Biozonation and biochronology of Miocene through Pleistocene calcareous nannofossils from low and middle latitudes

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With 10 figures and 4 tables

Abstract. Calcareous nannofossils are widely used in Cenozoic marine biostratigraphy. At present, the two most widely used calcareous nannofossil biozonations were established approximately 40 years ago. These were derived from marine land sections and Deep Sea Drilling Project rotary cored sediments. Over nearly three decades, we have generated Miocene through Pleistocene calcareous nannofossil data from deep sea sediments in low and middle latitude regions. The sediments used here have been mostly recovered using the advanced piston coring technique, generating less core disturbance and complete recovery via multiple penetration of the sediment column at single sites. A consistent trait in our work on calcareous nannofossil biostratigraphy has been to use semi-quantitative methods in combination with short sample distances, close enough to capture the details of the abundance behaviour of individual calcareous nannofossil taxa. Such data represent the foundation of the new biozonation presented here, which still partly relies on the pioneering work presented by Erlend Martini and David Bukry about 40 years ago. A key aim here has been to employ a limited set of selected biohorizons for the purpose of establishing a relatively coarsely resolved and stable biozonation. We present 31 biozones using a new code system: CNM1–CNM20; Calcareous Nannofossil Miocene biozones 1 through 20. CNPL1–CNPL11; Calcareous Nannofossil Plio-Pleistocene biozones 1 through 11. As the new biozonation encompasses 23 million years, the average biozone resolution becomes 0.74 million years, ranging from 0.15 to 2.20 million years. A single biohorizon is used for the definition of each biozone boundary. Auxiliary markers are avoided, as well as subzones, in order to maintain stability to the new biozonation. Virtually every biozone holds one or several additional biohorizons. These, together with all biozone boundary markers, are assigned age estimates derived chiefly from astronomically tuned cyclostratigraphies.

Key words. calcareous nannofossils, biozonation, biochronology, Miocene-Pleistocene

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1.   Introduction

About 40 years ago, a series of calcareous nannofossil biostratigraphic zonations was established for various parts of the Cenozoic stratigraphic column (Hay et al. 1967, Gartner 1969, 1971, Bukry and Bramlette 1970, Martini 1969, 1970, Martini and Worsley 1970). These were all based on the study of marine land sections and/or rotary cored Deep Sea Drilling Project sediments, a drilling technique characterised by low recovery and disturbed cores (JOIDES Journal, June 1979; www.odplegacy.org). Biozonations for the entire Cenozoic were developed by Martini (1971) and Bukry (1973, 1975, 1978). Martini introduced 25 Paleogene and 21 Neogene zones (NP/NN zones), whereas Okada and Bukry (1980) codified Bukry's 19 Paleogene and 15 Neogene zones (CP/CN zones). In addition, Okada and Bukry (1980) also codified 20 Paleogene and 24 Neogene subzones. These two zonal systems are still widely used, in spite of Bukry's (1973a) insightful comment that "...the continuing recovery of deep-ocean sediment sections by the D/V *Glomar Challenger* at various latitudes will provide the material needed to thoroughly evaluate the stratigraphic and geographic ranges of coccolith species. This will permit more consistent zonation." Bukry's zonation was "not intended to be exhaustive but simply illustrates the basis of a low-latitude open-ocean coccolith zonation". He thus aimed to establish a general framework for relative dating of open ocean sediments rather than producing the highest possible resolution. This spirit is adopted here, together with the general aim to produce a "more consistent zonation".

Among us, a paper by Rio (1974) was the first in a still ongoing effort (Fornaciari et al. 2010, Agnini et al. 2011) to generate biostratigraphic data using Cenozoic calcareous nannofossils. Many biostratigraphic studies of Cenozoic calcareous nannofossils present data in the form of range charts, characterised by qualitative estimates of relative abundances of taxa in widely spaced samples. As discussed by Backman and Raffi (1997), it is difficult to judge the quality of individual biohorizons from qualitative presence-absence listings in range charts. Inspired by the work of Thierstein et al. (1977), we developed methods to acquire census data (Backman and Shackleton 1983, Rio et al. 1990a, Raffi, 1999). By combining census data with short sample distances, we aimed to improve both the stratigraphic precision and resolution by which calcareous nannofossil biohorizons were determined. Census data have the advantage that they permit independent as-

sessments of the abundance behaviour and distribution of taxa, and hence the quality of the biohorizons. We have subsequently generated much data showing abundance variations of biostratigraphically important calcareous nannofossil taxa from marine sediments of Cenozoic age representing different low and middle latitude paleoenvironmental settings.

We here synthesise Miocene through Pleistocene data in order to a establish a basic biostratigraphic framework for relative dating of marine sediments using calcareous nannofossils. This synthesis clearly relies on the pioneering contributions by Erlend Martini and David Bukry, as many of the biohorizons they used for zonal boundary definitions have proven to provide consistent results. Several of their zonal boundary defining biohorizons, however, have proven less practical and explains the need for a revised biozonation. Our approach has been to employ a limited set of selected biohorizons in order to establish a relatively coarse and stable framework taking into account the biostratigraphic data that we have produced over nearly three decades, consistently using semi-quantitative methods and short sample distances. In addition, we here present some previously unpublished biostratigraphic data.

A secondary purpose has been to provide age estimates for all biohorizons. Age estimates of individual biohorizons are presented with their calibration references. In the Miocene through Pleistocene interval, the independent age control is provided primarily by astronomically tuned cyclostratigraphies.

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

A biostratigraphic unit, or biozone, is a body of strata that are defined on the basis of its unique content, sequential distribution, absence, or combinations thereof, of fossils. Here, we use selected calcareous nannofossil biohorizons to establish a revised biozonation for the Miocene through Pleistocene interval.

The major advantage of using a logically organised zonal scheme, e.g., Zone CN5 is relatively older than Zone CN6, etc., is its ease of use compared to learning and remember the names of the many taxa providing individual biohorizons and biozone boundary definitions. In our view, biozones in a zonal scheme should represent a relatively coarse and stable framework us-

ing carefully selected biohorizons for defining zonal boundaries rather than seeking to achieve the highest possible resolution. Other biostratigraphically useful biohorizons occur in virtually every biozone. We prefer to list these as biohorizons and their proper relative positions within the biozones as intra-zonal markers rather than to employ all or most of them for zonal boundary definitions, for the purpose to give stability to the zonal scheme and keep it simple. These latter points have motivated our reluctance to introduce subzones. Each biozone boundary should be defined by a single biohorizon. It follows that the use of 'auxiliary' biozone boundary markers is to be avoided.

Biozones may be defined using different concepts. We follow Wade et al. (2011) for five logical types of biozones that can be based on stratigraphic distributions of calcareous nannofossil taxa. These zones include:
1. Taxon Range Zone (TRZ)
2. Concurrent Range Zone (CRZ)
3. Base Zone (BZ)
4. Top Zone (TZ)
5. Partial Range Zone (PRZ)

However, Wade et al. (2011) used Lowest Occurrence (LO) and Highest Occurrence (HO) for categories 3 and 4, respectively. The commonly used acronym LO may refer to both Last Occurrence and Lowest Occurrence in calcareous nannoplankton biostratigraphy (e. g., Rio et al. 1984, Fornaciari et al. 2010). We thus prefer to use Base (**B**) and Top (**T**), respectively, to describe the stratigraphic lowest and highest occurrences of taxa (Fig. 1). This practice is not new (Roth et al. 1971, Raffi et al. 1993, Backman and Raffi 1997), and is considered unambiguous in comparison to HO and LO. The Base and Top concepts are here used in a chronostratigraphic sense. Although avoiding the use of LO and HO terms for the types of biohorizons in our proposed new calcareous nannofossil zonation, we adhere to the five types of biozones that were introduced by Wade et al. (2011) and that can be applied to all biozones introduced below.

In our calcareous nannofossil biostratigraphy, we have used three concepts that differ from the absolutely topmost or basalmost stratigraphic presence of taxa. It is not uncommon that the first evolutionary appearance of a taxon is characterised by discontinuous occurrences of rare to few specimens for some stratigraphic distance below its continuous presence at higher abundances. Similarly, a tail of discontinuous occurrences of rare to few specimens may exist above its continuous presence at higher abundances. A typical example of this phenomenon is illustrated below by the Base of common *Discoaster asymmetricus*. In such cases, the absolutely lowest or highest occurrences are considered to provide a less reliable biostratigraphic signal when compared to the base and top of the continuous occurrences of the taxon at higher abundances. In such cases, we use the concepts Base common (**Bc**) and Top common (**Tc**). Several other possibilities to codify such biohorizons have been published, although we here refer to them as Tc or Bc. Another, more unusual, concept that we have adopted is the cross-over (**X**) in abundance between two taxa. The two taxa may or may not be ancestor and descendant taxa. The key problem is that low and discontinuous abundances towards the end of the range of a (in some cases, ancestor) taxon and in the beginning of the range of another (in some cases, descendant) taxon may be difficult to determine precisely in terms of
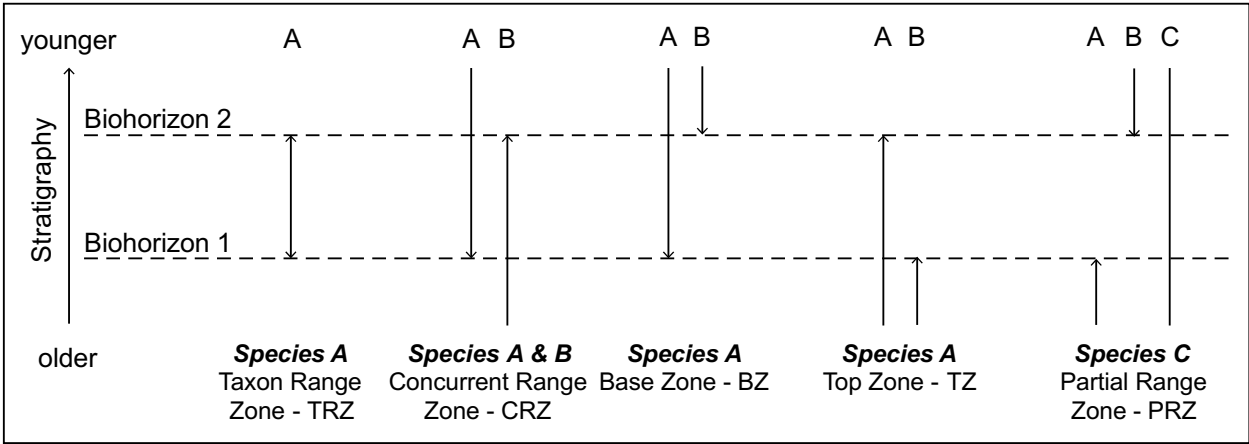
Fig. 1. The five logical possibilities for biostratigraphic characterization of biozones. Redrawn after Wade et al. (2011).

stratigraphic depth. In cases where the cross-over occurs between ancestor and descendant taxa, the problem may be extended to include presence of intermediate and overlapping morphotypes, although the cross-over in abundance between the ancestor and descendant taxa may be readily determined. The cross-over in abundance between *Helicosphaera euphratis* and *Helicosphaera carteri* is an example (see below) that do not appear to represent a direct ancestor/descendant (Haq 1973, Perch-Nielsen 1985), yet biostratigraphically useful, transition. The transition between *Ceratolithus acutus* and *Ceratolithus rugosus*, on the other hand, represents an illustrative example of an ancestor-descendant, biostratigraphically useful, transition (Backman and Raffi 1997).

Moreover, we use intervals in which an established species or genus temporarily disappears, to re-appear higher up in the stratigraphic column. Such absence intervals provide meaningful biostratigraphic information in a few cases. We thus refer to Base absence (**Ba**) for the temporary disappearance of *Reticulofenstra pseudoumbilicus* from the upper Miocene stratigraphic records and Top absence (**Ta**) for its re-entrance higher up in the upper Miocene stratigraphic column. Similarly, we use Ta for the biohorizon provided by the re-appearance of specimens ≥ 4 μm among the Pleistocene genus *Gephyrocapsa*. Specimens ≥ 4 μm first appears in the lower Pleistocene, followed by a stratigraphic interval of absence before this size class re-enters the stratigraphic record about 203 kyrs later. Size changes among the genus *Gephyrocapsa* have since long been successfully employed for stratigraphic subdivision of Pleistocene sediments (Gartner 1977, Rio 1982), including the re-entrance of specimens ≥ 4 μm following an absence interval of such large specimens (Raffi et al. 1993).

Thus, we employ seven concepts to characterise biohorizons (B, Bc, Ba, T, Tc, Ta, X), which are used to define five different types of biozones (CRZ, TZ, BZ, PRZ, TRZ, Fig. 1), as illustrated by Wade et al. (2011).

In Cenozoic planktonic foraminifera biostratigraphy, recent revisions have introduced a biozone code system that adds a code letter for each series and a number system that begins at the base (= biozone 1) of the series (Berggren and Pearson 2006, Wade et al. 2011). We follow this system here, introducing a new code system for the Miocene through Holocene calcareous nannofossil biozones. We prefer to merge the Pliocene and Pleistocene in our chosen biozone code system, which is hence grouped into two units: Plio-

Pleistocene (PL) and Miocene (M). The following codes are used (CN = Calcareous Nannofossil):
1. CNPL1 to CNPL11: Pliocene through Pleistocene/Holocene biozones 1 through 11
2. CNM1 to CNM19: Miocene biozones 1 through 20

A new Paleogene biostratigraphic zonation will be presented shortly in a different contribution, following the above approach and hence using CNO for Oligocene biozones, CNE for Eocene biozones and CNP for Paleocene biozones. The GSSP definitions of the Miocene, Pliocene and Pleistocene series boundaries (www.stratigraphy.org) are based on cyclostratigraphy (base Pleistocene, base Pliocene) and magnetostratigraphy (base Miocene). It follows that the above two groups of calcareous nannofossil biozones do not exactly coincide with the series boundaries, but are close enough to justify the code system. Of the four existing Miocene through Holocene series, the Holocene is too young (0.012 Ma) in order to be distinguished biostratigraphically, and the controversial Pliocene/Pleistocene boundary is not distinguished in order to avoid future potential problems in the case that the boundary definition will change. Here we have chosen to use the chronostratigraphic scheme of Lourens et al. (2004), which places the base of the Pleistocene at the top of the Gelasian Stage at an age of 1.81 Ma.

3. Age estimates of biohorizons

Age estimates in the Miocene through Pleistocene interval are chiefly derived from astronomically tuned cyclostratigraphies. These estimates are considered to represent an improvement from our previous synthesis (Raffi et al. 2006) and include new calibrations. For age estimates of biohorizons derived from correlation to Pleistocene Marine Isotope Stages (MIS), we used Lisiecki and Raymo's (2005) MIS boundary estimates. For age estimates derived from orbitally tuned lithologic cyclicities (magnetic susceptibility) in ODP Sites 925 and 926, we used Shackleton and Crowhurst's[1] (1997; Leg 154 CD-ROM Materials, Chapter 03 text files) age/depth tables. For age estimates derived from

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[1] These age estimates from ODP Site 926 in the western tropical Atlantic Ocean differ slightly from those originally presented by Backman and Raffi (1997) from the identical site, who used an early (unpublished) version of Shackleton and Crowhurst's (1997) astronomically tuned magnetic susceptibility records.

orbitally tuned lithologic cyclicities (gamma ray wet-bulk densities) in ODP Leg 138 sites, we converted the estimates from Shackleton et al. (1995) to the timescale of Lourens et al. (2004). For age estimates derived from lower Miocene cyclostratigraphies in ODP Hole 926B and ODP Site 1218, we used the orbitally tuned data produced by Pälike et al. (2006, 2007). In addition to astronomically tuned cyclostratigraphic age data, we have used magnetostratigraphy for a few late Miocene biohorizons (Schneider 1995).

In the literature, there is an abundance of previous age estimates for each biohorizon presented here, e.g. Berggren et al. (1985, 1995) and the numerous Initial Reports volumes (see Explanatory Notes) of the Ocean Drilling Program. Here we show only our own calibrations generated from low and middle latitude settings.

4. Biozone definitions in the Miocene interval

Biozones are presented in chronological order, from older to younger. The biohorizons that are used for de-

finitions of the CNM biozones are summarized in Table 1. Age estimates of zonal boundary markers and additional biohorizons in the Miocene interval are summarized in Table 2. The average error of age estimates for the 41 Miocene biohorizons is ± 0.02 million years, as deduced from Table 2 (depth uncertainty divided by sedimentation rate). An overview of the CNM zonation in a chronostratigraphic context, and comparison with Okada and Bukry's (1980) and Martini's (1971) Miocene zonations, is shown in Figure 2.

Name: Zone CNM1 – *Sphenolithus conicus* Partial Range Zone
Definition: Partial range of the nominate taxon between the Top of *Sphenolithus delphix* and the Base of *Sphenolithus disbelemnos*.
Reference section: ODP Site 1218 (central part of tropical Pacific Ocean)
Estimated age: 23.06 Ma–22.41 Ma (Fig. 2, Table 2)
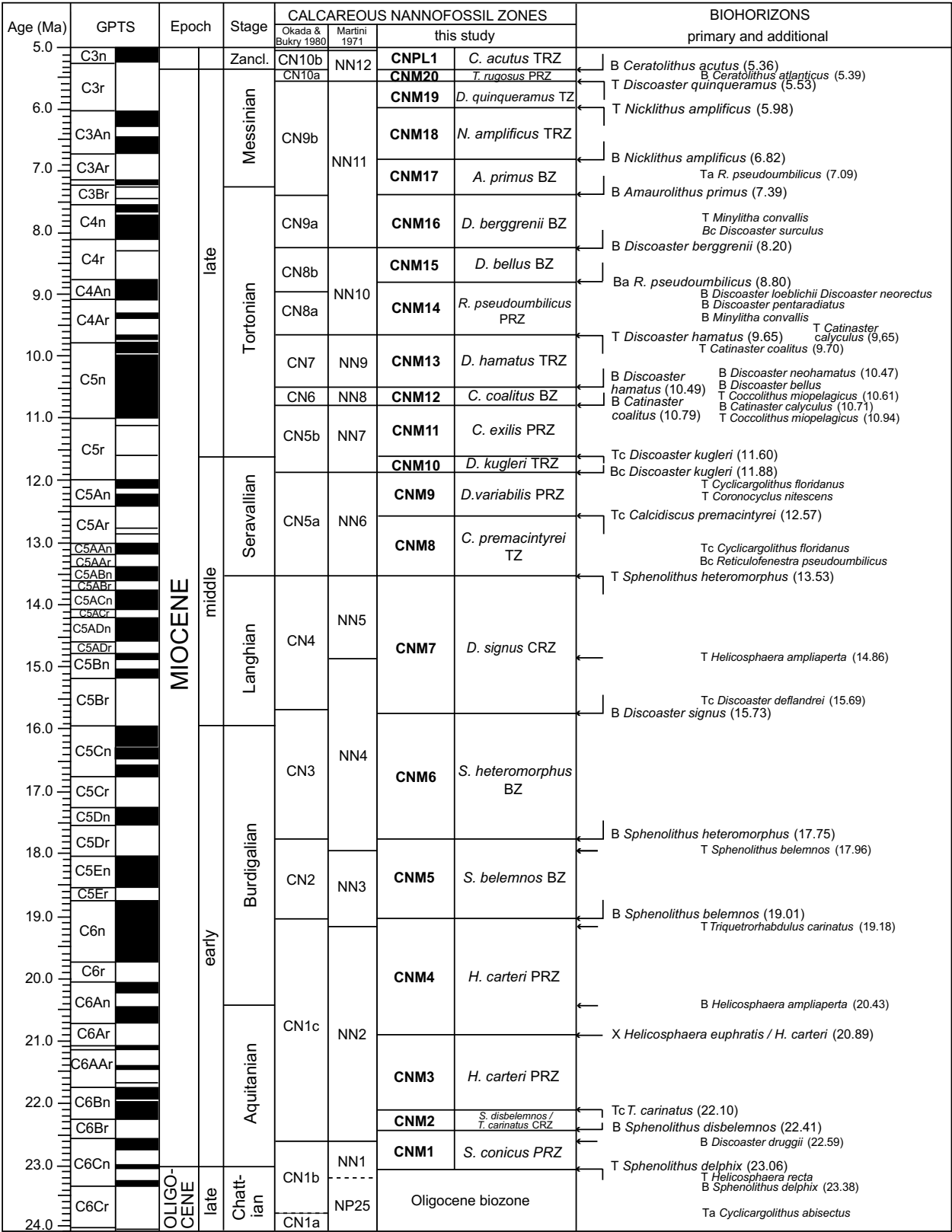**Duration:** 0.65 million years
Remarks: Martini (1971) defined Zone NN1 by the disappearance of *Helicosphaera recta* and the appearance of *Discoaster druggii*. The following zone, NN2, encompasses the interval from the *D. druggii* biohori-

Table 1   Biohorizons used for definitions of Miocene biozones.

Marker Taxon for Base of Zone	Type of Event	Marker Taxon for Top of Zone	Type of Event	Biozone*	Code
Discoaster quinqueramus	Top	*Ceratolithus acutus*	Base	*T. rugosus* PRZ	CNM20
Nicklithus amplificus	Top	*Discoaster quinqueramus*	Top	*D. quinqueramus* TZ	CNM19
Nicklithus amplificus	Base	*Nicklithus amplificus*	Top	*N. amplificus* TRZ	CNM18
Amaurolithus primus	Base	*Nicklithus amplificus*	Base	*A. primus* BZ	CNM17
Discoaster berggrenii	Base	*Amaurolithus primus*	Base	*D. berggrenii* BZ	CNM16
Reticulofenestra pseudoumbilicus	Base absence	*Discoaster berggrenii*	Base	*D. bellus* BZ	CNM15
Discoaster hamatus	Top	*Reticulofenestra pseudoumbilicus*	Base absence	*R. pseudoumbilicus* PRZ	CNM14
Discoaster hamatus	Base	*Discoaster hamatus*	Top	*D. hamatus* TRZ	CNM13
Ceratolithus coalitus	Base	*Discoaster hamatus*	Base	*C. coalitus* BZ	CNM12
Discoaster kugleri	Top common	*Ceratolithus coalitus*	Base	*C. exilis* PRZ	CNM11
Discoaster kugleri	Base common	*Discoaster kugleri*	Top common	*D. kugleri* TRZ	CNM10
Calcidiscus premacintyrei	Base	*Discoaster kugleri*	Base common	*D. variabilis* PRZ	CNM9
Sphenolithus heteromorphus	Top	*Calcidiscus premacintyrei*	Base	*C. premacintyrei* TZ	CNM8
Discoaster signus	Base	*Sphenolithus heteromorphus*	Top	*D. signus / S. heteromorphus* CRZ	CNM7
Sphenolithus heteromorphus	Base common	*Discoaster signus*	Base	*S. heteromorphus* BZ	CNM6
Sphenolithus belemnos	Base	*Sphenolithus heteromorphus*	Base common	*S. belemnos* BZ	CNM5
Helicosphaera euphratis / H. carteri	Cross-Over	*Sphenolithus belemnos*	Base	*H. carteri* PRZ	CNM4
Triquetrorhabdulus carinatus	Top common	*Helicosphaera euphratis / H. carteri*	Cross-Over	*H. euphratis* PRZ	CNM3
Sphenolithus disbelemnos	Base	*Triquetrorhabdulus carinatus*	Top common	*S. disbelemnos / T. carinatus* CRZ	CNM2
Sphenolithus delphix	Top	*Sphenolithus disbelemnos*	Base	*S. conicus* PRZ	CNM1

*Taxon Range Zone (TRZ), Concurrent Range Zone (CRZ), Base Zone (BZ), Top Zone (TZ), Partial Range Zone (PRZ)

Fig. 2. Calcareous nannofossil zones and biohorizons (Miocene through Pleistocene).

Age (Ma)	GPTS	Epoch	Stage	Okada & Bukry 1980	Martini 1971	this study		BIOHORIZONS primary and additional
5.0	C3n		Zancl.	CN10b	NN12	CNPL1	*C. acutus* TRZ	B *Ceratolithus acutus* (5.36) — B *Ceratolithus atlanticus* (5.39)
	C3r		Messinian	CN10a		CNM20	*T. rugosus* PRZ	T *Discoaster quinqueramus* (5.53)
6.0				CN9b		CNM19	*D. quinqueramus* TZ	T *Nicklithus amplificus* (5.98)
	C3An					CNM18	*N. amplificus* TRZ	
7.0	C3Ar				NN11	CNM17	*A. primus* BZ	B *Nicklithus amplificus* (6.82); Ta *R. pseudoumbilicus* (7.09)
	C3Br							B *Amaurolithus primus* (7.39)
8.0	C4n	late	Tortonian	CN9a		CNM16	*D. berggrenii* BZ	T *Minylitha convallis*; Bc *Discoaster surculus*; B *Discoaster berggrenii* (8.20)
	C4r			CN8b		CNM15	*D. bellus* BZ	Ba *R. pseudoumbilicus* (8.80)
9.0	C4An			CN8a	NN10	CNM14	*R. pseudoumbilicus* PRZ	B *Discoaster loeblichii* Discoaster neorectus; B *Discoaster pentaradiatus*; B *Minylitha convallis*
	C4Ar							T *Discoaster hamatus* (9.65) T *Catinaster calyculus* (9.65); T *Catinaster coalitus* (9.70)
10.0	C5n			CN7	NN9	CNM13	*D. hamatus* TRZ	B *Discoaster neohamatus* (10.47); B *Discoaster hamatus* (10.49); B *Discoaster bellus*
				CN6	NN8	CNM12	*C. coalitus* BZ	T *Coccolithus miopelagicus* (10.61); B *Catinaster coalitus* (10.79); B *Catinaster calyculus* (10.71); T *Coccolithus miopelagicus* (10.94)
11.0	C5r			CN5b	NN7	CNM11	*C. exilis* PRZ	
						CNM10	*D. kugleri* TRZ	Tc *Discoaster kugleri* (11.60); Bc *Discoaster kugleri* (11.88)
12.0	C5An	middle	Seravallian	CN5a	NN6	CNM9	*D. variabilis* PRZ	T *Cyclicargolithus floridanus*; T *Coronocyclus nitescens*
	C5Ar							Tc *Calcidiscus premacintyrei* (12.57)
13.0	C5AAn C5AAr C5ABn C5ABr					CNM8	*C. premacintyrei* TZ	Tc *Cyclicargolithus floridanus*; Bc *Reticulofenestra pseudoumbilicus*
14.0	C5ACn C5ACr C5ADn C5ADr		Langhian	CN4	NN5	CNM7	*D. signus* CRZ	T *Sphenolithus heteromorphus* (13.53)
15.0	C5Bn							T *Helicosphaera ampliaperta* (14.86)
16.0	C5Br							Tc *Discoaster deflandrei* (15.69); B *Discoaster signus* (15.73)
	C5Cn			CN3	NN4	CNM6	*S. heteromorphus* BZ	
17.0	C5Cr		Burdigalian					
	C5Dn							B *Sphenolithus heteromorphus* (17.75)
18.0	C5Dr			CN2	NN3	CNM5	*S. belemnos* BZ	T *Sphenolithus belemnos* (17.96)
	C5En C5Er							
19.0	C6n	early						B *Sphenolithus belemnos* (19.01); T *Triquetrorhabdulus carinatus* (19.18)
20.0	C6r					CNM4	*H. carteri* PRZ	
	C6An			CN1c	NN2			B *Helicosphaera ampliaperta* (20.43)
21.0	C6Ar		Aquitanian					X *Helicosphaera euphratis / H. carteri* (20.89)
	C6AAr					CNM3	*H. carteri* PRZ	
22.0	C6Bn					CNM2	*S. disbelemnos / T. carinatus* CRZ	Tc *T. carinatus* (22.10); B *Sphenolithus disbelemnos* (22.41); B *Discoaster druggii* (22.59)
	C6Br					CNM1	*S. conicus* PRZ	T *Sphenolithus delphix* (23.06)
23.0	C6Cn				NN1			T *Helicosphaera recta*; B *Sphenolithus delphix* (23.38)
	C6Cr	OLIGOCENE late	Chattian	CN1b	NP25		Oligocene biozone	Ta *Cyclicargolithus abisectus*
24.0				CN1a				

Fig. 2. Miocene through Pleistocene biozones and biohorizons are plotted versus the biozonations of Martini (1971) and Okada and Bukry (1980), and the Geomagnetic Polarity Time Scale (GPTS; Lourens et al. 2004). Abbreviations are explained in the text and in Table 1. Zancl. = Zanclean.

Table 2   Age estimates of biohorizons. Biohorizons defining biozone boundaries are marked in bold. mcd – meters composite depth. Acronyms used for depth and age columns are: SC97 – Shackleton and Crowhurst 1997; DAS95 – Schneider 1995; LL04 – Lourens et al. 2004; PÄL06 – Pälike et al. 2006; PÄL07 – Pälike et al. 2007.

			Depth		ODP	Interpolation between		Interpolation between		Rate	Age	
Event	Species	Reference	mcd	± m	Hole	Upper Depth	Lower Depth	Younger Age	Older Age	m/myr	Ma	
						SC97	SC97	SC97	SC97			
B	*C. larrymayeri*	Backman & Raffi, 1997	161.46	0.05	926A	161.21	161.41	5.32	5.34	10.0	5.35	
B	***C. acutus***	Backman & Raffi, 1997	162.16	0.05	926A	161.71	162.71	5.34	5.39	20.0	**5.36**	
B	*C. atlanticus*	Backman & Raffi, 1997	162.66	0.05	926A	161.71	162.71	5.34	5.39	20.0	5.39	
T	***D. quinqueramus***	Backman & Raffi, 1997	165.49	0.10	926C	165.46	165.91	5.53	5.55	22.5	**5.53**	
T	***N. amplificus***	Backman & Raffi, 1997	175.66	0.05	926C	175.56	176.06	5.98	6.00	25.0	**5.98**	
B	***N. amplificus***	Backman & Raffi, 1997	190.94	0.05	926B	190.71	191.01	6.80	6.82	15.0	**6.82**	
						DAS95	DAS95	LL04	LL04			
						C3An.2n (o)[1]	C3Bn (y)	C3An.2n (o)	C3Bn (y)			Mean age
B	*N. amplificus*	Raffi & Flores, 1995	39.19	0.15	844B	38.65	41.00	6.73	7.140	5.8	6.83	844/845
B	*N. amplificus*	Raffi & Flores, 1995	96.50	0.22	845A	96.28	101.18	6.73	7.140	12.0	6.75	6.79
						SC97	SC97	SC97	SC97			
Ta	*R. pseudoumbilicus*	Backman & Raffi, 1997	195.14	0.05	926B	195.11	195.76	7.09	7.14	13.0	7.09	
						DAS95	DAS95	LL04	LL04			
						C3An.2n (o)	C3Bn (y)	C3An.2n (o)	C3Bn (y)			Mean age
Ta	*R. pseudoumbilicus*	Raffi & Flores, 1995	40.99	0.15	844B	38.65	41.00	6.73	7.140	5.8	7.14	844/845
Ta	*R. pseudoumbilicus*	Raffi & Flores, 1995	99.26	0.28	845A	96.28	101.18	6.73	7.140	12.0	6.98	7.06
						SC97	SC97	SC97	SC97			
B	***A. primus***	Backman & Raffi, 1997	199.79	0.05	926A	198.91	200.01	7.35	7.40	22.0	**7.39**	
						DAS95	DAS95	LL04	LL04			
						C3Bn (y)	C4n.1n (y)	C3Bn (y)	C4n.1n (y)			Mean age
B	*A. primus*	Raffi & Flores, 1995	42.65	0.30	844B	41.80	43.15	7.140	7.528	3.5	7.38	844/845
B	*A. primus*	Raffi & Flores, 1995	106.18	1.50	845A	101.18	108.06	7.140	7.528	17.7	7.42	7.40
						SC97	SC97	SC97	SC97			
B	***D. berggrenii***	Backman & Raffi, 1997	217.60	0.56	926B/C	198.91	200.01	7.35	7.40	22.0	**8.20**	
						DAS95	DAS95	LL04	LL04			
						C4n.2n (o)	C4An (y)	C4n.2n (o)	C4An (y)			Mean age
B	*D. berggrenii*	Raffi & Flores, 1995	53.30	1.15	844C	49.95	56.75	8.108	8.769	10.3	8.43	844/845
	D. berggrenii	Raffi & Flores, 1995	126.41	0.25	845A	119.28	129.71	8.108	8.769	15.8	8.56	8.50
						SC97	SC97	SC97	SC97			
Ba	***R. pseudoumbilicus***	Backman & Raffi, 1997	225.51	0.20	926B	225.31	225.71	8.79	8.81	20.0	**8.80**	
T	***D. hamatus***	Backman & Raffi, 1997	237.77	0.35	926B	237.51	238.16	9.63	9.67	16.3	**9.65**	
T	*C. calyculus*	Backman & Raffi, 1997	237.87	0.05	926B	237.51	238.16	9.63	9.67	16.3	9.65	
T	*C. coalitus*	Backman & Raffi, 1997	238.67	0.05	926B	238.16	239.41	9.67	9.74	17.9	9.70	
B	*D. neohamatus*	Backman & Raffi, 1997	249.22	0.05	926B	248.61	249.31	10.43	10.48	14.0	10.47	
B	***D. hamatus***	Backman & Raffi, 1997	249.62	0.15	926B	249.31	250.31	10.48	10.52	25.0	**10.49**	
						DAS95	DAS95	LL04	LL04			
						C4n.2n (o)	C4An (y)	C4n.2n (o)	C4An (y)			
T	*C. miopelagicus* (Pacific)	Raffi & Flores, 1995	159.20	0.15	845B	150.80	166.05	9.987	11.118	13.5	10.61	
						SC97	SC97	SC97	SC97			
B	*C. calyculus*	Backman & Raffi, 1997	252.65	0.15	926A	252.26	252.96	10.68	10.73	14.0	10.71	
B	***C. coalitus***	Backman & Raffi, 1997	253.65	0.05	926A	253.36	254.26	10.77	10.84	12.9	**10.79**	
T	*C. miopelagicus* (Atlantic)	Backman & Raffi, 1997	255.45	0.15	926A	255.41	255.91	10.94	10.98	12.5	10.94	
Tc	***D. kugleri***	Backman & Raffi, 1997	262.96	0.05	926A	262.96	262.96	11.60	11.60	n/a	**11.60**	
Bc	***D. kugleri***	Backman & Raffi, 1997	266.16	0.05	926A	266.11	266.51	11.88	11.90	20.0	**11.88**	
Tc	***C. premacintyrei***	This study	276.77	0.05	926B	275.46	277.66	12.46	12.64	12.2	**12.57**	
T	***S. heteromorphus***	Backman & Raffi, 1997	294.06	0.20	926B	294.00	294.40	13.53	13.55	20.0	**13.53**	
						Heiko Pälike, personal communication, 2011						
T	*H. ampliaperta*	Curry, Shackleton et al., 1995	366.72	0.38	925D	366.43	367.14	14.85	14.87	28.4	14.86	
Tc	*D. deflandrei*	This study	395.89	0.05	925D	395.24	396.09	15.66	15.70	21.8	15.69	
B	***D. signus***	This study	396.92	0.08	925D	396.09	397.14	15.70	15.74	25.6	**15.73**	
B	***S. heteromorphus***	This study	346.91	0.10	926B	346.83	346.93	17.73	17.74	6.3	**17.74**	
						PÄL07	PÄL07	PÄL07	PÄL07			
T	*S. belemnos*	This study	352.01	0.50	926B	351.93	352.13	17.934	17.941	28.6	17.94	
B	***S. belemnos***	Curry, Shackleton et al., 1995	382.88	0.55	926B	382.83	382.93	19.006	19.010	25.0	**19.01**	

[1]   (y) – younger side of geomagnetic polarity chron; (o) – older side of geomagnetic polarity chron.

Table 2   Age estimates of biohorizons. Biohorizons defining biozone boundaries are marked in bold. mcd – meters composite depth. Acronyms used for depth and age columns are: SC97 – Shackleton and Crowhurst 1997; DAS95 – Schneider 1995; LL04 – Lourens et al. 2004; PÄL06 – Pälike et al. 2006; PÄL07 – Pälike et al. 2007.

			rmcd[3]			PÄL06[4]	PÄL06	PÄL06	PÄL06		
T	*T. carinatus*	Pälike et al., 2005	63.63	1.28	1218A	62.35	64.91	19.013	19.353	7.5	**19.18**
						PÄL07	PÄL07	PÄL07	PÄL07		
B	*H. ampliaperta*	Curry, Shackleton et al., 1995	421.46	0.35	926B	421.41	421.51	20.423	20.427	25.0	20.43
X	***H. euphratis/ H. carteri***	Fornaciari, 1996[2]	435.51	0.40	926B	435.41	435.61	20.890	20.897	28.6	**20.89**
			rmcd			PÄL06	PÄL06	PÄL06	PÄL06		
Tc	***T. carinatus***	This study	87.21	0.05	1218A	87.18	87.23	22.101	22.106	10.0	**22.10**
B	***S. disbelemnos***	This study	90.51	0.25	1218A	90.51	90.51	22.413	22.413	n/a	**22.41**
B	*D. druggii* (Pacific)[5]	Pälike et al., 2006	96.46	0.20	1218A	92.46	92.46	22.592	22.592	n/a	22.59
T	***S. delphix***	This study	96.65	0.05	1218B	96.65	96.65	23.062	23.062	n/a	**23.06**
B	*S. delphix*	This study	100.65	0.05	1218A	100.27	100.77	23.345	23.390	11.1	23.38

[2]   Unpublished PhD thesis; plot shown in this study.
[3]   Pälike et al. (2005); rmcd – revised meters composite depth.
[4]   http://doi.pangaea.de/10.1594/PANGAEA.547797; Pälike et al. (2006, reference 7).
[5]   This biohorizon occurs < 3 m above Top *S. delphix* in the Indian Ocean, ODP Hole 709C (Fornaciari 1996; see [2] above).

zon to the disappearance of *T. carinatus*. Okada and Bukry (1980) employed the interval between the disappearances of *Sphenolithus ciperoensis* and *Dictyococcites bisectus* and the end of the "acme" of *Cyclicargolithus abisectus* to define Subzone CN1a, the interval between the *C. abisectus* biohorizon and the appearance of *D. druggii* to define Subzone CN1b, and the interval between the *D. druggii* biohorizon and the appearance of *Sphenolithus belemnos* to define Subzone CN1c. However, the biohorizons provided by *H. recta*, *D. druggii*, *T. carinatus*, *D. bisectus* and *C. abisectus* all show problematic distributions, as expressed, for example, by Rio et al. (1990b, p. 182–183): "*Helicosphaera recta* rarely occur in oceanic sediments [...] because *H. recta* and *D. bisectus* are rare, the established relationships may be of only local value". They also remark that "no acme was recognized [...] of *C. abisectus*. Medium-sized *C. abisectus* are distributed as high as up as the lower part of Zone NN4, with no increase in abundance evident in the interval between the LO of *S. ciperoensis* and the FO of *D. druggii*." Rio et al. furthermore discuss the problems of the sporadic occurrences of *D. druggii*, and noticed the "short acme interval of *Sphenolithus delphix*, slightly below the FO of *D. druggii*, at all the sites investigated". At Site 709 in the tropical Indian Ocean, *D. druggii* appears < 3 m above the disappearance of *S. delphix* within a single core (Core 709C-21X) (Fornaciari 1996). This suggests that *D. druggii* has a time transgressive appearance, probably occurring a few hundred thousand years earlier in the tropi-

cal Indian Ocean compared to its first rare occurrences in the central tropical Pacific Ocean (Table 4). In conclusion, the set of biohorizons employed by Martini (1971) and Okada and Bukry (1980) for biostratigraphic subdivision of the uppermost Oligocene through lowermost Miocene stratigraphy is presently considered to be of limited quality.

An abundance plot of the two taxa used for defining Zone CNM1 is shown in Figure 3. The Oligocene-Miocene boundary at 23.030 Ma (Lourens et al. 2004) falls 30 ka after the onset of Zone CNM1 (Fig. 2), shortly after the disappearance of *S. delphix*.
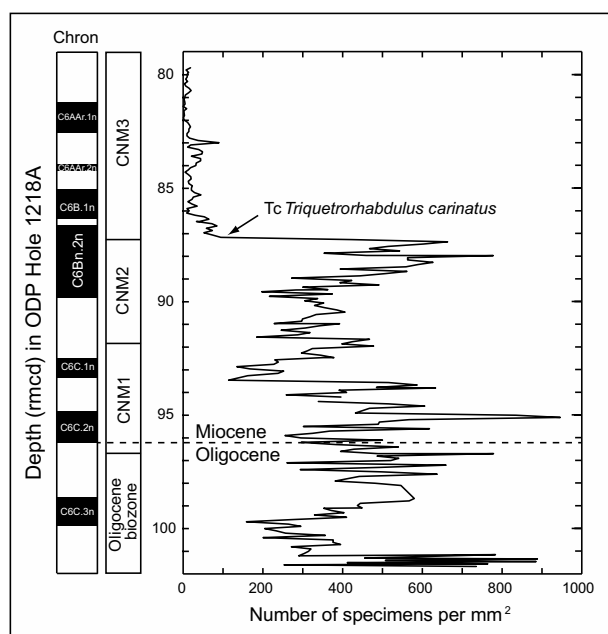
Name: Zone CNM2 – *Triquetrorhabdulus carinatus/ Sphenolithus disbelemnos* Concurrent Range Zone
Definition: Concurrent range of the nominate taxa between the Base of *S. disbelemnos* and the Top of common *T. carinatus*.
Reference section: ODP Site 1218 (central part of tropical Pacific Ocean)
Estimated age: 22.41 Ma – 22.10 Ma (Fig. 2, Table 2)
Duration: 0.31 million years
Remarks: This zone corresponds to the lower parts of both Zone NN2 of Martini (1971) and Subzone CN1c of Okada and Bukry (1980), respectively.
Remarks on assemblages: In this short biostratigraphic interval, the nominate taxon *S. disbelemnos* is not particularly abundant but is consistently recorded in the low latitude Indian, Pacific and Atlantic oceans (Rio et al. 1990 – referred to as *S. dissimilis – S. belemnos* intergrade; Fornaciari et al. 1993 – referred to as

S. dissimilis/S. belemnos; Pälike et al. 2006, Shackleton et al. 2000), and in the Mediterranean region, including the Oligocene/Miocene GSSP Section of Lemme Carrosio (Fornaciari and Rio 1996, Raffi 1999). An abrupt decrease in abundance of *T. carinatus* has been observed well prior to its exinction in lower latitudes, which provides a more distinct biohorizon than its final disappearance. At ODP Site 1218 (Fig. 4), the decrease occurs over a 10 cm interval, from an average of 24 specimens per mm^2 in 79 samples above the decrease to an average of 415 specimens per mm^2 in 149 samples below the decrease. Here, the change thus represents a factor of six decrease in abundance. The Top of common *T. carinatus* is near identical in terms of age in tropical Pacific Site 1218 (22.10 Ma, Table 2) and tropical Atlantic Site 929 (22.03 Ma, Flower et al. 1997, Shackleton et al. 2000; age estimates converted to the La_2004 astronomical solution by Heiko Pälike).

Fig. 4. The sharp 6-fold decrease in abundance of *T. carinatus* to values, here at ODP Site 1218 in the tropical Pacific Ocean, defines the Tc *T. carinatus* biohorizon. Positions of geomagnetic polarity chrons and revised meters composite depths (rmcd) are from Pälike et al. (2005). Abundances of taxa are expressed as numbers per unit area on the smear-slides investigated. The Oligocene/Miocene boundary is defined at the base of Chron C6C.2n (Lourens et al. 2004).

Fig. 3. Abundances of taxa defining biozones across the Oligocene-Miocene boundary at ODP Site 1218 in the tropical Pacific Ocean. Positions of geomagnetic polarity chrons and revised meters composite depths (rmcd) are from Pälike et al. (2005). Abundances of taxa are expressed as numbers per unit area on the smear-slides investigated.

Name: Zone CNM3 – *Helicosphaera euphratis* Partial Range Zone*

Definition: Biostratigraphic interval between the Top of common *T. carinatus* and the abundance cross-over between *H. euphratis* and *H. carteri*.

Reference section: ODP Site 1218 (lower biohorizon) and ODP Site 926 (upper biohorizon)

Estimated age: 22.10 Ma – 20.89 Ma (Fig. 2, Table 2)

Duration: 1.21 million years

Remarks: This zone corresponds to an interval in the lower part of Zone NN2 of Martini (1971) as well as of Subzone CN1c of Okada and Bukry (1980). *The use of a biohorizon provided by an abundance cross-over is a modified version of the Partial Range Zone concept as presented by Wade et al. (2011). This abundance cross-over provides a useful biohorizon, however, to subdivide the relatively poorly resolved biostratigraphic interval of the lower Miocene.

Remarks on assemblages: Data showing the cross-over between *H. euphratis* and *H. carteri* were originally presented by Fornaciari (1996), and here plotted in Figure 5.
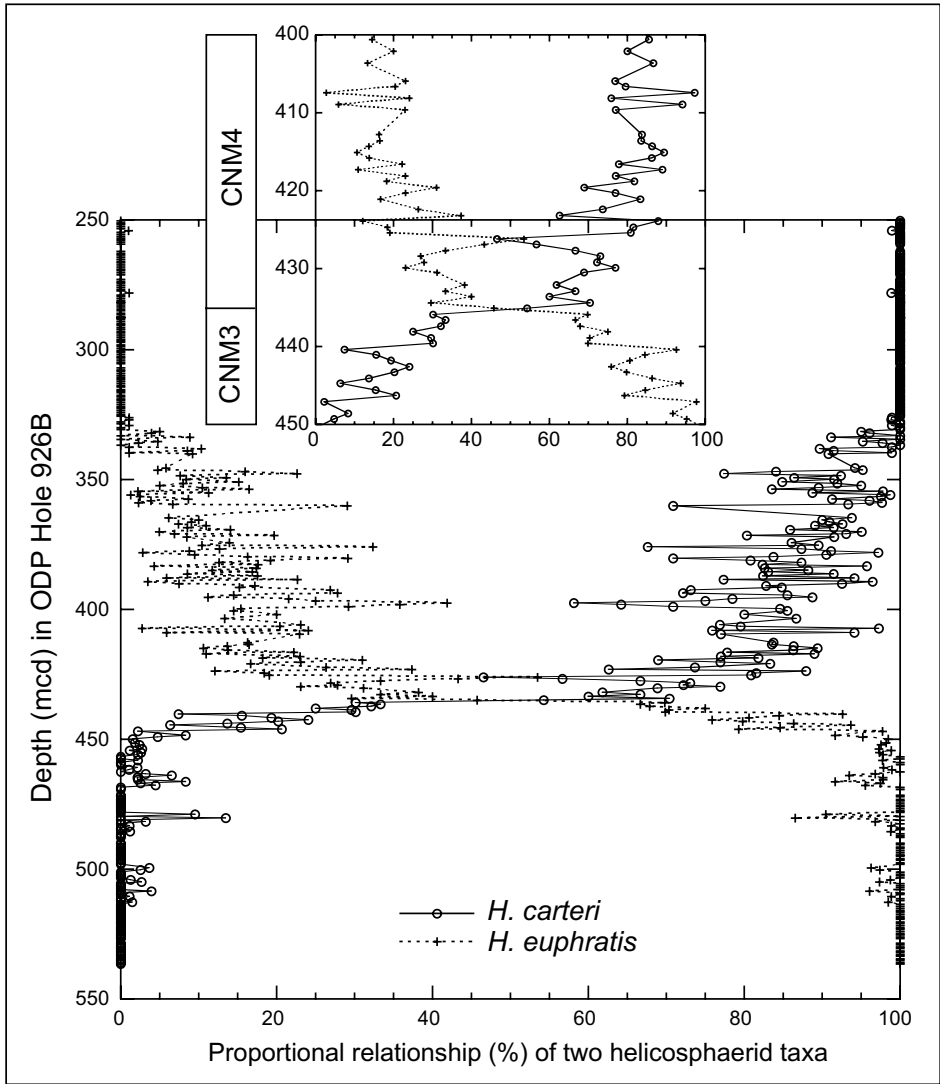
Fig. 5. Abundance cross-over between *H. euphratis* (dotted line) and *H. carteri* (solid line) from ODP Hole 926B in the western tropical Atlantic Ocean (Fornaciari 1996). Upper inserted panel shows an enlargement of the critical interval, which defines the CNM3/CNM4 biozone boundary.

Name: Zone CNM4 – *Helicosphaera carteri* Partial Range Zone*
Definition: Partial range of the nominate taxon between the abundance crossover between *H. euphratis* and *H. carteri* and the Base of *Sphenolithus belemnos*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
**Estimated age:** 20.89 Ma – 19.01 Ma (Fig. 2, Table 2)
Duration: 1.89 million years
Remarks: This zone corresponds to the upper parts of Zone NN2 of Martini (1971) and Subzone CN1c of Okada and Bukry (1980). *The use of a biohorizon

provided by an abundance cross-over is a modified version of the Partial Range Zone concept as presented by Wade et al. (2011).
Remarks on assemblages: Base of *Helicosphaera ampliaperta* occurs in the lower part of this biozone. An overlap in the ranges between *T. carinatus* and *S. belemnos* was demonstrated by Fornaciari et al. (1990) from the Indian Ocean, and by Raffi et al. (2006) from the Atlantic Ocean. Previously, Perch-Nielsen (1985, p. 443) remarked that "The FO of *S. belemnos* [...] usually is found slightly below the LO of *T. carinatus*." Low abundances in combination with sporadic occurrences of *T. carinatus* toward the

end of its range makes this marker less reliable (Raffi et al. 2006).

Name: Zone CNM5 – *Sphenolithus belemnos* Base Zone
Definition: Biostratigraphic interval between the Base of the nominate taxon *S. belemnos* and the Base of common *Sphenolithus heteromorphus*.
Reference section: ODP Site 926 (lower boundary) and ODP Site 925 (upper boundary)
Estimated age: 19.01 Ma – 17.75 Ma (Fig. 2, Table 2)
Duration: 1.26 million years
Remarks: This zone corresponds to Zone CN2 of Okada and Bukry (1980), and encompasses most of Zone NN3 of Martini (1971).
Remarks on assemblages: This biostratigraphic interval corresponds to the common and continuous range of the nominate taxon *S. belemnos* that shows a sharp decrease in abundance at the top of the biozone, occurring about 0.2 million years prior to the appearance of *S. heteromorphus* (Fig. 6). The calibration obtained for the latter biohorizon at ODP Site 926 (this study) conforms (within 0.01 million years) with the calibration suggested by shipboard data at ODP Site 925 (Curry, Shackleton et al. 1995).

Name: Zone CNM6 – *Sphenolithus heteromorphus* Base Zone
Definition: Biostratigraphic interval between the Base of the common nominate taxon *S. heteromorphus* and the Base of *Discoaster signus*.
Reference section: ODP Site 925 (western tropical Atlantic Ocean)
Estimated age: 17.75 Ma – 15.73 Ma (Fig. 2, Table 2)
Duration: 2.02 million years
Remarks: This zone approximately corresponds to the lower part of Zone NN4 of Martini (1971) and is nearly identical to Zone CN3 of Okada and Bukry (1980). The latter used the end of the acme of *D. deflandrei* to define the top of Zone CN3, whereas the appearance of *D. signus* is used here as a zonal boundary marker. Rio et al. (1990) introduced "the drop in abundance below 30% of *D. deflandrei* and the concomitant appearance of the *D. tuberi* – *D. signus* group to distinguish the NN4 (CN3) and NN5 (CN4) Zones in sites where *H. ampliaperta* is missing." The Base of *D. signus* and the Top of common (Tc) *D. deflandrei* are separated only by 0.04 million years (Table 2, Fig. 7).
Remarks on assemblages: The genus *Calcidiscus* appears within this biostratigraphic interval.
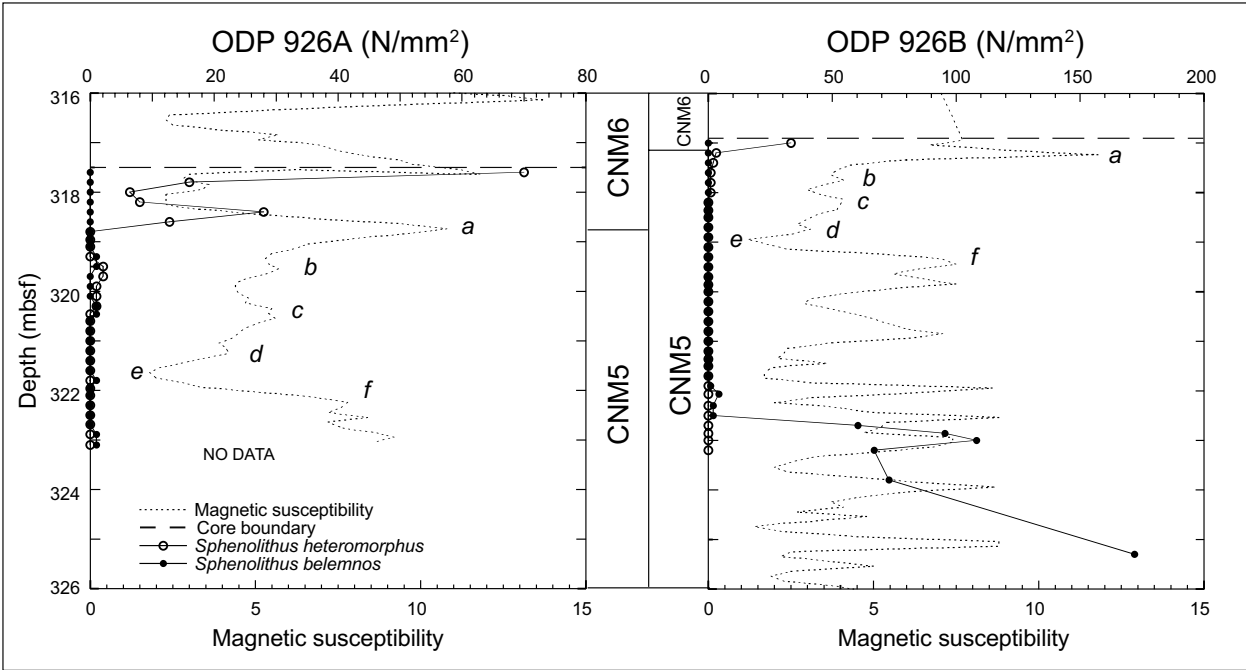
Fig. 6. Disappearance of *S. belemnos* and appearance of *S. heteromorphus* as recorded in ODP Site 926. The abundance distributions of the two taxa are expressed as number of specimens per unit area of the smear-slide (N/mm²). Peaks and troughs "a" to "f" in magnetic susceptibility shows a striking correlation between Holes 926A and 926B in a critical interval.
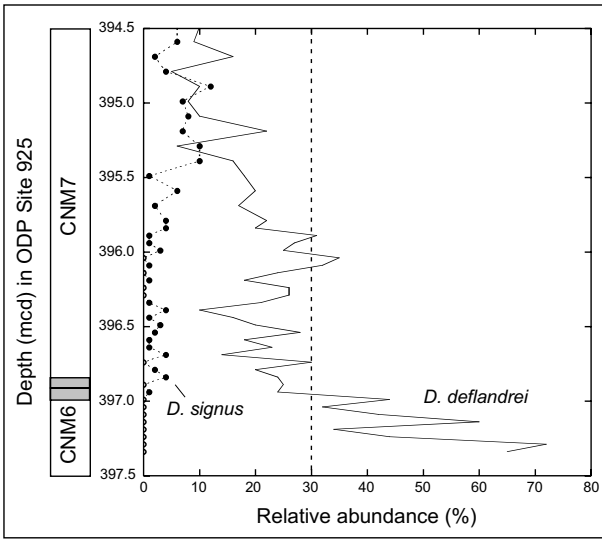
Fig. 7. Appearance of *D. signus* and sharp decrease in abundance of *D. deflandrei* in ODP Site 925 from the western tropical Atlantic Ocean. Both categories represent relative abundances versus the total number of all *Discoaster* spp.
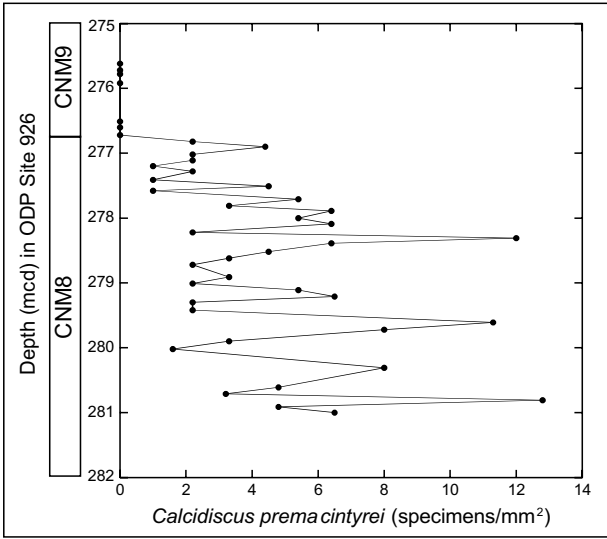
Fig. 8. Disapperance of *C. premacintyrei* as recorded in ODP Hole 926B.

Name: Zone CNM7 – *Discoaster signus/Sphenolithus heteromorphus* Concurrent Range Zone

Definition: Biostratigraphic interval between the Base of the nominate taxon *D. signus* and the Top of *S. heteromorphus*.

Reference section: ODP Site 925 (lower boundary) and ODP Site 926 (upper boundary)

Estimated age: 15.73 Ma – 13.53 Ma (Fig. 2, Table 2)

Duration: 2.20 million years

Remarks: The upper part of this zone corresponds to Zone NN5 of Martini (1971). Zone CN4 of Okada and Bukry (1980) used two biohorizons to define the base of Zone CN4 (*Sphenolithus heteromorphus* Zone), namely Top common *D. deflandrei* and Top *Helicosphaera ampliaperta*, which are separated by about 0.8 million years (Table 2). Here, Top *H. ampliaperta* it is not used for a zonal boundary marker due to the discontinuous and scattered distribution in its upper range. The appearance of *D. signus* occurs close to the distinct decrease in abundance (Tc) of *D. deflandrei* in the tropical Indian, Pacific and Atlantic (Fig. 7) oceans, and in the mid-latitude South Atlantic (Rio et al. 1990, Shackleton et al. 1995, Raffi et al. 2006, Zachos et al. 2004).

Remarks on assemblages: *Calcidiscus premacintyrei* appears and gradually increase in abundance within this biostratigraphic interval. In Mediterranean sections, the upper part of this biostratigraphic interval is characterised by the common presence of the small *Helicosphaera walbersdorfensis*, that provides a useful biohorizon for regional biostratigraphy (Fornaciari et al. 1996).

There exists some confusion regarding the taxonomic status of *D. signus*. We consider that *D. signus* is a valid species and that *Discoaster petaliformis* Moshkovitz and Ehrlich (1980) and *D. tuberi* (Filewicz 1985) both are junior synonyms of *D. signus* Bukry (1971). In Nannotax (http://nannotax.org/content/discoaster-petaliformis, December 2011), however, it is argued that "This form was independently illustrated by Filewicz (1985) as *D. tuberi*; Theodoridis (1984) as *D. signus*, and Moshkovitz & Ehrlich (1980) as *D. petaliformis*. The forms illustrated are of the same age (NN4–5) and extremely similar. They are clearly the same taxon, and given their distinctive form and restricted range it is useful to distinguish them. *D. signus* is an inappropriate name for them, since *D. signus* as described by Bukry (1971) lacks central knobs." The last statement is inconsistent with Bukry's (1971, p. 48) description: "a prominent knob forms the hub for the six equally spaced rays". And under remarks, Bukry continues: "The long slender bifurcation at the end of the rays and the prominent central knob in association with the long slender rays combine to produce the diagnostic appearance of the species".

Name: Zone CNM8 – *Calcidiscus premacintyrei* Top Zone

Definition: Biostratigraphic interval between the Top of *S. heteromorphus* and the Top of continuous nominate taxon *C. premacintyrei*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 13.53 Ma – 12.57 Ma (Fig. 2, Table 2)
Duration: 0.96 million years
Remarks: This zone corresponds to the lower parts of both Zone NN6 of Martini (1971) and Subzone CN5a of Okada and Bukry (1980).
Remarks on assemblages: The final part of the range of *Calcidiscus premacintyrei* is shown in Figure 8. *Cyclicargolithus floridanus* sharply decreases in abundance, while *Reticulofenestra pseudoumbilicus* and *Triquetrorhabdulus rugosus* begin to occur continously within this biostratigraphic interval. Specimens belonging to the *Discoaster exilis* group prevail within the *Discoaster* assemblages of the biozone.

Name: Zone CNM9 – *Discoaster variabilis* Partial Range Zone
Definition: Partial range of the nominate taxon between the Top of common *C. premacintyrei* and the Base of common *Discoaster kugleri*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 12.57 Ma – 11.88 Ma (Fig. 2, Table 2)
Duration: 0.68 million years
Remarks: This zone corresponds to the upper parts of both Zone NN6 of Martini (1971) and Subzone CN5a of Okada and Bukry (1980).
Remarks on assemblages: The successive disappearances of *Coronocyclus nitescens*, *Cyclicargolithus floridanus*, and *Triquetrorhabdulus serratus*, occur within this biozone, whereas *Calcidiscus macintyrei* gradually increases in abundance.

Name: Zone CNM10 – *Discoaster kugleri* Total Range Zone
Definition: Biostratigraphic interval characterised by the total range of common nominate taxon *D. kugleri*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 11.88 Ma – 11.60 Ma (Fig. 2, Table 2)
Duration: 0.28 million years
Remarks: This zone corresponds to the lowermost parts of both Zone NN7 of Martini (1971) and Subzone CN5b of Okada and Bukry (1980).
Remarks on assemblages: Among the *Discoaster* assemblages, six-ray stubby forms prevail, including *D. kugleri*, *Discoaster musicus* and *Discoaster bollii*.

The interval of common and continuous presence of *D. kugleri* has been observed in the tropical Pacific, mid-latitude northern and tropical Atlantic, and in the Mediterranean (Raffi et al. 1995, Backman and Raffi 1997, Hilgen et al. 2003).

Name: Zone CNM11 – *Discoaster exilis* Partial Range Zone
Definition: Partial range of the nominate taxon between the Top of common *D. kugleri* and the Base of *Catinaster coalitus*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 11.60 Ma – 10.79 Ma (Fig. 2, Table 2)
Duration: 0.81 million years
Remarks: This zone encompasses the upper 80% of both Zone NN7 of Martini (1971) and Subzone CN5b of Okada and Bukry (1980).
Remarks on assemblages: In the tropical Atlantic and the Mediterranean, *Coccolithus miopelagicus* disappears within upper CNM11. In the tropical Pacific, however, this species disappears within Zone CNM12, about 0.33 million years later. In the Mediterranean sections, the disappearance of representatives of small helicoliths, such as *H. walbersdorfensis* and *Helicosphaera stalis*, occurs within this biostratigraphic interval and provides biohorizons useful for regional biostratigraphy (Fornaciari et al. 1996).

Name: Zone CNM12 – *Catinaster coalitus* Base Zone
Definition: Biostratigraphic interval between the Base of the nominate taxon *C. coalitus* and the Base of *Discoaster hamatus*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 10.79 Ma – 10.49 Ma (Fig. 2, Table 2)
Duration: 0.30 million years
Remarks: This zone corresponds to Zones NN8 of Martini (1971) and CN6 of Okada and Bukry (1980).
Remarks on assemblages: This short biostratigraphic interval marks the beginning of a series of subsequent appearances and extinctions of taxa, occurring troughout the late Miocene. It is characterised by the appearance of the first star-shaped asteroliths with pointed slender rays, namely *Discoaster brouweri* (6 rays) and *Discoaster bellus* (5 rays), and the presence of *Discoaster calcaris*. The genus *Catinaster* evolves within the biozone, whereas *D. exilis* disappears in its upper part.

Name: Zone CNM13 – *Discoaster hamatus* Total Range Zone

Definition: Biostratigraphic interval characterised by the total range of the nominate taxon *D. hamatus*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 10.49 Ma–9.65 Ma (Fig. 2, Table 2)
Duration: 0.84 million years
Remarks: This zone corresponds to Zones NN9 of Martini (1971) and CN7 of Okada and Bukry (1980).
Remarks on assemblages: Shortly after the appearance of the nominate taxon *D. hamatus*, the six-rayed *Discoaster neohamatus* occurs. *Discoaster bollii*, *C. coalitus* and *Catinaster calyculus* disappear close to the top of the biozone.

Name: Zone CNM14 – *Reticulofenestra pseudoumbilicus* Partial Range Zone*
Definition: Partial range of the nominate taxon between the Top of *D. hamatus* and the Base of the interval of absence (Ba) of *R. pseudoumbilicus*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 9.65 Ma–8.80 Ma (Fig. 2, Table 2)
Duration: 0.85 million years
Remarks: This zone corresponds to the lower parts of Zone NN10 of Martini (1971) and Zone CN8 of Okada and Bukry (1980), respectively. Bukry (1978) used the appearance of both *Discoaster neorectus* and *Discoaster loeblichii* to define the top of the *Discoaster bellus* Subzone (top of CN8a). Among the adjacent biohorizons (Base *D. loeblichii*, Base *D. neorectus*, or Base *Discoaster pentaradiatus*) the Base of absence interval (Ba) of *R. pseudoumbilicus* is here considered to represent a more useful criterion for zonal boundary definition.
Remarks on assemblages: *Minylitha convallis* and *Discoaster pentaradiatus* appear within this biozone. *The use of the Ba concept for defining the top of this biozone differs from the strict definition of a Partial Range Zone as presented by Wade et al. (2011).

Name: Zone CNM15 – *Discoaster bellus* Base Zone*
Definition: Biostratigraphic interval between the Base of the interval of absence of *R. pseudoumbilicus* and the Base of *Discoaster berggrenii*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 8.80 Ma–8.20 Ma (Fig. 2, Table 2)
Duration: 0.60 million years
Remarks: This zone corresponds to the upper parts of Zone NN10 of Martini (1971) and Zone CN8 of Okada and Bukry (1980), respectively. *The use of the

Base absence concept for definition of the base of this biozone differs from the strict definition of a Base Zone as presented by Wade et al. (2011).
Remarks on assemblages: The interval of almost total absence of *R. pseudoumbilicus* in upper Miocene sediments (the so-called "*R. pseudoumbilicus* paracme") has been observed in different ocean basins, from the tropical Indian, Pacific and Atlantic oceans to the Mediterranean (Rio et al. 1990b, Gartner 1992, Takayama 1993, Young 1990, Raffi and Flores 1995, Backman and Raffi 1997, Raffi et al. 2003). *Discoaster bellus* and transitional forms between this species and *Discoaster berggrenii* occur within the biozone. This biozone also holds, e. g., in the tropical Pacific Ocean, the short-ranging *Discoaster loeblichii* and *Discoaster neorectus*, which Bukry (1978) used in his biozonation.

Name: Zone CNM16 – *Discoaster berggrenii* Base Zone
Definition: Biostratigraphic interval between the Base of the nominate taxon *D. berggrenii* and the Base of *Amaurolithus primus*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 8.20 Ma–7.39 Ma (Fig. 2, Table 2)
Duration: 0.81 million years
Remarks: This zone corresponds to the lower part of Zone NN11 of Martini (1971) and Subzone CN9a of Okada and Bukry (1980).
Remarks on assemblages: *Discoaster quinqueramus* appears just after the nominate taxon *D. berggrenii* and, with *Discoaster surculus*, characterises the *Discoaster* assemblages. *Minylitha convallis* disappears within this biozone.

Name: Zone CNM17 – *Amaurolithus primus* Base Zone
Definition: Biostratigraphic interval between the Base of the nominate taxon *Amaurolithus primus* and the Base of *Nicklithus amplificus*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 7.39 Ma–6.82 Ma (Fig. 2, Table 2)
Duration: 0.57 million years
Remarks: This zone corresponds to the middle part of Zone NN11 of Martini (1971) and to Subzone CN9b of Okada and Bukry (1980).
Remarks on assemblages: The beginning of the late Neogene horseshoe-shaped nannolith composite lineage (*Amaurolithus – Nicklithus – Ceratolithus*) marks

the Base of this biozone, by the genus *Amaurolithus* evolving from *Triquetrorhabdulus rugosus* (Raffi et al. 1998). The appearance of *Amaurolithus primus* is closely followed by *Amaurolithus delicatus*. The interval of absence of *R.pseudoumbilicus* ends within this biozone (Ta *R.pseudoumbilicus* biohorizon in Fig. 2).

Name: Zone CNM18 – *Nicklithus amplificus* Total Range Zone
Definition: Biostratigraphic interval characterised by the total range of the nominate taxon *N.amplificus*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 6.82 Ma – 5.98 Ma (Fig. 2, Table 2)
Duration: 0.83 million years
Remarks: This zone corresponds to an interval in the upper part of Zone NN11 of Martini (1971), and to the middle part of Subzone CN9b of Okada and Bukry (1980).
Remarks on assemblages: The short range of *N.amplificus*, bracketing Chron C3An, shows isochrony among tropical locations (Krijgsman et al. 1999). *Amaurolithus primus*, *A.delicatus*, and related transitional forms, characterise the nannofossil assemblages of this biozone.

Name: Zone CNM19 – *Discoaster quinqueramus* Top Zone
Definition: Biostratigraphic interval between the Top of *N.amplificus* and the Top of the nominate taxon *D.quinqueramus*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 5.98 Ma – 5.53 Ma (Fig. 2, Table 2)
Duration: 0.45 million years
Remarks: This zone corresponds to the uppermost parts of Zone NN11 of Martini (1971) and Subzone CN9b of Okada and Bukry (1980), respectively.
Remarks on assemblages: *Discoaster quinqueramus* is a major component of the *Discoaster* assemblages in the uppermost Miocene interval, where it gradually replaces *D.berggrenii*. Transitional forms between the two species are frequent in this biozone, together with *D.pentaradiatus*, *D.surculus*, *D.variabilis*, and very large (> 30 μm) specimens of *D.brouweri*.

Name: Zone CNM20 – *Triquetrorhabdulus rugosus* Partial Range Zone
Definition: Partial range of the nominate taxon between the Top of *D.quinqueramus* and the Base of *C.acutus*.

Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 5.53 Ma – 5.36 Ma (Fig. 2, Table 2)
Duration: 0.17 million years
Remarks: This zone corresponds to the lowermost part of Zone NN12 of Martini (1971) and to Subzone CN10a of Okada and Bukry (1980).
Remarks on assemblages: Horseshoe-shaped nannoliths of the genus *Ceratolithus* evolve within this biostratigraphic interval, branching from *T.rugosus* (Raffi et al. 1998). Different species of the *Ceratolithus* lineage characterise the nannofossil assemblages in the lower Pliocene interval.

5.   Biozone definitions in the Pliocene – Pleistocene – Recent interval

The definitions of the CNPL biozones are summarized in Table 3. Age estimates of zonal boundary markers and additional biohorizons in the Pliocene-Pleistocene interval are summarized in Table 4. The average error of age estimates for the 27 Pliocene-Pleistocene biohorizons is ± 0.007 million years, as deduced from Table 4 (depth uncertainty divided by sedimentation rate). An overview of the CNPL zonation in a chronostratigraphic context, and comparison with Okada and Bukry's (1980) and Martini's (1971) Pliocene-Pleistocene zonations, is shown in Figure 9.

Name: Zone CNPL1 – *Ceratolithus acutus* Taxon Range Zone
Definition: Biostratigraphic interval characterised by the total range of the nominate taxon *C.acutus*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 5.36 Ma – 5.05 Ma (Fig. 9, Table 4)
Duration: 0.31 million years
Remarks: This zone corresponds approximately to the upper part of Zone NN12 of Martini (1971), who used the appearance of *Ceratolithus rugosus* to define Base NN12. This zone corresponds to Subzone CN10b of Okada and Bukry (1980), although Bukry (1978) used four taxa to define the subzonal boundaries which were subsequently employed by Okada and Bukry (1980): its base by the appearance of *C.acutus* and the disappearance of *Triquetrorhabdulus rugosus*, and its top by the disappearance of *C.acutus* and the appear-

ance of *C. rugosus*. These two pairs of bioevents are separated in time by 30 ka (top Subzone CN10b) and 130 ka (base Subzone CN10b) (Table 2), respectively. The Miocene–Pliocene boundary at 5.332 Ma (Lourens et al. 2004) falls shortly (28 ka) after the onset of Zone CNPL1.

Remarks on assemblages: Within this biozone, the peculiar species *Ceratolithus atlanticus* and *Ceratolithus larrymayeri* (Raffi et al. 1998) occur concomi-tantly with the disappearance of *T. rugosus*, in a short distinct interval that precedes the appearance of *Ceratolithus rugosus*.

Name: Zone CNPL2 – *Sphenolitus neoabies* Partial Range Zone
Definition: Partial range of the nominate taxon between the Top of *C. acutus* and the Base of common *Discoaster asymmetricus*.
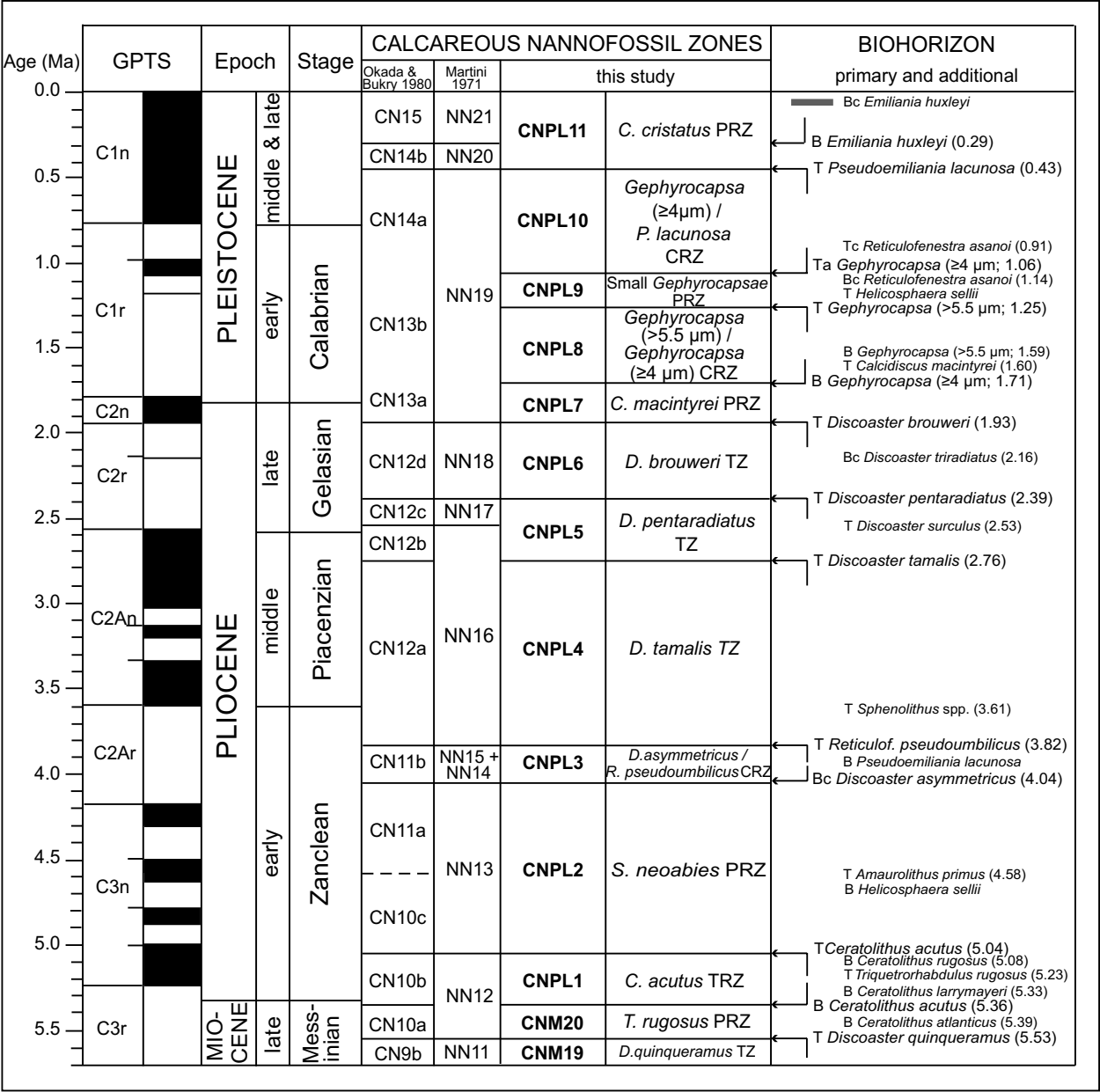
Fig. 9. Pliocene and Pleistocene biozones and biohorizons plotted versus "standard" zonations (Okada and Bukry 1980, Martini 1971) and the Geomagnetic Polarity Time Scale (GPTS; Lourens et al. 2004). Abbreviations are explained in the text. Middle and late Pleistocene stages are not yet formally defined. Bc *Emiliania huxleyi* is time transgressive (Thierstein et al. 1977), and marked with an interval rather than a line.

Table 3   Biohorizons used for definitions of Pliocene and Pleistocene biozones.

Marker Taxon for Base of Zone	Type of Event	Marker Taxon for Top of Zone	Type of event	Biozone*	Code
Pseudoemiliania lacunosa	Top	(The Recent)	n/a	*C. cristatus* PRZ	CNPL11
Gephyrocapsa spp. ≥4 μm	Top absence	*Pseudoemiliania lacunosa*	Top	*Gephyrocapsa* (≥4 μm) / *P. lacunosa* PRZ	CNPL10
Gephyrocapsa spp. >5.5 μm	Base	*Gephyrocapsa* spp. ≥4 μm	Top absence	Small *Gephyrocapsa* PRZ	CNPL9
Gephyrocapsa spp. ≥4 μm	Base	*Gephyrocapsa* spp. >5.5 μm	Top	*Gephyrocapsa* (>5.5 μm) / *Gephyrocapsa* (≥4 μm) CRZ	CNPL8
Discoaster brouweri	Top	*Gephyrocapsa* spp. ≥4 μm	Base	*C. macintyrei* PRZ	CNPL7
Discoaster pentaradiatus	Top	*Discoaster brouweri*	Top	*D. brouweri* TZ	CNPL6
Discoaster tamalis	Top	*Discoaster pentaradiatus*	Top	*D. pentaradiatus* TZ	CNPL5
Reticulofenestra pseudoumbilicus	Top	*Discoaster tamalis*	Top	*D. tamalis* TZ	CNPL4
Discoaster asymmetricus	Base common	*Reticulofenestra pseudoumbilicus*	Top	*D. asymmetricus / R. pseudoumbilicus* CRZ	CNPL3
Ceratolithus acutus	Top	*Discoaster asymmetricus*	Base common	*S. neoabies* PRZ	CNPL2
Ceratolithus acutus	Base	*Ceratolithus acutus*	Top	*C. acutus* TRZ	CNPL1

*Taxon Range Zone (TRZ), Concurrent Range Zone (CRZ), Base Zone (BZ), Top Zone (TZ), Partial Range Zone (PRZ)

Table 4   Age estimates of biohorizons. Biohorizons defining biozone boundaries are marked in bold. mcd – meters composite depth. Acronyms used for depth and age columns are: VG90 – Vergnaud Grazzini et al. 1990; LR05 – Lisiecki and Raymo 2005; RAY89 – Raymo et al. 1989; SC97 – Shackleton and Crowhurst 1997.

			Depth		DSDP/ODP	Interpolation between		Interpolation between		Rate	Age
Event	Species	Reference	mcd	± m	Hole	Upper Depth	Lower Depth	Younger Age	Older Age	m/myr	Ma
						VG90 (7/8)[1]	VG90 (8/9)[1]	LR05	LR05		
B	*E. huxleyi*	Rio et al., 1990	15.60	0.30	653A	12.50	16.50	243	300	0.1	0.29
						SC97	SC97	SC97	SC97		
T	***P. lacunosa***	This study	16.61	0.05	926C	16.05	16.95	0.42	0.44	45.0	**0.43**
T	*R. asanoi*	Raffi, 2002	30.52	0.15	926C	29.90	31.15	0.90	0.93	41.7	0.91
Ta	*Gephyrocapsa* (≥4 μm)	Raffi, 2002	34.58	0.05	926B	34.50	35.20	1.06	1.08	35.0	**1.06**
Bc	*R. asanoi*	Raffi, 2002	36.66	0.05	926C	36.60	37.55	1.14	1.18	23.7	1.14
						RAY89 (36/37)[1]	RAY89 (37/38)[1]	LR05	LR05		
T	*H. sellii* (Atlantic)	Raffi et al., 1993	50.60	0.23	607	49.81	50.63	1.215	1.244	28.3	1.24
						SC97	SC97	SC97	SC97		
T	***Gephyrocapsa* (>5.5 μm)**	Raffi, 2002	39.36	0.05	926C	38.55	39.50	1.22	1.25	31.7	**1.25**
B	*Gephyrocapsa* (>5.5 μm)	Raffi, 2002	50.00	0.25	926C	48.80	50.30	1.56	1.60	37.5	1.59
T	*C. macintyrei*	Raffi, 2002	50.40	0.05	926C	50.30	51.55	1.60	1.63	41.7	1.60
B	***Gephyrocapsa* (≥4 μm)**	Raffi, 2002	53.85	0.10	926B	53.75	54.45	1.71	1.73	35.0	**1.71**
T	***D. brouweri***	Curry, Shackleton et al., 1995	60.53	0.20	926A	60.15	61.35	1.92	1.96	30.0	**1.93**
Bc	*D. triradiatus*	Curry, Shackleton et al., 1995	66.73	0.35	926A	66.05	67.05	2.13	2.18	20.0	2.16
T	***D. pentaradiatus***	Curry, Shackleton et al., 1995	73.86	0.47	926A	73.75	74.00	2.38	2.41	8.3	**2.39**
T	*D. surculus*	Curry, Shackleton et al., 1995	78.87	0.25	926C	78.70	81.35	2.53	2.60	37.9	2.53
T	***D. tamalis***	Curry, Shackleton et al., 1995	86.83	0.25	926C	85.50	87.10	2.72	2.77	32.0	**2.76**
						Heiko Pälike, personal communication, 2011					
T	*Sphenolithus* spp.	Curry, Shackleton et al., 1995	117.18	0.38	925B	116.09	117.40	3.58	3.62	35.4	3.61
						SC97	SC97	SC97	SC97		
T	***R. pseudoumbilicus***	Curry, Shackleton et al., 1995	118.36	0.20	926A	118.10	119.60	3.81	3.85	37.5	**3.82**
Bc	*D. asymmetricus*	This study	125.78	0.10	926C	124.95	125.95	4.02	4.04	50.0	**4.04**
T	***C. acutus***	Backman & Raffi, 1997	154.82	0.05	926B	154.70	155.35	5.04	5.06	32.5	**5.04**
B	*C. rugosus*	Backman & Raffi, 1997	155.73	0.05	926C	155.70	156.25	5.08	5.10	27.5	5.08
T	*C. atlanticus*	Backman & Raffi, 1997	158.96	0.05	926A	158.91	159.91	5.22	5.27	20.0	5.22
T	*T. rugosus*	Backman & Raffi, 1997	159.01	0.50	926A	158.91	159.91	5.22	5.27	20.0	5.23
T	*C. larrymayeri*	Backman & Raffi, 1997	159.76	0.05	926A	158.91	159.91	5.22	5.27	20.0	5.26
B	*C. larrymayeri*	Backman & Raffi, 1997	161.45	0.05	926A	161.21	161.71	5.32	5.34	25.0	5.33
B	***C. acutus***	Backman & Raffi, 1997	162.16	0.05	926A	161.71	162.71	5.34	5.39	20.0	**5.36**
B	*C. atlanticus*	Backman & Raffi, 1997	162.66	0.05	926A	161.71	162.71	5.34	5.39	20.0	5.39
T	***D. quinqueramus***	Backman & Raffi, 1997	165.49	0.10	926C	165.46	165.91	5.53	5.55	22.5	**5.53**

[1]   Numbers in brackets refer to Marine Isotope Stage (MIS) boundaries.

Reference section: ODP Site 926 (western tropical Atlantic Ocean)

Estimated age: 5.05 Ma – 4.04 Ma (Fig. 9, Table 4)

Duration: 1.01 million years

Remarks: Taxonomic ambiguities of the *Amaurolithus – Ceratolithus* lineage during the early 1970s (Gartner 1969, Gartner and Bukry 1975) in combination with low abundances of the critical biohorizons make the lower Pliocene zonations of Martini (1971) and Bukry (1973a) problematic. Martini used Base *Discoaster asymmetricus* and Top "*Ceratolithus tricorniculatus*" for subdivision of the NN13/NN14 and NN14/NN15 zonal boundaries, respectively. Bukry used two biohorizons for subdivision of Subzone CN10c/CN11a (Top "*Ceratolithus primus*", Top "*Ceratolithus tricorniculatus*"), and the "Beginning of acme" of *D. asymmetricus* for subdivision of Subzones CN11a/CN11b without quantifying the "acme" concept. The appearance interval of *D. asymmetricus* as well as the disappearance intervals of *A. primus* and *A. tricorniculatus* are characterised by low and discontinuous occurrences. As a consequence, these biohorizons are still poorly calibrated to independent chronologies. Taken together, these factors make them less suitable for zonal boundary definitions. We have investigated the abundance behavior of *D. asymmetricus* at ODP Site 926 (Fig. 10), and suggest that the level where *D. asymmetricus* increases to > 10 % relative to its ancestor taxon *D. brouweri* represents a suitable criterion for defining the Base of common (Bc) *D. asymmetricus*. This occurs at 4.04 Ma.

Name: Zone CNPL3 – *Discoaster asymmetricus/ Reticulofenestra pseudoumbilicus* Concurrent Range Zone

Definition: Concurrent range of the nominate taxa between the Base of common *D. asymmetricus* and the Top of *R. pseudoumbilicus*.

Reference section: ODP Site 926 (western tropical Atlantic Ocean)

Estimated age: 4.04 Ma – 3.81 Ma (Fig. 9, Table 4)

Duration: 0.23 million years

Remarks: This zone encompasses Zones NN14 and NN15 of Martini (1971), and Subzone CN11b of Okada and Bukry (1980). The Top of *R. pseudoumbilicus* shows synchrony across the low latitude Atlantic Ocean (Gibbs et al. 2005).

Remarks on assemblages: In the upper part of this biostratigraphic interval, the first, small and rare specimens of *Pseudoemiliania lacunosa* begin to occur and rare specimens of *Discoaster tamalis* begin to occur

more consistently. The last representative of the genus *Amaurolithus*, *A. delicatus*, disappears within this biozone. Its disappearance horizon may be blurred for reasons pointed out by Raffi and Flores (1995): "Misidentification occurs in samples that contain nannofossils with calcite overgrowth and when specimens of different *Amaurolithus* and *Ceratolithus* species possess intergrade morphologic features. This is the case in most of the lower Pliocene sequences recovered during Leg 138. Ceratolithid species are irregularly distributed and are not easily differentiated because of the presence of overgrowth and intergrade morphotypes."

**Name:** Zone CNPL4 – *Discoaster tamalis* Top Zone

Definition: Biostratigraphic interval between the Top of *R. pseudoumbilicus* and the Top of the nominate taxon *D. tamalis*.

Reference section: ODP Site 926 (western tropical Atlantic Ocean)

Estimated age: 3.81 Ma – 2.76 Ma (Fig. 9, Table 4)

Duration: 1.05 million years

Remarks: This zone corresponds to part of Zone NN16 of Martini (1971) and to Subzone CN12a of Okada and Bukry (1980). Raffi and Flores (1995, table 2) proposed an identical age estimate (2.76 Ma) for the disappearance of *D. tamalis* from the low latitude eastern Pacific Ocean, whereas Shackleton et al.
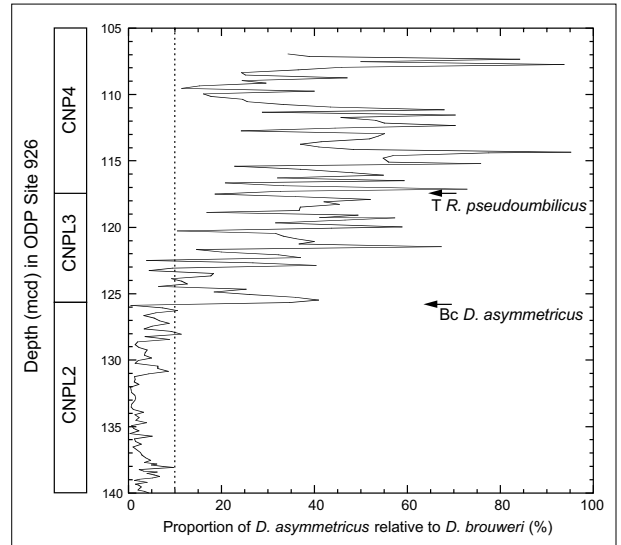
Fig. 10. Increase in relative abundance of *D. asymmetricus* relative to its ancestor species *D. brouweri*. The 10 % limit is used to define the Bc *D. asymmetricus* biohorizon and the CNPL2/CNPL3 biozone boundary. The T *R. pseudoumbilicus* biohorizon defines the CNPL3/CNPL4 biozone boundary.

(1995, tables 4, 7) indicated ages ranging from 3.01 Ma (Site 846) to 2.70 Ma (Site 848) and a "best estimate" of 2.78 Ma.

Remarks on assemblages: The genus *Sphenolithus*, represented by the species *S. abies* and *S. neoabies*, disappears about 0.2 million years after the onset of this biozone.

Name: Zone CNPL5 – *Discoaster pentaradiatus* Top Zone
Definition: Biostratigraphic interval between the Top of *D. tamalis* and the Top of the nominate taxon *D. pentaradiatus*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 2.76 Ma–2.39 Ma (Fig. 9, Table 4)
Duration: 0.37 million years
Remarks: This zone includes the uppermost part of Zone NN16 and Zone NN17 of Martini (1971) and Subzones CN12b and CN12c of Okada and Bukry (1980). Zone NN17 was established from findings of rare discoasters in five samples from two core sections characterised by severe drilling disturbance (Winterer, Riedel et al. 1971, p. 143) at DSDP Site 62 (Martini 1971, Martini and Worsley 1971).
Remarks on assemblages: The disappearance of *D. surculus* occurs within the biozone. According to Bukry (1973a), "The disappearance of *D. surculus* typically precedes *D. pentaradiatus*, but the interval is short and *D. surculus* survives diagenetic changes and reworking better than *D. pentaradiatus*. Therefore, for practical application their disappearances are considered similar". Subsequently, when Bukry (1975) established the *D. surculus* Subzone, the interval between the successive disappearances of *D. tamalis* and *D. surculus*, he remarked however that "Sampling interval, sedimentation rate and degree of reworking may determine whether this brief subzonal interval can be identified". The biostratigraphic distance between the successive disappearances of *D. surculus* and *D. pentaradiatus* (*D. pentaradiatus* Subzone – CN12c) is even briefer, and Bukry (1975, p. 678) did not distinguish the *D. pentaradiatus* Subzone in the investigated DSDP Leg 32 sites. Our experience is similar to Bukry's in that this short biostratigraphic interval often is difficult to distinguish consistently and, at some locations, the two taxa seem to disappear simultaneously. Here, we hence do not employ Top *D. surculus* for definition of a zonal boundary.

Name: Zone CNPL6 – *Discoaster brouweri* Top Zone

Definition: Biostratigraphic interval between the Top of *D. pentaradiatus* and the Top of the nominate taxon *D. brouweri*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 2.39 Ma–1.93 Ma (Fig. 9, Table 4)
Duration: 0.46 million years
Remarks: This zone corresponds to Zone NN18 of Martini (1971) and to Subzone CN12d of Okada and Bukry (1980).
Remarks on assemblages: The three-rayed morphotype of *D. brouweri*, *D. triradiatus*, shows a proportional increase relative to *D. brouweri* at about 0.23 million years prior to their mutual disappearance and extinction of the genus *Discoaster* at 1.93 Ma (Backman and Shackleton, 1983), shortly after the onset of Subchron C2n (Olduvai) at 1.945 Ma. The genus *Discoaster* thus existed for about 57 million years, considering the evolutionary appearance of the first discoaster species, *D. mohleri*, at ca. 58.93 Ma (Agnini et al. 2007). Continuous occurrences of small (< 4 μm) specimens of the genus *Gephyrocapsa* are recorded in the upper part of Zone CNPL6.

Name: Zone CNPL7 – *Calcidiscus macintyrei* Partial Range Zone
Definition: Partial range of the nominate taxon between the Top of *D. brouweri* and the Base of *Gephyrocapsa* (≥ 4 μm).
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 1.93 Ma–1.71 Ma (Fig. 9, Table 4)
Duration: 0.22 million years
Remarks: This zone corresponds to the lowermost part of Zone NN19 of Martini (1971). Bukry (1973a) employed the successive appearances of *Gephyrocapsa caribbeanica* and *G. oceanica* to subdivide the interval between Top *Discoaster brouweri* and Top *Pseudoemiliania lacunosa*. Okada and Bukry (1980) codified the three resulting subzones as CN13a, CN13b and CN14a. A consequence of our different taxonomic approach with respect to the use of gephyrocapsids in Pleistocene biostratigraphy (see remarks under Zone CNPL8), compared to Bukry's use of members of this genus, is that Subzones CN13a, CN13b and CN14a are not compatible with the fourfold subdivision we use for the identical biostratigraphic interval, from Zone CNPL7 through Zone CNPL10. There is hence no precise correspondence between the two zonal systems, despite the use of gephyrocapsids in both cases.

Remarks on assemblages: An increase in abundance of small (< 4 μm) *Gephyrocapsa* specimens and *H. sellii* characterise this biostratigraphic interval.

Name: Zone CNPL8 – *Gephyrocapsa* (> 5.5 μm)/ *Gephyrocapsa* (≥ 4 μm) Concurrent Range Zone*
Definition: Biostratigraphic interval between the Base of the nominate taxon *Gephyrocapsa* (≥ 4 μm) and the Top of *Gephyrocapsa* (> 5.5 μm).
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 1.71 Ma – 1.25 Ma (Fig. 9, Table 4)
Duration: 0.46 million years
Remarks: This zone corresponds to an interval in the lower part of Zone NN19 of Martini (1971). *The use of a taxon, or rather morphotype in this case, that appears within the biozone for definition of its top (Top *Gephyrocapsa* > 5.5 μm) differs from the strict concept of a Concurrent Range Zone by Wade et al. (2011).
Remarks on assemblages: The rapid morphologic evolution of the genus *Gephyrocapsa* during the Pleistocene provides a series of biohorizons useful for improving the biostratigraphic resolution of the previous zonations of Martini (1971) and Okada and Bukry (1980). For reasons discussed by Raffi et al. (1993), we have adopted an informal taxonomic subdivision of *Gephyrocapsa*, based on placolith length. This approach has proven successful in terms of biostratigraphic usefulness in many regions, including the western and eastern Pacific Ocean, the Caribbean Sea, the Mediterranean and the North Atlantic. It follows that our zonal boundary definitions are not based on presence/absence of single taxa, but may include several gephyrocapsid taxa. For example, specimens ranging from 4.0 μm to 5.5 μm in placolith length include both *Gephyrocapsa caribbeanica* and *Gephyrocapsa oceanica*. Specimens > 5.5 μm include *Gephyrocapsa lumina*, as well as *G. oceanica* sensu Bukry (1973b, p. 678). *Calcidiscus macintyrei* disappears in the lower part of the biozone, just prior to the appearance of *Gephyrocapsa* spp. > 5.5 μm. The group of gephyrocapsid placoliths being 4.0 through 5.5 μm in length is often referred to as "medium sized" in the literature. Here, it is referred to as *Gephyrocapsa* spp. ≥ 4 μm.

Name: Zone CNPL9 – Small *Gephyrocapsa* Partial Range Zone
Definition: Partial range of the nominate taxon between the Top of *Gephyrocapsa* (> 5.5 μm) and the re-entrance of *Gephyrocapsa* (≥ 4 μm).

Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 1.25 Ma – 1.06 Ma (Fig. 9, Table 4)
Duration: 0.19 million years
Remarks: This zone corresponds to an interval within Zone NN19 of Martini (1971).
Remarks on assemblages: The interval of almost total absence of what we refer to as medium-sized (4.0– 5.5 μm) and large (> 5.5 μm) *Gephyrocapsa* specimens (Rio 1982, Raffi et al. 1993) delineates the so-called "Small *Gephyrocapsa* Zone" of Gartner's (1977) Pleistocene zonation. This interval of absence has been observed in different oceanic basins (Gartner 1977, Rio 1982, Raffi et al. 1993, Wei 1993), and is characterised by a dominance of small *Gephyrocapsa* specimens and *P. lacunosa* in nannofossil assemblages. In the mid-latitude North Atlantic, *Helicosphaera sellii* disappears shortly after the onset of Zone CNPL9. *Reticulofenestra asanoi* appears in the upper part of this biozone.

Name: Zone CNPL10 – *Gephyrocapsa* (≥ 4 μm)/ *Pseudoemiliania lacunosa* Concurrent Range Zone
Definition: Concurrent range of the nominate taxa between the Top absence of *Gephyrocapsa* (≥ 4 μm) and the Top of *P. lacunosa*.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 1.06 Ma – 0.43 Ma (Fig. 9, Table 4)
Duration: 0.63 million years
Remarks: This zone corresponds to the upper part of Zone NN19 of Martini (1971).
Remarks on assemblages: The *Gephyrocapsa* specimens that re-enter the stratigraphic record following the interval of near-total dominance of gephyrocapsids < 4 μm are mostly medium-sized (4.0–5.5 μm), whereas larger forms (> 5.5 μm) occur sporadically. The ≥ 4 μm specimens that reaches prominence again, following the absence interval (Zone CNPL9), among the gephyrocapsid assemblages contain common to abundant *Gephyrocapsa parallela* (Hay and Beaudry 1973), with its characteristic wide central opening and its bridge nearly aligned with the elliptical placolith's short axis. *Gephyrocapsa omega* (Bukry 1973b) is a junior synonym of *G. parallela*. The medium-sized *Reticulofenestra asanoi* decrease in abundance prior to its extinction in the lower part of the biozone. Large specimens of *P. lacunosa* characterise its uppermost distribution range.

Name: Zone CNPL11 – *Ceratolithus cristatus* Partial Range Zone

Definition: Partial range of the nominate taxon between the Top of *P. lacunosa* and the Recent.
Reference section: ODP Site 926 (western tropical Atlantic Ocean)
Estimated age: 0.43 Ma–0.00 Ma (Fig. 9, Table 4)
Duration: 0.43 million years
Remarks: This zone includes Zones NN20 and NN21 of Martini (1971), and Subzone CN14b and Zone CN15 of Okada and Bukry (1980).
Remarks on assemblages: *Emiliania huxleyi* appears within this biostratigraphic interval, and increases in proportion relative to gephyrocapsids in the upper part of the biozone (Thierstein et al. 1977). Subsequent studies have confirmed the diachrony in this abundance cross-over, initially pointed out by Thierstein et al. (1977), spanning most of the latest glacial cycle (Jordan et al. 1996, Findley and Flores 2000, Villanueva et al. 2002, Baumann and Freitag 2004).

6.   Summary

The Miocene through Pleistocene biozonation presented here represents a basic biostratigraphic framework for relative dating of marine sediments using calcareous nannofossils. This new biozonation is an updated synthesis that relies on what Erlend Martini referred to as a "Standard [...] zonation", and the low-latitude zonation provided by David Bukry. Our biozonation, however, includes several of the biohorizons they used for zonal boundary definitions that have proven to be reliable, besides several new biohorizons. We take into account the biostratigraphic data that we have produced over nearly three decades from chiefly low and middle latitudes in all three major ocean basins and the Mediterranean Sea region, derived by applying semi-quantitative methods on high resolution sampling sets from core material retrieved by the Ocean Drilling Program. Previously unpublished biostratigraphic data showing the abundance behaviour of some of the marker species are presented.

Age estimates for all biohorizons are presented, with calibration references for all individual biohorizons. In the Miocene through Pleistocene interval, the independent age control is chiefly provided by astronomically tuned cyclostratigraphies.

Thirty-one (31) biozones are established that span the past 23 million years, implying an average duration of about 0.74 million years for the biozones. The span of duration of indidvidual biozones however varies from 0.15 to 2.20 million years. Pliocene-Pleistocene zones have an average duration of 0.48 million years, whereas the average duration of Miocene biozones is 0.89 million years. The longest biozone, the *Discoaster signus* Concurrent Range Zone encompasses ca. 50 % (2.20 million years) of the middle Miocene.

We employ a limited set of selected biohorizons in the new biozonation in order to maintain stability to the scheme and hence avoid introduction of subzones. Most of the new biozones, however, contains several additional biohorizons.

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