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Orbital tuning for the middle Eocene to early Oligocene Monte Cagnero Section (Central Italy): Paleoenvironmental and paleoclimatic implications

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ABSTRACT

During the middle Eocene to early Oligocene Earth transitioned from a greenhouse to an icehouse climate state. The interval comprises the Middle Eocene Climatic Optimum (MECO; ~40 Ma) and a subsequent long-term cooling trend that culminated in the Eocene-Oligocene transition (EOT; ~34 Ma) with the Oi-1 glaciation. Here, we present a refined calcareous nannofossil biostratigraphy and an orbitally tuned age model for the Monte Cagnero (MCA) section spanning the middle Eocene to the early Oligocene (~41 to ~33 Ma). Spectral analysis of magnetic susceptibility (MS) data displays strong cyclicities in the orbital frequency band allowing us to tune the identified 405 kyr eccentricity minima in the MS record to their equivalents in the astronomical solution. Our orbitally tuned age model allows us to estimate the position and duration of polarity chrons (C18 to C13) and compare them with other standard and orbitally tuned ages. We were also able to constrain the timing and duration of the MECO event, which coincides with a minimum in the 2.4 Myr and 405 kyr eccentricity cycles. Our study corroborates the previous estimated age for the base of the Rupelian stage (33.9 Ma) and estimates the base of the Priabonian stage in the MCA section to be at 37.4 Ma. Finally, calcareous nannofossils with known paleoenvironmental preferences suggest a gradual shift from oligotrophic to meso-eutrophic conditions with an abrupt change at ~36.8 Ma. Besides, nannofossil assemblages suggest that enhanced nutrient availability preceded water cooling at the late Eocene. Altogether, this evidence points to a poorly developed water column stratification prior to the cooling trend.

1. Introduction

The middle Eocene to early Oligocene was a key transition in Earth's climatic history represented by the shift from a greenhouse to an icehouse climate, when global climate changed from warm, comparatively ice-free conditions, to the colder, more glaciated state of the Neogene (Zachos et al., 2008). This interval is characterized by a gradual long-term cooling trend in which there is a superimposed important climatic event, known as the Middle Eocene Climatic Optimum (MECO; Bohaty and Zachos, 2003; Jovane et al., 2007a; Bohaty et al., 2009; Westerhold et al., 2020). Unlike the hyperthermal events such as the Paleocene-Eocene Thermal Maximum (PETM), and the Eocene Thermal maximum 2 and 3 (ETM2 and ETM3), the MECO is far more controversial to interpret (Bohaty and Zachos, 2003; Sluijs et al., 2013; Giorgioni et al., 2019). This ~500 kyr-long event, with the peak warming lasting <100 kyr and centered at ~40.0 Ma, is characterized by a global decline in oxygen isotopic values (δ^{18} O), being interpreted as a 4 to 6 °C warming of bottom and surface waters, and an evident shallowing of the

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Received 27 March 2021; Received in revised form 27 June 2021; Accepted 3 July 2021 Available online 10 July 2021 0031-0182/© 2021 Elsevier B.V. All rights reserved. carbonate compensation depth (CCD; Bohaty and Zachos, 2003; Bohaty et al., 2009). Despite this warming event, the global cooling trend continued until it reached its maximum during the Eocene-Oligocene transition (EOT) at ~34.0 Ma (Jovane et al., 2007b; Westerhold et al., 2014). δ^{18} O values increase over 1.0‰ during the transition (e.g., Kennett, 1977; Zachos et al., 1996; Coxall et al., 2005) and are interpreted as an Antarctic ice-sheet growth of 60 to 110% of the present volume and a 3 to 4 °C bottom waters cooling (Zachos et al., 1996; Lear et al., 2008). Concomitant to the onset of Antarctic glaciation, a > 1 kmdrop in the CCD occurred (Coxall et al., 2005). Both the ice-sheet growth and the CCD deepening occurred in two pulses lasting \sim 40 kyr each and positioned 300 to 400 kyr apart, pointing to a probable orbital pacing (Coxall et al., 2005). The cause of this major global climate reorganization is classically interpreted to be the thermal isolation of Antarctica due to the onset of Antarctic Circumpolar current, as a consequence of the Southern Ocean gateways opening (e.g., Kennett, 1977; Kennett and Exon, 2004; Barker et al., 2007). A more recent hypothesis for a main driving factor suggests that a pCO₂ threshold was crossed (e.g., DeConto and Pollard, 2003; Ladant et al., 2014), but the reason why pCO₂ declined is vet unresolved. A possible explanation is that the Arabia-Eurasia collision and closure of the Tethys Ocean gateway triggered different mechanisms that reduced atmospheric pCO₂ (Allen and Armstrong, 2008; Jovane et al., 2009).

Astronomically driven climatic fluctuations can be preserved as changes in the sediment properties within the stratigraphic record and the correlation of this cyclic variations recorded in climate proxies to astronomical models (extensively known as astronomical tuning) has become a standard tool for calibrating different epochs of the Geologic Time Scale (GTS) (e.g., Gradstein et al., 2012). The astronomical time scale (ATS) covered almost the entirely Cenozoic except for the middlelate Eocene, which is known as the middle-late Eocene gap (Hilgen et al., 2012). This is probably due to the CCD shallowing, which made carbonate-rich successions scarce for this time interval (Pälike et al., 2012). Although there are numerous studies attempting to close this gap (Jovane et al., 2010; Westerhold and Röhl, 2013; Westerhold et al., 2014, 2015; Boulila et al., 2018) there is not yet a consensus on the solution. Despite these discrepancies, recognizing Earth's astronomical cycles in sedimentary records and placing them in time by the astronomical tuning approach is yet one of the most powerful techniques due to its high temporal resolution (Hinnov, 2013). These orbital cycles can lead to changes in chemical, physical, paleontological, and sedimentological properties, and consequently, be detected in the sedimentary record by different proxies. Among all, one of the widest currently used proxy is magnetic susceptibility (MS) due to its rapid, low-cost, and nondestructive data acquisition (e.g., Kodama and Hinnov, 2014; Li et al., 2019a). Since its precursor studies, MS was proven to be an effective and reliable proxy for cyclostratigraphy, particularly when applied to marllimestone successions (Boulila et al., 2008a, 2008b, 2008c).

The Monte Cagnero (MCA) Section is the Global Boundary Stratotype Section and Point (GSSP) for the base of the Chattian stage (28.1 Ma; Coccioni et al., 2018). It comprises a pelagic carbonate succession made up of marl-limestone alternations, which characterize similar stratigraphic setting in nearby sections, such as the Massignano Section, GSSP for the base of the Rupelian stage (33.9 Ma; Premoli Silva and Jenkins, 1993) and Alano Section, recently ratified GSSP for the base of the Priabonian stage (37.7 Ma; Agnini et al., 2020). The orbital control on the MCA Section has already been demonstrated by the cyclostratigraphic analysis on the EOT interval presented (Hyland et al., 2009), which showed the presence of Milankovitch related cycles in the CaCO₃ content record. Our main goal is to extend this cyclostratigraphic approach towards the base of the MCA Section covering the interval studied by Jovane et al. (2013), which spans the middle Eocene to early Oligocene, and to test whether it is a suitable candidate section for studying the time interval covering the MECO to the EOT. Besides, another goal is to investigate paleoclimatic and paleoenvironmental changes based on calcareous nannofossil assemblages.



Fig. 1. Paleogeographic and paleoclimate settings. a) Paleogeographic reconstruction for 35 Ma (from http://www.odsn.de) with the approximate location of the MCA Section. b) Global compilation of Cenozoic $\delta^{18}O_{\text{benthic}}$ records (Westerhold et al., 2020) with a locally weighted smooth over 1 Myr (red curve) indicating the long-term cooling, which culminated in the Oi-1 glaciation event, and the rapid warming event of the MECO superimposed on this cooling trend. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Here, we developed a cyclostratigraphic analysis for the MCA Section using a high-resolution magnetic susceptibility record, which spans approximately 8 Myr from Chron C18n.2r (middle Eocene) to Chron C12r (early Oligocene). Constrained by a radiometric date, the cyclostratigraphic analysis allowed us to reliably tune the MS record to the ZB18a astronomical solution (Zeebe and Lourens, 2019) at the 405 kyr eccentricity level. The new orbitally tuned age model together with the calcareous nannofossils data allowed us to constrain the age of biozones, polarity chrons, and climatic events, and to discuss major paleoenvironmental changes within the studied interval.

2. Geological and stratigraphic setting

The MCA Section (43°38'50"N, 12°28'05"E; 727 m above sea-level) is a continuous Paleogene sedimentary record preserved in the Scaglia limestone, which consists of pelagic carbonate successions of the Umbria-Marche Basin, northeastern Apennines, Italy (e.g., Coccioni et al., 2008; Hyland et al., 2009; Coccioni et al., 2013; Jovane et al., 2013; Savian et al., 2014; Coccioni et al., 2018; Fig. 1a). The studied section ranges from 58 to 128 m stratigraphic level from the base (msl, 70 m thick) and comprises calcareous marl and marly limestone lithologies from the Scaglia Variegata and Scaglia Cinerea formations. Based on previous magnetostratigraphy (Jovane et al., 2013), the studied interval corresponds to the middle Eocene - lower Oligocene, therefore spanning Earth's greenhouse-to-icehouse transition and including important climatic events such as the MECO and the Oi-1 (Fig. 1b). The stratigraphic interval corresponding to the MECO event has been already well constrained at the MCA Section by Savian et al. (2014). The EOT on the other hand has not yet a reliable stratigraphic constraint due to the lack of δ^{18} O data. Following Hutchinson et al. (2021), here we



Fig. 2. MCA stratigraphic records from 58 to 128 msl spanning the middle Eocene through early Oligocene. From left to right: planktonic foraminifera (PF; Jovane et al., 2013) and calcareous nannofossil (CN; this study) biozonation following the schemes proposed by Wade et al. (2011) and Agnini et al. (2014), lithostratigraphic sequence, characteristic remanent magnetization inclination and magnetostratigraphic interpretation (Jovane et al., 2013), CaCO₃ content from Hyland et al. (2009; red) and Savian et al. (2014; green), magnetic susceptibility, and calcareous nannofossil events (this study). The most reliable magnetic polarity reversals are indicated by red stars. Biostratigraphic uncertainty is represented by unfilled rectangles. B = base; T = top; Bc = base common; Tc = top common; X = crossover. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

assumed the EOT as a \sim 790 kyr event with its onset stratigraphically correlated to the extinction of the calcareous nannofossil *Discoaster saipanensis*. The Eocene-Oligocene boundary (EOB) is well established within the section at 114.1 msl defined by the extinction of the planktonic foraminiferal Family Hantkeninidae (Premoli Silva and Jenkins, 1993; Coccioni et al., 2008; Hyland et al., 2009; Jovane et al., 2013).

3. Material and methods

3.1. Magnetic susceptibility

Low-field mass normalized magnetic susceptibility (χ , hereafter MS)

is extensively used as a paleoclimate proxy for cyclostratigraphic analyses since it is a rapid, non-destructive, and low-cost method (Kodama and Hinnov, 2014). Besides, it is considered as a reliable proxy for resolving astroclimatic cycles in mixed carbonate-clay successions; increased susceptibility implies a relative increase of ferrimagnetic and/ or paramagnetic minerals associated to terrigenous detrital input (e.g., Boulila et al., 2008a, 2008b, 2008c; Kodama and Hinnov, 2014; Li et al., 2019a). The MCA interval that extends from 58 to 72 msl has MS data available with ~5 cm resolution (Savian et al., 2014). Therefore, we opted for measuring the interval between 72 and 128 msl at the same spatial resolution. MS measurements were carried out at the National Oceanography Centre Southampton (NOCS) using an AGICO KLY-3 Kappabridge magnetic susceptometer. Combining both datasets, we generate a MS series with 1230 data points. Based on the average sediment accumulation rate (SAR) derived from magnetostratigraphy (Jovane et al., 2013), the MS series has an average temporal resolution of \sim 5.8 kyr.

3.2. Calcareous nannofossils

Calcareous nannofossil samples have been collected every 25 cm for the lower part of the section (58–78 msl) and every 50 cm up to 128 msl. Quantitative analyses have been performed on 180 samples. Smear slides were prepared from unprocessed samples according to standard techniques (Bown and Young, 1998) and analyzed under a polarized light microscope at a magnification of $1250\times$. Abundances were determined by counting 300 specimens of nannofossils in a variable number of visual fields. A supplementary counting has been performed on two traverses in order to recognize rare important biostratigraphic markers. For the biostratigraphic events recognized and the taxonomic criteria adopted we refer to Agnini et al. (2014 and references therein).

To statistically explore calcareous nannofossil data, we used a multivariate analysis approach. Principal component analysis (PCA) was performed using the PAST (PAleontological STatistics) software (Hammer et al., 2001) in order to understand major changes in calcareous nannofossil assemblages. Prior to the analysis, we grouped rare or discontinuous taxa at the genus level and excluded the remaining taxa that presented less than 0.5% of standard deviation of their relative abundances to eliminate rarely occurring species (Dunkley Jones et al., 2008). Relative abundances were then rescaled to sum to 100% and zero values were replaced by non-negative values (0.01%). Finally, we performed an additive log-ratio (ALR) transformation of relative abundances data using *Cyclicargolithus floridanus* as the denominator, as it is one of the dominant species with continuous occurrences throughout the section. To test the reliability of the PCA outcome, we also performed a classical Q-mode cluster analysis on the same dataset.

3.3. Time-series analysis

Prior to time-series analysis, MS series was log-transformed, detrended, linearly interpolated, and resampled at 5 cm (depthdomain) and 6 kyr (age-domain). Calcium carbonate content (CaCO₃) data with sampling resolution varying between 5 and 11 cm are available from 58 to 72 msl (Savian et al., 2014) and from 108 to 128 msl (Hyland et al., 2009). Coherence and phase relationships were calculated between MS and CaCO3 records with the R-package "biwavelet" (Gouhier et al., 2019) based on the MATLAB coherence and phase analysis tool (Grinsted et al., 2004). Spectral analyses, as well as data filtering, were processed in the Acycle software (Li et al., 2019b). Spectral and evolutionary spectral analyses of depth- and age-domain MS series were conducted by applying the multitaper method (MTM) with five 2π prolate tapers (Thomson, 1982) with conventional AR1 red noise modeling, and the evolutive fast Fourier transform (FFT), respectively. To isolate orbital-linked periodicities, filtered signals were extracted using Gaussian bandpass windows. The MS filtered signal was manually tuned to the ZB18a astronomical solution (Zeebe and Lourens, 2019) in the QAnalySeries software (Kotov and Pälike, 2018).

4. Results

4.1. Magnetic susceptibility

Magnetic susceptibility measurements indirectly show the concentration and composition of ferromagnetic, diamagnetic, and paramagnetic minerals (Kodama and Hinnov, 2014). These measurements vary between ~0.6 and 22.6 × 10^{-8} m³/kg, following mainly changes in lithology and increasing towards the top of the section (Fig. 2). Since the section exhibits alternations between marks and limestones, it is

Table 1

Calcareous nannofossil biostratigraphic datums for the MCA Section between 58 and 128 msl. B = base; T = top; Bc = base common; Tc = top common; X = crossover.

Depth (m	ı; msl)		Nanno zone	Biostratigraphic	Datum confidence	
Тор	Bottom	Mid- point	boundary	datum		
128.00	127.50	127.75	Base CNO2	T E. formosa	high	
125.50	125.00	125.25		B C. altus	low	
115.50	115.00	115.25		X C. subdistichus >/<5.5 μm	high	
114.50	114.00	114.25	Base CNO1	Bc C. subdistichus > 5.5 μm	high	
109.00	108.50	108.75	Base CNE21	T D. saipanensis	high	
108.00	107.50	107.75		T D. barbadiensis	high	
105.00	104.50	104.75	Base CNE20	T C. reticulatum	high	
100.00	99.50	99.75		Bc I. recurvus	low	
91.00	90.50	90.75	Base CNE18	Tc C. erbae	high	
85.50	85.00	85.25	Base CNE17	Bc C. erbae	high	
84.00	83.50	83.75		B C. oamaruensis	low	
74.25	74.00	74.12	Base CNE16	T S. obtusus	high	
64.50	64.25	64.37		B S. obtusus	high	
58.75	58.50	58.62	Base CNE15	B D. bisectus	high	

hypothesized that MS is inversely proportional to the CaCO₃. Therefore, we statistically compare the MS record to published CaCO₃ records (Hyland et al., 2009; Savian et al., 2014). Although there is not CaCO₃ data throughout the entire section, comparing the MS record with the available CaCO₃ records allow us to obtain a reliable response, which covers about half the length of the studied interval, with data at the base and the top of the section. Besides the visual analysis, cross wavelet coherence and phase analysis from the two intervals also demonstrates that MS varies in anti-phase with CaCO₃ content (Figs. S1 and S2). Furthermore, we extrapolate this phase relation for the interval without CaCO₃ measurements in order to determine the phase relation between MS and eccentricity at the tuning step.

4.2. Calcareous nannofossil biostratigraphy

Calcareous nannofossils are abundant throughout the section and moderately to poorly preserved. The studied interval spans the Bartonian – early Rupelian, and most of the expected calcareous nannofossil events have been identified. Table 1 summarizes the identified biohorizons and their reliability throughout the studied interval, following the calcareous nannofossil biozonation scheme proposed by Agnini et al. (2014), which provides new events as substitutes for previous standard schemes considered partly unreliable. A detailed description of each datum and the identification of classical biohorizons following the biozonation schemes proposed by Martini (1971) and Okada and Bukry (1980) can be found in the supplementary material.

4.3. Calcareous nannofossil abundance changes and paleoclimatic events

Calcareous nannofossil assemblages show several fluctuations in abundance that were related to environmental variability that characterized the middle Eocene to early Oligocene transition (Fig. 3). Different groups have been recognized in the MCA assemblages. The Coccolithaceae are represented by the genera *Clausicoccus*, *Coccolithus*, *Chiasmolithus* and *Ericsonia*. *Clausicoccus* (mainly small sized) is recorded as scarce (<1%) and discontinuous up to the middle part of the section. From 100 msl up to the section *Clausicoccus* increases in size and abundance. The small sized specimens (<5.5 µm) rapidly increase and



Fig. 3. Relative abundance (%) of significant calcareous nannofossil groups and species against orbitally tuned ages. Planktonic foraminiferal (PF; Jovane et al., 2013) and calcareous nannofossil (CN; this study) biozonation following the schemes proposed by Wade et al. (2011) and Agnini et al. (2014), respectively. Black and red horizontal dashed lines indicate the Eocene-Oligocene boundary (EOB) and the *Discoaster* extinction event (DEE), respectively. Blue interval indicates the EOT as a \sim 790 kyr event started at the extinction of *D. saipanensis* (Hutchinson et al., 2021). Orange interval indicates the MECO based on its stratigraphic constraint as proposed by Savian et al. (2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

show peaks of 5–7%, then they decrease in abundance in proximity of the EOT and are replaced by larger forms of *Clausicoccus* > 5.5 to 8 μ m. The genus *Coccolithus* consists of *C. pelagicus* and *C. eopelagicus*. The abundance record of the group shows a decreasing trend above the MECO and then a slight increasing trend up to 100 msl. Above this level, *C. pelagicus* becomes one of the major components of the assemblage (about 20%) up to the end of EOT, afterwards a slightly decrease is observed. The genus *Chiasmolithus* is rare and discontinuously present throughout the section. Few species belonging to this genus are identified, namely *C. grandis, C. oamaruensis, C. solitus* and *C. altus*. The low percentages (<1%) and the sporadic occurrence prevent here their use as reliable biostratigraphic markers. *Ericsonia formosa* is continuously present with higher abundances (around 10%) in the lower part of the

section within the MECO. The overall trend shows a marked decrease from 90 msl up to the top of the section, where the Top of *E. formosa* (127.50 msl) has been observed.

The Noelaerabdaceae are represented by the genera *Cribrocentrum*, *Cyclicargolithus*, *Dictyococcites* and *Reticulofenestra*. *Cribrocentrum* is present from the lower to the middle part of the section, it reaches an acme and then drops in abundance at ~87 msl. This genus, characterized by three marker species *C. reticulatum*, *C. erbae* and *C. isabellae*, shows very pronounced variations in abundance from 1% up to 50% during the acme of *C. erbae*. *Cribrocentrum reticulatum* occurs from the base and gets extinct at 104.75 msl, where it defines the base of CNE20 Zone. *Cribrocentrum erbae* is continuously present from 76 msl, showing a rapid increase in abundance between 85.5 and 91 msl (marker of



Fig. 4. Principal component analysis of the calcareous nannofossil abundance data. a) Cross-plot of PC1 and PC2 showing the four groups of samples. b) Bar charts of PC1 and PC2 loadings showing positive (blue) and negative (red) correlations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

CNE17 Acme Zone). Cribrocentrum isabellae occurs rarely, with very low abundances and seems to be an unreliable bioevent. Cyclicargolithus floridanus is among the main calcareous nannofossil constituents of the MCA Section, and shows peaks of abundance (up to 48%) during the MECO. The genus Dictyococcites is represented by the two species D. bisectus and D. scrippsae. Dictyococcites bisectus occurs from the base with percentages around 10%, but very low percentages (<1%) during the MECO have been observed. The abundance of Dictyococcites scrippsae vary abruptly (from <1% to 30%) during the MECO interval, but has also wide fluctuations thereafter up to the top of the section. The genus Reticulofenestra comprises R. daviesii, R. dictyoda group (specimens with length > 5 and $< 14 \ \mu m$ and specimens of *R. minutula* $< 5 \ \mu m$) and R. umbilicus (>14 µm). Reticulofenestra daviesii is rare and shows sporadic occurrence in the lower part of the section; it becomes continuous from 92 msl with an increase in abundance around the EOT. Overall, R. dictyoda together with R. umbilicus show spikes of abundance during the MECO, R. umbilicus shows a decreasing trend upwards, while R. dictyoda shows an increase in abundance during the EOT.

Discoaster, mainly represented by *D. barbadiensis*, *D. saipanensis* and *D. deflandrei*, exhibits a clear decreasing trend from the lower part of the section upwards that culminates with the extinction (Top) of the *D. barbadiensis* and *D. saipanensis* (rosette-shaped *Discoaster*). A sharp decline of *Discoaster* is noticeable from 84.5 msl. *Discoaster barbadiensis* is commonly more abundant than *D. saipanensis* and shows two peaks in abundance during the MECO. Following the extinctions of the rosette-shaped *Discoaster* at 108 msl, the abrupt decrease in abundance of the whole genus gives rise to a very evident and widespread paracme event, useful for biostratigraphic purpose (Wei and Wise, 1990). *Discoaster* remain below their usual Cenozoic percentages for about 4 Myr, with an abundance of less than 1% in the upper part of the MCA Section. This paracme spans from the top of the NP19-20 to the base of the NP24 (i.e., from C13r to C11n; Maiorano and Monechi, 2006; Tori, 2008).

The genus *Sphenolithus* shows high percentages (roughly 30–40%) during the MECO and post MECO, while upwards a significant decreasing trend has been observed. Several species have been identified: *S. obtusus, S. moriformis, S. predistentus, S. radians, S. spiniger* and specimens that can be related to the *S. predistentus-distentus* lineage. The occurrence of *S. furcatolithoides* above its range (CN14 Zone) can be interpreted as reworking or a final tail of distribution as evidenced in several sections (Fornaciari et al., 2010).

Holococcoliths and, in particular, *Lanternithus minutus* and *Zyghrablithus bijugatus* are present throughout the section showing several peculiar changes in abundance. *Lanternithus minutus* occurs throughout the section, is rare during the MECO, shows a slight increase starting

from 75.5 to 90 msl, then decreases rapidly above it and significantly rebounds at the top of rosette-shaped *Discoaster*, below the EOT, and through the upper part of the section. *Zygrhablithus bijugatus* is continuously and more or less commonly present, with peaks of abundance in the MECO interval and up to 80 msl; above this level the abundances drop and then increase again below the EOT, with a trend similar to L. *minutus*.

The genus *Helicosphaera* occurs discontinuously in very low percentages (<1%) gathering specimens referable to *H. compacta*, *H. euphratis* and *H. salebrosa*. The same occurs to the calcareous dinoflagellate *Thoracosphaera*, occurring discontinuously throughout the section with percentages <1%.

4.4. Principal component analysis of abundance data

The PCA allows identifying the variables that can explain most of the variance enclosed in the analyzed dataset (Davis and Sampson, 1986), highlighting groups of samples or taxa which are associated to particular environmental changes. Working in the sample space (with taxa as variables), we have gathered two new matrices, which represent the spatial dispersion of the samples (scores plot and scatter diagram) and the loadings of the taxa on the principal components, respectively (PCs; see Fig. 4). PCs 1 and 2 of the transformed abundance data explain 48.8% and 12.1% of the variance, respectively. A cross-plot and ranked bar charts of PC1 and PC2 loadings display how the calcareous nannofossil taxa define groups of samples (Fig. 4). The PCA scatter diagram displays three clusters that comprise four groups of samples corresponding to different time-intervals (Fig. 4a). The groups are determined by assemblages' variations over time as indicated by the taxa correlations (Fig. 4b) and probably associated to taxa evolutionary turnover and paleoclimatic changes. The recognized clusters are the following: (i) a cluster with negative PC1 is composed of both Bartonian (first group, blue dots) and Priabonian samples (second group, red dots) from the Priabonian/Bartonian boundary up to Bc I. recurvus; (ii) a second cluster (third group, pink dots) is composed of Priabonian samples from Bc I. recurvus to the Discoaster Extinction Event (DEE); (iii) a third cluster (fourth group, green dots) comprises the samples from the DEE to the top of the section. (Fig. 4a).

Based on the PCA analysis, we can observe a clear change among the assemblages. Samples from the interval comprising the Bartonian up to the Bc *I. recurvus* show a similar assemblage and are characterized by strong negative PC1 values (mainly characterized by *Cribrocentrum* spp., *Discoaster* spp. and *R. umbilicus*) and variable PC2 values. Thereafter, a "transitional" interval from the Bc *I. recurvus* up to the DEE is associated



Fig. 5. Cross-plot of PC1 and PC2 scores of calcareous nannofossil abundance data and its paleoecological interpretation.

with changes in the assemblage, with the occurrence of *Clausicoccus, Blackites, R. dictyoda* < 14 μ m group, *Helicosphaera* + *Pontosphaera* group, and *R. daviesii*, suggesting a cooler and mesotrophic environment. This interval is characterized by increasing PC1 values, ranging from strong negative towards positive values, and also variable PC2 values. Finally, a completely different assemblage has been observed above the DEE characterized by the strongest positive PC1 values and slightly variable PC2 values, suggesting a cooler and eutrophic Oligocene interval (Fig. 4a). Comparable assemblage behavior in PCA analysis has been observed at the DEE event by Jones et al. (2019).

We also performed an alternative PCA analysis on the transposed data matrix (R mode) with the samples as variables, in order to reduce the complexity of the relations among taxa. In this case, PC1 and PC2 explain 60.4% and 17% of the variance, respectively. The PCA scatter diagram shows the dispersion of taxa (scores from PC1 and PC2) and explains the relation between most significant taxa and their paleoecological preferences (Fig. 5). Thus, we can interpret PC1 as a proxy for sea surface temperature, while PC2 probably represents nutrient availability. On this assumption and, in agreement with the literature, Cribrocentrum spp., R. umbilicus $> 14 \,\mu\text{m}$, Discoaster spp. and E. formosa had a preference for a warm and oligotrophic environment (Monechi et al., 2000; Bralower, 2002; Gibbs et al., 2006; Angori et al., 2007; Villa et al., 2008; Schneider et al., 2011; Nyerges et al., 2020), while C. eopelagicus and C. protoannulus seemed to prefer a cooler and oligotrophic environment (Dunkley Jones et al., 2008). Reticulofenestra daviesii had a preference for cold waters regardless of nutrients (Wei and Wise, 1990; Monechi et al., 2000; Villa et al., 2008, 2014; Fioroni et al., 2015) as well as the Helicosphaera + Pontosphaera group and Blackites spp. that were weakly related to nutrients (slightly mesotrophic) and had a preference for cooler environments (Nyerges et al., 2020). Sphenolithus had a preference for warm waters (Haq and Lohmann, 1976; Wei and Wise, 1990; Aubry, 1992; Wei et al., 1992; Monechi et al., 2000; Bralower, 2002; Tremolada and Bralower, 2004; Villa and Persico, 2006; Schneider et al., 2011) and was, according to our results, weakly related to nutrients, while Z. bijugatus, L. minutus and D. bisectus were better adapted to warm/temperate waters and also weakly related to nutrient. L. minutus and D. bisectus seemed slightly mesotrophic adapted. Dictyococcites scrippsae and C. pelagicus had a preference for warm and eumesotrophic waters (Haq and Lohmann, 1976; Bukry, 1981; Wei and Wise, 1990); while Clausicoccus spp. had a preference for cool and

Table 2

Inferred paleoenvironmentally significant groups based on the paleoecological preferences of calcareous nannofossil taxa.

Sea surface wa	ater conditions	Trophic conditions			
Warm-water taxa	Warm/ Temperate- water taxa	Cool-water taxa	Oligotrophic taxa	Meso- eutrophic taxa	
Sphenolithus spp.	E. formosa	Blackites spp.	Cribrocentrum spp.	Clausicoccus spp.	
D. scrippsae	D. bisectus	C. protoannulus	C. eopelagicus	D. scrippsae	
C. pelagicus	Z. bijugatus	R. daviesii	R. umbilicus > 14 μm	<i>R. dictyoda</i> group <14 μm	
Discoaster spp.	Cribrocentrum spp.	Clausicoccus spp.	Discoaster spp.	C. pelagicus	
	L. minutus	Helicosphaera + Pontosphaera	C. protoannulus	Blackites spp.	
		-	E. formosa	L. minutus D. bisectus	

eutrophic waters (Tori, 2008; Nyerges et al., 2020). Reticulofenestra dictyoda group <14 μ m had a preference for waters rich in nutrients regardless of the temperature (Dunkley Jones et al., 2008; Jones et al., 2019). Therefore, the results of PCA analysis allow us to define paleo-environmentally significant groups based on the paleoecological preferences of taxa (Table 2). These results are also confirmed by cluster analysis performed on the same dataset (supplementary material; Figs. S3 and S4), where *Z. bijugatus* and L. *minutus* show an additional strict relation, that according to the literature can be related to their preference for near-shore/shelf region (Monechi et al., 2000; Nyerges et al., 2020).

4.5. Orbital tuning

The MCA entire succession consists of rhythmic alternation of calcareous marl and marly limestones with terrigenous clay and silt (Jovane et al., 2013; Coccioni et al., 2018). Because of the proximity, we adopted here the same interpretation of Jovane et al. (2006, 2010) for the Contessa and Massignano sections that limestone layers (high CaCO₃ and low MS) were deposited during cool and dry periods, while marl



Fig. 6. Spectral analysis of the MS series in stratigraphic domain. a) Logthe transformed, detrended and 5-cm interpolated MS series with low-frequency noise removed after high-pass filtering (cut frequency of 0.1 cycles m⁻¹). b) MTM power spectrum and estimated noise spectrum and confidence levels. Interpreted long-, and short-eccentricity, obliquity, and precession bandwidths are labeled as E, e, O, and P, respectively. Orbital cycles were interpreted based on the magneto- and biostratigraphic age model from Jovane et al. (2013). c) Evolutive FFT with a 10 m sliding window.

layers (low CaCO₃ and high MS) were deposited during warm and wet periods. Additionally, there is no evidence of large dissolution except during the peak warming within the MECO event in the MCA Section (Savian et al., 2014). Thus, it is reasonable to assume a negative relation between CaCO₃ and eccentricity based on the interpretation that high eccentricity enhanced chemical weathering and runoff, which leads to an increase in terrigenous input and, consequently, a relative decrease in the CaCO₃ content. Once demonstrated that MS reflects mainly CaCO₃ variability in an anti-phase relation (Figs. S1 and S2), our adopted strategy was to tune the minima in the long eccentricity filtered MS to the long eccentricity minima from the astronomical solution. The tuning process was constrained by an available 206 Pb/ 238 U date of 33.291 ±

0.057 Ma for the MCA Section at 123.1 msl (Sahy et al., 2017). Concerning the target curve, despite different astronomical solutions disagree before ~50 Ma due to chaotic behavior of the solar system (e.g., Laskar et al., 2004, 2011a, 2011b; Zeebe, 2017; Zeebe and Lourens, 2019), they all closely agree during the studied interval. We thus opted to use the ZB18a astronomical solution (Zeebe and Lourens, 2019) as the target curve, since it represents the most precise and up to date solution.

To establish a reliable astrochronology, we tuned the MS series to the stable long eccentricity geochronometer, which is related to the Venus-Jupiter interaction (g2-g5) with a period of 405 kyr (Hinnov, 2018). Magnetostratigraphic interpretation from Jovane et al. (2013) gives a mean SAR of 0.86 cm kyr⁻¹ for the studied interval. Based on this SAR,



Fig. 7. Astronomical calibration of the MCA Section. a) MS record in the stratigraphic domain and the interpreted 405 kyr cycle extracted with a Gaussian bandpass filter centered at 0.25 ± 0.13 cm⁻¹ (red dashed line). b) Long-eccentricity tuned MS record with the 405 kyr (blue dashed line) and the 2.4 Myr (green dashed line) components filter outputs. c) ZB18a astronomical solution (Zeebe and Lourens, 2019) with the 405 kyr (blue area) and the 2.4 Myr (green area) components. d) Tuning-derived sediment accumulation rate (SAR). Orange diamond and line represent the ²⁰⁶Pb/²³⁸U radioisotope age tie point (Sahy et al., 2017). Vertical gray dashed lines show the tuning tie points. The 405 kyr and the 2.4 Myr components were extracted with a Gaussian bandpass filter centered at 0.002469 \pm 0.0006 kyr⁻¹, and 0.00042 \pm 0.00004 kyr⁻¹ respectively. Polarity time scale is from GPTS 2020 (Ogg, 2020). Period, Epoch, and Stage from GTS2020 (Speijer et al., 2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

we can assume that the stable long eccentricity cycle (405 kyr) has a mean thickness of ~3.5 m. MTM spectrum and evolutive FFT of the MS series in the stratigraphic domain corroborates this assumption and displays a stable and strong signal around this periodicity (Fig. 6). The MTM analysis shows two distinct peaks within the interpreted long eccentricity bandwidth, at 0.19 and 0.30 cycles m⁻¹, corresponding to periodicities of \sim 5.2 and \sim 3.3 m (Fig. 6). Using a Gaussian bandpass filter centered at the average frequency between those peaks (0.25 cycles $m^{-1})$ we extracted the 405 kyr eccentricity signal from the MS series and tuned it to the long eccentricity signal from the ZB18a astronomical solution (Fig. 7). It is noteworthy that the evolutive FFT shows a drastic shift in the long eccentricity signal towards a lower frequency in the interval between ~75 to ~80 msl (Fig. 6), implying an increased SAR within this interval. Although abrupt, this higher SAR interval was already identified in the magneto- and biostratigraphic age model from Jovane et al. (2013). Once interpreting this interval as two long eccentricities cycles would result in an interval with lower SAR compared to the surrounding interval, it was interpreted as a single long eccentricity cycle (Fig. 7).

Furthermore, we intended to perform a fine-tuning at the short eccentricity level, but due to a weak short eccentricity signal in the MS series, even after the 405 kyr tuned (Fig. 8), we opted to use only the long eccentricity tuning in order to maintain the robustness of the MCA age model. This weak signal is probably due to the fact that MS reflects mainly CaCO₃, which in some Neo-Tethys sections, such as the Alano Section, show a weak short eccentricity signal (Galeotti et al., 2019). Galeotti et al. (2019) suggested the sum of changes in runoff and tectonic activity (Doglioni and Bosellini, 1987; Carminati and Doglioni, 2012) as a possible cause. Another possible cause is related to the low SAR leading to a smoothing in the precession signal which, in turn, would have obliterated the eccentricity signal, as shown at Blake Nose (Röhl et al., 2001, 2003) and Walvis Ridge sites (Lourens et al., 2005; Westerhold et al., 2007), in the Atlantic Ocean. We thus suggest a future astrochronological refinement study for the MCA using a different proxy in order to resolve the short eccentricity signal, such as carbon isotope records, which seem to better resolve this cycle (e.g., Galeotti et al., 2019; Giorgioni et al., 2019). Despite of it, spectral analysis of the resultant 405 kyr orbitally tuned MS series displays strong signals in



Fig. 8. Power spectra of MS record on astrochronology. a) MTM power spectrum and estimated noise spectrum and confidence levels. Long- and short-eccentricity, obliquity, and precession bandwidths are shown by gray areas labeled as E, e, O, and P, respectively. b) Evolutive FFT with an 800 kyr sliding window.

orbital frequencies of long eccentricity, obliquity, and precession (Fig. 8), suggesting that our orbital tuning is reliable. Another important feature to support its robustness is that our estimated age based solely on the tuning process for 123.1 msl is 33.304 Ma, a difference of only 13 kyr to the available high-resolution radiometric date for the same stratigraphic level (Sahy et al., 2017). The presence of a precessional signal suggests that the absence of a reliable signal within the short eccentricity band is most likely explained by the first of the two mentioned hypotheses. It is also worth noting the presence of a prominent obliquity signal in the power spectrum (Fig. 8a), despite the relatively low latitude of the MCA Section. The evolutive FFT analysis shows that the obliquity seems to exert more influence on the MS record mainly near the EOT interval (Fig. 8b), an orbital configuration similar to those identified by Galeotti et al. (2016) in high latitudes, and recently by Messaoud et al. (2020) in another Neo-Tethys section. The reliability of our age model is also corroborated by the matching between the 2.4 Myr amplitude modulation component of the resultant tuned MS series with the one from the astronomical solution (Fig. 7). Furthermore, the SAR derived from the independent orbital tuning (Fig. 7d) agrees with the first lower resolution SAR curve derived from the magnetostratigraphy (Jovane et al., 2013).

5. Discussion

The developed astrochronologic time scale allows us to revise the previous MCA chronologic framework based on magnetostratigraphy (Jovane et al., 2013) and better constrain important events recorded within the section, such as the MECO, the EOT, and the Oi-1 event. Our long eccentricity tuning, together with new high-resolution calcareous nannofossil biostratigraphy, suggest that the MCA Section is complete, at least at the scale of hundreds of thousands of years.

5.1. Comparison of MCA chron positions and durations

Based on the most up to date magnetostratigraphic interpretation for the MCA (Jovane et al., 2013), together with our developed astrochronologic age model, new polarity chron boundaries ages and durations between chrons C18n and C13n have been estimated and compared to standard and tuning-derived magnetic polarity reversals ages for the same interval (Tables 3 and 4). Firstly, we highlight the similarity between our estimated ages with the ones from Hyland et al. (2009) for the common time intervals. This fact corroborates both the consistency of the MCA astrochronology, at least in the upper part of the section, and once again that MS represents mainly changes in CaCO₃ content. On the other hand, due to ambiguous data from magnetostratigraphy (Fig. 2), there are ages and durations discrepancies in the lowest part, and also unidentified reversals in the middle part of the section, which require a refined magnetostratigraphic analysis in order to solve this issue (Tables 3 and 4). Despite these discrepancies, the reliable magnetostratigraphic data in the lowest part of the section allow us to estimate the age of the onset of Chron C18n based on astrochronology. The onset age of Chron C18n is relatively younger when compared to classical standards and tuning-derived ages, but it coincides surprisingly well with the age proposed by Boulila et al. (2018); (Table 3), even though the studied geological record has a controversial stratigraphic interpretation (Vahlenkamp et al., 2020). Despite that, once this reversal is positioned within the MECO interval, it is important to support our further time constraint of the event in the MCA Section.

5.2. MCA biostratigraphy

Integrating the planktonic foraminiferal (Jovane et al., 2013) and our revised calcareous nannofossil biostratigraphies, together with the developed age model, we provide here an up-to-date biostratigraphic framework for the MCA Section spanning the middle Eocene to the early Oligocene interval. Jovane et al. (2013) identified all planktonic zones proposed by Wade et al. (2011) for the same interval of our study, which spans zones E11 through O1. Revisiting the calcareous nannofossil biostratigraphy and following the biozonation from Agnini et al. (2014), we were able to define all the biozones that characterize the studied interval (CNE15 to CNO2), except for the base of CNE19, defined by the base of *C. isabellae*. Based on our developed orbitally tuned age model, we have been able to place the important calcareous nannofossil and planktonic foraminiferal biohorizons identified in the MCA Section on a timeframe and compare our estimated ages with those of Agnini et al. (2014) and Wade et al. (2011) (Table 5).

Our estimated planktonic foraminiferal ages based on the biostratigraphy from Jovane et al. (2013) are in agreement with those proposed by Wade et al. (2011). Differences are around 200 kyr, except for the base of zone E15 with a relatively higher offset (Table 5). It is noteworthy the similarity between the proposed and our estimated age for the extinction of *H. alabamensis*, marker for the EOB (Premoli Silva and Jenkins, 1993). The calculated age of the EOB does not only match

Table 3

Comparison of polarity chron boundary ages in millions of years (Ma). In our estimated ages column, bold numbers represent the most reliable magnetostratigraphic interpretation, whereas regular font numbers represent ambiguous interpretation and hyphen represents the boundaries that were not identified. For the studied interval, the recently published GPTS 2020 (Ogg, 2020) used all ages from the Pacific Equatorial Age Transect (PEAT) sites (Westerhold et al., 2014).

Chron	on Standard GPTS				Astronomie	Astronomically calibrated						
	CK95 (Cande and Kent, 1995)	GPTS 2004 (Ogg and Smith, 2004)	GPTS 2012 (Ogg, 2012)	MQSD20 ((Malinverno et al., 2020))	ODP Site 1218 (Pälike et al., 2006)	Massignano (Jovane et al., 2006)	Monte Cagnero (Hyland et al., 2009)	Contessa Highway (Jovane et al., 2010)	PEAT Sites (Westerhold et al., 2014)	IODP Exp. 342 composite U1408-U1410 (Boulila et al., 2018)	Monte Cagnero (this study ^a)	-
C13n (y)	33.058	33.266	33.157	33.076	33.232		33.230		33.214		33.231	
C13n (o)	33.545	33.738	33.705	33.675	33.705		33.750		33.726		33.712	
C15n (y)	34.655	34.782	34.999	34.875	35.126	34.640			35.102		34.836	
C15n (o)	34.940	35.043	35.294	35.199	35.254	34.960			35.336		35.202	
C16n.1n	35.343	35.404	35.706	35.627	35.328	35.343			35.580		35.540	
(y)												
C16n.1n	35.526	35.567	35.892	35.863	35.554				35.718		_	
(o)												
C16n.2n	35.685	35.707	36.051	36.054	35.643				35.774		_	
(y)												
C16n.2n	36.341	36.276	36.700	36.728	36.355				36.351		_	
(o)												
C17n.1n	36.618	36.512	36.969	37.049	36.668				36.573		-	
(y)												
C17n.1n	37.473	37.235	37.753	37.741	37.520				37.385		36.982	
(o)												
C17n.2n	37.604	37.345	37.872	37.934	37.656				37.530		37.220	
(y)												
C17n.2n	37.848	37.549	38.093	38.150	37.907				37.781		37.372	
(o)												
C17n.3n	37.920	37.610	38.159	38.287	37.956				37.858		37.439	
(y)												
C17n.3n	38.113	37.771	38.333	38.477	38.159				38.081		37.973	
(o)												
C18n.1n	38.426	38.032	38.615	38.835	38.449				38.398	38.527	38.273	
(y)												
C18n.1n	39.552	38.975	39.627	39.734	39.554				39.582	39.458	38.861	
(o)												
C18n.2n	39.631	39.041	39.698	39.897	39.602				39.666	39.597	38.929	
(y)												
C18n.2n	40.130	39.464	40.145	40.366	40.084			40.120	40.073	39.989	39.959	
(0)												

^a Tuned to the ZB18a astronomical solution (Zeebe and Lourens, 2019).

Table 4

Comparison of polarity chron boundary durations in millions of years (Myr). In our estimated durations column, bold numbers represent reliable magnetostratigraphic interpretation for base and top boundaries, whereas regular font numbers represent ambiguous interpretation for either base and/or top boundaries, and hyphen represents that base and/or top boundaries were not identified. For the studied interval, the recently published GPTS 2020 (Ogg, 2020) used all ages from the PEAT sites (Westerhold et al., 2014), resulting in the same durations.

Chron	Standard GPTS			Astronomica	Astronomically calibrated					
	CK95 (Cande and Kent, 1995)	GPTS 2004 (Ogg and Smith, 2004)	GPTS 2012 (Ogg, 2012)	MQSD20 ((Malinverno et al., 2020))	ODP Site 1218 (Pälike et al., 2006)	Massignano (Jovane et al., 2006)	Monte Cagnero (Hyland et al., 2009)	PEAT Sites (Westerhold et al., 2014)	IODP Exp. 342 composite U1408- U1410 (Boulila et al., 2018)	Monte Cagnero (this study ^a)
C13n	0.487	0.472	0.548	0.599	0.473		0.520	0.512		0.481
C13r	1.110	1.044	1.294	1.200	1.421			1.376		1.124
C15n	0.285	0.261	0.295	0.324	0.128	0.320		0.234		0.366
C15r	0.403	0.361	0.412	0.428	0.074	0.383		0.244		0.338
C16n.1n	0.183	0.163	0.186	0.236	0.226			0.138		-
C16n.1r	0.159	0.140	0.159	0.191	0.089			0.056		-
C16n.2n	0.656	0.569	0.649	0.674	0.712			0.577		-
C16n.2r	0.277	0.236	0.269	0.321	0.313			0.222		-
C17n.1n	0.855	0.723	0.784	0.692	0.852			0.812		-
C17n.1r	0.131	0.110	0.119	0.193	0.136			0.145		0.238
C17n.2n	0.244	0.204	0.221	0.216	0.251			0.251		0.152
C17n.2r	0.072	0.061	0.066	0.137	0.049			0.077		0.067
C17n.3n	0.193	0.161	0.174	0.190	0.203			0.223		0.534
C17n.3r	0.313	0.261	0.282	0.358	0.290			0.317		0.300
C18n.1n	1.126	0.943	1.012	0.899	1.105			1.184	0.931	0.588
C18n.1r	0.079	0.066	0.071	0.163	0.048			0.084	0.139	0.068
C18n.2n	0.499	0.423	0.447	0.469	0.482			0.407	0.392	1.030

^a Tuned to the ZB18a astronomical solution (Zeebe and Lourens, 2019).

Table 5

Estimated ages for calcareous nannofossil (CN) and planktonic foraminiferal (PF) zones compared to their respective standard ages. CN and PF biozonations are after Agnini et al. (2014) and Wade et al. (2011), respectively.

Zone	Biostratigraphic	Age (Ma)				
(base)	datum	CN zones (Agnini et al., 2014)	PF zones (Wade et al., 2011)	Monte Cagnero (this study)		
CNO2	T E. formosa	32.92		32.98		
CNO1	Bc C. subdistichus >	33.88		33.92		
01	5.5 μm T H alabamansis		33.0	33.03		
CNF21	T D sainanensis	34 44	55.9	34 56		
E16	T G. index	51.11	34.5	34.69		
CNE20	T C. reticulatum	35.24		34.96		
E15	T G. semiinvoluta		35.8	35.32		
CNE18	Tc C. erbae	37.46		36.57		
CNE17	Bc C. erbae	37.88		37.39		
E14	T M. crassatus		37.7	37.43		
CNE16	T S. obtusus	38.47		38.63		
E13	T O. beckmanni		39.4	39.75		
E12	B O. beckmanni		39.8	40.00		
CNE15	B D. bisectus	40.34		40.50		

recent ones (e.g., Speijer et al., 2020) but is also virtually the same age – less than 20 kyr of difference – found by Hyland et al. (2009) in their MCA study, once again highlighting the robustness of MCA astrochronology.

Estimated ages for calcareous nannofossil markers seem to agree even better than planktonic foraminifera, which may result from the higher sampling resolution. Most of the estimated ages closely agrees to those of Agnini et al. (2014) with less than ~150 kyr of difference (Table 5). This is particularly true for zones CNO1 and CNO2 that display offsets of 40 and 60 kyr, respectively, which once again support our estimated age for the EOB. The exceptions are the bases of zones CNE17, CNE18, and CNE20, which have differences of approximately 500, 900, and 300 kyr, respectively. Despite the relatively high age difference, we suggest the base of common *C. erbae* as the most reliable datum in the MCA Section for the base of the Priabonian stage, since its GSSP was recently ratified (Agnini et al., 2020) as the base of the Tiziano bed in the Alano Section with an astrochronological age of 37.710 \pm 0.01 Ma (Galeotti et al., 2019).

5.3. Paleoenvironmental and paleoclimatic implications

Increasing sedimentation rates towards the top of the section (Fig. 7) (Jovane et al., 2013 and this study) agrees with paleobathymetric estimates by benthic foraminiferal data (Guerrera et al., 1988; Parisi et al., 1988), which indicate a gradual shallowing from lower bathyal (1000–2000 m) during the middle Eocene to upper bathyal depth (400–600 m) in the early Oligocene. This could explain a relative increase in SAR simply by increasing the terrigenous input due to the gradually more proximal sediment input setting. Following the interpretation that MS reflects mostly terrigenous input in a pelagic carbonate succession, a sea level fall would lead to an increase in the terrigenous/carbonate ratio, which can be observed in the raw MS data by its gradually increasing values towards the top of the MCA Section (Fig. 2).

The MCA Section is one of the few middle latitude successions that records continuous, rich, and well preserved calcareous nannoflora, enabling the reconstruction of the biotic and paleoceanographic changes from middle Eocene to lower Oligocene. We can observe significant changes in the calcareous nannofossil assemblages within the studied interval (Fig. 3). Modifications in the abundances of calcareous nannofossil taxa are mainly related to paleoenvironmental changes. Paleotemperatures and paleofertility are the main factors that affect the presence and abundance of taxa. Up to now, it does not exist a specific scheme that establishes the paleoecological preferences of calcareous nannofossils, because species preferences could have changed through time and among different biogeographical settings. However, a general agreement on the preferences of some taxa can be identified. To infer possible temperature and trophic variations of surface waters, most calcareous nannofossils were allocated into groups of environmental affinities, largely following Haq and Lohmann (1976), Aubry (1992), Gardin and Monechi (1998), Monechi et al. (2000), Bralower (2002), Persico and Villa (2004), Tremolada and Bralower (2004), Gibbs et al. (2006), Villa et al. (2008, 2014), Agnini et al. (2011), Jones et al. (2019) and Nyerges et al. (2020). Together with the cited literature, the multivariate statistical analysis performed on the MCA calcareous nannofossil dataset allowed the recognition of major community changes and the identification of five groups of taxa with similar paleoecological preferences as shown in Fig. 9 and Table 2.

Variations in relative abundances of the paleoenvironmentally significant groups revealed important environmental changes and trends throughout the MCA Section (Fig. 9). Overall, we can observe that the warm and warm/temperate-water taxa are quite abundant throughout the section with a slightly decreasing trend in the upper part of the section. Cool-water taxa are rare until the upper Priabonian at \sim 35.5 Ma (100 msl) coinciding with the base of the range of I. recurvus and an enrichment in meso-eutrophic taxa. These taxa increased in abundance during the EOT, corroborating the long-term global cooling. A peak in abundance of oligotrophic taxa is observed in the early Priabonian at ~37.3 Ma (86 msl) related to the acme of C. erbae (marker of the CNE7 zone). Despite that, oligotrophic taxa show a decreasing trend with an abrupt drop in abundance and diversity related to the extinction of the rosette-shaped Discoaster, which has been recently defined as the Discoaster Extinction Event (DEE; Jones et al., 2019). Jones et al. (2019) placed the event between 34.44 and 34.77 Ma, while a recent study in the southwestern Neo-Tethys estimated an orbitally tuned age of 34.35 Ma for the event (Messaoud et al., 2020). Based on our orbitally tuned age model, the extinctions of D. saipanensis and D. barbadiensis occurred respectively at 34.58 and 34.69 Ma (Fig. 3), therefore agreeing better with the estimated ages from Jones et al. (2019). On the contrary, mesoeutrophic taxa increase in abundance started at ~36.8 Ma (89 msl), defining a definitive crossover from oligotrophic to mesotrophic taxa dominance.

In the lower part of the section (up to the acme of the *Cribrocentrum*), several fluctuations in abundance between oligotrophic and mesotrophic taxa have been observed with a persistent dominance of warmwater taxa. Although the MECO event could be defined as a warm oligotrophic interval, it still shows very dynamic cycles (Giorgioni et al., 2019). At the onset of the MECO event, a reduction of D. bisectus and Sphenolithus (oligotrophic taxa) was associated with a sharp increase in the abundance of C. floridanus (eutrophic taxon), Z. bijugatus, and small Reticulofenestra (Fig. 3). The MECO interval is then characterized by fluctuations in eutrophic and oligotrophic taxa (Fig. 9), clearly linked to nutrient availability, in warmer SSTs, as suggested by the marked increases in Discoaster and E. formosa. A similar shift from oligotrophic to eutrophic conditions has also been identified at Alano Section (Luciani et al., 2010; Toffanin et al., 2011) and in the Southern Ocean (Villa et al., 2014). After the MECO, the decreasing trend of warm-water taxa reflects the cooling trend that characterizes the middle late Eocene (Zachos et al., 2008). Above the acme of the C. erbae and the subsequent collapse of this genus, the progressive decline of warm-water and oligotrophic taxa continued. Assemblages remained mostly characterized by warmwater taxa and were enriched with mesotrophic taxa linked to subsequent changes in the nutrient level up to the base of the range of I. recurvus. Increased abundances of species adapted to colder and medium-to-rich nutrient waters indicate a gradual cooling of SST that began at the base of the range of I. recurvus. The DEE marked the definitive prevalence of cool eu-mesotrophic forms. During the late Eocene the gradual reduction of the stratification of the water column (Tori et al., 2008) and the cooling of SST seem to be the cause of the



Fig. 9. Astrochronology time scale of the MCA Section established by 405 kyr tuning and groups of paleoenvironmentally significant calcareous nannofossils. From left to right: Planktonic foraminiferal (PF; Jovane et al., 2013) and calcareous nannofossil (CN; this study) biozonation following the schemes proposed by Wade et al. (2011) and Agnini et al. (2014), magnetostratigraphic interpretation after Jovane et al. (2013) with the most reliable magnetic polarity reversals indicated by red stars, ZB18a astronomical solution (Zeebe and Lourens, 2019) with the 405 kyr (blue area) and the 2.4 Myr (green area) components, MS record, and the relative abundance (%) of calcareous nannofossil groups (Table 2; Notice the scale difference for the cool-water taxa). Black and red horizontal dashed lines indicate the Eocene-Oligocene boundary (EOB) and the *Discoaster* extinction event (DEE), respectively. Dark blue interval indicates the EOT as a ~ 790 kyr event started at the extinction of *D. saipanensis* (Hutchinson et al., 2021). Light blue interval indicates the late Eocene cooling showed by calcareous nannofossil cool-water taxa. Purple interval indicates the MECO based on its stratigraphic constraint as proposed by Savian et al. (2014). Warm-water taxa comprehend *Sphenolithus* spp., *D. scrippsae, C. pelagicus, and Discoaster* spp.; warm/temperate-water taxa comprehend *E. formosa*, and meso-eutrophic water taxa comprehend *Clausicoccus* spp., *D. scrippsae, R. dyctioda* group, *C. pelagicus, Blackites* spp., *L. minutus,* and *D. bisectus*. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Discoaster crisis, which were deep dwellers taxa (Aubry, 1992). The interval spanning the EOT is characterized by a sudden turnover towards dominantly meso-eutrophic taxa (*Clausicoccus* spp., *D. scrippsae, R. dictyoda* and *C. pelagicus*), and an increase in abundance of *R. daviesii*, *Blackites* spp. and *Clausicoccus* spp. in response to changing SST and nutrient supply (Coccioni et al., 2008; Villa et al., 2008, 2014). Calcareous nannofossils show a significant reorganization of the assemblages with the replacement of the dominant genera, a gradual decrease in species diversity, a decrease in the abundance of warmwater taxa (*Discoaster* spp. and *Sphenolithus* spp.), and the collapse of oligotrophic taxa (*Cribrocentrum* spp., *R. umbilicus, Discoaster* spp., and *E. formosa*). All these changes seem to be mainly related to a gradual (step-by-step) eutrophication, environmental instability, and small changes of SST.



Fig. 10. The MECO event (yellow) at the MCA Section with peak warming defined as the negative δ^{18} O anomaly (orange). a) ZB18a astronomical solution (Zeebe and Lourens, 2019) with the 2.4 Myr and the 405 kyr cycles extracted by a Gaussian bandpass filter centered at 0.00042 \pm 0.00004 kyr⁻¹ and 0.002469 \pm 0.0006 kyr⁻¹, respectively. b-e) CaCO₃, δ^{13} C, δ^{18} O and MS data from Savian et al. (2014). Magnetostratigraphic interpretation is from Jovane et al. (2013). Planktonic foraminiferal (PF; Jovane et al., 2013) and calcareous nannofossil (CN; this study) biozonation following the schemes proposed by Wade et al. (2011) and Agnini et al. (2014), respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Thus, the high-resolution record of calcareous nannofossil reported here clearly suggests a loss of stratification, increased instability, and general eutrophication trend in the water column during this time interval. Nutrient enrichment shows a stable trend starting at ~37 Ma, therefore preceding the water cooling. This may mean that first there was a generalized loss of stratification in the water column and, later, a decrease of SST. All these changes could be related to an increase in seasonality, carbon cycle variability, and also to modification in oceanic circulation. Furthermore, the increased abundance of *Z. bijugatus* and L. *minutus*, known as shallow-water taxa, corroborates the sea level shallowing assumed by the increasing terrigenous/carbonate ratio interpreted from high MS values in the upper part of the section.

5.4. Timing of the MECO event in the MCA Section

The MECO is recognized as one of the most enigmatic warming events of the Cenozoic, probably related to pCO_2 global changes (Bohaty and Zachos, 2003). Its duration was firstly estimated to last over than 600 kyr (Bohaty and Zachos, 2003), but the recently estimated duration decreased to about 500 kyr, with the peak warming lasting less than 100 kyr and placed around 40.0 Ma (Bohaty et al., 2009). Savian et al. (2014) recognized the stratigraphic interval corresponding to the MECO event in the MCA Section based on a multi-proxy study. Micropaleontological, geochemical, rock magnetic, and stable isotopic data, constrained by a magneto- and biostratigraphic framework, allowed them to place the entire event between ~61.0 and ~ 65.5 msl and the peak warming together with its aftermath specifically between ~63.2 and ~ 65.5 msl. In addition to micropaleontological and geochemical evidence, Savian et al. (2014) reported increased aeolian iron supply and enhanced putative magnetofossil concentrations within this shorter interval, which altogether was interpreted as a period of high primary productivity. Our age model allowed us to place this interval in time domain and compare it with other records in which MECO was identified. Based on the MECO constraint from Savian et al. (2014), together with our developed age model, we have been able to place the event approximately between 40.24 and 39.75 Ma (Fig. 10), which supports the duration of about 500 kyr with peak warming occurring around 40.0 Ma. Besides, it consistently agrees with the recent placing of MECO event in the Neo-Tethys (Giorgioni et al., 2019).

Our study also highlights the importance of the orbital forcing influencing the MECO climate warming due to its coincidence with a node of lows in the 405 kyr and 2.4 Myr components of eccentricity, as firstly suggested by Westerhold and Röhl (2013). Giorgioni et al. (2019) already showed the same behavior in the Neo-Tethys, and here we demonstrate it again for the MCA Section (Fig. 10). As discussed by Giorgioni et al. (2019), this orbital forcing could have enhanced the effects of the India-Asia collisional event in the Tethys (Jovane et al., 2009; Najman et al., 2010), functioning as a trigger for climate warming and carbon cycle instability.

6. Conclusions

Based on previous studies of correlated sections, marls and limestones at the MCA Section are inferred to have been deposited during warm/wet and cold/dry intervals, respectively. Together with a radiometric date and magneto- and biostratigraphic tie points, we were able to construct a new high-resolution age model for the MCA Section, by tuning the minima in the identified long eccentricity cycle of the MS record to minima in the astronomical solution. Our orbitally tuned age model allowed us to place the base of the Priabonian stage in the MCA Section at \sim 37.4 Ma, based on the identification of the base of common C. erbae, and to independently confirm the base of the Rupelian stage at \sim 33.9 Ma, as previously suggested. We constrained the MECO event duration to be \sim 500 kyr with its peak warmth at \sim 40.0 Ma, coinciding with a minimum in the 2.4 Myr and 405 kyr eccentricity components, also corroborating previous studies. The developed age model also points out the necessity of revisiting the MCA magnetostratigraphy, particularly between chrons C18n to C15r. Calcareous nannofossil paleoenvironmentally significant groups allowed the identification of a gradual eutrophication with an abrupt change in the nutrient availability at ~36.8 Ma, shifting from maximum oligotrophic conditions at \sim 37.2 Ma to subsequent meso-eutrophic conditions. Assemblages show that nutrient enrichment preceded water cooling at the late Eocene, suggesting that, prior to the cooling, a loss of water column stratification took place. Furthermore, we strongly reinforce the need for a study within the EOT interval at the MCA Section with high-resolution isotopic records in order to constrain important events such as the Oi-1 based on isotopic signature. Despite these, the MCA is a continuous section in the hundreds of thousand years scale, spanning the late Eocene through the early Oligocene. Therefore, it has the potential to become instrumental in understanding major paleoceanographic and paleoclimatic changes during this interval, over important events such as the MECO and the EOT.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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