Terra Antartica
2000, 7(3), 379-388

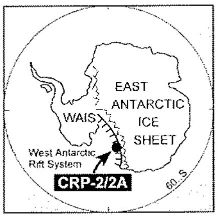
High-Frequency Analysis of Physical Properties from CRP-2/2A, Victoria Land Basin, Antarctica and Implication for Sedimentation Rate

M. CLAPS[1*], F. NIESSEN[2] & F. FLORINDO[3,4]

[1]Istituto di Scienze del Mare, Università di Ancona, Via Breece Bianche, 60131 Ancona- Italy
(Present address: OKIOC, Raamweg 26, 2596 HL - The Hague - Netherlands)
[2]Alfred Wegener Institute for Polar and Marine Research, P.O. Box 20161, D-27515 Bremerhaven - Germany
[3]Istituto Nazionale di Geofisica, Via di Vigna Murata 605, I-00143 Rome - Italy
[4]School of Ocean and Earth Sciences, University of Southampton, Southampton Oceanography Centre, European Way, Southampton SO14 3ZH - United Kingdom

**Corresponding author* (m.claps@okioc.nl)

Received 17 August 1999; *accepted in revised form* 23 February 2000



Abstract - Siliciclastic sediments of Quaternary to Oligocene age were drilled in the Victoria Land Basin (Antarctica) 14 km east of Cape Roberts by the Cape Roberts Project during the Austral Spring of 1998. The cored section consists of a suite of lithofacies, from diamictite and conglomerate to sandstone and mudstone; these are organized in stratigraphic sequences yielding a record of glacial advance and retreat and substantial changes in sea level. In this study, the analysis of the physical properties (low-field magnetic susceptibility and wet bulk density) is conducted on selected fine-grained intervals in association with sedimentological observations in order to better understand high-resolution stratigraphy and cyclostratigraphy. These two physical parameters are characterized by distinctive high-frequency cyclicities. To investigate the presence of possible deterministic periodicities recorded in selected portions of the cored section, frequency analysis techniques were applied to both physical properties data series. The results demonstrate the presence of three main sets of periodicities, in tune with those associated with Milankovitch orbital perturbations. The approach used in this study outlines the potential of spectral analysis as a tool for high-resolution stratigraphy. Furthermore, the detected periodicities allow a refined evaluation of sedimentation rates for the fine-grained intervals, further constraining rates estimated by other independent methods.

INTRODUCTION

Cyclicity recorded in sedimentary successions represents a very important aspect in geological investigation since it sheds light on the occurrence of periodic changes (of any type) occurring in depositional environments, as a possible response to external forcing. Milankovitch cycles, which have gained particular interest in geology in recent years (Fischer, 1986; Fischer et al., 1990; Fischer & Bottjer, 1991; de Boer & Smith, 1994; House, 1995), have been demonstrated to be responsible for producing rhythmic variations in sediment composition in several depositional settings. The main Milankovitch components are the precession cycle (caused by the lag between equinox and perihelion, with two main components at 19 and 23 ky, and average time length 21 ky), the obliquity cycle (an effect of the tilt of Earth's axis, with two main components at 41 and 54 ky) and the short-term eccentricity cycle (variation in the eccentricity of the Earth's orbit, with two main components at 95 and 123 ky, average time length *ca.* 100 ky) (see for references Berger, 1984; Fischer et al., 1990; Berger & Loutre, 1994). Spectral analysis is the most useful technique to test if the cyclicity observed in a stratigraphic record is controlled by non-random discrete periodicities. The comparison between these periodicities and the orbital perturbations becomes then instrumental in order to discuss the presence of Milankovitch periods. For a review on the application of time series analysis to stratigraphy see Pestiaux & Berger (1984), Weedon (1991) and Doveton (1994).

A pilot study investigating the CRP-2/2A core in terms of high-frequency cyclicity was carried out on site after the drilling (Cape Roberts Science Team, 1999). Frequency analysis was performed on a selected fine-grained interval (lithostratigraphical Sub-unit 11.3), which revealed a strong and regular cyclic pattern. These promising results led to a more complete search for cyclicity throughout the entire CRP-2/2A record, suggesting that the fine-grained laminated facies of the recovered section yield a high potential for the application of this type of analysis.

Grain size data from other intervals of the CRP-2/2A core have been analysed using spectral analysis by Naish et al. (this volume) and give additional information on the presence of periodic components in the Milankovitch time-window.

Previous studies demonstrated that the concentration of the ferromagnetic fraction seems to be the resulting effect of changes between glacial and interglacial times, where its highest concentration corresponds to maximum ice-rafted detrital supply and discharge from glacial areas (Robinson, 1986). Studies of depositional environments with relatively high sedimentation rates, such as shelf and slope settings, confirmed that the concentration of ferromagnetic minerals decreases during interglacial periods and reaches high values during glacial times (Davies et al., 1991). In several of these cases, low-field magnetic susceptibility variations (indicative of modification in the concentration of highly-magnetic minerals) correlate with changes in the insolation curve, as predicted by the Milankovitch theory (Robinson, 1986; Bloemendal & deMenocal, 1989; Thibal et al., 1995; Arai et al., 1997; Barthes et al., 1999).

Downhole geophysical logs (*e.g.* sonic, resistivity, gamma ray, density, magnetic susceptibility) have been used for almost a decade to detect regular variations in mineralogy and porosity. Fluctuations of these physical properties provide a high-resolution continuous stratigraphic record and in many examples allow the detection of the dominant frequencies, which might have driven such variations. Jarrard & Arthur (1989) showed that the cyclicity detected in the downhole logs from ODP Leg 105, Labrador Sea and Baffin Bay, is primarily expressed by porosity fluctuations, and demonstrated that Milankovitch orbital periodicities are their forcing factor.

The core of this paper is to examine the cyclic pattern that can be observed at high-frequency scale in the physical properties record from selected lithostratigraphical intervals of the CRP-2/2A core. Spectral analysis techniques (Pestiaux & Berger, 1984; Fischer et al., 1990; Doveton, 1994, Paillard et al., 1996) are applied to the numerical values extracted from the low-field magnetic susceptibility and wet bulk density arrays of the core. Since these sets of analytical data are recorded with a high-resolution level they demonstrated to be very suitable for this purpose.

STRATIGRAPHY AND SEDIMENTOLOGY OF THE STUDIED INTERVALS

The Cape Roberts Project is an international drilling project, specifically designed to core strata on the western side of McMurdo Sound (Antarctica) in order to investigate and reconstruct the climatic and tectonic histories of this geological region during the Cenozoic. The CRP-2/2A core was drilled in western McMurdo Sound (approximately 15 km off Cape Roberts) during the Austral Spring 1998 and penetrated *ca.* 624 m of sediments. Biostratigraphic and magnetostratigraphic investigations establish an age for the entire CRP-2/2A succession spanning from Quaternary to early Oligocene (Cape Roberts Science Team, 1999).

Sedimentologically, the section comprises a number of lithofacies, from mudstone and very fine to fine sandstone, medium and coarse sandstone up to diamictite and conglomerate (Cape Roberts Science Team, 1999; Powell et al., this volume). Fifteen lithostratigraphical units, based on major changes in lithology, have been distinguished in the sedimentary succession. These have been subdivided into sub-units, when small scale lithological changes occur (Fig. 1). A preliminary investigation of the cored section, based on facies and sequence analysis, recognized twenty three unconformity-bound depositional sequences; these are vertically stacked and interpreted to record times of substantial changes in sea level and glacial advance and retreat episodes (Cape Roberts Science Team, 1999; Fielding et al., this volume). In this paper, we focus attention on four intervals represented by fine-grained lithologies: mudstone, sandy

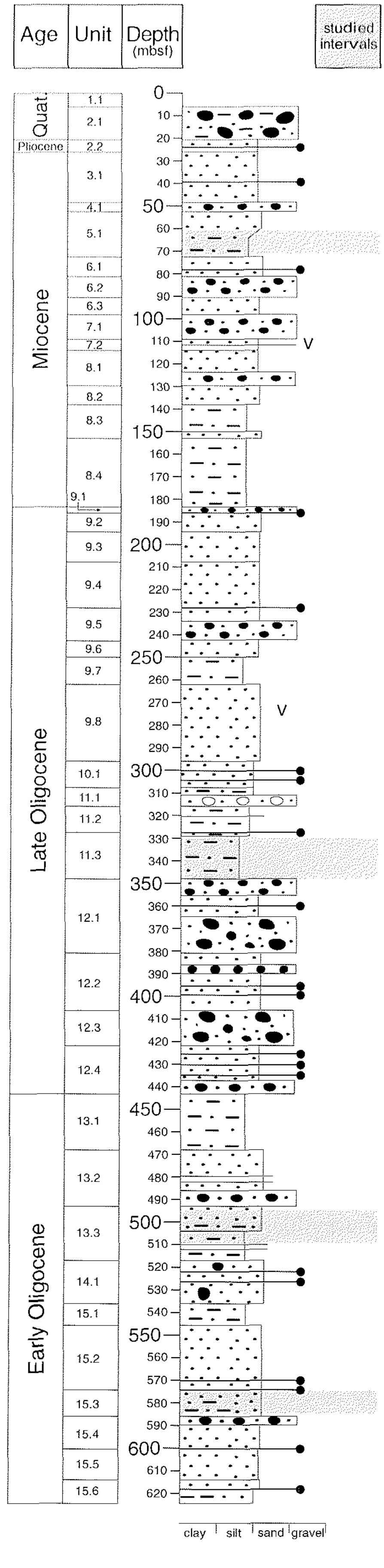


Fig. 1 - Lithostratigraphic column of the CRP-2/2A core showing the four fine-grained intervals where magnetic susceptibility and wet bulk density have been analysed for high-frequency cycles (indicated by grey areas on the right). Ages are after Wilson et al. (this volume).

siltstone, muddy very fine and fine sandstone (Fig. 1). Their sedimentological characteristics are summarized in the following section.

1) Interval 59.77-71.78 mbsf
(within Lithostratigraphical Sub-unit 5.1)

Consists of black massive mudstone and very fine sandy mudstone, with very few, scattered and isolated clasts. Compositionally it is represented by 40 to 50% of clay minerals, mainly illite. Generally, sedimentary structures are lacking and bioturbation is absent to weak. Where laminations are present, they occur as mm-thick muddy very fine sandstone laminae, rich in quartz grains, within the mudstone matrix. Carbonate cementation is rare and irregularly distributed along the interval.

2) Interval 329.30-347.31 mbsf
(within Lithostratigraphical Sub-unit 11.3)

Contains almost entirely dark grey and dark greenish grey massive mudstone (represented by illite and smectite), locally with beds and laminae of fine sandy siltstone and fine to medium sandstone. Granules and small clasts are locally dispersed, but scarce overall. The degree of bioturbation ranges from weak to moderate. Few areas of weak carbonate cementation are present.

3) Interval 494.18-509.19 mbsf
(within Lithostratigraphical Sub-unit 13.3)

Dominated by various lithologies, which appear thinly interbedded to interlaminated at different scales. The more common lithologies are represented by dark greenish grey fine and very fine sandstone, either massive or interbedded, and clayey siltstone, sometimes interlaminated with fine and very fine sandstone laminae (in particular within the lower portion of the interval). A low degree of bioturbation is common in the finer grained lithologies. Clasts are locally dispersed, while granules are normally concentrated in a few layers. Carbonate cementation occurs as nodules in patchy areas.

4) Interval 574.30-584.70 mbsf
(within Lithostratigraphical Sub-unit 15.3)

Composed of greenish grey, laminated to massive, fine and very fine sandstone interbedded with dark greenish grey massive mudstone. Fine and very fine sandy laminae and thin beds range from planar to slightly crossed at low angle. Laminations of mm-thick very fine sandstone and siltstone might occur within the mudstone, commonly fining upwards to claystone. Clast and granules are rare and bioturbation structures are entirely absent. Local areas of carbonate cementation occur.

These lithological intervals, in particular where mudstone is the dominant lithofacies, are interpreted to represent deposition in a relatively deep and quiet marine environment. The presence of marine macrofossils and bioturbation suggest that hemipelagic sedimentation was the main contributor to the deposition of these intervals (Cape Roberts Science Team, 1999). The sandy components are characteristic of fluvially derived highly dilute turbid plumes; the fine and very fine sandy beds and laminations represent episodes of wave and current action (Cape Roberts Science Team, 1999).

Because of the nature of the hemipelagic background sedimentation, which took place at the margin of the Victoria Land Basin (Cooper & Davey, 1985, 1987), the lithostratigraphic intervals used in this study represent the best candidates to have recorded a cyclic signature. Nevertheless, their close visual examination does not display a prominent sedimentological cyclicity, in terms of strong and clear patterns of alternating beds or repetition of lithologies. In this case the comparison between the high-resolution record gained from the measurement of physical properties variability and the sedimentological pattern does not reveal a good correlation in terms of periodic alternations. Therefore we suggest that magnetic susceptibility and wet bulk density are essential tools for investigating in detail sequences which do not show any cyclicity at a macro-scale investigation.

It should be noted that both magnetic susceptibility and wet bulk density are recorded downhole in depth, and the two parameters are treated in the following analysis as depth series. Detailed sedimentological analysis (Cape Roberts Science Team, 1999) proves that the sedimentary record represented by the four intervals under investigation is complete with no evidence of important hiatuses, and based on their inferred hemipelagic nature it is hypothesized that sedimentation rate has remained approximately constant throughout.

METHODS

PHYSICAL PROPERTIES MEASUREMENTS

Low-field magnetic susceptibility was measured continuously along the whole core down-section at the drill-site laboratory, with a constant sampling rate of 2 cm, using a Bartington MS-2C magnetic susceptibility meter connected to a loop sensor of 80 mm internal diameter. Data were later corrected for loop sensor and core diameter using a sensor-specific coefficient, in order to obtain a series of directly comparable values (Niessen et al., 1998; Cape Roberts Science Team, 1999). This method provides an excellent and complete record of fluctuations within the CRP-2/2A sedimentary succession.

Low-field magnetic susceptibility values include the contribution of all magnetic minerals (diamagnetic, paramagnetic and ferromagnetic *sensu latu*) present in the sediment in proportion to their susceptibility and abundance. Generally, if a sediment contains paramagnetic minerals as common constituents, for susceptibilities larger than 3×10^{-3} (SI) the susceptibility is primarily dominated by the ferrimagnetic fraction (this is mainly true for magnetite concentration >~1%). In the last years, magnetic susceptibility has been frequently used as a proxy for magnetic mineral concentration (Thompson & Olfield, 1986; Verosub & Roberts, 1995; Dekkers, 1997) even if it has been demonstrated that the low-field magnetic susceptibility (in magnetite) could also be a function of grain size (Maher, 1988). Rock magnetic analyses (Wilson et al., this volume; Verosub et al., this volume) indicate that the magnetic mineralogy is mainly dominated by magnetite and/or titanomagnetite. Moreover, for the selected fine-grained intervals of CRP-2/2A, comparison with other bulk magnetic parameters, such as isothermal (IRM) and anhysteretic (ARM) remanent magnetizations, confirm that the magnetic susceptibility is controlled by the concentration of ferrimagnetic minerals.

Wet bulk density was measured from attenuation of a gamma-ray beam transmitted from a radioactive source, through the core-centre and the underlying carrier and finally focused into a detector. Output from the gamma detector was then calibrated for the different core diameters to equalize the final values (Cape Roberts Science Team, 1999). Wet bulk density is used to derivate variation in porosity, in particular for short core intervals where the depth-induced compaction can be assumed as a constant factor. If the compaction trend is small or negligible, as is the case of these fine-grained intervals of CRP-2/2A (Cape Roberts Science Team, 1999), porosity in turn is directly linked to clay content and average grain size (Hamilton, 1976). For these reasons the wet bulk density can be of extreme importance in identifying fine-scale lithological changes, which cannot be clearly recognised during the visual core description at macro-scale examination. Although the overall correlation between grain size and porosity (calculated from wet bulk density) is moderate for the entire CRP-2/2A core, mudstone units are clearly associated with increased porosity (Niessen & Jarrard, 1998). This implies a primary control of grain size on wet bulk density for the intervals discussed in this paper.

Using the formula given in Niessen et al. (1998) the magnetic susceptibility has been corrected for porosity (computed from wet bulk density). Then the original data have been compared with the new calculated values: the two curves show only shifts in amplitude but shape and oscillations of the magnetic susceptibility signal appear to be not affected by porosity variations. Therefore it is possible to assume that magnetic susceptibility is mainly indipendent from changes in porosity and consequently in wet bulk density.

In each lithostratigraphical interval the cross correlation of magnetic susceptibility and wet bulk density show that the curves are dominantly opposite in phase. Bearing in mind that, for the lithological intervals under study, the wet bulk density is controlled by the relative proportion of mud and silt-sand fractions and that the magnetic signal is mainly produced by concentration changes within the more granular fraction, it can be inferred that this antiphase relationship is likely to be directly controlled by grain size changes. Therefore, it can be concluded that fluctuations in grain size, at the scale investigated here, are controlling the physical properties signals.

SPECTRAL ANALYSIS

The logs of the two physical properties analysed exhibit a very strong cyclic signal, in particular throughout fine and very fine-grained sediments (mudstone and fine to very fine sandstone intervals), providing an unique opportunity for testing the existence of high-frequency cycles in the CRP-2/2A glaciomarine setting. The investigation was carried out by spectral analysis techniques (Paillard et al., 1996) on the data series obtained after "cleaning" and filtering the original logs. In particular, these procedures were applied where granitoid and basalt clasts or areas of cementation occurred, which could modify the original signal: such alteration are recognizable by abrupt shift of the original value. The best approach in performing high-frequency analysis on a stratigraphic data set is to apply a combination of different methodologies, each one providing particular advantages in processing the selected depth series (Pestiaux & Berger, 1984; Hinnov & Goldhammer, 1991; Reijmer et al., 1994). This strategy better controls possible mathematical artefacts and mimimizes possible problems in the geological interpretation of the results.

To avoid any predictable alteration of the signal amplitude in parts of the function and obtain the highest level of precision during processing, some conditions must be checked before applying the selected algorithms. The effect of long-term trends, which can cause a shift of the real amplitude in parts of the series, should be compensated for and eventually subtracted (linear trend and mean correction, Diggle, 1990). Then it must be verified that the statistical properties of the data series remain unchanged by shifts in the origin of the sampled interval (stationary condition) and that the values of the data series are statistically normally distributed.

Since each processing routine is sensitive to a specific character of spectral analysis (*e.g.* resolution vs. noise), an integrated approach allows a better understanding of the major properties of the original signal. The data series is processed using two spectral estimators: the Blackman-Tukey (BT) and the Maximum Entropy algorithms (ME) (see Paillard et al., 1996). Using these two techniques in combination allows for a better reconstruction of the most important spectral features and therefore ensures a high degree of significance when interpreting the results. One of the most simple and powerful algorithms is the ME (Press et al., 1989), a routine designed to fit the sharp spectral peaks in the signal. This algorithm provides a high-frequency resolution within the range of autoregressive models selected in the analysis, as well as good control on the regularity of the *quasi*-periodic frequency. These advantages are sometimes diminished by the lack of statistical confidence estimates and non-linearity in the evaluation of spectral lines, and can therefore produce undesirable spurious results. To test the statistical significance of the spectral values, the ME method is used in this study in combination with the BT, a very stable procedure for processing data series (Blackman & Tukey, 1958). This algorithm estimates the autocorrelation function from the data series, weighted by specifically-designed windows, in order to discard possible bias (Harris, 1978). It then computes the Fourier transform to obtain the power spectrum. The design of the algorithm enables an estimate of random-noise models, like those originating by low-order autoregressions (Hinnov & Goldhammer, 1991), which are likely to be incorporated into the depth series when sampling stratigraphical data. The spectral peaks are tested against two orders of autoregression and only the values passing the noise levels are taken into consideration. Thus, the combination of the two techniques ensures a good degree of validity in the following interpretation.

In the spectra, the values on the vertical axis indicate the power (expressed in normalized units) while the horizontal axis refers to frequencies in cycles/metre, from low-frequency (left) to high-frequency (right) periodicities. The power spectra presented and discussed in the following section are computed using the Maximum Entropy algorithm; the statistical significance of the peaks are tested using the Blackman-Tukey routine and only those periodicities which appear significant are labelled with their values converted in length of periodicity (in cm), while the others remain disregarded.

RESULTS

The data series investigated in detail for the lithological intervals are presented in figures 2, 3, 6, 8, 10 and 11: the horizontal axis refers to thickness in meters below sea floor (mbsf) and the vertical axis to the appropriate value for the investigated parameter. Using the visual description logs (Cape Roberts Science Team, 1999) as reference, these intervals are treated in order to compensate for the effect of carbonate cementation and the presence of large clasts (mainly granitoid and basalt). In these cases the physical properties might have been somewhat altered and therefore the corresponding values were disregarded and substituted by linear interpolation of the closest ones.

The results of frequency analysis for each lithostratigraphical sub-unit under investigation are next briefly commented upon, and displayed as tables. The strongest peaks are first expressed in cm. Then, using the shortest significant wavelength as a reference periodicity line, the peaks are compared against each other and the relative ratios are calculated: these are displayed by the numbers in brackets.

Since the Milankovitch cycles are always characterised by hierarchies, the numerical ratios will provide important "fingerprints" when looking for climatic-orbital control.

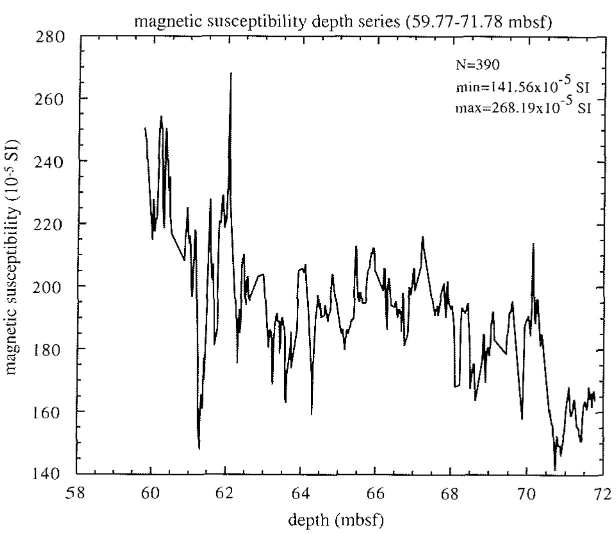


Fig. 2 - Magnetic susceptibility depth series (interval 59.77-71.78 mbsf).

For example, the ratio between short-term eccentricity and precession cycles has been approximately 5 during the Mesozoic and Cenozoic times (but with some variability between 4 and 6.5, see Fischer & Bottjer, 1991). When this approach is properly used it can give very valuable reults (Fischer et al., 1991; Hinnov & Goldhammer, 1991; Claps & Masetti, 1994; Bellanca et al., 1996).

When the spectral peaks are normalised, the values obtained refer to adimensional hierarchies. These can be compared with the values predicted for the Milankovitch orbital cycles during the Cenozoic: precession, obliquity and short-term eccentricity (respectively 23-19 kyr, 54-41 kyr and 123-95 kyr, Berger & Loutre, 1994). These time durations are normalized and tuned to the shortest periodicities of the orbital perturbations (the precession cycles); then they are reported for correlation, as in the following table:

Milankovitch orbital cycles	eccentricity	obliquity	precession
corresponding duration	123-95 kyr	54-41 kyr	23-19 kyr
ratios (relative to precession)	6.5-4.2	2.8-1.8	1

Since the orbital cycles are composed by a number of harmonics, their period cannot be assumed to be absolutely constant. Precession and obliquity are likely to have increased their wavelength through time (Berger & Loutre, 1989; Schwarzacher, 1991). Therefore, during the geological interval tested, the ratios computed for the eccentricity cycle might have been slightly higher.

STUDIED INTERVALS AND SEDIMENTATION RATE ESTIMATE

1) Interval 59.77-71.78 mbsf
(within Lithostratigraphical Sub-unit 5.1, Fig. 2 & 3)
Results from the magnetic susceptibility data series (Fig. 4)

wavelengths	235 cm	100 cm	61-46 cm (average ca. 54 cm)
ratios	4.4	1.9	1

Results from the wet bulk density data series (Fig. 5)

wavelengths	~250 cm	ca. 110 cm	59-44 cm (average ca. 52 cm)
ratios	4.8	ca. 2.1	1

The periodic nature of the two data series processed appears clear from the presented spectra. The match between the orbital ratios and those computed from spectral analysis is straightforward and correlates the two shortest wavelengths with average value of 54 cm (magnetic susceptibility) and 52 cm (wet bulk density) to the precession cycle. The small offset of the main spectral lines between the two series processed is probably due to the shift in amplitude of the two signals. The correspondence between the magnetic susceptibility and wet bulk density series becomes even more consistent since they display the same hierarchies of frequency peaks, suggesting coherent characterisation and similar cyclic pattern. In particular, the magnetic

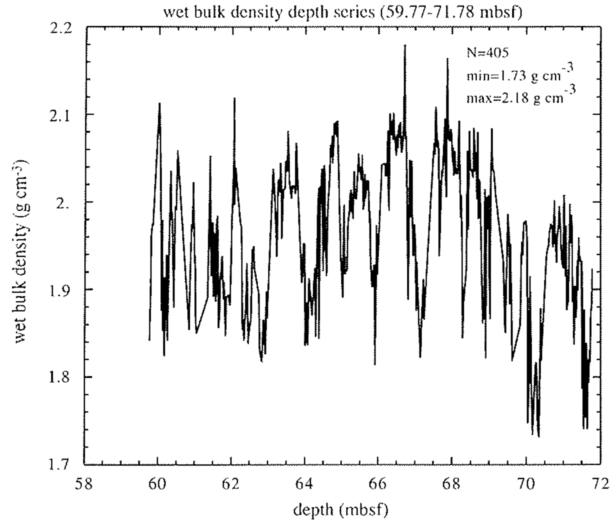


Fig. 3 - Wet bulk density depth series (interval 59.77-71.78 mbsf).

susceptibility peaks at 235 cm (ratio 4.4) and 100 cm (ratio 1.9) correspond closely to the obliquity and eccentricity cycles respectively. In the case of wet bulk density, the peaks are found at 250 cm (ratio 4.8) and 110 cm (ratio 2.1), testifying the same correspondence.

A closer examination of the peaks in the high-frequency domain reveals that the ratio between the two spectral lines assigned to the precessional cycle (which is equal to approximately 1.3 for both magnetic susceptibility and wet bulk density) closely corresponds to the ratios computed for the two orbital components of the precession cycle itself (23 ky/19 ky=1.2). This suggests that the two spectral lines are the real expression of the splitted precession components and strongly supports an orbital cyclic origin for the oscillations of both the physical properties tested.

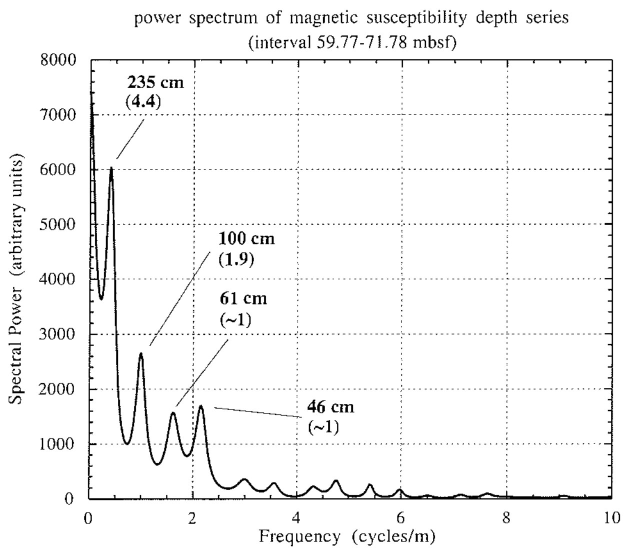


Fig. 4 - Power spectrum of the magnetic susceptibility depth series (interval 59.77-71.78 mbsf). In all the presented spectra only the statistically significant periodicities are labelled: values in cm refer to periodicity in thickness, numbers in brackets to the ratio between the specific wavelengths and the shortest significant wavelength detected in this analysis. The peaks at 235 cm and at 100 cm match very closely the eccentricity and obliquity ratios. The two peaks centered at 61 cm and 46 cm are interpreted as the two components of the precession cycle (19 and 23 kyr).

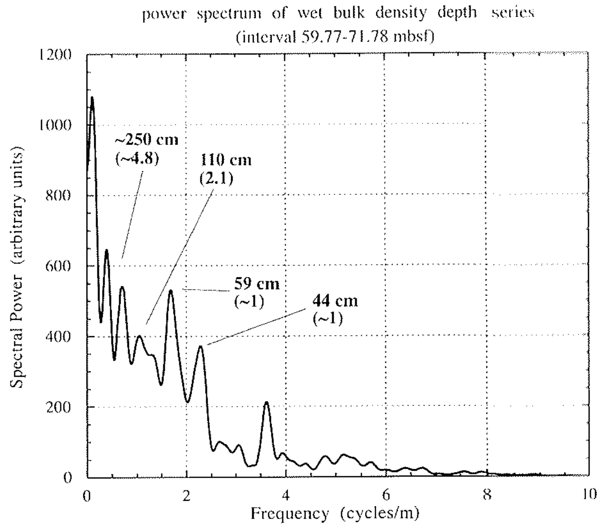


Fig. 5 - Power spectrum of the wet bulk density depth series (interval 59.77-71.78 mbsf). The peaks at 250 cm and at 110 cm match very closely the eccentricity and obliquity ratios. The two peaks centered at 59 cm and 44 cm are interpreted as the two components of the precession cycle (19 and 23 kyr) (see Fig. 4 for explanation).

Assuming that the periodicities at 54-52 cm are precession forced, it is possible to extrapolate for the analysed interval an average sedimentation rate of *ca.* 2.5 cm/ky.

2) Interval 329.30-347.31 mbsf
(within Lithostratigraphical Sub-unit 11.3, Fig. 6)
Results from the magnetic susceptibility data series (Fig. 7)

wavelengths	423 cm	107 cm	60 cm
ratios	~7	1.8	1

The spectral analysis applied to this interval has been already discussed in the Initial Report (Cape Roberts Science Team, 1999), in order to test the presence and stability of periodicities in the low-field magnetic

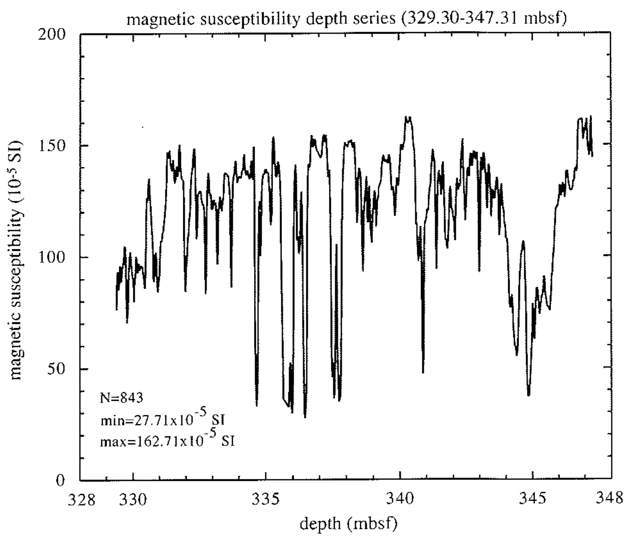


Fig. 6 - Magnetic susceptibility depth series (interval 329.30-347.31 mbsf).

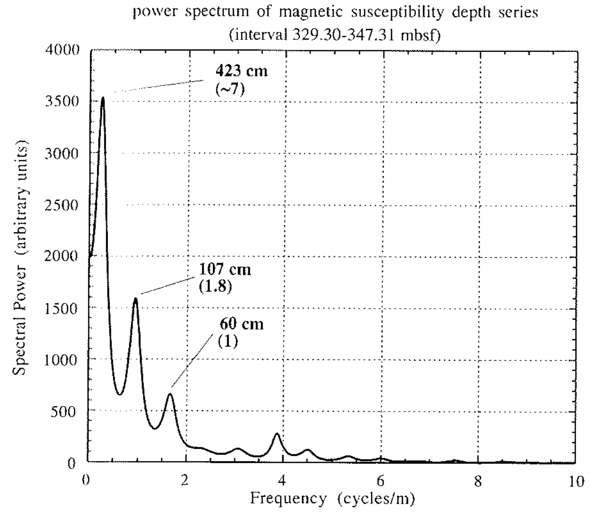


Fig. 7 - Power spectrum of the magnetic susceptibility depth series (interval 329.30-347.31 mbsf). Assuming the line at 60 cm as the expression of the precession cycle, the periodicity at 107 cm matches perfectly the obliquity, while the 423 cm line gives a ratio slightly higher for the eccentricity (see Fig. 4 for explanation).

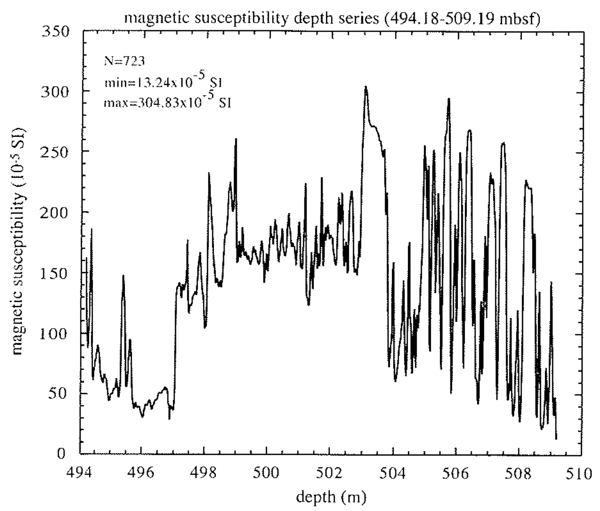


Fig. 8 - Magnetic susceptibility depth series (interval 494.18-509.19 mbsf).

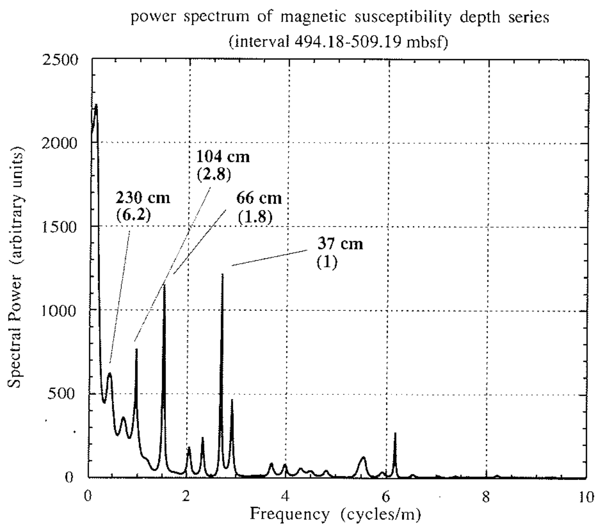


Fig. 9 - Power spectrum of the magnetic susceptibility depth series (interval 494.18-509.19 mbsf). Assuming that the line at 37 cm refers to the precession cycle, the periodicity at 66 cm corresponds to the obliquity, while the group of lines at 104 and 230 cm gives an intermediate ratio for the eccentricity cycles (see Fig. 4 for explanation).

susceptibility record. These results display a good affinity with the Milankovitch orbital ratios. In particular, assuming the wavelength of 60 cm as expression of the precession cycle, the peak at 107 cm yields a ratio of 1.8 and shows a high degree of similarity with the obliquity cycle. Using the same assumption, the ratio between the 423 cm prominent spectral line and that at 60 cm yields a value of 7, which can represent a slightly high eccentricity/ precession ratio. Nonetheless, it appears to be in close match with what can be calculated from orbital periodicities. The wet bulk density depth series processed by the same techniques does not show a clear cyclic pattern, because of high noise level and abrupt shifts in amplitudes which affect the original signal. Since these irregularities the wet bulk density is not presented and commented here.

Based on the match of the 60 cm peak with the precession cycle, the suggested sedimentation rate is approximately 2.9 cm/ky.

3) Interval 494.18-509.19 mbsf

(within Lithostratigraphical Sub-unit 13.3, Fig. 8)
Results from the magnetic susceptibility data series (Fig. 9)

wavelengths	230-104 cm	66 cm	37 cm
ratios	6.2-2.8	1.8	1

The presence, in the magnetic susceptibility spectra, of the spectral peaks at 66 cm and 37 cm allows hypothesis of the existence of the obliquity and precession cycles respectively. In this particular case, their ratio (1.8) fits perfectly with the obliquity/precession ratio. The relationship between the periodicity wavelength at 104 cm (with a broad dispersion of power up to the spectral line at 230 cm) and what is inferred to represent the precession cycle (37 cm) yields a variable value, with the prominent peak pointing to a ratio (2.8), lower than expected, and the subordinate peak yielding a ratio of 6.2. Therefore, the presence of the eccentricity cycle cannot be revealed here, but not excluded. It should be noted that rapid fluctuations in the sedimentation rate are probably responsible for the dispersion of the spectral energy and, as a consequence, for the lack of a perfect match between the eccentricity and the spectral lines at 230 and 104 cm. Also in this interval, as for the previous one, the wet bulk density spectra displays a rapid decrease in power, caused by shifts in its original amplitude: for this reason its interpretation appears meaningless and it is not presented here.

On the basis of the hypothesized correspondence between the peak at 37 cm and the precession cycle, an average sedimentation rate of 1.8 cm/ky is estimated.

4) Interval 574.30-584.70 mbsf

(within Lithostratigraphical Sub-unit 15.3, Fig. 10 & 11)
Results from the magnetic susceptibility data series (Fig. 12)

wavelengths	160 cm	64 cm	40 cm
ratios	4	1.6	1

Results from the wet bulk density data series (Fig. 13)

wavelengths	148 cm	60 cm	34 cm
ratios	4.4	1.8	1

The data series relative to magnetic susceptibility corresponds only to the first part of the chosen interval (spanning between 581.01 and 584.70) since the signal recorded in the lower part appears to be too noisy. Processing this data series evidences three main peaks at 40, 64 and 160 cm respectively. Assuming the 40 cm wavelength as a reference line for the precession cycle, the ratios computed from the other peaks (1.6 and 4) fall in the range of the orbital periodicities (respectively obliquity and eccentricity). The spectrum computed on the wet bulk density data series displays very close values (at 34, 60 and 148 cm) and yields ratios of 1.8 and 4.4. These appear to be almost coincident with the magnetic susceptibility ratios and also suggest for this interval a link with Milankovitch periodicities.

Based on the assumption that the shortest significant wavelength at 34-40 cm corresponds to the precessional cycle, it is possible to infer for this interval an average sedimentation rate of ca 1.8 cm/ky.

IMPLICATIONS

There are several important implications arising from the results of this study that can be discussed and further developed.

High-frequency cyclicity. The physical properties of fine-grained intervals of CRP-2/2A display a strong cyclic signal, which is often not clearly recognizable by lithological variations. In this respect, their analysis is instrumental for studying high-frequency variations in the sedimentary record at a much higher detail than strictly visual sedimentological investigation. Using high-frequency analysis, we detect significant and stable frequencies, which suggest the existence of a deterministic forcing mechanism controlling the deposition of the lithostratigraphical intervals analysed. A similar conclusion was already suggested for some of the very fine sandstone and mudstone intervals of the CRP-1 sequence (Niessen et al., 1998).

Milankovitch origin. The ratios amongst the strongest spectral peaks are similar to those computed from orbital periodicities. In several of the cases presented in this study, the correlation with the eccentricity, obliquity and precession orbital cycles reaches a very high degree, strongly suggesting a Milankovitch origin for the fluctuations observed in the physical properties record.

Integration of the results. It has been suggested (see Methods) that variations in magnetic susceptibility are mainly controlled by changes in the ferrimagnetic concentration of the sediment. The terrigenous supply into the depositional environment hypothesized for these CRP-2/2A intervals can be strongly controlled by changing proximity of the shoreline and/or by bathymetry variations induced through sea-level fluctuations at various scales. Transgressions and regressions will concentrate the magnetic minerals (in particular in the silt-sand size range) respectively in a more landward or in a more seaward

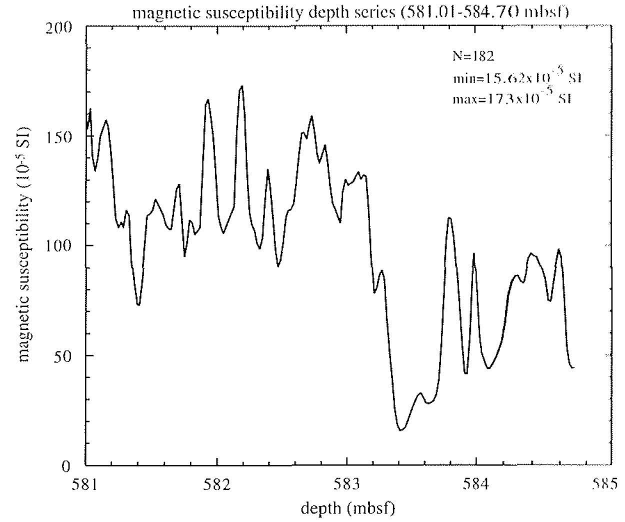


Fig. 10 - Magnetic susceptibility depth series (interval 581.01-584.70 mbsf).

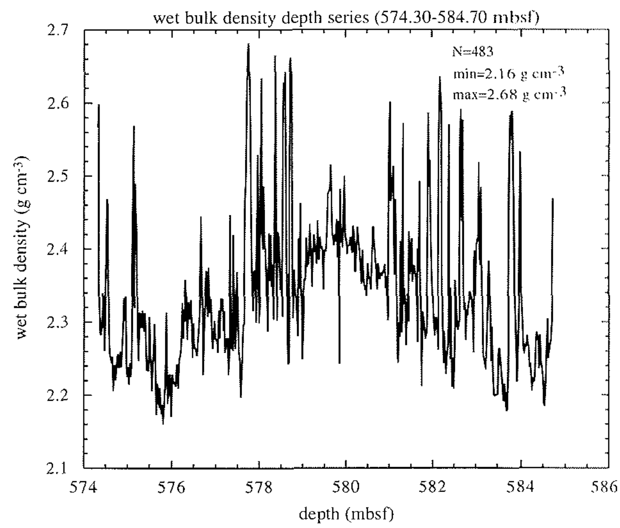


Fig. 11 - Wet bulk density depth series (interval 574.30-584.70 mbsf).

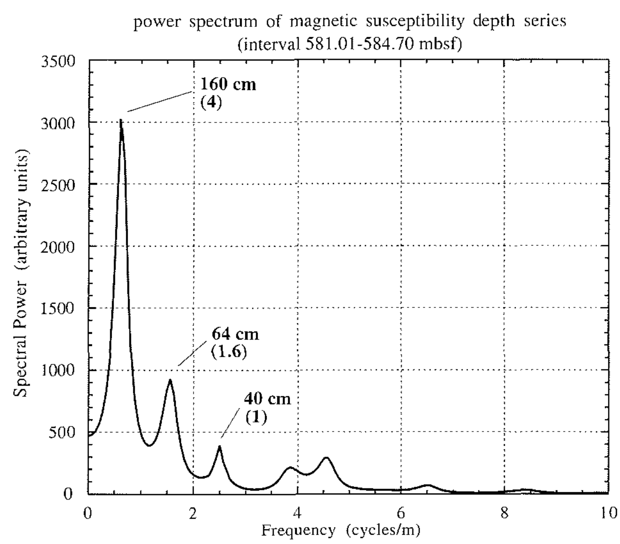


Fig. 12 - Power spectrum of the magnetic susceptibility depth series (interval 581.01-584.70 mbsf). Assuming the shortest spectral line at 40 cm as the precession cycle expression, the periodicities at 160 cm and 64 cm closely match respectively the ratios of the eccentricity and obliquity orbital cycles (see Fig. 4 for explanation).

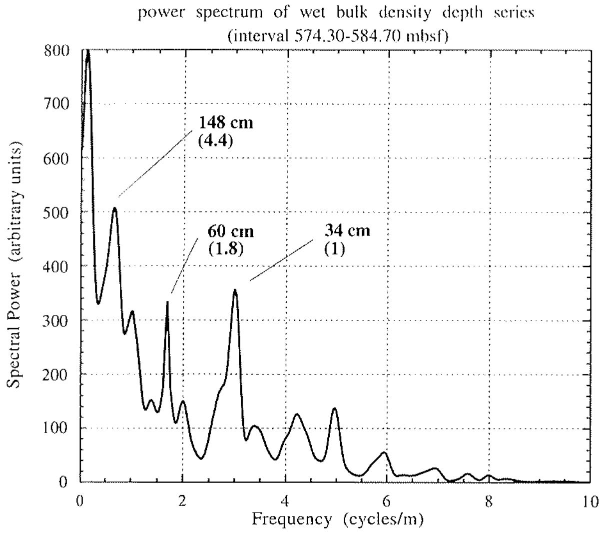


Fig. 13 - Power spectrum of the wet bulk density depth series (interval 574.30-584.70 mbsf). When the shortest spectral line at 34 cm is compared to the precession cycle, the periodicity at 148 cm corresponds to the eccentricity/precession ratio and that at 60 cm to the obliquity/precession ratio (see Fig. 4 for explanation).

position. Therefore we hypothisise that the magnetic signal recorded in the investigated intervals will likely reflect high-frequency sea-level fluctuations. Arai et al. (1997) discussed this hypothesis and proposed that changes in near-land and near-shore positions, probably controlled by sea-level fluctuations, have a substantial effect on the concentration of heavy magnetic components within the terrigenous sediment supply.

At the same time, the relative abundance of highly-magnetic minerals is likely to be climatically controlled via modifications of the dominant weathering and erosion processes in the source area and subsequent transport. Alternation of humid and dry conditions in the provenance area will change the degree of erosion of the basement and sedimentary cover and consequently influence the supply of magnetic minerals in the terrigenous fraction. A similar process has been previously identified beneath and at the Eocene/Oligocene boundary of CIROS-1 core (Sagnotti et al., 1998). In that case, fluctuation in the input of detrital magnetite to the southern Victoria Land Basin, McMurdo Sound, was attributed respectively to alternating intervals of relatively warm-humid climate conditions (chemical weathering of source rocks) and cold-dry conditions (mechanical weathering of source rocks).

Similarly to the magnetic susceptibility record also the qualitative relationship between wet bulk density curves and variations in clay and silt-sand concentration has been interpreted as the response of fluctuating sea-level in the depositional setting, with consequent shift between proximal and distal conditions of the depositional environment. Therefore these changes can be directly reflected in the relative concentration of the different grain size fractions (see Methods).

Based on the previous conclusions, we suggest that both magnetic susceptibility and wet bulk density are most likely controlled by fluctuations in sea-level or in weathering-erosion processes occurring in the source area, or by the combination of both mechanisms. In these respects, they can be used as a valuable proxy for investigating short-term, high-frequency changes and represent important palaeoclimate-sensitive indicators.

Sedimentation rate. The approach applied in this study reveals its intrinsic importance when assessing the problem of sedimentation rate estimate. The sedimentation rates calculated by matching the frequency ratios obtained via spectral analysis and the Milankovitch orbital ratios are relatively similar and consistent in the four lithological intervals analysed, giving a major constraint to these results. Conventional methods of dating stratigraphic sequences (*e.g.* paleontology, magnetostratigraphy) often do not offer a good level of resolution, and consequently, are not always suitable for evaluating sedimentation rate in very short intervals such as the fine-grained intervals investigated here. It should be noted that some of the rates evaluated here are different from what has been suggested in the age-depth plots of the Initial Report (Cape Roberts Science Team, 1999) and of subsequent studies (Wilson et al., this volume), but are still of the same order of magnitude.

Moreover, the mudstone intervals tested are part of major sequences constituted by several lithologies (*e.g.* diamictite, conglomerate, sandstone and mudstone), which yield very different sedimentation rates (Fielding et al., this volume). The use of the sedimentation rate estimates proposed with our analysis helps to allocate time duration to the fine-grained intervals and consequently gives narrow constraints on the values extrapolated for lithostratigraphical units dominated by other lithologies. Intuitively, the application of this methodoloy becomes instrumental and valuable in particular when sedimentary successions are studied at a very high level of resolution, as in this case. Therefore, we believe that the future integration of these methodologies will be the best tool for assigning a time duration to specific intervals in the depositional sequences.

CONCLUDING REMARKS

The cyclicity present in the low-field magnetic susceptibility and wet bulk density extracted from the CRP-2/2A core provides an unique opportunity to test the existence of non-random periodicities in the stratigraphic record. The cyclostratigraphic study performed on some fine-grained intervals from the drilled sequence allows to draw speculative conclusions on their nature and suggest some interpretations.

- Processing these two physical properties by spectral analysis demonstrates that many of the detected frequencies show good consistency with those estimated from the astronomical Milankovitch periodicities (precession, obliquity and eccentricity cycles).
- The marine depositional environments were affected by changes in depositional processes in response to periodic sea-level fluctuations at various scales or by climatically controlled modifications in the weathering processes occurring in the source area, both of them might have been orbitally driven. In this respect, the analysed physical properties can have precisely recorded such high-frequency fluctuations and therefore be used as highly sensitive palaeoclimate indicators.
- The cyclicity recorded in portions of the drilled succession, which exhibits a likely orbital control, might give a very

precise evaluation of sedimentation rates. These estimates should be correlated with those obtained through more traditional approaches and combined with them, in order to provide an integrated approach to precise time evaluation.
- It should be highlighted that further sedimentological analyses of the cored intervals will supply fundamental compositional and textural information allowing the comparison with this set of data. This integration can essentially contribute to the understanding of the Ross Sea stratigraphy during the Cenozoic and to better develop the cyclostratigraphic approach in glaciomarine settings.

ACKNOWLEDGEMENTS

We wish to express our gratitude to all the colleagues of the Cape Roberts Team and to the people of McMurdo Station, Scott Base and Cape Roberts Camp for logistical support. We gratefully acknowledge Christian Bücker and Jan Piotrowsky for constructive review and Jaap van der Meer for careful editorial handling. We cordially thank Adam Harris for a thorough grammatical review of the manuscript. Financial support was provided by Italian *Programma Nazionale di Ricerche in Antartide* (PNRA) and *MURST ex-40%* (M. Sarti). This is also contribution No. 1677 of the Alfred Wegener Institute for Polar and Marine Research.

REFERENCES

Arai K., Sakai H. & Konishi K., 1997. High-resolution rock-magnetic variability in shallow marine sediment: a sensitive paleoclimatic metronome. *Sedimentary Geology*, **110**, 7-23.

Barthes V., Pozzi J.P., Vibert-Charbonnel P., Thibal J. & Meliers M.A., 1999. High-resolution chronostratigraphy from down-hole susceptibility logging tuned by palaeoclimatic orbital. *Earth and Planetary Sciences Letters*, **165**, 97-116.

Bellanca A., Claps M., Erba E., Masetti D., Neri R., Premoli Silva I. & Venezia F., 1996. Orbitally induced limestone/marlstone rhythms in the Albian-Cenomanian Cismon section (Venetian region, northern Italy): sedimentology, calcareous and siliceous plankton distribution, elemental and isotope geochemistry. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **126**, 227-260.

Berger A., 1984. Accuracy and frequency stability of the earth's orbital elements during the Quaternary. In: Berger A.L., Imbrie J., Hays J., Kukla G. & Saltzman B. (eds.), *Milankovitch and Climate, Part 1*, Reidel Publ. Co., Dordrecht, 3-39.

Berger A. & Loutre M.F., 1994. Astronomical forcing through geological time. In: de Boer P.L. & Smith D.G. (eds.), *Orbital forcing and cyclic sequences*, IAS Special Publication, Oxford, **19**, 15-24.

Berger A. & Loutre M.F., 1989. Pre-Quaternary Milankovitch frequencies. *Nature*, **342**, 133.

Blackman R.B. & Tukey J.W., 1958. *The measurement of power spectra from the point of view of communication engineering.* Dover Publications, New York, 190 p.

Bloemendal J. & de Menocal P., 1989. Evidence for a change in the periodicity of tropical climate cycles at 2.4 Myr from whole-core magnetic susceptibility measurements. *Nature*, **342**, 897-900.

de Boer P.L & Smith D.G., 1994. Orbital forcing and cyclic sequences. In: de Boer P.L. & Smith D.G. (eds.), *Orbital forcing and cyclic sequences*, IAS Special Publication, Oxford, **19**, 1-14.

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

Claps M. & Masetti D., 1994. Milankovitch periodicities recorded in Cretaceous deep-sea sequences from Southern Alps (Northern Italy). In: de Boer P.L. & Smith D.G. (eds.), *Orbital forcing and cyclic sequences*, IAS Special Publication, Oxford, **19**, 99-107.

Cooper A.K. & Davey F.J., 1985. Episodic rifting of Phanerozoic rocks in the Victoria Land Basin, western Ross Sea, Antarctica. *Science*, **229**, 1085-1087.

Cooper A.K. & Davey F.J., 1987. The Antarctic Continental Margin: Geology and Geophysics of the Western Ross Sea. Circumpacific Council for Energy & Mineral Resources. *Earth Sciences Series*, **5B**, Houston.

Davies P.J., Mackenzie J.A., Palmer-Julson A. *et al.*, 1991. Site 811-826 Northeast Australian Margin. *Proc. ODP Init. Rep.*, **133**, 810 p.

Dekkers M.J. 1997. Environmental magnetism: an introduction, *Geologie en Mijnbou*, **76**, 163-182.

Doveton J.H., 1994. *Geologic log analysis using computer methods.* Am. Ass. Petr. Geol. Computer Application in Geology 2, 169 p.

Diggle P.J., 1990. *Time series. A Biostatistical Introduction.* Oxford University Press, London, 257 p.

Fischer A.G., 1986. Climatic rhythms recorded in strata. *Annual Review of Earth and Planetary Sciences*, **14**, 351-376.

Fischer A.G., de Boer P.L. & Premoli Silva I., 1990. Cyclostratigraphy. In: Ginsburg R.N. & Beaudoin B. (eds.), *Cretaceous Resources, Events and Rhythms - Background and Plans for Research*, Kluwer Academic Publ., Dordrecht, 139-172.

Fischer A.G. & Bottjer D.J., 1991. Orbital forcing and sedimentary sequences. *Journal of Sedimentary Petrology*, **61**, 1063-1069.

Fischer A.G., Herbert T.D., Napoleone G., Premoli Silva I. & Ripepe M., 1991. Albian Pelagic Rhythms (Piobbico Core). *Journal of Sedimentary Petrology*, **61**, 1164-1172.

Hamilton E.L., 1976. Variations of density and porosity with depth in deep-sea sediments. *Journal of Sedimentary Petrology*, **46**, 280-300.

Harris F.J., 1978. On the use of windows for harmonic analysis with the discrete Fourier transform. *Proceedings of the IEEE*, **66**, 51-83.

Hinnov L.A. & Goldhammer R.K., 1991. Spectral analysis of the Middle Triassic Latemar Limestone. *Journal of Sedimentary Petrology*, **61**, 1173-1193.

House M.R., 1995. Orbital forcing timescales. In: House M.R. & Gale A.S. (eds.), *Orbital Forcing Timescales and Cyclostratigraphy*, The Geological Society of London, London, 1-18.

Jarrard R.D. & Arthur M.A., 1989. Milankovitch paleoceanographic cycles in geophysical logs from ODP Leg 105, Labrador Sea and Baffin Bay. In: Srivastava S.P., Arthur M.A., Clement B. *et al.* (eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*, College Station, **105**, 757-772.

Maher B.A. 1988. Magnetic properties of some synthetic sub-micron magnetites, *Geophysical Journal International.*, **94**, 83-96.

Niessen F. & Jarrad R.D., 1998. Velocity and porosity of sediments from CRP-1 drillhole, Ross Sea, Antarctica. *Terra Antartica*, **5**(3), 311-318.

Niessen F., Jarrad R.D. & Bücker C., 1998. Log-based physical properties of the CRP-1 core, Ross Sea, Antarctica. *Terra Antartica*, **5**(3), 299-310.

Paillard D., Labeyrie L. & Yiou P., 1996. Macintosh program performs time-series analysis. *Eos Trans. AGU*, **77**, 379 p.

Pestiaux P. & Berger A., 1984. An optimal approach to the spectral characteristics of deep-sea climatic records. In: Berger A.L., Imbrie J., Hays J., Kukla G. & Saltzman B. (eds.), *Milankovitch and Climate, Part 1*, Reidel Publ. Co., Dordrecht, 417-445.

Press W.H., Flannery B.P., Teukolsky S.A. & Vetterling W.T., 1989. *Numerical recipes in Pascal: the art of scientific computing.* Cambridge University Press, Cambridge, 759 p.

Reijmer J.J.G., Sprenger A., Ten Kate W.G.H.Z., Schlager W. & Krystyn L., 1994. Periodicities in the composition of Late Triassic calciturbitides (Eastern Alps, Austria). In: de Boer P.L. & Smith D.G. (eds.), *Orbital forcing and cyclic sequences*, IAS Special Publication, Oxford, **19**, 323-343.

Robinson S.G., 1986. The late Pleistocene paleoclimatic record of North Atlantic deep-sea sediments revealed by mineral-magnetic measurements. *Phys. Earth Planet. Inter.*, **42**, 22-47.

Sagnotti L., Florindo F., Verosub K.L., Wilson G.S. & Roberts A.P., 1998. Environmental magnetic record of Antarctic palaeoclimate from Eocene/Oligocene glaciomarine sediments, Victoria Land Basin. *Geophysical Journal International*, **134**, 653-662.

Schwarzacher W., 1991. Milankovitch cycles and the measurements of time. In: Einsele G., Ricken W. & Seilacher A. (eds.), *Cycles and events in stratigraphy*, Springer-Verlag, Berlin, 855-863.

Thibal J., Pozzi J.P., Barthes V., & Dubuisson G. 1995. Continuos record of geomagnetic field intensity between 4.7 and 2.7 Ma from downhole measurements. *Earth and Planet. Sci. Lett.*, **131**, 371-380.

Thompson R. & Olfield F., 1986. Environmental Magnetism. *Allen & Unwin*, London, 227 p.

Verosub K.L. & Roberts A.P., 1995. Environmental magnetism: Past, present and future. *Geophysical Journal International*, **121**, 267-278.

Weedon G.P., 1991. The spectral analysis of stratigraphic time series. In: Einsele G., Ricken W. & Seilacher A. (eds.), *Cycles and events in stratigraphy*, Springer-Verlag, Berlin, 840-854.