



Orbital chronology of Early Eocene hyperthermals from the Contessa Road section, central Italy

Simone Galeotti ^{a,*}, Srinath Krishnan ^b, Mark Pagani ^b, Luca Lanci ^a, Alberto Gaudio ^a, James C. Zachos ^c, Simonetta Monechi ^d, Guia Morelli ^d, Lucas Lourens ^e

^a Dipartimento GeoTeCA, Università degli Studi di Urbino 'Carlo Bo', Località Crocicchia, 61029 Urbino, Italy

^b Department of Geology and Geophysics, Yale University, United States

^c Earth and Planetary Sciences Department, University of California, Santa Cruz, Santa Cruz, CA 95064, USA

^d Dipartimento di Scienze della Terra, Università degli Studi di Firenze, Via La Pira 4, 50121 Firenze Italy

^e Faculty of Geosciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands

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ABSTRACT

High-resolution geochemical analyses of the Lower Eocene Contessa Road section (Italy) reveal orbitally controlled fluctuations in the percent concentration of calcium carbonate (wt.% CaCO₃) that include the ETM2 (Elmo) and ETM3 ("X") hyperthermal events. Patterns of increased dissolution, negative carbon isotope excursions, and warmer global climates are intimately linked to maxima in insolation, through the global carbon cycle. Extraction of short- and long-eccentricity orbital periodicities of the wt.% CaCO₃ record provides a relative cyclochronology for the interval ranging from ~52 to ~55.5 Ma. The Contessa Road section is easily accessible and offers a continuous integrated stratigraphic record (stable isotopes, standard calcareous plankton biostratigraphy, magnetostratigraphy, and cyclostratigraphy), thus providing a potential type succession for the study of Early Eocene hyperthermals.

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1. Introduction

The Late Paleocene to Early Eocene is characterized by a series of short-term (10⁴ to 10⁵ years) changes in the carbon isotope composition of the ocean–climate system (Cramer et al., 2003) as a response to episodic release of ¹³C-depleted carbon (Lourens et al., 2005; Nicolo et al., 2007). During the two largest negative carbon isotope excursions (CIEs), including the Paleocene–Eocene Thermal Maximum (PETM) (Kennett and Stott, 1991; Zachos et al., 2005) and Eocene Thermal Maximum 2 (ETM2) (or Elmo Event, Lourens et al., 2005), global temperatures rose by 4 to 8 °C. Extreme global warming and marked negative carbon isotope excursions in marine and terrestrial carbonates and organic carbon are associated with widespread carbonate dissolution in response to shoaling of the carbonate lysocline and lowering of the carbonate saturation state (Zachos et al., 2005) potentially caused by the dissociation of gas hydrates (Dickens et al., 1997). Enhanced runoff inferred from more marginal settings (Zachos et al., 2006; Giusberti et al., 2007; Nicolo et al., 2007) suggests an invigorated hydrological cycle and enhanced seasonality concomitant with peak warming phases. These episodes of global warming, known as hyperthermals,

temporarily altered assemblages of planktonic and benthic foraminifera, calcareous nannofossils and dinoflagellates (Thomas and Zachos, 2000; Lourens et al., 2005). Available information from deep-sea records suggests the occurrence of other short-lived hyperthermals characterized by negative CIEs, biotic perturbations, elevated seasurface temperatures and carbonate dissolution during the Paleocene and Early Eocene and (Thomas and Zachos, 2000; Cramer et al., 2003; Zachos et al., 2004; Röhl et al., 2005; Thomas et al., 2006; Nicolo et al., 2007; Quillevéré et al., 2008; Agnini et al., 2009).

In addition to the PETM and ETM2, other hyperthermals might include event I (~53.2 Ma) and event K (~52.5 Ma) of Cramer et al. (2003), the latter corresponding to event X (Röhl et al., 2005; Agnini et al., 2009) here referred to as ETM3.

Previous analysis and astronomical tuning of oceanic records provided evidence that the timing of the Early Eocene hyperthermal series and their associated $\delta^{13}\text{C}$ anomalies were linked to relatively small orbital changes in insolation, implying that small temperature changes were amplified to produce extreme global warming (Cramer et al., 2003; Lourens et al., 2005). Cyclochronologies by the latter authors, however, differ in the number of cycles identified in the interval spanning the Paleocene Eocene Thermal Maximum (PETM) to the base of Chron C24n, thus adding uncertainties in the construction of an astrochronological scale for the Early Eocene.

* Corresponding author.

E-mail address: simone.galeotti@uniurb.it (S. Galeotti).

Recent work challenges the supposition that orbital forcing was the primary triggering mechanism for extreme warming based on the observation that the onset of the PETM is not in phase with eccentricity as it is for ETM2 (Westerhold et al., 2007). These results have yet to be confirmed from other paleogeographic and depositional settings. Given the uncertainties in the total number of hyperthermal events and time relationships between them (see Agnini et al., 2009), the development of a cyclochronological record encompassing the entire series of known and suspected Early Eocene hyperthermals is a fundamental prerequisite to ascertain their global distribution and to resolve their causal relationships.

For this study, we present an integrated stratigraphic analysis, including biostratigraphy, magnetostratigraphy and cyclostratigraphy, and wt.% CaCO₃ and bulk carbonate isotope records across the Upper Paleocene–Lower Eocene interval from the Western Tethys Contessa Road section comprising the PETM, ETM2, and ETM3. We use these data to directly assess how orbitally controlled changes in

insolation paced the carbon isotope excursions and patterns of dissolution in a pelagic setting.

2. The Contessa Road section

A continuous record of the Paleocene and Early Eocene is preserved in the Scaglia Rossa pelagic red limestones of the Umbria–Marche succession from central Italy. Magneto- and biostratigraphic data from Paleogene sections near the Gubbio area enabled the first calibration of geomagnetic reversals for most of the Paleogene interval (Alvarez et al., 1977; Lowrie et al., 1982; Monechi and Thierstein, 1985). For this work, we studied the Contessa Road section (Fig. 1) which provides a continuous and undisturbed sequence across the Paleocene–Eocene (P/E) boundary and the Lower Eocene (Luterbacher, 1964; Lowrie et al., 1982; Galeotti et al., 2000).

The 54.5 m-thick Contessa Road section starts at the Cretaceous–Tertiary (K/T) boundary, which is defined as level 0 in the section

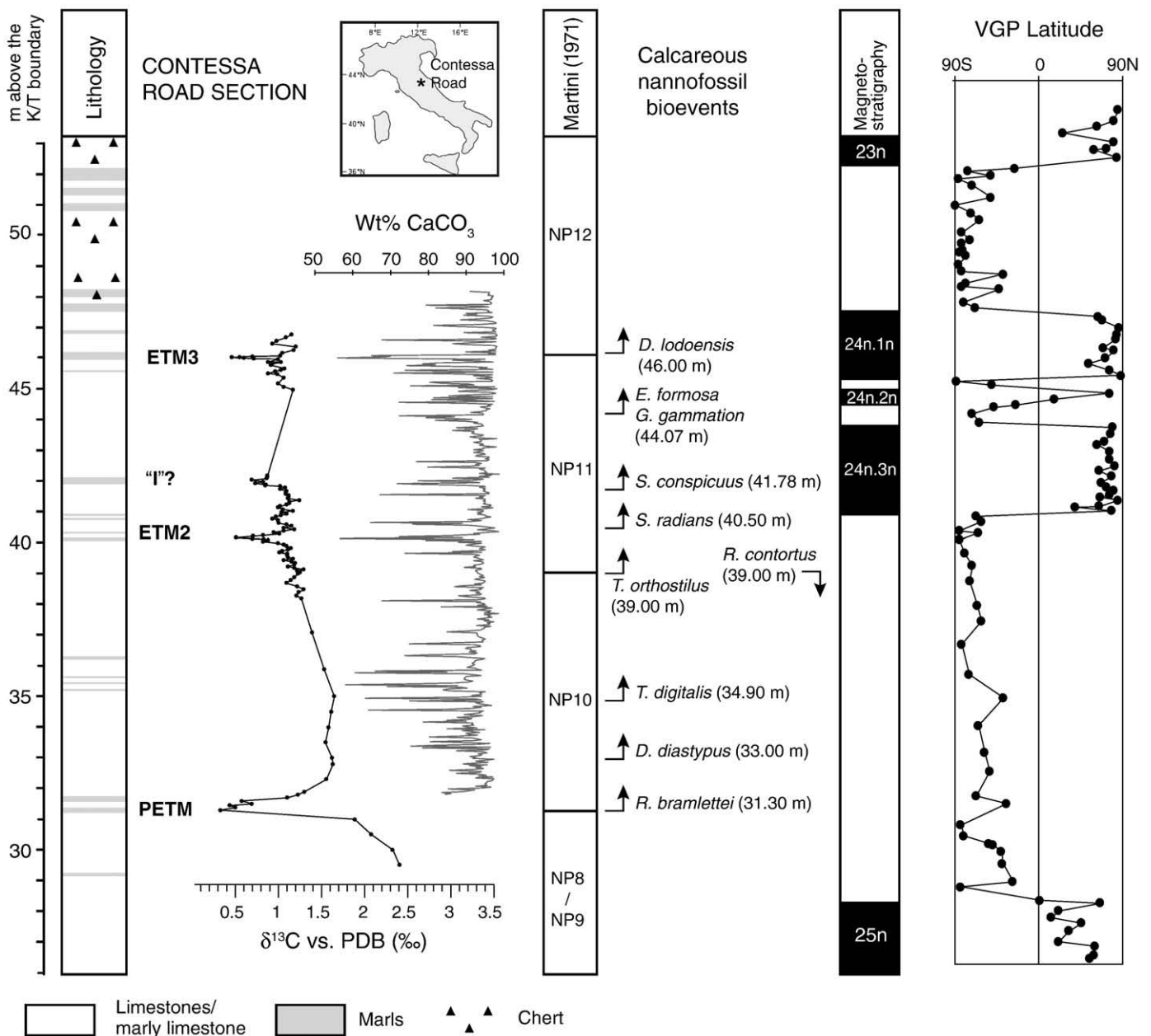


Fig. 1. Integrated bio-, magneto- and chemostratigraphy ($\delta^{13}\text{C}$, wt.% CaCO₃) of the Lower Eocene Contessa Road section. We report $\delta^{13}\text{C}$ anomalies identified as hyperthermals based on comparison with the records produced by different authors (Cramer et al., 2003; Lourens et al., 2005; Nicolo et al., 2007; Westerhold et al., 2007; Agnini et al., 2009).

measurement. Previous bio- and magnetostratigraphy of the lower Paleogene portion of the Contessa Road section have been published by Lowrie et al. (1982) and Galeotti et al. (2000, 2005) from ca. 24 m above the K/T boundary to the top of the section at 54.5 m above the K/T boundary. A 2‰ negative carbon isotope excursion and the extinction of benthic foraminifera mark the onset of the PETM at 30.3 m (Galeotti et al., 2000). For this study, we have remeasured the section and revised the lithostratigraphy between 24.0 and 54.5 m and consequently placed the onset of the PET at 31.3 m. Further, a series of smaller negative CIEs are apparent in the Lower Eocene at Contessa Road (Coccioni et al., 2006), similar to isotope patterns recorded in deep-sea sequences elsewhere (Cramer et al., 2003; Lourens et al., 2005) and marginal settings (Nicolo et al., 2007; Agnini et al., 2009).

3. Materials and methods

3.1. Biostratigraphy and magnetostratigraphy

Qualitative and semiquantitative analyses of calcareous nannofossils were performed on standard smear slides from 43 samples collected between 37 and 50 m using the biostratigraphic data of Galeotti et al. (2000, 2005) from the PETM to 37 m.

A highly resolved magnetostratigraphic record was constructed on 104 closely spaced (ca. 30 cm on average) samples from 26.4 m to the top of the section and then used to identify reversal boundaries with respect to wt.% CaCO_3 and isotopic stratigraphy. Measurements followed standard paleomagnetic procedures and involved stepwise thermal demagnetization and principal component analysis of each specimen. Magnetic polarity was interpreted after calculation of the virtual geomagnetic polarity latitude following Cande and Kent (1995) (see Fig. 1).

3.2. Cyclostratigraphy

Cyclostratigraphic analysis was performed using wt.% CaCO_3 obtained from 3 cm-spaced samples collected from the top of the CIE associated with the PETM at 31.70 m (Galeotti et al., 2000) to 48.18 m. Calcimetry was performed using the “Dietrich-Fruhling” calcimeter. Precision of wt.% CaCO_3 measurements, based on replicate analyses is within 1%.

To obtain a basic framework for the cyclochronological interpretation of the surveyed interval we first performed a Blackman–Tukey (B–T) spectral analysis in the depth domain and extracted the 1.9-m period, corresponding to ~400 kyr, using the AnalySeries program (Paillard et al., 1996) and a Gaussian filter with a $\pm 10\%$ bandwidth. Wavelet analysis was then used to compute evolutionary spectra in the depth domain using the Wavelet Script of Torrence and Compo (1998). Dominant periodicities and changes in the cycle periods, due to fluctuations in the sedimentation rate determined by evolutionary spectra, were used to tune the wt.% CaCO_3 record to the astronomical solution of Laskar et al. (2004) using an age of 53.53 ± 0.04 Ma for the base of Chron C24n (Option 1 in Westerhold et al., 2007) as a fixed point. We use the thickness of individual cycle of the prominent short-eccentricity period to develop a sedimentation rate model for the Lower Eocene Contessa Road section. Periodic components of the tuned records were identified by B–T and Multi Taper Method (MTM). Filtering of the tuned record was conducted by MTM reconstruction using components exceeding the 99% significance level according to the method proposed by Mann and Lees (1996). The interval containing the PETM is characterized by a distinct decrease in wt.% CaCO_3 that is more prolonged and larger than any other wt.% CaCO_3 excursion of the Lower Eocene interval. To avoid the predominance of the PETM signal in our treatment, spectral analysis was restricted to 31.70–48.18 m interval. We apply the age of the top of the PETM provided by Westerhold et al. (2007) as a tie-point to develop our cyclochronology.

3.3. Stable isotopes

Relative to the PETM, several smaller negative CIEs have been identified in the Upper Paleocene–Lower Eocene Contessa Road section (Galeotti et al., 2000, 2006; Coccioni et al., 2006). In order to assess the relationship between CIEs and wt.% CaCO_3 , high-resolution sampling was conducted across intervals where CIEs were anticipated on the basis of bio- and magnetostratigraphic data (Fig. 1). Samples were crushed, dried, and split for isotope and carbonate analyses. Bulk carbonate stable carbon and oxygen isotope analyses from the interval 44.9–46.80 m were performed on an Autocarb coupled to an OPTIMA Dual Inlet Mass Spectrometer at University of California, Santa Cruz. External precision for $\delta^{13}\text{C}$ was better than $\pm 0.05\%$ based on replicate analyses of Carrera Marble standard. Isotope analyses for samples from the interval 38.0–42.0 m were analyzed on a Delta plus XP coupled with a Gas Bench II at Yale University. External precision of analysis for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ was $\pm 0.1\%$ and $\pm 0.15\%$, respectively, based on replicate analysis of NBS-19 and NBS-18.

4. Results

4.1. Chronostratigraphy of the Lower Eocene Contessa Road

Several biostratigraphic events have been recognized in the studied interval: lowest occurrence (LO) of *Tribachiatulus orthostylus* and highest occurrence (HO) of *Rhombasteria contortus* (39.0 m), LO of *Sphenolithus radians* (40.50 m), LO of *Sphenolithus conspicuus* (41.78 m), lowest rare occurrence (LRO) of *Calcidiscus protoannulus* (41.93 m), LRO of *Ericsonia formosa* (42.63 m), LO of *Ericsonia formosa* (44.07 m), LO of *Girgisina gammation* (44.07 m), LO of *Discoaster lodoensis* (46.0 m) and highest rare occurrence (HRO) of *Discoaster multiradiatus* (47.10 m). The HO of *R. contortus* defines the lower limit of Zone P11 of Martini (1971) while the LO of *D. lodoensis* defines the lower limit of the Zone NP12 (Martini, 1971).

Paleomagnetic data indicate five magnetozones interpreted as Chron 25n to 23r based on comparison with calcareous plankton biostratigraphy (Fig. 1). Our detailed results compare well with a lower resolution record (Lowrie et al., 1982), but further refine magnetostratigraphy across C24n.

4.2. The $\delta^{13}\text{C}$ record and stratigraphic position of hyperthermals

On the basis of our bio-magnetostratigraphic results and comparisons with results from deep-sea cores (Cramer et al., 2003; Röhl et al.,

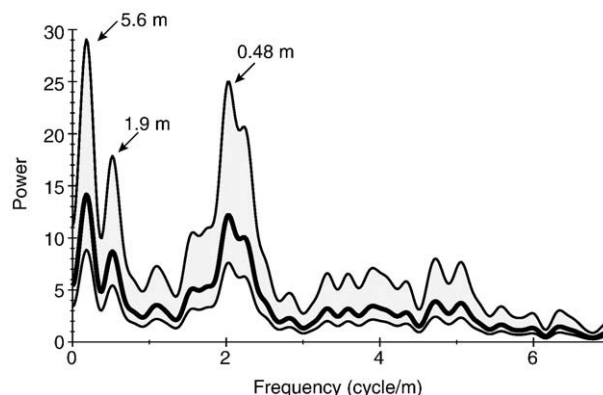


Fig. 2. Blackman–Tukey power spectra of wt.% CaCO_3 calculated in the depth domain by the AnalySeries program (Paillard et al., 1996) using 80% confidence interval (gray area, 30% of series). Bandwidth (BW) and confidence limits are based on a Bartlett window with a number of lags that equal 30% of the length of the data series. The numbers at the spectral peaks denote the period in metres.

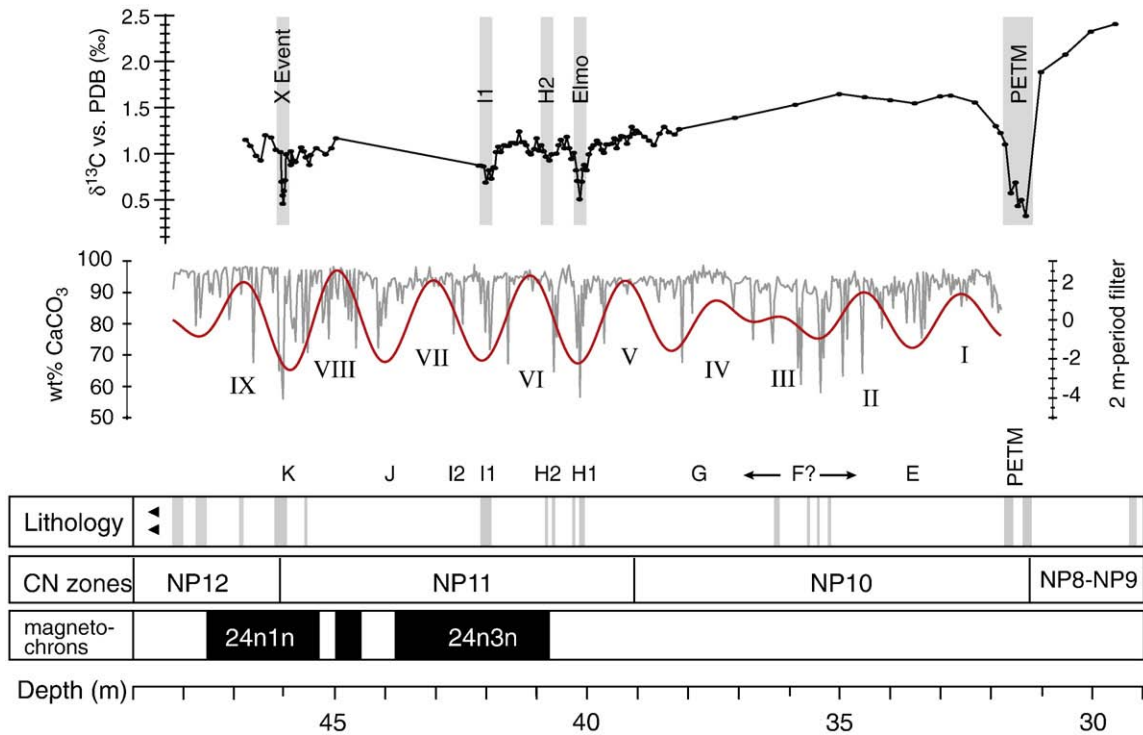


Fig. 3. The extracted 1.9 m periodic component against litho-, magneto-, and biostratigraphy and $\delta^{13}\text{C}$ record from the Contessa Road section. The inferred position of CIE events described in Cramer et al. (2003), Lourens et al. (2005), Röhl et al. (2005) and Agnini et al. (2009) is reported.

2005; Lourens et al., 2005; Westerhold et al., 2007) and land-based sections (Nicolo et al., 2007; Agnini et al., 2009), we identify three CIEs, previously interpreted as hyperthermals in the Contessa Road section. In

particular, ETM2 – corresponding to Elmo of Lourens et al. (2005) and H1 event of Cramer et al. (2003) – occurs at 40.10 m just below the C24r/C24n magnetochron boundary (within NP11 calcareous

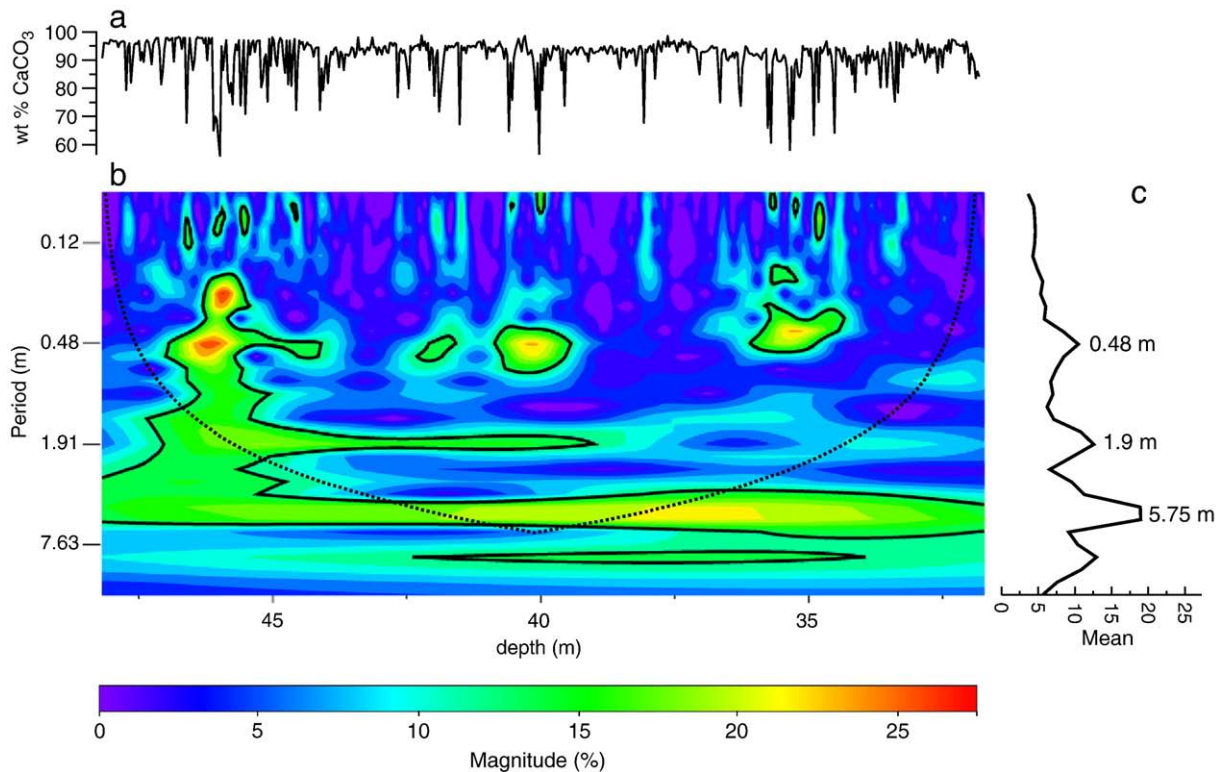


Fig. 4. (a) Weight % CaCO_3 from the Lower Eocene Contessa Road section. The record goes from just above the PETM (CIE between 31.30 and 31.70) to above ETM3 (centered at 46.18 m) thus including ETM2 (centered at 40.1 m). (b) Evolutionary wavelet analysis for wt% CaCO_3 value from the interval 32–48 m at the Contessa Road section calculated using a Morlet mother wavelet with an order of 6. Black contour is the 95% significance level, using a red-noise (autoregressive lag1) background spectrum. (c) The global wavelet power spectrum.

nannofossil zone of Martini, 1971). ETM3 occurs at 46.00 m above the K/T boundary in the Contessa Road section, within magnetochron C24n.1n. The onset of ETM3 corresponds to the NP11/NP12 boundary in calcareous nannofossil zonation of Martini (1971) in agreement with Röhl et al. (2005) and Agnini et al. (2009). We also identify a $\sim 0.4\%$ CIE at 42.00 m, within calcareous nannofossil biozone NP11 and within magnetochron C24n.3n, which likely correlates to event I1 that occurs ~ 400 kyr after H1 according to Cramer et al. (2003).

4.3. Spectral analysis

The surveyed interval spans the PETM to the lower part of Chron C23r, corresponding to calcareous nannofossil biozone NP10 to the lower part of Zone NP12 (Fig. 1). An average sedimentation rate of 0.47 cm/kyr across C24r and C24n, following the time scale of Cande and Kent (1995), is estimated from bio-magnetostratigraphy. Sampling resolution in the time domain averages ~ 6.0 kyr. Spectral analysis in the depth domain reveals high power at period of 5.6 m, 1.9 m and 0.48 m (Fig. 2). Extraction of the 1.9-m period in the wt.% CaCO_3 record provides a basic cyclochronological foundation for the studied interval. From the top of the PETM to the top of Chron C24n.1n we count nine 1.9-m cycles (labeled I–IX in Fig. 3). These cycles correspond to ~ 400 kyr eccentricity periods based on the average sedimentation rate, and therefore span ~ 3.6 Myr.

Wavelet analysis of the wt.% CaCO_3 record reveals that spectral power greater than the 95% confidence limit is confined to distinct frequency intervals (Fig. 4) with periods of ~ 200 , ~ 50 , and a component of ~ 9 cm (Fig. 4b, c). Considering the average sedimentation rate of the surveyed interval derived from bio-magnetostratigraphy (i.e. 0.47 cm/

kyr), these periods correspond to the long (405 kyr) and short (100 kyr) eccentricity cycles, and the precessional cycle (21 kyr), respectively. Also, a significant signal, interpreted to reflect changes in obliquity, corresponds to the ~ 20 cm period across centers of maximal power at 35 m and 42 m above the PETM. A shift to shorter periods with the same frequency ratios reveals an interval of lower sedimentation rate between 34 and 37 m.

Importantly, much of the spectral power is confined to the frequency range between 5.1 and 6.5 m centered on a 5.75 m period corresponding to the time domain 1.08–1.38 Myr centered on a ~ 1.2 Myr period. This ~ 1.2 Myr periodicity is largely within the cone of influence but clearly modulates both short- and long-eccentricity periods and the precession cycle with maximum amplitude modulation centered at 35 m, 40 m and 46 m in the wavelet spectrum.

In order to evaluate the control of orbital forcing over wt.% CaCO_3 changes and CIEs, we extracted significant orbital periodicities from the wt.% CaCO_3 record after re-scaling and tuning it to the astronomical solution of Laskar et al. (2004). Re-scaling was performed strictly following periodicities revealed by the B–T and wavelet power spectrum in the depth domain. After re-scaling and tuning, B–T analysis revealed strong spectral peaks at both short- and long-eccentricity-related periodicities, including a split peak of the short-eccentricity period (Fig. 5a). These components are all statistically significant above the 99% confidence limit in the MTM spectra according to the robust noise estimation of Mann and Lees (1996) (Fig. 5b). MTM reconstruction of the re-scaled wt.% CaCO_3 record allows detection of the amplitude modulations for each periodic component. Using the filtered signal, a finer-scale cyclochronology of the CIEs was established by counting short-eccentricity cycles from the top of the PETM excursion at 31.70 m

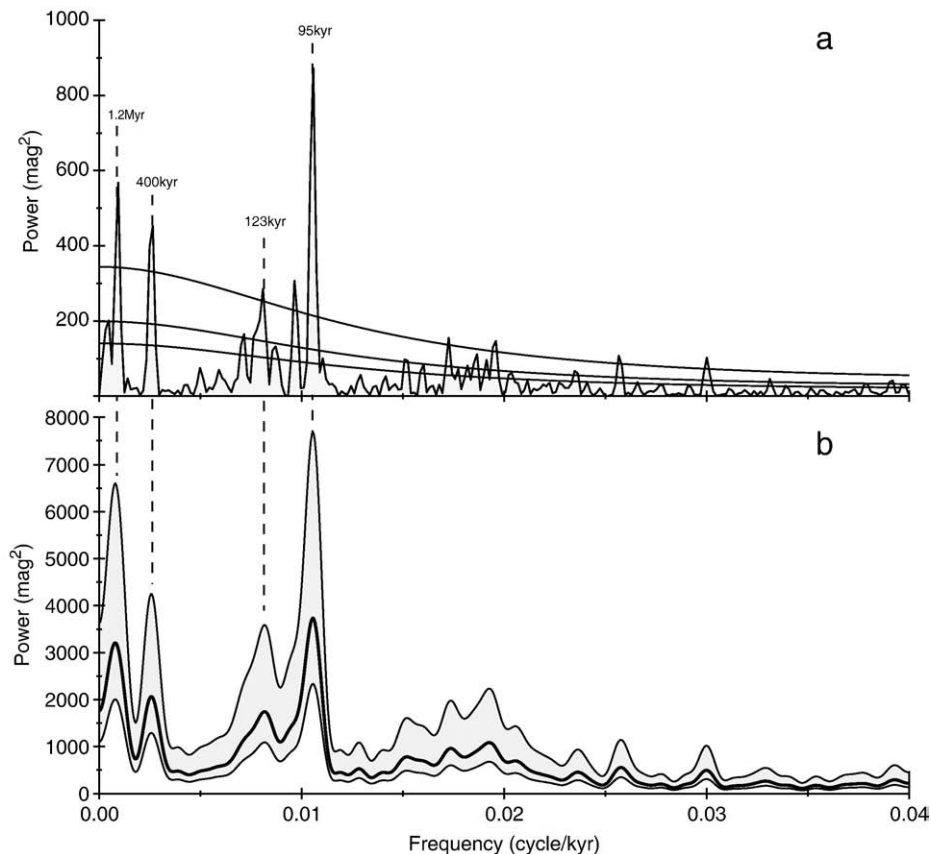


Fig. 5. (a) Blackman–Tukey power spectra (bold black line) have been calculated by the AnalySeries program (Paillard et al., 1996) using 80% confidence interval (gray area, 30% of series). Bandwidth (BW) and confidence limits are based on a Bartlett window with a number of lags that equal 30% of the length of the data series. (b) Multitaper spectral analysis of the tuned wt.% CaCO_3 record. Vertical lines correspond to the principal frequencies for the very long modulation of eccentricity (1.2 Myr) and short- and long eccentricity as revealed by the Blackman–Tukey spectra. Multitaper spectral analysis was performed using the SSA-MTM Toolkit (Ghil et al., 2002) with robust red-noise significance testing; smooth gray lines indicate 0.90, 0.95, and 0.99 confidence levels. The numbers at the spectral peaks denote periods.

to the top of the studied interval (Fig. 6). Although we do not include the PETM interval in this study, we notice that, using an age of 53.53 ± 0.04 Ma for the base of Chron C24n as a fixed point for our floating cyclochronology and assuming a total duration of 170 kyr for the CIE associated with the PETM (Röhl et al., 2007), results in an absolute age of 55.7 Ma for its onset. The obtained number falls within the absolute age range for the onset of the PETM recently reported as Option 2 by Westerhold et al. (2009) based on the integration of cyclochronology and radiogenic isotope chronology of the Lower Eocene of DSDP Leg 80 Site 550.

5. Discussion

5.1. Relative cyclochronology

Several cyclostratigraphic models have been proposed for the time period spanned by this study. In particular, Lourens et al. (2005) and Westerhold et al. (2007) identified five long-eccentricity cycles between the PETM and ETM2, while Cramer et al. (2003) identified only four. The conflicting models imply a major difference in the total duration of magnetochron C24r. It should be noticed that the analyses of Lourens et al. (2005) and Westerhold et al. (2007) were based on core logged records of light reflectance (L^*), magnetic susceptibility (MS) and Fe content, each of which ultimately reflects on changes in wt.% CaCO_3 , while Cramer et al. (2003) based their cyclostratigraphic interpretation on the analysis of $\delta^{13}\text{C}$ values. The ~ 1 Myr-long interval following the PETM is characterized by successive carbonate minima (Cramer et al., 2003; Lourens et al., 2005; Westerhold et al., 2007; this paper), that are not associated with relevant CIEs at several oceanic localities (Cramer et

al., 2003) or the Contessa Road section (Coccioni et al., 2006). This short-lived decoupling of the wt.% CaCO_3 and $\delta^{13}\text{C}$ records after the PETM may explain the different cyclostratigraphic interpretations. The 1.9 m period signal in wt.% CaCO_3 from the Lower Eocene Contessa Road supports other evidence for 5 long-eccentricity cycles between the PETM and ETM2. The shorter period and lower amplitude of the filtered signal across cycle III and IV (Fig. 3) is explained by a slight reduction in sedimentation rate across this interval as revealed by the wavelet analysis (Fig. 4). Application of the Cramer et al. (2003) age model to our record, would require an extended condensed interval, with a sedimentation rate of ~ 0.3 cm/kyr against an average of 0.47 cm/kyr, between the PETM (31.30 m) and the top of C25n (29.00 m) in order to match the total duration (~ 2.6 Myr) of Chron C24r (Cande and Kent, 1995). This scenario is very unlikely as no major lithological break occurs below the PETM in the Contessa Road record.

The occurrence of nineteen 0.48 m cycles between the top of PETM (31.70 m) and ETM2 (centered at 39.95, just below the FO of *S. radians*) in the Contessa Road section is consistent with the number of short-eccentricity cycles initially identified in the MS and L^* records of the Walvis Ridge sites 1262 and 1267 (Lourens et al., 2005) (Fig. 7). However, inclusion of ETM2 and ETM3 in the spectral analysis of Contessa Road yields a significant ~ 1.2 Myr periodicity (Fig. 6), that modulates the eccentricity signal. Three maxima within the 1.2 Myr eccentricity modulation are observed in the Contessa Road section ~ 0.6 , ~ 1.8 , and ~ 3.0 million years after the PETM event. Interestingly, a similar modulation occurs in the wavelet power spectrum from ODP Leg 208 records (particularly Site 1262) from the southeastern Atlantic Ocean (Fig. 3 of Westerhold et al., 2007). At these sites, maximum power of both short- and long-eccentricity periods occur every ~ 1.2 Myr,

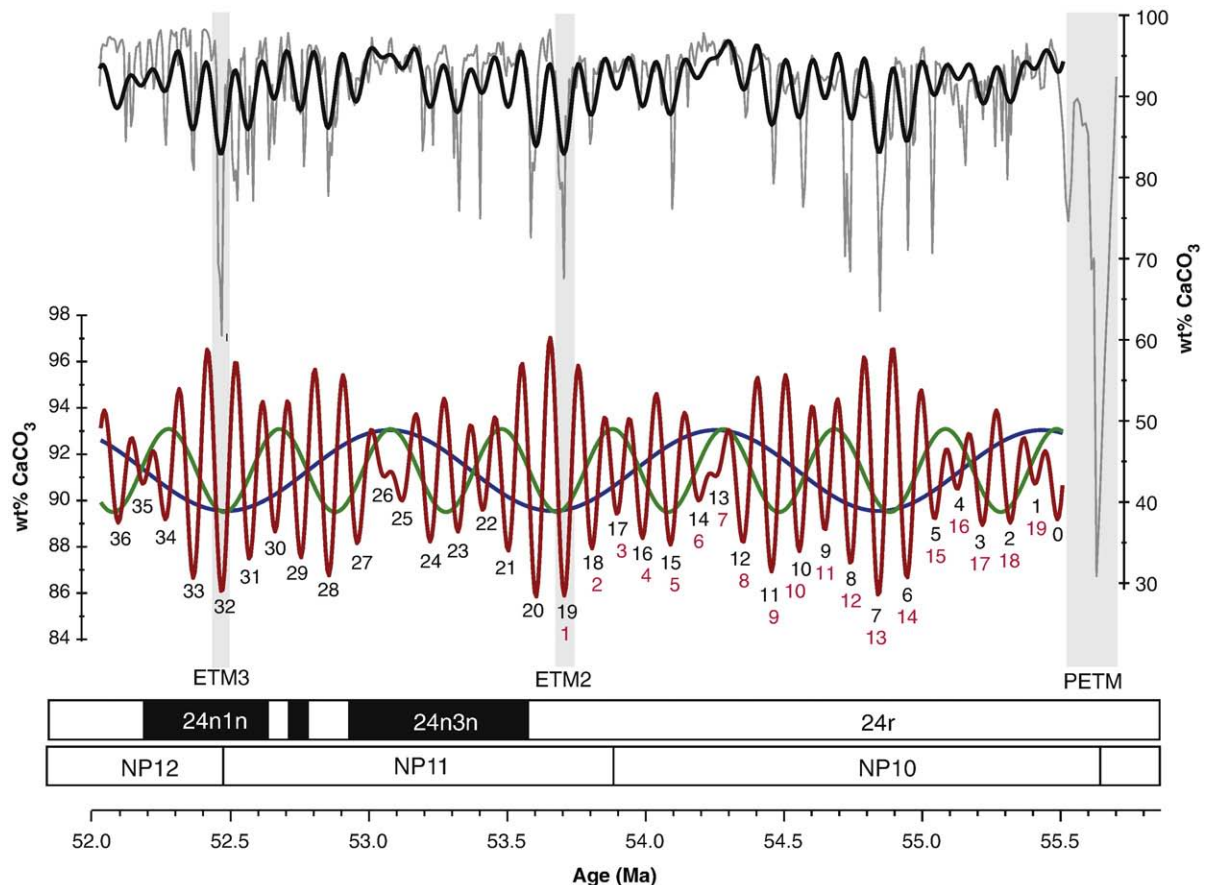


Fig. 6. MTM reconstruction of individual components exceeding the 0.99 confidence level and CaCO_3 record from the Contessa Road section. The short-eccentricity component is the red bold line; the long-eccentricity component is the blue bold line; the 1.2 Myr modulation is the green bold line. The black bold line plotted against the wt.% CaCO_3 record is the sum of these individual components. To allow a more direct evaluation of the variance expressed by each component all the reconstructions have been re-scaled to the wt.% CaCO_3 record.

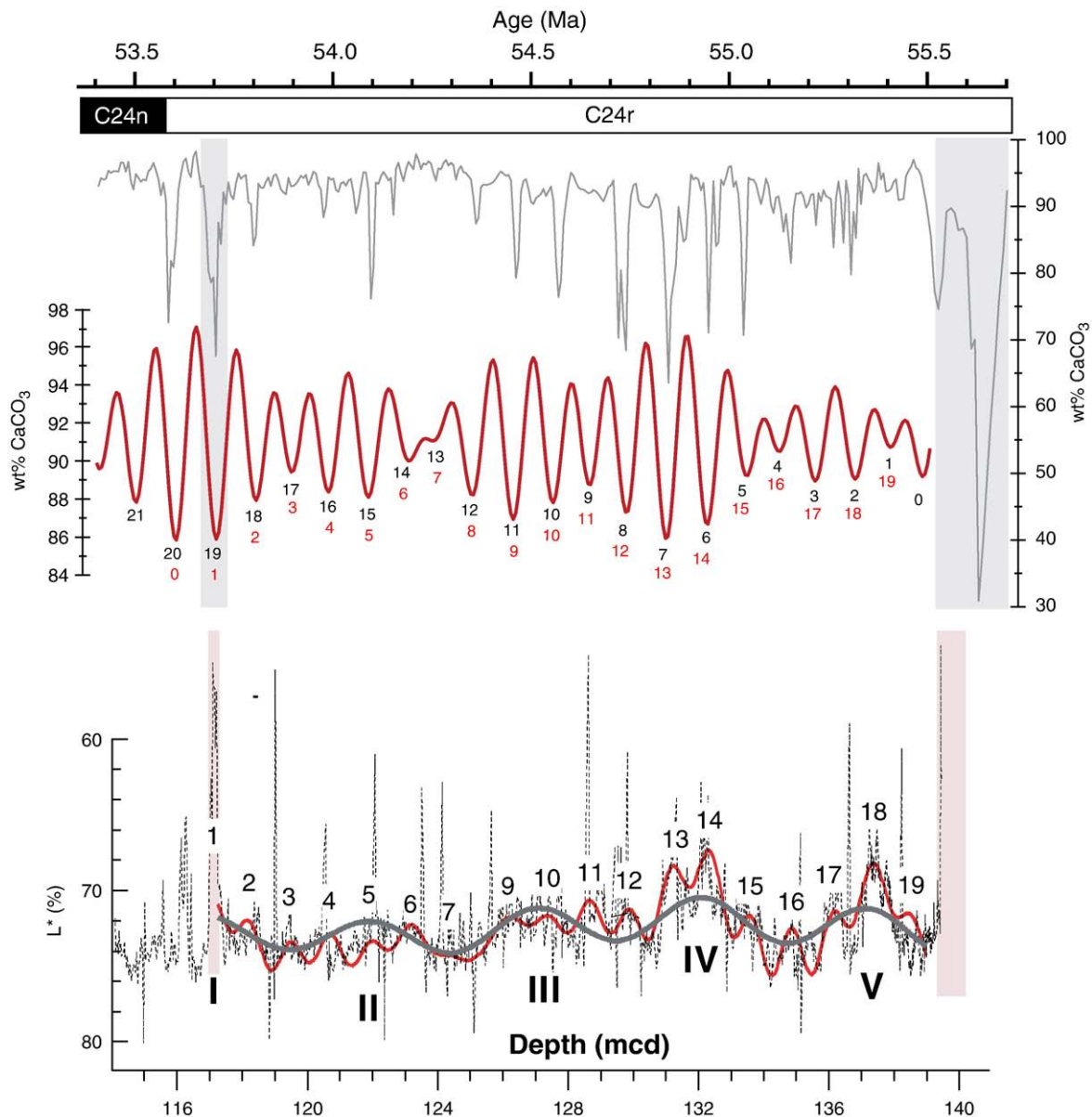


Fig. 7. Comparison of the short-eccentricity cycles counted in the Contessa Road section with the record of the Walvis Ridge published by Lourens et al. (2005). The two records show the same number of eccentricity cycles identified in the two localities between PETM and ETM2.

based on the age models proposed by Lourens et al. (2005) and Westerhold et al. (2007), suggesting that the two records show similar spectral signatures.

5.2. Dissolution cycles

Our results show that the Lower Eocene wt.% CaCO₃ record at Contessa Road is intimately linked to orbital cycles of eccentricity. Lower wt.% CaCO₃ is associated with increased insolation and arguably warmer global temperatures. Noteworthy, this study now demonstrates that hyperthermals ETM2 and ETM3 are larger expressions of a continuum of low wt.% CaCO₃ horizons during the Early Eocene. In general, the PETM is associated with a large perturbation of the carbonate saturation state of the ocean (Zeebe and Zachos, 2007) and carbonate dissolution. An obvious consequence of dissolution is a large decrease of apparent sedimentation rates across clay-rich horizons marking the ETMs (Zachos et al., 2005; Lourens et al., 2005; Westerhold et al., 2007), such as those associated with the PETM and ETMs in continental margin

depositional settings (e.g., Schmitz et al., 2001; Giusberti et al., 2007; Nicolo et al., 2007). However, in these marginal depositional settings ETM horizons are expanded – most likely a consequence of enhanced continental erosion and runoff caused by an enhanced hydrological cycle under warmer conditions (Ravizza et al., 2001; Bowen et al., 2004). Based on cyclochronology, the average rock accumulation rate between the PETM and the top of the surveyed interval is 0.47 cm/kyr which is identical to the value estimated from bio-magnetostratigraphy across C24r and C24n following the time scale of Cande and Kent (1995). However, the variability of wt.% CaCO₃ within this section suggests that the sedimentation rates have varied in response to either dissolution or dilution (Zachos et al., 2005; Giusberti et al., 2007; Nicolo et al., 2007; Westerhold et al., 2007). The influence of either dissolution or terrigenous sediment flux dilution over fluctuations in wt.% CaCO₃ can be assessed partly by examining the sedimentation rates across shorter intervals of depth and time with and without major marly horizons. Changes in the thickness of individual short-eccentricity cycles indicate that the intervals across ETM2 and ETM3 are relatively condensed in the

Contessa Road section (Fig. 8), suggesting that carbonate dissolution is the main cause of changes in wt.% CaCO₃ and sedimentation rate. Lower proportions of planktonic foraminifera (more sensitive to dissolution than benthic species) and higher proportions of agglutinating specimens (more resistant to dissolution than calcareous hyaline forms) in benthic foraminiferal assemblages (Boltovskoy and Totah, 1992) within clay-rich layers from the Contessa Road section provide further evidence for dissolution as a driving mechanism for the observed cyclicity.

5.3. Orbital forcing and ETMs

Lourens et al. (2005) suggested that the occurrence of the PETM and ETM2 was paced by a long-term, ~2.25 Myr modulation of eccentricity, superimposed on the Late Paleocene–Early Eocene warming trend. The inclusion of ETM2 and ETM3 in the spectral analysis of Contessa Road, however, yields a significant ~1.2 Myr periodicity that also appears in the wavelet power spectrum ODP Leg 208 records. This finding is at odds with the available astronomical solutions (e.g. Laskar et al., 2004) that contain a ~2.4 Myr modulation of eccentricity and precession for this time interval. Importantly, ETM2 and ETM3 directly correspond to these maxima and strongly implicate orbital forcing as the primary trigger for these smaller rhythmic climatic and sedimentological patterns. Given relatively small changes in orbitally controlled insolation on these timescales, the repeated occurrence of orbitally induced carbonate dissolution requires feedbacks between insolation, the climate system, and the biosphere. Given the similarity between the residence time of gas hydrate system and the observed long-term period (~1.2 Myr) of orbital forcing, it is conceivable that the two phenomena could produce a resonance, which would largely increase the effect of the otherwise faint orbital forcing related to the long-term modulation of

eccentricity. Alternatively, long-term recharge of gas hydrate systems could provide a non-linear mechanism that is phase-locked to the 405-kyr eccentricity cycle, providing an explanation for the discrepancy between our observation of the 1.2 Myr and the La04 astronomical solution. Indeed, assuming a duration of 170 kyr for the CIE associated to the PETM, we notice that its onset would correspond to a 405 kyr maximum as already proposed by Lourens et al. (2005). Given estimates of the gas hydrate reservoir during this time (Dickens, 2003) and magnitudes of carbon input implied by CIEs and patterns of carbonate dissolution (Pagani et al., 2006; Zeebe et al., 2009) these scenarios require a very high climate sensitivity to CO₂ doubling during the time.

6. Conclusion

The integrated stratigraphic analysis of the Contessa Road section in the Umbria–Marche basin of north eastern Italy was used to construct a well-defined magneto-, bio- and cyclostratigraphy of the Early Eocene, and then applied to establish a relative cyclochronology (i.e. cycle counting) of the included hyperthermal events including the PETM, ETM2 and ETM3. Our results are consistent with the cyclostratigraphic record from coeval interval at ODP Leg 208 (Lourens et al., 2005; Westerhold et al., 2008), with both records showing comparable numbers of short- and long-eccentricity cycles between the PETM and ETM2. Differences with the cyclochronological interpretations previously presented for the Early Eocene (Cramer et al., 2003) are attributed to the use of a different type of record ($\delta^{13}\text{C}$ as opposed to wt.% CaCO₃) for cyclostratigraphic analyses.

In particular, we find that the ETM2 occurs 1 short-eccentricity cycle before Chron C24r/C24n3n boundary, whereas ETM3 falls 1.5 eccentricity cycles above the base of C24n1n. Both events correspond to

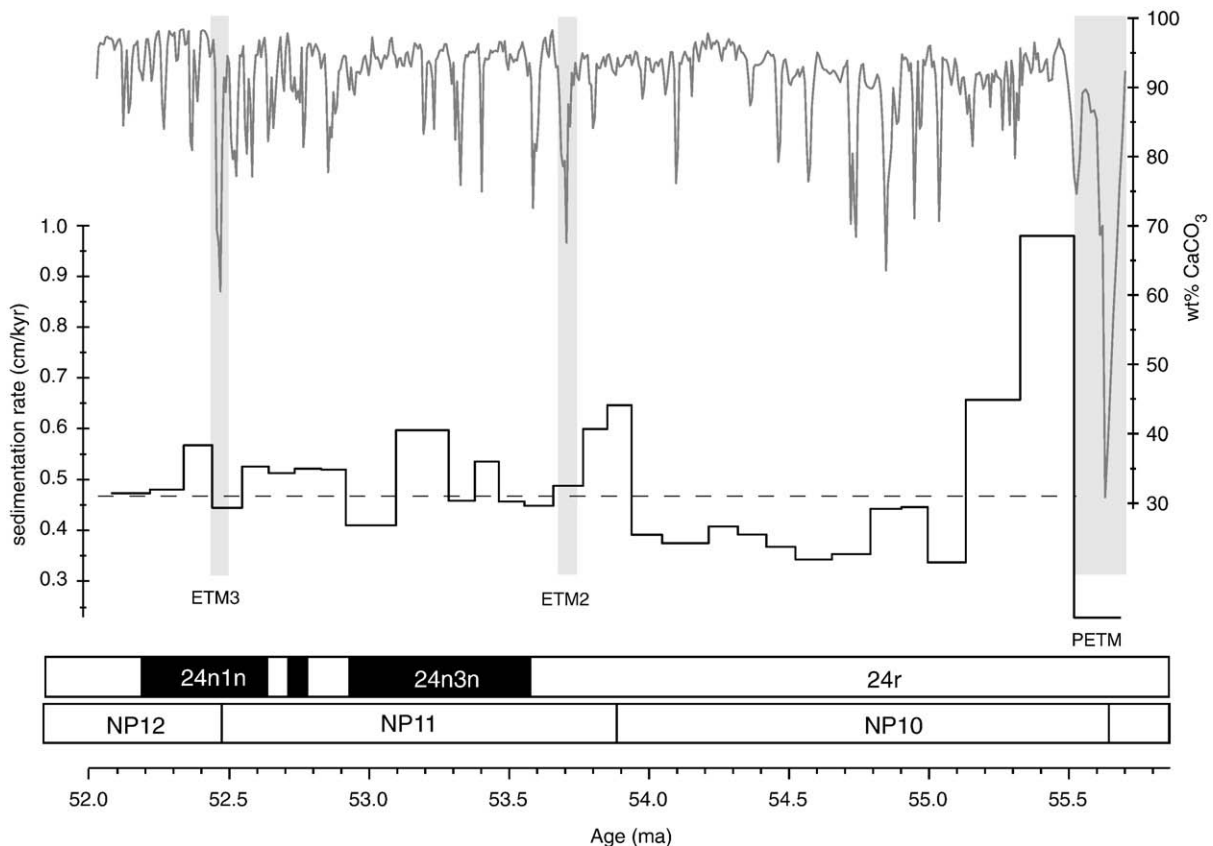


Fig. 8. Changes in sedimentation rate (black line) and wt.% CaCO₃ record from the Lower Eocene Contessa Road section. Sedimentation rates through the surveyed interval are calculated for each eccentricity cycle above the PETM. The dashed line represents the average sedimentation across the surveyed interval whose value (0.47 cm/kyr) is the same as inferred from bio-magnetostratigraphy.

insolation maxima within a very long modulation period of eccentricity (~ 1.2 Myr) suggesting that orbital control may have had a role in triggering ETM2 and ETM3. The ~ 1.2 Myr modulation of the short- and long-eccentricity periods appear at odds with the currently available astronomical solution that predicts a 2.4 Myr modulation of eccentricity and precession cycles in the studied interval and will require further attention.

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