Cyclostratigraphic Analysis of Pelagic Carbonates and Astronomical Correlation in the Early Oligocene at Monte Cagnero (Piobbico, Italy)

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Senior Integrative Exercise
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Abstract

High-resolution calcium carbonate data from a continuous section of the early Oligocene Scaliga Cineria exposed at Monte Cagnero, Italy, is presented. Spectral analysis indicates that orbital forcing of depositional cycles at frequencies corresponding to eccentricity, obliquity, and precessional cycles are dominant in the bulk calcium carbonate record. Correlation of the those signals with a theoretical astronomical curve provides very precise absolute dates for the analyzed sequence, increases the resolution and precision of correlations between Monte Cagnero and other sections of the same age such as Contessa and the GSSP site at Massignano, and constrains the Eocene Oligocene boundary, correlated to meter 119.0, to 33.12 ± 0.03 Ma. Also, the direct correlation of the calcium carbonate curve to the lithologic log increases the reliability of the MCA lithologic log and adds to its utility for further correlation between MCA and other sites.

KEYWORDS: Milankovitch theory, spectral analysis, calcium carbonate

INTRODUCTION

The idea of using sedimentary cycles to astronomically date stratigraphic sequences and events was first proposed when Gilbert (1895) deduced that a cyclic sequence of Cretaceous limestone and marl in Colorado were controlled by the precession of the Earth's axis. It is now widely accepted that deep-water sedimentary cycles reflect orbitally controlled climatic oscillations (Hilgen et al., 1997a). Recent decades have seen several studies (Cleaveland et al., 2002; Laskar et al., 1993; Shackleton et al., 1999; Shackleton et al., 2000) apply Milankovich's theory (Milankovitch, 1941) and astronomical models to develop, refine, and advance this idea into practical dating methods. This study applies some of those methods to a sequence of Oligocene pelagic limestones and marls in order to continuously date the sequence with a high degree of precision and accuracy, and thereby refine previously determined ages within the sequence.

The subject strata are found in an outcrop of the Scaglia Cinerea formation at Monte Cagnero (MCA) near Piobbico, Italy which is a favorable site for cyclo- and magnetostratigraphic analysis because of the continuity of its carbonate strata. For reasons not yet fully explained the majority of the ash layers found at MAS are not present. Monte Cagnero displays a continuous, 130 meter thick stratigraphic sequence of pelagic limestone and marl from the upper Eocene to the upper Oligocene.

The alternating limestone and marl layers show an apparent rhythmicity (see figure 1), that I hypothesize is in part due to astronomically influenced calcium carbonate content. The amount of calcium carbonate preserved in pelagic sediment is controlled by a variable combination of bioproduction, dilution by terrigenous input, and dissolution of

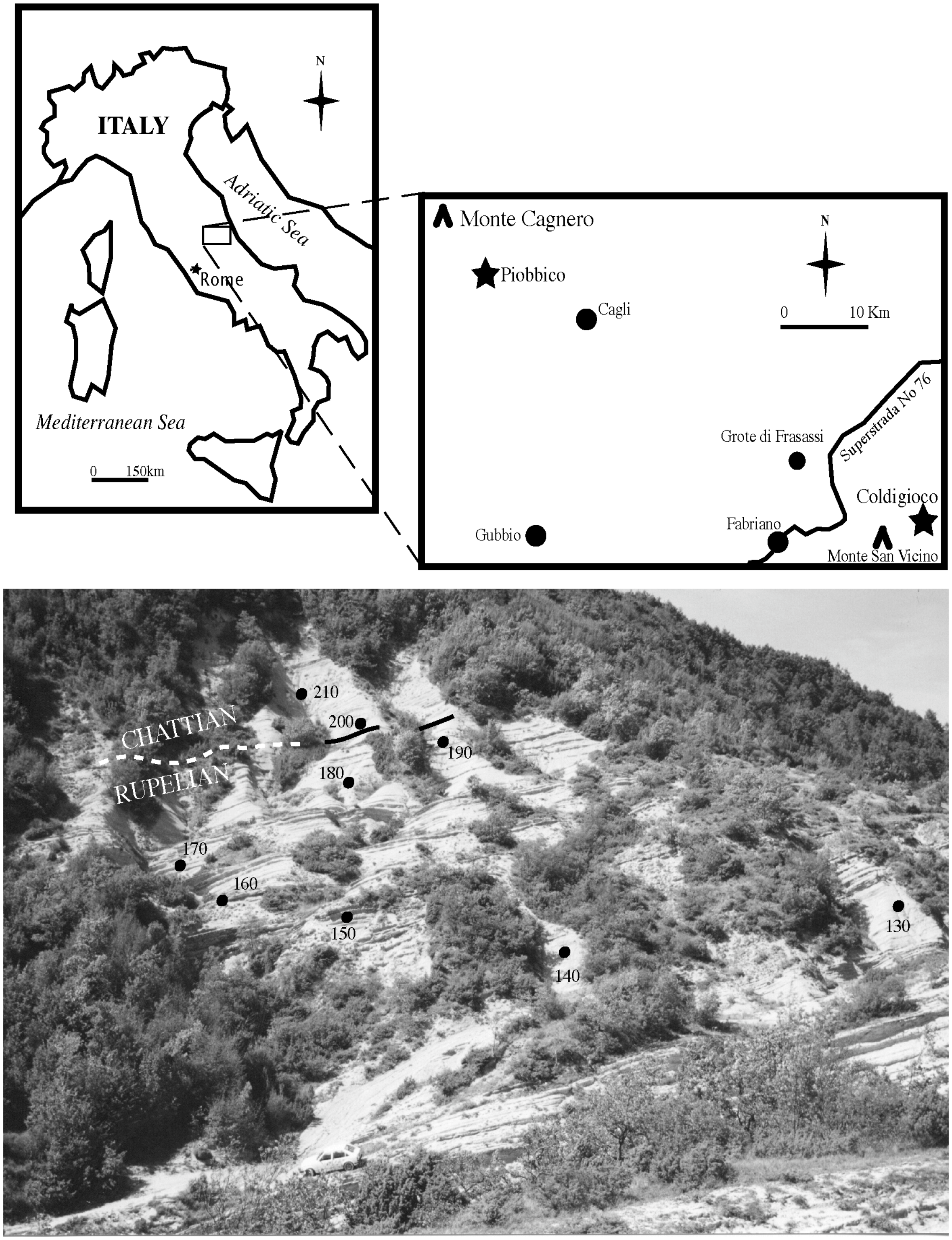

Figure 1: Location and photograph of the field site at Monte Cagnero. Samples were gathered from meter levels 135 to 100, which are partially visible in the lower right.

the carbonate material (Einsele and Ricken, 1991) which likely results in a non-linear relationship between climate variation and a carbonate record. However, for the purposes of this paper neither the specific methods by which the rock record records changes in climate nor how climate responds to orbital variations needs to be identified or evaluated. A simplifying assumption can be made that orbital forcing influences changes in the geologic record (Hays et al., 1976). I consider that there are probably other events, acting on a rage of scales, included in this record that constitute noise which may partially or completely obscure the orbital signals. Also, I do not presume that any orbital variations are transcribed to the rock record in a linear or completely consistent manner.

Astronomical influences refer to the net gravitational forces exerted by other celestial bodies on the Earth's orbit. These influences cause oscillations in the amount and distribution of incoming solar radiation over time. The three orbital cycles with their corresponding periods are eccentricity at 400, 125, and 95 Kyr, obliquity at 41 Kyr, and precession at 23 and 19 Kyr. Eccentricity refers to the shape of the Earth's orbit, from near circular to more elliptical. Obliquity refers to the variance in the tilt of the Earth's spin axis with respect to the ecliptic. That tilt ranges between 22.1° and 24.5° and a larger angle generally corresponds to increased seasonality. Precession refers to the wobble of the Earth's spin axis. This is analogous to readily observable wobble of a spinning top but on a 26 Kyr cycle and determining where in the orbit about the sun seasons occur. Modulations by eccentricity cause the precessional signal to show up in the geologic record with periods of 23 and 19 Kyr (Zachos et al., 2001).

Multiple layers within the sequence can provide constraining dates. Ash layers at meter level 145.5 and 208.3 were dated to 31.5 ± 0.20 Ma and 27.15 ± 0.18 Ma respectively by $^{40}Ar/^{39}Ar$ (Coccioni et al., 2004). Layers 108 and 125 were dated to 35.1 ± 0.1 Ma, 33.0 ± 0.1 Ma respectively (Montanari, 2004b) by correlation to interpolated dates in the Massignano (MAS) Global Stratotype Section and Point (GSSP). Also, the Eocene/Oligocene boundary is located at level 19 in the MAS section (Silva et al., 1987) with an interpolated radiometric age of 33.7 ± 0.4 Ma (Montanari and Koeberl, 2000) and should correlate to MCA meter level 119 (Montanari, 2004b). Lithographic correlation between MCA and MAS is corroborated by their ^{3}He profiles (Figure 2), both contain a spike at MCA meter 110 (Montanari, 2004b).

The bulk calcium carbonate content of these strata may be used as a proxy for in climate system responses to changes in the Earth's orbit. The astronomical signals of eccentricity, obliquity, and precession, can be used in conjunction with constraining dates found by other means, to correlate with the modeled astronomical curve (Laskar et al., 1993; Shackleton et al., 2000) to date the section with a very high precision and refine previously determined dates.

Spectral analysis has played vital role in establishing the importance of astronomical forcing in climate and connecting astronomical models to cycles found in Earth records for calibrating timescales (Hilgen et al., 1997a; Muller and MacDonald, 2000). It is a field of with many everyday applications but with techniques and terminology that are relatively uncommon. The key terms and techniques of spectral analysis used here are Fast Fourier Transforms, band-pass filters, and sliding-window spectral analysis. Based on algorithms invented by a French mathematical physicist named Joseph Fourier, a Fast Fourier Transform (FFT) is a very expedient method used

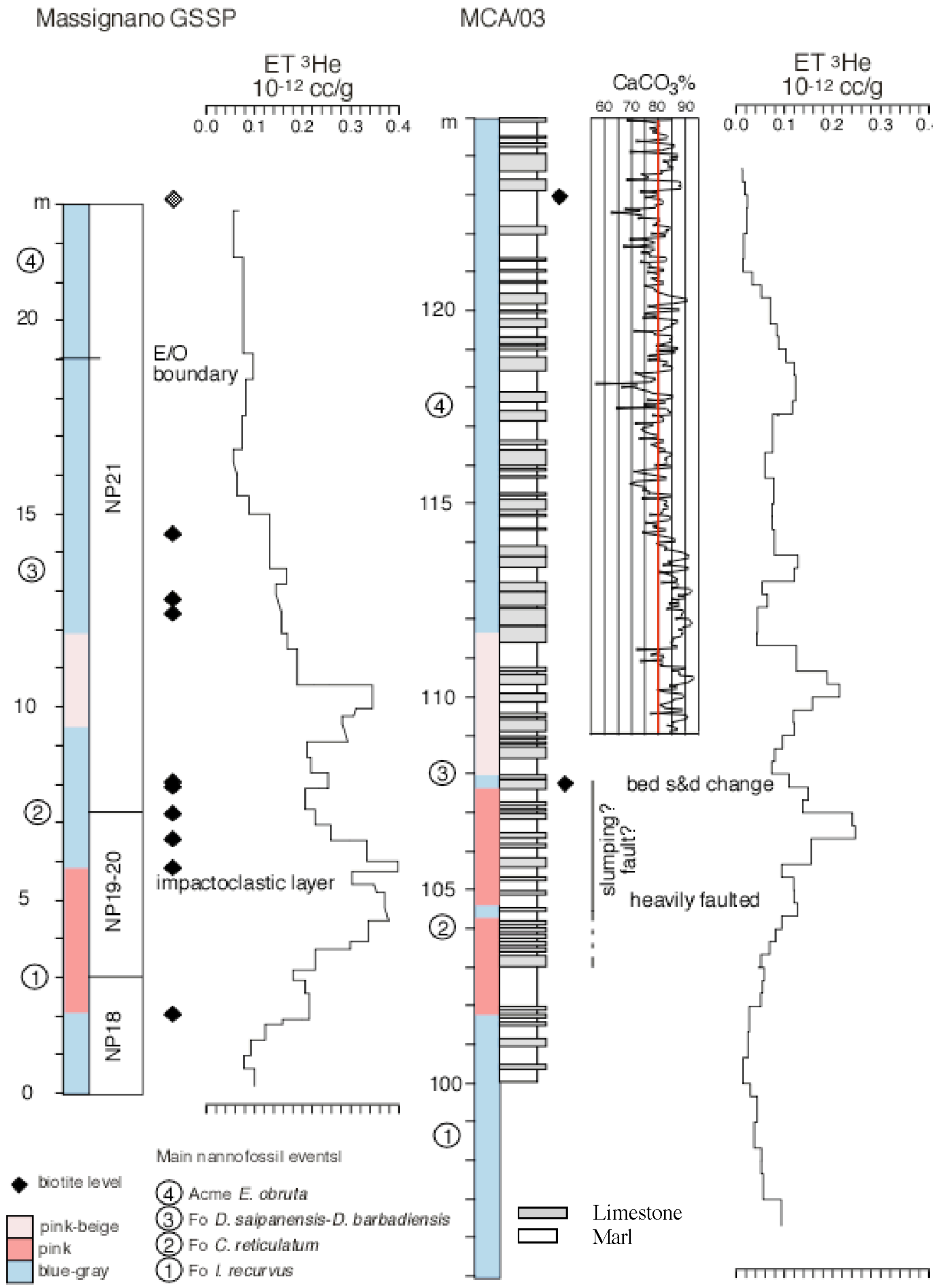

Figure 2: Multiple method correlation between the Massignano GSSP and Monte Cagnero. Notice the consistency between the visual litholog of limestone and marl layers and the calcium carbonate content, the absence of biotite layers at MCA, and the similarities between the 3He profiles (Montanari et al., Unpublished figure).

to identify the set of harmonic functions that describe a curve or set of data. Harmonic functions usually refer to sine and cosine waves but many methods have been developed. The relative influence of the harmonic functions with specific frequencies is referred to as their spectral power. A band-pass filter removes signals outside specified frequencies for the purpose of isolating a probable source's signal or removing noise or other statistically insignificant harmonic functions from the description of the data. Sliding-window spectral analyses are used to identify changes in the contribution of different frequency signals over time.

PROCEDURE

Field Methods

The meter system used follows from (Coccioni et al., 2004) where it was previously marked to have meter level 100 stratigraphically equivalent to meter level 0 of the GSSP for the Eocene/Oligocene boundary at Massignano (Premoli Silva & Jenkins, 1993 in (Coccioni et al., 2004)). Samples were collected continuously every five centimeters between meter levels 100-135 on October 19, 2003. From sedimentation rate estimates derived from radiometric dates outside of the subject strata this sample spacing should provide a 4-6 Kyr resolution. Samples were gathered from the surface with a small trowel and rock hammer then bagged and labeled in the field.

Lab Methods

For calcium carbonate analysis samples were rinsed by hand, dried, ground with a mortar and pestle, and sieved to 130 μm to ensure complete dissolution during reaction. Sample masses of 305.0 mg (15.0 mg) were reacted for one minute, including at least thirty seconds of agitation, with an excess of 10% HCl in a Dietrich-Fruling water calcimeter with ± 2% precision. The percentage of calcium carbonate in the sample was calculated from the volume of water displaced by carbon dioxide, read from the calcimeter, in conjunction with the mass of the sample, and the pressure and temperature of the reaction. Standards of pure calcium carbonate (Carara Marble) were run every twenty samples and the water level in the calcimeter was recalibrated daily to ensure proper calibration of the calcimeter. Calcimetry was performed both at the Osservatorio Geologico di Coldigioco and in the geochemistry lab at Carleton College.

Spectral Analysis

In order to find cyclicities in the bulk calcium carbonate content for correlation with the theoretical astronomical curve (Laskar et al., 1993) extended by Shackleton et al. (Shackleton et al., 1999) (1999) several techniques of spectral analysis were employed with the use of MatLab version 5.2.1. These techniques include Fast Fourier Transforms (FFT), band pass filters, and sliding-window techniques, primarily following from the methods of (Muller and MacDonald, 2000) and (Cleaveland et al., 2002).

Before performing a FFT on the calcium carbonate data the mean was subtracted to reduce the influence of long-term (whole data set) trends. This proved not to be entirely sufficient so an additional broad band-pass filter (500 to 15 Kyr window) was also used. To check for the statistical significance of the spectral peaks produced by the FFT MatLab was used to generate 1000 sets of random numbers the same size as the MCA calcium carbonate data set. A curve two standard deviations above spectral power of the frequencies used to describe the composite noise was plotted with the spectral power of the frequencies found in the calcium carbonate data. Peaks greater than the spectral power of the noise are statistically significant with 95% certainty. Sliding-window analyses also removed noise in a similar manner.

An initial range for the sedimentation rate was found by assuming it was constant between the various dated layers. A rate within this range then enabled the calculation of spectral powers resulting from a FFT in terms of years rather than meters. The aspect of strong signals was compared to those of the Milankovitch cycles to reconfirm astronomical forcing.

RESULTS

Calcium carbonate data for meters 109.00 through 125.00 are presented just right of center in Figure 2. The percentage of calcium carbonate fluctuated between 56.4% and 92.9% with minima and maxima at meter levels 118.10 and 110.40 respectively with a mean content of 80.8%. Correlation with the lithologic log (Montanari et al., Unpublished figure) showed a very consistent direct correlation of calcium carbonate content with marl and limestone strata.

For use in initial calculations a constant sedimentation rate was assumed. Values from 7.9 to 18.5 m/myr were derived from combinations of radiometric dates and correlated layers, and a modified average rate of 12.7 m/myr was used where estimates of a constant sedimentation rate were practical in spectral analysis. The spectral analysis performed on preliminary data for meters 118.00 to 121.85 in October of 2003 used a sedimentation rate of 12.0 m/myr and yielded two dominant peaks at 48 and 28 Kyr that have an aspect of 1.71, very close to the ratio of the periods of the Earth's obliquity to its precession (41 to 23 = 1.78). A FFT performed on the carbonate data yielded several statistically significant spectral peaks with frequencies close to 100, 41, and 23 thousand years (see figure 3).

The correlation of the presumed eccentricity signal by pattern matching to the astronomical curve (Laskar et al., 1993) is shown in figure 4. Not all the tie lines used for tuning are drawn in for the sake of clarity, with the exception of the eccentricity low in the astronomical curve around 35.53 Ma tie points were correlated peak to trough, trough to peak for nearly all of the overlapping interval. Laskar's astronomical prediction only extends back to 33.999 m.y. before present. Sliding-window analyses, with windows of 200 k.y., were used on Laskar's theoretical insolation, the raw calcium carbonate data with an estimated constant rate of sedimentation, and the eccentricity tuned carbonate curve to generate the resulting signals are shown in figure 5.

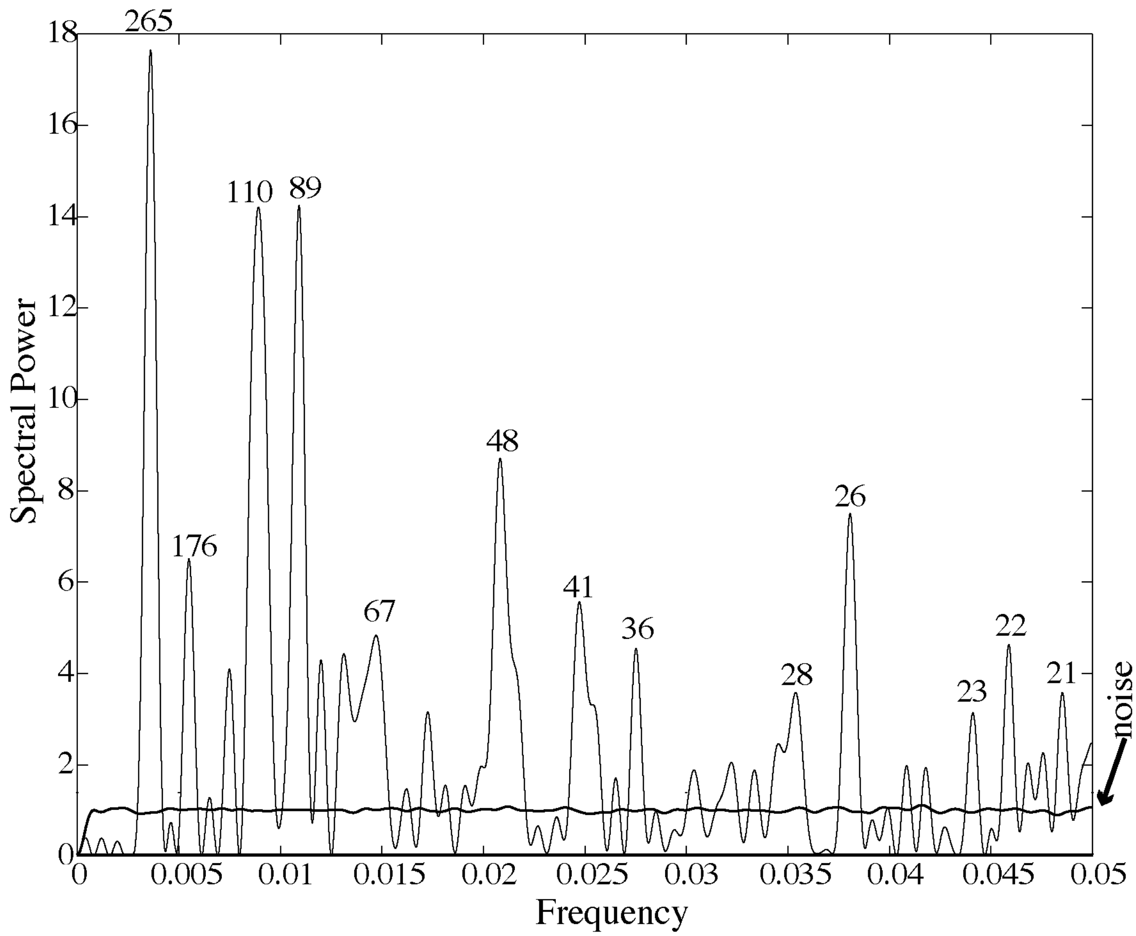

Figure 3: Spectral analysis results for Monte Cagnero carbonate data. An initial sedimentation rate of 12.7 m/Ma was used in generating this plot but due to error associated with radiometric and correlated dates the peak patterns can be shifted slightly in either direction to accommodate variance in the sedimentation rate. The nearly flat curve with a spectral power around one is a plot of the frequencies present in 1000 data sets of randomly generated noise.

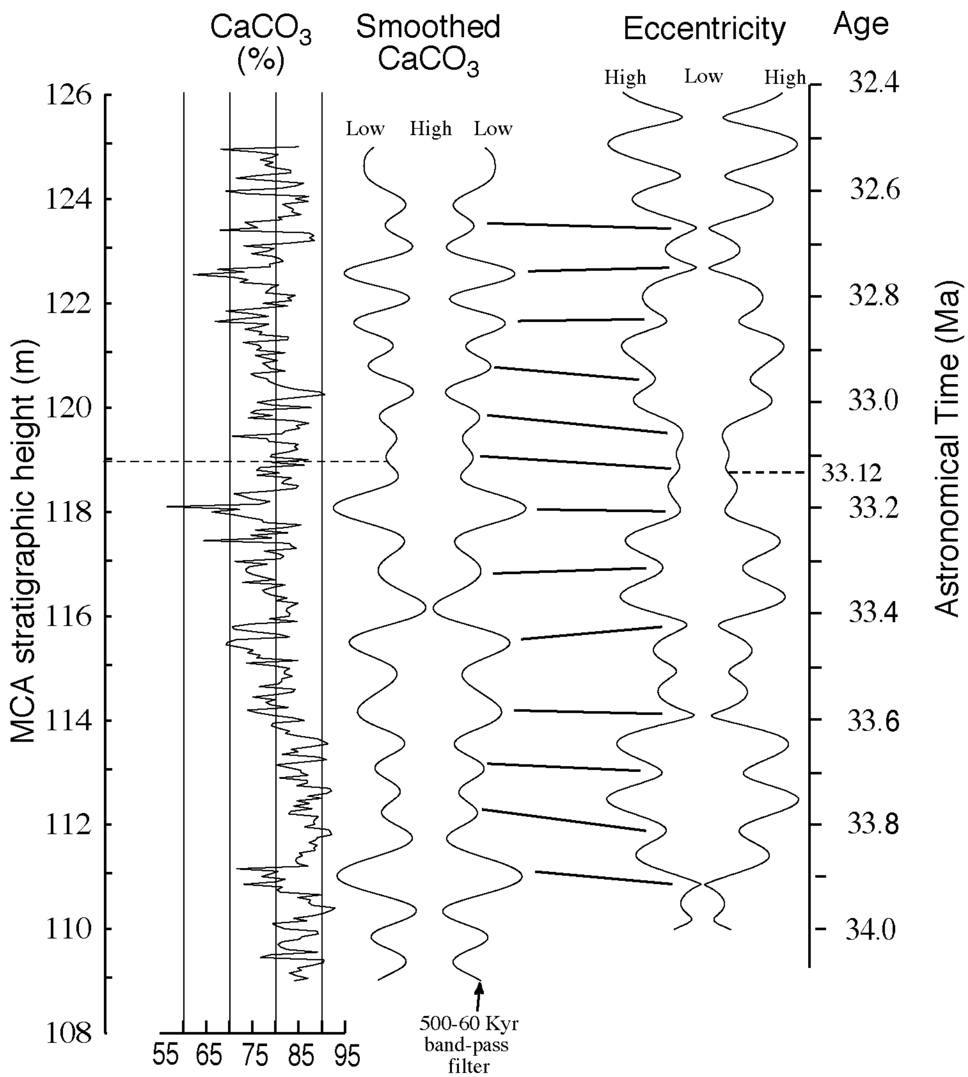

Figure 4: Correlation between Monte Cagnero calcium carbonate data and astronomical time scale (Laskar et al., 1993). The calcium carbonate data were smoothed by a band-pass filter. Vase-like images were constructed to aid correlation. Notice slightly uneven spacing in both curves indicating influences of different frequencies. Correlation here yields 26 tie points (not all shown) and indicates that meter 119.0 is 33.12 ± 0.02 Ma, significantly younger than the age previously determined for the Eocene-Oligocene boundary.

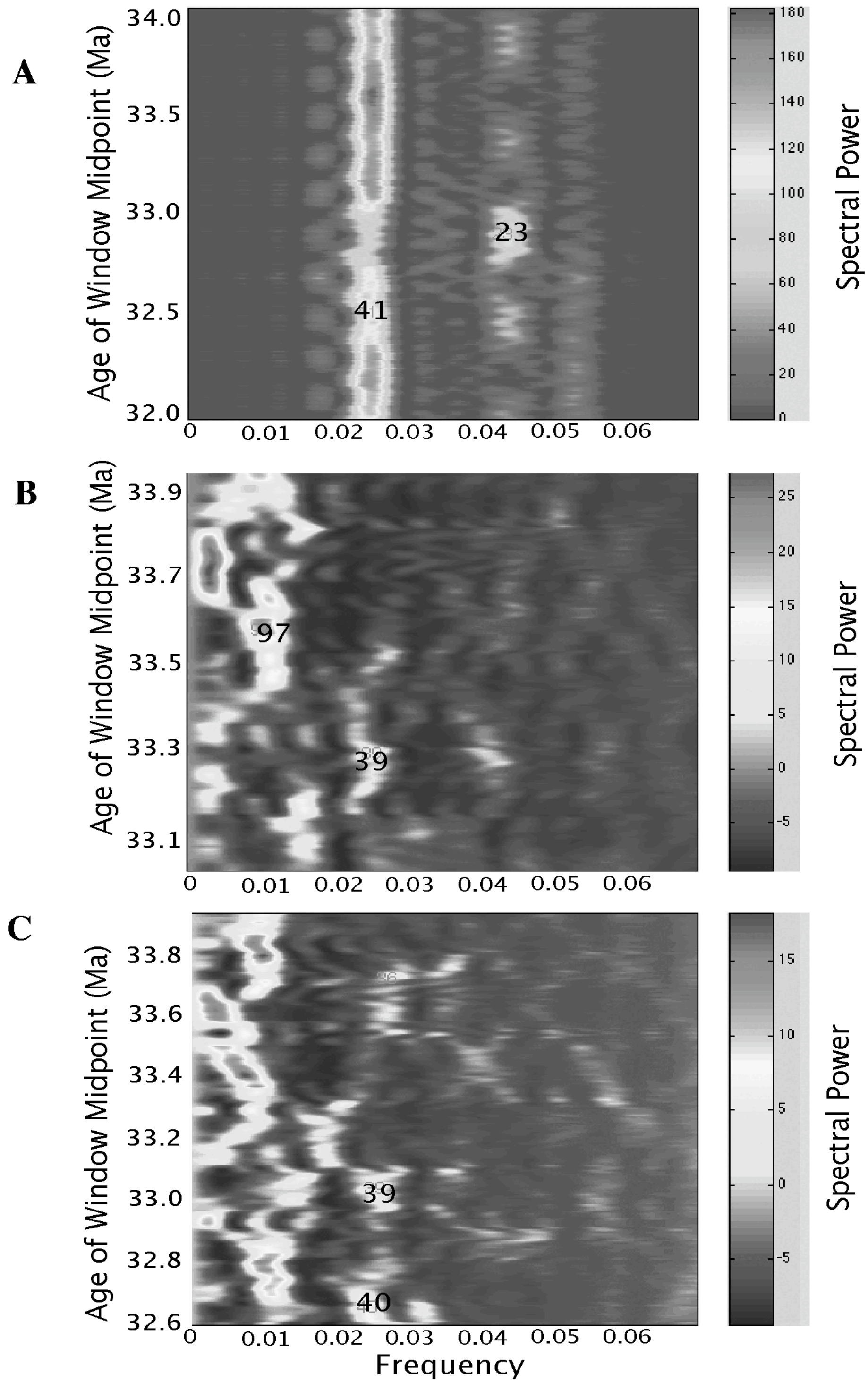

Figure 5: Variations in spectral power over time from sliding-window spectral analysis with windows of 200 k.y. A) Analysis of theoretical 65°N summer insolation curve for 32.0-34.0 Ma (Laskar et al., 1993). This shows that climate during this period, with the exception of some relatively brief precessional dominance, was likely driven primarily by changes in obliquity. B) Analysis of the raw carbonate data assuming a constant sedimentation rate. Note the inconsistency over time and dominance of low frequency signals. C) Analysis of the eccentricity tuned carbonate data. Note the slightly stronger and more continuous signal in the obliquity band.

DISCUSSION

The results of my analysis indicate that the rhythmically bedded pelagic sequence from Monte Cagnero reflects astronomically influenced climate variations during the late Eocene through the early Oligocene. Although the analyzed data set is not large enough to expect a ~400 Kyr signal the occurrence of the ~100 Kyr signal points to eccentricity forcing of climate. It has been found repeatedly that the strength of the eccentricity signal is far out of proportion to its theoretical contribution to insolation, similar results were found in several other studies including and referred to in (Cleaveland et al., 2002 (e.g. Fischer, 1991; Clemens and Tiedemann, 1997; van Vugt et al., 2001)).

Due to the lack of radiometric ages within the subject strata my correlation between the smoothed carbonate curve and the theoretical eccentricity curve for this interval relies heavily on pattern matching. Curve shape of individual peaks, number of peaks of relative amplitude, and relative changes in amplitude were taken into account in the process of matching the curves and yielded 26 tie points. The correlation does however, point to generally younger than expected ages as detailed in figure 4. Specifically, it indicates that meter 119.0 is 33.12 ± 0.02 Ma, younger by nearly 0.5 Ma than the age previously determined for the Eocene-Oligocene boundary (Silva et al., 1987).

The multitude of peaks clustered around Milankovitch-cycle frequencies in figure 3 and of the sliding window analysis shown in figure 5b confirms that the sedimentation rate did not remain constant during the deposition of this section of the Scaglia Cinerea. During the Rupelian insolation was dominated by influence from the Earth's obliquity (see fig. 5 top) with the exception of about 250 k.y. beginning 33.0 m.y. ago and a few other brief periods during which precession also played a major part. This led me to expect that a sufficiently strong obliquity signal would be detectable after tuning to eccentricity so as to allow obliquity tuning to astronomical time. However, signals in the obliquity band were strengthened only slightly (see fig. 5 middle and bottom). Though some positive result does support that these are indeed Milankovitch signals, I can think of two possible explanation for the weak eccentricity tuning results. Either 1) the sedimentation rate varied with sufficient frequency and amplitude to disrupt signals with frequencies much higher than that of eccentricity. At least, the double peaks at 110 and 89 Kyr may signify two dominant sedimentation regimes differing from 12.7m/Ma by nearly the same amount. Or 2) the limitations of curve correlation by pattern matching alone for this data set prohibit precise enough tuning to bring out the obliquity signal better. A non-linear relationship between eccentricity and the carbonate record would make pattern matching complicated in either case.

Numerous band-pass filters run before and after tuning to eccentricity failed to detect an obliquity signal that could be correlated by pattern matching with any confidence to the astronomical curve. Unlike most of the band pass results, the theoretical astronomical obliquity curve shows very little variation in amplitude over even the scale of 10^5 years, or over just less than tens of peaks. At greater orders of magnitude there is a low amplitude “node” which displays a period of ~1.2 m.y. However the subject data set is too small for this node to be used for correlation. The discrepancy between relative amplitudes supports a nonlinear relationship between in pelagic carbonate deposition and insolation fluctuation.

If incorrect, the young estimate for the Eocene-Oligocene boundary is likely due to one of three causes, improper identification of the E/O transition layer at MCA, rapidly varying deposition rates at MAS, or error in spectral analysis. The miscorrelation of the E/O boundary is unlikely given the familiarity of Montanari with both the GSSP and MAS, but not impossible and work is ongoing. Nano- fossil work by Flavia Tori, currently in progress, does not match up with other MCA-MAS correlations (Montanari, 2004a). Confidence in the spectral analysis results based on pattern matching is primarily limited by the range of ages represented. A larger data set could allow additional pattern matching correlation by the ~400 kyr eccentricity or the 1.2 myr obliquital node cycle. Such high fidelity stratigraphic records may even be able to help improve radiometric dates (Hilgen et al., 1997b) in (Cleaveland et al., 2002) but the strata analyzed in this project cannot provide such robust conclusions. And, if more radiometric dates can be determined within the section they could help make a much more robust astronomical correlation.

This location offers many directions for further work. Additional carbonate analysis could expand the subject strata upward to encompass level 145.5 to provide at least one radiometric date with which to correlate the astronomical dates. The direct correlation of the calcium carbonate curve to the litholog should help settle uncertainty as to the accuracy of the MCA litholog and adds to its utility in further correlation between MCA and MAS. More detailed correlation between MCA and Massignano site may be facilitated now with the carbonate correlated lithologic log and the location of any datable biotite lower than meter 145.5.

CONCLUSIONS

Spectral analysis of high-resolution calcium carbonate data indicates orbital forcing of depositional cycles at Monte Cagnero. The sedimentation rate varies within the analyzed sequence. A constant sedimentation rate, estimated within the range calculated from various dated layers, yields a strong spectral signal in a frequency range that corresponds to eccentricity. This variable could be adjusted further to enhance spectral analysis results. The presumed eccentricity signal was correlated to the theoretical astronomical curve by pattern matching to provide astronomical ages for nearly the entire section. These dates include an adjustment of the age of meter level 119.0, thought to correlate to the Eocene-Oligocene boundary at 33.7 ±0.1 Ma, to 33.12 ± 0.03 Ma. This should not be considered an age revision for two reasons, astronomical age results of this analysis are based entirely on pattern matching with a smaller than ideal data set, and the correlation of meter 119 with the Eocene-Oligocene boundary has yet to be verified. Finally, the direct correlation of the calcium carbonate curve to the litholog increases the reliability of the MCA litholog and adds to its utility for further correlation between MCA and other sites.

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