A Cenozoic calcareous nannofossil biozonation from low and middle latitudes: A synthesis

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Abstract The need for an update of the calcareous nannofossil biozonations proposed by Martini (1971) and Bukry (1973,1975), more than 40 years ago, prompted us to develop two new biozonations published in 2012 and 2014, one for the Miocene through Pleistocene interval and one for the Paleogene interval (Backman *et al.*, 2012; Agnini *et al.*, 2014). These biozonations are here combined into a single Cenozoic biozonation from low and middle latitudes. A key strategy has been to employ a set of selected biohorizons for defining biozone boundaries, rather than aiming for obtaining the highest possible biostratigraphic resolution. This approach is aimed to find a balance between accuracy, applicability, and ease of communication and viability in practical geologic work. Each biozone boundary is defined with a single biohorizon. Subzones and auxiliary markers are avoided in order to maintain stability to the new biozonation. Combining the Paleogene and Neogene biozonations, a total of 38 Paleogene biozones and 31 Neogene-Pleistocene biozones are proposed: 11 Calcareous Nannofossil (CN) Paleocene biozones (CNP1–CNP11), 21 Eocene biozones (CNE1–CNE21), 6 Oligocene biozones (CNO1–CNO6), 20 Miocene biozones (CNM1–CNM20), and 11 Plio-Pleistocene biozones (CNPL1-CNPL11). Each of these 69 biozones contains one or several secondary biohorizons that are useful for biozone characterization. Age estimates are provided for all biozone boundary markers and the majority of the additional biohorizons. These estimates are derived from astronomically tuned cyclostratigraphies in the Pleistocene to middle Eocene (base of Chron C19n at 41.510Ma) interval and magnetostratigraphy in the early Paleogene, back to the Cretaceous-Paleogene boundary.

Keywords *calcareous nannofossils, biozonation, Cenozoic*

1. Introduction

Nicholas J. Shackleton (1937–2006) was a leading marine stable isotope and cyclostratigrapher during the late 20th century. He also understood and embraced marine biostratigraphy: "Despite advances in magnetostratigraphy, stable isotope stratigraphy and various manifestations of cyclostratigraphy, it is still true that biostratigraphy is the essential tool by which the geological evidence for environmental change is put into a temporal framework" (Shackleton *et al.,* 1995).

The two major contributors to Cenozoic calcareous deep-sea sediments are calcareous nannofossils and planktonic foraminifera. The study of these groups grew and accelerated after the 2nd World War, concomitantly with increasing geological studies related to hydrocarbon exploration on the one hand and with the beginning of systematic sampling of short deep-sea sediment cores on the other. Early efforts, devoted to research drilling of deep sea sediments, include the development of the piston corer, first employed by the Swedish Deep Sea Expedition of 1947–48, and thereafter during the numerous research cruises with the R/V *Vema* under the leadership of Maurice Ewing.

In 1954, Milton N. Bramlette and William R. Riedel published a seminal paper on the biostratigraphic value of calcareous nannofossils. About 15 years later, this research field had grown to the extent that calcareous nannofossil biozonations began to emerge for different segments of the Cenozoic (Hay *et al.,* 1967; Gartner, 1969; Bukry & Bramlette, 1970). The field continued to develop when

scientific deep-sea drilling began in 1968, resulting in the first calcareous nannofossil biozonation based solely on deep-sea drilling sediments and encompassing the entire Cenozoic Era (Bukry, 1973). These early calcareous nannofossil biozonations were developed within two decades after calcareous nannofossil biostratigraphy had been established as a research field. Over four decades later, Erlend Martini's (1971) and David Bukry's (1973, 1975) biozonations are still used, although the need for revision has grown in the light of new calcareous nannofossil biostratigraphic data that have accumulated over the past four decades.

A large amount of calcareous nannofossil biostratigraphic data has become available during the past three decades. These data represent primarily low- and middle-latitude environments from deep-sea sediments as well as from marine on-land sections in the Mediterranean and western Tethys region. Results have been put together in two new calcareous nannofossil biozonations, one by Backman *et al.* (2012) focusing on the Neogene and Pleistocene, and the other by Agnini *et al.* (2014) focusing on the Paleogene. Below, these are referred to as BA12,14. The underlying biostratigraphic information of both studies rely on the use of census data of individual calcareous nannofossil species in combination with short sample distances, typically one or a few decimetres, as published in many separate articles. The biozonations by BA12,14 provided age estimates of species used for the definition of biozone boundaries as well as for a plethora of other biohorizons within the biozones. These age estimates were derived from direct calibration to magnetostratigraphic records or orbitally tuned cyclostratigraphies. A new code system was employed for the biozones, explained in BA12,14.

A common critical character of the two new biozonations is that neither of them aim to establish the highest possible resolution in terms of number of biozones, but rather aim to employ a limited set of selected biohorizons in order to establish a basic and stable biostratigraphic framework for relative dating of marine sediments in low and middle latitude settings using calcareous nannofossils. Other additional biohorizons are successfully used in regional biostratigraphic schemes and often improve the biostratigraphic resolution in specific time intervals, e.g., in the middle Miocene of the Mediterranean area, but are not included as marker biohorizons for the reason explained above.

Here, these two biozonations are synthesised into a single and coherent Cenozoic calcareous nannofossil biozonation.

2. Biohorizons

Calcareous nannofossil biostratigraphy chiefly relies on the evolutionary appearance or extinction of individual species, forming recognizable changes in assemblage compositions. Such appearances or extinctions are commonly referred to as "biohorizons", "bioevents" and even "datums". The term biohorizons is here adopted for such events. As appears from BA12,14, the use of census data have in many cases revealed that the "absolutely" first or last specimen (Base, Top) observed may not represent the optimal choice for the most precise placing of a biohorizon in chronostratigraphy. The first or last continuous presence of a species may be a better choice, for which BA12,14 adopted the concepts "Base common" or "Top common". It is considered that "Top" and Base" represent concepts that are not easily confused with each other, as is the case with other acronyms that have been used to represent evolutionary extinctions or first appearances, for example LO, which may stand for either Last Occurrence or Lowest Occurrence.

Thus, in all but three cases, four different types of biohorizons were employed by BA12,14: Top (T), Top common (Tc), Base (B) and Base common (Bc). The three exceptions refer to established species that virtually disappear from the biostratigraphic record during a defined interval within their range: (1) Top absence (Ta) *Gephyrocapsa* spp. ≥4μm re-appearance in the early Pleistocene after having been virtually absent for an interval following its evolutionary appearance in the earliest Pleistocene; (2) Base absence (Ba) for the virtual disappearance of *Reticulofenestra pseudoumbilicus* for an interval during the late Miocene following its evolutionary appearance during the middle Miocene; (3) the cross-over (X) in abundance between two helicoliths in the early Miocene, namely from dominant *Helicosphaera euphratis* to dominant *Helicosphaera carteri*. It remains uncertain whether or not these two species represent an ancestor-descendant relationship.

3. Study areas, time scales and biohorizon age estimate uncertainties

The relative order of the biohorizons that are used for definition of biozone boundaries are well established from numerous deep-sea drilling sites and marine on-land sections. Age estimates of these biohorizons, however, are derived from a limited number of such sites in the Atlantic and Pacific oceans, and from two marine on-land sections in the western Tethys.

The Cenozoic time scale is still under development, showing less problems in the Neogene and more in the Paleogene. When considering that this work represents a synthesis of BA12,14 and the present problems of the Paleogene time scale, we have chosen to keep the time scale combination employed by BA12,14 (Lourens *et al.*, 2004; Pälike *et al.*, 2006; Cande & Kent, 1995), rather than converting age estimates of biohorizons to the Geomagnetic Polarity Time Scale (GPTS) published in 2012 (Gradstein *et al.*, 2012).

In the Pliocene-Pleistocene interval, Backman *et al.* (2012) provide ages for 24 biohorizons. 21 of these 24 age estimates (88%) were derived from ODP Site 926 (lat. 4°N; Ceara Rise, western tropical Atlantic), one from ODP Site

925 (lat. 4°N), one from the middle latitude North Atlantic ODP Site 607 (lat. 41°N), and one from ODP Site 653 (lat. 40°N; Tyrrhenian Sea) (Figure 1). Among the age estimates of 39 Miocene biohorizons, 26 (67%) were derived from ODP Site 926, three from ODP Site 925, five from ODP Sites 844 (lat. 8°N) and ODP 845 (lat. 9°N) in the tropical Pacific, and five from ODP Site 1218 (lat. 9°N) in the tropical Pacific (Figure 1). The details about the calibration of all 63 Neogene and Pleistocene biohorizons are reported in Backman *et al.* (2012; chapter 3, tables 2, 4). Only 5 of the 63 biohorizons are calibrated using magnetostratigraphy (ODP Sites 844, 845), the remaining thus rely on astronomical tuning of lithostratigraphic data and, in two cases, oxygen isotope data. This reliance on cyclostratigraphy reflects the limited availability of sediment sections from lower latitude settings having continuous high-quality magnetostratigraphies. The ideal calibration targets for calcareous nannofossil biohorizons would be in sediment sections having both magnetostratigraphies and astronomically tuned cyclostratigraphies, so as to be able to capture the details of the variations in sedimentation rates between successive geomagnetic reversal boundaries. It follows that the age estimates of individual biohorizons may very well change when these are calibrated in sections having both magneto- and cyclostratigraphies. Improved age estimates of individual biohorizons will also permit better assessments of the degree of diachrony/synchrony between different regions if the biostratigraphic calibration occurs in more than one sediment section having both magneto- and cyclostratigraphy. Even if the presented age
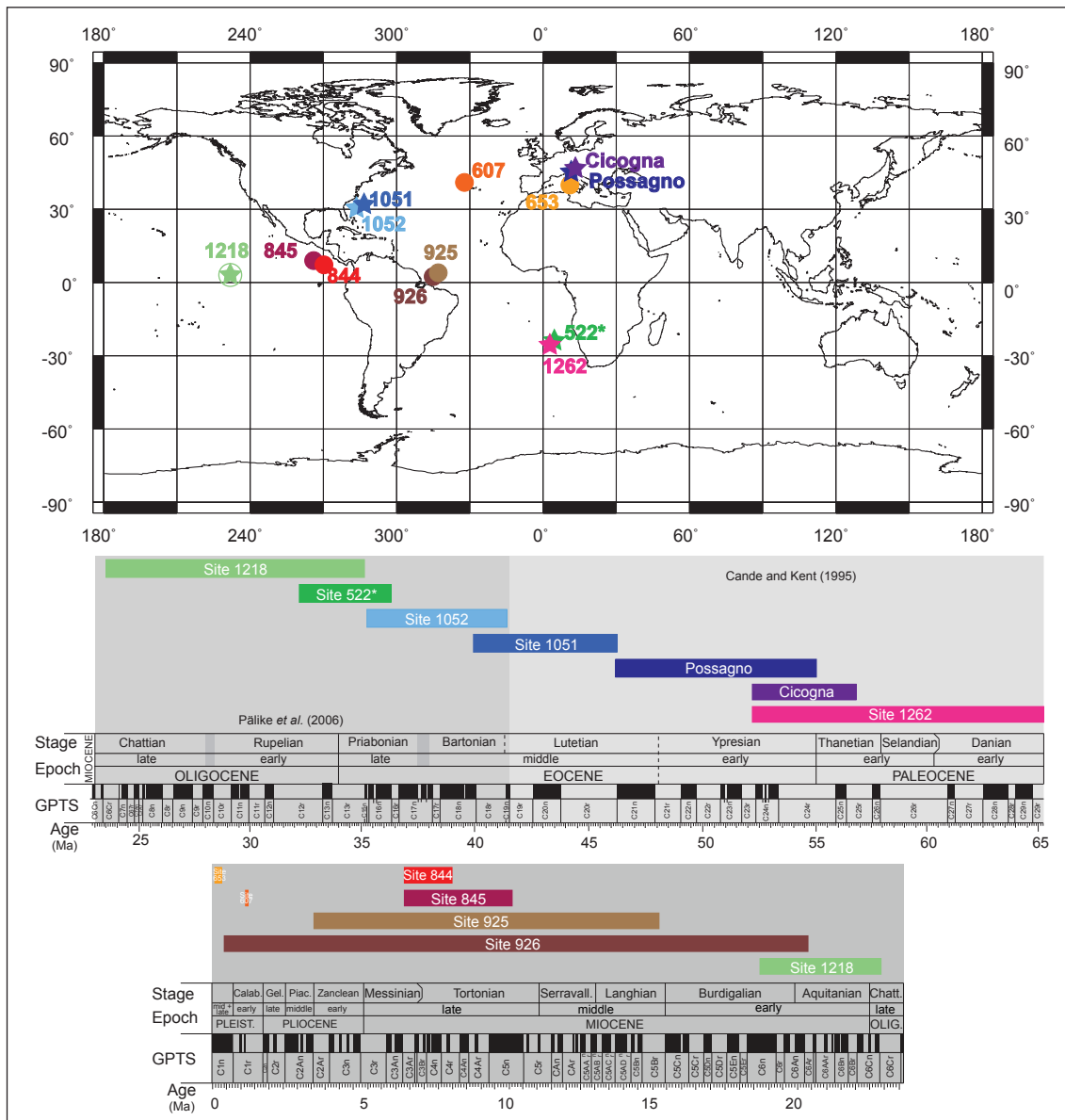

Figure 1: Geographic location and stratigraphic range of the reference sections considered in Backman *et al.* (2012) and Agnini *et al.* (2014)

estimates may change as better calibrations become available, we consider that the present age estimates will likely not differ by more than a few percent (1–2?), as the relative order of the series of Neogene and Pleistocene calcareous nannofossil biohorizons is well established.

In the Paleogene, Agnini *et al.* (2014) provided age estimates for 54 biohorizons, 10 in the Oligocene, 31 in the Eocene, and 13 in the Paleocene. All Paleogene biohorizons are calibrated against magnetostratigraphy in five deep-sea drilling sites from the Atlantic (four sites) and Pacific (one site) and two marine on-land sections (Figure 2) from the western Tethys. The present latitudes of these sections are: 30°N for ODP Site 1051; 30°N for ODP Site 1052; 26°S for ODP Site 522; 27°S for ODP Site 1262; 9°N for ODP Site 1218; 46°N for the Cicogna section; and 46°N for the Possagno section. The calibration of the Paleogene biohorizons relies on linear interpolation between successive geomagnetic reversal boundaries. It follows that potential variations in sedimentation rates within individual polarity zones are not accounted for
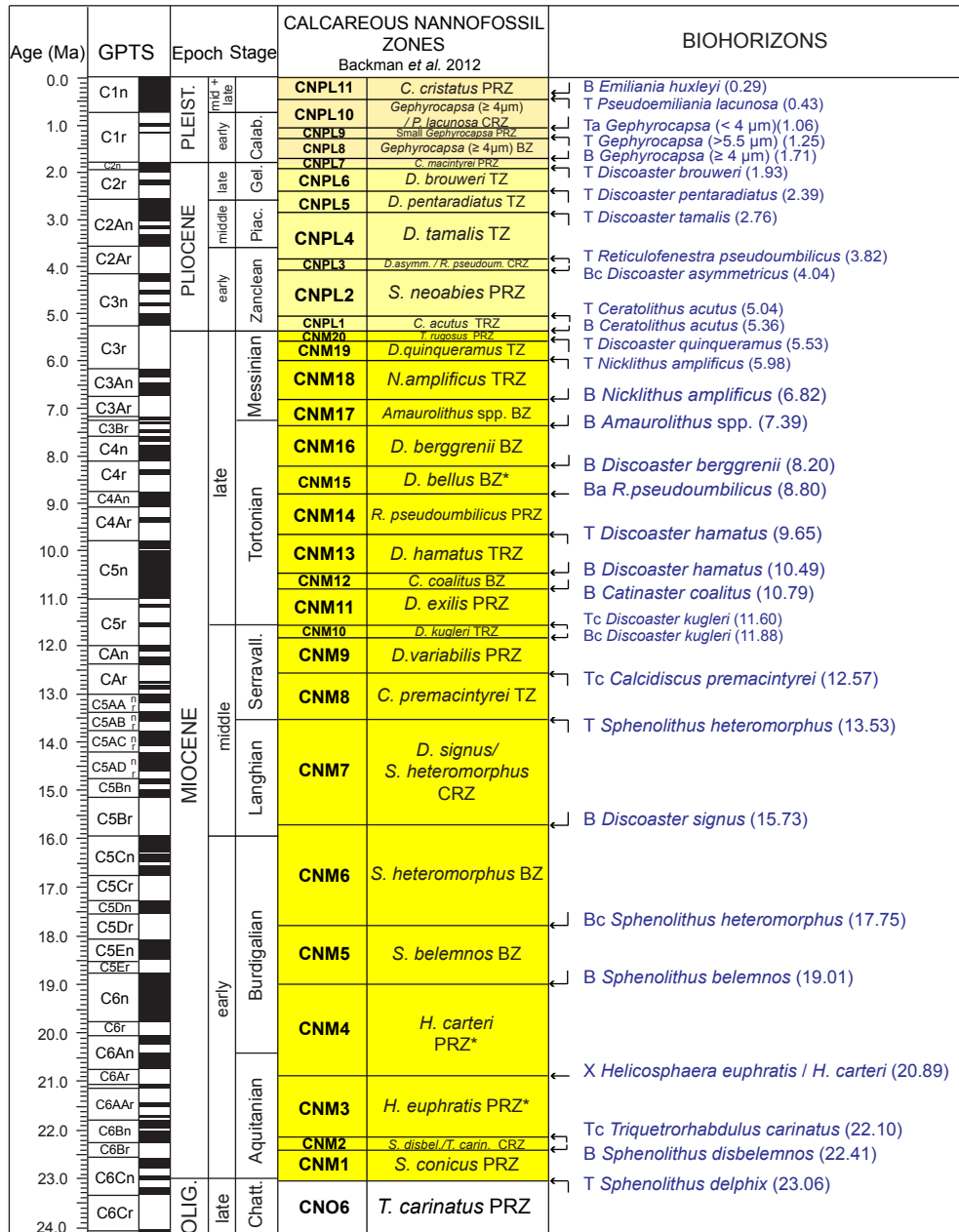
Figure 2: Proposed calcareous nannofossil biozones and biohorizons plotted versus the chronostratigraphic scale and the Geomagnetic Polarity Time Scale (GPTS; Lourens *et al.*, 2004). Biohorizons: blue characters indicate biohorizons calibrated in deep-sea sections, brown characters indicate biohorizons calibrated in land sections. TRZ = Total Range Zone; CRZ = Concurrent Range Zone; BZ = Base Zone; TZ = Top Zone; PRZ = Partial Range Zone; B = Base; Bc = Base common; T = Top; Tc = Top common. **Figure 2a**: Miocene to Pleistocene biostratigraphy. OLIG. - Oligocene; PLEIST. = Pleistocene; Chatt. = Chattian; Serravall. = Serravallian; Piac. = Piacenzian; Gel. = Gelasian; Calab. = Calabrian

when calculating age estimates of the calcareous nannofossil biohorizons.

The Paleogene time scale remains problematic, particularly in the middle Eocene through Paleocene interval. Agnini *et al.* (2014) therefore combined two different time scales for the Paleogene. The orbitally tuned time scale of Pälike *et al.* (2006) is used from the top of Chron C6Cn.3n (23.278Ma) to the base of Chron C19n (41.510Ma). This time scale provided revised age estimates for all geomagnetic reversal boundaries between the above two chron boundaries. From top Chron C20n to base Chron C29n, the time scale of Cande & Kent (1995) is used, leading to an age estimate of the Cretaceous/Paleogene boundary of 65.0Ma. Renne *et al.* (2013) convincingly demonstrated that this boundary occurred at 66.0Ma. Yet, the present uncertainties in the middle Eocene-Paleocene interval made it reasonable to adopt the Cande & Kent (1995) time scale. For most Paleogene biohorizons, however, Agnini *et al.*

(2014) provided information about their distance from nearest higher geomagnetic chron boundary. For example, the Base of *Prinsius martinii* occurred 11% from the top of Chron C28n at ODP Site 1262 (see Table 1 in Agnini *et al.*, 2014), where the entire duration of Chron C28n equals 100%. When new age estimates will be available for the boundaries of Chron C28n, the Base of *Prinsius martinii* is easily recalculated considering that this biohorizon falls 11% from the top of this polarity zone. This reasoning is applied to all other biohorizons.

With respect to present uncertainties regarding age estimates of middle Eocene through Paleocene biohorizons, the errors presumably will be larger close to the Cretaceous/Paleogene boundary and decrease when approaching Pälike's *et al.* (2006) time scale in the middle Eocene. For example, the oldest biohorizon used in the new biozonation is Base *Coccolithus pelagicus*, having an age estimate of 64.76Ma on the Cande & Kent (1995) time scale.
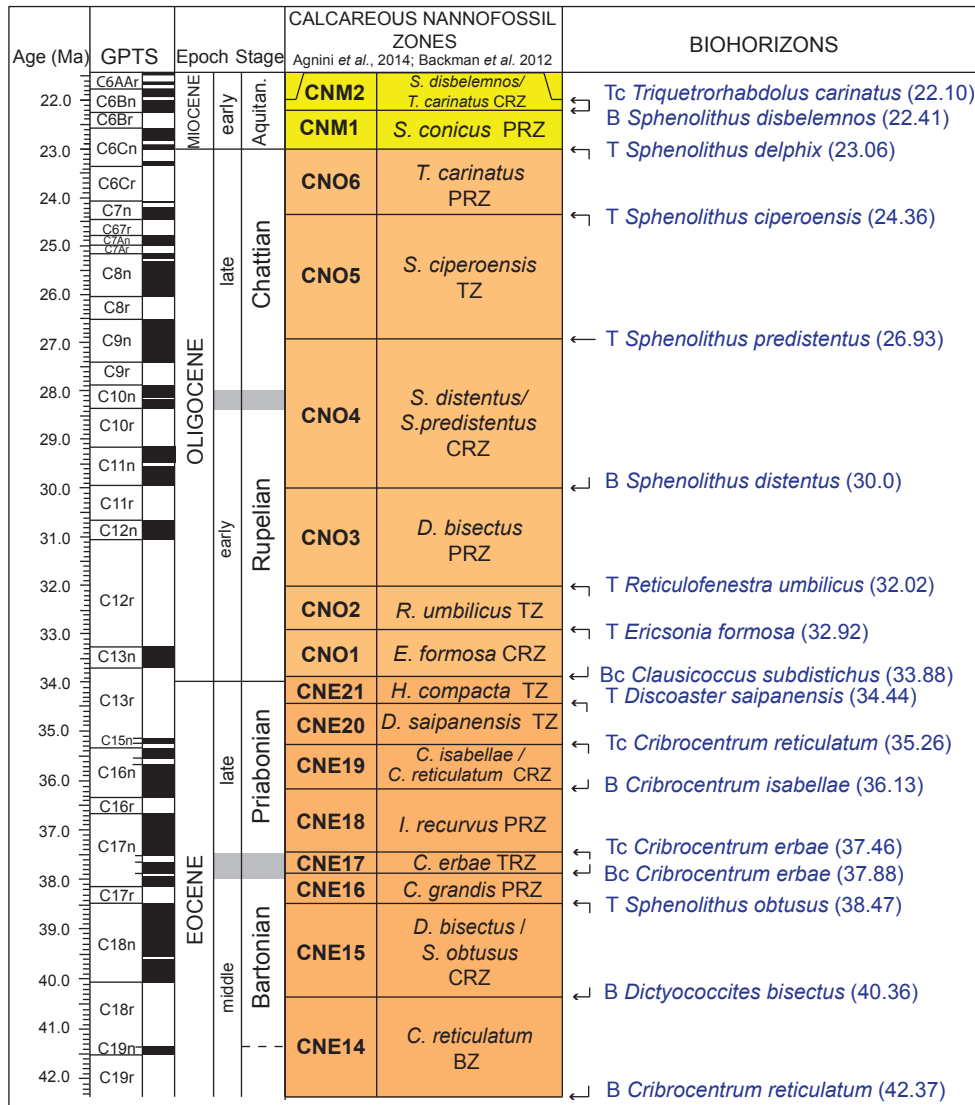

Figure 2b: Middle upper Eocene to Oligocene biostratigraphy. Aquitan. = Aquitanian

Figure 2c: Paleocene to middle Eocene biostratigraphy

In the future, when the problems of the Paleogene time scale are solved, this biohorizon will probably receive an age just younger than 66Ma rather than just younger than 65Ma, implying an age correction on the order of 1.0%. Again, the relative order of the series of Paleogene calcareous nannofossil biohorizons is well established, and changes in the order of biohorizons are not expected, and, like in the Neogene case, it is assumed that future corrections of age estimates of the Paleogene calcareous nannofossil biohorizons will be limited to <2% in low and middle latitude environmental settings.

4. A synthesis of the Cenozoic calcareous nannofossil biozonations

A synthesis of the BA12,14 biozonations is presented in Figures 2a (0-24Ma), 2b (21.5–42Ma) and 2c (39.5–65Ma), showing 69 biozones together with chronostratigraphic information, biozone codes and primary biohorizons. Primary biohorizons define biozone boundaries, with secondary biohorizons occurring within biozones. Information on these additional biohorizons and zonal assemblage descriptions is available in BA12,14.
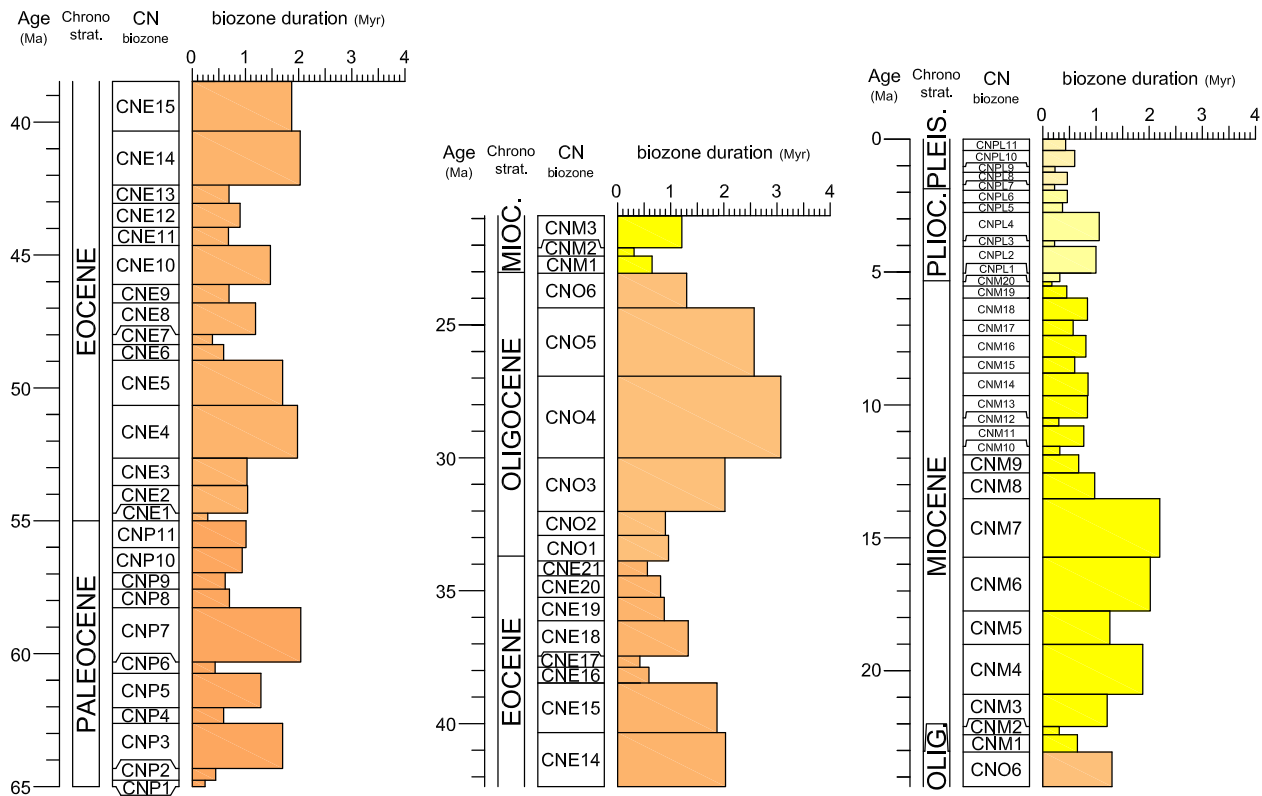
Figure 3: Duration of the CN zones throughout the Cenozoic. MIOC. = Miocene; OLIG. = Oligocene; PLIOC. = Pliocene; PLEIS. = Pleistocene

Five logical types of biozones were defined. These include:
1. Taxon Range Zone (TRZ)
2. Concurrent Range Zone (CRZ)
3. Base Zone (BZ)
4. Top Zone (TZ)
5. Partial Range Zone (PRZ)

Each biozone has a code consisting of a combined acronym for Calcareous Nannofossil (CN) and for each series (P = Paleocene, E = Eocene, O = Oligocene, M = Miocene, PL = Pliocene-Pleistocene), and a number for each biozone, starting from the base (= biozone 1) of the series. The Paleogene is subdivided into 11 Paleocene (CNP1–CN11), 21 Eocene (CNE1–CNE21) and 6 Oligocene (CNO1–CNO6) biozones. The Neogene is subdivided into 20 Miocene (CNM1–CNM20) and 11 Pliocene-Pleistocene (CNPL1-CNPL11) biozones.

The proposed biozonations provide variable biostratigraphic resolution for each series. Average biostratigraphic resolution is: 0.9Myr/biozone in the Paleocene, 1.0Myr/biozone in the Eocene, 1.8Myr/biozone in the Oligocene, 0.9Myr/biozone in the Miocene, and 0.5Myr/biozone in the Pliocene-Pleistocene.

In Figure 3, the biozones are plotted together with their duration in millions of years (Myr). The figure roughly synthesises the imprint of the evolutionary history of Cenozoic calcareous nannofossils, marking both intervals with long durations of the biozones (in the lower Eocene,

in the upper part of the middle Eocene, in the Oligocene), and intervals showing increased rates of taxonomic evolution which resulted in shorter durations of the biozones.

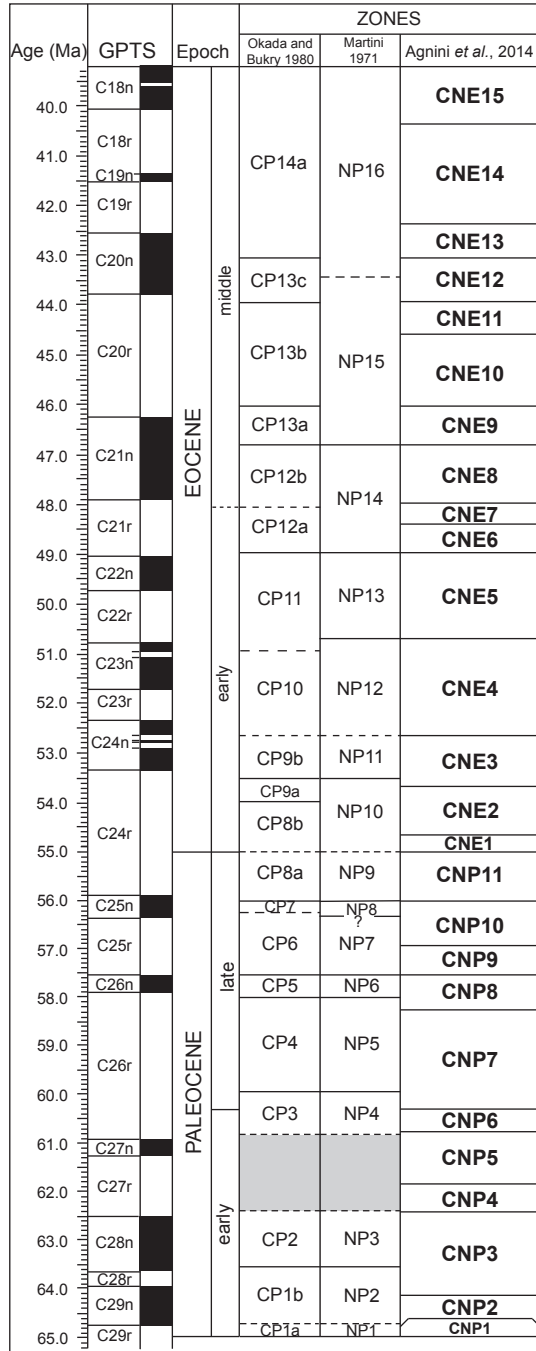## 5. Cenozoic calcareous nannofossil biostratigraphy and biochronology: adjustments, changes, novelties

As explained by BA12,14, these efforts were meant to integrate the classical biohorizons that have proved to be reliable in Bukry's (1973) and Martini's (1971) biozonations with new biohorizons that could substitute the problematic biohorizons in Bukry's and Martini's work. This synthesis therefore partly relies on older biozonations and employs several biozone definitions that refer to biohorizons used also by Martini (1971) and Okada and Bukry (1980), hereafter referred as M71 and OB80, respectively. A direct comparison among BA12,14, M71 and OB80 is shown in Figure 4a–c, differences and mutual features are shown in Figure 5a–e and summarized in the following subchapters, and are discussed in stratigraphic order.

5.1 Paleocene: Figures 4a, 5c

During the Danian Stage, species belonging to *Coccolithus, Praeprinsius* and *Prinsius* evolved, which often became dominant components of the early Paleocene assemblages and providing distinct biohorizons. These taxa are used in place of species belonging to the genera *Cruciplacolithus* and/or *Chiasmolithus* that were included in the M71 and OB80 biozonations. In this way, taxonomic

problems related to small sized species of *Cruciplaco-lithus* and *Chiasmolithus* disappear. Other novelties introduced in the Paleocene biozonation include three new biohorizons, Base *Sphenolithus moriformis*, Base *Discoaster backmanii* and Top *Fasciculithus richardii* group. These biohorizons are approximate substitutes for problematic biostr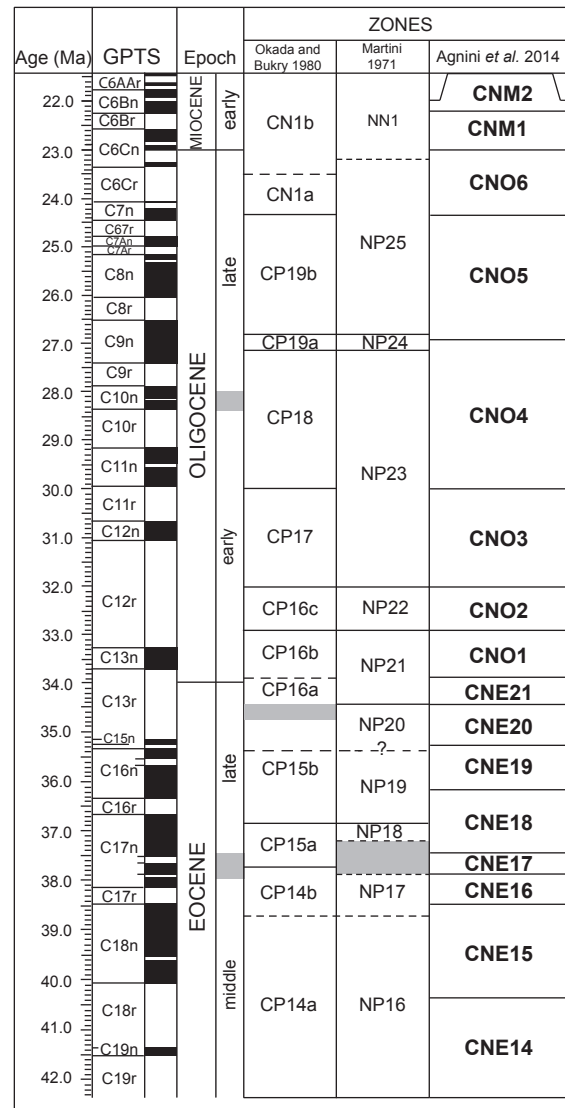atigraphic markers such as the evolutionary appearances of *Ellipsolithus macellus*, *Heliolithus riedeli*, and *Tribrachiatus bramlettei*, which M71 and OB80 used in the lower Paleocene, the upper Paleocene and the Paleocene/Eocene transition, respectively. Furthermore, other new biohorizons are the Base of *Fasciculithus/Lithopty-chius ulii*, the first species appearing in the second radiation of the fasciculiths, and Base *Heliolithus cantabriae*, the first representative of the genus *Heliolithus*. Both biohorizons approximately replace Base *F. tympaniformis* and Base *H. kleinpellii*, the precise positioning of which can be blurred by the presence of transitional morphotypes.

5.2 Eocene: Figures 4a, 5b

The complex Eocene biostratigraphic framework presumably reflects the variability of environmental/climatic conditions during this long time interval, with relatively stable intervals interrupted by several episodes of climatic instability that resulted in alternating phases between higher and lower rates

Figure 4: CN biozones plotted versus the biozonations of Martini (1971) and Okada & Bukry (1980), and the Geomagnetic Polarity Time Scale (GPTS; Lourens *et al.*, 2004). Dashed lines correspond to biohorizons that lack of reliable calibration and, in some cases, unclear taxonomic definition.
Figure 4a: Paleocene to middle Eocene interval

Figure 4b: Middle upper Eocene to Oligocene interval

Age (Ma)	GPTS	Epoch	ZONES		
			Okada and Bukry 1980	Martini 1971	Backman et al. 2012
0.0	C1n	PLEIST. mid+late	CN15 / CN14b	NN21 / NN20	CNPL11
1.0	C1r	early	CN14a / CN13b	NN19	CNPL10 / CNPL9 / CNPL8
2.0	C2n / C2r	PLIOCENE late	CN13a / CN12d	NN18	CNPL7 / CNPL6
3.0	C2An	middle	CN12c / CN12b / CN12a	NN17 / NN16	CNPL5 / CNPL4
4.0	C2Ar	early	CN11b / CN11a	NN15+NN14	CNPL3
5.0	C3n		CN10c / CN10b / CN10a	NN13 / NN12	CNPL2 / CNPL1 / CNM20
6.0	C3r	MIOCENE late			CNM19
	C3An		CN9b	NN11b	CNM18
7.0	C3Ar / C3Br				CNM17
8.0	C4n / C4r		CN9a	NN11a	CNM16
			CN8b		CNM15
9.0	C4An / C4Ar		CN8a	NN10	CNM14
10.0	C5n		CN7	NN9	CNM13
			CN6	NN8	CNM12
11.0	C5r		CN5b	NN7	CNM11
12.0	CAn				CNM10 / CNM9
13.0	CAr / C5AA / C5AB	middle	CN5a	NN6	CNM8
14.0	C5AC / C5AD		CN4	NN5	CNM7
15.0	C5Bn				
16.0	C5Br / C5Cn		CN3	NN4	CNM6
17.0	C5Cr / C5Dn				
18.0	C5Dr / C5En / C5Er	early	CN2	NN3	CNM5
19.0	C6n				
20.0	C6r / C6An		CN1c	NN2	CNM4
21.0	C6Ar / C6AAr				CNM3
22.0	C6Bn / C6Br				CNM2
23.0	C6Cn	OLIG.	CN1b	NN1	CNM1 / CNO6
24.0	C6Cr		CN1a	NP25	

Figure 4c: Miocene to Pleistocene interval. OLIG. = Oligocene

of some biohorizons, characterized by scattered abundance patterns and/or taxonomic ambiguities, was forced by the lack of better alternatives. Examples include Base *Discoaster subodoensis* and Top *Chiasmolithus gigas*. Biohorizons that rely on species belonging to *Chiasmolithus* are not used, that is *C. solitus, C. grandis* and *C. oamaruensis*, because these taxa have problematic taxonomy or provide unreliable/uncertain biostratigraphic signal. *Isthmolithus recurvus* is not used for similar reasons. These traditional biohorizons have been replaced with species belonging to genus *Cribrocentrum, C. reticulatum* and *C. erbae*, which, by contrast, provide more robust biostratigraphic signals. Some Eocene intervals still suffer from a deficiency of good biohorizons, and future improvements will possibly be developed by means of high resolution studies of critical intervals.
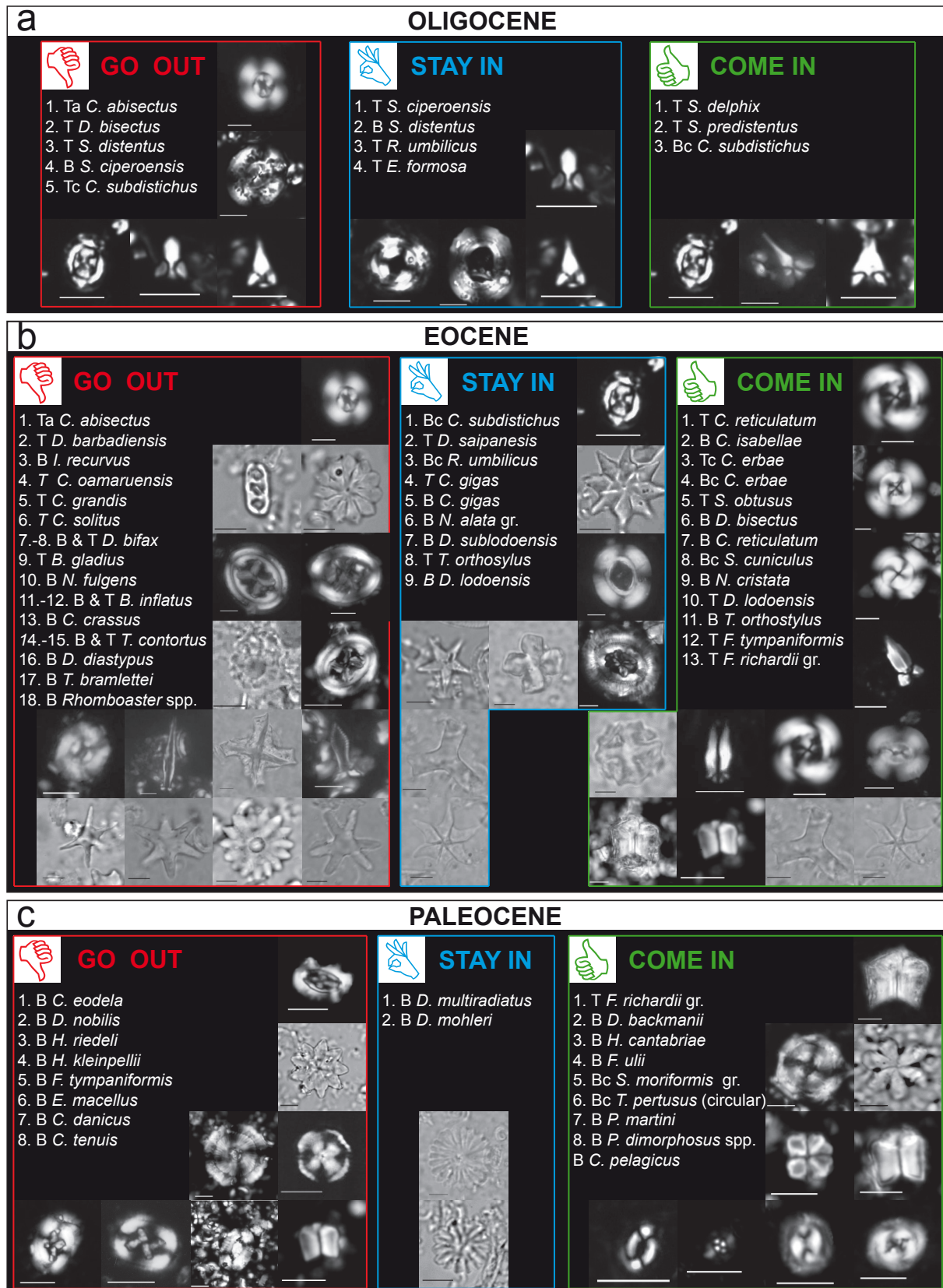
5.3 Oligocene: Figures 4b, 5c

The Oligocene is characterized by low biostratigraphic resolution, caused by a low rate of taxonomic evolution and hence a lack of useful biohorizons in low and middle latitude marine settings. The Oligocene biozones presented by Agnini *et al.* (2014) approximately parallel Bukry's (1973) biozonation (Figure 4b). Major differences with previous biozonations are in the lower Chattian and at the Oligocene-Miocene transition. Top *Sphenolithus predistentus* is considered to be the most distitinctive biohorizon among three closely spaced biohorizons occurring within 0.35Myr: Base *S. ciperoensis*, Top *S. predistentus* and Top *S. distentus*. In the uppermost Oligocene, Top acme *Cyclicargolithus abisectus* and Top *Dictyococcites bisectus* have limited correlation value and are replaced with Top *Sphenolithus delphix* .

5.4 Miocene - Pleistocene interval: Figures 4c, 5d−e

In the lowermost Miocene, at the Pliocene/Pleistocene transition and within the Pleistocene intervals, the biozonations of BA12,14 provide only a slight improvement in biostratigraphic resolution compared with the M71 and OB80 biozonations, whereas the reliability of some biohorizons, used as biozone boundary markers, significantly improved.

Helicosphaera recta and *Discoaster druggii* show problematic distributions, representing examples of less suitable M71, OB80 biohorizons for Miocene biozone boundary definitions. These are replaced by other biohorizons, including those related to the distribution patterns of *Sphenolithus delphix* and *S. disbelemnos*.

In the lower Pliocene interval, biohorizons presently considered to be of limited quality were not employed: the disappearance of *Amaurolithus primus* and *A. tricorniculatus* are not used for definition of a biozone boundary because the two taxa are characterized by low and discontinuous occurrences, and remain poorly calibrated. In the upper Pliocene Top *Discoaster surculus* is not used. The short interval between the successive extinctions of *D. surculus* and *D. pentaradiatus* are not included in the biostratigraphic scheme because of problematic distribution patterns.

of taxonomic evolution. Therefore, the Eocene nannofossil biostratigraphy includes intervals of more closely spaced biohorizons as well as intervals with few available biohorizons. Examples are the highly resolved biostratigraphy in the lower part of the Ypresian Stage (lower Eocene) and in the transition interval Bartonian – Priabonian (middle-late Eocene), with intervening intervals having only a limited number of useful biohorizons. As shown in Figure 5b, 18 classical biohorizons have been replaced in the Eocene zonation. The replaced taxa have, for example, displayed sporadic and discontinuous abundance patterns, represented lower quality and/or limited datasets, and/or have been affected by ambiguous taxonomy. There are exceptions to this plan because the use

Figure 5: Changes, exclusions and novelties among calcareous nannofossil biostratigraphic markers; bars = 5μm. Photomicrographs from different sources: Agnini *et al*., 2007, 2014; Fornaciari *et al*., 2010; Norris *et al*., 2012; Raffi *et al*., 2006. **Figure 5a**: Photomicrographs of Oligocene taxa. **Figure 5b**: Photomicrographs of Eocene taxa. **Figure 5c**: Photomicrographs of Paleocene taxa; *H. riedeli* after Okada & Thierstein, 1979; *C. danicus* after Varol, 1998
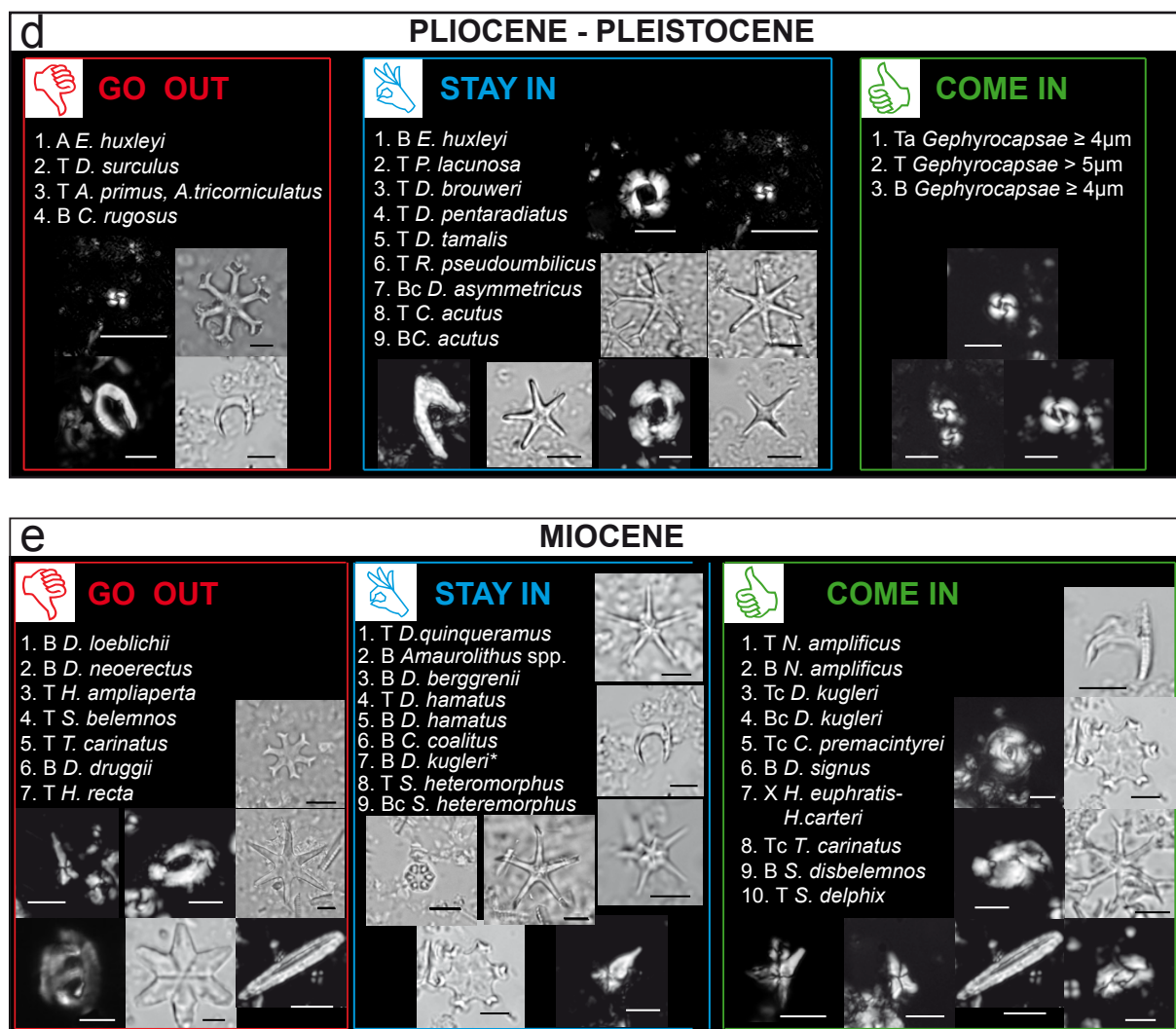
Figure 5: Continued. **Figure 5d**: Photomicrographs of Pliocene-Pleistocene taxa. **Figure 5e**: Photomicrographs of Miocene taxa

In the Pleistocene, the rapid evolution among the genus *Gephyrocapsa* provides a series of useful biohorizons that made it possible improve the biostratigraphic schemes of M71 and OB80. Morphometric concepts are used for discriminating species within the genus *Gephyrocapsa*, which has proved to be reliable for stratigraphic correlation over wide geographic distances and that provide a robust biochronology.

6. Conclusions

The generation of an abundance of new calcareous nannofossil biostratigraphic data over the past three decades have resulted in two new Cenozoic biozonations (Backman *et al.*, 2012; Agnini *et al.*, 2014). Here, a combined Cenozoic synthesis of these two biozonations is presented. The new datasets consist of biostratigraphic information acquired at higher resolution and through semi-quantitative counting methodologies using sediments from both DSDP/ODP/IODP deep-sea sites and on-land marine sections. The number of useful biohorizons variably influences the biostratigraphic resolution,

resulting in an increase in some intervals, as in the middle and upper Eocene, or no improvement in others, as in most of the Oligocene, when compared to the previous biozonations. Several additional biohorizons are included within each biozone. However, the introduction of subzones is avoided with the aim to obtain a more stable Cenozoic biozonation that is applicable in practical geologic work. In spite of the fact that some stratigraphic intervals still lack reliable biohorizons, e.g., within parts of the Eocene, improvements may possibly be obtained in the future by means of high resolution studies of critical intervals.

A total of 69 Cenozoic biozones are defined using a new code system, referring to the series and a number for each biozone. The 38 Paleogene biozones comprise 11 Calcareous Nannofossil (CN) Paleocene biozones (CNP1–CNP11), 21 Eocene biozones (CNE1–CNE21), and 6 Oligocene biozones (CNO1–CNO6); the 31 Neogene-Pleistocene biozones comprise 20 Miocene biozones (CNM1–CNM20) and 11 Plio-Pleistocene biozones (CNPL1–CNPL11).

Age estimates are assigned to all biozone boundary biohorizons as well as to most additional biohorizons. These estimates are derived from astronomically tuned cyclostratigraphies in the Pleistocene through middle Eocene interval, and from magnetostratigraphy from the middle Eocene back to the Cretaceous-Paleogene boundary.

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