Biozonation and biochronology of Paleogene calcareous nannofossils from low and middle latitudes

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With 17 figures, 4 plates and 3 tables

Abstract. Calcareous nannofossils have provided a powerful biostratigraphic tool since the 1950’s and 1960’s, when several milestone papers began to highlight their potential use in dating Cenozoic sediments and rocks. Here, we present a new calcareous nannofossil biozonation for the Paleogene Period, which is based on biostratigraphic data collected during the past 30 years. Semi-quantitative counting methods applied on DSDP/ODP drill sites and marine on-land sections have been used to demonstrate the details of the abundance patterns of each biostratigraphically useful calcareous nannofossil taxon. This new biozonation still partly relies on older biozonations and thus represents an integration between those classical biohorizons that proved reliable and new biohorizons proposed as substitutes for bioevents considered problematic. Thirty-eight new Paleogene biozones are proposed using a new code system: 11 Paleocene biozones (CNP1–CNP11), 21 Eocene biozones (CNE1–CNE21) and 6 Oligocene biozones (CNO1–CNO6). The new scheme uses a limited number of biohorizons, one for each biozone boundary, which guarantees more stability although with a coarser resolution. A series of additional biohorizons are included in almost every biozone. This new Paleogene biozonation has an average duration of 1.1 Myr per biozone, ranging from 0.9 Myr in the Paleocene, to 1.0 Myr in the Eocene, and 1.8 Myr in the Oligocene. Age estimates provided for calcareous nannofossil biohorizons are calculated using both magnetostratigraphic and astronomically tuned cyclostratigraphic data.

Key words. Calcareous nannofossils, biozonation, biochronology, Paleogene
1. Introduction

Calcareous nannofossils are a major component of Cenozoic deep-sea carbonate sediments. This group of marine phytoplankton is widely used in marine biostratigraphy due to its rapid rate of evolution and widespread distribution in carbonate bearing sediments. The fact that the group is less susceptible to carbonate dissolution, compared with planktonic foraminifera, also contributes to its usefulness (Hay 1970, McIntyre and McIntyre 1971, Berger 1973, Blaj et al. 2009). Several Cenozoic calcareous nannofossil biozonations were established about 40 years ago, two of which (Martini 1971, 1976, Bukry 1973, 1975, 1978) are still employed by the IODP community (Stow et al. 2013) and individual biostratigraphers (Toffanin et al. 2013).

In a major revision of the Miocene through Pleistocene calcareous nannofossil biozonations, Backman et al. (2012) remarked that although many of the biohorizons used by Martini and Bukry for biozonal definitions have provided consistent results, several others cannot be considered reliable in view of the large amount of new information that has accumulated over the past four decades. This observation applies also to Martini’s and Bukry’s Paleogene biozonations.

We present here a new calcareous nannofossil biozonation for the Paleogene. This biozonation is based on data we have acquired from key low- and middle-latitude deep-sea drilling sequences over the past three decades, as well as from marine on-land sections in the Tethyan region (Fig. 1). Previously unpublished biostratigraphic data are presented and age estimates are calculated for all biohorizons used for biozone boundary definitions as well as for many additional biohorizons.

2. Biozones, defining biohorizons and a revised biozone code system

Criteria for biozone definitions follow the approach discussed by Backman et al. (2012). We use Base (B) and Top (T) to describe the stratigraphic lowest and highest occurrences of taxa, respectively. The Base and Top concepts are used here in a chronostratigraphic sense. This avoids the ambiguity of the use of the acronym LO, that may refer to both Last Occurrence and Lowest Occurrence. The LO acronym has been used in combination with both FO (First Occurrence) and HO (Highest Occurrence), that further adds to the ambiguity.

Evolutionary first appearances of calcareous nannofossil taxa are initially often followed by low and in many cases sporadic occurrences, prior to becoming well-established members of the assemblages. Correspondingly, extinctions of taxa are often preceded by low and sporadic occurrences prior to their final demise. This is why the first or last continuous and relatively common occurrence of a taxon may represent a better biohorizon than the absolute first or last occurrence, and is why the concepts Base common (Bc) and Top common (Tc) are employed here for biozone boundary definitions. Following these principles, a Bc biohorizon is positioned where the abundance of the species index becomes continuous and, hopefully, more abundant, whereas Tc biohorizon is positioned where the abundance of index species starts to show discontinuous and, usually, rare abundances. The only exception to this rule is represented by the Bc and Tc of Cribrocentrum erbae for which we adopt specific values to precisely define the positions of these bioevents.

Fig. 1. Location map of DSDP/ODP Sites and marine on-land successions used in this study as reference sections.
The application of high-resolution semi-quantitative methods, which consists of counting the number of specimens of the same taxon observed in or normalized to a prefixed area (e.g., 1 mm²; Backman and Shackleton 1983), allows to capture any sporadic abundances especially in the initial and final range of each taxon and, hence, to precisely define the position of the biohorizon.

Thus, four concepts are adopted to characterize four types of biohorizons (B, Bc, T and Tc), which are used to define five different types of biozones: Base Zone (BZ), Top Zone (TZ), Taxon Range Zone (TRZ), Concurrent Range Zone (CRZ) and Partial Range Zone (PRZ). These five logical possibilities are those proposed by Wade et al. (2011), re-illustrated and re-defined to include also Bc and Tc by Backman et al. (2012):

- Species A Base Zone (BZ) is defined as the interval between the Base of species A and the Base of species B.
- Species A Top Zone (TZ) is defined as the interval between the Top of Species A and the Top of species B.
- Species A Taxon Range Zone (TRZ) is defined as the interval between the Base and the Top of species A.
- Species A/species B Concurrent Range Biozone (CRZ) is defined by the concurrent range of species A and species B.
- Species C Partial Range Zone (PRZ) is comprised within the stratigraphical range of species C, between the Top of species A and the Base of species B.

The biozone code system employed here was inspired by the recent revision of Cenozoic planktonic foraminifera biostratigraphy (Wade et al. 2011), and implies a code letter for each series (P = Paleocene, E = Eocene, O = Oligocene) and a number for each biozone, starting from the base (= biozone 1) of the series.

The following Calcareous Nannofossil (CN) codes are used:
1. CNP1 to CNP11: Paleocene biozones 1 through 11;
2. CNE1 to CNE21: Eocene biozones 1 through 21;
3. CNO1 to CNO6: Oligocene biozones 1 through 6.

The GSSP definitions of the lower boundaries of the Paleocene, Eocene and Oligocene (www.stratigraphy.org) are based on chemoostratigraphy and biostratigraphy (base Paleocene), carbon isotope stratigraphy (base Eocene) and planktonic foraminifer biostratigraphy (base Oligocene). It follows that the above three groups of calcareous nannofossil biozones do not exactly coincide with these series boundaries, but are close enough to justify the code system.

### 3. Age estimates of biohorizons

On November 7th, 1964, Christopher Harrison and Brian Funnell published a brief note in *Nature* on the “Relationship of Palaeomagnetic Reversals and Micropalaontology in Two Late Cenozoic Cores from the Pacific Ocean”. This was the first in a successful approach to determining geologic age in deep-sea sediments by combining biostratigraphy and magnetostratigraphy. At about that time, radiometric dating of geomagnetic reversal boundaries in lava sequences on land had begun to be coupled to geomagnetic polarity changes in deep-sea sediments (Cox et al. 1963), which permitted marine stratigraphers to convert biomagnetostratigraphic correlations into geologic age information. William Berggren (1972) presented one of the first major syntheses of such correlations between marine biostratigraphic and magnetostratigraphic information with a focus on the Cenozoic Era, which was followed by widely used revised versions (Berggren et al. 1985, 1995).

The expression of Earth’s orbital parameters in sediment properties (physical, chemical, biological) has been used to produce an accurate time scale for the Holocene to middle Eocene time span (Lourens et al. 2004, Pälike et al. 2006). When it comes to the older parts of the Cenozoic, however, the cyclostratigraphic approach has proven less straightforward for several reasons (Pälike et al. 2004, Westerhold et al. 2012). Because these problems continue to affect the Paleocene to middle Eocene sequence, there is still no single coherent Cenozoic time scale; thus, biohorizons used in this study are calibrated against two different time scales, which rely on different tools.

From the base of Chron C6Cn2n (23.026 Ma), which is the estimated age of the top of the Oligocene, to the base of Chron C19n (41.510 Ma) in the middle Eocene, the orbitally tuned time scale of Pälike et al. (2006) is used, recognizing that age estimates for the Eocene still have larger uncertainties attached to them than for the Oligocene. From the top of Chron C20n (42.536 Ma) to the Cretaceous-Paleogene boundary (65.0 Ma), the geomagnetic polarity time scale of Cande and Kent (1995; CK95) is used. This approach was proposed by Backman et al. (2008) and implies that the duration of Chron C19r has been artificially ex-
tended by 11 kyr (1.1% of the chron’s total duration), when moving from Pälike et al. (2006) to CK95. The revised age of 66.0 Ma for the Cretaceous-Paleogene boundary (Renne et al. 2013) is hence not employed. However, by adding the relative distance for all biohorizons to nearest youngest geomagnetic polarity chron boundary, following the approach used by Agnini et al. (2007a), age estimates can be easily revised when a new accurate Paleogene geological time scale is published. This approach applies also to Chron C19r, here placed between 42.536 Ma and 41.510 Ma.

We have applied Backman’s et al. (2012) views regarding the type of data (semi-quantitative), sample distance intervals used (cm- to dm-scale), and the resolution of the biozones, while not seeking to establish the highest possible resolution but rather a relatively coarsely resolved, and hopefully stable, biozonation. The average duration of the biozones in this revised Paleogene biozonation is 1.1 million years for the 38 biozones that are distributed over nearly 42 million years. Age estimates of biohorizons are considered to be accurate to within ± 50 kyrs.

4. Paleocene

4.1 Remarks on Paleocene taxonomy

All biozone boundary marker species are illustrated in Plate 1. The taxonomic concepts adopted here are based on the following observations:

Cruciplacolithus: Placoliths belonging to the genus Cruciplacolithus are key components of the lowermost Paleocene calcareous nanofossil assemblages. The taxonomy of the different species in this genus is partly controversial. The concepts adopted here follow Fornaciari et al. (2007):

- Cruciplacolithus primus < 7 μm includes smaller specimens generally 4–7 μm in size, that is, the “small” C. primus of Perch-Nielsen (1977);
- Cruciplacolithus intermedius includes the “large” C. primus of Perch-Nielsen (1981), C. tenuis s.l. (sensu Hay and Mohler 1967) and larger specimens (> 7 μm) of C. primus (sensu Romein 1979);
- Cruciplacolithus edwardsii includes Cruciplacolithus asymmetricus (van Heck and Prins 1987), because of presence of specimens with intermediate morphologies between the two species;
- Cruciplacolithus tenuis s.s. (sensu Romein 1979) includes forms with an axial cross structure having “feets”. This taxon thus comprises the “early morphotypes” of Galbrun and Gardin (2004) and excludes large forms of Cruciplacolithus lacking basal blocks.

Cruciplacolithus asymmetricus/Chiasmolithus edwardsii/Chiasmolithus danicus: The species commonly referred to as Chiasmolithus danicus was first described by Brotzen (1959), who did not provide a holotype, thus invalidating the species. Subsequently, van Heck and Perch-Nielsen (1987) formally validated this taxon. Chiasmolithus edwardsii is a species similar to C. danicus, that was described by Romein (1979). Perch-Nielsen (1985) suggested to use the appearance of C. edwardsii (= Brotzen’s C. danicus s.l.) to mark the onset of Zone NP3 of Martini (1971), or Zone CP2 of Okada and Bukry (1980). Perch-Nielsen’s suggestion has been shared by several authors during the last three decades (Monechi et al. 1985, van Heck and Prins 1987, Westerhold et al. 2008). However, even if C. danicus and C. edwardsii are merged into a single taxonomic entity, problems remain because of the presence of intermediate morphologies between C. edwardsii and Cruciplacolithus asymmetricus, which is considered to be the ancestor of the former species. These ambiguities preclude a consistent distinction between these species concepts and prompt us to avoid the use of C. danicus in our biostratigraphic scheme.

Chiasmolithus solitus group: This group includes C. bidens, Chiasmolithus edentulus and Chiasmolithus solitus and has a distinctive central cross with two straight and two slightly bent arms that sometimes are blurred by poor preservation; it includes specimens with intermediate morphologies among the three species.

Praeprinsius dimorphosus group: this group consists of very small (2–3 μm) elliptical to circular placoliths with narrow to closed central area. Praeprinsius dimorphosus and Praeprinsius tenuiculus are included in this taxonomic group. We follow the recommendation by Perch-Nielsen (1985) in referring elliptical morphotypes 2–3 μm in length to P. dimorphosus group.

P. martini: Small elliptical forms with a closed central area ranging from 3 to 5 μm.

P. bisulcus: This elliptical species with a closed central area is distinguished from P. martini by size (Wei and Liu 1992) following Perch-Nielsen (1985), who referred all specimens larger than 5 μm in length to P. bisulcus.
**Toweius pertusus**: This species is defined as subelliptical to circular medium-sized placoliths (6–9 μm) (Sullivan 1965). We propose to split this common Paleocene taxon into two morphotypes. The first includes slightly elliptical specimens and the second, here referred to as *T. pertusus* (circular), includes circular forms.

**Fasciculithus**: The genus *Fasciculithus* was originally described by Bramlette and Sullivan (1961). Members of this genus constitute an important component of middle to late Paleocene calcareous nannofossil assemblages. This lineage existed into the earliest Eocene, when its last species, *Fasciculithus tympaniformis*, became extinct.

Aubry et al. (2011) proposed a taxonomic revision of the genus *Fasciculithus*, involving an emendation of the genus *Fasciculithus* and the establishment of two new genera, *Gomphiolithus* and *Lithoptychius*, that incorporate several species previously included in *Fasciculithus*.

Fasciculiths, as emended by Aubry et al. (2011), consist of forms with a well-developed proximal column and an overlying distal calyptra. They suggest that a further subdivision is needed, based on the presence or absence of two newly introduced structural units, the collaret and the central body.

The first two species belonging to the fasciculith lineage were originally ascribed to the genus *Fasciculithus* (*F. magnus* and *F. magnicordis*). Aubry et al. (2011) nominated these to be included in the new genus *Gomphiolithus* because of the absence of calyptra and presence of a central body. These two species have a limited range constrained to Chron C27r (Agnini et al. 2007a), which may be interpreted as an independent evolutionary episode because of the discontinuity between this group and the rest of the fasciculith lineage, as presently known.

Aubry and colleagues (2011) also introduce the new genus *Lithoptychius*, which is characterized by a prominent collaret interposed between the column and the calyptra. This new genus includes several species such as *F./L. chowii* and *F./L. varolii* and other recently described taxa, all showing overlapping short ranges at the very base of Chron C26r. This series of appearances is referred to as the first radiation, or diversification, event of fasciculiths (Steurbaut and Sztrákos 2008, Aubry et al. 2012, Monechi et al. 2013) and shows a distribution that is separated from the so-called second radiation of fasciculiths (sensu Steurbaut and Sztrákos 2008, Monechi et al. 2013), suggesting that the appearance of the taxa of the first radiation could represent an isolated and temporarily constrained evolutionary episode.

Species ascribed to the emended genus *Fasciculithus* (i.e., *F. tympaniformis* and *F. involutus*), which comprised a column plus a calyptra and a central body, enter in the geologic record virtually concomitantly with *F./L. ulii* and *F./L. pileatus* in lower Chron C26r, close to the Danian/Selandian boundary (Perch-Nielsen 1985; Agnini et al. 2007a). The evolution of the earliest part of fasciculiths thus involved three steps with apparently no known, at present, continuity between *F./G. magnicordis*/*F./G. magnus* on the one hand and *F./L. chowii* and *F./L. varolii* on the other, or between *F./L. chowii* and *F./L. varolii* on the one hand and *F./L. ulii* and *F./L. pileatus* on the other.

A third major radiation event among the fasciculiths occurred in topmost Chron C25n/lowestmost Chron C24r in the upper Thanetian, and includes, among others, *F. alanii*, *F. hayii*, *F. lilianae*, *F. mitreus*, *F. richardii*, *F. schaubii* and *F. tonii* (Romein 1979, Perch-Nielsen 1985, Agnini et al. 2007a). These species show similar stratigraphic ranges, with a common first appearance close to Chron C25n/C24r boundary and a last occurrence in correspondence with the onset of the PETM and hence the Paleocene-Eocene boundary. These taxa are here all included in the single *Fasciculithus richar-dii* taxonomic group.

Although we certainly agree that structural differences exist within fasciculiths (Aubry et al. 2011, Monechi et al. 2013), we also hold the view that more data are needed in order to warrant a systematic emendation of this group. For example, the paracme interval (Monechi et al. 2013) observed within the new genus *Lithoptychius* suggests a possible different evolution among fasciculiths, which likely is not related only to the morpho-structural characters of this group. Furthermore, taxonomic/nomenclatural stability is important *per se*. This consideration applies also for the species involved in the three major radiation events among the fasciculiths. Until a more comprehensive revision of the whole lineage can be documented, we prefer to maintain taxonomic stability in using the genus *Fasciculithus* for the entire lineage from *F. magnicordis* and *F. magnus* to *F. tympaniformis*.

**Fasciculithus/Lithoptychus ulii**: The column of *F./L. ulii* has a trapezoidal outline that is slightly curved in the proximal part. This structural unit is overlaid with a dome, which consists of a thin yet well delin-
eated collaret and a slightly less wide calyptra (Aubry et al. 2011).

**Sphenolithus moriformis** group: *Sphenolithus primus* and *Sphenolithus moriformis* are included in this taxonomic group.

**Heliolithus**: The species *Heliolithus cantabriae* and *Heliolithus kleinpellii* are a characteristic part of the calcareous nannofossil assemblages in the middle part of the upper Paleocene. The species *Heliolithus riedelii* is affected by taxonomic ambiguities (Varol 1989, Agnini et al. 2007a) and rare and sporadic occurrences (Bukry 1973). Furthermore, this species is considered biogeographically controlled as judged from differences in stratigraphic range at different locations (Okada and Thiess 1979, Romein 1979, Aubry 1989, Berggren et al. 2000). Morphotypes ascribable to *Heliolithus* are present also above the highest occurrences of *H. cantabriae* and *H. kleinpellii*. Most of them, except for *Heliolithus bukryi*, a distinct species characterized by a short range in the lower part of Chron C25r, have not yet been formally described and a thorough revision of this group is needed in order to arrange the helioliths in a proper taxonomic context.

<table>
<thead>
<tr>
<th>Age (Ma)</th>
<th>GPTS</th>
<th>Epoch</th>
<th>Stage</th>
<th>Okada &amp; Bukry 1980</th>
<th>Cande and Kent (1995; CK95)</th>
<th>Grey boxes show the uncertainty in defining chronostratigraphic and biozone boundaries.</th>
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**Fig. 2.** CN Paleocene biozones and biohorizons are plotted versus the biozonations of Martini (1971) and Okada and Bukry (1980). The Geomagnetic Polarity Time Scale (GPTS) is after Cande and Kent (1995; CK95). Grey boxes show the uncertainty in defining chronostratigraphic and biozone boundaries.
**Ericsonia robusta**: Bramlette and Sullivan (1961) described *Cyclolithus? robustus* as a large (9–15 μm) circular placolith forming a thick ring and emphasized that the “large size and especially heavy or robust ring are distinctive features of the species”. In 1977, Perch-Nielsen subdivided this taxon into two morphotypes, *E. robusta* that includes smaller forms occurring from the upper part of the Danian (Zone NP3) and *Ericsonia cf. E. robusta* that includes larger forms typically observed only in the late Paleocene (Zone NP8). In agreement with this distinction, Romein (1979) re-combined *Heliolithus universus* Wind and Wise into *Ericsonia universa*. Since then it has become a common practice to refer smaller longer-ranging Paleocene forms to *E. robusta*, while forms larger than 9 μm having a short stratigraphic range in the late Paleocene is referred to as *Ericsonia cf. E. robusta* or *Ericsonia universa*.

Here, we follow Bramlette and Sullivan’s (1961) original concept and use *Ericsonia robusta* for the large *Ericsonia* specimens, as discussed by Raffi et al. (2005). The extinction of this large species provides a distinct biohorizon in upper Chron C25n. The Paleocene genus *Ericsonia* (i.e., *E. robusta*, *E. cf. E. robusta*, *E. subpertusa*, *E. universa*) is in need of a thorough taxonomic revision.

### 4.2 Paleocene biozone definitions

The new Paleogene biozones are presented in chronological order, from older to younger. The biohorizons that are used for definitions of the CNP biozones are summarized in Table 1. An overview of the CNP biozonation in a chronostratigraphic context, and comparison with the CP Paleocene zonation of Okada and Bukry (1980) and NP Paleocene zonation of Martini (1971), is shown in Fig. 2. Figure 3 shows the lower part of the Paleocene with biozone boundary markers and additional biohorizons. Figure 4 shows initial abundances of *Coccolithus pelagicus* from South Atlantic and Tethyan locations. Figure 5 shows abundance patterns of the lower part of the Paleocene biozone boundary markers from ODP Site 1262 and their direct correlation to magnetostratigraphy. Figure 6 shows the upper part of the Paleocene with biozone boundary markers and additional biohorizons. Figure 7 shows abundance patterns of the upper part of the Paleocene biozone boundary markers from ODP Site 1262 and their direct correlation to magnetostratigraphy. The Paleocene biozones have been recently discussed by Fornaciari et al. (2007) and Agnini et al. (2007a). Age estimates of the biozone boundary mark-
ers and additional Paleocene biohorizons are summarized in Table 1. Nine out of the eleven Paleocene biozones apply the Base Zone concept, which witnesses about the evolutionary radiation of Paleogene calcareous nannofossils after the Cretaceous-Paleogene boundary mass extinction event. Plate 1 illustrates Paleocene biozone boundary markers.

**Name:** Zone CNP1 – *Braarudosphaera bigelowi* Partial Range Zone  
**Definition:** Interval from the extinction of “Cretaceous nannoflora” (e.g., *Micula* spp., *Watznaueria* spp.) to Base *Coccolithus pelagicus*  
**Reference section:** ODP Site 1262 (South Atlantic, 27°11.1’ S, 1°34.6’ E, 4755 m WD)

**Ardo section**

![Ardo section](image)

**Contessa section**

![Contessa section](image)

**Fig. 4.** *Coccolithus pelagicus* abundance patterns versus magnetostratigraphy from ODP Site 1262 (SE Atlantic), and marine on-land Ardo (NE Italy) and Contessa (central Italy) sections. Paleomagnetic data are after Westerhold et al. (2008), Dallanave et al. (2012) and Coccioni et al. (2012), respectively.* abundance pattern of *C. pelagicus* from Dallanave et al. (2012).

Base zone: ODP 1262C-13H-2, 69 cm to 1262C-13H-2, 70 cm  
Top zone: ODP 1262B-22H-3, 145 cm to 1262B-22H-4, 5 cm  
**Estimated age:** 65.00 Ma–64.76 Ma (Figs. 2–5; Table 1; Plate 1)  
**Duration:** 0.24 Myr  
**Remarks:** Zone CNP1 approximately corresponds to Zone NP1 and Subzone CP1a. Its base, defined as “Top Cretaceous Nannoflora”, corresponds to the extinction of the uppermost Cretaceous nannofossil species such as *Micula murus*, *Micula prinsii*, and *Watznaueria* spp. A distinct biohorizon, Base *C. pelagicus* (Figs. 4, 5), is chosen in order to avoid the uncertainty caused by preservation problems and/or taxo-
nomic ambiguities that affect some of the marker species that have been used for biostratigraphic subdivision of the lowermost Paleocene. For example, we disregard zonal boundary markers such as Neobiscutum romeini and Neobiscutum parvulum, the small and large C. primus used by Perch-Nielsen (1985), and C. tenuis s.l. (= large C. primus), which was used by Martini (1971) and Okada and Bukry (1980). **Remarks on assemblages:** Cretaceous survivor species are the dominant taxa, mainly Braarudosphaera bigelowii and Thoracosphaera spp. and other calcispheres which are rare in the Maastrichtian (Fornaciari et al. 2007). Zone CNP1 may show a general scarcity of calcareous nannofossils and even fewer specimens of the taxa that evolved after the onset of the Paleocene (Fornaciari et al. 2007), such as Neobiscutum spp., Biaantholithus sparsus, Cyclagelosphaera alta, Futyania petalosa and C. primus (< 7 μm). Among the genuine Cretaceous survivor species, only Cyclagelosphaera reinhardtii and Octolithus multiplus attain significant abundances (Fornaciari et al. 2007). The distribution of taxa in Zone CNP1 shows strong variability in both neritic and pelagic settings (Pospichal 1996), suggesting influence of regional environmental conditions in terms of strong provincialism on the nannofossil assemblages. For example, high abundances of N. romeini and N. parvulum, observed in some Tethyan sections such as El Kef, Elles, Agost and Petriccio (Pospichal 1996, Gardin and Monechi 1998) are absent in the Tethyan Forada section (Fornaciari et al. 2007).

![Fig. 5. Early-middle Paleocene selected calcareous nannofossil abundance patterns from ODP Site 1262 (SE Atlantic). Calcareous nannofossil abundance patterns include new and published data (this study; Agnini et al. 2007a). Magnetostratigraphy is after Westerhold et al. (2008).](image-url)
Table 1  Age estimates of Paleocene biohorizons. Position of biohorizons from Top chron is reported. Additional information (Time Scale reference, calibration reference, Site/section used from calibration and Top ID sample and Base ID samples) are also provided.

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<th>Event</th>
<th>Species</th>
<th>Base Zone</th>
<th>Site/Section</th>
<th>Calibration Ref.</th>
<th>Sample Top</th>
<th>Sample Base</th>
<th>Time-scale Ref.</th>
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<td>CNP1</td>
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<td>ODPI262C-13H-2,69</td>
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</table>

Cretaceous/Paleogene boundary
**Name:** Zone CNP2 – Coccolithus pelagicus Base Zone  
**Definition:** Interval from Base Coccolithus pelagicus to Base common Praeprinsius dimorphosus group.  
**Reference section:** ODP Site 1262 (South Atlantic, 27° 11.1′ S, 1° 34.6′ E, 4755 m WD)  
Base zone: ODP 1262B-22H-3, 145 cm to 1262B-22H-4, 5 cm  
Top zone: ODP 1262B-22H-1, 85 cm to 1262B-22H-1, 95 cm  
**Estimated age:** 64.76 Ma – 64.32 Ma (Figs. 2–5; Table 1; Plate 1)  
**Duration:** 0.44 Myr  
**Remarks:** Zone CNP2 corresponds to lower Zone NP2 and Subzone CP1b.  
**Remarks on assemblages:** The *P. dimorphosus* group evolved shortly after *C. pelagicus*. Base *P. dimorphosus* group is considered to provide a reliable biohorizon that has been observed in several successions located in the Tethys domain and the North-Atlantic area (Romein 1979, Varol 1998, Pospichal 1996, Fornaciari et al. 2007, Dallanave et al. 2012). It is not used here to define a biozone boundary because of the short age distance (< 100 kyr) to the slightly older Base *C. pelagicus*. The diversity and abundance of Paleocene taxa such as *C. primus*, *C. intermedius*, *C. edwardsii* and *Erissonia subpertusa* increase during the brief Zone CNP2, concomitantly with the increase in abundance of *C. pelagicus* (Fornaciari et al. 2007).

**Name:** Zone CNP3 – *Praeprinsius dimorphosus* Base Zone  
**Definition:** Interval from Base common *Praeprinsius dimorphosus* group to Base *Prinsius martinii*  
**Reference section:** ODP Site 1262 (South Atlantic, 27° 11.1′ S, 1° 34.6′ E, 4755 m WD)  
Base zone: ODP 1262C-12H-2, 85 cm to 1262B-12H-2, 95 cm  
Top zone: ODP 1262C-11H-1, 17 cm to 1262B-21H-1, 110 cm  
**Estimated age:** 62.62 Ma – 62.03 Ma (Figs. 2–3, 5; Table 1; Plate 1)  
**Duration:** 0.59 Myr  
**Remarks:** Base *Ellipsolithus macellus* was used by Martini (1971) and Okada and Bukry (1980) to mark the base of Zone NP4 and CP3, respectively. It has turned out, however, that this biohorizon shows discontinuous distributions and diachrony (Fig. 3), making it unsuitable as a biozone boundary marker (Backman 1986, Monechi et al. 1985, Berggren et al. 1995, 2000, Agnini et al. 2007a, Dallanave et al. 2012).  
**Remarks on assemblages:** *Prinsius bisulcus* (5–10 μm) becomes common to abundant in lower Zone CNP4. The presence of transitional specimens between *P. bisulcus* and elliptical morphotypes of *T. pertusus* makes us avoid the latter forms for biostratigraphic purposes. Small and large specimens of *C. primus* are not consistently observed above the top of Zone CNP4.

**Name:** Zone CNP5 – Toweius pertusus Base Zone  
**Definition:** Interval from Base *Toweius pertusus* (circular) to Base common *Sphenolithus moriformis*  
**Reference section:** ODP Site 1262 (South Atlantic, 27° 11.1′ S, 1° 34.6′ E, 4755 m WD)  
Base zone: ODP 1262C-11H-1, 17 cm to 1262B-21H-1, 110 cm  
Top zone: ODP 1262B-20H-4, 8 cm to 1262B-20H-4, 29 cm
Estimated age: 62.03 Ma–60.74 Ma (Figs. 2–3, 5; Table 1; Plate 1)
Duration: 1.29 Myr
Remarks: Zone CNP5 corresponds to the middle part of Zone NP4, and Zone CP3. Circular morphotypes of T. pertusus (sensu Agnini et al. 2007a) are clearly distinguished within the assemblage and their first appearance in the stratigraphic column provide a distinct biohorizon.
Remarks on assemblages: Base F. magnicordis group occurs within Zone CNP5. There is an extensive discussion on the biostratigraphic relationships between sphenoliths and fasciculiths (Romein 1979, Monechi 1985, Backman 1986, Berggren et al. 1995, Bernaola et al. 2009, Varol 1989, Berggren et al. 2000, Agnini et al. 2007a, Aubry et al. 2011, Monechi et al. 2013). There is a consensus view, however, that the first appearance of sphenoliths occurs close to the first radiation of fasciculiths sensu Aubry et al. (2011; L./F. choowii, L./F. varolii).
Placoliths belonging to C. bidens, here included in the C. solitus group, appear and rapidly increase in abundance in the uppermost part of Zone CNP5. Base C. bidens is used in the North Sea zonations (Perch...
Nielsen 1979, van Heck and Prins 1987, Varol 1989). This biohorizon is observed close to the top of Chron C27n (Agnini et al. 2007a), a position that is consistent with Berggren’s et al. (2000) data. *Praeprinsius dimorphosus* disappears within Zone CNP5 (Dallanave et al. 2012).

**Name:** Zone CNP6 – *Sphenolithus moriformis* group

**Base Zone**

**Definition:** Interval from Base common *Sphenolithus moriformis* group to *Base Fasciculithus ulii*

**Reference section:** ODP Site 1262 (South Atlantic, 27° 11.1’ S, 1° 34.6’ E, 4755 m WD)

Base zone: ODP 1262B-20H-4,8 cm to 1262B-20H-4,29 cm

Top zone: ODP 1262C-10H-6,23 cm to 1262C-10H-6,44 cm

**Estimated age:** 60.74 Ma–60.31 Ma (Figs. 2–3, 5; Table 1; Plate 1)

**Duration:** 0.43 Myr

**Remarks:** Zone CNP6 approximately corresponds to the upper part of Zone NP4 and Zone CP3. The appearance of the *S. moriformis* group represents the evolutionary emergence of the genus *Sphenolithus*. Base *Fasciculithus ulii* marks the onset of the second radiation of fasciculith sensu Aubry et al. (2011), and the continuous occurrence of the Paleocene fasciculith lineage.

**Remarks on assemblages:** The main components of Zone CNP6 assemblages are *C. pelagicus, P. martinii, P. bisulcus* and *Toweius*. The *S. moriformis* group rapidly increases in abundance in lower Zone CNP6.

**Name:** Zone CNP7 – *Fasciculithus ulii* Base Zone

**Definition:** Interval from Base *Fasciculithus ulii* to Base *Heliolithus cantabriae*

**Reference section:** ODP Site 1262 (South Atlantic, 27° 11.1’ S, 1° 34.6’ E, 4755 m WD)

Base zone: ODP 1262C-10H-6,23 cm to 1262C-10H-6,44 cm

Top zone: ODP 1262A-17H-3,31 cm to 1262A-17H-3,52 cm

**Estimated age:** 60.31 Ma–58.27 Ma (Figs. 2–3, 5; Table 1; Plate 1)

**Duration:** 2.04 Myr

**Remarks:** Zone CNP7 corresponds approximately to Zone NP5 and Zone CP4. Base *F. ulii* precedes Base *Fasciculithus tympaniformis* by about 0.4 Myr. The latter was employed as biozone boundary marker by both Martini (1971) and Okada and Bukry (1980). Transitional morphotypes between these two species occur near the base of *F. tympaniformis*, which may make it difficult to determine Base *F. tympaniformis* precisely.

**Remarks on assemblages:** The genus *Toweius* increases in abundance in Zone CNP7 until it becomes a
dominant component of the assemblages. The *S. moriformis* group increases in abundance in Zone CNP7. In the upper part of the zone, *F. ulii* and *F. pileatus* decrease in abundance. Top common *P. martini* occurs in upper Zone CNP7.

**Name:** Zone CNP8 – *Heliolithus cantabriae* Base Zone  
**Definition:** Interval from Base *Heliolithus cantabriae* to Base *Discaster mohleri*  
**Reference section:** ODP Site 1262 (South Atlantic, 27° 11.1’S, 1° 34.6’E, 4755 m WD)  
Base zone: ODP 1262A-17H-3, 31 cm to 1262A-17H-3, 52 cm  
Top zone: ODP 1262B-18H-3, 40 cm to 1262B-18H-3, 61 cm  
**Estimated age:** 58.27 Ma – 57.57 Ma (Figs. 2, 6–7; Table 1; Plate 1)  
**Duration:** 0.70 Myr  
**Remarks:** Zone CNP8 corresponds to the uppermost part of Zone NP5 and Zone NP6, and the uppermost part of Zone CP4, and Zone CP5. Transitional morphotypes between *H. cantabriae* and *H. kleinpellii* occur near the Base *H. kleinpellii*, which may make it difficult to determine Base *H. kleinpellii* precisely.  
**Remarks on assemblages:** *Fasciculithus clinatus* appears in Zone CNP8, although the appearance of this species may be blurred by the presence of specimens with intermediate morphology with *F. tympaniformis*. The genus *Bomolithus* becomes common in uppermost Zone CNP8, where the first sporadic occurrences of *Sphenolithus anarrhopus* also is observed.

**Name:** Zone CNP9 – *Discaster mohleri* Base Zone  
**Definition:** Interval from Base *Discaster mohleri* to Base *Discaster backmanii*  
**Reference section:** ODP Site 1262 (South Atlantic, 27° 11.1’S, 1° 34.6’E, 4755 m WD)  
Base zone: ODP 1262A-16H-1, 133 cm to 1262A-16H-2, 25 cm  
Top zone: ODP 1262B-16H-6, 24 cm to 1262B-16H-6, 45 cm  
**Estimated age:** 56.95 Ma – 56.01 Ma (Figs. 2, 6–7; Table 1; Plate 1)  
**Duration:** 0.94 Myr  
**Remarks:** Zone CNP9 corresponds to the upper part of Zone NP7 and Zone NP8, and to the upper part of Zone CP6 and Zone CP7. Zone NP8 is difficult to determine because *Heliolithus riedelii* has an ambiguous taxonomy and is lacking in most deep-sea sections. Base *Discaster nobilis* defines base Zone CP7, which consistently falls within Zone CNP10. This biohorizon however is not employed here because of the existing uncertainty with respect to its precise calibration to magnetostratigraphy (upper Chron C25r to middle Chron C25n) (Monechi and Thierstein 1985, Backman 1986, Berggren et al. 1995, 2000, Agnini et al. 2007a).  
**Remarks on assemblages:** The asymmetrical *Discaster okadai* is consistently present over a short but distinctive range. A phylogenetic relationship between *D. backmanii* and *D. okadai* is documented by the presence of forms with intermediate morphological features between the two taxa (Agnini et al. 2007a, 2008). *Discaster backmanii* is a dominant form within the *Discaster* assemblage of Zone CNP10, and shows a final sharp decrease in abundance in upper Zone CNP10. *Ericsonia robusta* (sensu Bramlette and Sullivan 1961) increases in abundance. The total range of *E. robusta* provides a distinct biostratigraphic fea-
ture (Agnini et al. 2007a), with Base *E. robusta* shortly preceding the base of the subsequent Zone CNP11. *Zygrhablithus bijugatus* has its first occurrence in upper Zone CNP10, together with Top common *S. anarhopus*. The appearance of *D. delicatus* occurs within Chron C25n, providing a distinct biostratigraphic signal (Agnini et al. 2007a, Dallanave et al. 2009, 2012).

**Name:** Zone CNP11 – *Discoaster multiradiatus/Fasciculithus richardii* group Concurrent Range Zone

**Definition:** Interval from Base *Discoaster multiradiatus* to Top *Fasciculithus richardii* group

**Reference section:** ODP Site 1262 (South Atlantic, 27° 11.1′ S, 1° 34.6′ E, 4755 m WD)

Base zone: ODP 1262B-16H-6, 24 cm to 1262B-16H-6, 45 cm

Top zone: ODP 1262B-15H-3, 72 cm to 1262B-15H-3, 73 cm

**Estimated age:** 56.01 Ma–55.00 Ma (Figs. 2, 6–7; Table 1; Plate 1)

**Duration:** 1.01 Myr

**Remarks:** Zone CNP11 corresponds to most of Zone NP9 and Subzone CP8a, although the definition of the top differs among the three biozones. Base *D. multiradiatus* represents one of the best Paleocene biohorizons (Bramlette and Sullivan 1961, Hay and Mohler 1967, Radomsky 1968, Edwards 1971, Romein 1979, Backman 1986, Wei and Wise 1989, Berggren et al. 1995, 2000, Raffi et al. 2005, Agnini et al. 2007a). Base *D. multiradiatus* has been recorded within Chron C25n in both deep-sea and on-land marine sections in the Atlantic, Pacific and Tethyan areas (Backman 1986, Raffi et al. 2005, Müller 1985, Monechi et al. 1985, Agnini et al. 2007a). Martini (1971) used the appearance of *Marthasterites bramlettei* (now *Tribrachiatus bramlettei*) to define Top Zone NP9, whereas Okada and Bukry (1980) used the appearance of both *Campylosphaera eodela* and *Rhomboaster* spp. to define Top Subzone CP8a. These three marker species suffer from ambiguous taxonomies (*T. bramlettei*, *Rhomboaster* spp.) or sporadic distributions (*C. eodela*), making them less suitable to use for biozone boundary definitions. In contrast, the disappearance of the *F. richardii* group represents an easily observable evolutionary change among the nannofossil assemblages, and is here employed to define Top Zone CNP11.

**Remarks on assemblages:** The distinct range of *E. robusta* encompasses uppermost Zone CNP10 and lowermost Zone CNP11. The extinction of *E. robusta* is an

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### Table: Biochronology of Paleogene calcareous nannofossils

<table>
<thead>
<tr>
<th>Age (Ma)</th>
<th>GPTS</th>
<th>Epoch</th>
<th>Stage</th>
<th>Okada &amp; Bukry '80</th>
<th>Martini 1971</th>
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<th>BIOHORIZONS (primary and additional)</th>
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<td>NP10</td>
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<td><strong>B. Rhomboaster spp</strong> (54.99)</td>
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<td></td>
<td><strong>Heliolithus bukryi</strong></td>
</tr>
<tr>
<td>58.0</td>
<td>C26r</td>
<td></td>
<td></td>
<td>CP4</td>
<td>NP5</td>
<td></td>
<td><strong>B. Discoaster mohleri</strong> (57.57)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>B. Heliolithus kleinpellii</strong> (58.03)</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td><strong>B. Heliolithus cantabriae</strong> (58.27)</td>
</tr>
</tbody>
</table>

**Fig. 6.** Blow-up of late Paleocene interval. Late Paleocene CN biozones and biohorizons are plotted versus the biozona-

Fig. 7. Middle-late Paleocene selected calcareous nannofossil abundance patterns from ODP Site 1262 (SE Atlantic). Calcareous nannofossil abundances are after Agnini et al. (2007a). Magnetostratigraphy is after Westerhold et al. (2008).

Plate 2. Microphotographs of early to middle Eocene calcareous nannofossil index species from the ODP Sites 1051, 1262 and U1410, and Possagno section. Scale bar 5 μm.


5. **Eocene**

5.1 **Remarks on Eocene taxonomy**

All biozone boundary marker species are illustrated in Plates 2 and 3. The taxonomic concepts adopted here are based on the following observations:

*Rhomboaster* and *Tribrachiatus*: Bybell and Self-Trail (1995) recombined *Tribrachiatus bramlettei*, *T. contortus* and *T. orthostylus* into *Rhomboaster*. Here we follow Raffi et al. (2005) and distinguish between
**Rhomboaster cuspis** and the **R. calcitrapa** group on the one hand, and **T. bramlettei**, **T. contortus** and **T. orthostylus** on the other.

**Coccolithus crassus:** **Coccolithus crassus** was described by Bramlette and Sullivan (1961) as a medium to large, elliptical to subelliptical placolith showing straight-radiating striae in transmitted light. Here we adopt the detailed description provided by Wei (1993) and Wei et al. (1993).

**Toweius** spp.: This group includes all species ascribed to the genus, except **Girgisia gammation** and **Coccolithus crassus**.

**Discoaster sublodoensis:** **Discoaster sublodoensis** is a small discoaster with 5 (or less commonly 4 or 6) straight sharply pointed rays (Bramlette and Sullivan 1961). Specimens of **D. sublodoensis** are distinguished from small specimens of **D. lodoensis** by the straight rays of the former. However, 6-rayed specimens of **D. sublodoensis** may show intermediate morphologies with **D. lodoensis** that may make the identification of the two morphotypes problematic, particularly in overgrown specimens. Here we follow the suggestion of Backman (1986) and Agnini et al. (2006) to use the base of 5-rayed **D. sublodoensis** as a biozone boundary marker.

**Nannotetris fulgens** and **Nannotetris alata** group: The two species **Nannotetris fulgens** and **Nannotetris alata** are merged into this group. **Nannotetris fulgens** (Martini in Martini and Stradner 1960, p. 5, Figs. 9, 15) was originally thought to differ from **N. alata** (Stradner in Martini and Stradner 1960, p. 5–6, Figs. 10, 16) in having more slender arm tips. This feature is difficult to observe in poorly preserved material due to overgrowth and uncertainty therefore exists whether or not these are two distinct species. Haq and Lohmann (1976) re-combined **Nannotetris alatus** (Martini) to **Nannotetris alata** and remarked that **N. alata** has priority over **N. fulgens**.

**Chiasmolithus gigas:** This species includes coccoliths with broad centro-distal cycles and a very narrow central opening spanned by cross bars with median extinction lines that occupy most of the central area. This is a more detailed taxonomic characterization in comparison with the original description that included all unusually large placoliths spanned by a X-shape structure (Bramlette and Sullivan 1961, Radomski 1968). A strict taxonomic definition of **C. gigas** is necessary in order to distinguish this species from similar morphotypes ascribed to **Chiasmolithus mutatus** by Bown (2005).

**Sphenolithus furcatolithoides:** The original description (Locke 1967) is focused on the morphology rather than the birefringence and the extinction pattern. **Sphenolithus furcatolithoides** is a relatively small sphenolith with two parallel long spines diverging at an acute angle. The spines are always bright when viewed at 0° under cross-polarized light (XPL) (Perch-Nielsen 1985). When the sphenolith is oriented at 45° under XPL, it shows two different patterns: in morphotype **A** the base is birefringent forming a cross-shaped figure and the apical spines are extinct (Perch-Nielsen 1985; Fig. 71). At 20° under XPL, the morphotype **B** shows a chessboard-like extinction pattern with one half of the base and the overlying apical spine alternatively becoming extinct (Fornaciari et al. 2010, Pl. 1, figs. 15–16). The different extinction patterns and stratigraphic distributions of these two morphotypes may suggest that they could be split into two separate taxa, but more data, not yet available, are needed to formalize this taxonomic revision. For nomenclature stability we thus prefer to refer to both these morphotypes as **S. furcatolithoides**.

The genera **Cribrocentrum**, **Dictyococcites** and **Reticulofenestra** have been often merged into a single genus: **Reticulofenestra** (e.g., Gallagher 1989, Young 1990). Here, we prefer to follow Perch-Nielsen (1985) and Fornaciari et al. (2010), who maintain these three genera as separate taxonomic entities.

**Reticulofenestra umbilicus:** The morphometric definition by Backman and Hermelin (1986) is adopted, which includes specimens ≥ 14 μm.

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**Fig. 8.** CN Eocene biozones and biohorizons are plotted versus the biozonations of Martini (1971) and Okada and Bukry (1980). The Geomagnetic Polarity Time Scale (GPTS) is after Pälike et al. (2006), from the top of Chron C13r (33.705 Ma), to the base of Chron C19n (41.510 Ma) in the middle Eocene, and after Cande and Kent (1995; CK95), from the top of Chron C20n (42.356 Ma) downward. Grey boxes show the uncertainty in defining chronostratigraphic and biozone boundaries.
Fig. 9. Blow-up of early Eocene interval. Early Eocene CN biozones and biohorizons are plotted versus the biozonations of Martini (1971) and Okada and Bukry (1980). The Geomagnetic Polarity Time Scale (GPTS) is after Cande and Kent (1995; CK95).

<table>
<thead>
<tr>
<th>Age (Ma)</th>
<th>GPTS</th>
<th>EPOCH/Stage</th>
<th>Okada &amp; Bukry 1980</th>
<th>Martini 1971</th>
<th>this study</th>
<th>BIOHORIZONS (primary and additional)</th>
</tr>
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<tbody>
<tr>
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<td>C24r</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>53.0</td>
<td></td>
<td>CP9a</td>
<td>NP10</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>CP9b</td>
<td>NP11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CNE3</td>
<td></td>
<td></td>
<td></td>
<td>Bc Discoaster lodoensis (52.64)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>B Chiprasingamulithus spp.</td>
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<tr>
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<td></td>
<td>B Discoaster lodoensis (53.1)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>T Girgisia gammoni (53.14)</td>
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<td></td>
<td>B Sphenolithus radians (53.53)</td>
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<td></td>
<td></td>
<td>Tc Discoaster multiradiatus (53.58)</td>
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<td>B Trichiuris orthostylytus (53.67)</td>
</tr>
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<td></td>
<td></td>
<td>CNE2</td>
<td></td>
<td></td>
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<td>B Trichiuris contortus (54.0)</td>
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<td>B Discoaster diastypus (54.13)</td>
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<td></td>
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<td>T Fasciculithus tympaniformis (54.71)</td>
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<td></td>
<td></td>
<td>B Rhomboaster spp. (54.99)</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>T Fasciculithus richardii gr. (55.0)</td>
</tr>
</tbody>
</table>

ODP Site 1262

Fig. 10. Late Paleocene–early Eocene selected calcareous nannofossil abundance patterns from ODP Site 1262 (SE Atlantic) and the Cicogna section (NE Italy). Calcareous nannofossil abundances are after Agnini et al. (2007a) and Dallanave et al. (2009), respectively. Magnetostratigraphies are after Westerhold et al. (2008) and Dallanave et al. (2009) respectively.
Dictyococcites hesslandii and Dictyococcites bisectus: Dictyococcites scrippsae Bukry and Percival (1971) is considered (Haq and Lohmann 1976, Backman 1987) to be a junior synonym of D. hesslandii (Haq 1971). This taxon includes elliptical placoliths < 10 μm, with continuous, sharply bent extinction lines and a filled central area. Dictyococcites bisectus (> 10 μm) is similar to D. hesslandii (< 10 μm), from which it differs by size, the solid plug in the central area and the extinction pattern with nearly linear extinction lines (Bralower and Mutterlose 1995, Fornaciari et al. 2010, Toffanin at al. 2013). Dictyococcites bisectus shows scattered stratigraphic occurrences in being reported from Zone CP12 and younger zones (Mita 2001, Larrasoaña et al. 2008). This may be explained by presence of early Dictyococcites specimens that show some atypical features with respect to the nominal taxon, such as a sub-circular to sub-elliptic outline and a

Possagno section

Fig. 11. Early-middle Eocene selected calcareous nannofossil abundance patterns from the Possagno section (NE Italy). Calcareous nannofossil abundances and magnetostratigraphy are after Agnini et al. (2006).
smaller central area covered by a thin and fragile plug. These morphotypes are here not considered to represent genuine D. bisectus.

Cribrocentrum: The taxonomy of Cribrocentrum reticulatum, Cribrocentrum erbae and Cribrocentrum isabellae follows the concepts proposed by Fornaciari et al. (2010):

- Cribrocentrum reticulatum is a medium to large (6–12 μm) circular placolith with a narrow central opening spanned by a reticulum, which produces a distinctive extinction pattern looking like two crossed dumbbells in light microscope (Perch-Nielsen 1985).
- Cribrocentrum erbae is medium to large (7–12 μm) circular placolith with a virtually closed central area, very bright in cross polarized light.
- Cribrocentrum isabellae is very large (> 12 μm) circular placolith with a partially filled central area, bright in cross polarized light.

5.2 Eocene biozone definitions

The biohorizons that are used for definitions of the CNE biozones are summarized in Table 2. An overview of the CNE biozonation in a chronostratigraphic context, and comparison with the CP Eocene zonation of Okada and Bukry (1980) and NP Eocene zonation of Martini (1971), is shown in Figure 8. Figure 9 shows the lower part of the Eocene with biozone boundary markers and additional biohorizons. Figure 10 shows abundance patterns of the lower part of the Eocene biozone boundary markers from ODP Site 1262 and Cicogna section and their direct correlation to magnetostratigraphy. Figure 11 shows abundance patterns of the middle part of the Eocene biozone boundary markers from ODP Site 1262 and Cicogna section and their direct correlation to magnetostratigraphy. Figure 12 shows the middle part of the Eocene with biozone boundary markers and additional biohorizons. Figure 13 shows abundance patterns of the middle part of the Eocene biozone boundary markers from ODP Site 1051 and their direct correlation to magnetostratigraphy. Figure 14 shows abundance patterns of the upper part of the Eocene biozone boundary markers from ODP Site 1052 and their direct correlation to magnetostratigraphy. Figure 15 shows the Eocene/Oligocene boundary interval and the Oligocene with biozone boundary markers and additional biohorizons.

Definition: Interval from Top Fasciculithus richardii group to Top Fasciculithus typaniformis

Reference section: ODP Site 1262 (South Atlantic, 27° 11.1’ S, 1° 34.6’ E, 4755 m WD)
Base zone: ODP 1262B-15H-3, 72 cm to 1262B-15H-3, 73 cm
Top zone: ODP 1262A-13H-3, 65 cm to 1262A-13H-3, 86 cm
Estimated age: 55.00 Ma–54.71 Ma (Figs. 8–10, Table 2, Plate 1–2)
Duration: 0.29 Myr
Remarks: This zone corresponds to lower Zone NP10, and to lower Subzone CP8b. We avoid the use of the appearances of Tribrachiatus bramlettei and Campyl조사 sphæra eodela because these biohorizons are considered unreliable (Raffi et al. 2005, Agnini et al. 2007a).

Remarks on assemblages: The nannofossil assemblages of the lower part of CNE1 are affected by the PETM conditions in the photic zone in terms of both composition and preservation. Fasciculithus typaniformis and F. involutus are consistently present in Zone CNE1 and become extinct shortly after the recovery of the Carbon Isotope Excursion (CIE) of the PETM. Different morphotypes of Rhomboaster evolve and radiate within the PETM interval together with Tribrachiatus (Romein 1979). Specimens of the R. calci-trapa group (sensu Raffi et al. 2005) and two asymmetrical Discoaster species, Discoaster araneus and Discoaster anartios, are common and typically restricted to the CIE interval (Bybell and Self-Trail 1995, Cramer et al. 2000, Kahn and Aubry 2004, Tremolada and Bralower 2004).

Name: Zone CNE2 – Toweius eminens Partial Range Zone

Definition: Interval from Top Fasciculithus typaniformis to Base Tribrachiatus orthostylus

Reference section: ODP Site 1262 (South Atlantic, 27° 11.1’ S, 1° 34.6’ E, 4755 m WD)
Base zone: ODP 1262B-13H-3, 65 cm to 1262A-13H-3, 86 cm
Top zone: ODP 1262B-13H-4, 2 cm to 1262B-13H-4, 23 cm
Estimated age: 54.71 Ma–53.67 Ma (Figs. 8–10, Table 2, Plate 2)
Duration: 1.04 Myr
Remarks: Zone CNE2 corresponds to middle to upper Zone NP10, and upper Subzone CP8b to lower Subzone CP9a.

Remarks on assemblages: Discoaster diastypus (sensu Agnini et al. 2007a) appears in the middle part of
Table 2  Age estimates of Eocene biohorizons. Position of biohorizons from Top chron is reported. Additional information (Time Scale reference, calibration reference, Site/section used from calibration and Base ID samples) are also provided.

<table>
<thead>
<tr>
<th>Event</th>
<th>Species</th>
<th>Base Zone</th>
<th>Site/Section</th>
<th>Calibration Ref.</th>
<th>Sample Top</th>
<th>Sample Base</th>
<th>Time-scale Ref.</th>
<th>Age (Ma)</th>
<th>Chron</th>
<th>Position from Top Chron</th>
</tr>
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<tbody>
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<td>T</td>
<td>Discoaster saipanensis</td>
<td>CNE21</td>
<td>ODP 1218</td>
<td>Blaj et al. 2009</td>
<td>ODP1218A-24X-4.65</td>
<td>ODP1218A-24X-4.77</td>
<td>Pälike et al. 2006</td>
<td>34.44</td>
<td>C13r</td>
<td>n/a</td>
</tr>
<tr>
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<td>Discoaster barbadiensis</td>
<td>ODP 1218</td>
<td>Blaj et al. 2009</td>
<td></td>
<td></td>
<td></td>
<td>Pälike et al. 2006</td>
<td>34.77</td>
<td>C13r</td>
<td>n/a</td>
</tr>
<tr>
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<td>Cribrocentrum reticulatum</td>
<td>CNE20</td>
<td>DSDP522*</td>
<td>Backman 1987</td>
<td>ODP1218A-24X-4.65</td>
<td>ODP1218A-24X-4.77</td>
<td>Pälike et al. 2006</td>
<td>35.24</td>
<td>C15n</td>
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<td>ODP 1052</td>
<td>Fornaciari et al. 2010</td>
<td></td>
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<td></td>
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<td>36.13</td>
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<td>Fornaciari et al. 2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>36.84</td>
<td>C17n.1n</td>
<td>0.20</td>
</tr>
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<td>CNE18</td>
<td>ODP 1052</td>
<td>Fornaciari et al. 2010</td>
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<td>Fornaciari et al. 2010</td>
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<td>ODP 1051</td>
<td>This study</td>
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<td>40.34</td>
<td>C18n.1n</td>
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<td>ODP 1051</td>
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<td>40.51</td>
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<td>Possagno</td>
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<td>0.93</td>
</tr>
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<td>Possagno</td>
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<td>Possagno</td>
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<td></td>
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<td>C18r</td>
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</tr>
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<td>Discoaster multiradiatus</td>
<td>CNE5</td>
<td>Possagno</td>
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<td></td>
<td></td>
<td>54.66</td>
<td>C18r</td>
<td>0.93</td>
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</table>

**Name:** Zone CNE3 – *Tribrachiatus orthostylus* Base Zone  
**Definition:** Interval from Base *Tribrachiatus orthostylus* to Base common *Discoaster lodoensis*  
**Reference sections:** ODP Site 1262 and Tethyan Cicogna section (46.06° N, 12.24° E)  
Base zone: ODP 1262B-13H-4, 2 cm to 1262B-13H-4, 23 cm  
Top zone: Cicogna (Dallanave et al. 2009, Position 71.10 ± 0.10 m)  
**Estimated age:** 53.67 Ma−52.64 Ma (Figs. 8−10, Table 2, Plate 2)  
**Duration:** 1.03 Myr  
**Remarks:** Zone CNE3 corresponds to the uppermost part of Zone NP10 and Zone NP11, and to uppermost Subzone CP9a and Subzone CP9b. We prefer not to use Top *T. contortus*, which defines the base of Zones NP11 and CP9b, because this taxon is often rare or missing. The appearance of *T. orthostylus* is characterized by higher abundances and occurs concomitantly with the decrease of *T. contortus* (Agnini et al. 2007a).  
**Remarks on assemblages:** Base *Sphenolithus radians* occurs in the lowermost part of Zone CNE3, and is close to Base *T. orthostylus* in the Pacific, Atlantic and Indian oceans as well as in the western Tethys (Raffi et al. 2005, Agnini et al. 2006, 2007a, Shamrock and Watkins 2012). *Discoaster multiradiatus* shows a sharp decrease in abundance in lowermost Zone CNE3, followed by an interval of absence that precedes the final tail of its range within Chron C24n.3n. This final, multiple stepped, abundance pattern of *D. multiradiatus* has been observed at middle latitudes in the Atlantic Ocean and the Tethyan realm, and in the paleoequatorial Pacific Ocean (Agnini et al. 2006, 2007a, Dickens and Backman 2013) and may explain the large inconsistencies in previous calibrations (Backman 1986, Berggren et al. 1995) of Base common *D. lodoensis*, which is used to define the base of Zones NP12 and CP10, respectively. Given this peculiar abundance pattern of *D. lodoensis*, we propose to use Base common *D. lodoensis* as the Zone CNE3/CNE4 boundary. *Girgisia gamma-tion*, a taxon with a modified *Toweous*-type structure (Varol 1989), has its first occurrence in Zone CNE3, virtually in coincidence with Base *D. lodoensis*. Moreover, the genus *Chiphragmalithus* appears and evolves in Zone CNE3 through morphological modifications from *Neococcolithes* (Perch-Nielsen 1985, Agnini et al. 2007a).

**Name:** Zone CNE4 – *Discoaster lodoensis/Tribrachiatus orthostylus* Concurrent Range Zone  
**Definition:** Interval from Base common *Discoaster lodoensis* to Top *Tribrachiatus orthostylus*  
**Reference sections:** Tethyan Cicogna (46.06° N, 12.24° E) and Possagno (45° 51’ 5 N, 11° 51’ 31 E) sections  
Base zone: Cicogna (Dallanave et al. 2009, Position 71.10 ± 0.10 m)  
Top zone: Possagno (Agnini et al. 2006, Position 20.90 ± 0.10 m)  
**Estimated age:** 52.64 Ma−50.66 Ma (Figs. 8−11, Table 2, Plate 2)  
**Duration:** 1.98 Myr  
**Remarks:** Zone CNE4 corresponds to Zone NP12, and Zone CP10 through lowermost Zone CP11.  
**Remarks on assemblages:** Circular specimens of *Chiphragmalithus* show a sharp brief increase in abundance in the lower part of Zone CNE4. *Discoaster lodoensis* is common and continuous throughout Zone CNE4, showing variability in terms of size and number of rays. *Discoaster kuepperi* is the dominant species among discoasters, displaying high abundances especially in the upper part of Zone CNE4. Base *C. crassus*, which defines the base of Zone CP11, generally occurs in upper Zone CNE4, slightly preceding Top *T. orthostylus* (Bukry 1971, Agnini et al. 2006, Shamrock and Watkins 2012) in upper Chron C23n (Agnini et al. 2006, Coccioni et al. 2012). *Toweous* spp. decreases sharply in abundance in upper Zone CNE4 before becoming extinct at the top of Zone CNE4. This is an important change in the assemblages which correlates with the first entry of rare and spo-

Name: Zone CNE 5 – Reticulofenestra dictyoda Partial Range Zone
Definition: Interval from Top Trirachiatius orthostylus to Base Discoaster sublodoensis (5-rayed morphotype)
Reference section: Tethyan Possagno section (45° 51′ 5 N, 11° 51′ 31 E)
Base zone: Possagno (Agnini et al. 2006, Position 20.90 ± 0.10 m)
Top zone: Possagno (Agnini et al. 2006, Position 32.90 ± 0.10 m)
Estimated age: 50.66 Ma–49.96 Ma (Figs. 8, 11, Table 2, Plate 2)
Duration: 1.70 Myr
Remarks: Zone CNE5 corresponds to Zone NP13 and to most of Zone CP11, except for its lowermost part.
Remarks on assemblages: The turnover in abundance between Prinsiaceae (Toweius) and Noelaerhabdaceae (Dictyococcites and Reticulofenestra) represents a major and permanent modification in Cenozoic calcareous nannofossil assemblages. This change occurred over three phases, spanning the interval from upper Zone CNE4 to lower Zone CNE5 (Aubry 1998, Bown et al. 2004, Agnini et al. 2006, Schneider et al. 2011, Shamrock and Watkins 2012, Coccioni et al. 2012). The first phase is characterized by a dominance of Toweius in upper Zone CNE4. The second phase shows a sharp decrease in abundance of Toweius concomitantly with the first and sporadic entry of members of the Noelaerhabdaceae family (Reticulofenestra/Dictyococcites) in uppermost Zone CNE4. In the final phase, the transition between Toweius and Reticulofenestra/Dictyococcites is completed following the extinction of Toweius (Agnini et al. 2006) in Zone CNE5.

Name: Zone CNE 6 – Discoaster sublodoensis/Discoaster lodoensis Concurrent Range Zone
Definition: Interval from Base Discoaster sublodoensis (5-rayed) to Top Discoaster lodoensis
Reference section: Tethyan Possagno section (45° 51′ 5 N, 11° 51′ 31 E)
Base zone: Possagno (Agnini et al. 2006, Position 32.90 ± 0.10 m)
Top zone: Possagno (Agnini et al. 2006, Position 39.50 ± 0.50 m)
Estimated age: 48.96 Ma–48.37 Ma (Figs. 8, 11, Table 2, Plate 2)
Duration: 0.59 Myr
Remarks: Zone CNE6 corresponds to lower Zone NP14 and to most of Subzone CP12a. Although the recognition of Base D. sublodoensis may be problematic (see taxonomic notes), this biohorizon is used as a biozone boundary marker due to the lack of other more reliable biohorizons in this part of the calcareous nannofossil biostratigraphic column.
Remarks on assemblages: Reticulofenestra and Dictyococcites become the major components of the assemblages within Zone CNE6. Coccolithus crassus disappears in the uppermost part, just predating Top D. lodoensis (Agnini et al. 2006, Shamrock and Watkins 2012).

Name: Zone CNE 7 – Discoaster barbadiensis Partial Range Zone
Definition: Interval from Top Discoaster lodoensis to Base Nannotetrina cristata
Reference section: Tethyan Possagno section (45° 51′ 5 N, 11° 51′ 31 E)
Base zone: Possagno (Agnini et al. 2006, Position 39.50 ± 0.50 m)
Top zone: Possagno (Agnini et al. 2006, Position 43.70 ± 0.10 m)
Estimated age: 48.37 Ma–47.99 Ma (Figs. 8, 11, Table 2, Plate 2)
Duration: 0.38 Myr
Remarks: This zone corresponds to middle Zone NP14 and upper Subzone CP12a.
Remarks on assemblages: Calcareous nannofossil assemblages show several changes in the relatively short Zone CNE7. Base Pseudotriquetrorhabdulus inversus occurs in its lower part, close to Top D. lodoensis (Backman 1986). Chiphragmalithus acanthodes occurs over a short interval shortly above the extinction of D. lodoensis, slightly preceding Base Nannotetrisn spp. (Backman 1986, Agnini et al. 2006). The appearance of Blackites inflatus, used to mark the base of Zone CP12b and to approximate the GSSP of the base of Lutetian Stage (Molina et al. 2011), occurs virtually in coincidence with Base Nannotetrisn spp. at some locations (Larrasoainia et al. 2008, Molina et al. 2011, Norris et al. 2014).

Name: Zone CNE 8 – Nannotetris cristata Base Zone
Definition: Interval from Base Nannotetris cristata to Base Nannotetris alata group
Reference section: Tethyan Possagno section (45° 51’ 5 N, 11° 51’ 31 E)
Base zone: Possagno (Agnini et al. 2006, Position 43.70 ± 0.10 m)
Top zone: Possagno (Agnini et al. 2006, Position 55.90 ± 0.10 m)
Estimated age: 47.99 Ma–46.80 Ma (Figs. 8, 11, Table 2, Plate 2)
Duration: 1.19 Myr
Remarks: Zone CNE8 corresponds to upper Zone NP14 and to Subzone CP12b. Base *N. cristata* is preferred as a biozone boundary marker over Base *Blackites inflatus* because the former taxon, although relatively rare, is present in a wide range of depositional settings and is easy to recognize even in poorly preserved calcareous nannofossil assemblages. In contrast, *B. inflatus* is generally reported to be abundant in shallow-water to hemipelagic settings but is not observed in truly pelagic settings or in poorly preserved assemblages.

Remarks on assemblages: When present in the same succession, Base *B. inflatus* and Base *N. cristata/Nannotetrina* spp. occur close to each other. Available calibrations for these two biohorizons are not consistent, ranging from the middle part of Chron C21r (Larrea-soña et al. 2008, Molina et al. 2011, Gradstein et al. 2012) to the Chron C21r/C21n transition (Backman 1986, Agnini et al. 2006, Norris et al. 2014). The appearance of *S. spiniger* occurs in upper part of Zone CNE8 (Perch-Nielsen 1985, Bown and Dunkley Jones 2012, Norris et al. 2014).

Name: Zone CNE9 – *Nannotetrina alata* group Base Zone
Definition: Interval from Base *Nannotetrina alata* group to Base *Chiasmolithus gigas*
Reference sections: Tethyan Possagno section (45° 51’ 5 N, 11° 51’ 31 E) and ODP Site 1051 (NW Atlantic, 30° 3.2’ N, 76° 21.5’ W, 1990 m WD)
Base zone: Possagno (Agnini et al. 2006, Position 55.90 ± 0.10 m)

<table>
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<tr>
<th>Age (Ma)</th>
<th>GPTS</th>
<th>Epoch</th>
<th>Stage</th>
<th>CALCAREOUS NANNOFOSSIL ZONES</th>
<th>BIOHORIZONS (primary and additional)</th>
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<td>T Sphenolithus furcatolithoides “B” (40.51)</td>
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Fig. 12. Blow-up of middle Eocene interval. Middle Eocene CN biozones and biohorizons are plotted versus the biozones of Martini (1971) and Okada and Bukry (1980). The Geomagnetic Polarity Time Scale (GPTS) are after Pälike et al. (2006), from the top of Chron C6Cn.3n (23.278 Ma), to the base of Chron C19n (41.510 Ma) in the middle Eocene, and after Cande and Kent (1995; CK95), from the top of Chron C20n (42.356 Ma) to the Cretaceous–Paleogene boundary (65.00 Ma).
**ODP Site 1051**

**Fig. 13.** Middle Eocene selected calcareous nannofossil abundance patterns from ODP Site 1051 (NW Atlantic). Calcareous nannofossil abundances (this study). Magnetostratigraphy is after Ogg and Bardot (2001) and Edgar et al. (2010).

Top zone: ODP 1051A-36X-CC, 28 cm to 1051A-37X-1, 120 cm  
**Estimated age:** 46.80 Ma–46.11 Ma (Figs. 8, 11–13, Table 2, Plates 2–3)  
**Duration:** 0.69 Myr  
**Remarks:** Zone CNE9 corresponds to lower Zone NP15 and to Subzone CP13a.  
**Remarks on assemblages:** *Sphenolithus perpendicu-laris* is the first species that occurs within the *S. perpendicu-laris* – *S. furcatolithoides* – *S. cuniculus* lineage in the basal part of Zone CNE9 (Shamrock 2010). Top *Discoaster sublodoensis* is observed in Zone CNE9 (Agnini et al. 2006). Specimens ascribable to *Nannotetra* are present throughout Zone CNE9, although in sporadic numbers (Fig. 13, Bukry 1973).

**Name:** Zone CNE10 – *Chiasmolithus gigas*  
**Definition:** Interval from Base *Chiasmolithus gigas* to Base common *Sphenolithus cuniculus*  
**Reference section:** ODP Site 1051 (NW Atlantic, 30° 3.2’ N, 76° 21.5’ W, 1990 m WD)  
Base zone: ODP 1051A-36X-CC, 28 cm to 1051A-37X-1, 120 cm  
Top zone: ODP 1051A-30X-1, 53 cm to 1051A-30X-2, 103 cm  
**Estimated age:** 46.11 Ma–44.64 Ma (Figs. 8, 12–13, Table 2, Plate 3)  

**Duration:** 1.47 Myr  
**Remarks:** This zone corresponds to middle Zone NP15 and lower-middle Subzone CP13b. It may be difficult to precisely determine Base *C. gigas* because of the presence of intermediate morphotypes between *C. gigas* and *C. mutatus* (sensu Bown 2005).  
**Remarks on assemblages:** The *S. perpendicu-laris* – *S. furcatolithoides* – *S. cuniculus* lineage continues to evolve within Zone CNE10, with Base *S. furcatoli-thoides* (morphotype A) appearing in lowermost Zone CNE10 and with a range that continues throughout Zone CNE10 (Shamrock 2010, Norris et al. 2014, this study).

**Name:** Zone CNE11 – *Sphenolithus cuniculus/Chiasmolithus gigas* Concurrent Range Zone  
**Definition:** Interval from Base common *Sphenolithus cuniculus* to Top *Chiasmolithus gigas*  
**Reference section:** ODP Site 1051 (NW Atlantic, 30° 3.2’ N, 76° 21.5’ W, 1990 m WD)  
Base zone: ODP 1051A-30X-1, 53 cm to 1051A-30X-2, 103 cm  
Top zone: ODP 1051A-27X-2, 145 cm to 1051A-27X-3, 45 cm  
**Estimated age:** 44.64–43.96 Ma (Figs. 8, 12–13, Table 2, Plate 3)  
**Duration:** 0.68 Myr
Remarks: Zone CNE11 corresponds to upper Zone NP15, and to upper Subzone CP13b. Top C. gigas may be difficult to determine precisely because of rare, sometimes scattered, occurrences of this taxon during the final part of its range.

Remarks on assemblages: Discoaster bifax may be sporadically present in upper Zone CNE11, in showing a short overlap in range with C. gigas. Base S. furcatolithoides (morphotype B) occurs in upper Zone CNE11. At Site 1051, Chiasmolithus gigas displays a first decline in abundance in the basal part of Zone CNE11 (middle part of Chron C20r) followed by a sporadic abundance up to its final extinction in the upper part of Chron C20r. Top C. gigas has an age estimate of 43.96 Ma in the NW Atlantic. Backman (1986) depicted a sharp decline of C. gigas at Site 527 (138.85 mbsf) in the SE Atlantic, which results in an age estimate of 43.95 Ma if extrapolating the sedimentation rate given by Chron C20n into uppermost Chron C20r using Chron C20n boundary data from Shackleton et al. (1984). These different patterns of extinction are possibly the result of different paleoenvironmental conditions in the two areas.
Name: Zone CNE12 – *Nannotetrina* spp. Partial Range Zone

Definition: Interval from Top *Chiasmolithus gigas* to Base common *Reticulofenestra umbilicus* (≥ 14 μm)

Reference section: ODP Site 1051 (NW Atlantic, 30° 3.2’ N, 76° 21.5’ W, 1990 m WD)

Base zone: ODP 1051A-27X-2, 145 cm to 1051A-27X-3, 45 cm
Top zone: ODP 1051B-22X-4, 78 cm to 1051B-22X-4, 140 cm

Estimated age: 43.96 Ma–43.06 Ma (Figs. 8, 12–13, Table 2, Plate 3)

Duration: 0.90 Myr

Remarks: Zone CNE12 corresponds to uppermost Zone NP15 and lowermost Zone NP16, and to Subzone CP13c. Martini (1971) employed the extinction of *Blackites gladius* to define Zone NP15/16 boundary (Martini 1971), a biohorizon considered to be correlative with Top *C. gigas* (Okada and Bukry 1980, Perch-Nielsen 1985, Martini and Müller 1986). Wei and Wise (1989) demonstrated that the extinction of *B. gladius* falls above Base *R. umbilicus* and Top *N. alata* group. This implies that Top *B. gladius* has a range that extends into Zone NP16 and perhaps also into lower Zone NP17, as discussed by Berggren and Aubry (1984).

Remarks on assemblages: *Discoaster bifax* becomes common and continuous in CNE12, concomitantly with the extinctions of the *N. alata* group and *S. cucullus*. Top *D. bifax* falls between Top *C. gigas* and Base common *R. umbilicus* (Perch-Nielsen 1985), that is, within Zone CNE12.

Name: Zone CNE13 – *Reticulofenestra umbilicus* Base Zone

Definition: Interval from Base common *Reticulofenestra umbilicus* to Base common *Cribrocentrum reticulatum*

Reference section: ODP Site 1051 (NW Atlantic, 30° 3.2’ N, 76° 21.5’ W, 1990 m WD)

Base zone: ODP 1051B-22X-4, 78 cm to 1051B-22X-4, 140 cm
Top zone: ODP 1051B-18X-4, 14 cm to 1051B-18X-4, 64 cm

Estimated age: 43.06 Ma–42.37 Ma (Figs. 8, 12–13, Table 2, Plate 3)

Duration: 0.69 Myr

Remarks: Zone CNE13 corresponds to lower Zone NP16, and to lower Subzone CP14a.

Remarks on assemblages: The use of a precise morphometric definition (≥ 14 μm) of *R. umbilicus* together with the use of the base of continuous and common concept, that is Base common rather than Base *R. umbilicus*, provides a biohorizon having a more consistent position with respect to magnetostratigra-

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**Plate 3.** Microphotographs of middle to late Eocene calcareous nannofossil index species from the ODP Sites 1051 and 1052. Scale bar 5 μm.

phy (Backman 1986, Backman and Hermelin 1986, Wei and Wise 1989, Fornaciari et al. 2010, Norris et al. 2014). If the very first occurrence of *R. umbilicus* would be used, its position would fall close to Top *C. gigas*, or even before Top *C. gigas*. Highly resolved semi-quantitative data are needed to determine Base common *R. umbilicus*.

**Name:** Zone CNE14 – *Cribrocentrum reticulatum*  
**Base Zone**

**Definition:** Interval from Base common *Cribrocentrum reticulatum* to Base *Dictyococcites bisectus*

**Reference section:** ODP Site 1051 (NW Atlantic, 30° 3.2′ N, 76° 21.5′ W, 1990 m WD)  
Base zone: ODP 1051B-18X-4, 14 cm to 1051B-18X-4, 64 cm  
Top zone: ODP 1051B-11X-2, 133 cm to 1051B-11X-3, 44 cm

**Estimated age:** 42.37 Ma–40.34 Ma (Figs. 8, 12–13, Table 2, Plate 3)

**Duration:** 2.03 Myr

**Remarks:** This zone corresponds to middle Zone NP16, and to middle Subzone CP14a. A sporadic occurrence of rare specimens ascribable to *C. reticulatum* has been observed in upper Zone CNE13, the common and continuous presence of this taxon thus represents a more reproducible biohorizon and is used here to define the base of Zone CNE14.

**Remarks on assemblages:** Base *D. hesslandii* occurs well below Zone CNE14 (Mita 2001, Larrasoaña et al. 2008, Fornaciari et al. 2010). This taxon, however, is generally absent in lower Zone CNE14 (Backman 1987), and shows a distinct increase in abundance (Bukry 1973, Monechi and Thierstein 1985, Backman 1987, Fornaciari et al. 2010, Agnini et al. 2011) in upper Zone CNE14, here referred to as Base common *D. hesslandii*. Top *S. fucatulithoides* (morphotype B) in uppermost Zone CNE14 slightly precedes both Base common *D. hesslandii* and Base *D. bisectus* (Fornaciari et al. 2010, Norris et al. 2014).

**Name:** Zone CNE15 – *Dictyococcites bisectus/Sphenolithus obtusus* Concurrent Range Zone  
**Definition:** Interval from Base *Dictyococcites bisectus* to Top *Sphenolithus obtusus*

**Reference sections:** ODP Site 1051 (NW Atlantic, 30° 3.2′ N, 76° 21.5′ W, 1990 m WD) and ODP Site 1052 (NW Atlantic, 29° 57.1 N, 76° 37.6 W, 1345 m WD)

![Fig. 14. Middle-late Eocene to Oligocene calcareous nannofossil abundance patterns from ODP Site 1052 (NW Atlantic) and DSDP 522* (SE Atlantic). Calcareous nannofossil abundances from Fornaciari et al. (2010) and Backman (1987). Magnetostratigraphy of ODP Site 1052 is after Ogg and Bardot (2001) and Pälike et al. (2001). The 600 kyr hiatus at ca. 113 rmcdf is based on cyclostratigraphic data of Pälike et al. (2001). Magnetostratigraphy of DSDP 522* is after Tauxe et al. (1984).](image-url)
Base zone: ODP 1051B-11X-2, 133 cm to 1051B-11X-3, 44 cm
Top zone: ODP 1052F-12H-3, 70 cm to 1052F-12H-3, 131 cm

**Estimated age:** 40.34 Ma – 38.47 Ma (Figs. 8, 12–14, Table 2, Plate 3)

**Duration:** 1.87 Myr

**Remarks:** Zone CNE15 corresponds to upper Zone NP16 and lower NP17, and to upper Subzone CP14a and lower CP14b. The strict taxonomic concept adopted in this study for distinguishing *D. bisectus* provides a more consistent position for the base of this taxon at low to middle latitude locations. At southern high latitudes this biohorizon seems to be located significantly higher, within Chron C17n.1n (Villa et al. 2008).

**Remarks on assemblages:** Top *Sphenolithus spiniger* occurs in lowermost Zone CNE15 (Proto Decima et al. 1975, Nocchi et al. 1988, Wei and Wise 1989, Okada 1990, Mita 2001, Fornaciari et al. 2010). More recent data show a prominent decrease of *S. spiniger* within Zone CNE15, followed by a tail of sporadic occurrences that eventually led to extinction of the species (Fornaciari et al. 2010). The prominent decrease of *S. spiniger* (= Top common) consistently occurs just below Base *S. obtusus* (Fornaciari et al. 2010). A sporadic occurrence of *S. predistentus* has been observed in Zone CNE15 (Perch-Nielsen 1985, Fornaciari et al. 2010, Toffanin et al. 2013). The first rare and sporadic specimens of *Chiasmolithus oamaruensis* occur in upper Zone CNE15 at southern high latitudes (Villa et al. 2008). Top *Chiasmolithus solitus* defines the base of Zones CP14b and NP17, respectively. The sporadic distribution in its uppermost range causes large differences in the relative position of this biohorizon, both with respect to the sequence of calcareous nanofossil biohorizons and magnetostratigraphy. The ranges of *C. oamaruensis* and *C. solitus* have been shown to overlap at southern high latitudes, thus invalidating the use of Base *C. oamaruensis* for defining the base of Zone NP18 (Marino and Flores 2002a, 2002b, Villa et al. 2008).

**Name:** Zone CNE16 – *Chiasmolithus grandis* Partial Range Zone

**Definition:** Interval from Top *Sphenolithus obtusus* to Base common *Cribrocentrum erbae*

**Reference section:** ODP Site 1052 (NW Atlantic, 29° 57.1 N, 76° 37.6 W, 1345 m WD)

Base zone: ODP 1052F-10H-2, 129 cm to 1052F-10H-3, 9 cm
Top zone: ODP 1052F-8H-5, 40 cm to 1052F-8H-5, 100 cm

**Estimated age:** 38.47 Ma – 37.88 Ma (Figs. 8, 14, Table 2, Plate 3)

**Duration:** 0.59 Myr

**Remarks:** Zone CNE16 broadly corresponds to upper Zone NP17, and to middle-upper Subzone CP14b.

**Remarks on assemblages:** *Chiasmolithus grandis* shows a first decrease in abundance within Zone CNE16 followed by a rare to sporadic occurrence up to its final presence usually observed in lowermost Zone CNE17. *Cribrocentrum erbae* is present throughout Zone CNE16 displaying rare abundances, which dramatically increase at the base of Zone CNE17.

**Name:** Zone CNE17 – *Cribrocentrum erbae* Total Range Zone

**Definition:** Interval from Base common *C. erbae* to Top common *Cribrocentrum erbae*

**Reference section:** ODP Site 1052 (NW Atlantic, 29° 57.1 N, 76° 37.6 W, 1345 m WD)

Base zone: ODP 1052F-10H-2, 129 cm to 1052F-10H-3, 9 cm
Top zone: ODP 1052F-8H-5, 40 cm to 1052F-8H-5, 100 cm

**Estimated age:** 37.88 Ma – 37.46 Ma (Figs. 8, 14, Table 2, Plate 3)

**Duration:** 0.42 Myr

**Remarks:** Zone CNE17 approximately corresponds to lower Zone NP18, and to uppermost Subzone CP14b and lowermost CP15a. *Cribrocentrum erbae* is characterized by a short interval of high abundances in both Atlantic and Tethyan sections (Fornaciari et al. 2010, Agnini et al. 2011, Norris et al. 2014). In this high abundance interval, *C. erbae* rises up to 20–50% of the total calcareous nanofossil assemblages. Following Fornaciari et al. (2010), we define Base common *C. erbae* as the initial increase from ≅ 1% to ≅ 5% of the total assemblage, and Top common as the decrease in abundance from ≅ 4% to ≅ 2% of the total assemblage.

**Remarks on assemblages:** Top *C. grandis* occurs within Zone CNE17. This taxon is generally rare, particularly in the uppermost part of its range. Top *C. grandis* is thus a problematic biohorizon. Base *C. oamaruensis* is used to define the Zone NP17/NP18 boundary, and has been used to approximate the onset of the Pribonian Stage (Berggren et al. 1995). They suggest that Base *C. oamaruensis* is consistently calibrated to within Chron C17n.1n (Percival 1984, Poore et al. 1984, Aubry 1992). The discontinuous and sporadic occurrences of *C. oamaruensis*, and demonstrated diachrony of its first appearance over latitudinal
distance (Wei and Wise 1992, Marino and Flores 2002a, 2002b, Villa et al. 2008, Fornaciari et al. 2010), however, indicate that this biohorizon is a poor guiding criterion for definition of a chronostratigraphic stage boundary.

**Name:** Zone CNE18 – *Isthmolithus recurvus* Partial Range Zone

**Definition:** Interval from Top common *Cribrocentrum erbae* to Base *Cribrocentrum isabellae*

**Reference section:** ODP Site 1052 (NW Atlantic, 29° 57.1 N, 76° 37.6 W, 1345 m WD)

**Base zone:** ODP 1052F-4H-4, 140 cm to 1052F-4H-5, 50 cm

**Top zone:** ODP 1052F-4H-4, 140 cm to 1052F-4H-5, 50 cm

**Estimated age:** 37.46 Ma–36.13 Ma (Figs. 8, 14–15, Table 2, Plate 3)

**Duration:** 1.33 Myr

**Remarks:** Zone CNE18 corresponds to Zone NP18 and to the lower and undifferentiated Zone NP19/20, and to upper Subzone CP15a and lower CP15b.


**Name:** Zone CNE19 – *Cribrocentrum isabellae/ Cribrocentrum reticulatum* Concurrent Range Zone

**Definition:** Interval from Base *Cribrocentrum isabellae* to Top *Cribrocentrum reticulatum*

**Reference sections:** ODP Site 1052 (NW Atlantic, 29° 57.1 N, 76° 37.6 W, 1345 m WD) and DSDP Site 522 (SE Atlantic, 26° 06.84 S, 05° 07.78 W, 4441 m WD)

**Base zone:** ODP 1052F-4H-4, 140 cm to 1052F-4H-5, 50 cm

**Top zone:** DSDP 522*-29H-3, 80 cm to 522*-30H-1, 20 cm

**Estimated age:** 36.13 Ma–35.24 Ma (Figs. 8, 14–15, Table 2, Plate 3)

**Duration:** 0.89 Myr

**Remarks:** Zone CNE19 approximately corresponds to the middle undifferentiated Zone NP19/NP20, and to middle Subzone CP15b. Martini (1976) proposed to combine Zones NP19 and NP20 into a single undifferentiated interval between Top *C. grandis* and Top *D. saipanensis*. Subsequently, Aubry (1983) provided an alternative definition for this undifferentiated zone as the interval between Base *I. recurvus* and Top *D. saipanensis*. It is thus commonly accepted that Zones NP19 and NP20 of Martini (1971) should be combined because Base *Sphenolithus pseudoradians* is considered unreliable, either for the difficulty in distinguishing larger specimens of *S. radians* from primitive forms of *S. pseudoradians* at the base of Zone NP20 or for the inconsistent stratigraphic ranges recorded for *S. pseudoradians* in different areas (Perch-Nielsen 1985, Gradstein et al. 2012). Here we propose to use Top *C. reticulatum* for subdivision of the long stratigraphic interval between Base *C. isabellae* and Top *D. saipanensis*.


**Name:** Zone CNE20 – *Discoaster saipanensis* Top Zone

**Definition:** Interval from Top *Cribrocentrum reticulatum* to Top *Discoaster saipanensis*

**Reference section:** DSDP Site 522 (SE Atlantic, 26° 06.84 S, 05° 07.78 W, 4441 m WD) and ODP Site 1218 (Pacific Ocean, 8° 53.38 N, 135° 22.0 W, 4826 m WD)

**Base zone:** DSDP 522*-29H-3, 80 cm to 522*-30H-1, 20 cm

**Top zone:** ODP 1218A-24X-4, 65 cm to 1218A-25X-4, 77 cm
Estimated age: 35.24 Ma–34.44 Ma (Figs. 8, 14–16, Table 2, Plate 3)
Duration: 0.80 Myr

Remarks on assemblages: The extinction of Discoaster saipanensis marks the base of Zone NP21, whereas the extinctions of both D. saipanensis and D. barbadiensis mark the base of Subzone CP16a. Top D. barbadiensis falls below Top D. saipanensis at low and middle latitudes (Poore et al. 1984, Backman 1986, Wei and Wise 1989), within Chron C13r. The disappearance of these rosette-shaped discoasters occurs at about 40 Ma in higher latitude environments (Wei and Wise 1990, Wei and Thierstein 1991, Arney and Wise 2003, Persico and Villa 2004, Villa et al. 2008, Fioroni et al. 2012), and at about 34.5 Ma in low and middle latitude settings (Berggren et al. 1995).

Name: Zone CNE21 – Helicosphaera compacta Partial Range Zone
Definition: Interval from Top Discoaster saipanensis to Base common Clausicoccus subdistichus
Reference sections: ODP Site 1218 (Pacific Ocean, 8° 53.38 N, 135° 22.0 W, 4826 m WD) and DSDP Site 522 (SE Atlantic, 26° 06.84 S, 05° 07.78 W, 4441 m WD)
Base zone: ODP 1218A-24X-4, 65 cm to 1218A-25X-4, 77 cm
Top zone: DSDP 522*-35H-2, 80 cm to 522*-35H-2, 100 cm
Estimated age: 34.44 Ma–33.88 Ma (Figs. 8, 14–16, Table 2, Plates 3–4)
Duration: 0.56 Myr
Remarks: Zone CNE21 corresponds to lower Zone NP21 and to lower Subzone CP16a. This zone straddles the Eocene/Oligocene boundary.
Remarks on assemblages: Following the demise of the rosette-shaped discoasters in the uppermost Eocene, the Discoaster assemblages are represented by a few species across the Eocene/Oligocene boundary that continue throughout the Oligocene. These include D. deﬂandrei, Discoaster nodifer and Discoaster tanii. Other species such as Chiasmolithus altus, Helicosphaera compacta and Helicosphaera reticulata persist from the uppermost Eocene.

6. Oligocene

6.1 Remarks on Oligocene taxonomy
All biozone boundary marker species are illustrated in Plate 4. The taxonomic concepts adopted here are based on the following observations:

Ericsonia: The genus Ericsonia was introduced by Black (1964) for “circular and elliptical coccoliths with a well-deﬁned central opening . . .”. Its taxonomic status has been discussed and questioned (www.nanotax.org). Romain (1979) stated that “Strictly speaking, Ericsonia is a junior synonym of Coccolithus”. Yet, he suggested to retain the name in order “to avoid the ‘loaded’ name Coccolithus”, and recombined Cyclcoccolithus formosus Kämpfner to Ericsonia formosa. We adopt Romain’s strategy, in order to maintain taxonomic stability and since E. formosa is a well-established and much used concept in lower Oligocene biostratigraphy.

Clausiococcus: Some species previously included in, for example, the genera Ericsonia or Coccolithus, were recombined into the genus Clausicoccus by Prins (1979). Among these are the Paleogene species Clau sicoccus subdistichus, Clau sicoccus obrutus, Clau sicoccus fenestratus and Clau sicoccus vanheckiae. Bukry (1973) observed that overgrown specimens of C(occ lithus) fenestratus, C.obrutus and C.sub distichus may be virtually indistinguishable in openocean sediments. Clau sicoccus obrutus is considered to be a junior synonym of C. subdistichus (www.nanotax.org). The former is here included in the C. sub distichus concept.

6.2 Biozone deﬁnitions in the Oligocene interval
The deﬁnitions of the CNO biozones are summarized in Table 3. An overview of the CNO biozonation in a chronostratigraphic context, and comparison with the CP Oligocene zonation of Okada and Bukry (1980) and NP Oligocene zonation of Martini (1971), is
shown in Figure 15. Figure 16 shows the abundances of biozone boundary markers across the Eocene/Oligocene transition and up through the Oligocene from ODP Site 1218, plus their direct correlation with magnetostratigraphy.

Name: Zone CNO1 – *Ericsonia formosa/Clausicoccus subdistichus* Concurrent Range Zone

Definition: Interval from Base common *Clausicoccus subdistichus* to Top *Ericsonia formosa*

Reference sections: DSDP Site 522 (SW Atlantic, 26° 06.84 S, 05° 07.78 W, 4441 m WD) and ODP Site 1218 (Pacific Ocean, 8° 53.38 N, 135° 22.0 W, 4826 m WD)

Base zone: DSDP 522*-35H-2, 80 cm to 522*-35H-2, 100 cm

Top zone: ODP 1218A-23X-2, 105 cm to 1218A-23X-2, 115 cm

Estimated age: 33.88 Ma–32.92 Ma (Figs. 15–16, Table 3, Plate 4)

Duration: 0.96 Myr

Remarks: Zone CNO1 corresponds to upper Zone NP21 and upper Subzone CP16a and CP16b. Bukry (1973) used the end of an “acme” interval of *C. sub-
distichus to define Top Subzone CP16a. He placed Top common C. subdistichus within the range of E. formosa. Subsequent work has shown that Top common C. subdistichus vary with geographic location (Catanzariti et al. 1997, Toffanin et al. 2013). Backman (1987) noticed a sharp increase in abundance of C. subdistichus (referred to as C. obruta) shortly after the Eocene/Oligocene boundary from DSDP Sites 522 and 523 in the SE Atlantic. This increase in abundance has been observed from several other sections shortly above the Eocene/Oligocene boundary within Subzone CP16a: Southern Ocean (Marino and Flores 2002b), Tethyan region (Coccioni et al. 1988, Hyland et al. 2009), NW Atlantic (Norris et al. 2014) and equatorial Pacific (Toffanin et al. 2013). Base common C. subdistichus is here adopted to define the onset of Zone CNO1.

Remarks on assemblages: Istmolithus recurvus shows rare and scattered occurrences up to its disappearance. Cyclicargolithus floridanus is a major component of the assemblages together with Dictyococ- cites hesslandii, Dictyococites bisectus and Reti- culofenestra dictyoda. Sphenolithus predistentus is present in Zone CNO1, and the appearance of Sphe- nolithus akropodus has been observed in the Indian, the middle latitude Atlantic and Tethy- an deep-sea sec- tions (Okada 1990, de Kaenel and Villa 1996, Maiorana and Monechi 2006).

Name: Zone CNO2 – Reticulofenestra umbilicus Top Zone
Definition: Interval from Top Ericsonia formosa to Top Reticulofenestra umbilicus
Reference section: ODP Site 1218 (Pacific Ocean, 8° 53.38 N, 135° 22.0 W, 4826 m WD)
Base zone: ODP 1218A-23X-2, 105 cm to 1218A-23X-2, 115 cm
Top zone: ODP 1218C-15X-4, 77 cm to 1218B-22X-1, 96 cm
Estimated age: 32.92 Ma–32.02 Ma (Figs. 15–16, Table 3, Plate 4)
Duration: 0.90 Myr
Remarks: Zone CNO2 corresponds to Zone NP22 and Subzone CP16c.

Remarks on assemblages: Specimens of the Cyclicargolithus floridanus/Cyclicargolithus abisectus group (<10 μm) are common in Zone CNO2, together with Chiasmolithus altus that represents the last representative of the genus to enter the stratigraphic record. Helicosphaera reticulata gradually disappears in upper CNO2, and the first rare specimens of Helicosphaera recta are recorded in North Atlantic (de

Plate 4. Microphotographs of late Eocene to Oligocene calcareous nanofossil index species from the ODP Site 1218. Scale bar 5 μm.
Kaenel and Villa (1996) and Tethyan sections (Catanzariti et al. 1997). Other Helicosphaera species present in the zone are Helicosphaera euphratis, Helicosphaera bramlettei, Helicosphaera compacta, rare Helicosphaera wilcoxonii and Helicosphaera perchnielseniae.

Name: Zone CNO3 – Dictyococcites bisectus Partial Range Zone
Definition: Interval from Top Reticulofenestra umbilicus to Base Sphenolithus distentus
Reference section: ODP Site 1218 (Pacific Ocean, 8° 53.38 N, 135° 22.0 W, 4826 m WD)
Base zone: ODP 1218C-15X-4, 77 cm to 1218B-22X-1, 96 cm
Top zone: ODP 1218A-19H-2, 44 cm to 1218A-19H-2, 53 cm
Estimated age: 32.02 Ma – 30.00 Ma (Figs. 15–16, Table 3, Plate 4)
Duration: 2.02 Myr
Remarks: Zone CNO3 corresponds to lower Zone NP23, and to Zone CP17.
Remarks on assemblages: Sphenolithus akropodus disappears in upper Zone CNO3 (Maiorano and Monechi 2006). Large specimens of C. abisectus (> 10 μm) begin to occur (Bukry 1973, Fornaciari et al. 1990) in upper Zone CNO3. This zone also may hold rare specimens showing an intermediate morphology between S. predistentus and S. distentus. These intergrading morphotypes occurs before genuine S. distentus are established. Helicosphaerids are represented by H. compacta and discontinuous and rare H. recta.

Name: Zone CNO4 – Sphenolithus distentus/Sphenolithus predistentus Concurrent Range Zone
Definition: Interval from Base Sphenolithus distentus and the Top of Sphenolithus predistentus
Reference section: ODP Site 1218 (Pacific Ocean, 8° 53.38 N, 135° 22.0 W, 4826 m WD)
Base zone: ODP 1218A-19H-2, 44 cm to 1218A-19H-2, 53 cm
Top zone: ODP 1218A-14H-5, 95 cm to 1218A-14H-5, 105 cm
Estimated age: 30.00 Ma – 26.93 Ma (Figs. 15–16, Table 3, Plate 4)
Duration: 3.07 Myr
Remarks: Zone CNO4 encompasses upper Zone NP23 and most of Zone NP24, and Zone CP18 and most of Subzone CP19a. Differentiation of Zone NP24 and Subzone CP19a turned out to be inconsistent be-
cause the biohorizons used in both Martini’s and Okada and Bukry’s zonations, namely Base *Sphenolithus ciperoensis* and Top *S. distentus*, occur closely below and above the Top of *S. predistentus*.

**Remarks on assemblages:** *Helicosphaera compacta* disappears in upper Zone CNO4, large (> 10 μm) *C. abisectus* increases in abundance and *H. recta* is continuously present in the assemblages. Specimens with intermediate morphology between *S. ciperoensis* and *S. distentus* are present before the genuine *Sphe- nolithus ciperoensis* is established (Olafsson and Villa 1992, Blaj et al. 2009).

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**Fig. 15.** CN Oligocene biozones and biohorizons are plotted versus the biozonations of Martini (1971) and Okada and Bukry (1980). The Geomagnetic Polarity Time Scale (GPTS) is after Pälike et al. (2006). Grey boxes show the uncertainty in defining chronostratigraphic and biozone boundaries.
Fig. 16. Oligocene selected calcareous nannofossil abundance patterns from ODP Site 1218 (equatorial Pacific). Calcareous nannofossil abundances are after Blaj et al. (2009). Magnetostratigraphy is after Pälike et al. (2006).

Name: Zone CNO5 – *Sphenolithus ciperoensis* Top Zone

**Definition:** Interval from Top *Sphenolithus predistentus* to Top *Sphenolithus ciperoensis*

**Reference section:** ODP Site 1218 (Pacific Ocean, 8°53.38 N, 135°22.0 W, 4826 m WD)

Base zone: ODP 1218A-14H-5, 95 cm to 1218A-14H-5, 105 cm

Top zone: ODP 1218A-11H-2, 130 cm to 1218A-11H-3, 130 cm

**Estimated age:** 26.81 Ma–24.36 Ma (Figs. 15–16, Table 3, Plate 4)

**Duration:** 2.45 Myr

**Remarks:** This zone broadly corresponds to lower Zone NP25, and to Subzone CP19b.

**Remarks on assemblages:** Rare *Triquetrorhabdulus carinatus* is present in lower Zone CNO5 and subsequently increases in abundance, becoming a major component of the assemblages in upper Zone CNO5. The assemblages of Zone CNO5 are partly characterized by *Triquetrorhabdulus longus* (Blaj and Young 2010), referred to as *T. aff. carinatus* by Blaj et al. (2009). The distinct cross-over in abundance from dominant *T. longus* to dominant *T. carinatus* at 25.0 Ma (Blaj et al. 2009) may prove to be biostratigraphically useful in Atlantic and Pacific equatorial regions, where *S. ciperoensis* typically is rare towards the end of its range (Kroenke et al. 1991, p. 121, Curry et al. 1995, p. 164, Blaj et al. 2009), in contrast to the equatorial Indian Ocean (Fornaciari et al. 1990).

Name: Zone CNO6 – *Triquetrorhabdulus carinatus* Partial Range Zone

**Definition:** Interval from Top *Sphenolithus ciperoensis* to Top *Sphenolithus delphix*

**Reference section:** ODP Site 1218 (Pacific Ocean, 8°53.38 N, 135°22.0 W, 4826 m WD)

Base zone: ODP 1218A-11H-2, 130 cm to 1218A-11H-3, 130 cm

Top zone: ODP 1218B-10H-4, 140 cm to 1218B-10H-4, 150 cm

**Estimated age:** 24.36 Ma–23.06 Ma (Figs. 15–16, Table 3, Plate 4)

**Duration:** 1.3 Myr

**Remarks:** Zone CNO6 corresponds to upper Zone NP25 and lowermost Zone NN1, and to Subzone...
CN1a and lowermost Subzone CN1b. The set of biohorizons employed by Martini (1971) and Okada and Bukry (1980) for defining biozones across the Oligocene/Miocene transition is considered to be of limited value (Rio et al. 1990, Backman et al. 2012). Top *Sphenolithus delphix*, however, provides a distinct biohorizon occurring 30 kyr prior to the Oligocene/Miocene boundary.

**Remarks on assemblages:** The lower part of Zone CNO6 may show relatively high abundances of large (> 10 μm) *C. abisectus*. The *Sphenolithus* population is characterized by common *Sphenolithus dissimilis*, *Sphenolithus moriformis*, *Sphenolithus conicus*, *Sphenolithus delphix* and *Sphenolithus capricornatus*, the last two both having distinct short ranges. *Discoaster deflandrei* is common to abundant in upper Zone CNO6, and *Discoaster druggii* occurs sporadically in uppermost Zone CNO6 at some locations, for example, in the tropical Pacific and in the Tethyan region (Bukry 1973, Fornaciari and Rio 1996), whereas its first rare appearance falls above Top *S. delphix* in the tropical Indian Ocean (Rio et al. 1990).

**7. The new biozonation:**

**innovation and preservation, open problems and possible improvements**

The Paleocene represents an epoch that is bounded by two major global perturbations which severely affected marine and terrestrial biota, namely the mass extinction at the Cretaceous-Paleogene (K-Pg) boundary and the virtually concomitant hyperthermal event and major carbon isotope excursion at the Paleocene-Eocene (P-E) boundary. The Danian Stage represents the aftermath of the K-Pg mass extinction, when new taxa of calcareous nannoplankton evolved and relatively quickly became established and in some cases dominant in early Paleocene assemblages. These new taxa, such as species belonging to *Coccolithus*, *Praeprinsius* and *Prinsius*, are employed in our new biozonation.

**Fig. 17.** Duration of Paleogene CN biozones. The Time Scale adopted is based on Pälike et al. (2006), from the top of Chron C6Cn.3n (23.278 Ma), to the base of Chron C19n (41.510 Ma) in the middle Eocene, and on Cande and Kent (1995; CK95), from the top of Chron C20n (42.356 Ma) to the Cretaceous-Paleogene boundary (65.00 Ma).
The taxa employed here differ from the “standard” biozonation of Martini (1971) and that of Okada and Bukry (1980), who primarily used species belonging to the genera Cruciplacolithus and/or Chiasmolithus. The benefit of this strategy is at least two-fold. First, we avoid taxonomic problems affecting species of the genera Cruciplacolithus and Chiasmolithus. Second, the taxa chosen as biozone boundary markers rapidly increase in abundance and become a common component of the assemblages, thereby providing distinct biohorizons.

Some other novelties are introduced in the Paleocene biozonation. Three new biohorizons, Base S. moriformis, Base D. backmani and Top F. richardii group, are substituted approximately for the evolutionary first appearances of E. macelius, H. riedeli and T. bramletteei, all of which have proved to be biostratigraphically problematic. Furthermore, we have utilized the Base F./L. ulii, the first species appearing in the second radiation of the fasciculiths, and Base H. cantabriae, the first representative of the genus Heliolithus. These two biohorizons approximately replace Base F. tympaniformis and Base H. kleinpellii, because of presence of transitional morphotypes between F./L. ulii and F. tympaniformis on the one hand and H. cantabriae and H. kleinpellii on the other, that tend to blur precise positioning of the H. kleinpellii and F. tympaniformis biohorizons. All these changes result in a Paleocene biozonation composed of 11 zones (CNP1–CNP11) having an average resolution of 0.9 Myr/biozone.

The Eocene was a time of change. This epoch starts with the PETM, a prominent hyperthermal event occurring during the Cenozoic greenhouse climate regime (Kennett and Stott 1991), and ends at the onset of the icehouse climate regime, when the first major Antarctic ice-sheet develops (Zachos et al. 2001). This long transition is usually described as a period with relatively stable intervals interrupted by several episodes of climate instability. In this context, the Eocene biostratigraphic framework seems to mirror this large heterogeneity as it is characterized by phases with high evolutionary rates, thus potentially providing several useful biohorizons, and phases with lower evolutionary rates, where available biohorizons are few. For example, calcareous nannofossils offer a large number of potential biohorizons in the lower part of the Ypresian Stage, from Zone CNE1 to CNE3, as well as in the middle part of the Bartonian Stage, close to the Middle Eocene Climatic Optimum. In contrast, the number of useful biohorizons in the upper part of the Ypresian Stage, from Zone CNE4 to CNE6, is limited. This situation continues into the middle to upper part of the Eocene, from Zone CNE13 to CNE18. An additional issue involves the ambiguous taxonomy of some of the Eocene index species, including for example Coccolithus crassus, Discoaster sublodoensis, and Chiasmolithus gigas.

Overall, our strategy for the Eocene excluded, where possible, taxa either displaying sporadic abundance patterns or taxa that are based on a lower quality and/or limited datasets. For these reasons, we resolved not to use biohorizons that rely on species belonging to Chiasmolithus, that is C. solitus, C. grandis and C. oamaruensis, or Isthmolithus recurvus. These “classic” biohorizons have been replaced by species belonging to genus Cribrocentrum, C. reticulatum, C. erbae and C. isabellae, which, in contrast, are based on more robust abundances. Unfortunately, we have been obliged to continue to use some biohorizons, such as Base D. sublodoensis and Top C. gigas, although they show scattered abundance patterns, are based on a limited datasets and suffer from taxonomic drawbacks. This stems from the lack of better alternatives to these non-optimal biohorizons.

To summarize, the long Eocene Epoch consists mostly of well-studied intervals in which the biostratigraphic subdivisions are well established and considered relatively unproblematic. However, some Eocene intervals still suffer from a deficiency of good biohorizons, although improvements may be obtained in the future by means of high-resolution studies of critical intervals. For now the proposed Eocene biozonation consists of 21 biozones (CNE1–CNE21) with an average resolution of 1.0 Myr/biozone.

The Oligocene Epoch represents a crucial interval in the climate evolution of our planet that is constrained by two major global cooling events, the onset of the Southern Hemisphere glaciation at its base and a major expansion of ice on East Antarctica at its top (Mi1, Miller et al. 1991). The longest Oligocene biozone encompasses 3.07 Myr, which is 1.04 Myr longer than the longest Eocene biozone and 1.03 Myr longer than the longest Paleocene biozone. The longevity of these biozones, and particularly the Oligocene ones, represents a lack of useful biohorizons in low and middle latitude marine settings. Thus the 40+ years of effort that has been invested in Oligocene calcareous nannofossil biostratigraphy after Martini’s (1971) and Bukry’s (1973) Cenozoic biozonations were published have not resulted in an improved resolution. The underlying reason is the low rate of taxonomic evolution.
among the Oligocene calcareous nannofossil assemblages. In the present biozonation, the Oligocene is partitioned into 6 biozones (CNO1–CNO6) having an average duration of 1.8 Myr/biozone.

Biostratigraphy and biochronology are tightly connected, the former focuses on relative age dating of rocks/sediments based on biohorizons, the latter provides age estimations of these biohorizons. Two fundamental prerequisites are needed in order to improve the precision of the age calibrations of the biohorizons. The first is an unambiguous magnetostratigraphy in the same sediment section in which the biohorizons are determined. The second is presence of astronomically tuned cyclostratigraphic data, hopefully in sediment sections having adequate bio- and magnetostratigraphies from different areas. These conditions are still only rarely met.

An example of a reliable biohorizon is Base *D. multiradiatus*, which defines the base of Zone CNP11. The appearance of this taxon is consistently observed in the same relative position with respect to other surrounding biohorizons. What makes this biohorizon valid, however, is the multiple age calibrations available from different areas and/or depositional settings, which show a consistent position within Chron C25n (Backman 1986; Raffi et al. 2005; Müller 1985; Monechi et al. 1985; Agnini et al. 2007a). In contrast, the top of *C. gigas*, which defines the base of Zone CNE12, is an example of less reliable biohorizons due to the relatively low number of calibrations, the scarcity of the marker species close to the biohorizon, or remaining taxonomic ambiguities. Although it is clear that this does not represent an ideal biohorizon, we decided to use it in our biozonation because of the lack of good alternatives in the critical middle Eocene time interval.

The use of two different time scales (Cande and Kent 1995, Pälike et al. 2006) deserves a comment. One is based on magnetostratigraphy and the other on a fully tuned astronomical cyclostratigraphy. Only floating astrocyclostratigraphic chronologies are presently available for the early Paleogene, that is from the early Paleocene to the middle Eocene. What is needed are deep-sea sediment sections having biomagnetostratigraphies and anchored astrocyclochronologies. The present lack of such a fully anchored astronomical time scale will likely be solved in the near future with material from IODP Expedition 342 to the Newfoundland Ridge (Expedition 342 Scientists 2012, Norris et al. 2014), but for now the problem remains of unanchored Paleogene time intervals due to a gap in Chron C20r.

Many efforts have been undertaken and should be continued in the future to provide a comprehensive and integrated time scale for the entire Paleogene. This present problem could be particularly acute when we try to provide ages for calcareous nannofossil biohorizons using two different timescales. We need a firm Paleogene calcareous nannofossil biochronology.

### 8. Conclusions

We have presented a revised version of the Paleogene portion of the low to middle latitude calcareous nannofossil biozonations originally proposed by Martini (1971) and Okada and Bukry (1980). In this new biozonation, we employ several of the biohorizons previously suggested combined with a series of new biohorizons.

Our dataset consists of high-resolution biostratigraphic datums from the Atlantic and Pacific oceans and Tethyan region determined by semi-quantitative counts on sediments recovered by DSDP/ODP cores or sampled from on-land marine sections.

New early Paleocene and middle Eocene biostratigraphic data from ODP Sites 1262 and 1051 respectively are presented.

Age calibrations provided for calcareous nannofossil biohorizons are based either on magnetostratigraphies from the Paleocene to middle Eocene, or on astronomically tuned cyclostratigraphies from the middle Eocene to Oligocene.

In summary, we described thirty-eight (38) Paleogene biozones, which extend from the K-Pg boundary to the Oligo-Miocene boundary covering an interval of 42 Myr. The average duration for the biozones is of about 1.1 Myr, with a minimum duration of 0.9 Myr for the Paleocene and a maximum duration of 1.8 Myr for the Oligocene.

We propose a robust biostratigraphic scheme defined by a limited number of biohorizons. This method provides a more stable biozonation that avoids the introduction of subzones, however, several additional biohorizons are included within each biozone.

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Appendix

Taxonomic list: Taxa cited in the text are reported in alphabetical order.

**Biantholithus** Bramlette and Martini 1964
*Biantholithus sparsus* Bramlette and Martini 1964

**Blackites** Hay and Towe 1962
*Blackites inflatus* (Bramlette and Sullivan 1961) Kapellos and Schaub 1973
*Blackites gladius* (Locker 1967) Varol 1989

**Bomolithus** Roth 1973

**Braarudosphaera** Deflandre 1947
*Braarudosphaera bigelowi* (Gran and Braarud 1935) Deflandre 1947

**Campylosphaera** Kamptner 1963
*Campylosphaera eodela* Bukry and Percival 1971

**Chiasmolithus** Hay et al. 1966
*Chiasmolithus altus* Bukry and Percival 1971
*Chiasmolithus bidens* (Bramlette and Sullivan 1961) Hay and Mohler 1967
*Chiasmolithus edentulus* van Heck and Prins 1987
*Chiasmolithus gigas* (Bramlette and Sullivan 1961) Radomski 1968
*Chiasmolithus grandis* (Bramlette and Riedel 1954) Radomski 1968
*Chiasmolithus mutatus* Perch-Nielsen 1971
*Chiasmolithus notus* Perch-Nielsen 1977
*Chiasmolithus oamaruensis* (Deflandre 1954) Hay et al. 1966
*Chiasmolithus solitus* (Bramlette and Sullivan 1961) Locker 1968

**Chiphragmalithus** Bramlette and Sullivan 1961
*Chiphragmalithus acanthoides* Bramlette and Sullivan 1961
*Chiphragmalithus calathus* Bramlette and Sullivan 1961

**Clausicoccus** Prins 1979
*Clausicoccus subdistichus* (Roth and Hay in Hay et al. 1967) Prins 1979
*Clausicoccus fenestratus* (Deflandre and Fert 1954) Prins 1979
*Clausicoccus obtusus* (Perch-Nielsen 1971) Prins 1979
*Clausicoccus vanheckiae* (Perch-Nielsen 1986)

**Coccolithus** Schwartz 1894
*Coccolithus pelagicus* (Wallich 1877) Schiller 1930
*Coccolithus crassus* Bramlette and Sullivan 1961

**Cripbrocentrum** Perch-Nielsen 1971
*Cripbrocentrum erbae* Fornaciari et al. in Fornaciari et al. 2010
*Cripbrocentrum isabellae* Catanzariti et al. in Fornaciari et al. 2010
*Cripbrocentrum reticulatum* (Gartner and Smith 1967) Perch-Nielsen 1971

**Cruciplacolithus** Hay and Mohler in Hay et al. 1967
*Cruciplacolithus asymmetricus* van Heck and Prins 1987
*Cruciplacolithus danicus* (Brotzen 1959) van Heck and Perch-Nielsen 1987
*Cruciplacolithus intermedius* van Heck and Prins 1987
*Cruciplacolithus edwardsii* Romein 1979
*Cruciplacolithus primus* Perch-Nielsen 1977
*Cruciplacolithus tenuis* (Stradner 1961) Hay and Mohler in Hay et al. 1967

**Cyclagelosphaera** Noël 1965
*Cyclagelosphaera alta* Perch-Nielsen 1979
*Cyclagelosphaera reinhardtii* (Perch-Nielsen 1968) Romein 1977

**Cyclicargolithus** Bukry 1971
*Cyclicargolithus floridanus* (Roth and Hay in Hay et al. 1967) Bukry 1971

**Dictyococites** Black 1967
*Dictyococites bisectus* (Hay et al. 1966) Bukry and Percival 1971

**Discoaster** Tan 1927
*Discoaster anartios* Bybell and Self-Trail 1995
*Discoaster areneus* Bukry 1971
*Discoaster backmanii* Agnini et al. 2008
*Discoaster barbadiensis* Tan 1927
*Discoaster bifux* Bukry 1971
*Discoaster deflandrei* Bramlette and Riedel 1954
*Discoaster druggii* Bramlette and Wilcoxon 1967
*Discoaster diastypus* Bramlette and Sullivan 1961
Discoaster kuepperi Stradner 1959
Discoaster lodoensis Bramlette and Sullivan 1961
Discoaster mohleri Bramlette and Percival 1971
Discoaster multiradiatus Bramlette and Riedel 1954
Discoaster nodifer (Bramlette and Riedel 1954)
Bukry 1973
Discoaster okadai Bukry 1981
Discoaster saipanensis Bramlette and Riedel 1954
Discoaster sublodoensis Bramlette and Sullivan 1961
Discoaster tanii Bramlette and Riedel 1954

Ellipsolithus Sullivan 1964
Ellipsolithus macellus (Bramlette and Sullivan 1961)
Sullivan 1964

Ericsonia Black (1964)
Ericsonia formosa (Kamptner 1963) Haq 1971
Ericsonia robusta (Bramlette and Sullivan 1961)
Edwards and Perch-Nielsen 1975

Fasciculithus Bramlette and Sullivan 1961
Fasciculithus alanii Perch-Nielsen 1971
Fasciculithus chowii Varol 1989
Fasciculithus clinatus Bukry 1971
Fasciculithus hayi Haq 1971
Fasciculithus involutus Bramlette and Sullivan 1961
Fasciculithus lilianae Perch-Nielsen 1971
Fasciculithus magnicordis Romein 1979
Fasciculithus magnus Bukry and Percival 1971
Fasciculithus mitreus Gartner 1971
Fasciculithus pileatus Bukry 1973
Fasciculithus richardii Perch-Nielsen 1971
Fasciculithus schaubii Hay and Mohler 1967
Fasciculithus tonii Perch-Nielsen 1971
Fasciculithus tympaniformis Hay and Mohler in Hay et al. 1967
Fasciculithus ulii Perch-Nielsen 1971
Fasciculithus varolii Steurbaut and Sztràkos 2007

Futyania Varol 1989
Futyania petalosa (Ellis and Lohmann 1973) Varol 1989

Girgisia Varol 1989
Girgisia gammatia (Bramlette and Sullivan 1961)
Varol 1989

Gomphiolithus Aubry et al. 2011

Helicosphaera Kamptner 1954
Helicosphaera bramlettei Müller 1970

Helicosphaera compacta Bramlette and Wilcoxon 1967
Helicosphaera euphratis Haq 1966
Helicosphaera perch-nielseniae Haq 1971
Helicosphaera recta (Haq,1966) Jafar and Martini, 1975
Helicosphaera reticulata Bramlette and Wilcoxon 1967
Helicosphaera wilcoxonii Gartner 1971

Heliolithus Bramlette and Sullivan 1961
Heliolithus bukryi Wei, 1988
Heliolithus cantabrieae Perch-Nielsen 1971
Heliolithus kleinpellii Sullivan 1964
Heliolithus riedelii Bramlette and Sullivan 1961

Istholithus Deflandre 1954
Istholithus recurvus Deflandre 1954

Lithoptychius Aubry et al. 2011

Micula Vekshina 1959
Micula murus (Martini 1961) Bukry 1973
Micula prinsii (Perch-Nielsen 1979)

Nannotetrella Achuthan and Stradner 1969
Nannotetrella alata (Martini in Martini and Stradner 1960) Haq and Lohmann 1976
Nannotetrella cristata (Martini 1958) Perch-Nielsen 1971
Nannotetrella fulgens (Stradner in Martini and Stradner 1960) Achuthan and Stradner 1969

Neobiscutum Varol 1989
Neobiscutum parvulum (Romein 1979) Varol 1989

Neococcolithes Sujkowski 1931

Octolithus Romein 1979
Octolithus multiplus (Perch-Nielsen 1973) Romein 1979

Praeprinsius Varol and Jakubowski 1989
Praeprinsius dimorphosus (Perch-Nielsen 1981)
Varol and Jakubowski 1989
Praeprinsius tenuiculus (Okada and Thierstein, 1979)
Varol and Jakubowski 1989

Prinsius Hay and Mohler 1967
Prinsius bisulcus (Stradner 1963) Hay and Mohler 1967

Pseudotriquetrorhabdulus Wise in Wise and Constansts 1976
Pseudotriquetrorhabdulus inversus (Bukry and Bramlette 1969) Wise in Wise and Constansts 1976

Reticulofenestra Hay et al. 1966
Reticulofenestra dictyoda Deflandre in Deflandre and Fert 1954
Reticulofenestra umbilicus (Levin 1965) Martini and Ritzkowski 1968

Rhomboaster Bramlette and Sullivan 1961
Rhomboaster cuspis Bramlette and Sullivan 1961
Rhomboaster calcitrapa Gartner 1971

Sphenolithus Deflandre in Grassé, 1952
Sphenolithus akropodus de Kaenel and Villa 1996
Sphenolithus anarrhopus Bukry and Bramlette 1969
Sphenolithus capricornatus Bukry and Percival 1971
Sphenolithus ciperoensis Bramlette and Wilcoxon 1967
Sphenolithus conicus Bukry 1971
Sphenolithus cuniculus Bown 2005
Sphenolithus delphix Bukry 1973
Sphenolithus dissimilis Bukry and Percival 1971
Sphenolithus distentus (Martini 1965) Bramlette and Wilcoxon 1967

Sphenolithus furcatolithoides Locker 1967
Sphenolithus moriformis (Brönnimann and Stradner 1960) Bramlette and Wilcoxon 1967
Sphenolithus obtusus Bukry 1971
Sphenolithus perpendicularis Shamrock 2010
Sphenolithus predistentus Bramlette and Wilcoxon 1967
Sphenolithus primus Perch-Nielsen 1971
Sphenolithus pseudoradians Bramlette and Wilcoxon 1967
Sphenolithus radians Defandre in Grassé 1952
Sphenolithus spiniger Bukry 1971

Thoracosphaera Kamptnrer 1927

Toweius Hay and Mohler 1967
Toweius eminens Bramlette and Sullivan 1961
Toweius pertusus (Sullivan 1965) Romein 1979

Tribrachiatus Shamrai 1963
Tribrachiatus bramlettei (Brönnimann and Stradner 1960) Proto Decima et al. 1975
Tribrachiatus contortus (Stradner 1958) Bukry 1972
Tribrachiatus orthostylus (Bramlette and Riedel 1954) Shamrai 1963

Triquetrorhabdulus Martini 1965
Triquetrorhabdulus carinatus Martini 1965
Triquetrorhabdulus longus Blaj and Young 2010

Watznaueria Reinhardt 1964