

Latest Oligocene to early middle Miocene quantitative calcareous nannofossil biostratigraphy in the Mediterranean region

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ABSTRACT: The distribution patterns of selected calcareous nannofossils were investigated by means of quantitative methods in uppermost Oligocene to lower middle Miocene sediments from onland stratigraphic sections in Italy. Our goal was to test the reliability, in the Mediterranean region, of the biohorizons used in the standard zonations of Martini (1971) and Bukry (1973, 1975) and of others recently proposed in the literature. Biostratigraphic reliability was evaluated by considering the mode of occurrence of single biohorizons and their potential for correlation among distant and various facies sections. Several conventionally used boundary definition biohorizons (*Discoaster druggii* FO, *Triquetrorhabdulus carinatus* LO, *Helicosphaera recta* LO, *Cyclicargolithus abisectus* acme end) are considered as not reliable. They are therefore of limited use for solving the geological problems of the region. However, by using distinct changes in the distribution patterns of calcareous nannofossils, like first common and continuous occurrence (FCO), last common and continuous occurrence (LCO), and acme end (AE), besides classical first occurrence (FO) and last occurrence (LO), at least 13 biohorizons can be consistently correlated among the studied sections. We established a set of 11 regional biostratigraphic zones and subzones, which are also recognized in poorly fossiliferous turbiditic successions. The average time resolution of the proposed zonal system is less than 1 m.y., which can be substantially improved by integrating calcareous nannofossil and planktonic foraminifera biostratigraphies. The correlation of the proposed zonal system to the Standard Chronostratigraphic Scale is discussed. The Oligocene/Miocene and Aquitanian/Burdigalian boundaries lack formal definition and are currently recognized by different criteria. We propose that, for the time being, these boundaries should be recognized by buffer intervals which include several calcareous nannofossil biohorizons. A new *Sphenolithus* species is described, *Sphenolithus disbelemnus* n. sp.

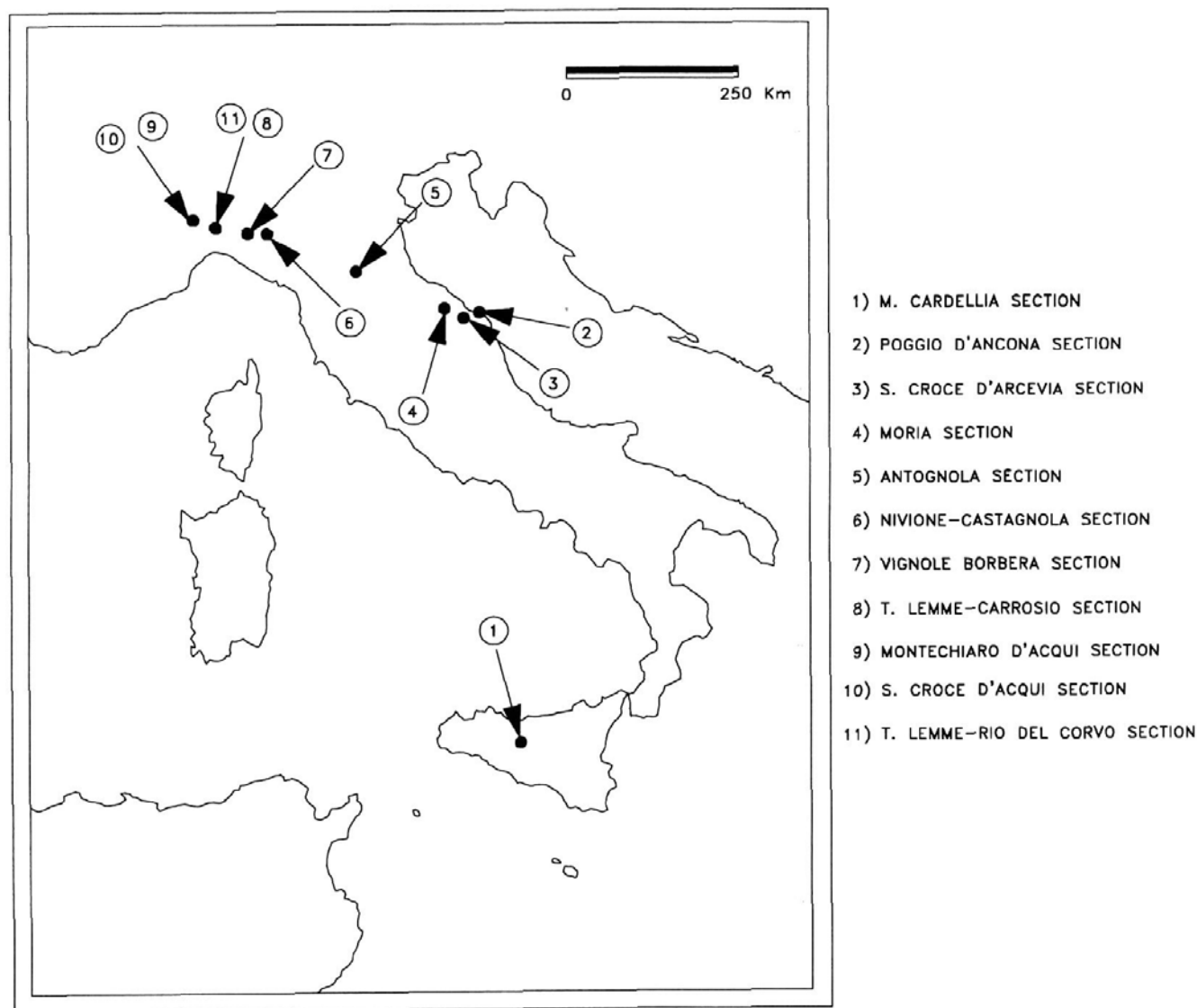
INTRODUCTION

The Oligocene and Miocene were times of dynamic geologic evolution in the Mediterranean region. The continuing collision of the European and African plates resulted in the final closure of the Tethys Ocean, the birth of the present Mediterranean Sea, and the main structuring of peri-Mediterranean thrust-and-fold belts like the Alps and the Apennines. The solution of many of the geologic problems associated with the above processes depends on a sound time framework. Biostratigraphy is essential to the establishment of such a framework, and calcareous nannofossils are recognized as a powerful tool for regional and worldwide biostratigraphic correlations. The Cenozoic set of biozones summarized by Martini (1971) and Okada and Bukry (1980) are recognizable over wide areas and are regarded as an international standard for dating (Haq et al. 1988). However, the time resolution they offer in the late Oligocene-early Miocene time interval is poor (Fornaciari et al. 1993) and the paleobiogeographic and paleoecological controls affecting the distributions of organisms require reliability testing on a regional basis before they can be confidently applied. The aim of this study was to test the biostratigraphic reliability of Oligocene and Miocene nannofossil marker species in order to improve the time resolution in Mediterranean sediments. For this purpose, we established their distribution patterns by means of quantitative methods in sediments deposited in widely different geological settings. Quantitative distribution patterns are fundamental for evaluating the reliability of classic first occurrence (FO) and last occurrence (LO) events (Backman and Shackleton 1983). In addition, detailed quantitative distribution patterns can provide supplementary biohorizons based on abundance fluctuations (abundance-acme intervals, absence-paracme intervals) which may be biostratigraphically useful, especially for regional correlations.

This investigation resulted in the proposal of a better resolved regional Mediterranean zonal scheme, which can be correlatable to standard zonations and which appears to be widely applicable in the Italian on-land stratigraphic record, which often is represented by poorly fossiliferous turbiditic successions. In addition, we present a tentative integration of calcareous nannofossil and planktonic foraminifera data and discuss the chronostratigraphy of the time interval as a contribution to the establishment of an integrated time frame for the uppermost Oligocene-lower middle Miocene marine stratigraphic record in the Mediterranean area.

STRATEGY

In order to make our conclusions and procedures clearer, it is necessary to state our concepts of biohorizons and of biostratigraphic reliability. A biohorizon (biostratigraphic event) is a change in the paleontologic properties of the stratigraphic record which may be used for the purposes of classification and correlation (Hedberg 1976). In dealing with planktonic microfossils, the most widely used properties for defining biohorizons are data on first occurrence (FO) and last occurrence (LO). Hence, the most frequently followed procedure in biostratigraphy is to collect the presence and absence data of fossil marker species. Actually, as demonstrated by recent work in stratigraphic intervals and areas where biostratigraphic knowledge is considered as mature (i.e. the Mediterranean Pliocene or, in general, the Pleistocene), much biostratigraphically useful information is provided by frequency variations in the distribution of sensitive species. Specifically, abundance fluctuations may reflect regional paleobiogeographic-paleoclimatic events and/or evolutionary turnovers which do not result in extinctions and may be correlatable on regional as well as supraregional scales. The most easily recorded abundance fluctua-



TEXT-FIGURE 1
 Location map showing positions of investigated sections.

tions are absence (paracme) intervals, abundance (acme) intervals, last common and continuous occurrence (LCO) and first common and continuous occurrence (FCO). On the basis of our experience and of the most recent literature (Backman 1986), we consider that the above-mentioned prominent changes in species frequency distribution provide biohorizons which can be correlated more consistently than the traditional absolute first and last occurrences. Intervals of rare and discontinuous occurrences of calcareous nannofossils may be present around the appearance and extinction of species which make it difficult to assess the firm positions of the evolutionary events in various sections or when comparing data produced by various authors. Presence of a few specimens above or below the interval of common occurrence may be caused by reworking or contamination. Therefore, in this work we rely more on unique (non-repetitive) prominent changes in the frequency distribution of species rather than on absolute FO and LO data.

As far as biostratigraphic reliability is concerned - a topic much discussed recently (e.g., Gradstein et al. 1985; Hills and Thierstein 1989; Bralower et al. 1989) - we think that a biohorizon may be considered as reliable when it is easily reproducible by the various workers and can be consistently correlated on a regional basis among various facies sections while still maintaining its position relative to other biohorizons. The latter feature, recently called "ranking" by Gradstein et al. (1985), is simply the scientific paradigm (the principle of faunal succession) on the basis of which William Smith founded biostratigraphy at the end of the 18th century (see Prothero 1990).

The reproducibility of a biohorizon among various authors depends on: 1) clear taxonomic definition of the index species; 2) the mode of occurrence (subtle, abrupt, etc.) of the change in distribution patterns (first occurrence, last occurrence, first common and con-

STANDARD ZONATIONS				MEDITERRANEAN ZONATIONS										
Martini, 1971		Okada & Bukry, 1980		Roth et al., 1971		Müller, 1978 (DSDP Leg 42)		Theodoridis, 1984			Present work			
Zone	Def.	Zone/Subzone	Def.	Zone	Def.	Zone	Def.	Zone	Subzone	Def.	Code	Zone	Subzone	Biohorizons
NN5 <i>Sphenolithus heteromorphus</i>	H. ampl.	CN4 <i>Sphenolithus heteromorphus</i>	H. ampl.	NOT CONSIDERED		"NN5" <i>Sphenolithus heteromorphus</i>	H. ampl.	<i>Sphenolithus heteromorphus</i>	<i>Helicosphaera waltronsi</i> <i>Helicosphaera perot-nuelsenii</i> <i>Eu-discosaster signus</i> <i>Helicosphaera obliqua</i> <i>Helicosphaera ampliaptera</i>	R. waltr. LO H. per. R. ampl. B. ampl. B. eris.	NOT CONSIDERED			PB <i>S. heteromorphus</i> ↓ LCO <i>H. ampliaptera</i>
NN4 <i>Helicopontosphaera ampliaptera</i>		CN3 <i>Helicopontosphaera ampliaptera</i>	S. hel.			"NN4" <i>Helicosphaera ampliaptera</i>	S. hel.				MNN4a	<i>Helicosphaera ampliaptera</i> <i>Sphenolithus heteromorphus</i> (IZ)		FCO <i>S. heteromorphus</i>
NN3 <i>Sphenolithus belemnus</i>	S. bel. T. car.	CN2 <i>Sphenolithus belemnus</i>	S. bel.			"NN3" <i>Sphenolithus belemnus</i>	AS H. ampl.		<i>Triquetrorhabdulus milowii</i>		MNN3b	<i>Sphenolithus belemnus</i> <i>Sphenolithus heteromorphus</i> (IZ)		LCO <i>S. belemnus</i>
NN2 <i>Discosaster drugii</i>		CN1c <i>Discosaster drugii</i>		<i>Discosaster drugii</i>		"NN2" <i>Discosaster drugii</i>	H. ampl.				MNN3a	<i>Sphenolithus belemnus</i> (TRZ)		FO <i>S. belemnus</i>
NN1 <i>Triquetrorhabdulus carinatus</i>	D. drug.	CN1 <i>Triquetrorhabdulus carinatus</i>		<i>Triquetrorhabdulus carinatus</i>		"NN1" <i>Triquetrorhabdulus carinatus</i>			<i>Helicosphaera tedderi</i> <i>Eu-discosaster drugii</i> <i>Eu-discosaster deflandrei</i>	G. rotu. H. ampl. D. drug.	MNN2b	<i>Helicosphaera ampliaptera</i> (PRZ)		↑ FO <i>H. mediterranea</i>
NP25 <i>Sphenolithus ciperoensis</i>	H. recta	CN1a <i>Cyclonargolithus abisectus</i>	AS C. bel.	<i>Sphenolithus ciperoensis</i>		"NP25" <i>Sphenolithus ciperoensis</i>	H. recta				MNN2a	<i>Helicosphaera carteri</i> (PRZ)		↑ FO <i>H. ampliaptera</i>
		CP19b <i>Dictyococcales bisectus</i>	S. cip. D. bis.	<i>Sphenolithus dislentus</i>							MNN1d	<i>Sphenolithus disbelemnus</i> <i>Helicosphaera carteri</i> (IZ)		AE <i>H. euphratis</i>
											MNN1c	<i>Sphenolithus delphiz</i> <i>Sphenolithus disbelemnus</i> (IZ)		↑ FCO <i>H. carteri</i>
											MNN1b	<i>Sphenolithus delphiz</i> (TRSZ)		FO <i>S. disbelemnus</i>
											MNN1a	<i>Dictyococcales bisectus</i> <i>Sphenolithus delphiz</i> (IZ)		LO <i>S. delphiz</i>
														FO <i>S. delphiz</i>
														LCO <i>D. bisectus</i>
														LO <i>S. ciperoensis</i>
														LO <i>S. dislentus</i>

TEXT-FIGURE 2

Uppermost Oligocene-lower Miocene calcareous nannofossil events and zonations proposed for Mediterranean area, compared with standard zonations of Martini (1971) and Okada and Bukry (1980). MNN = Mediterranean Neogene Nannoplankton; MNP = Mediterranean Paleogene Nannoplankton.

tinuous occurrence, last common and continuous occurrence, abundance-acme intervals and absence-paracme intervals). Therefore, here we :

- 1) choose as index species only easily recognizable forms, in several cases using biometric criteria for species definition;
- 2) establish distribution patterns of index species in various environmental settings in order to evaluate the mode of occurrence ("morphology") of the biohorizons.

We consider as reliable biohorizons those which are based on relatively abrupt changes in distribution patterns and show the same ranking in distant and various facies sections.

BIOSTRATIGRAPHIC RELIABILITY AND SYNCHRONY

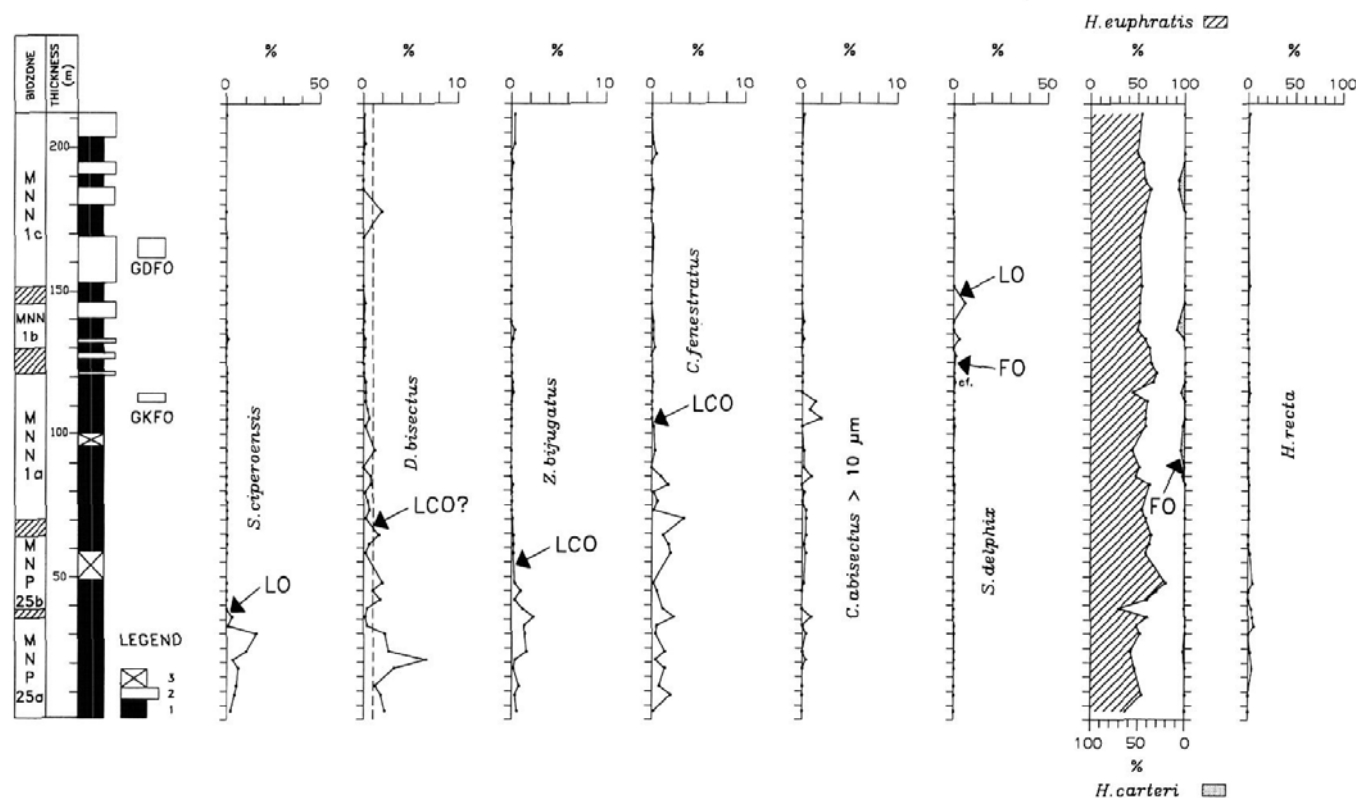
The reliability of a biohorizon is commonly evaluated by the degree of synchrony which can be established through correlation to magnetostratigraphy and/or stable isotope stratigraphy (e.g., Thierstein et al. 1977; Backman and Shackleton 1983; Raffi et al. 1993). A biohorizon is usually not considered reliable because it is not synchronous among distant regions. We agree that a biohorizon which is synchronous is biostratigraphically reliable (e.g., Raffi et al. 1993), but not with the reverse statement. In fact, most

biohorizons are probably diachronous to different degrees, even over short distances; nevertheless, they retain their stratigraphic utility in so far as they are non-repetitive events which aid the interpretation of the synchronous but repetitive signals of magnetic reversal stratigraphy and of geochemical, lithologic and biotic records. Synchrony is a property of chronostratigraphy, whereas "although biostratigraphic correlation may approach time correlation, biostratigraphic units are not the same as chronostratigraphic units" (Hedberg 1976).

METHODS

Preparation of slides for light microscope study followed standard techniques. The distributions of the taxa listed in tables 1 and 2 were determined by light microscope techniques (normal light and crossed nicols). Data were collected by quantitative methods. The application of quantitative methods to calcareous nannofossil biostratigraphy was discussed at length by Backman and Shackleton (1983) and Rio et al. (1990a) and we follow their approach in this work.

Considering the main objective of this work (biostratigraphy in Italian mainland sections) and the kind of material investigated (hemipelagic and terrigenous sediments), we applied two counting methods:



TEXT-FIGURE 3

Abundance patterns of selected upper Oligocene to lower Miocene calcareous nannofossils in Monte Cardella section (Central Sicily). 1. Mudstone; 2. Glauconitic mudstone; 3. Covered intervals. GKFO= first occurrence of *Globorotalia kugleri*; GDFO= first occurrence of *Globoquadrina dehiscens*. LO= Last Occurrence; FO= First Occurrence; LCO= Last Common and Continuous Occurrence. Data on planktonic foraminifera collected by R. Sprovieri (in Micarelli et al. 1990).

1) Counting index species *versus* total assemblages, taking into account about 500 nannofossils larger than 4 microns;

2) Counting index species *versus* a fixed number of taxonomically related forms. Abundance patterns of index sphenoliths were established by counting 100 sphenoliths, those of index discoasterid species by counting 200 discoasterids, and those of index helicoliths by counting 50-100 helicoliths.

STUDY MATERIAL

Oligocene and Miocene marine sediments are widespread in Italy and in the Mediterranean region but, because of extensive tectonics, the record is fragmentary. Pelagic and hemipelagic sediments, which are best suited for biostratigraphic work, occur discontinuously. Turbiditic and generally redeposited sediments related to the infilling of foredeep, perisutural, and episutural basins are the dominant lithology in the Apennines chain.

Table 3 lists the sections considered (text-fig. 1). Detailed stratigraphy, planktonic foraminifera and calcareous nannofossil data will be dealt with in separate papers. The location and field stratigraphic setting of each section is summarized in table 3 and briefly commented on below. Except for the Monte Cardella section, located in central Sicily, all the other sections are located in northern Italy.

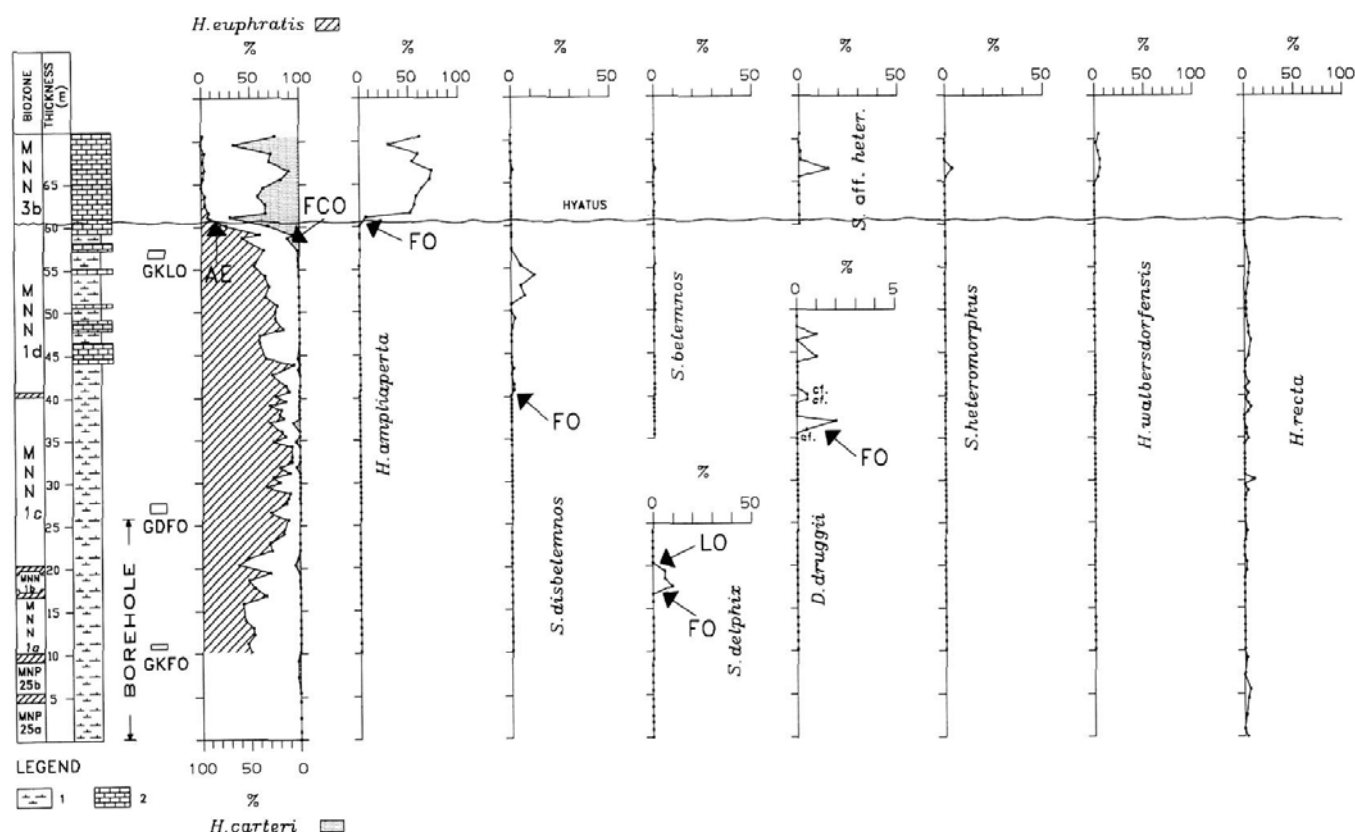
The sections are indicative of very different geological settings. Those of the Umbria and Marche regions were deposited in pelagic

to hemipelagic conditions, in an area that was acting as the foreland for the Northern Apennines thrust-and-fold belt. Those of the Tertiary Piedmont Basin (BTP) and Antognola were deposited in episutural basins. We have also lately been studying the calcareous nannofossil contents of turbiditic successions deposited in the foredeep of the Northern Apennines thrust-and-fold belt. Analytical data will be reported elsewhere, but we anticipate here some results for the sections of Bobbio, Gova, and Lizzano Belvedere (table 3).

The stacked record provided by the 11 sections documented here represents the entire interval from Zone NP25 to Zone NN4, in terms of Martini's (1971) zonal scheme.

PREVIOUS STUDIES

The pioneering work on global upper Oligocene-lower Miocene calcareous nannofossil biostratigraphy is that of Bramlette and Wilcoxon (1967), upon which the standard zonations of Martini (1971) and Bukry (1973, 1975) are based. Bramlette and Wilcoxon (1967) also used reference material from the Italian Miocene record. Other relevant studies on calcareous nannofossil biostratigraphy of the upper Oligocene and lower Miocene Mediterranean stratigraphic record are those of Roth (1970), Roth et al. (1971), Müller (1978), Theodoridis (1984), Biolzi (1985), Mazzei (1985) and Patacca et al. (1992). They show that many markers used in standard zonations are of limited use in the Mediterranean. Hence, changes in the original definitions of some zonal boundaries (e.g., Müller 1978) or regional schemes were proposed by Roth et al. (1971) and Theodoridis (1984), as summarized in text-figure 2.



TEXT-FIGURE 4

Abundance patterns of selected upper Oligocene to lower Miocene calcareous nannofossils in Poggio d'Ancona section (Marche Region). 1. Mainly marlstone; 2. Mainly calcareous marlstone. GKFO= first occurrence of *Globorotalia kugleri*; GDFO= first occurrence of *Globoquadrina dehiscens*; GKLO= last occurrence of *Globorotalia kugleri*. LO= Last Occurrence; FO= First Occurrence; FCO= First Common and Continuous Occurrence; AE= Acme End. Data on planktonic foraminifera collected by A. Micarelli and M. Potetti (in Micarelli et al. 1990).

REMARKS AND TAXONOMY

The taxa considered in the present work are listed by generic epithet in Appendix 1. Index species are illustrated in plates 1-4, and most of them are referenced in Perch-Nielsen (1985). Consistency in taxonomic concepts is a key factor in biostratigraphy and we have described our taxonomic concepts in previous papers (Rio et al. 1990b; Fornaciari et al. 1990). A new sphenolith species is described in the taxonomic section.

RESULTS

Calcareous nannofossils are common to abundant in upper Oligocene to middle Miocene Mediterranean marine sediments. They are also well represented in terrigenous turbiditic successions, where other fossil groups are scarce (Andreozzi et al. 1992; Catanzariti et al. 1992; Fornaciari and Labaume 1992). Placoliths, sphenoliths and, in well-preserved material, helicoliths are the major components of the assemblages. Discoasterids are generally a minor component and triquetrorhabdulus are very rare. All species that are used in standard zonations occur in the area in varying abundances. Text-figures 3-14 show the abundance distribution patterns of selected calcareous nannofossils. Correlations between various sections and the ranking of various biohorizons are shown in text-figures 15 and 16. A comment on the distributions of secondary taxa will be given in the descriptions of the proposed zonal system. A summary of the distribution patterns of index

species and of the most important assemblage components is shown in text-figure 17. We comment below on the reliability of single biohorizons in the light of the criteria discussed previously.

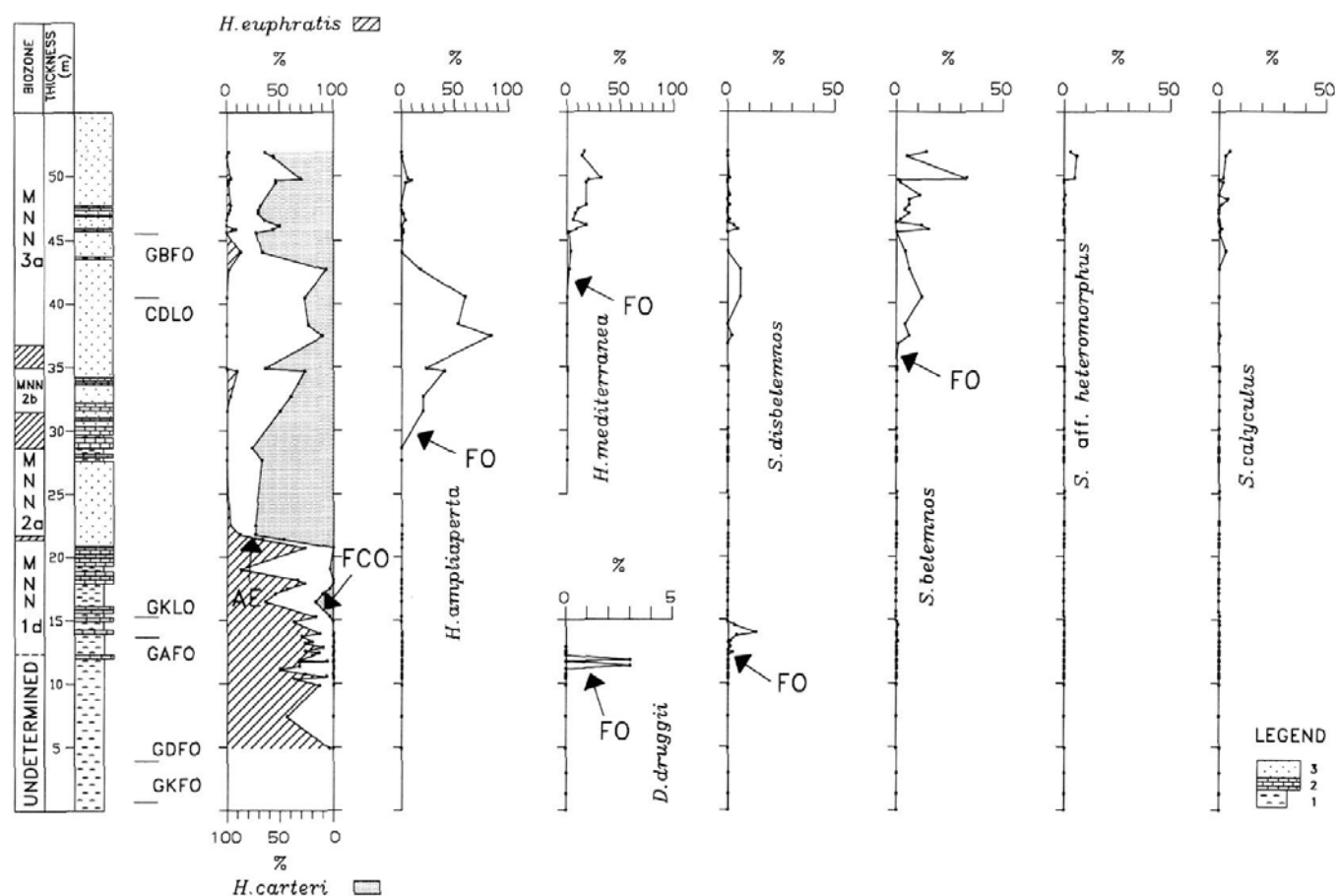
RELIABILITY OF STANDARD BIOHORIZONS

LO of *Sphenolithus distentus*

The LO of *S. distentus* is used as a zonal boundary in both Martini's (1971) and Bukry's (1973, 1975) schemes (NP24/NP25 and CP19a/CP19b boundaries). The LO of *S. distentus* is considered as difficult to pinpoint by Wei and Wise (1989) and Fornaciari et al. (1990). In the Contessa Quarry section, Perch-Nielsen (in Lowrie et al. 1982) found the LO of this species below the FO of *S. ciperoensis*. Data from the Nivione-Castagnola composite section (text-fig. 8) and from our ongoing work in other Italian sections indicate that, in its final range, *S. distentus* is rare and discontinuous, making its extinction difficult to locate precisely. However, provisionally we use the LO of *S. distentus* as a zonal boundary because we have not yet established firm alternative events for subdividing the long interval between the FO and LO of *S. ciperoensis* (Zone CP19 of Okada and Bukry 1980).

LO of *Sphenolithus ciperoensis*

The LO of *S. ciperoensis* (plate 3, fig. 7) is the primary definition criterion for the CP19b/CN1a boundary (Bukry 1975; Okada and



TEXT-FIGURE 5

Abundance patterns of selected lower Miocene calcareous nannofossils in Santa Croce d'Arcevia section (Marche Region). 1. Mainly marlstone; 2. Mainly calcareous marlstone; 3. Mainly marlstone and volcanic deposits. GKFO= first occurrence of *Globorotalia kugleri*; GDFO= first occurrence of *Globoquadrina dehiscens*; GKLO= last occurrence of *Globorotalia kugleri*; CDLO= last occurrence of *Catapsydrax dissimilis*; GBFO= first occurrence of *Globigerinoides bisphaericus*. FO= First Occurrence; FCO= First Common and Continuous Occurrence; AE= Acme End. Data on planktonic foraminifera collected by R. Coccioni (in Coccioni et al. 1992).

Bukry 1980), and is generally considered as a reliable and synchronous biohorizon over extended areas (Wei and Wise 1989; Fornaciari et al. 1990; Olafsson 1991). We show the final distribution pattern of *S. ciperoensis* in the Monte Cardellia (text-fig. 3), Antognola (text-fig. 7) and Nivione-Castagnola (text-fig. 8) sections. Although the species is not abundant, the end of its continuous presence is easily recognized in these sections, and it may be concluded that its LO is a reliable biohorizon in the Mediterranean, as it is in low- and mid-latitude oceanic sediments (Wei and Wise 1989).

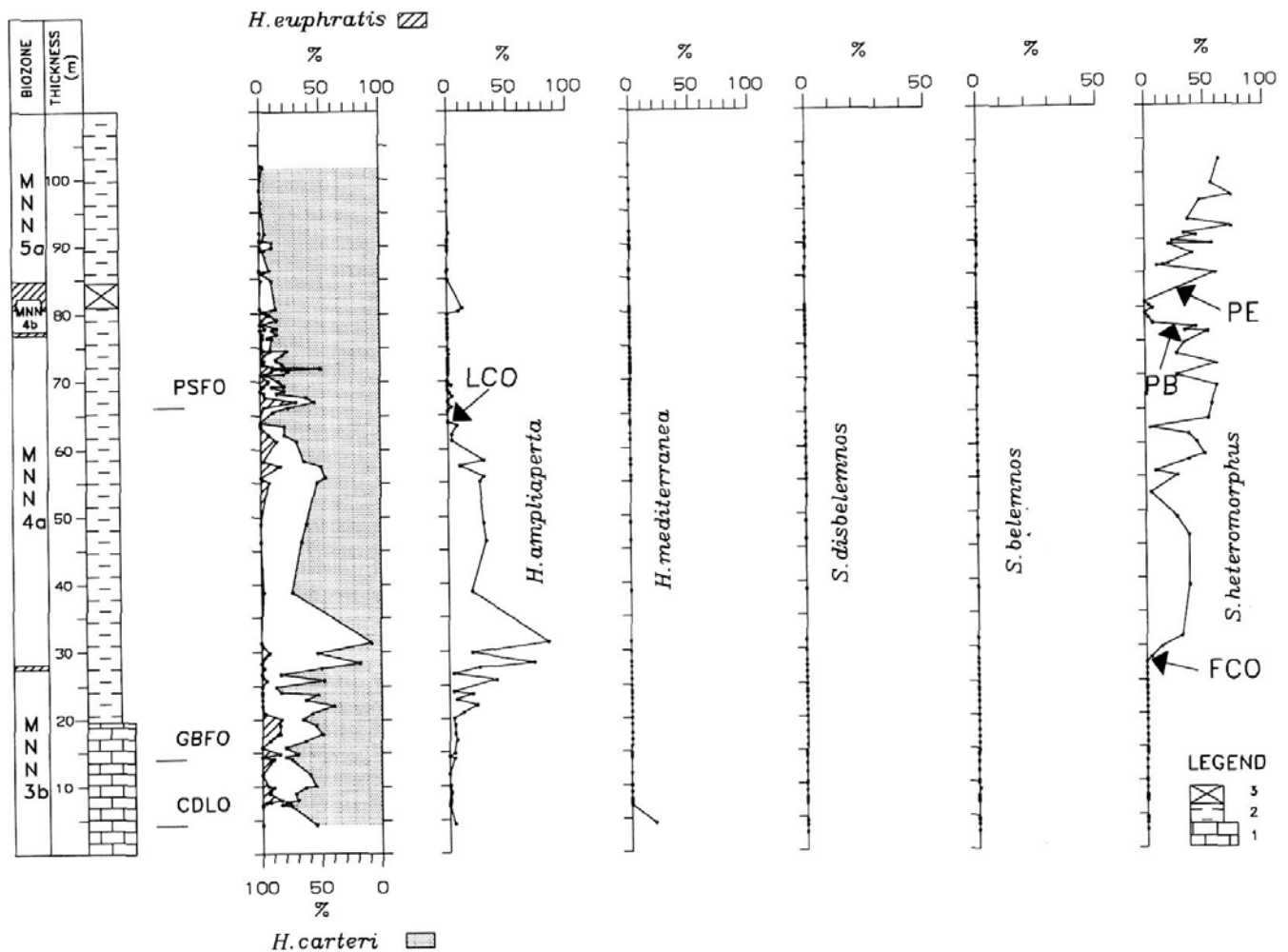
LO of *Helicosphaera recta*

The LO of *H. recta* (plate 1, figs. 18, 19) represents the original definition of the NP25/NN1 boundary (Martini 1971). However, the form is rare or absent in many oceanic sediments, and several alternative criteria have been proposed for recognizing this boundary (Bizon and Müller 1979a; Rio et al. 1990b; Fornaciari et al. 1993). Rio et al. (1990b) and Fornaciari et al. (1993) have in fact demonstrated that *H. recta* ranges well above the FO of *D. druggii*, and hence the LO of *H. recta* is unsuitable for defining any zonal boundary between the LO of *S. distentus* (NP25 bottom) and the

FO of *D. druggii* (NN2 bottom). Because of these findings, Fornaciari et al. (1993) redefined Zone NP25 of Martini (1971) as the interval between the LO of *S. distentus* and that of *S. ciperoensis*.

The species is well represented in the Mediterranean region, mostly in Oligocene sediments. However, Biolzi (1985) reported quite variable extinction levels in numerous sections across the Oligocene-Miocene boundary. Here we document the final distribution of *H. recta* in the Monte Cardellia (text-fig. 3) and Poggio d'Ancona (text-fig. 4) sections, based on counts of at least 50 helicoliths per sample. *Helicosphaera recta* is rare and shows discontinuous distribution. Data from the Poggio d'Ancona section (text-fig. 4) indicate that, also in the Mediterranean region, *H. recta* is present well within the Miocene, above the FO of *D. druggii*. Our ongoing work on Italian turbiditic successions shows that *H. recta* is often missing in badly preserved assemblages, probably because of its low potential for preservation.

We conclude that the LO of *H. recta* is unreliable in the biostratigraphic classification of the Mediterranean stratigraphic record.



TEXT-FIGURE 6

Abundance patterns of selected lower to middle Miocene calcareous nannofossils in Moria section (Marche Region). 1. Mainly calcareous marlstone (Bisciaro Formation); 2. Mainly mudstone (Schlier Formation); 3. Covered intervals. CDLO= last occurrence of *Catapsydrax dissimilis*; GBFO= first occurrence of *Globigerinoides bisphaericus*; PSFO= first occurrence of *Praeorbulina sicana*. FO= First Occurrence; LCO= Last Common and Continuous Occurrence; PB = Paracme Beginning; PE = Paracme End. Data on planktonic foraminifera collected by R. Cocconeri (in Cocconeri et al. 1992).

Acme end of *Cyclicargolithus abisectus*

Cyclicargolithus abisectus (plate 3, figs. 11, 12) is a controversial taxonomic unit (Martini and Müller 1986; Olafsson 1989; Rio et al. 1990b). Following Rio et al. (1990b) we distinguished large (>10µm) from small (<10µm) forms. The latter are difficult to distinguish from those of *Cyclicargolithus floridanus*, and are therefore of limited biostratigraphic value; their distribution is not reported here. Bukry (1971) observed an acme of *C. abisectus* close to the Oligocene-Miocene boundary in the Pacific Ocean, and used this acme end (AE) as a boundary definition (CN1a/CN1b) in his low-latitude zonation (Bukry 1973; Okada and Bukry 1980; text-fig. 2). This event has been used for recognizing the Oligocene/Miocene boundary (e.g. Bukry 1973). In the Mediterranean area, this biohorizon was used by Theodoridis (1984) as a zonal boundary definition (text-fig. 2). The applicability of the AE of *C. abisectus* has been questioned by several authors. Martini and Müller (1986) note that *C. abisectus* ranges up to Zone NN6, and that it shows several acme intervals up to this level and cannot be used to define a reliable zone near the Oligocene-Miocene boundary. Fornaciari et al. (1990, 1993), in their quantitatively derived distribution pattern

of *C. abisectus* in the equatorial Indian and Pacific oceans, did not observe any features which may be referred to as acme intervals, and concluded that Bukry's original observation probably has only local value. In our material too (text-figs. 3, 10), large specimens of *C. abisectus* in the interval above the *S. ciperoensis* LO account for less than 5% of the total assemblage and thus cannot be linked with "abundant" or "acme-like" occurrences. Therefore, we conclude that the acme end of large *C. abisectus* can not be used as a biohorizon for the biostratigraphic classification of Mediterranean sediments.

FO of *Discoaster druggii*

Both Martini (1971) and Okada and Bukry (1980) used the FO of *Discoaster druggii* in their zonal schemes, the former to define the base of Zone NN2 and the latter to define the base of Subzone CN1c (text-fig. 2). This species is generally a rare component of nannofossil assemblages and the NN1/NN2 and CN1b/CN1c boundaries are often not recognized. In the Mediterranean material investigated here, typical large specimens of *D. druggii* (plate 3, fig. 13) are very rare and go unobserved in routine work. Previous authors

TABLE 1

List of calcareous nannofossil biohorizons used as primary zonal boundary definitions in standard zonations of Martini (1971) and Okada and Bukry (1980) in the upper Oligocene to middle Miocene (listed top to bottom from youngest to oldest). Also reported: stratigraphic sections where biohorizons have been established, with observations on their biostratigraphic reliability in the Mediterranean stratigraphic record.

STANDARD BIOHORIZONS	REFERENCE SECTION	RELIABILITY
<i>Helicosphaera ampliaperta</i> LO	MORIA, T.LEMME-RIO DEL CORVO	SCATTERED IN FINAL RANGE; RELIABLE AS LCO
<i>Sphenolithus heteromorphus</i> FO	MORIA, T.LEMME-RIO DEL CORVO	RELIABLE AS FCO
<i>Sphenolithus belemnus</i> LO	VIGNOLE BORBERA, S.CROCE D'ACQUI, T.LEMME-RIO DEL CORVO	SCATTERED IN FINAL RANGE; RELIABLE AS LCO
<i>Triquetrorhabdulus carinatus</i> LO	MONTE CARDELLIA	VERY POOR
<i>Sphenolithus belemnus</i> FO	S.CROCE D'ARCEVIA, MONTECHIARO D'ACQUI	GOOD
<i>Discoaster druggii</i> FO	POGGIO D'ANCONA, S.CROCE D'ARCEVIA	POOR
<i>Cyclicargolithus abisectus</i> AE	MONTE CARDELLIA, ANTIGNOLA, NIVIONE-CASTAGNOLA, T.LEMME-CARROSIO	POOR
<i>Helicosphaera recta</i> LO	MONTE CARDELLIA, POGGIO D'ANCONA, NIVIONE-CASTAGNOLA	UNRELIABLE
<i>Sphenolithus ciperoensis</i> LO	MONTE CARDELLIA, ANTIGNOLA, NIVIONE-CASTAGNOLA, T.LEMME-CARROSIO	GOOD
<i>Sphenolithus distentus</i> LO	NIVIONE-CASTAGNOLA	MODERATELY GOOD

(Müller 1978; Moshkovitz and Ehrlich 1980; Theodoridis 1984) also noted that this species sporadically occurs in lower Miocene Mediterranean sediments. We established the distribution pattern of *D. druggii* by counting 200 discoasterids in the Poggio d'Ancona and Santa Croce d'Arcevia sections (text-figs. 4, 5). The species is rare and occurs discontinuously and is hence of limited biostratigraphic value. However, to have established its distribution in the Mediterranean area facilitates correlation of our regional Mediterranean scheme with standard zonations.

FO of *Sphenolithus belemnus*

Bukry (1973) used the FO of *S. belemnus* to define the base of Zone CN2. The FO of this species was determined quantitatively by Fornaciari et al. (1990, 1993) in low-latitude oceanic sediments and by Olafsson (1991) in mid-latitude areas. These authors obtained similar age evaluations for this biohorizon, which may be considered as synchronous over large geographic areas (Olafsson 1991). There are some contradictions in the literature concerning the presence of *S. belemnus* in the Mediterranean stratigraphic record. Bramlette and Wilcoxon (1967, p.118) reported it as present in the "upper Pteropod marls" near Turin (northern Italy) and Roth et al. (1971) used its FO as a zonal boundary definition (text-fig. 2). Instead, Müller (1978), Ellis and Lohman (1979) and Theodoridis (1984) did not record its presence in the numerous sections they studied and concluded that *S. belemnus* was useless for the biostratigraphy of the Mediterranean region. We document here that typical specimens of *S. belemnus* definitely occur in the lower Miocene Mediterranean record (plate 2, figs. 1-6). The distribution patterns of the species reported in text-figures 5, 9, 11, 12 and 13 indicate that it is easily detected in sphenolith counting and that it is biostratigraphically useful. We believe that its absence in the Mediterranean record assumed by previous authors is due to the widespread hiatuses and unconformities which characterize the interval of the early distribution of *S. belemnus* in sections located in marginal settings (see Poggio d'Ancona, Vignole Borbera, Lemme-Rio del Corvo and Santa Croce d'Acqui sections in text-figure 16). Corresponding to these hiatuses we consistently find the FO and total distribution of *S. belemnus* in foredeep or

depocentral settings (Trebbia Valley and Montechiaro d'Acqui sections in text-figure 16).

LO of *Triquetrorhabdulus carinatus*

The LO of *Triquetrorhabdulus carinatus*, the original definition of the NN2/NN3 boundary, is a poor event and rarely used (Fornaciari et al. 1993). Several workers (e.g., Parker et al. 1985; Olafsson 1989, 1991; Fornaciari et al. 1993) have proposed the FO of *S. belemnus* as an alternative marker event for the NN2/NN3 boundary.

Triquetrorhabdulus carinatus is only sporadically present in the Mediterranean, as suggested by several authors (Müller 1978; Theodoridis 1984; Moshkovitz and Ehrlich 1980) and as documented here in the Monte Cardellia section (text-fig. 3). Therefore, its LO appears to be of no value for the biostratigraphic classification of the Mediterranean record.

LO of *Sphenolithus belemnus* and FO of *Sphenolithus heteromorphus*

The FO of *Sphenolithus heteromorphus* (plate 2, figs. 17, 18) was used by Bukry (1973) to define the CN2/CN3 boundary, while the LO of *S. belemnus* was used by Martini (1971) to define the NN3/NN4 boundary. *S. heteromorphus* is abundantly present in the Mediterranean Miocene record and both FO and LO are biostratigraphically useful (Müller 1978; Theodoridis 1984; Fornaciari et al., in press). Of interest in the present work is the initial appearance of the species and the stratigraphic relationship of the LO of *S. belemnus* with the FO of *S. heteromorphus*. The two species have been reported as co-occurring by some authors (e.g., Bukry 1972; Pujos 1985; Haq and Takayama 1984; Takayama and Sato 1985), while others have indicated that the ranges of the two species can hardly be considered to overlap (Olafsson 1989; Rio et al. 1990b; Fornaciari et al. 1990, 1993). Recently Olafsson (1991) established the abundance patterns of the two species at DSDP Site 608 (northern North Atlantic Ocean) by quantitative methods and demonstrated that the intervals of high abundance of the two species do not overlap, but that they are present in very low

TABLE 2

List of calcareous nannofossil biohorizons used in the literature or proposed in the present study for biostratigraphic correlation and classification in the upper Oligocene-middle Miocene time interval. Also reported: stratigraphic sections where biohorizons have been established, with observations on their biostratigraphic reliability in the Mediterranean stratigraphic record.

BIOHORIZONS	REFERENCE SECTIONS	RELIABILITY
<i>Ceminiolithella rotula</i> FO	NOT RECORDED IN MEDITERRANEAN EARLY MIOCENE	POOR
<i>Helicosphaera mediterranea</i> FO	S.CROCE D'ARCEVIA, ANTIGNOLA, MONTECHIARO D'ACQUI	POSSIBLY GOOD; NOT YET SUFFICIENTLY TESTED
<i>Helicosphaera ampliaperata</i> FO	S.CROCE D'ARCEVIA, MONTECHIARO D'ACQUI	GOOD
<i>Helicosphaera euphratis</i> AE	S.CROCE D'ARCEVIA, MONTECHIARO D'ACQUI	GOOD
<i>Helicosphaera carteri</i> FCO	POGGIO D'ANCONA, S.CROCE D'ARCEVIA, NIVONE-CASTAGNOLA, T.LEMME-CARROSIO, MONTECHIARO D'ACQUI	GOOD
<i>Sphenolithus disbelemnos</i> FO	POGGIO D'ANCONA, S.CROCE D'ARCEVIA, NIVONE-CASTAGNOLA, T.LEMME-CARROSIO	MODERATELY GOOD
<i>Triquetrorhabdulus serratus</i> FO	NOT RECORDED IN MEDITERRANEAN	UNRELIABLE
<i>Sphenolithus delphix</i> LO	MONTE CARDELLIA, POGGIO D'ANCONA, T.LEMME-CARROSIO	MODERATELY GOOD
<i>Sphenolithus delphix</i> FO	MONTE CARDELLIA, POGGIO D'ANCONA, T.LEMME-CARROSIO	MODERATELY GOOD
<i>Zygrhablithus bijugatus</i> LO	MONTE CARDELLIA	POOR
<i>Clausicoccus fenestratus</i> LO	MONTE CARDELLIA	POOR
<i>Dictyococcites bisectus</i> LCO	MONTE CARDELLIA, T.LEMME-CARROSIO	MODERATELY GOOD

abundances between the last common *S. belemnos* and the first common *S. heteromorphus*. These findings probably reconcile the contradictions in the literature and demonstrate the need for quantitative data for precise assessment of calcareous nannofossil events. In this work, we document the initial range of *S. heteromorphus* in the Moria (text-fig. 6) and T. Lemme-Rio del Corvo (text-fig. 13) sections. The final range of *S. belemnos* is documented in the Vignole-Borbera (text-fig. 9), Santa Croce d'Acqui (text-fig. 12), and T. Lemme-Rio del Corvo (text-fig. 13) sections. Integrating the distribution patterns (text-fig. 17), it may be concluded that, in the Mediterranean region too, the intervals of high abundance of the two species do not overlap, but that between the last common and continuous presence of *S. belemnos* and the first common and continuous presence of *S. heteromorphus*, the two forms may be present discontinuously and in low abundances (text-figs. 9, 13). On the basis of the observed distribution patterns, we define two biohorizons, the LCO of *S. belemnos* and the FCO of *S. heteromorphus*, which are easily correlated in the Mediterranean region (text-fig. 16), where they are biostratigraphically useful.

LO of *Helicosphaera ampliaperata*

The LO of *Helicosphaera ampliaperata* (plate 1, figs. 5-10) represents the original definition of the NN4/NN5 and CN3/CN4 boundaries. However, the species is often missing or sporadic in oceanic sediments and various alternative events have been suggested for recognizing the above zonal boundary (Rio et al. 1990b).

Helicosphaera ampliaperata is well represented in Miocene Mediterranean sediments, and its LO has been used in all previous Mediterranean zonations (text-fig. 2). Data reported here (text-figs. 6, 13) and by Fornaciari et al. (in press) indicate that the absolute last occurrence of the species is difficult to pinpoint, and we do not use it in our zonal scheme. However, the LCO of *H. ampliaperata*

is stratigraphically useful, as discussed by Fornaciari et al. (in press).

RELIABILITY OF ADDITIONAL BIOHORIZONS

The previous discussion indicates that, in the interval between the LO of *S. ciperoensis* and *H. ampliaperata*, only three of the seven biohorizons used in standard zonations are reliable in the lower Miocene Mediterranean stratigraphic record (see table 1). In order to recover biostratigraphic resolution, we considered the distribution pattern of other species which have been proposed as useful or which, because they are common in Mediterranean sediments, may provide reliable biohorizons (table 3).

LO of *Dictyococcites bisectus*

The LO of *Dictyococcites bisectus* (plate 1, fig. 1) was proposed by Bukry (1973) as a secondary criterion for recognizing the CP19/CN1 boundary and has been extensively used to approximate the NP25/NN1 boundary in sediments where *H. recta* is missing (e.g., Berggren et al. 1985). However, the relationships of the *D. bisectus* LO with both the *S. ciperoensis* LO (primary definition of the CP19/CN1 boundary) and *H. recta* LO (original definition of the NP25/NN1 boundary) are complex (Rio et al. 1990b). The most recent data clearly indicate that *D. bisectus* has a latitudinally controlled last occurrence (Wei and Wise 1989; Olafsson 1991; Fornaciari et al. 1993).

In this work we document the abundance pattern of *D. bisectus* in its final range by evaluating its abundance in 500 counted placoliths in the Monte Cardellia (text-fig. 3), Antignola (text-fig. 7) and T. Lemme-Carrosio (text-fig. 10) sections. The distribution patterns are compared in text-figure 14. *Dictyococcites bisectus* is abundant and continuously present in the Italian Oligocene sediments studied so far. It drops in abundance shortly below the *S. ciperoensis* LO (text-fig. 14), as it does at mid-latitude Atlantic Sites 522 and 608 (Olafsson 1991). Above the LO of *S. ciperoensis*, *D.*

TABLE 3

Summary of stratigraphic sections considered in this study.

STRATIGRAPHIC SECTIONS STUDIED

SECTION	LOCATION	GEOLOGICAL SETTING and MAIN LITHOLOGY	FIELD STRATIGRAPHIC INFORMATION
MONTE CARDELLIA	Sicily	Slope - foredeep ?	Micarelli et al., 1990
POGGIO D'ANCONA	Marche (Central Apennines)	Foreland basin	Micarelli et al., 1990
S.CROCE D'ARCEVIA	Umbria (Central Apennines)	Foreland basin	Coccioni et al., 1992
MORIA	Marche (Central Apennines)	Foreland basin Mainly basinal hemipelagic sediments	Coccioni et al., 1992
ANTOGNOLA	Parma (Northern Apennines)	Piggyback basin	Papani, Iaccarino, Fornaciari and Rio (In preparation)
NIVIONE-CASTAGNOLA	Piedmont	Episutural basin	Ziveri, 1990
VIGNOLE BORBERA	Piedmont	Episutural basin	Massari, Ghibaudo (in preparation)
T.LEMME-CARROSIO	Piedmont	Episutural basin	Borsetti, 1992; Gelati et al. (in preparation)
MONTECHIARO D'ACQUI	Piedmont	Episutural basin	d'Atri, 1990
S.CROCE D'ACQUI	Piedmont	Episutural basin	d'Atri, 1990
T.LEMME-RIO DEL CORVO	Piedmont	Episutural basin	Massari, Ghibaudo (in preparation)
BOBBIO	Piacenza (Northern Apennines)	Foredeep basin	Fornaciari and Labaume, 1992
LIZZANO BELVEDERE	Bologna (Northern Apennines)	Foredeep basin	Andreozzi, 1989
GOVA	Reggio Emilia (Northern Apennines)	Foredeep basin	Andreozzi, 1989

bisectus remains continuously present, in excess of 1% for a short interval, and then drops to low values or is absent (text-fig. 14). The end of the relatively common (>1%) and continuous presence (LCO) of *D. bisectus*, although not a sharp event, can be correlated consistently in the investigated section (text-fig. 15), and we use it as a zonal boundary definition. The interval of discontinuous presence of *D. bisectus* observed above the level indicated as LCO may be caused by low productivity. It is difficult to distinguish reworked from indigenous occurrences. Reworking affects most Italian onland Miocene and Pliocene sediments, and *D. bisectus* is abundant in upper Paleogene Italian sediments and thus becomes easily reworked. Although the final range of *D. bisectus* is difficult to determine, its abundant presence is a convenient and quick criterion for recognizing Oligocene sediments in the Mediterranean area.

LO of *Clausicoccus fenestratus*

The LO of *Clausicoccus fenestratus* (plate 3, figs. 9, 10) has been proposed to approximate the top of Zone NP25 (Bizon and Müller 1979a). Fornaciari et al. (1993) established the distribution pattern of this species in the equatorial Pacific Ocean and found that its extinction occurs well above the LO of *S. ciperoensis*, in the lower part of the *Sphenolithus delphix* range. The final distribution pattern of *C. fenestratus* has been established in the Monte Cardellia section (text-fig. 3). The species clearly survived *S. ciperoensis* and underwent a drop in abundance close to the FO of *S. delphix*. It is not clear from the data of this single section if the biohorizon is reliable. However, as the species is not easily

recognizable in poorly preserved material, we do not use it in our zonal scheme.

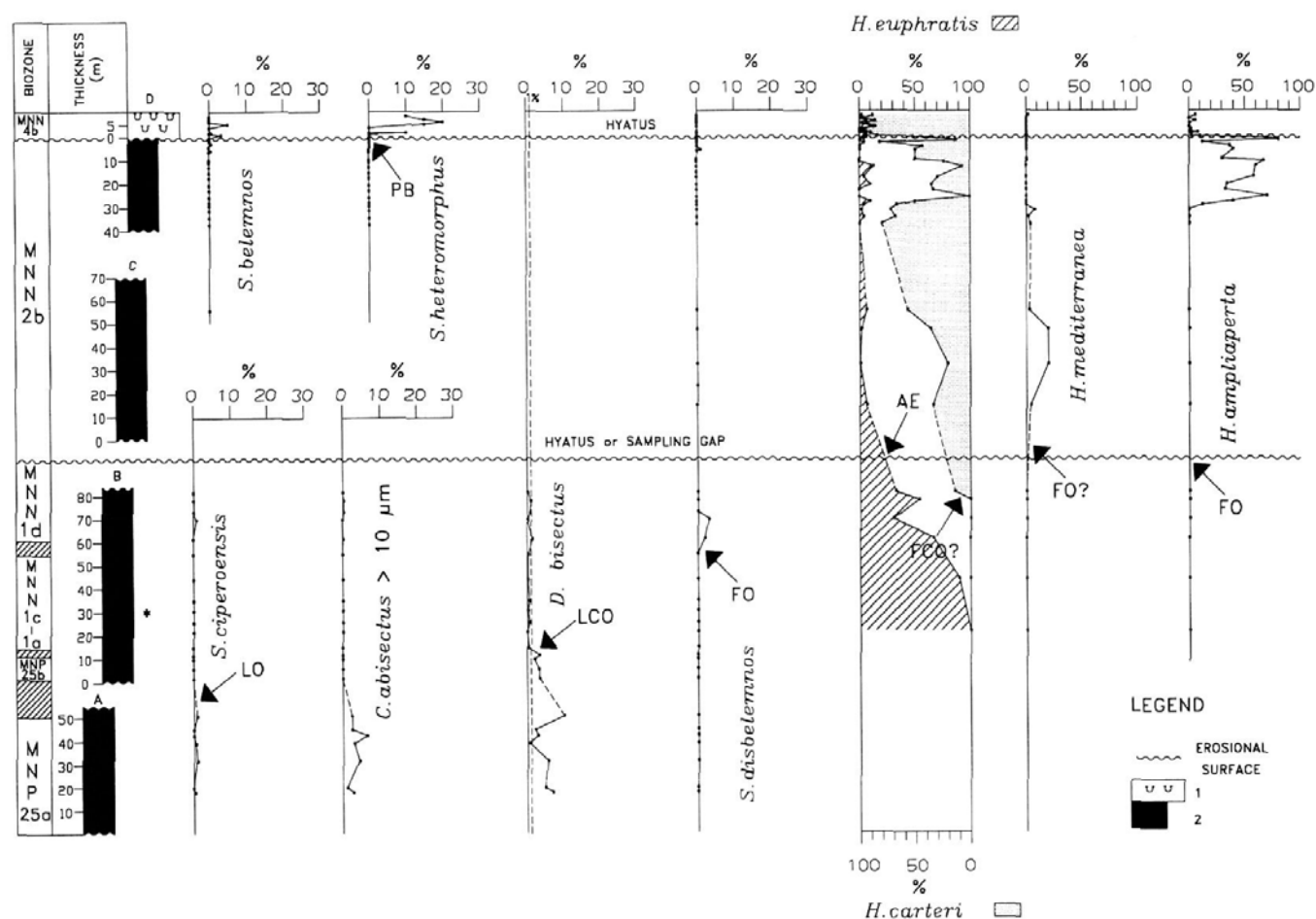
LO of *Zygrhablithus bijugatus*

Zygrhablithus bijugatus (plate 3, fig. 8) is an easily recognized holococcolith, the LO of which has been used to recognize the Oligocene/Miocene boundary (e.g., Edwards 1971; Edwards and Perch-Nielsen 1975), and to approximate the top of Zone NP25 in nearshore sequences (Martini and Müller 1975; Müller 1976). However, recent work (Backman 1980; Parker et al. 1985; Olafsson 1991) indicate that the range of *Z. bijugatus* may extend well into the lower Miocene. Specifically, Olafsson (1991) determined the LO of *Z. bijugatus* as occurring in Chron C6Bn, i.e., close to the FO of *D. druggii*.

The final distribution of *Z. bijugatus* was established in the Monte Cardellia (text-fig. 3), Nivione-Castagnola (text-fig. 8) and T. Lemme-Carrosio (text-fig. 10) sections by counting 500 nannofossils. The form occurs discontinuously, undergoing a frequency drop close to the LO of *S. ciperoensis*. Occurrences above this event may either be related to genuine productivity or to reworking. Because of these problems, we do not use the LO of *Z. bijugatus* in our zonal scheme.

FO and LO of *Sphenolithus delphix*

Sphenolithus delphix (plate 2, figs. 11-16) is an easily recognized species often found associated with *Sphenolithus capricornutus* (Rio et al. 1990b). Rio et al. (1990b) and Fornaciari et al. (1990, 1993) pointed out that the FO and LO of this species probably



TEXT-FIGURE 7

Abundance patterns of selected upper Oligocene to lower Miocene calcareous nannofossils in Antognola section (Northern Apennines, Parma Province). 1. Alternating bioturbated mudstone and sandstone (shelf sediments); 2. Mainly mudstone. LO= Last Occurrence; FO= First Occurrence; LCO= Last Common and Continuous Occurrence.

represent synchronous events between the equatorial Pacific and Indian oceans and are suitable for subdividing the interval between the LO of *S. ciproensis* and the FO of *D. druggii*. A restricted range of *S. delphix* has also been reported in the mid-latitude North Atlantic by Miller et al. (1985), where the total range of the species occurs in a similar position and is associated with Chron C6Cn.

In the examined material, *S. delphix* and, particularly, the conspecific (?) *S. capricornutus* are rare. However, *S. delphix* occurs in all closely sampled sections (text-figs. 3, 4, 10), apparently in the identical stratigraphic position (text-fig. 15). The interval of occurrence of *S. delphix* in the Mediterranean area can be correlated to the range as observed in the equatorial Indian and Pacific oceans. Although the species is rare and its presence may go unobserved in loosely sampled sections, we use the short presence interval of *S. delphix* in our zonal system at the subzonal rank.

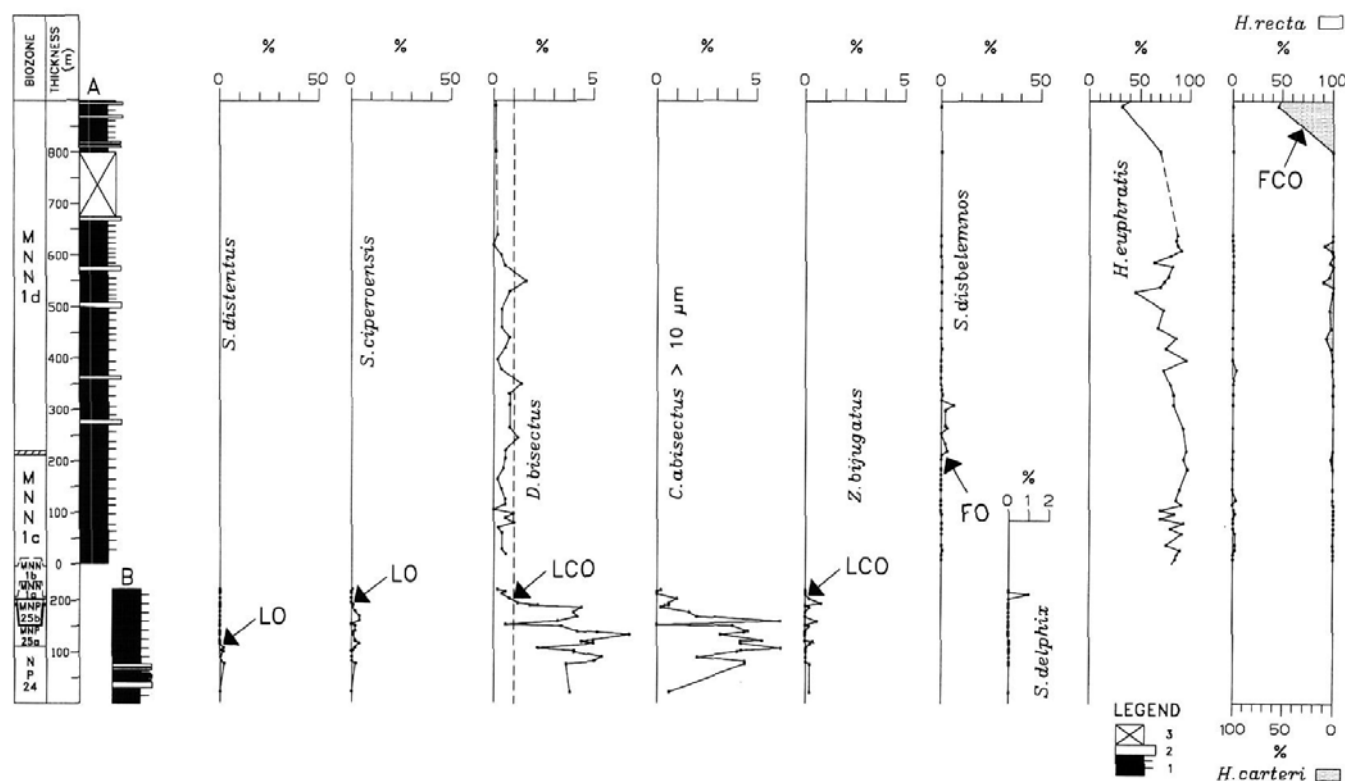
FO of *Triquetrorhabdulus serratus*

Bukry (1973) and Olafsson (1989) both proposed that the FO of *Triquetrorhabdulus serratus* (synonym of *Orthorhabdus serratus* of Bramlette and Wilcoxon 1967, and of *Triquetrorhabdulus martinii* of Theodoridis 1984) is a good alternative event to the FO of *D. druggii* for recognizing the CN1b/CN1c (NN1/NN2) bound-

ary. The species, however, has not been observed in the Mediterranean sections we investigated, or by Theodoridis (1984).

FO of *Sphenolithus disbelemnus*

Rio et al. (1990b) observed in the lower Miocene (Zone NN2, Subzone CN1c) a small sphenolith similar to *Sphenolithus belemnus* when viewed between crossed nicols at 0°, and similar to *Sphenolithus dissimilis* when viewed between crossed nicols at 45°. This form, described as *Sphenolithus disbelemnus* (plate 2, figs. 7-10; plate 4, figs. 1-4; see Taxonomic section), was reported in the equatorial Pacific Ocean in the identical stratigraphic position by Fornaciari et al. (1993). The distribution patterns of *S. disbelemnus* were established in the Poggio d'Ancona (text-fig. 4), Santa Croce d'Arcevia (text-fig. 5), Nivione-Castagnola (text-fig. 8), and T. Lemme-Carrosio (text-fig. 10) sections. The species is not abundant, but occurs in all investigated sections in a comparable biostratigraphic position (text-figs. 15, 16). In the Poggio d'Ancona (text-fig. 4) and Santa Croce d'Arcevia (text-fig. 5) sections, the FO of *S. disbelemnus* occurs slightly above that of *D. druggii*, as it does in the equatorial Indian and Pacific Oceans (Rio et al. 1990b; Fornaciari et al. 1993). *Sphenolithus disbelemnus* is apparently restricted to a short interval in the early Miocene (text-figs. 4, 5, 8, 10), but forms virtually undistinguishable from it characteristically



TEXT-FIGURE 8

Abundance patterns of selected upper Oligocene to lower Miocene calcareous nannofossils in composite Nivione-Castagnola section (eastern sector of Tertiary Piedmont Basin). 1. Mainly mudstone with thin bedded turbidite; 2. Thick bedded turbidite; 3. Covered intervals. LO = Last Occurrence; FO = First Occurrence; FCO = First Common and Continuous Occurrence.

occur together with *S. belemnos* (text-figs. 5, 9, 11, 12, 13). A similar feature was observed by Rio et al. (1990b) in the equatorial Indian Ocean. Since we determined the FO of *S. disbelemnos* in all sections so far investigated, including poorly fossiliferous sections from turbiditic foredeep settings, we consider this biohorizon to be useful for the biostratigraphic classification of the lower Miocene Mediterranean stratigraphic record.

Reversal in abundance of *Helicosphaera carteri* and *Helicosphaera euphratis*

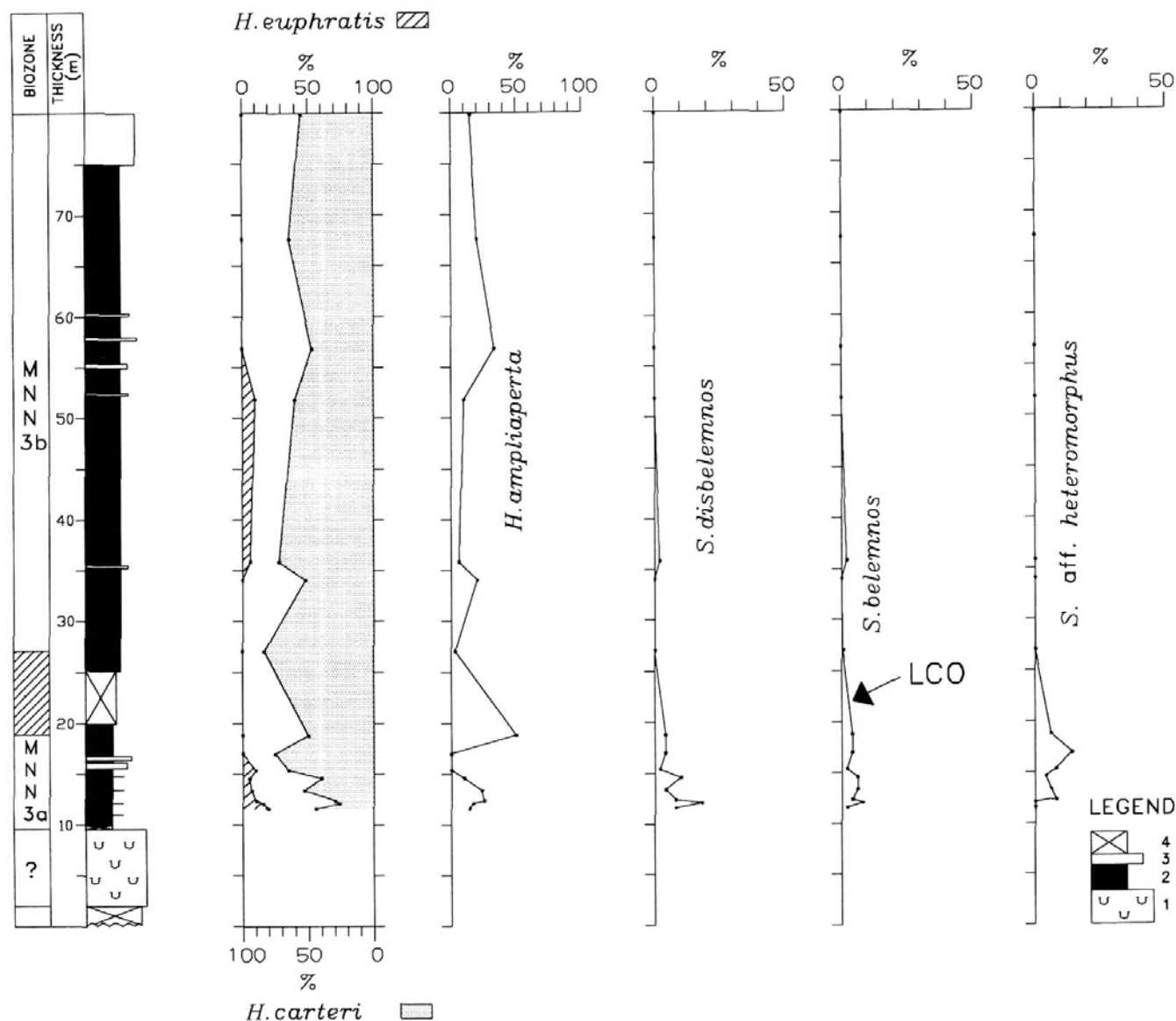
Helicoliths occur intermittently in deep-sea sediments, while they commonly and continuously occur in hemipelagic sediments like those generally represented in the Mediterranean Miocene stratigraphic record. The group is solution-prone. Helicoliths are therefore rarely used for zoning oceanic sediments, but they can provide useful biohorizons in terrigenous sections. Previous studies of the Mediterranean Miocene stratigraphic record used helicoliths for regional biostratigraphic classification (text-fig. 2). We determined the distribution of helicoliths in our sections in order to find supplementary biohorizons.

A major change affecting Mediterranean lower Miocene helicolith assemblages is a reversal in abundance between *Helicosphaera euphratis* (plate 1, fig. 13) and *Helicosphaera carteri* (plate 1, figs. 11, 12). *Helicosphaera euphratis* is dominant in the late Oligocene and earlier part of the Miocene. Subsequently, over a relatively short interval of time, *H. carteri* increases in abundance, concomitantly with a decrease of the former species, and gradually becomes dominant in the helicolith assemblage. We observed this

feature in all sections investigated so far, and it represents an easily determined and convenient divide in lower Miocene calcareous nannofossil biostratigraphy. The reversal in abundance between the two species can be observed in detail in the Santa Croce d'Arcevia (text-fig. 5) and Montichiari d'Acqui (text-fig. 11) sections. On the basis of the distribution patterns, we define two biohorizons: 1) the first common and continuous occurrence (FCO) of *H. carteri* when its abundance increases to over 8-10%, and 2) the acme end of *H. euphratis* when its abundance decreases to below about 30%. The 30% value was chosen because such high value was not observed in the upper lower Miocene and middle Miocene. Although *H. carteri* occurs sporadically in the Miocene interval below the level we have defined as FCO, its absolute first occurrence is difficult to evaluate and it does not correlate consistently among the various sections. On the contrary, both the increase in abundance of *H. carteri* and the acme end of *H. euphratis* correlate well (text-figs. 15, 16). Since the two biohorizons are close to each other, we only use the acme end of *H. euphratis* as a zonal boundary definition.

FOs of *Helicosphaera ampliaperta* and *Helicosphaera mediterranea*

The FO of *Helicosphaera ampliaperta* (plate 1, figs. 5-10) was used as a zonal marker in the Mediterranean Miocene stratigraphic record by Roth et al. (1971) to define the base of the "Discoaster druggii Zone", by Theodoridis (1984) to define the base of the "Helicosphaera vedderi Subzone", and by Müller (1978) to approximate the NN1/NN2 boundary (text-fig. 2). We established the initial distribution pattern of *H. ampliaperta* in the Santa Croce d'Arcevia (text-fig. 5) and Montechiaro d'Acqui (text-fig. 11)



TEXT-FIGURE 9

Abundance patterns of selected lower Miocene calcareous nannofossils in Vignole Borbera section (eastern sector of Tertiary Piedmont Basin). 1. Mainly calcareous sandstone (shelf sediments, Visone Formation); 2. Mainly mudstone; 3. Turbidite; 4. Covered intervals. LCO = Last Common and Continuous Occurrence.

sections. The FO of the species is consistently correlated among the various sections (text-fig. 16) and is believed to be biostratigraphically useful.

The FO of *Helicosphaera mediterranea* (plate 1, fig. 15) is recorded above the FO of *H. ampliaperta* in the above-mentioned sections. Apparently, the two species anticovary so that, when *H. mediterranea* is common, *H. ampliaperta* may be rare or even absent (text-figs. 5, 11).

FO of *Geminilithella rotula*

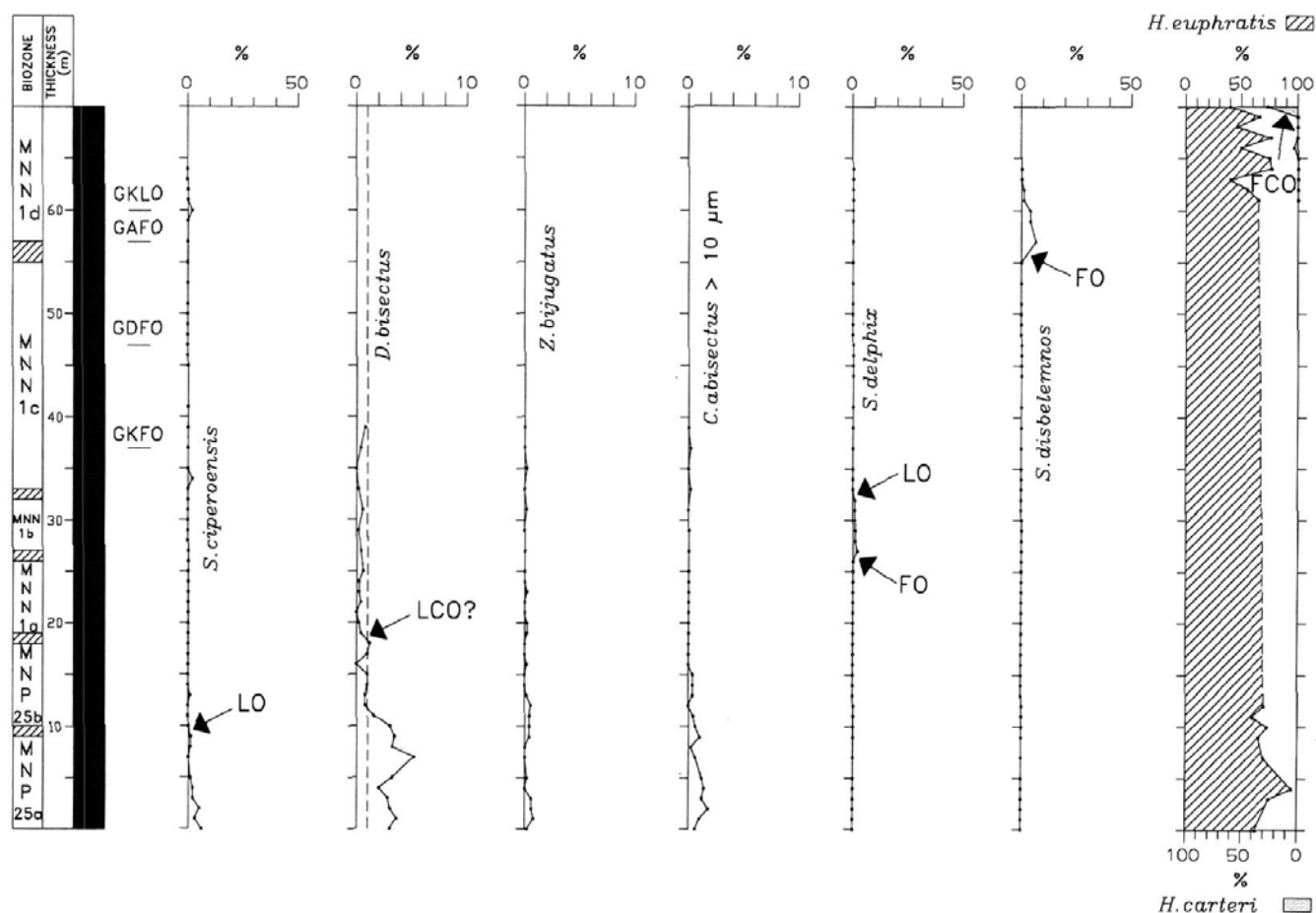
Theodoridis (1984) used the FO of *Geminilithella rotula* to define the bottom of his lower Miocene "Triquetrorhabdulus milowii Zone", below the FO of *S. heteromorphus* and above the FO of *H. ampliaperta* (text-fig. 2). Fornaciari et al. (1993) established the

distribution pattern of the species in the western equatorial Pacific Ocean and concluded that it is difficult to pinpoint a distinct FO level.

In the lower Miocene sediments considered here, *G. rotula* is very rare, becoming relatively common only within the range of *S. heteromorphus*. As the species may be difficult to recognize in poorly preserved material, we do not use its FO in our zonal scheme.

BIOSTRATIGRAPHIC CLASSIFICATION

The previous discussion has shown that, during latest Oligocene-early Miocene times, many of the biohorizons defining zonal boundaries in standard zonations can not be recognized in the



TEXT-FIGURE 10

Abundance patterns of selected upper Oligocene to lower Miocene calcareous nannofossils in T. Lemme-Carrosio section (eastern sector of Tertiary Piedmont Basin). Lithology represented by mudstones. GKFO= first occurrence of *Globorotalia kugleri*; GDFO= first occurrence of *Globoquadrina dehiscens*; GAFO= first occurrence of *Globigerinoides altipertura*; GKLO= last occurrence of *Globorotalia kugleri*. LO= Last Occurrence; FO= First Occurrence; LCO= Last Common and Continuous Occurrence; FCO = First Common and Continuous Occurrence. Data on planktonic foraminifera provided by S. Iaccarino (written communication).

Mediterranean region (table 1). Instead, distinct changes in the regional distribution patterns of selected calcareous nannofossils provide many biohorizons which are useful for regional correlation (text-figs. 15, 16; table 2). Therefore, it seems legitimate to propose a new regional Mediterranean zonal system which is described in the following section from older to younger zones. This scheme is presented in text-figure 2 together with standard and previous Mediterranean zonations, and in text-figure 17, where a summary of the range of the most important taxa is given.

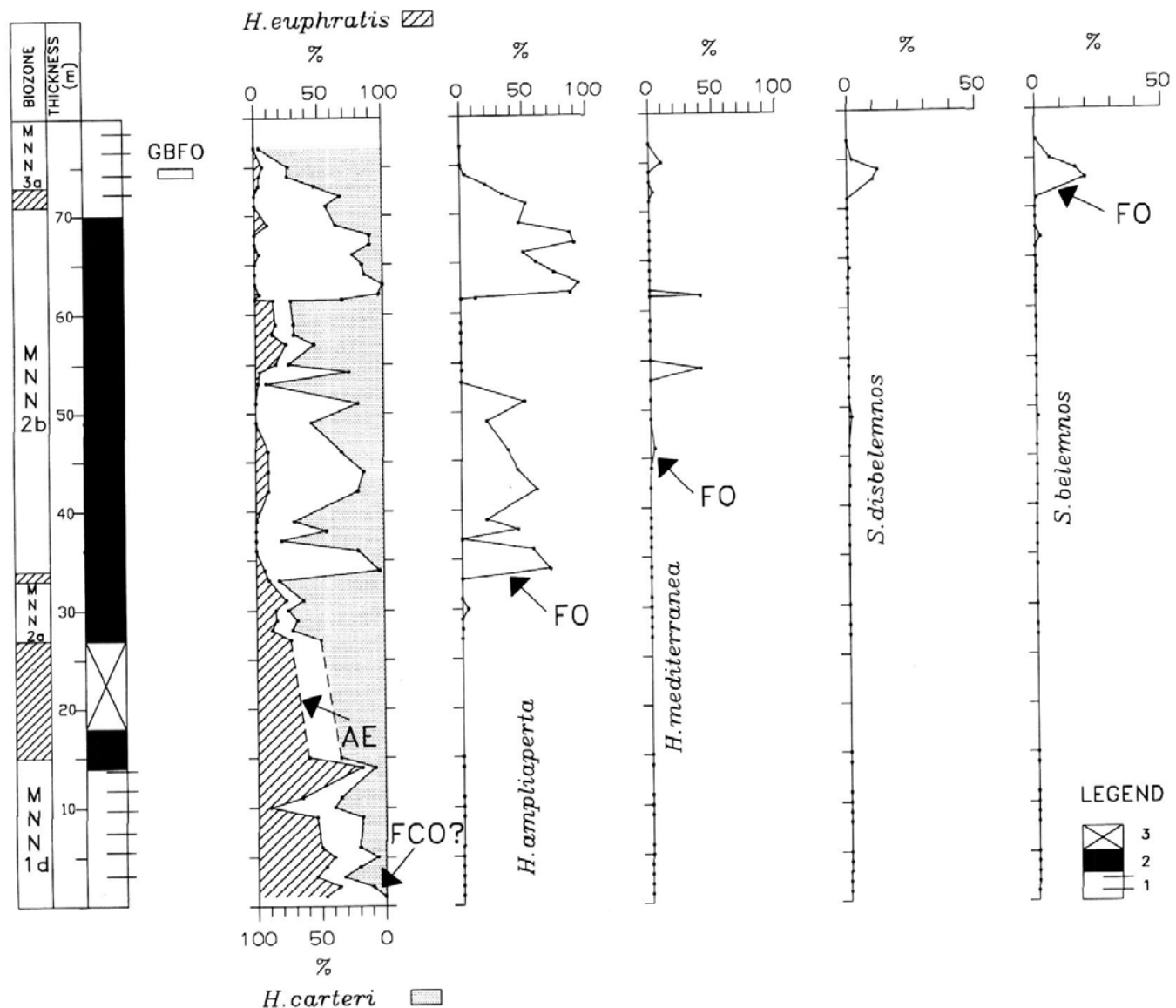
Biostratigraphic zonal concepts and terminology

The biostratigraphic zonal concepts and terminology followed here are basically those of the International Stratigraphic Guide (ISG 1976, Hedberg, H., editor). In our zonal system we use range zones and interval zones. A range zone is defined as a group of strata representing the "stratigraphic range of some selected element" of the total assemblage of fossil forms present. An interval zone is defined as the stratigraphic interval between two biohorizons. Since a "biostratigraphic unit may be considered to be present only within the observed limits of occurrence of paleontologic features on which it is based" (ISG 1976, p. 46), range zones can be recognized legitimately only if the taxa named in the definition are present.

Accordingly, range zones in the present system are based on species continuously and commonly distributed in the area (text-fig. 17) and have a higher degree of recognizability than interval zones, the recognition of which may be difficult in spot samples because they lack distinctive features.

The ISG (1976) adopted 4 types of range zone (total-range zone, concurrent-range zone, Oppel zone, lineage-range zone). The ISG does not recognize a partial-range zone, widely used in calcareous plankton biostratigraphy (e.g., Berggren and Miller 1988); it would appear that it has been considered as a synonym for the interval zone. Here we prefer to refer to partial-range zone to indicate the body of strata within the range of a common and continuously distributed taxon partitioned by prominent biohorizons (see discussion in Berggren and Miller 1988).

In our system we make use of zones and subzones. Zones are bounded by major paleontological changes and are easily recognized even in spot samples, short sections and poorly preserved material. Subzones are defined by paleontological features which may not be recognized in spot samples or short or widely sampled sections.



TEXT-FIGURE 11

Abundance patterns of selected lower Miocene calcareous nannofossils at Montechiaro d'Acqui section (central sector of Tertiary Piedmont Basin). 1. Mainly mudstones and turbidites; 2. Mainly mudstones; 3. Covered intervals. GBFO = first occurrence of *Globigerinoides bisphericus*. FO = First Occurrence; FCO = First Common and Continuous Occurrence; AE = Acme End. Data on planktonic foraminifera collected by A. D'Atri (personal communication).

As regards the terminology adopted, we adhere strictly to the suggestions of the ISG (1976). The names of interval zones are derived from those of boundary horizons, the name of the basal horizon preceding that of the upper boundary. Concurrent-range zones are named from the two taxa which characterize them by their co-occurrence. Total-range and partial-range zones are named from the taxon whose range they express. Although this terminology has the disadvantage of cumbersome length, it does avoid the problem of using the same name for different biostratigraphic units which is so common in calcareous nannoplankton literature.

The Oligocene-Miocene zones and subzones have been given numerical notations (MNN2, etc.) for ease of communication, similar to those used by Rio et al. (1990a) and Fornaciari et al. (in press) for the Mediterranean Pliocene-Pleistocene and middle Miocene stratigraphic records respectively.

LATEST OLIGOCENE-EARLY MIOCENE MEDITERRANEAN ZONAL SYSTEM

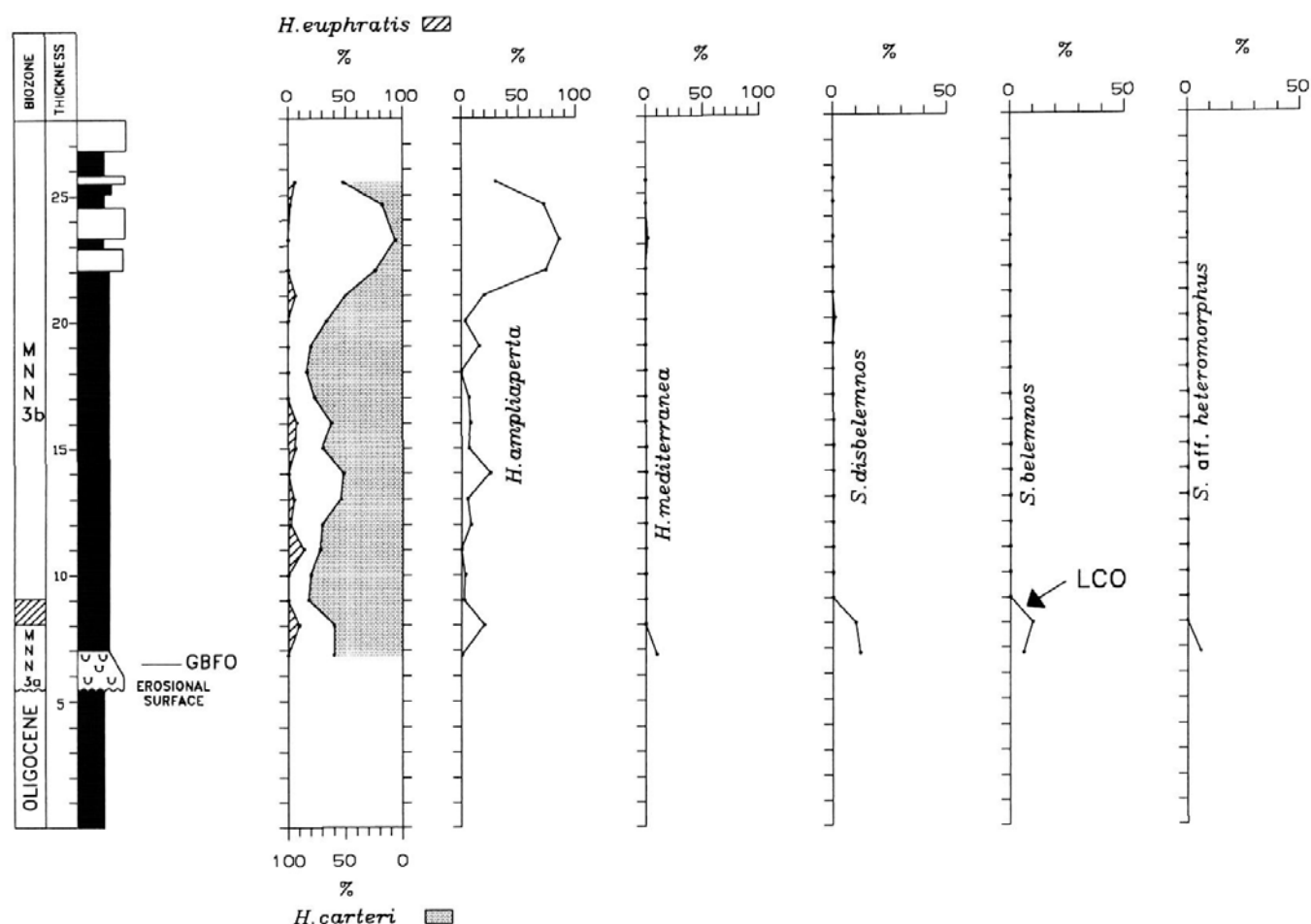
Sphenolithus ciperoensis Partial-range Zone (MNP25a)

Authors: Bukry and Bramlette (1970) emended Fornaciari and Rio, present work.

Definition: Interval of common presence of *S. ciperoensis* above LO of *S. distentus*.

Reference section: Nivione-Castagnola (text-fig. 8).

Characteristics: A normal assemblage in this zone contains: *Clausicoccus fenestratus*, *Coccolithus eoelagicus* (rare), *C. miopelagicus*, *C. pelagicus*, *Coronocyclus nitescens* (rare), *Cycliticargolithus abisectus* <10µm, *C. abisectus* >10µm, *C. flori-*



TEXT-FIGURE 12

Abundance patterns of selected lower Miocene calcareous nannofossils in Santa Croce d'Acqui section (central sector of Tertiary Piedmont Basin). GBFO= first occurrence of *Globigerinoides bisphericus*. See text-figure 9 for lithology legend. LO = Last Occurrence. Data on planktonic foraminifera collected by A. D'Atri (personal communication).

danus, *Dictyococcites bisectus*, *D. aff. bisectus*, *D. hesslandii-scrippsae*, *Discoaster deflandrei*, *Helicosphaera euphratis*, *H. obliqua* (rare), *H. perch-nielseniae*, *H. recta*, *H. truempyi* (very rare), *Ilseolithina fusa* (rare), *Reticulofenestra* spp., *Reticulofenestra daviesii*, *Sphenolithus ciperoensis*, *S. conicus* (rare), *S. moriformis*, *Triquetrorhabdulus carinatus* (rare), *Zygrhablithus bijugatus*.

Dictyococcites bisectus decreases in abundance at the top of the zone. Among helicoliths *H. euphratis* is dominant, *H. perch-nielseniae* is subordinate and *H. recta*, *H. obliqua* and *H. truempyi* are rare. Among sphenoliths *S. moriformis* is abundant, while the zone marker *S. ciperoensis* may be missing in a few samples; *S. conicus* is rare.

Remarks: Bramlette and Wilcoxon (1967) introduced the *Sphenolithus ciperoensis* Zone by defining its top by the LO of *H. recta* (their *Helicosphaera truncata*). Bukry and Bramlette (1970) emended the Zone defining its top by the LO of *S. ciperoensis* and *D. bisectus*.

Dictyococcites bisectus Partial-range Zone (MNP25b)

Authors: Fornaciari and Rio, present work.

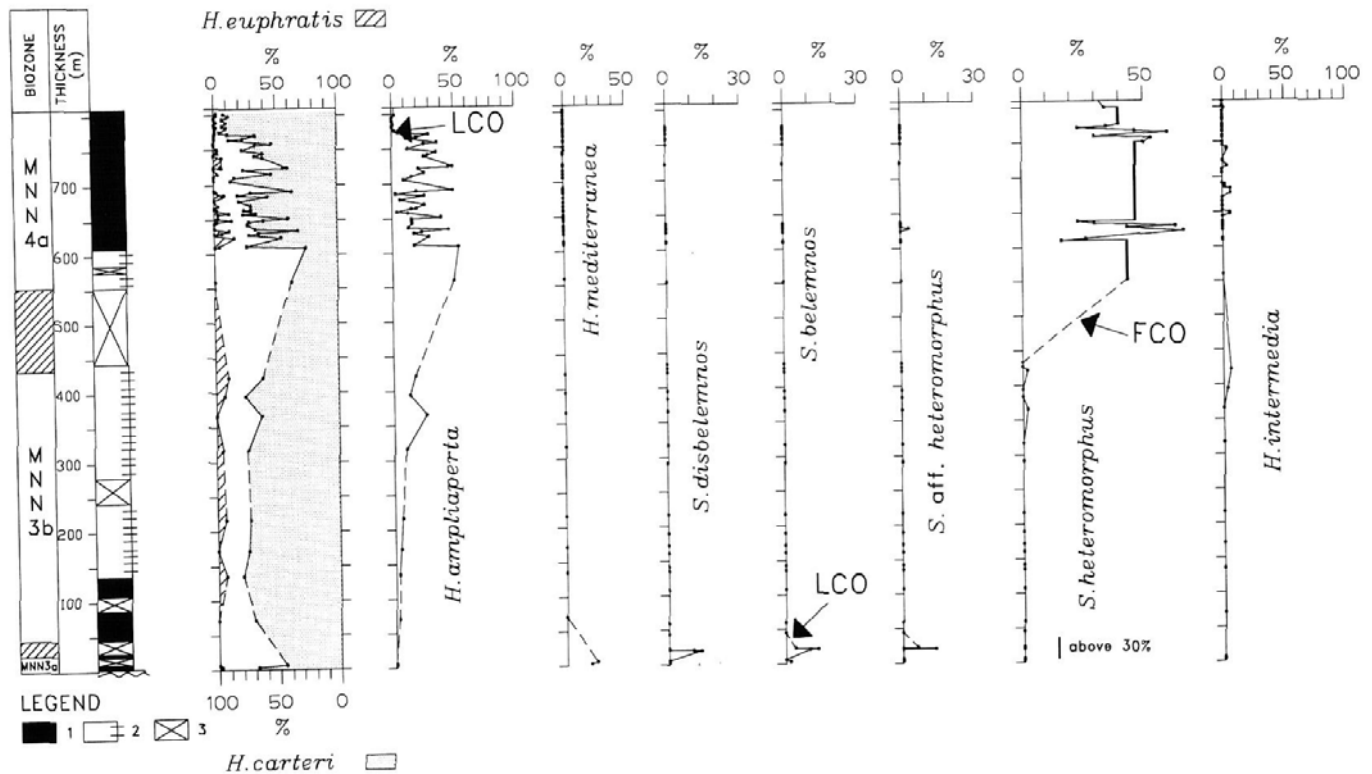
Definition: Interval of continuous and relatively common presence of *D. bisectus* above LO of *S. ciperoensis*.

Reference sections: Monte Cardellia, T. Lemme-Carrosio and Antognola (text-figs. 3, 7, 10).

Characteristics: A normal assemblage in this zone contains: *Clausicoccus fenestratus*, *Coccolithus miopelagicus*, *C. pelagicus*, *Coronocyclus nitescens* (rare), *Cyclicargolithus abisectus* <10µm, *C. abisectus* >10µm (rare), *C. floridanus*, *Dictyococcites bisectus*, *D. aff. bisectus*, *D. hesslandii-scrippsae*, *Discoaster deflandrei*, *Helicosphaera euphratis*, *H. obliqua* (rare), *H. Perch-nielseniae*, *H. recta*, *Ilseolithina fusa* (rare), *Reticulofenestra* spp., *Reticulofenestra daviesii*, *Sphenolithus conicus* (rare), *S. moriformis*, *Triquetrorhabdulus carinatus* (rare), *Zygrhablithus bijugatus*.

Although in low frequency, *D. bisectus* is continuously present; *C. eopelagicus* and *H. truempyi* were not observed; *Z. bijugatus* apparently drops in abundance in the middle part of this zone.

Remarks: *Dictyococcites bisectus* is present discontinuously and in low frequency even above the top of the zone (see previous



TEXT-FIGURE 13

Abundance patterns of selected lower to middle Miocene calcareous nannofossils in Lemme-Rio del Corvo section (eastern sector of Tertiary Piedmont Basin). 1. Mainly mudstone; 2. Mudstone and turbidite; 3. Covered intervals. LO= Last Occurrence; FO= First Occurrence; LCO= Last Common and Continuous Occurrence.

discussion and text-figure 14); therefore the zonal interval denotes the partial range of the common presence of this taxon.

Helicosphaera euphratis Partial-range Zone (MNN1)

Authors: Fornaciari and Rio, present work.

Definition: Interval of abundant presence of *H. euphratis* between LCO of *D. bisectus* and acme end of *H. euphratis*.

Reference sections: Antognola and T. Lemme-Carrosio (text-figs. 7, 10) (lower part), and Santa Croce d'Arcevia and Monte Chiaro d'Acqui (text-figs. 5, 11) (upper part).

Remarks: *Helicosphaera euphratis* is well represented above the top of the Zone, but is subordinate to the *H. carteri*-*H. ampliaperta* group. The zone should be defined more properly as a partial-abundance range zone.

The interval can be subdivided into four subzones, as outlined below.

Dictyococcites bisectus-*Sphenolithus delphix* Interval Subzone (MNN1a)

Authors: Fornaciari and Rio, present work.

Definition: Interval from LCO of *D. bisectus* to FO of *S. delphix*.

Reference sections: Monte Cardellia and T. Lemme-Carrosio (text-figs. 3, 10).

Characteristics: A normal assemblage in this subzone contains: *Clausicoccus fenestratus*, *Coccolithus miopelagicus*, *C. pelagicus*, *Coronocyclus nitescens* (rare), *Cyclicargolithus abisectus* <10µm, *C. abisectus* >10µm, *C. floridanus*, *Dictyococcites bisectus* (very rare), *D. aff. bisectus* (very rare), *D. hesslandii-scrippsae*, *Discoaster deflandrei*, *Helicosphaera carteri* (very rare and atypical), *H. euphratis*, *H. obliqua* (rare), *H. perch-niel-senae*, *H. recta*, *Ilseolithina fusa* (rare), *Reticulofenestra* spp., *Reticulofenestra daviesii*, *Sphenolithus calyculus*, *S. conicus* (rare), *S. dissimilis* (very rare), *S. moriformis*, *Triquetrorhabdulus carinatus* (rare), *Zygrhablithus bijugatus* (rare).

Dictyococcites bisectus and *D. aff. bisectus* are rare and discontinuously present. *Clausicoccus fenestratus* drops in abundance. Large forms of *C. abisectus* (>10µm) apparently become extinct in the uppermost part of the subzone. Among sphenoliths a few specimens of *S. calyculus* are present for short intervals.

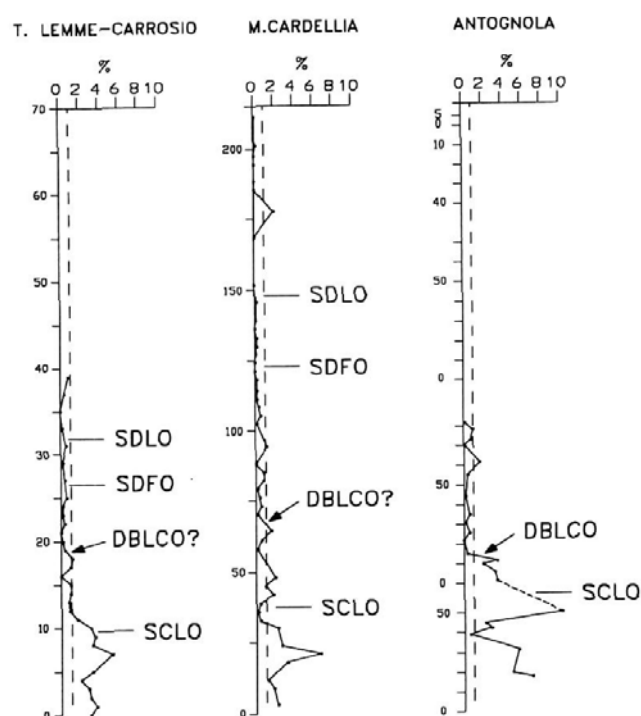
Sphenolithus delphix Total-range Subzone (MNN1b)

Authors: Fornaciari and Rio, present work.

Definition: Interval corresponding to the total range of *S. delphix*.

Reference sections: Monte Cardellia, Poggio d'Ancona and T. Lemme-Carrosio (text-figs. 3, 4, 10).

Characteristics: A normal assemblage in this subzone contains: *Clausicoccus fenestratus* (rare), *Coccolithus miopelagicus*, *C. pelagicus*, *Coronocyclus nitescens* (rare), *Cyclicargolithus abisectus* <10µm, *C. floridanus*, *Dictyococcites bisectus* (rare), *D.*



TEXT-FIGURE 14

Comparison of abundance patterns shown by *Dictyococcites bisectus* in its final range in T. Lemme-Carrosio, Monte Cardellia and Antognola sections. SCLO = *Sphenolithus ciperoensis* LO; DBLCO = *D. bisectus* last common and continuous occurrence; SDFO = *Sphenolithus delphix* FO; SDLO = *S. delphix* LO.

aff. *bisectus* (rare), *D. hesslandii-scrippsae*, *Discoaster deflandrei*, *Helicosphaera carteri* (very rare), *H. euphratis*, *H. obliqua* (rare), *H. perch-nielseniae*, *H. recta* (rare), *Ilseithina fusa* (rare), *Reticulofenestra* spp., *Reticulofenestra daviesii*, *Sphenolithus capricornutus* (rare), *S. conicus* (rare), *S. dissimilis* (very rare), *S. delphix*, *S. moriformis*, *Triquetrorhabdulus carinatus* (rare), *Zygrhablithus bijugatus* (rare).

Remarks: The interval is short and the zonal marker is never abundant in the Mediterranean stratigraphic record.

***Sphenolithus delphix*-*Sphenolithus disbelemnus* Interval Subzone (MNN1c)**

Authors: Fornaciari and Rio, present work.

Definition: Interval from LO of *S. delphix* to FO of *S. disbelemnus*.

Reference sections: Poggio d'Ancona and T. Lemme-Carrosio (text-figs. 4, 10).

Characteristics: A normal assemblage in this subzone contains: *Clausicoccus fenestratus* (rare), *Coccolithus miopelagicus*, *C. pelagicus*, *Coronocyclus nitescens* (rare), *Cyclicargolithus abisectus* <10µm, *C. floridanus*, *Dictyococcites bisectus* (rare and probably reworked), *D. aff. bisectus* (rare and probably reworked), *D. hesslandii-scrippsae*, *Discoaster deflandrei*, *D. druggii* (rare), *Helicosphaera carteri* (very rare), *H. euphratis*, *H. obliqua* (rare), *H. perch-nielseniae*, *H. recta* (rare), *Ilseithina fusa* (rare), *Reticulofenestra* spp., *Reticulofenestra daviesii*, *Spheno-*

lithus conicus (rare), *S. dissimilis* (very rare), *S. moriformis*, *Triquetrorhabdulus carinatus* (rare), *Zygrhablithus bijugatus* (rare).

The occurrence of rare but typical *D. druggii* in the uppermost part of the interval is noteworthy. Above the FO of *S. disbelemnus*, *H. perch-nielseniae* is rare.

***Sphenolithus disbelemnus*-*Helicosphaera carteri* Interval Subzone (MNN1d)**

Authors: Fornaciari and Rio, present work.

Definition: Interval from LO of *S. disbelemnus* to acme end of *H. euphratis*.

Reference sections: Poggio d'Ancona (text-fig. 4) (lower part) and Santa Croce d'Arcevia (text-fig. 5) (upper part).

Characteristics: A normal assemblage in this subzone contains: *Coccolithus miopelagicus*, *C. pelagicus*, *Coronocyclus nitescens* (rare), *Cyclicargolithus abisectus* <10µm, *C. floridanus*, *Dictyococcites* spp., *Discoaster deflandrei*, *D. druggii* (rare), *Helicosphaera carteri*, *H. euphratis*, *H. obliqua* (rare), *H. perch-nielseniae*, *H. recta*, *Ilseithina fusa* (rare), *Reticulofenestra* spp., *Reticulofenestra daviesii*, *Sphenolithus conicus* (rare), *S. disbelemnus*, *S. dissimilis* (very rare), *S. moriformis*, *Triquetrorhabdulus carinatus* (rare), *Zygrhablithus bijugatus* (rare).

Dictyococcites bisectus, *D. aff. bisectus*, and *D. hesslandii-scrippsae* are often present in low abundance and discontinuously in this and in overlying intervals, most probably as a result of the reworking which affected virtually all investigated sections. *Clausicoccus fenestratus* and *I. fusa* were not observed in this interval. *Discoaster druggii* was sporadically observed. *Helicosphaera perch-nielseniae* and *H. recta* apparently become extinct shortly below the acme-end of *H. euphratis*. A distinct overlap interval of common *H. euphratis* and *H. carteri* occurs at the top of the interval which is biostratigraphically useful. *Sphenolithus disbelemnus* was observed only in the lower part of the subzone.

***Helicosphaera carteri* Partial-range Zone (MNN2a)**

Authors: Fornaciari and Rio, present work.

Definition: Interval of common *H. carteri* above acme end of *H. euphratis* and below FO of *H. ampliaperta*.

Reference sections: Santa Croce d'Arcevia and Montechiaro d'Acqui (text-figs. 5, 11).

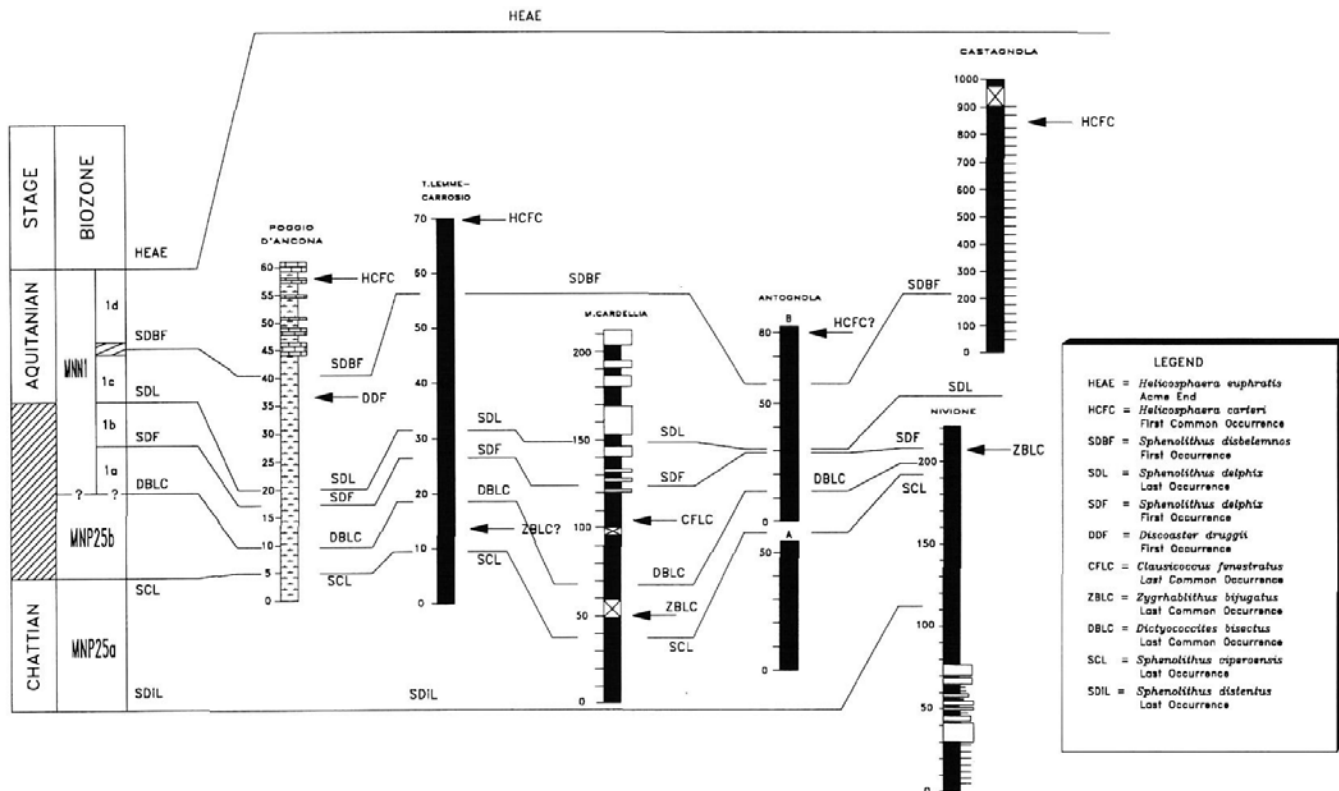
Characteristics: A normal assemblage in this zone contains: *Coccolithus miopelagicus*, *C. pelagicus*, *Coronocyclus nitescens* (rare), *Cyclicargolithus abisectus* <10µm, *C. floridanus*, *Dictyococcites* spp., *Discoaster deflandrei*, *Helicosphaera carteri* (dominant), *H. euphratis*, *H. intermedia*, *H. obliqua* (rare), *Reticulofenestra* spp., *Reticulofenestra daviesii*, *Sphenolithus conicus* (rare), *S. dissimilis* (very rare), *S. moriformis*, *Triquetrorhabdulus carinatus* (rare), *Zygrhablithus bijugatus* (rare; reworked?).

The first occurrence of rare and scattered *H. intermedia* was observed in this zone.

Remarks: The interval is very distinctive because of the dominance of *H. carteri* over *H. euphratis*.

***Helicosphaera ampliaperta* Partial-range Zone (MNN2b)**

Authors: Fornaciari and Rio, present work.



TEXT-FIGURE 15

Biostratigraphic correlations among upper Oligocene to lower Miocene stratigraphic sections considered in this work.

Definition: Interval of partial range of *H. ampliapertura* below FO of *S. belemnus*.

Reference sections: Santa Croce d'Arcevia and Montechiaro d'Acqui (text-figs. 5, 11).

Characteristics: A normal assemblage in this zone contains: *Coccolithus miopelagicus*, *C. pelagicus*, *Coronocyclus nitescens* (rare), *Cyclicargolithus abisectus* <10µm, *C. flordanus*, *Dictyococcites* spp., *Discoaster deflandrei*, *Helicosphaera ampliapertura*, *H. carteri*, *H. euphratis*, *H. intermedia*, *H. mediterranea*, *H. obliqua* (rare), *Reticulofenestra* spp., *Reticulofenestra daviesii*, *Sphenolithus conicus* (rare), *S. dissimilis* (very rare), *S. moriformis*, *Triquetrorhabdulus carinatus* (rare), *Zygrrhabdulus bijugatus* (rare).

Helicosphaera mediterranea first occurs within the zone and anticorrelates with *H. ampliapertura*. The last specimens of *Z. bijugatus* (reworked?) were observed in the uppermost part of this zone.

***Sphenolithus belemnus* Total-range Zone (MNN3a)**

Authors: Fornaciari and Rio, present work.

Definition: Interval of common and continuous presence of *S. belemnus*.

Reference sections: Santa Croce and Montechiaro d'Acqui (text-figs. 5, 11).

Characteristics: A normal assemblage in this zone contains: *Coccolithus miopelagicus*, *C. pelagicus*, *Coronocyclus nitescens* (rare), *Cyclicargolithus abisectus* <10µm, *C. flordanus*, *Dictyococcites* spp., *Discoaster deflandrei*, *Helicosphaera am-*

pliapertura, *H. carteri*, *H. euphratis*, *H. intermedia*, *H. mediterranea*, *H. obliqua* (rare), *Reticulofenestra* spp., *Reticulofenestra daviesii*, *Sphenolithus belemnus*, *S. calyculus* (rare), *S. conicus* (rare), *S. disbelemnus*, *S. dissimilis* (very rare), *S. aff. heteromorphus*, *S. moriformis*, *Triquetrorhabdulus carinatus* (rare).

The last specimens of *T. carinatus* were observed in the basal part of the zone. *Helicosphaera mediterranea* apparently becomes extinct in this interval. After a long absence, *S. disbelemnus* "reappears"; in the upper part the occurrence of rare *S. calyculus* and *S. aff. heteromorphus* (plate 2, figs. 19, 20) appears to be a useful biostratigraphic feature.

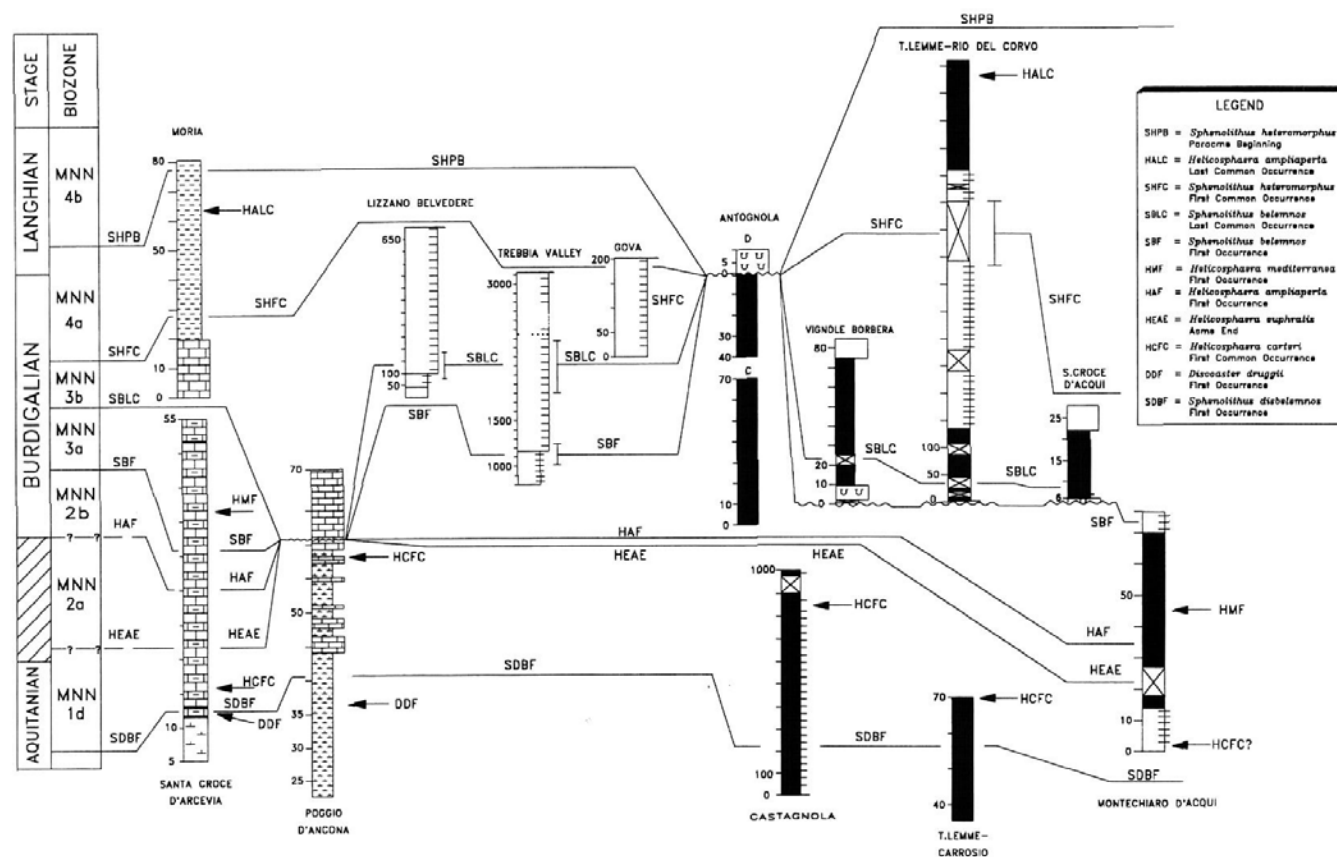
***Sphenolithus belemnus*-*Sphenolithus heteromorphus* Interval Zone (MNN3b)**

Authors: Fornaciari and Rio, present work.

Definition: Interval from the last common and continuous occurrence (LCO) of *S. belemnus* to the first common and continuous occurrence (FCO) of *S. heteromorphus*.

Reference sections: T. Lemme-Rio del Corvo (text-fig. 13); but see also Moria, Vignole Borbera and Santa Croce d'Acqui (text-figs. 6, 9, 12).

Characteristics: A normal assemblage in this zone contains: *Coccolithus miopelagicus*, *C. pelagicus*, *Coronocyclus nitescens* (rare), *Cyclicargolithus abisectus* <10µm, *C. flordanus*, *Dictyococcites* spp., *Discoaster deflandrei*, *Helicosphaera am-*



TEXT-FIGURE 16

Biostratigraphic correlations among lower to middle Miocene stratigraphic sections considered in this work or studied by the present authors.

pliaptera, *H. carteri*, *H. euphratis*, *H. intermedia*, *H. obliqua* (rare), *H. walbersdorfensis*, *Reticulofenestra* spp., *Reticulofenestra daviesii*, *Sphenolithus belemnus* (very rare), *S. calyculus* (very rare), *S. conicus* (very rare), *S. dissimilis* (very rare), *S. aff. heteromorphus*, *S. heteromorphus* (very rare), *S. moriformis*.

An interval of discontinuous occurrence of *H. walbersdorfensis* was observed in the lower-middle part of the zone. The last rare specimens of *S. aff. heteromorphus* and *S. calyculus* were observed in this zone.

Remarks: See discussion above (pages 8 and 9) on the relationships between the ranges of *S. belemnus* and *S. heteromorphus*.

Helicosphaera ampliaptera-*Sphenolithus heteromorphus* Interval Zone (MNN4a)

Authors: Fornaciari, Di Stefano and Rio (in Fornaciari et al., in press).

Definition: Interval between the FCO and the paracme beginning of *S. heteromorphus*.

Reference section: Moria (text-fig. 6).

Remarks: This zonal interval is discussed in Fornaciari et al. (in press).

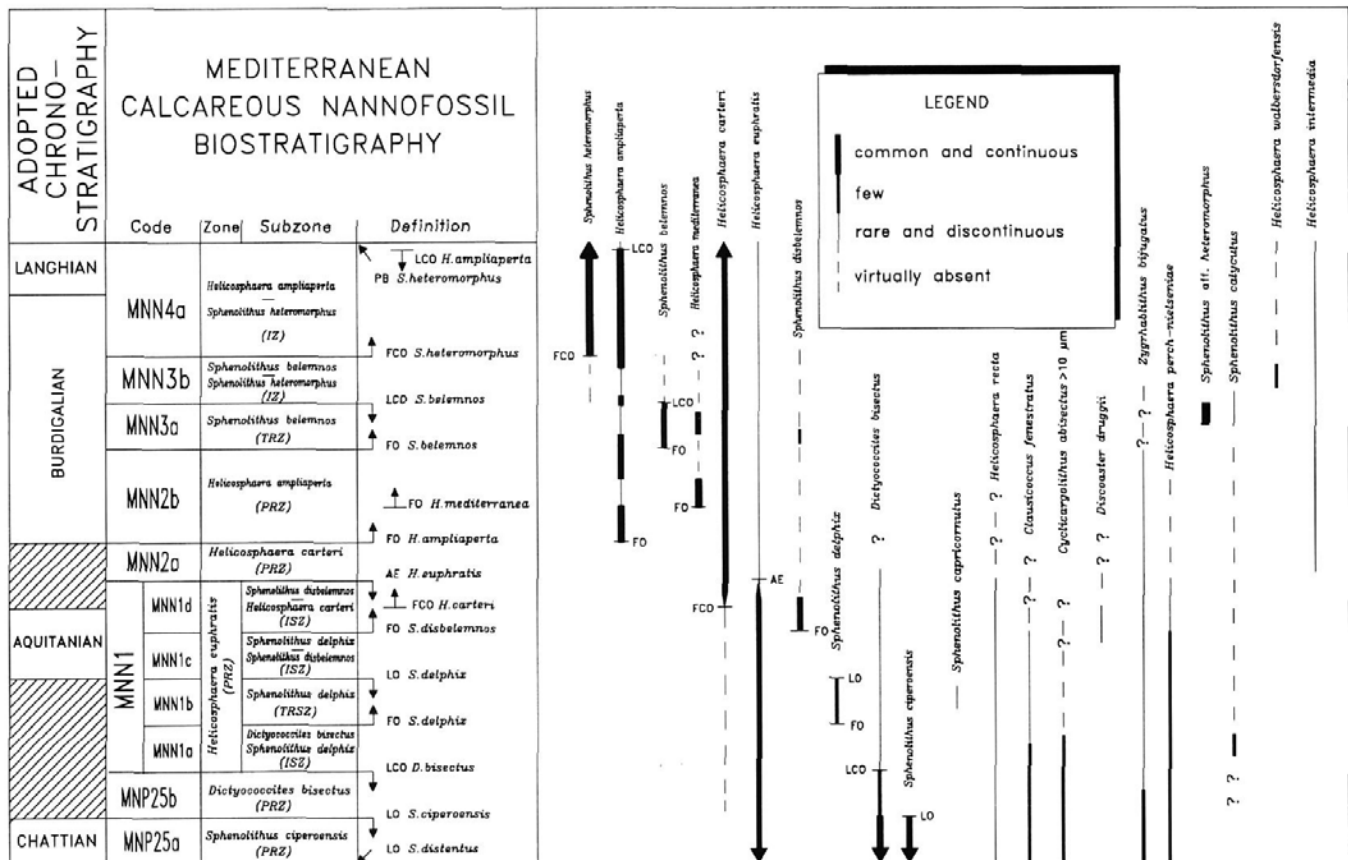
CORRELATION WITH PLANKTONIC FORAMINIFERA BIOHORIZONS

A plethora of Mediterranean planktonic foraminifera zonal schemes has been proposed (reviewed by Iaccarino 1985). A tentative correlation of the Mediterranean calcareous nannofossil zonal scheme proposed here with the Mediterranean planktonic foraminifera zonal scheme of Iaccarino (1985) is presented in text-figure 18. This correlation, based on a limited number of sections, must be considered as preliminary and is discussed below.

The FO of *Globorotalia kugleri*, defining the P22/N4 boundary (Berggren and Miller 1988), occurs in both the Monte Cardellia and Poggio d'Ancona sections in Subzone MNN1a (text-figs. 3, 4). In the T. Lemme-Carrosio section (text-fig. 10) the biohorizon is recorded within the lower part of Zone MNN1c. It is not clear if these contrasting results are related to taxonomic problems in the recognition of *G. kugleri* or to a delayed arrival of this tropical-subtropical taxon to the mid-latitude T. Lemme-Carrosio section (text-fig. 1).

The FO of *Globoquadrina dehiscens* occurs consistently in the Monte Cardellia, Poggio d'Ancona and T. Lemme-Carrosio sections within Subzone MNN1c (text-figs. 3, 4, 10).

Both the LO of *G. kugleri*, defining the top of Zone N4 of Blow (1969), and the FO of *Globigerinoides altiapertura* are recorded in the Santa Croce d'Arcevia and T. Lemme-Carrosio sections within Subzone MNN1d, shortly below the FCO of *H. carteri* (text-figs. 5, 10).



TEXT-FIGURE 17
Mediterranean calcareous nannofossil zonal system proposed in this work and ranges of most important taxa.

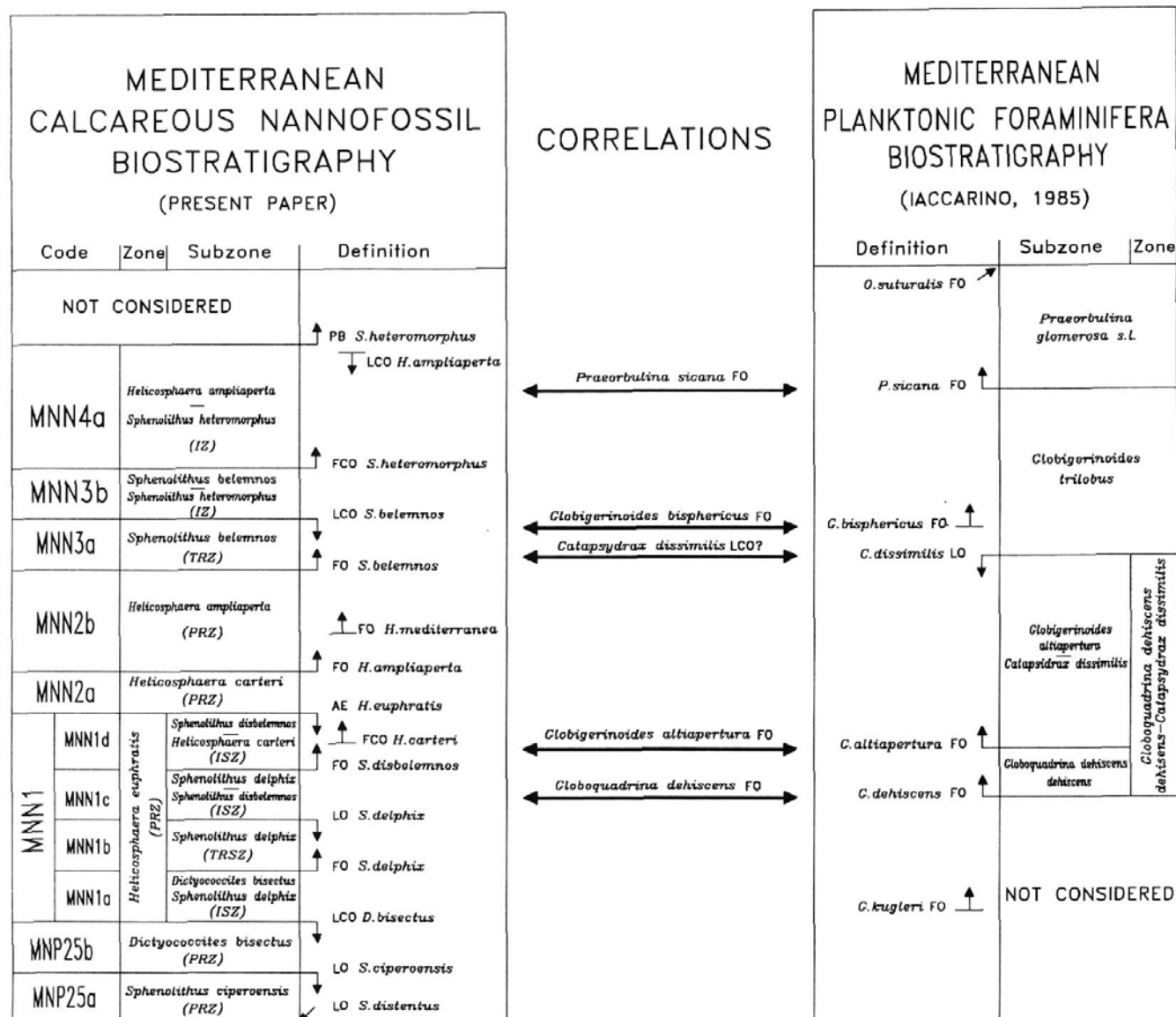
The LO of *Catapsydrax dissimilis* is recorded in the Santa Croce d'Arcevia section within Zone MNN3a (text-fig. 5) and in the Moria section within Zone MNN3b (text-fig. 6). This discrepancy may be related to reworking or to a tail of low productivity of *C. dissimilis* in the Moria section. In the Mediterranean region, the LO of *C. dissimilis* is considered as occurring below the FO of *Globigerinoides bisphericus* (Iaccarino 1985), found in the Santa Croce d'Arcevia and Santa Croce d'Acqui sections in the uppermost part of Zone MNN3a, within the range of *S. belemnos* (text-figs. 5, 12). The FO of *G. bisphericus* is also recorded at DSDP Site 608 (mid-latitude North Atlantic) within the short range of *S. belemnos* (compare data of Olafsson 1991 and Miller et al. 1991a), and we therefore consider the correlation of this biohorizon to Zone MNN3a (text-fig. 18) as firmly established. At DSDP Site 608 and in other extra-Mediterranean sections, *C. dissimilis* overlaps with *G. bisphericus*, and its LO is recorded slightly above the FO of *S. heteromorphus* (see Berggren et al. 1985; for DSDP Site 608 compare data of Olafsson 1991 and Miller et al. 1991a, 1991b).

In the Mediterranean sections the FO of *Praeorbulina sicana* occurs within Zone MNN4a (text-fig. 6; Rio et al., in press).

CORRELATION WITH OCEANIC SEDIMENTS: BIOCHRONOLOGY AND BIOSTRATIGRAPHIC RESOLUTION

Biochronology, i.e. establishing age estimates of biohorizons, is important because it provides a quick and convenient tool for evaluating durations of geological events and processes, and for

correlating various geologic environments (marine, continental, volcanic, metamorphic) even over long distances (Berggren and Van Couvering 1978). In addition, by establishing age estimates of biohorizons, we can evaluate biostratigraphic resolution, i.e., the number of biostratigraphic increments per time unit. Biohorizon ages are commonly estimated through direct correlation to magnetostratigraphy and, hence, to the geomagnetic polarity time scale (GPTS). However, calibration of the GPTS to the absolute time scale is in a state of flux, and errors in evaluations of Chron boundaries may be of the order of 4-8% (Shackleton et al. 1990; Baksi 1993). Magnetostratigraphic data are not available from the investigated or other upper Oligocene-lower Miocene Mediterranean sections except for those of Moria (Channell and Montanari 1992; Coccioni et al. 1992) and Contessa (Coccioni and Monechi 1992). In the absence of such data, information on the approximate ages of biohorizons may only be gained by considering ages derived from oceanic sediments. We can obtain clues by comparing the ranking and spacing of calcareous plankton biohorizons in the Mediterranean and in oceanic sections with reliable magnetostratigraphic data. Available biochronologic data on selected calcareous plankton biohorizons are reported in text-figure 19 and table 5. All calcareous nannofossil biohorizons (LO of *S. ciperoensis*, FO and LO of *S. delphix*, FO of *S. disbelemnus*, FO and LO of *S. belemnus*, and FO of *S. heteromorphus*) considered as reliable in low-latitude oceanic sediments by Fornaciari et al. (1993), are recorded in the Mediterranean in the same relative stratigraphic order as in oceanic areas. The FO of *D. druggii* and the LO of *H. ampliaperta*, although considered to be poorly reliable in oceanic



TEXT-FIGURE 18

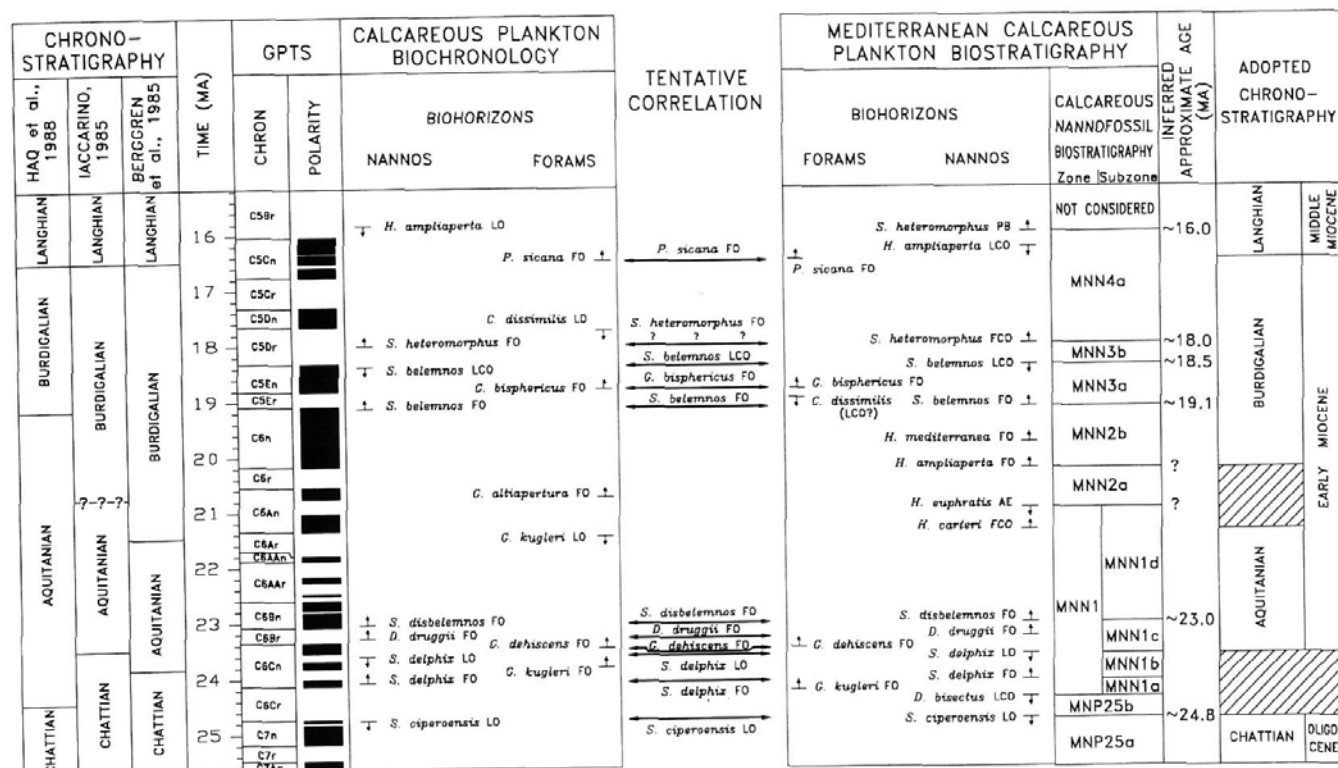
Tentative correlation between proposed regional Mediterranean calcareous nannofossil zonation and Mediterranean planktonic foraminifera zonation proposed by Iaccarino (1985).

areas, also maintain the same ranking with respect to other biohorizons in the two areas (text-fig. 19). Considering that they fall into two relatively short time intervals (see text-fig. 19), we believe it is highly improbable that major diachronies (let us say, more than 0.3-0.4 m.y.) are involved. Note how in the interval between the top of Chron C7n and the base of Chron C6Bn (less than 2 m.y. in the age model of Cande and Kent 1992), five calcareous nannofossil biohorizons (LO of *S. ciperoensis*, FO and LO of *S. delphix*, FO of *D. druggii*, FO of *S. disbelemnus*) and one planktonic foraminifera biohorizon (FO of *G. dehiscens*) show the same ranking. In the interval between the top of Chron C6n and the lower part of Chron C5Br (some 3 m.y. following Cande and Kent 1992), six calcareous plankton biohorizons are recorded in the same relative stratigraphic positions in the Mediterranean and in DSDP Site 608 core (text-fig. 19). In this interval, however, the LO of *C.*

dissimilis shows a different position in the Mediterranean with respect to the oceanic areas.

On the basis of the above considerations, it is assumed that ages established in oceanic areas by direct calibration to the GPTS represent reasonable first approximations of the ages of the biohorizons in the Mediterranean region too. The ages of the bottom of zones MNN2a and MNN2b cannot be evaluated because they are based on local Mediterranean biohorizons not yet calibrated to the GPTS.

The proposed zonal system includes eleven zonal boundaries over about 9 m.y. (between the top of Chron C7n and the lower part of Chron C5Br; text-fig. 19) providing an average time resolution of about 0.8 m.y. This is better than that provided by standard



TEXT-FIGURE 19

Comparison of ranking of calcareous plankton biohorizons in Mediterranean region and in oceanic areas. Calibration of calcareous plankton biohorizons to geomagnetic polarity time scale (GPTS) based on references listed in table 5. Adopted age model for GPTS after Cande and Kent (1992). See text for discussion of chronostratigraphic problems.

zonations, which do not allow any reliable subdivision of the 4 m.y. interval between the top of Chron C6Bn and the top of Chron C6n (Fornaciari et al. 1993; text-fig. 19). The planktonic foraminifera biohorizons discussed previously provide at least six other biohorizons (FOs of *G. kugleri*, *G. dehiscens*, *G. altiapertura*, *G. bisphericus*, *P. sicana*, and LO of *C. dissimilis*), increasing the time resolution to about half a million years.

CHRONOSTRATIGRAPHY

Correlation of the established Mediterranean calcareous nannofossil biostratigraphic scheme (text-fig. 2, 17) with the Standard Chronostratigraphic Scale is of interest because chronostratigraphy is the common language for interdisciplinary and international communications in Earth Sciences (Cowie et al. 1986). Our concern here is: what is the relationship between our calcareous nannofossil biostratigraphic analyses and the standard chronostratigraphic units? This is important because most earth scientists are familiar with, and make use of, chronostratigraphic units. However, most units of the standard Geologic Time Scale are not rigidly and unequivocally defined, and various specialists have established their own "biostratigraphic definitions" of chronostratigraphic boundaries, which in most instances have quite different chronologic meanings. As a result, chronostratigraphy is often a source of confusion and misunderstanding rather than the common language which should facilitate long-distance correlations and communications among various specialists. The time interval (latest Oligocene-early Miocene) considered here is a typical example of this situation.

Oligocene-Miocene boundary

The Oligocene-Miocene boundary is one of the most controversial in the stratigraphic column. Conflicts derive basically from the limits of the European upper-Oligocene (Chattian) and lower-Miocene (Aquitanian) stratotypes, which are located far apart from one another (in Germany and south-west France, respectively). They are poor in planktonic fossils, and most probably represent short intervals of time bounded by unconformities. An *ad hoc* Working Group was established at the International Geological Congress of Sydney in 1976 to define the Oligocene-Miocene boundary, but so far, after two decades, no consensus has been reached in proposing a Global Stratotype and Point Section (GSSP). As a result, various specialists use quite different criteria to recognize the Oligocene-Miocene boundary, which should represent a major subdivision of the Cenozoic, the Paleogene-Neogene boundary. Extensive reviews of this problem have been carried out by Srinivasan and Kennett (1983) and Berggren et al. (1985).

In recent years, most nannofossil paleontologists have recognized the Oligocene-Miocene boundary at the top of Zones NP25 or CP19. However, these are recognized according to differing criteria (LOs of *H. recta*, *S. ciproensis*, *D. bisectus*, *Z. bijugatus*, and *C. fenestratus*) which have different geochronologic meanings in different areas (Rio et al. 1990b; Fornaciari et al. 1993; this paper).

Planktonic foraminifera criteria widely used are the "explosive appearance" of *Globigerinoides* (Bolli and Saunders 1985, p. 191), the FO of *Globorotalia kugleri* (Berggren et al. 1985), and the FO of *Globoquadrina dehiscens* (Srinivasan and Kennett 1983).

TABLE 4

Summary of positions of calcareous nannofossil biohorizons at various stratigraphic sections investigated in this study.

Monte Cardella section			
Biohorizon	Sample	Meter level	
<i>H. carteri</i> FO	? CARD15-CARD16	? 82.18-85.00	
<i>S. delphix</i> LO	CARD34-CARD36	145.62-151.56	
<i>S. delphix</i> FO	CARD27-CARD29	121.25-127.18	
<i>C. fenestratus</i> LCO	CARD21-CARD22	102.50-105.31	
<i>D. bisectus</i> LCO	? CARD9-CARD11	? 64.37-70.31	
<i>Z. bijugatus</i> LCO	CARD6-CARD7	47.81-58.12	
<i>S. ciperoensis</i> LO	CARD2-CARD3	35.93-38.75	
Poggio d'Ancona section			
Biohorizon	Sample	Meter level	
<i>H. ampliaperia</i> FO	OM110-OM111	60.10-61.10	
<i>H. euphratis</i> AE	OM110-OM111	60.10-61.10	
<i>H. carteri</i> FCO	OM107-OM108	57.30-58.70	
<i>S. disbelemnus</i> FO	OM87-OM88	40.20-40.80	
<i>D. druggii</i> FO	OM79-OM81	36.10-37.10	
<i>S. delphix</i> LO	SB20-SB24	19.40-20.40	
<i>S. delphix</i> FO	SB33-SB30	16.70-17.70	
S. Croce D'Arcevia section			
Biohorizon	Sample	Meter level	
<i>S. belemnus</i> FO	71-72	34.95-36.83	
<i>H. mediterranea</i> FO	77-79	40.50-42.70	
<i>H. ampliaperia</i> FO	61-66	28.62-31.55	
<i>H. euphratis</i> AE	48-49	21.42-21.78	
<i>H. carteri</i> FCO	34-36	15.30-16.48	
<i>S. disbelemnus</i> FO	22-23	12.25-12.45	
<i>D. druggii</i> FO	11-13	11.15-11.40	
Moria section			
Biohorizon	Sample	Meter level	
<i>H. ampliaperia</i> LO	?	?	
<i>S. heteromorphus</i> PE	165-166	80.70-84.80	
<i>S. heteromorphus</i> PB	158-159	77.00-77.60	
<i>H. ampliaperia</i> LCO	121-122	63.44-63.94	
<i>S. heteromorphus</i> FCO	53-54	27.55-28.25	
Antognola composite section			
Biohorizon	Component segment	Sample	Meter level
<i>H. mediterranea</i> FO	B-C	? 1144	? 0.00-4.00
<i>H. carteri</i> FCO	B	? 1457-1459	? 78.30-81.70
<i>S. disbelemnus</i> FO	B	1445-1449	55.00-61.70
<i>S. delphix</i> FO	B	1430-1432	25.80-30.80
<i>D. bisectus</i> LCO	B	1423-1425	11.70-15.00
<i>S. ciperoensis</i> LO	A-B	? 1418	? 0.00-1.70
Nivione - Castagnola composite section			
Biohorizon	Component segment	Sample	Meter level
<i>H. carteri</i> FCO	B	CT60-CT61	802.50-890.00
<i>S. disbelemnus</i> FO	B	CT22-CT23	212.50-220.00
<i>Z. bijugatus</i> LCO	A	NIV29-NIV31	203.60-212.40
<i>D. bisectus</i> LCO	A	NIV27-NIV29	194.80-203.60
<i>S. ciperoensis</i> LO	A	NIV26-NIV27	190.20-194.80
<i>S. distentus</i> LO	A	NIV9-NIV7	107.60-116.40
Vignole - Borbera section			
Biohorizon	Sample	Meter level	
<i>S. belemnus</i> LCO	M90/58-M90/60	18.79-27.80	
T. Lemme - Carrosio section			
Biohorizon	Sample	Meter level	
<i>H. carteri</i> FCO	1-0	69.00-70.00	
<i>S. disbelemnus</i> FO	15-13	55.00-57.00	
<i>S. delphix</i> LO	38-37	32.00-33.00	
<i>S. delphix</i> FO	44-43	26.00-27.00	
<i>D. bisectus</i> LCO	? 52-51	? 18.00-19.00	
<i>S. ciperoensis</i> LO	61-60	9.00-10.00	
Montechiaro D'Acqui section			
Biohorizon	Sample	Meter level	
<i>S. belemnus</i> FO	M62-M64	71.00-73.00	
<i>H. mediterranea</i> FO	M36-M38	44.00-46.00	
<i>H. ampliaperia</i> FO	M25-M26	33.00-34.00	
<i>H. euphratis</i> AE	M15-M19	15.00-27.00	
<i>H. carteri</i> FCO	? M1-M2	? 1.00-2.00	
S. Croce d'Acqui section			
Biohorizon	Sample	Meter level	
<i>S. belemnus</i> LCO	S8-S9	8.00-9.00	
T. Lemme - Rio del Corvo section			
Biohorizon	Sample	Meter level	
<i>H. ampliaperia</i> LCO	M157-M158	773.18-776.18	
<i>S. heteromorphus</i> FCO	M336-M338	433.02-433.17	
<i>S. belemnus</i> LCO	M189-M190	23.00-45.00	

Depending upon the chosen biostratigraphic event (*S. ciperoensis* LO, *D. bisectus* LO, *H. recta* LO, *G. kugleri* FO, "explosive appearance" of *Globigerinoides*, or *G. dehiscens* FO), the Oligocene-Miocene boundary can be placed in different positions in the same section (text-fig. 19).

Borsetti (1992) recently reviewed the state of work carried out by the the Paleogene-Neogene Boundary Working Group. A proposal is apparently being submitted to the International Commission of Stratigraphy (ICS) to designate the GSSP for the base of the Aquitanian (and hence the Oligocene-Miocene and Paleogene-Neogene boundaries) in the T. Lemme-Carrosio section (text-fig. 1), corresponding to the bottom of Subchron C6Cn.2n and close to the local FO of *G. kugleri*. With reference to calcareous nannofossil biostratigraphy, the proposed definition of the Oligocene-Miocene boundary is associated with the short presence interval of *S. delphix* (text-fig. 19). Should this proposal be accepted by the ICS, nannofossil paleontologists should approximate the Oligocene-Miocene boundary by the LO of *S. delphix*. This biohorizon may be difficult to recognize, and we are using it as a subzonal boundary definition (text-fig. 2). We consider that the LO of *S. ciperoensis*, occurring in low- and mid-latitude areas at the top of Chron C7n (table 5, text-fig. 19), offers the best potential of global correlation

in the critical interval for defining the Oligocene-Miocene boundary.

Because of the lack of a formal definition and of the contradictory criteria used so far in recognizing the Oligocene-Miocene boundary, in order to avoid adding to the existing confusion, we have decided to adopt a buffer interval at the transition between the Oligocene and the Miocene in the correlation of our zonal scheme with standard chronostratigraphy (text-fig. 19). Accordingly, Zone MNP25a is referred to the Chattian (upper Oligocene). Zones-Subzones MNP25b, MNN1a, and MNN1b are referred to the buffer interval between Oligocene and Miocene. Zone MNN1c is referred to the Aquitanian (lower Miocene).

Aquitania-Burdigalian boundary

Like the Oligocene-Miocene boundary, the Aquitanian-Burdigalian boundary has not been formally defined and therefore the base of the Burdigalian stratotype should guide us in recognizing the boundary. The "gisement de Coquillat" in the Aquitanian basin is generally accepted as the stratotype of the Burdigalian. Poignant and Pujol (1978) observed *Globigerinoides altiapertura* at the base of the Burdigalian stratotype, where *G. kugleri*, the LO of which defines the top of Zone N4 of Blow (1969), is missing. They

TABLE 5

Summary of available data on calibration of upper Oligocene-lower Miocene calcareous plankton biohorizons to the geomagnetic polarity time scale (GPTS). Age evaluations are inferred with reference to the GPTS age model proposed by Cande and Kent (1992). For purposes of this work, ages are only approximate because of problems in the GPTS age model (see Baksi, 1993).

BIOHORIZON	CALIBRATION TO GPTS	SITE SECTION	REFERENCES	APPROXIMATE AGE	REMARKS
<i>H. ampliaperta</i> LO	C5Br	608	7, 11	~16.0 MA	Recorded in a reversed polarity interval in Moria section (9)
<i>P. sicana</i> FO	C5Cn	608, 563, 516, 558?	2, 6	~16.5 MA	Recorded in a reversed polarity interval in Moria section (9)
<i>S. heteromorphus</i> FCO	C5Dr	608	7, 10	~18.0 MA	Recorded in a reversed polarity interval in Moria section (9)
<i>C. dissimilis</i> LO	C5Dr (top)	608	6	~17.7 MA	
<i>S. belemnus</i> LCO	C5E (top)	710, 608	4, 5, 7, 11	~18.3 MA	
<i>G. bisphericus</i> FO	C5En	608	6	~18.6 MA	Recorded in a positive polarity interval in Moria section (9)
<i>S. belemnus</i> FO	C6n (top)	710, 608	4, 5, 7, 11	~19.2 MA	
<i>G. altiapertura</i> FO	C6An	516, Contessa	1, 9	~20.6 MA	
<i>G. kugleri</i> LO	C6Ar	516, Contessa	1, 9	~21.6 MA	Recorded in Chron C6Bn at Site 608 (6)
<i>S. disbelemnus</i> FO	C6Bn	608	Fornaciari unpublished	~23.0 MA	
<i>G. dehiscens</i> FO	C6Cn (top)	563, 608, Contessa	1, 6, 9	~23.4 MA	
<i>D. druggii</i> FO	C6Br (bottom) C6Cn (top)	563, 608	1, 2, Fornaciari unpublished	~23.4 MA	
<i>S. delphix</i> LO	C6Cn.1r	608	Fornaciari unpublished	~23.6 MA	
<i>S. delphix</i> FO	C6Cn (bottom)	608	Fornaciari unpublished	~24.0 MA	
<i>G. kugleri</i> FO	C6Cn and C6Cr	563, Contessa	1, 2, 9	~24.0 MA + ~24.4 MA	
<i>S. ciproensis</i> LO	C7n (top)	608, 522, 711, 516, 528, 558, 563	2, 3, 4, 5, 7, 8	~24.8 MA	Widely synchronous between low and middle latitudes

1) Berggren et al., 1985; 2) Miller et al., 1985; 3) Wei and Wise, 1989; 4) Backman et al., 1990; 5) Rio et al., 1990b; 6) Miller et al., 1991a.

7) Olafsson, 1991; 8) Olafsson and Villa, 1992; 9) Coccioni and Monechi, 1992; 10) Coccioni et al., 1992; 11) Gartner, 1992.

therefore referred the Burdigalian stratotype to Zone N5 and perhaps to the base of Zone N6 of Blow (1969). Müller (in Bizon and Müller 1979) reported small *Helicosphaera ampliaperta* at the base of the stratotype and hence Zone NN2 of Martini (1971).

Berggren et al. (1985) associated the Aquitanian-Burdigalian boundary with the base of Zone N5, at the extinction level of *Globorotalia kugleri*, calibrated to Chron C6Ar (table 5).

Iaccarino (1985) drew the boundary at the FO of *Globigerinoides altiapertura*, which was calibrated to the top of Chron C6An by Berggren et al. (1985) and Coccioni and Monechi (1992). It should be noted that the relationships between the ranges of *G. altiapertura* and *G. kugleri* are controversial. While Blow (1969), Iaccarino (1985) and Coccioni and Monechi (1992) considered the FO of *G. altiapertura* as occurring above the LO of *G. kugleri*, the reversed relationship occurs between the two biohorizons in the Santa Croce d'Arcevia and T. Lemme-Carrosio sections (text-figs. 5, 10), and in the equatorial Pacific Ocean (Chaisson and Leckie 1993).

Haq et al. (1988) associated the Aquitanian-Burdigalian boundary with the FO of *Sphenolithus belemnus*, occurring within Zone N5 of Blow (1969), at the top of Chron C6n (table 5).

With reference to the GPTS age model proposed by Cande and Kent (1992), the age of the Aquitanian-Burdigalian boundary varies according to the chosen criterion from about 21.6 Ma (LO of *G. kugleri*, Berggren et al. 1985) to about 19.2 Ma (FO of *S. belemnus*, Haq et al. 1988) (text-fig. 19). Clearly, an international agreement to define rigidly the base of the Burdigalian by a GSSP is needed.

For the time being, we consider it reasonable to use a buffer interval between the Aquitanian and the Burdigalian, as we did for the Oligocene-Miocene boundary. Since *H. ampliaperta* is found in the Burdigalian stratotype, we assign our Zones MNN2b, MNN3a, MNN3b and the lower part of Zone MNN4a to the Burdigalian. Zone MNN2a and the top part of Subzone MNN1d, above the Mediterranean LO of *G. kugleri* and within the lower range of *G. altiapertura*, are assigned to the buffer interval between the Aquitanian and the Burdigalian (text-fig. 19). Subzones MNN1c and MNN1d (up to the FCO of *H. carteri*) are assigned to the Aquitanian (text-fig. 19). Note that the distinction between the Aquitanian and the Burdigalian is easy to recognize in Mediterranean sections because of the above-mentioned change in the helicolith assemblages at the top of Zone MNN1d, but it is difficult to recognize by calcareous nannofossils in oceanic sediments because it falls within the long Zone NN2 (CN1c), which is difficult to subdivide (Fornaciari et al. 1993; text-fig. 19).

Lower-Middle Miocene Boundary (Burdigalian-Langhian boundary)

No boundary stratotype section has been proposed for the Burdigalian-Langhian boundary, which by general agreement represents the boundary between the lower and middle Miocene. Therefore, the lithostratigraphically defined base of the Langhian stage conventionally serves as the provisional definition for the top of the Burdigalian and for the lower-middle Miocene boundary (Berggren et al. 1985). The base of the Langhian is linked biostratigraphically to the FO of *Praeorbulina* spp. (Berggren et al. 1985), which occurs in the stratotype section and worldwide above the FO of *Sphenolithus heteromorphus* and below the LO of *Helicosphaera ampliaperta*, within the upper part of Zone MNN4 (Martini 1971; Rio et al., in press). Therefore, the Burdigalian-Langhian boundary does not coincide with a calcareous nannofossil zonal boundary, and can only roughly be approximated with the LCO of *H. ampliaperta* in the Mediterranean region or the acme end of *Discoaster deflandrei* in low-latitude oceanic sediments (Rio et al. 1990b).

BIOSTRATIGRAPHY IN TURBIDITIC SEDIMENTS

The upper Oligocene-Miocene onland stratigraphic record in Italy is characterized by widespread deposition in a foredeep setting of huge accumulations of siliciclastic turbidites (Sestini 1970), often referred to as "Apenninic Flysch" (Ricci Lucchi 1986). The paleontologic contents of these deepwater sediments are very scarce, and the age relationships are poorly constrained. Planktonic foraminifera are few and poorly preserved because of terrigenous dilution and burial diagenesis, and they are therefore virtually useless for dating and correlating most of the Apenninic Oligocene-Miocene Flysch. A systematic study of the calcareous nannofossil contents of northern Apennine flysch sediments has been carried out by us (unpublished). Our results from these deposits suggest that calcareous nannofossils, although poorly preserved and not

abundant, are normally sufficient for biostratigraphic classification and correlations. Only a few successions belonging to deeply buried structures (e.g., some internal units of the Cervarola Sandstone) are barren. By using our quantitative approach, the zonal system here proposed was recognized even at the subzonal level in high-resolution samplings. Text-figure 16 shows the correlation and dating of three Cervarola Sandstone successions (Tebbia Valley, Lizzano Belvedere, and Gova).

CONCLUSIONS

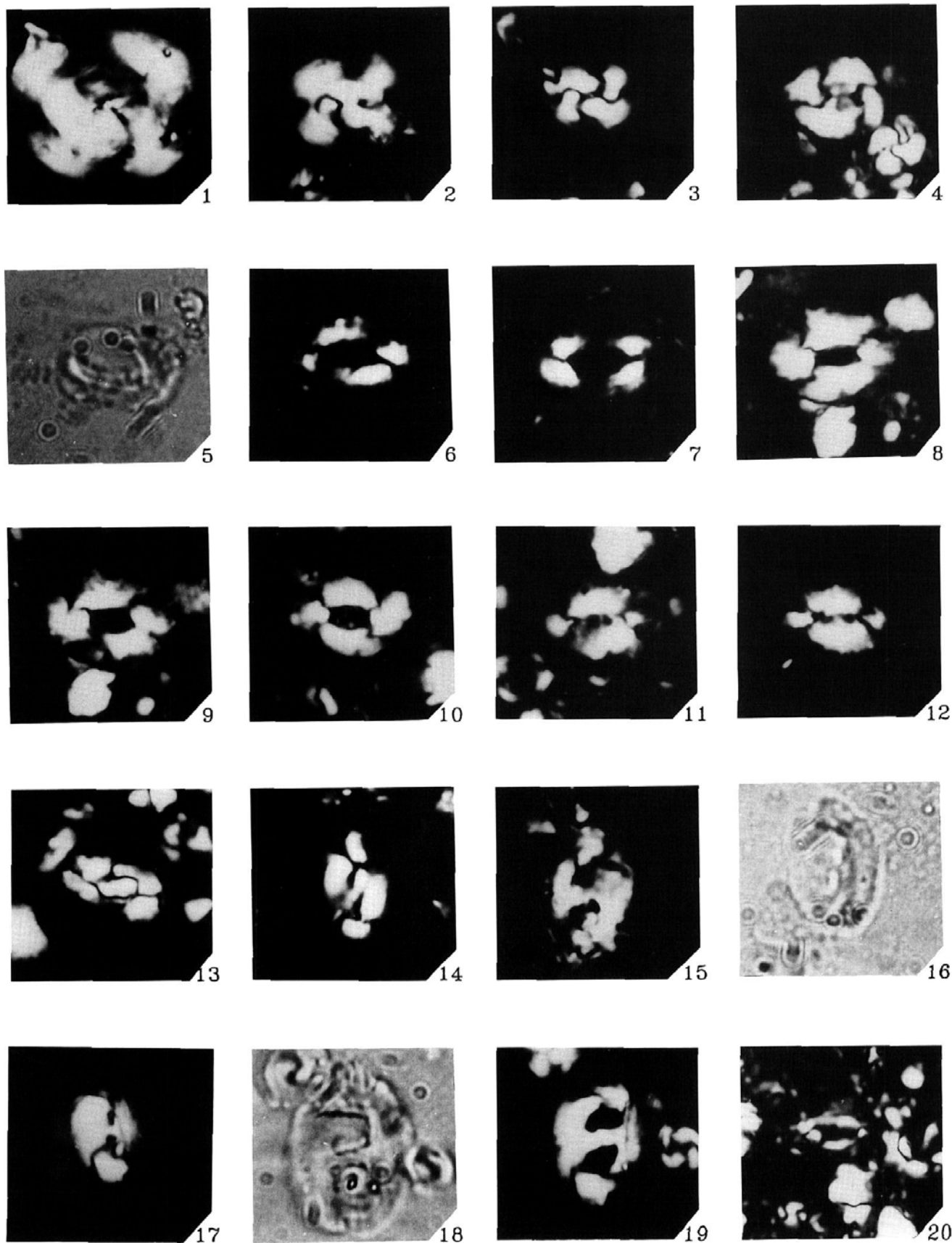
We have presented abundance based distribution patterns of important calcareous nannofossils in the uppermost Oligocene to basal middle Miocene Mediterranean stratigraphic record. The standard zonations of Martini (1971) and Okada and Bukry (1980) provide low resolution in this time interval (Fornaciari et al. 1993). Furthermore, they are only partially applicable in the Mediterranean region, because some of the boundary definition species are rare and discontinuous (*D. druggii*, *T. carinatus*) or show stratigraphic distributions different from those assumed in standard zonations (*D. bisectus*, *H. recta*, *C. abisectus*). We suggest that 13 calcareous nannofossil biohorizons (tables 2 and 3) are reliable for classifying and correlating the uppermost Oligocene to lower-middle Miocene Mediterranean stratigraphic record. On the basis of these biohorizons, we have proposed a set of 11 zones and subzones, which may also be recognized in the poorly fossiliferous turbiditic successions which make up much of the Mediterranean stratigraphic record in the time interval in question.

We have discussed the correlation of the proposed zonal system to the global standard chronostratigraphic scale. The Oligocene-Miocene (Chatian-Aquitania) and Aquitania-Burdigalian boundaries have not yet been properly defined, and contrasting criteria are currently being used. To avoid the possibility of having to re-adjust our chronostratigraphic inferences once these boundaries have been

PLATE 1

All specimens $\times 2400$ ca.

- | | | | |
|------|--|--------|---|
| 1 | <i>Dictyococcites bisectus</i> (Hay, Mohler and Wade) Bukry and Percival; crossed nicols. Sample CARD F (M. Cardellia section) | 11 | <i>Helicosphaera carteri</i> (Wallich) Kamptner; crossed nicols. Sample OM 120 (Poggio D'Ancona section) |
| 2 | <i>Dictyococcites</i> aff. <i>bisectus</i> ; crossed nicols. Sample CARD F (M. Cardellia section) | 12 | <i>Helicosphaera carteri</i> (Wallich) Kamptner; crossed nicols. Sample M 172 (T. Lemme-Rio del Corvo section) |
| 3 | <i>Dictyococcites scrippsae</i> Bukry and Percival; crossed nicols. Sample CARD F (M. Cardellia section) | 13 | <i>Helicosphaera euphratis</i> Haq; crossed nicols. Sample SB 30 (Poggio D'Ancona section) |
| 4 | <i>Reticulofenestra daviesii</i> (Haq) Backman; crossed nicols. Sample OM 104 (Poggio d'Ancona section) | 14 | <i>Helicosphaera intermedia</i> Martini; crossed nicols. Sample M 172 (T. Lemme-Rio del Corvo section) |
| 5-7 | <i>Helicosphaera ampliaperta</i> Bramlette and Wilcoxon; 5, parallel light; 6, crossed nicols 0°; 7, crossed nicols 20°. Sample M 172 (T. Lemme-Rio del Corvo section) | 15 | <i>Helicosphaera mediterranea</i> Müller; crossed nicols. Sample 99 (S. Croce d'Arcevia section) |
| 8-10 | <i>Helicosphaera ampliaperta</i> Bramlette and Wilcoxon; 8, crossed nicols 0°; 9, crossed nicols 20°; 10, crossed nicols 0°. Sample OM 120 (Poggio D'Ancona section) | 16, 17 | <i>Helicosphaera perch-nielseniae</i> Haq; 16, parallel light; 17, crossed nicols. Sample CARD 0 (M. Cardellia section) |
| | | 18, 19 | <i>Helicosphaera recta</i> Haq; 18, parallel light; 19, crossed nicols. Sample CARD 1 (M. Cardellia section) |
| | | 20 | <i>Helicosphaera walbersdorfensis</i> (Müller) Theodoridis; crossed nicols. Sample OM 117 (Poggio d'Ancona section) |



formally defined, we have adopted "buffer intervals" for the recognition of both Oligocene-Miocene and Aquitanian-Burdigalian boundaries.

The biostratigraphic resolution of the proposed zonal system is higher than that provided by standard zonations. On average, it provides a time resolution of about 0.8 m.y. The integration (in progress) of planktonic foraminifera and calcareous nannofossil biostratigraphies seems to improve the time resolution to about half a million years. A highly resolved and integrated calcareous plankton biostratigraphic framework is essential for further chronological refinements, which may be obtained by using repetitive signals in the stratigraphic record such as ash levels (widespread in the region), magnetic polarity reversals and rhythmic sedimentation patterns. Such high stratigraphic resolution is badly needed to solve the geological and paleoenvironmental problems of the Mediterranean region in latest Oligocene and early Miocene times.

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SYSTEMATIC PALEONTOLOGY

Family SPHENOLITHACEAE Deflandre in Grassé (1952)

Genus SPHENOLITHUS Deflandre in Grassé (1952)

Sphenolithus disbelemnus Fornaciari and Rio, n. sp.

Plate 2, figs. 7-10; plate 3, figs. 19, 20; plate 4, figs. 1-4

Diagnosis: A small form of *Sphenolithus* with intermediate characters between *S. dissimilis* and *S. belemnus*. Specifically, the basal part is similar to the latter and the apical part to the former. At crossed nicols, when the long axis is at 0°, it looks like *S. belemnus*, while when the long axis is at 45° it does not show a spine (like *S. belemnus*) but a tripartite apical part, similar to that shown by *S. dissimilis* when viewed at 45°.

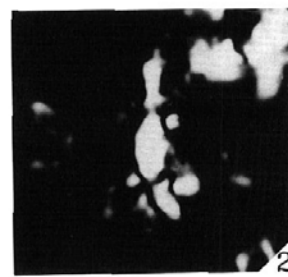
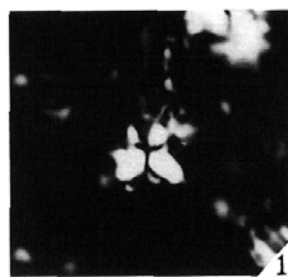
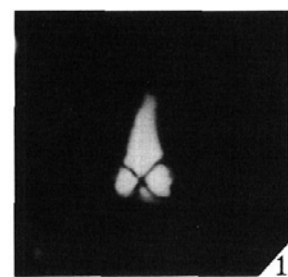
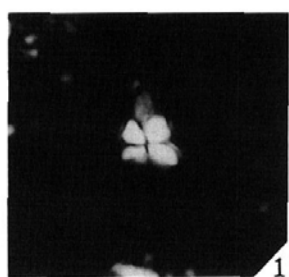
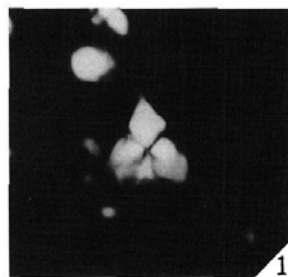
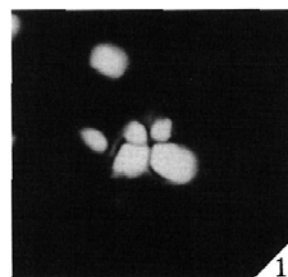
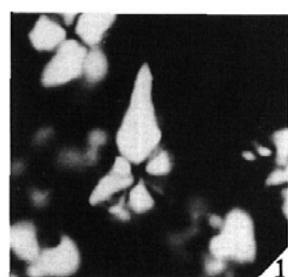
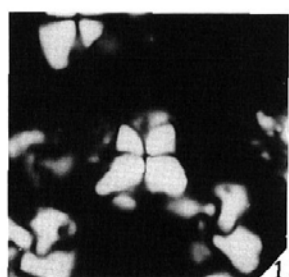
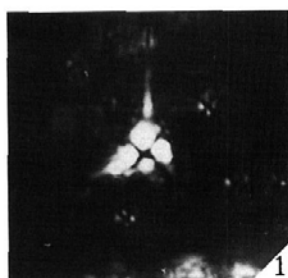
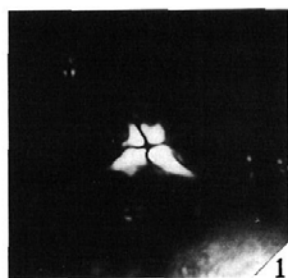
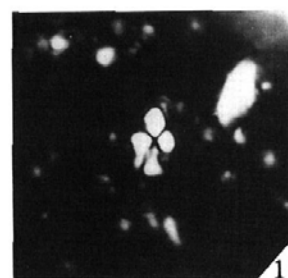
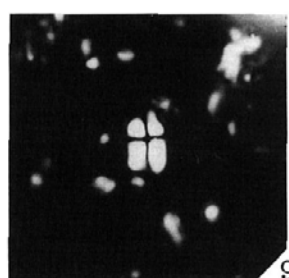
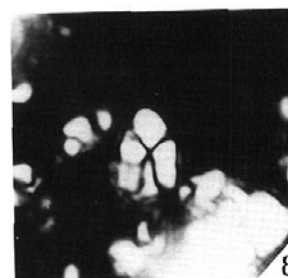
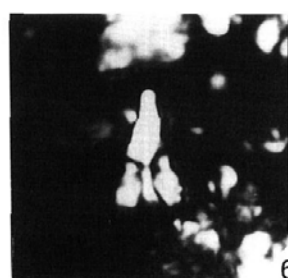
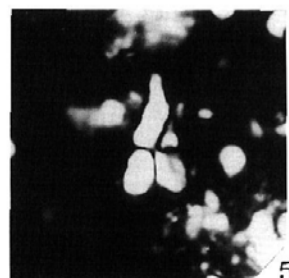
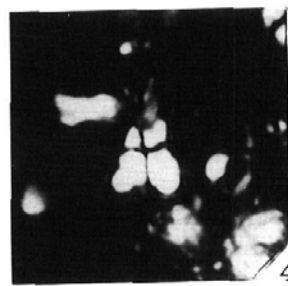
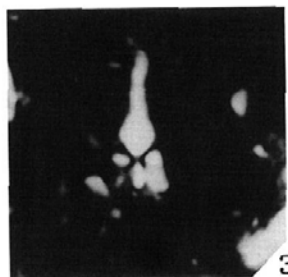
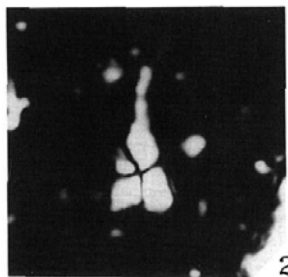
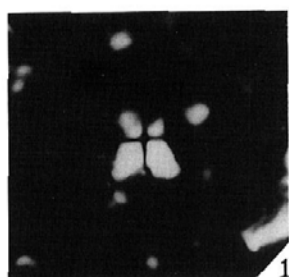
Description: This small sphenolith is composed of a columnar base (proximal shield) made up of 8-10 wedge-shaped elements from which variously sized spines radiate. Some of these are inserted above the proximal shield and are oblique or perpendicular to the median axis of the sphenolith ("lateral elements" in the terminology of Roth et al. 1971). Two or three larger elongated wedge-shaped elements are oriented parallel to the median axis constituting the distal-apical end of the sphenolith.

Remarks: The species was first described by Rio et al. (1990b) in the tropical Indian Ocean as *Sphenolithus dissimilis-Sphenolithus belemnus* intergrade. The species, although small, is quite distinctive and easily recognized between crossed nicols. In spite of the intermediate optical and morphological features, no phylogenetic relationships between *S. dissimilis* and *S. belemnus* are inferred here. Actually, in all sections investigated so far (equatorial Indian and Pacific oceans, Mediterranean) *S. disbelemnus* is restricted to the lower part of Zone NN2 of Martini (1971) and is missing below the first occurrence of *S. belemnus*. Specimens virtually identical to *S. disbelemnus* occur together with *S. belemnus* in all areas investigated so far. However, it is impossible to decide whether these specimens (plate 4, text-fig. 3) refer to *S. disbelemnus* (plate 4, figs. 1-4) or whether they represent homeomorphs of it.

PLATE 2

All specimens $\times 2400$ ca.

- | | | | |
|--------|---|--------|---|
| 1-3 | <i>Sphenolithus belemnus</i> Bramlette and Wilcoxon; 1, crossed nicols 0°; 2, crossed nicols 20°; 3, crossed nicols 45°. Sample 85 (S. Croce d'Arcevia section) | 13, 14 | <i>Sphenolithus delphix</i> Bukry; 13, crossed nicols 0°; 14, crossed nicols 45°. Sample SB 30 (Poggio d'Ancona section) |
| 46 | <i>Sphenolithus belemnus</i> Bramlette and Wilcoxon; 4, crossed nicols 0°; 5, crossed nicols 20°; 6, crossed nicols 45°. Sample 72 (S. Croce d'Arcevia section) | 15, 16 | <i>Sphenolithus delphix</i> Bukry; 15, crossed nicols 0°; 16, crossed nicols 45°. Sample 43 (T. Lemme-Carrosio section) |
| 7-10 | <i>Sphenolithus disbelemnus</i> n. sp.; 7, 9, crossed nicols 0°; 8, 10, crossed nicols 45°. Sample OM 104 (Poggio d'Ancona section) | 17, 18 | <i>Sphenolithus heteromorphus</i> Deflandre; 17, crossed nicols 0°; 18, crossed nicols 45°. Sample 45 (Moria section) |
| 11, 12 | <i>Sphenolithus delphix</i> Bukry; 11, crossed nicols 0°; 12, crossed nicols 45°. Sample CARD 34 (M. Cardellia section) | 19, 20 | <i>Sphenolithus</i> aff. <i>heteromorphus</i> ; 19, crossed nicols 0°; 20, crossed nicols 45°. Sample OM 116b (Poggio d'Ancona section) |



Occurrence: *Sphenolithus disbelemnus* is present in the lower part of Zone NN2 of Martini (1971), in equatorial Indian Ocean Sites 709 and 710, and in western equatorial Pacific Ocean Sites 806 and 807 (Fornaciari et al. 1993). It is also present in the same biostratigraphic position at DSDP Site 608 (Fornaciari, unpublished data) and in the Mediterranean record, as documented in this work.

Size: 3-4 µm. Holotype: height, 3 µm; width of proximal shield, 1.7 µm.

Holotype: Plate 4, fig. 2.

Paratypes: Plate 3, figs. 19, 20; plate 4, figs. 1, 4.

Type locality: Western Equatorial Indian Ocean ODP Leg 115 Site 709C-20H-2, 60 cm.

Holotype and paratypes are deposited in the permanent collections of the Museum of Paleontology of the University of Padova, Padova, Italy.

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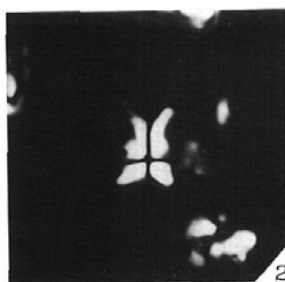
PLATE 3

All specimens $\times 2400$ ca.

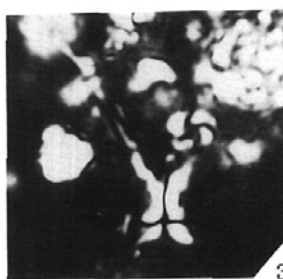
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|---|--|
| <p>1-4 <i>Sphenolithus capricornutus</i> Bukry and Percival; 1-3, crossed nicols 0°; 4, crossed nicols 45°. Sample CARD 34 (M. Cardellia section)</p> <p>5,6 <i>Sphenolithus calyculus</i> Bukry; 5, crossed nicols 0°; 6, crossed nicols 45°. Sample CARD 15 (M. Cardellia section)</p> <p>7 <i>Sphenolithus ciperoensis</i> Bramlette and Wilcoxon; crossed nicols 45°. Sample CARD 0 (M. Cardellia section)</p> <p>8 <i>Zygrhablithus bijugatus</i> (Deflandre in Deflandre and Fert) Deflandre; crossed nicols. Sample CARD 1 (M. Cardellia section)</p> <p>9,10 <i>Clausiococcus fenestratus</i> (Deflandre and Fert) Prins; 9, parallel light; 10, crossed nicols. Sample CARD 0 (M. Cardellia section)</p> | <p>11,12 <i>Cyclicargolithus abisectus</i> $>10\mu\text{m}$; 11, parallel light; 12, crossed nicols. Sample CARD 24 (M. Cardellia section)</p> <p>13 <i>Discoaster druggii</i> Bramlette and Wilcoxon; parallel light. Sample 13 (S. Croce d'Arcevia section)</p> <p>14-16 <i>Sphenolithus belemnus</i> Bramlette and Wilcoxon; 14, crossed nicols 0°; 15, crossed nicols 20°; 16, crossed nicols 45°. Sample 115-714A-19X-3, 130 cm (western equatorial Indian Ocean)</p> <p>17-18 <i>Sphenolithus dissimilis</i> Bukry and Percival; 17, crossed nicols 0°; 18, crossed nicols 45°. Sample 115-709C-15H-6, 60 cm (western equatorial Indian Ocean)</p> <p>19-20 <i>Sphenolithus disbelemnus</i> n. sp.; 19, crossed nicols 0°; 20, crossed nicols 45°. Paratype; Museum of Paleontology of the University of Padova. Sample 115-710A-14X-3, 130 cm (western equatorial Indian Ocean)</p> |
|---|--|



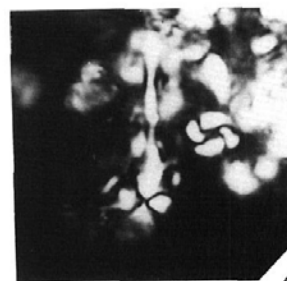
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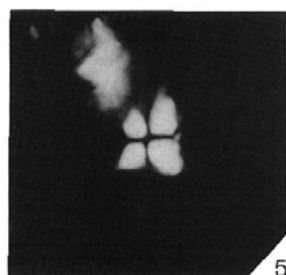
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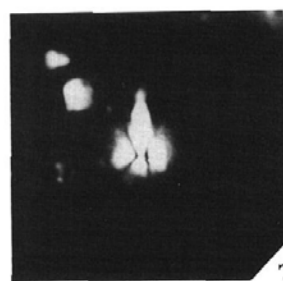
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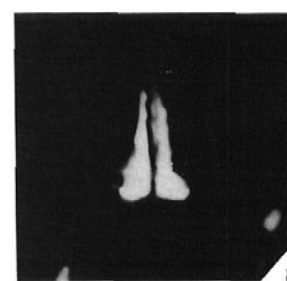
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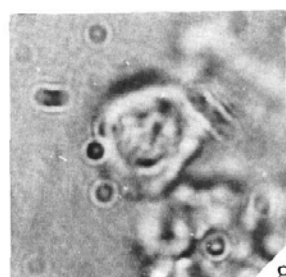
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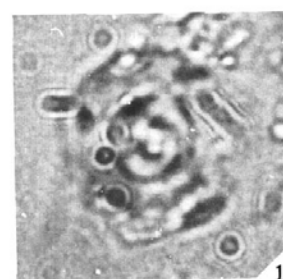
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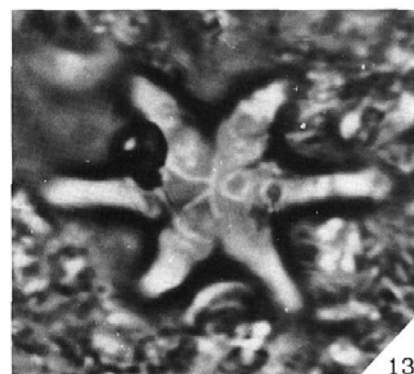
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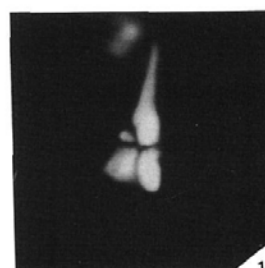
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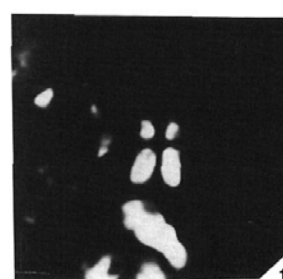
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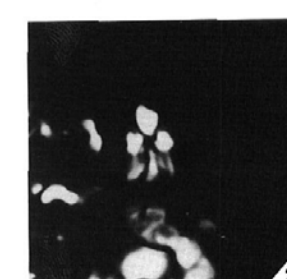
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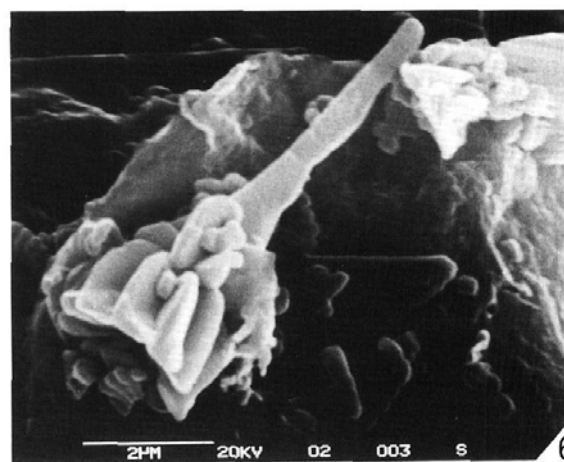
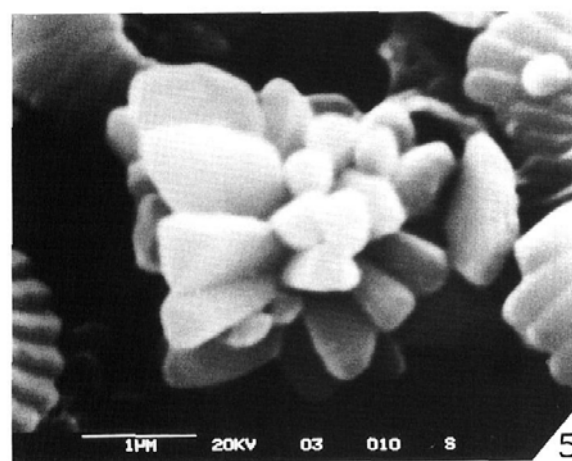
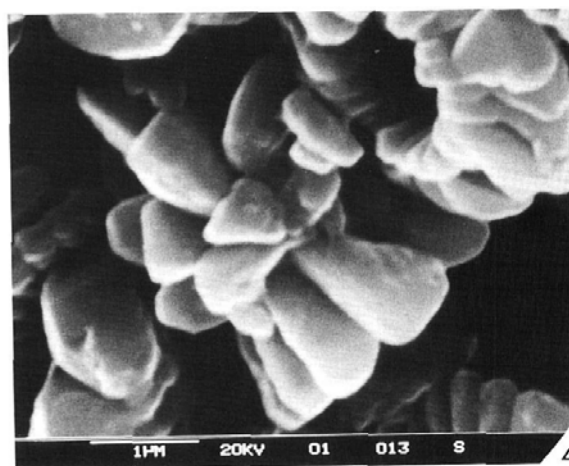
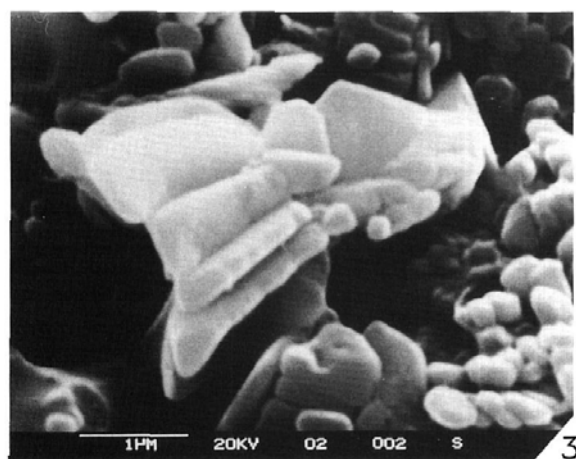
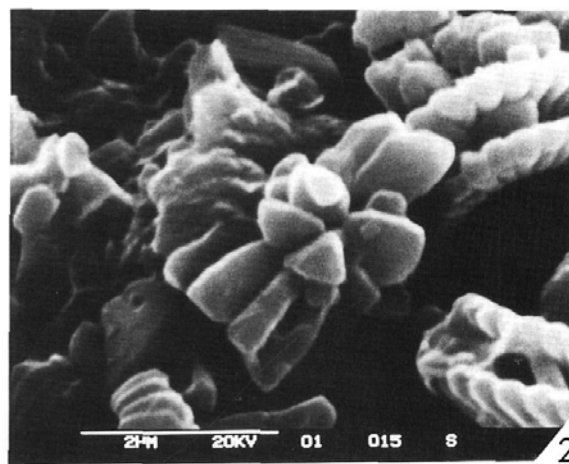
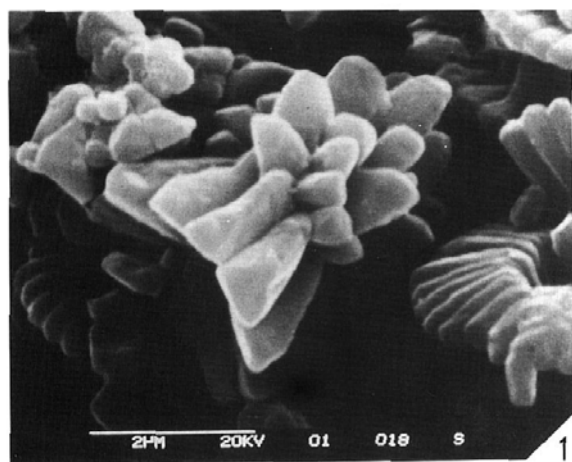
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PLATE 4

Scanning electron microscope micrographs of lower Miocene spenoliths

- | | | | |
|-----|--|---|--|
| 1,4 | <i>Sphenolithus disbelemnus</i> n. sp.; Paratype; Museum of Paleontology of the University of Padova. Sample 115-709C-20H-2, 60 cm (western equatorial Indian Ocean) | 3 | <i>Sphenolithus disbelemnus</i> n. sp.; Sample 115-714A-19X-3, 130 cm (western equatorial Indian Ocean) |
| 2 | <i>Sphenolithus disbelemnus</i> n. sp.; Holotype; Museum of Paleontology of the University of Padova. Sample 115-709C-20H-2, 60 cm (western equatorial Indian Ocean) | 5 | <i>Sphenolithus dissimilis</i> Bukry and Percival; Sample 115-709C-20H-6, 20 cm (western equatorial Indian Ocean) |
| | | 6 | <i>Sphenolithus belemnus</i> Bramlette and Wilcoxon; Sample 115-714A-19X-3, 130 cm (western equatorial Indian Ocean) |



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APPENDIX 1

Calcareous Nannofossils Considered (in alphabetic order of generic epithets)

- Clausicoccus fenestratus* (Deflandre and Fert 1954) Prins 1979
Coccolithus eopelagicus (Bramlette and Riedel 1954) Bramlette and Sullivan 1961
Coccolithus miopelagicus Bukry 1971
Coccolithus pelagicus (Wallich 1877) Schiller 1930
Coronocyclus nitescens (Kamptner 1963) Bramlette and Wilcoxon 1967
Cyclicargolithus abisectus (Müller 1970) Wise 1973
Cyclicargolithus floridanus (Roth and Hay in Hay et al. 1967) Bukry 1971
Dictyococcites bisectus (Hay, Mohler, and Wade 1966) Bukry and Percival 1971
Dictyococcites hesslandii (Haq 1966) Haq and Lohman 1976
Dictyococcites scrippsae Bukry and Percival 1971
Discoaster deflandrei Bramlette and Riedel 1954
Discoaster druggii Bramlette and Wilcoxon 1967
Geminolithella rotula (Kamptner 1956) Backman 1980
Helicosphaera ampliapertura Bramlette and Wilcoxon 1967
Helicosphaera carteri (Wallich 1877) Kamptner 1954
Helicosphaera crouchii Bukry 1981 = *Helicosphaera mediterranea*
Helicosphaera euphratis Haq 1966
Helicosphaera intermedia Martini 1965
Helicosphaera mediterranea Müller 1981
Helicosphaera obliqua Bramlette and Wilcoxon 1967
Helicosphaera perch-nielsinae Haq 1971
Helicosphaera recta Haq 1966
Helicosphaera truempyi Biolzi and Perch-Nielsen 1982
Helicosphaera walbersdorfensis (Müller 1974b) Theodoridis 1984
Iselithina fusa Roth 1970
Reticulofenestra daviesii (Haq 1968) Backman 1980
Sphenolithus belemnus Bramlette and Wilcoxon 1967
Sphenolithus calyculus Bukry 1985
Sphenolithus capricornutus Bukry and Percival 1971
Sphenolithus ciperoensis Bramlette and Wilcoxon 1967
Sphenolithus conicus Bukry 1971
Sphenolithus delphix Bukry 1973
Sphenolithus disbelemnus n. sp., this study
Sphenolithus dissimilis Bukry and Percival 1971
Sphenolithus distentus (Martini 1965) Bramlette and Wilcoxon 1967
Sphenolithus heteromorphus Deflandre 1953
Sphenolithus moriformis (Brönnimann and Stradner 1960) Bramlette and Wilcoxon 1967
Triquetrorhabdulus carinatus Martini 1975
Triquetrorhabdulus serratus (Bramlette and Wilcoxon 1967) Olafsson 1989
Zygrhahlithus bijugatus (Deflandre in Deflandre and Fert 1954) Deflandre 1959
- nes. In: Proto Decima, F., Monechi, S., and Rio, D., Eds., Proceedings of the International Nannoplankton Association Conference, Firenze 1989. Memorie di Scienze Geologiche, già Memorie degli Istituti di Geologia e Mineralogia dell'Università di Padova. Allegato al Vol. 43: 297-337.
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