). This illustrates the discrepancies that can arise between measurements that employ direct and pulsed fields. Despite these differences, consistent patterns are observed in the coercivity-dependent parameters for the two methods (Fig. 2). Differences between the low and high coercivity zones are evident in IRM acquisition data: saturation is reached in fields of *c.* 200 mT in the low coercivity zones, whereas saturation is reached in inducing fields of *c.* 500 mT in the high coercivity zones (Fig. 3).

The presence of a distinct Curie temperature of *c.* 580°C in the heating portion of the high temperature magnetisation curves indicates that magnetite is the main magnetic mineral in the sequence (Fig. 4b, d, e & f). A paramagnetic component dominates the ferrimagnetic signal in many

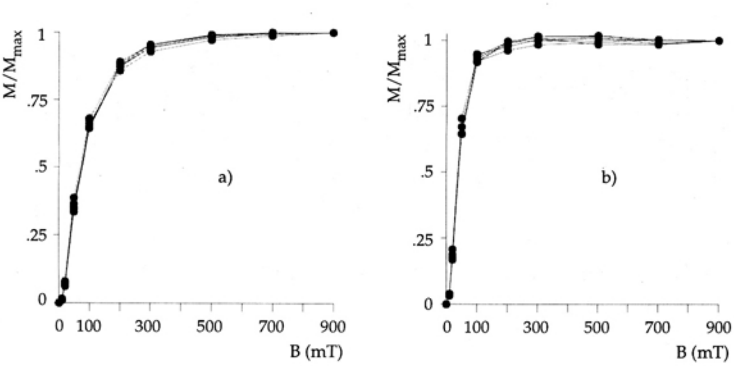


Fig. 3 - Representative IRM acquisition curves, up to 0.9 T, for: *a*) 7 samples from a high-coercivity interval (58 - 82 mbsf) which reach saturation at *c.* 500 mT, and *b*) 6 samples from a low-coercivity interval (97 - 100 mbsf) which reach saturation at *c.* 200 mT.

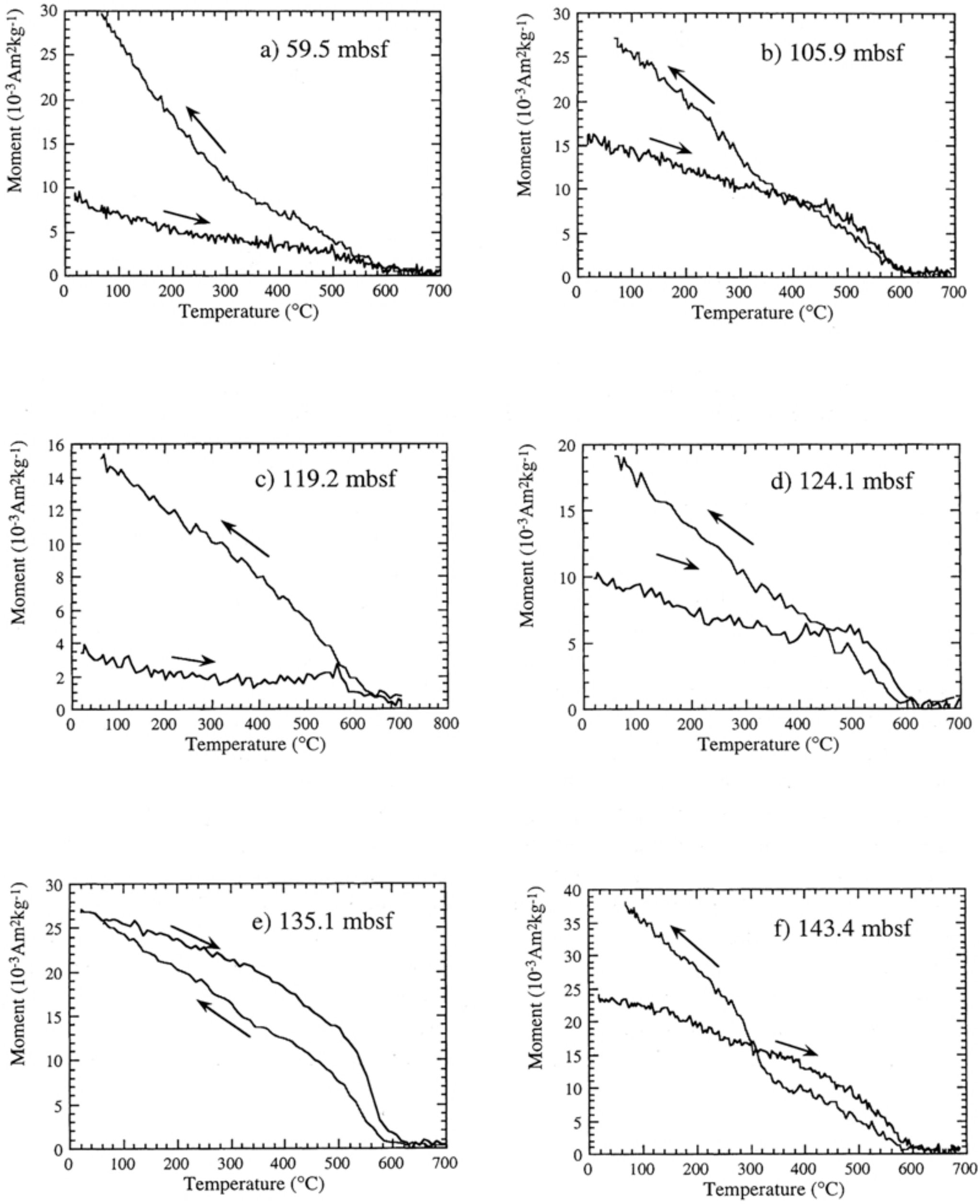


Fig. 4 - Variation of the magnetic moment *vs.* temperature in a heating-cooling cycle from room temperature to 700°C for samples from CRP-1 at depths of: *a)* 59.5 mbsf; *b)* 105.9 mbsf; *c)* 119.2 mbsf; *d)* 124.1 mbsf; *e)* 135.1 mbsf,and *f)* 143.4 mbsf. Though the paramagnetic component swamps the ferrimagnetic signal in many of the low magnetic intensity samples (*a*, *c*), a distinct Curie temperature at *c.* 580°C indicates that magnetite is the dominant magnetic mineral in the sequence.

samples (*e.g.*, Fig. 4a & c).

There is a clear difference in hysteresis properties between the low and high coercivity zones in a plot (Fig. 5) of M_r/M_s *vs.* B_{cr}/B_c (*cf.* Day et al., 1977). The high coercivity zones have higher M_r/M_s and B_{cr}/B_c ratios than the low coercivity zones, which probably indicates a greater relative contribution of high-coercivity minerals (*i.e.*, hematite) rather than any difference in grain size. Moreover, the measured hysteresis ratios plot above the trends reported for synthetic single size magnetites and magnetite mixtures (Fig. 5b); which is consistent with the presence of high-coercivity minerals. However, the hysteresis loops have conventional shapes that are typical of SD and PSD ferrimagnetic minerals and they do not show characteristics typical for mixtures of magnetic minerals with markedly different coercivities (*i.e.*, "wasp-waisted" shapes; see Roberts et al., 1995). This suggests that high-coercivity minerals must occur only in moderate amounts. It should also be noted that hysteresis parameters from the lower 4.5 m of the core are highly variable and have a large range of values, which is difficult to explain with currently available data.

Given that the observed alternations in coercivity in the CRP-1 core probably reflect variations in magnetic mineralogy, it is not appropriate to use ratios of magnetic parameters, such as SIRM/k, SIRM/ARM, M_r/M_s and B_{cr}/B_c, to make detailed inferences about magnetic grain size and/or domain state.

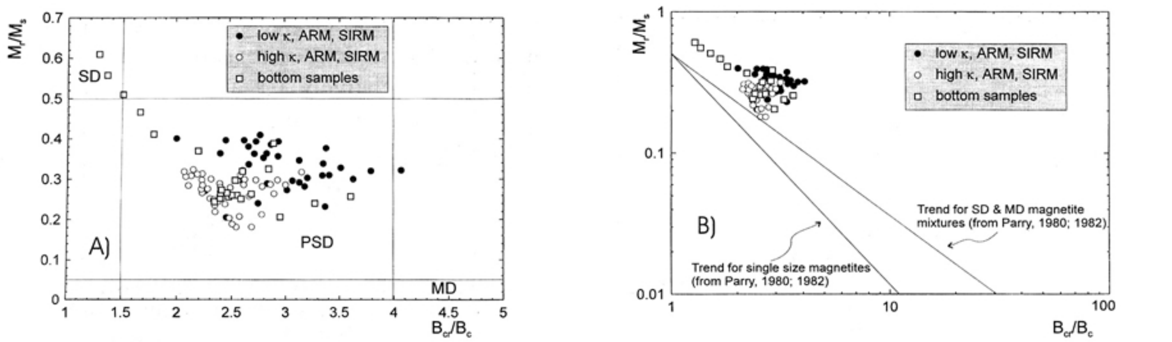


Fig. 5 - Plot of M_r/M_s *vs.* B_{cr}/B_c for samples from the CRP-1 core. "Bottom" samples refer to samples from below 143.8 mbsf. *A)* Plot with linear scales - the lines indicate the fields for single domain (SD), pseudo-single domain (PSD) and multidomain (MD) magnetites (*cf.* Day et al., 1977). *B)* Bilogarithmic plot - the trends for synthetic single size magnetites and magnetite mixtures (Parry, 1980, 1982) are shown for comparison.

ANISOTROPY OF MAGNETIC SUSCEPTIBILITY

The AMS data were used to compute the anisotropy parameters of Jelinek (1981). In particular, the corrected anisotropy degree (P') and the shape factor (T) were used to quantify the intensity of the anisotropy and the shape of the AMS ellipsoid, respectively. The magnetic fabric of the samples appears to vary according to facies and in accord with the ferrimagnetic concentration-dependent parameters: sands have low concentrations of ferrimagnetic minerals and almost isotropic magnetic fabrics (*i.e.*, P' < 1.01), whereas siltstones and fine-grained sediments (including the matrix of some diamictites) have a detectable magnetic anisotropy (*i.e.* P' > 1.01), which indicates a preferred orientation of the magnetic grains (Fig. 6). Mean susceptibility ranges between 227 and 3200 µSI (average of 1131 µSI). The high values of the mean susceptibility in zones of high ferrimagnetic concentration provide evidence that the ferrimagnetic contribution dominates the paramagnetic and diamagnetic contributions of the rock matrix in these zones (*cf.* Tarling & Hrouda, 1993). Therefore, AMS reflects the preferred orientation of only the ferrimagnetic grains. By fitting a regression line to a plot of SIRM *vs.* κ (Fig. 7), we estimate that there is a base level of paramagnetically-controlled susceptibility of *c.* 235 µSI. This is consistent with observations from thermomagnetic data (Fig. 4), in which the paramagnetic component is dominant in the zones of low ferrimagnetic mineral concentration. In samples with measurable anisotropy, oblate (*i.e.*, T > 0) ellipsoids prevail and there is a tendency for the minimum susceptibility axes (κ_{min}) to be perpendicular to the bedding plane (especially in the fine-grained sediments). However, prolate fabrics (*i.e.*, T < 0) and low-angle κ_{min} are also present throughout the sequence (Fig. 6). Whereas the development of a magnetic foliation parallel to bedding is to be expected due to compaction, the cause of the prolate magnetic fabrics is not understood and could be investigated through detailed

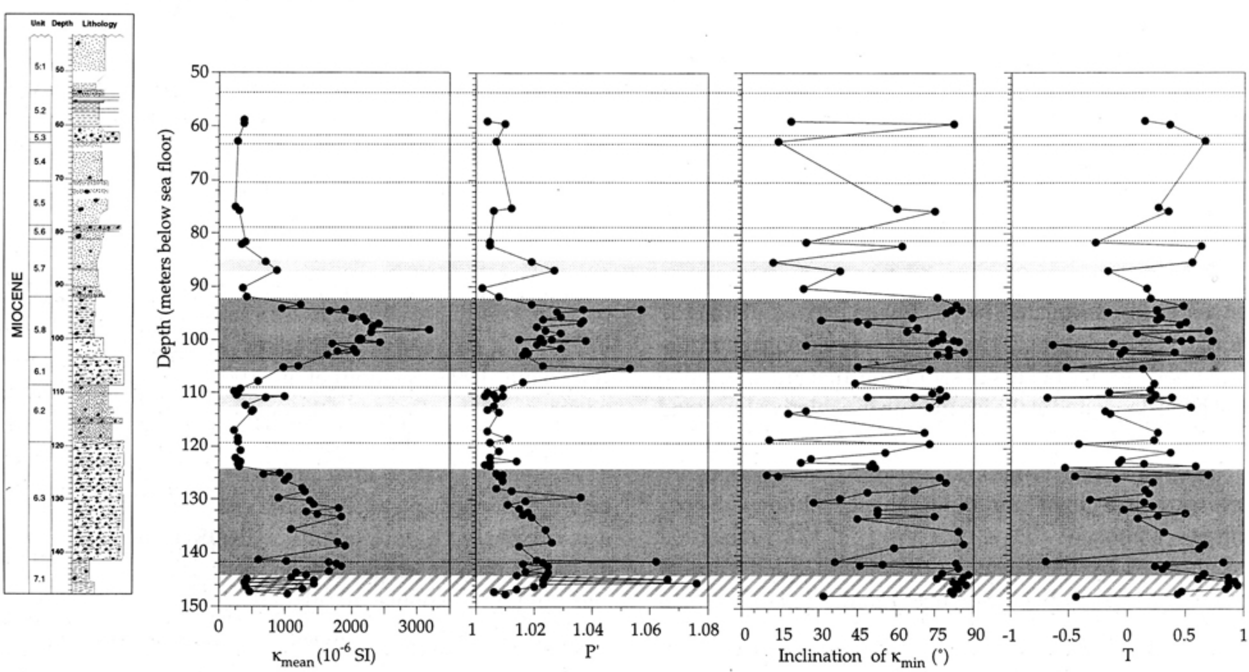


Fig. 6 - Downcore variation of the magnetic anisotropy parameters (κ_{mean}, P', Inclination of κ_{min} and T) in the CRP-1 core. The corrected anisotropy degree P' and the shape factor T are from Jelinek (1981). The zonation is the same as in figure 1 (see also Fig. 2).

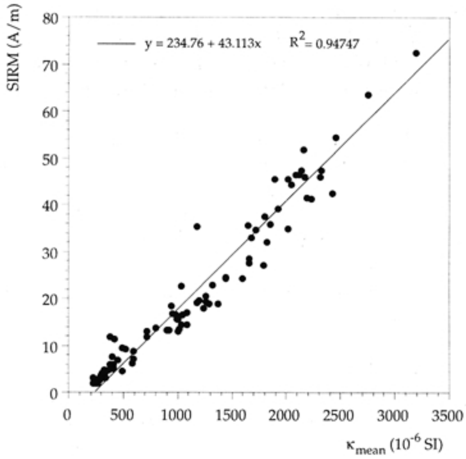


Fig. 7 - SIRM *vs.* low-field magnetic susceptibility (κ_{mean}). The intersection of the regression line with the κ-axis provides an estimate of the base level contribution from the paramagnetic susceptibility (235 µSI).

analysis of the domain-state and shape of the ferrimagnetic grains. High variability and the lack of regular trends in the shape of the AMS ellipsoids were also found in the high ferrimagnetic intensity zones recognized in the lower sequence of the CIROS-1 core (Sagnotti et al., 1998).

DISCUSSION

Nearly all of the sequence studied lies below 62 mbsf (dated at *c.* 18 Ma), which is recognised as the boundary that marks the onset of eruptive activity associated with the McMurdo Volcanic Group (Cape Roberts Science Team, 1998c). Because the sequence studied was deposited prior to this episode of volcanism, we assume that the mineral magnetic record reflects changes in detrital input that are linked to environmental processes and not to variations in volcanic activity in the area. The upper zone of high ferrimagnetic concentration and the two thinner zones of high ferrimagnetic concentration are associated with finer-grained sediments (mudstones and siltstones), that were deposited during periods of high relative sea level or in a relatively distal position from the ice margin, under relatively mild climatic conditions and with input of minor ice rafted detritus (Cape Roberts Science Team, 1998c, d).

Most of the lower zone of high ferrimagnetic concentration is located in the lower part of diamictite Unit 6.3 (124 - 141 mbsf). Here, the increased concentration of magnetic grains occurs in sediments that are inferred to have been deposited at the ice margin in a relative lowstand in sea level. Furthermore, the change from high to low ferrimagnetic concentration at the top of this zone does not correspond to a major lithological change, although it does coincide with a possible unconformity at 124.2 mbsf that was inferred by the presence of mineral-filled vertical fractures (Cape Roberts Science Team, 1998e; see also Roberts et al., this volume).

Zones of low concentration of ferrimagnetic minerals in the sequence usually occur in sandstones that are interpreted as having been deposited during lowstands in relative sea level when glaciers advanced toward the drill site (Cape Roberts Science Team, 1998c, d). These deposits also have a relatively larger contribution from high coercivity magnetic minerals, which suggests a significant decrease or dilution of the influx of strongly magnetic low-coercivity grains. This is probably related to varying climatic conditions.

The AMS data can be used to investigate changes in the magnetic fabric of the sequence. Random magnetic fabrics suggest deposition in quiet water, either by fallout of detrital grains from suspension or by the dropping of debris from floating ice. The increase in anisotropy degree found in the siltstones and clays (*i.e.,* Units 5.8 and 7.1) is essentially controlled by an increase in the degree of magnetic foliation, with oblate AMS ellipsoids and vertical κ_{min}. This degree of anisotropy may reflect compaction in fine-grained sediments, which produces a preferential orientation of particles in the bedding plane. With regard to the diamictites, in Unit 6.3 a decreasing trend exists in the AMS intensity from values at the bottom which are similar to those measured in the underlying clay (Unit 7.1), toward values at the top which are similar to those in the overlying sandy Unit 6.2. This may indicate a tendency toward a progressively coarser-grained matrix in the diamictite.

CONCLUSIONS

It is possible that variations in the environmental magnetic data from the CRP-1 core are due to fluctuations in position of the termini of temperate glaciers. Despite this possible link between sediment magnetic properties and glacial activity, there are currently few constraints from non-magnetic data to indicate the environmental process that controls the magnetic signal (*e.g.*, weathering, depositional energy, diagenesis, etc.). Until such a link is evident, it is not possible to rigorously interpret the sediment magnetic record. Also, in this case, the magnetic properties are not uniquely associated with one lithology. In fact high ferrimagnetic (unoxidised magnetite) content seems to be preferentially associated with fine-grained sediments (*i.e.*, distal with respect to the ice front), high ferrimagnetic concentrations are also found in one of the diamictites (Unit 6.3).

In the case of the CIROS-1 core, the alternation between zones of high and low magnetic mineral concentration corresponds to variations in clay mineralogy which are interpreted to represent changes in weathering style (Ehrmann, 1997; Sagnotti et al., 1998). These variations occur near the Eocene-Oligocene boundary and are coincident with the timing of Antarctic cryosphere development (Wilson et al., 1998). Given the direct link between magnetic parameters and indicators of weathering, it is reasonable to interpret the CIROS-1 environmental magnetic data in terms of continent-wide cooling and warming in response to glacial fluctuations. Similar phenomena may be responsible for the environmental magnetic record in the CRP-1 core. However, in this case, the absence of a correlation with clay mineralogy suggests climatic fluctuations in a relatively cold environment, that is below the threshold for a change in the style of weathering. The magnetic fluctuations in the CRP-1 sequence may reflect a change in the degrees of physical weathering on the Antarctic craton which changes the amount of magnetite being liberated and transported to the CRP-1 site. We interpret this to be a regional climatic phenomenon that may be enhanced in the stratigraphic record by fluctuating sea level which draws the ice tongue out across the continental shelf across the CRP-1 site.

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