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MILANKOVITCH CYCLICITY OF MAGNETIC DIRECTIONS IN CRETACEOUS SHALLOW-WATER CARBONATE ROCKS, SOUTHERN ITALY

Abstract. Spectral analyses of 115 m continuous bore-cores of Lower Cretaceous shallow marine carbonates establish identical cyclicities for sedimentary features (textural and diagenetic parameters) and for remanent magnetization (intensity, inclination and declination). Identical spectral peaks also occur in the estimated perturbations of the Earth's orbit (Milankovitch cycles) for the same geological period, suggesting that the lithological and magnetic parameters are controlled, directly or indirectly, by astronomically determined phenomena. Such observations enable cyclical stratigraphic methods to be applied on a cm-scale, and open the possibility of high-precision relative dating and correlation of sedimentary sequences and their controlling processes.

INTRODUCTION

In the last decade, progress in quantitative cyclostratigraphy with the widespread use of time series analysis techniques has definitively proven the existence of a strong correlation between variations in the Earth's orbital parameters and the high frequency periodicities observed in sedimentary sequences, as far as their depositional and paleontologic characteristics are concerned (cfr. Terra Nova, 1989; Fisher et al., 1990; Fisher and Bottjer, 1991; Larson et al., 1992). However similar periodic variations in the magnetic remanence directions of sedimentary rocks have only been observed in short stratigraphic intervals.

The study reported here was performed on very shallow water Early Cretaceous carbonates over a time interval of more than 3 Ma, mostly deposited under peritidal conditions (D'Argenio, 1967). These deposits were laid in waters of a few meters depth and are quite different from the carbonate rocks previously studied by Robinson (1986), Bloemendal et al. (1988b), Napoleone and Ripepe (1989) and by Tarduno et al. (1991), which are all pelagic deposits, with variable concentrations of terrigenous material and post-depositional dissolution of magnetite by reduction diagenesis. They are not very comparable with those discussed here, which are characterized by high textural diversification, early diagenesis and high rate of sedimentation, yelding a very accurate record of environmental change, including eustatic oscillation. (Aissaoui and Kirschvink, 1990; Longo et al., 1993; D'Argenio et al., 1993). Despite these advantages there is a lack of extensive magneto-stratigraphic studies of shallow-water carbonates due to their relatively weak magnetization. However the discovery of abundant magnetite-producing organisms and the new generation of sensitive cryogenic magnetometers now allow the application of palaeomagnetic methods to shallow-water marine carbonates. (cfr. discussion in McNeill, 1990).

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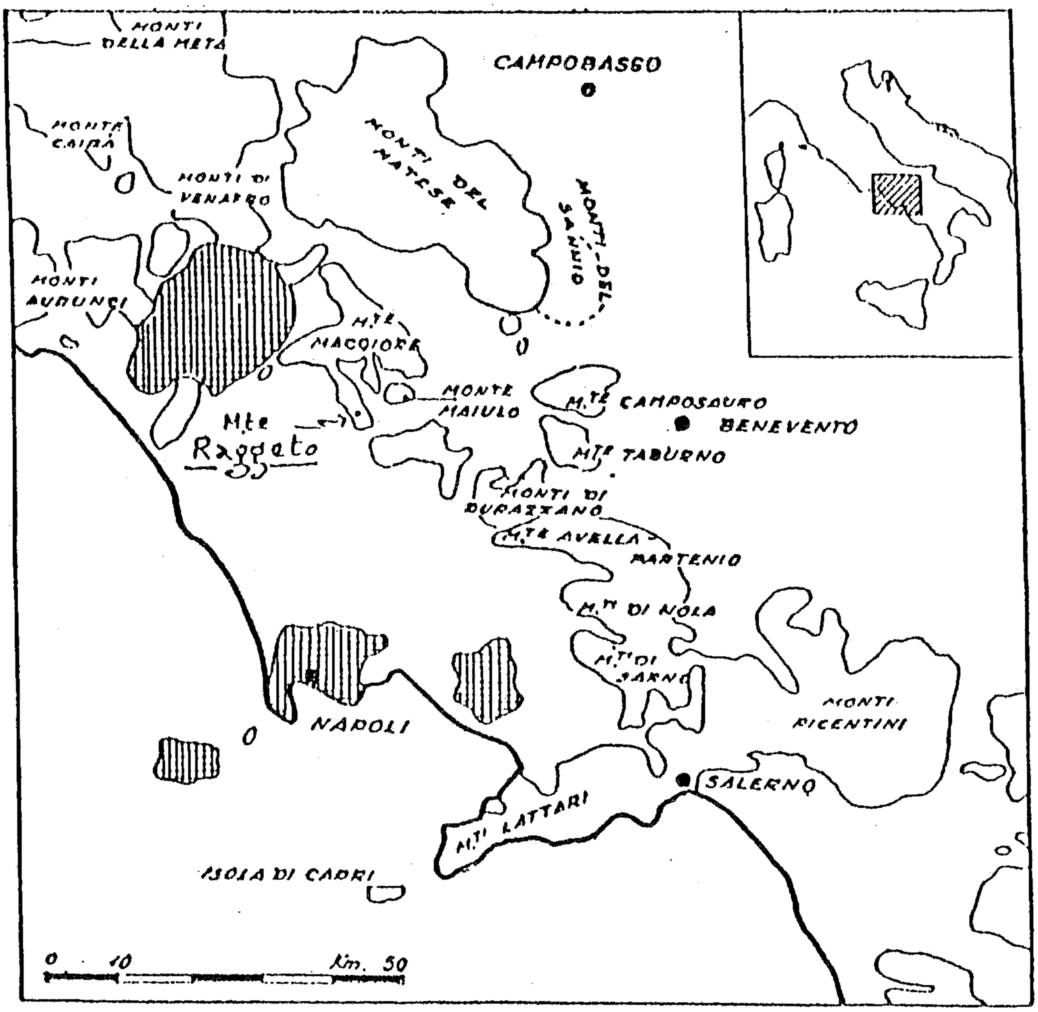

Fig. 1 — Location of Monte Raggeto in the studied area. The solid contour lines enclose areas predominantly formed by Mesozoic carbonate platform strata; the shading indicates volcanic areas.

GEOLOGY OF THE STUDIED SEQUENCE

The studied core materials were recovered at Monte Raggeto (Fig. 1) in the region of Monte Maggiore North of Naples. Monte Maggiore is a tectonic unit of the Southern Apennine fold and thrust belt, deformed during the late Tertiary and affected by Pliocene-Pleistocene extensional tectonics, with high angle normal faults exposing thick (>2000 m) carbonate sequences.

These sequences are limestones and dolomites mostly deposited in very shallow waters from the late Triassic to the Miocene, with some major stratigraphic gaps in the Cretaceous and lower Tertiary (D'Argenio and Pescatore, 1962; Pescatore and Vallario, 1963; D'Argenio 1963b). Regional data suggest that in Cretaceous times the area was part of a passive continental margin in a mature stage and dominated by steady subsidence rates (D'Argenio 1976; D'Argenio and Alvarez, 1980). The palaeomagnetic analysis was performed on continuous bore-cores, spanning in age from the late Hauterivian to Middle Barremian, and obtained from two wells drilled in the north-western base of the Monte Raggeto slopes. Part of the studied sequence is also well exposed in several large quarries which provide both stratigraphic (vertical) and lateral continuity. The observations are on precisely oriented cores, which present a total thickness of 115 m, including two zones of overlap, whereby the total stratigraphic thickness analyzed is 88 m.

The carbonate strata are made of several lithofacies associations, each suggesting specific environments of sedimentation and early diagenesis in a shallow lagoon. They evolved rythmically under open to restricted conditions and are punctuated by tidal flat deposits and storm layers (Longo et al., 1993). Eight lithofacies, grouped into the following four associations (D'Argenio et al., 1993) alternate in the sequence:

- Limestone and dolomitic limestones with molluscs and green algae (open lagoon deposits).
- Limestones and dolomitic limestones with forams and small gastropods (restricted lagoon deposits).
- Stromatolitic and loferitic limestones and dolomitic limestones (tidal flat deposits).
- Limestones and dolomitic limestones with intraclasts and bioclasts (storm deposits).

INSTRUMENTATION

Palaeomagnetic analyses of hand samples, from quarry outcrops where the boreholes were later drilled, showed that their magnetic remanences were weak but measurable on the JR4 spinner magnetometer at the Eotvös Lorand Geophysical Institute, Budapest, and at the University of Plymouth. The samples were then subjected to either thermal, or alternating field partial demagnetization and proved to be remarkably stable, showing univectoral properties under both forms of treatment.

The two bore-cores (c. 10 cm diameter) were then drilled and carefully oriented using their primary sedimentary structures and bedding. Each core was cut into quadrants, with one quadrant from each core being studied magnetically using a "2-G Enterprises" long-core cryogenic magnetometer at the Department of Oceanography, Southampton University, U.K. Core lengths, of up to 1.5 m, were measured at 2-cm intervals and then subjected to alternating magnetic field partial demagnetization in 5 mT steps up to 40 mT. The low-field susceptibility was similarly measured at 2 cm intervals using a "Bartington" long-core susceptibility meter. The average initial remanence was 5 μA/m, dropping by 40% to 80% during demagnetization with very little change in the direction of remanence. (Although the results reported here are based on the initial remanent values (N.R.M.), preliminarly spectral analyses of the demagnetized values indicate no difference in the periodicities found). The low-field susceptibility of the cores was entirely diamagnetic, with most variations corresponding to white noise, i.e. random within the limits of the measurement, and these are not considered further at this stage. The data, stored on a 486 Personal Computer in ASCII files, are plotted against the stratigraphic position in Fig. 2 (a), (b) and (c).

DATA SELECTION

Fourier analysis requires numerical time-series data. The data used here to investigate the systematic recurrence of certain parameters are listed below and briefly commented on.

Textural parameters (Embry and Klovan, 1971), intensity of dolomitization, sedimentary and diagenetic features were evaluated at 1 cm (stratigraphic) intervals, using a 10x magnification hand-lens and checked with thin sections, acetate peels and/or with large, oriented samples when lateral continuity was recognized.

For each parameter the time series consists of the thickness of the particular sedimentary feature against its position in the sequence (i.e., a sequential evaluation of the thickness of each prevailing feature).

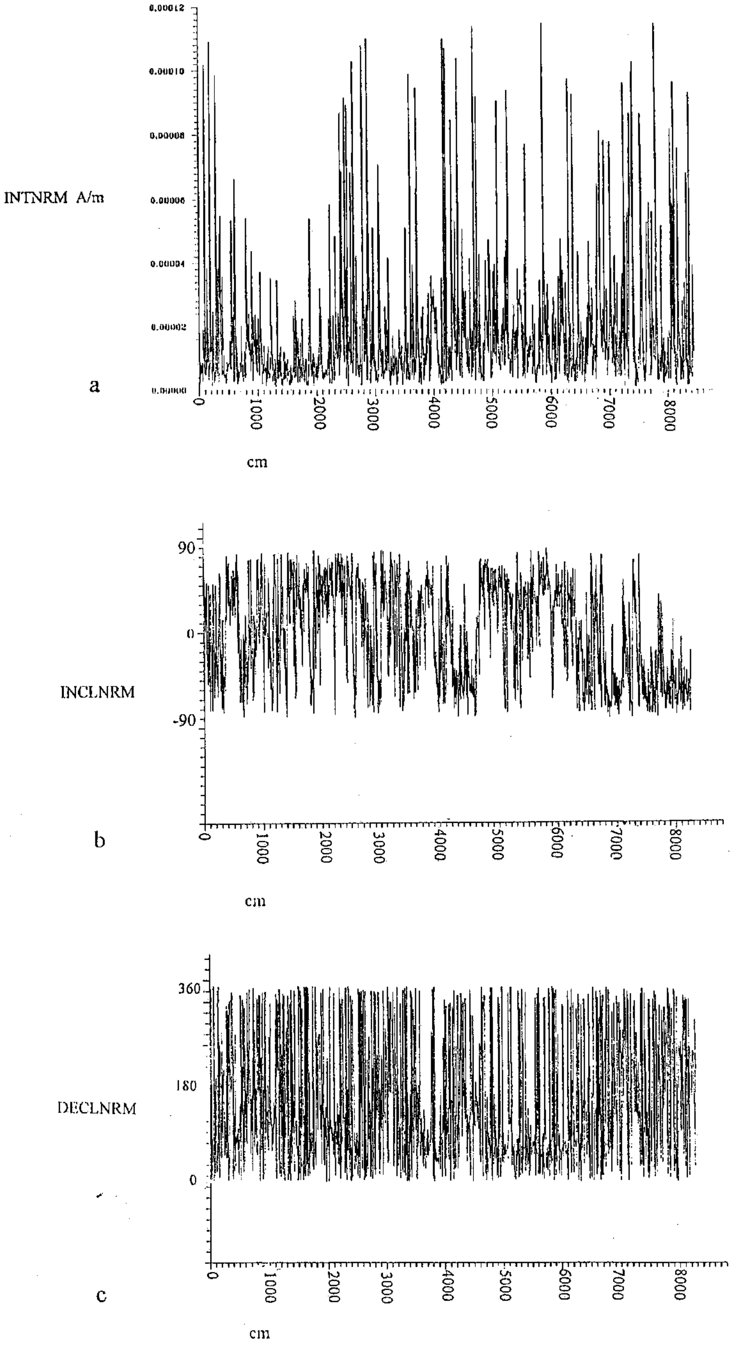

Fig. 2 — Data plots of intensity (a) inclination (b) declination (c) of Natural Remanent Magnetization (N.R.M.) vectors. The stratigraphical position is on the horizontal axis.

a) *Textural parameters:*

8: Calcirudites with intraclasts and lithoclasts (Rudstone).

7: Greyish to greenish clayey horizons, resting on erosional surfaces (Clayey levels).

6: Calcilutites with rare green algae and ostracods (Mudstone).

5: Calcilutites with benthic forams, green algae, gastropods and oncoids (Wackestone).

4: Calcilutites-Calcarenites with benthic forams, green algae, micritized grains, gastropods and intraclasts (Packstone).

3: Calcarenites with intraclasts, lithoclasts and rare bioclasts (Grainstone).

2: Stromatolites, locally with "fenestrae" sheet cracks and microtepees, more or less deeply dolomitized (Bindstone).

1: Dolomites whose original textural features have been completely obscured (D1).

b) *Dolomitization:*

The intensity of dolomitization (D1-D6) was also computed in terms of thickness, on the basis of the number of crystals per square centimeter. Six degrees of dolomitization were distinguished by means of visual estimate, from D1 indicating that the dolomitic crystals have completely obliterated the original textures (and corresponding to parameters 1 reported above), to D6 indicating that there is no dolomitization at all.

The lateral continuity of the lithofacies, single features and sedimentological cycles at a distance of about 300 m was checked by comparing sedimentary logs (1-cm scale), between the well S1 and the outcrop (overlapping 30 m), between the well S1 and the well S2 (overlapping 16 m).

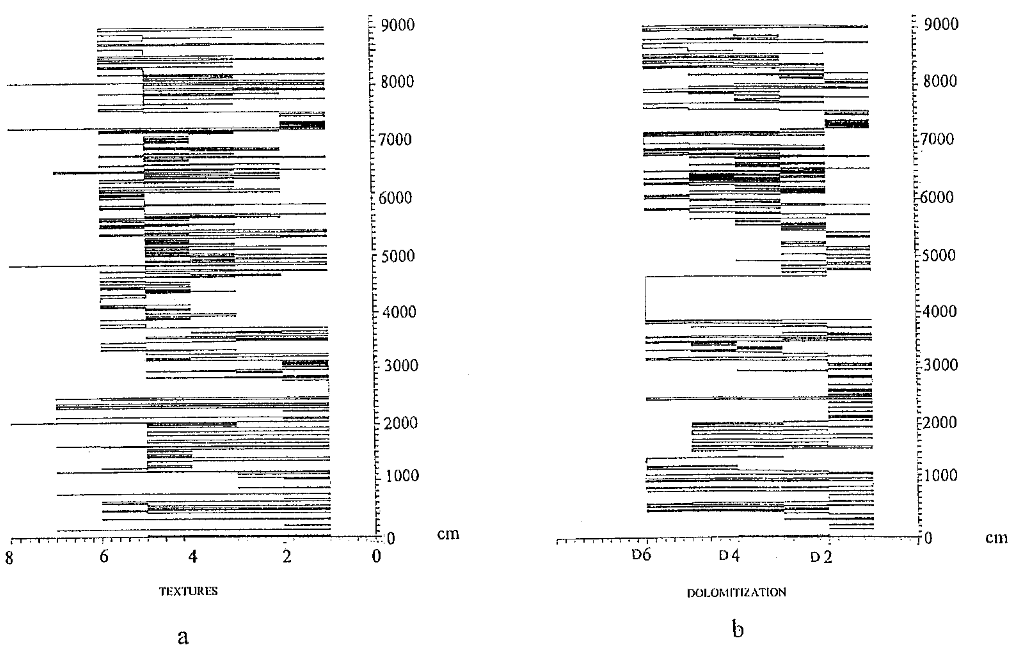

Fig. 3 — Data plots of the textures (a) and degrees of dolomitization (b). (a) Textures are organized as follows: 8, rudstone 7, clayey levels; 6, mudstone; 5: wackestone, 4, packstone; 3, grainstone; 2, bindstone; 1, dolomites (D1). (b) On the horizontal axis, D1-D6 indicate density variation of dolomitic crystals (number of crystals per square centimetre). Six degrees of dolomitization have been empirically distinguished by means of visual estimates: D1 indicating that the dolomitic crystals have completely obliterated the original textures, to D6 indicating that there is no dolomitization at all.

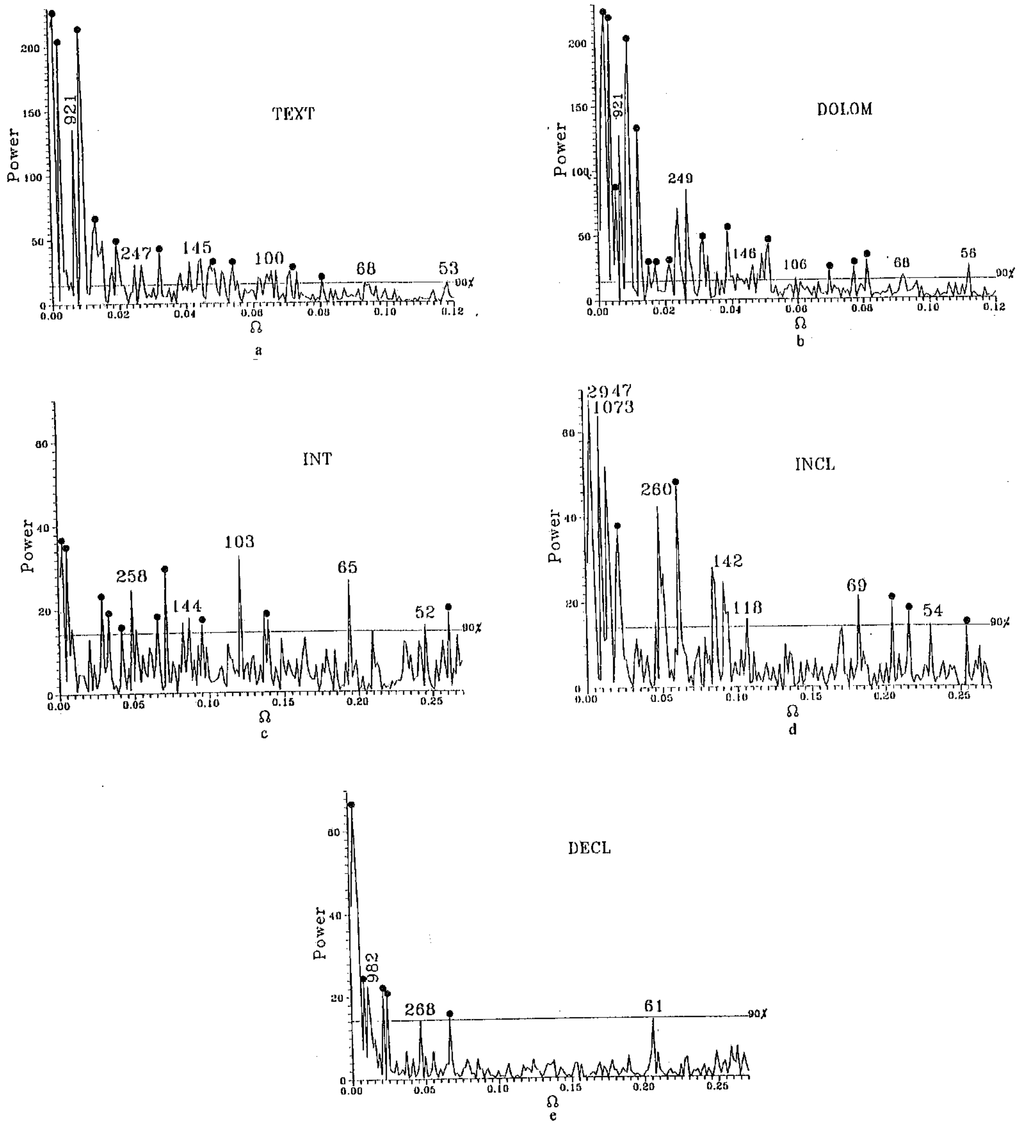

Fig. 4 — Power spectra of textures (a), degrees of dolomitization (b), intensities of natural remanent magnetization (N.R.M.) vectors (c), inclinations of N.R.M. vectors (d), declinations of N.R.M. vectors (e).
The horizontal line marks the 90% probability that a given peak does not originate from the noise, and it was computed using the False Alarm Probability. The P.S.D. are all based on Scargle, 1982, Horne and Baliunas, 1986 (see text). For peaks above the 90% horizontal line, all those arising from the harmonic trend generated by the number of sampled intervals introduced are marked by dots (•), those remaining are marked with the relative periodicity computed in cm.

To quantify the sedimentological and diagenetic features for computer analysis, the relative numerical value, given for each cm, was subsequently typed in ASCII files on a 486 Personal Computer. The data plotted against the stratigraphic position are in Figs. 3 (a) and (b).

PERIOD ANALYSIS AND INTERPRETATION OF UNEVENLY SAMPLED TIME SERIES

The palaeomagnetic and lithologic data were mathematically processed to evaluate the

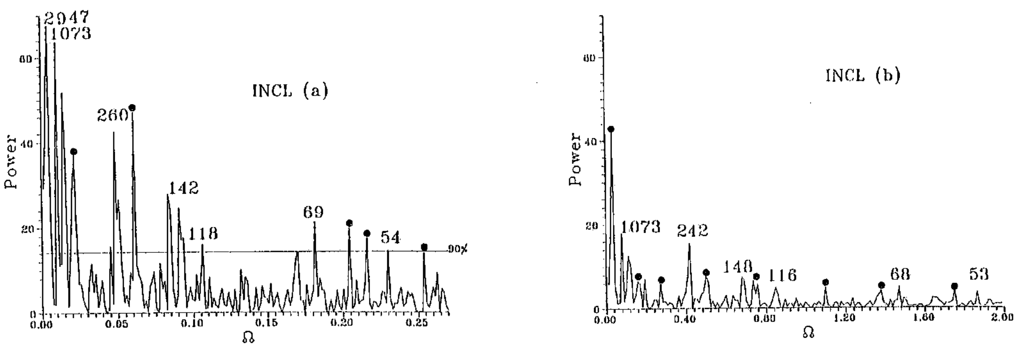

Fig. 5 — A "standard" F.F.T. analysis (Singleton, 1969) has been applied to the inclination data (b), for comparision with the Scargle (1982) and Horne and Baliunas (1986) method for the same data (a).

periodicities. Sedimentary sequences are usually affected by randon errors introduced by long and medium-term variations in the sedimentation rate. In the present case, the sedimentation rate is assumed to have been quasi-constant for the following combination of conditions:

- the regional regime of thermal subsidence is in its mature stage;
- the rate of subsidence ≅ rate of sedimentation due to the shallowness of the depositional areas and to the high sedimentation potential of peritidal carbonates;
- there has been no substantial compaction, as is suggested by the pervasive early cementation and by generally moderate pressure-solution features;
- there is no evidence of synsedimentary tectonics.

All techniques, regardless of the type of data they are applied to, share the same problems:

- a strong dependence of the P.S.D. (Power Spectrum Density) on the noise present in the data;
- unreliability of the low frequencies due to the finite width of the sampled signal (spectral leakage);
- unreliability of the high frequencies due to the uneven spacing of the data (in a sequence, the "invisible", undetectable, interruptions in depositional continuity have an unknown duration rendering the sampled signal apparently equally spaced);
- time scale drifts which might affect the low-frequency side of the P.S.D.

Our spectral analysis program, originally written to deal with unevenly spaced astronomical data sets, is based on the technique developed by Scargle (1982) and Horne and Baliunas (1986). This technique detects the presence and significance of a period in unequally sampled data series and has the following characteristics:

- it deals with unevenly spaced data;
- it allows to discriminate between meaningful frequencies and spurious ones on a physical basis (evaluation of the False Alarm Probability);
- it renders the P.S.D. invariant to a shift in the signal origin.

To tailor the specific needs of statigraphic data the signals were processed with a (tapering) window function before being submitted to spectral analysis. For this purpose we used the following Gaussian function:

$$w(n)=e^{\frac{\left(\frac{2n}{N-1}\right)^{2}}{2}} .$$

This tapering is indispensable to eliminate spectral leakage due to the discontinuities at the extremities of the finite sampled signal.

Table 1 — Peak periodicities in the power spectra.
Text. lists the textural parameters; Dolom. the degree of dolomitization. The magnetic parameters are Int. (intensity of N.R.M.), Incl. (inclination of N.R.M.) and Decl. (declination of N.R.M.). The astronomical periodicities (Astr.) are from Berger et al. (1989, 1992).

Text. (cm)	Dolom. (cm)	Int. (cm)	Incl. (cm)	Decl. (cm)	Astr. (years)
53	56	52	54	—	18.350
68	68	65	69	61	22.200
100	106	103	118	—	38.200
145	146	144	142	—	48.750
247	249	258	260	268	95.800
921	921.	—	1073	982	403.800

Table 2 — Relative ratios of the observed periodicities and orbital parameters.
The ratios are based, from left to right, on 53, 56, 52, and 54 cm and 18.350 years. Abbreviations as for Table 1.

Text. (cm)	Dolom. (cm)	Int. (cm)	Incl. (cm)	Decl. (cm)	Astr. (years)
1.0	1.0	1.0	1.0	—	1.0
1.3	1.2	1.2	1.3	—	1.2
1.9	1.9	2.0	2.2	—	2.0
2.7	2.6	2.7	2.6	—	2.6
4.6	4.4	4.9	4.8	—	5.2
17.3	16.4	—	19.8	—	22.0

Furthermore, among the peaks arising above the 90% False Alarm Probability, it was necessary to identify and ignore those due to the harmonic trend generated by the number of sampled intervals. In Figs. 4 and 5, such harmonics are marked by dots. On the remaining peaks, chosen as significant, the number indicates the relative periodicity computed in cm (Figs. 4 and 5).

Well-defined cyclicities were clearly present in all parameters, although the magnetic declination showed fewer defined peaks. In order to test the results obtained, the inclination data sets were also processed with a conventional F.F.T. program, Singleton, 1969. See Figs. 5 (a) and 5 (b).

In addition to the direct geological/geophysical observations, the periodicities of postulated Milankovitch cyclicities for this part of the Lower Cretaceous (Berger et al., 1989; Berger et al., 1992) were examined to enable comparison with the dynamical evolution of the inner solar system (Table 1).

In order to compare thickness-(cm) based periodicities with time-(Ky) based periodicities, (Longo et al., 1993) the orbital calculations were normalised to their highest defined frequency, 18,350 years, and the bore-core parameter data were normalised to their highest well defined frequencies, i.e., 53, 56, 52 and 54 cm respectively (Table 2). Linear regression analysis of these time and thickness relative ratio, grouped in sets, gives correlation factors that are all above 0.98, and hence they can be considered linked even though they involve both linear and temporal scales.

CONCLUSIONS

The importance of the relationships among high-frequency periodic variations of stratigraphic, sedimentologic, palaeomagnetic parameters and dating techniques cannot be under-estimated. In fact while the mechanism linking the measured parameters still requires assessment, their correlation with the postulated Milankovitch cycles provides a basis for absolute dating at a cm scale.

For example, at Monte Raggeto, sediment accumulation rates for the Barremian range between 1.5 to 5 cm/1000 years, depending on uncertainties and interpolation validity in the absolute dates for different time scales (Cowie et al., 1989; Palmer et al., 1983; Haq et al., 1987; Harland et al., 1990). Our Milankovitch-based analysis enables this rate to be quantified at 3.5 cm/1000 years.

The correlations also have clear implications for the rapidity and very early nature of cementation in these deposits, and for the locking in of the palaeomagnetic signal. The palaeomagnetic signal can thus be used to provide a rapid assessment of the other cyclical rhythms and, conversely, the longer term geomagnetic secular variation and short-period polarity oscillations at the time of the longer term geomagnetic polarity transitions can be quantified (<2 Ky). Similar studies on other intervals of the same sequence and on other Cretaceous sequences from the Southern Apennines are now attempting to evaluate the phase relationships between the various geological, geomagnetic and orbital parameters, to provide a much fuller understanding of the timing and palaeo-environmental control of such processes and to continue the establishment of this high resolution (centimetre scale) stratigraphy.

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