Rivista Italiana di Paleontologia e Stratigrafia	volume 121	no. 2	pp. 000-000	July 2015

CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY OF PALEOCENE TO MIDDLE EOCENE SUCCESSIONS (TERTIARY FLYSCH *AUCTT.*) OF THE NORTHERN APENNINES

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Received: May 16, 2014; accepted: June 04, 2015

Key words: Biostratigraphy, Calcareous nannofossils, Paleocene, Middle Eocene, External Ligurides, Northern Apennines, Italy.

Abstract. An accurate biostratigraphic study of the Paleocene-middle Eocene calcareous nannofossils was performed on the turbiditic successions that characterize the Northern Apennines Mt. Caio, Farini d'Olmo, Mt. Sporno and Mt. Penice Units, belonging to the "Tertiary Flysch *Auctt*." and referable to the External Ligurides. This geologic complex accumulated in a link key area, located between the oceanic Ligure-Piedmontese domain and the Adria continental margin. The reference biostratigraphic scheme used in the study is the recently published calcareous nannofossil biozonation proposed for the Paleogene by Agnini et al. (2014). The obtained biostratigraphic and chronostratigraphic data suggest that further investigation is needed to clarify the tectono-sedimentary evolution and to unravel the complex architecture of the External Ligurides.

Introduction

During the setting up of the Geological Map of Italy at 1:50.000 scale (CARG Project), we studied calcareous nannofossil assemblages in a great number of formations outcropping in the Northern Apennines and belonging to the External Ligurides. This extensive biostratigraphic study permitted us to constrain the age of many tectonic units (http://www.isprambiente.gov.it/en/projects/carg-project-geologic-and-geothematic-cartography/default). Our recent effort was mainly focused on refining the biostratigraphy of the Cenomanian-Maastrichtian successions of the External Ligurides (Catanzariti & Perilli 2011). These units, that are mostly made up of marly-calcareous fine-grained turbidite sequences, the Helminthoid Flysch *Auctt*., were deposited in a key area representing the conjunction between the "Ligure-Piedmontese" oceanic domain and the continental margin of the Adria Plate, from Early Cretaceous to middle Eocene (Marroni et al. 1992, 2001; Daniele & Plesi 2000). In this paper, we report on calcareous nannofossils biostratigraphic and chronostratigraphic study of the Paleogene sections of the External Ligurides that comprise some of the most representative pelitic-arenaceous and marly-calcareous successions of Caio, Farini, Sporno, and Penice Units. The study has been performed in order to revise the biostratigraphy of these successions, with reference to the published literature (Tab. 1), and improve the chronology through recognition of useful biohorizons.

Geological background

In the investigated area of the Northern Apennines three main superimposed tectonic units are present: the Tuscan Units, the Subligurian Units and the Liguride Units, sealed by thrust top basin deposits (Fig. 1). The Tuscan Units were deposited on the continental margin of the Adria Plate. The Subligurian Units accumulated in a transitional area located between the Tuscan and the Ligurian-Piedmont paleogeographic domains. The Liguride Units comprise the Internal Ligurides, piled up on the oceanic crust of the Ligurian-Piedmont domain, and the External Ligurides, accumulated in a connection area between the continental margin of the Adria Plate and the Ligurian-Piedmont oceanic ba-

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Zone	Member/Ltf	Formation (CARG)	Formation (this paper)	Unit	References
NP15	Calestano	Flysch di M. Sporno	Mt. Sporno Flysch	Sporno	Rio 1987, Cerrina Feroni et al. 1991
	Carpadasco	Flysch di M. Dosso	Mt. Dosso Flysch	Farini	Rio & Achilli 1980, Martini & Zanzucchi 2000
NP14	Armorano and Calestano	Flysch di M. Sporno	Mt. Sporno Flysch	Sporno	Rio 1987, Cerrina Feroni et al. 1991
	Rigolo	Flysch di M. Dosso	Mt. Dosso Flysch	Farini	Rio & Achilli 1980, Martini & Zanzucchi 2000
	Costa	Flysch di Farini d'Olmo	Farini d'Olmo Flysch	Farini	Cerrina Feroni et al., 1994b
	Castelmozzano	Marne rosate di Tizzano	Tizzano Marl	Caio	Cerrina Feroni et al. 1991, 1994a
NP13	Armorano	Flysch di M. Sporno	Mt. Sporno Flysch	Sporno	Rio 1987, Cerrina Feroni et al. 1991
	Rigolo	Flysch di M. Dosso	Mt. Dosso Flysch	Farini	Rio & Achilli 1980, Martini & Zanzucchi 2000
	Costa	Flysch di Farini d'Olmo	Farini d'Olmo Flysch	Farini	Cerrina Feroni et al., 1994b
NP12	Armorano	Flysch di M. Sporno	Mt. Sporno Flysch	Sporno	Rio 1987, Cerrina Feroni et al. 1991
	Rigolo	Flysch di M. Dosso	Mt. Dosso Flysch	Farini	Rio & Achilli 1980, Martini & Zanzucchi 2000
	Rigolo	Flysch di Farini d'Olmo	Farini d'Olmo Flysch	Farini	Cerrina Feroni et al. 1994b, Ottria 1997
NP11	Armorano	Flysch di M. Sporno	Mt. Sporno Flysch	Sporno	Rio 1987, Cerrina Feroni et al. 1991
	Rigolo	Flysch di M. Dosso	Mt. Dosso Flysch	Farini	Rio & Achilli 1980, Martini & Zanzucchi 2000
	Rigolo	Flysch di Farini d'Olmo	Farini d'Olmo Flysch	Farini	Ottria 1997
NP10	Armorano	Flysch di M. Sporno	Mt. Sporno Flysch	Sporno	Rio 1987, Cerrina Feroni et al. 1991
	Rigolo	Flysch di M. Dosso	Mt. Dosso Flysch	Farini	Rio & Achilli 1980, Martini & Zanzucchi 2000
	Predalbora	Flysch di M. Dosso	Mt. Dosso Flysch	Farini	Rio & Achilli 1980, Martini & Zanzucchi 2000
	Rigolo	Flysch di Farini d'Olmo	Farini d'Olmo Flysch	Farini	Ottria 1997
	Castelmozzano	Marne rosate di Tizzano	Tizzano Marl	Caio	Cerrina Feroni et al. 1991, 1994a
NP9	Rio Brugnara	Flysch di M. Sporno	Mt. Sporno Flysch	Sporno	Rio 1987, Cerrina Feroni et al. 1991
	Predalbora	Flysch di M. Dosso	Mt. Dosso Flysch	Farini	Rio & Achilli 1980, Martini & Zanzucchi 2000
	Predalbora	Flysch di Farini d'Olmo	Farini d'Olmo Flysch	Farini	Cerrina Feroni et al. 1994b, Ottria 1997
	Folgheto	Marne rosate di Tizzano	Tizzano Marl	Caio	Cerrina Feroni et al. 1991, 1994a
NP8	Predalbora	Flysch di M. Dosso	Mt. Dosso Flysch	Farini	Rio & Achilli 1980, Martini & Zanzucchi 2000
	Predalbora	Flysch di Farini d'Olmo	Farini d'Olmo Flysch	Farini	Ottria, 1997
NP7	Rio Brugnara	Flysch di M. Sporno	Mt. Sporno Flysch	Sporno	Rio 1987, Cerrina Feroni et al. 1991
	Predalbora	Flysch di M. Dosso	Farini d'Olmo Flysch	Farini	Rio & Achilli 1980, Martini & Zanzucchi 2000
	Predalbora	Flysch di Farini d'Olmo	Farini d'Olmo Flysch	Farini	Ottria 1997
	Folgheto	Marne rosate di Tizzano	Tizzano Marl	Caio	Cerrina Feroni et al. 1991, 1994a
NP6	Predalbora	Flysch di M. Dosso	Mt. Dosso Flysch	Farini	Rio & Achilli 1980, Martini & Zanzucchi 2000
	Predalbora	Flysch di Farini d'Olmo	Farini d'Olmo Flysch	Farini	Cerrina Feroni et al., 1994b; Ottria, 1997
	Folgheto	Marne rosate di Tizzano	Tizzano Marl	Caio	Cerrina Feroni et al. 1991
NP5	Predalbora	Flysch di M. Dosso	Mt. Dosso Flysch	Farini	Rio & Achilli 1980, Martini & Zanzucchi 2000
	Predalbora	Flysch di Farini d'Olmo	Farini d'Olmo Flysch	Farini	Ottria, 1997
	Bersatico	Marne rosate di Tizzano	Tizzano Marls	Caio	Cerrina Feroni et al. 1991, 1994a
NP3/NP4	Predalbora	Flysch di M. Dosso	Mt. Dosso Flysch	Farini	Rio & Achilli 1980, Martini & Zanzucchi 2000
NP2	Predalbora	Flysch di M. Dosso	Mt. Dosso Flysch	Farini	Rio & Achilli 1980, Martini & Zanzucchi 2000
	Predalbora	Flysch di Farini d'Olmo	Farini d'Olmo Flysch	Farini	Cerrina Feroni et al., 1994b; Ottria, 1997
	Bersatico	Marne rosate di Tizzano	Tizzano Marl	Caio	Cerrina Feroni et al. 1991, 1994a
NP1		Flysch di M. Caio	Mt. Caio Flysch	Caio	Rio et al. 1983

Tab. 1 - List of members and formations investigated with the calcareous nannofossil zones reported in literature.

sin. The investigated successions belonging to the External Ligurides are the units of Caio, Farini, Sporno and Penice (Abbate et al. 1970, 1980; Rio et al. 1983; Marroni et al. 1992, 2001; Gardin et al. 1994; Daniele & Plesi 2000) and crop out in the Emilian side of the Northern Apennines (Fig. 1). The Caio Unit comprises an ophiolitic-rich "basal complex" and the Late Cretaceous Helminthoid Flysch of Mt. Caio with the Tizzano Marl above, mostly composed of pelitic-arenaceous and marly-calcareous successions Paleocene to middle Eocene in age. The Farini and Sporno Units, corresponding to the Farini D'Olmo Flysch and the Mt. Sporno Flysch, are characterized by pelitic-arenaceous and very thick marly-calcareous successions with megatubidites. The marly-calcreous Penice Unit is here assigned to the External Ligurides (Ottria et al. 2007), although it was previously included in the Subligurian Units (Barbieri & Zanzucci 1963; Elter et al. 1997).

Stratigraphy of the investigated successions

In Fig. 2 the lithostratigraphic features of the Caio, Farini, Sporno and Penice Units are reported, and are briefly described as follows.

Caio Unit - The upper portion of this unit, the Tizzano Marl, crops out in the Parma and Enza Valleys (Anelli 1935; Zanzucchi 1980; Rio 1987; Cerrina Feroni et al. 1994a) and includes the Bersatico-Folgheto and

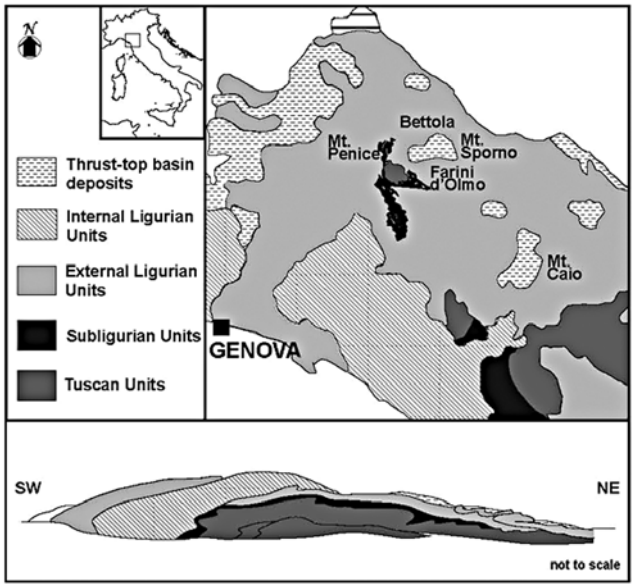

Fig. 1 - Tectonic sketch map of the Northern Apennines, location of the study areas, and schematic cross-section (from Elter 1975).

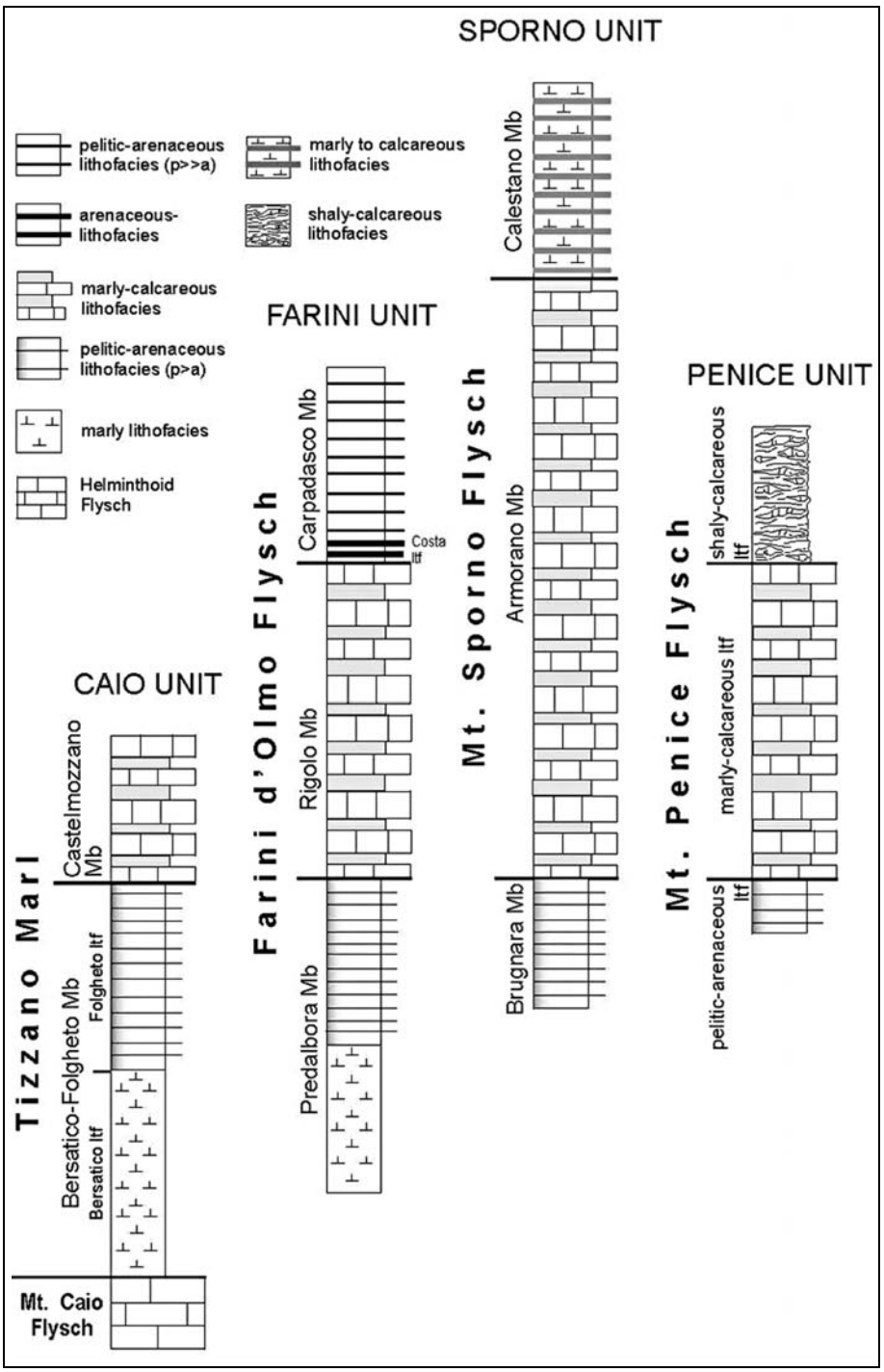

Fig. 2 - Stratigraphy of the Caio, Farini, Sporno, and Penice Units. Mb = Member, ltf = lithofacies.

Castelmozzano members. The Bersatico lithofacies is mainly composed of pinkish to reddish clayey to calcareous marls (*cf.* Marne Rosate *Auctt.*), with arenaceous-pelitic interlayers. The overlying pelitic-arenaceous Folgheto lithofacies shows rare pinkish to reddish marly intercalations. It grades into the marly-calcareous Castelmozzano Member (Mb.), that is characterized by pelitic-arenaceous turbidites as well, more frequent in the lower portion of the member.

Farini Unit - The three members of the Farini d'Olmo Flysch (= Mt. Dosso Flysch of Venzo 1966) crop out in the Nure and Ceno Valleys. The Predalbora Mb. includes a basal marly calcareous lithofacies of Case Poncini, and an upper pelitic-arenaceous lithofacies. The marly-calcareous Rigolo Mb. above is characterized by thick or very thick megaturbidites (up to 5-10 m in thickness), and thin to medium thick pelitic-arenaceous turbidites, more frequent in the lower portion of the member. The upper part of the Farini Unit comprises the pelitic-arenaceous Carpadasco Mb. that sometimes overlies the arenaceous-pelitic Costa lithofacies.

Sporno Unit - The three members of the Mt. Sporno Flysch are well exposed in the Parma and Baganza

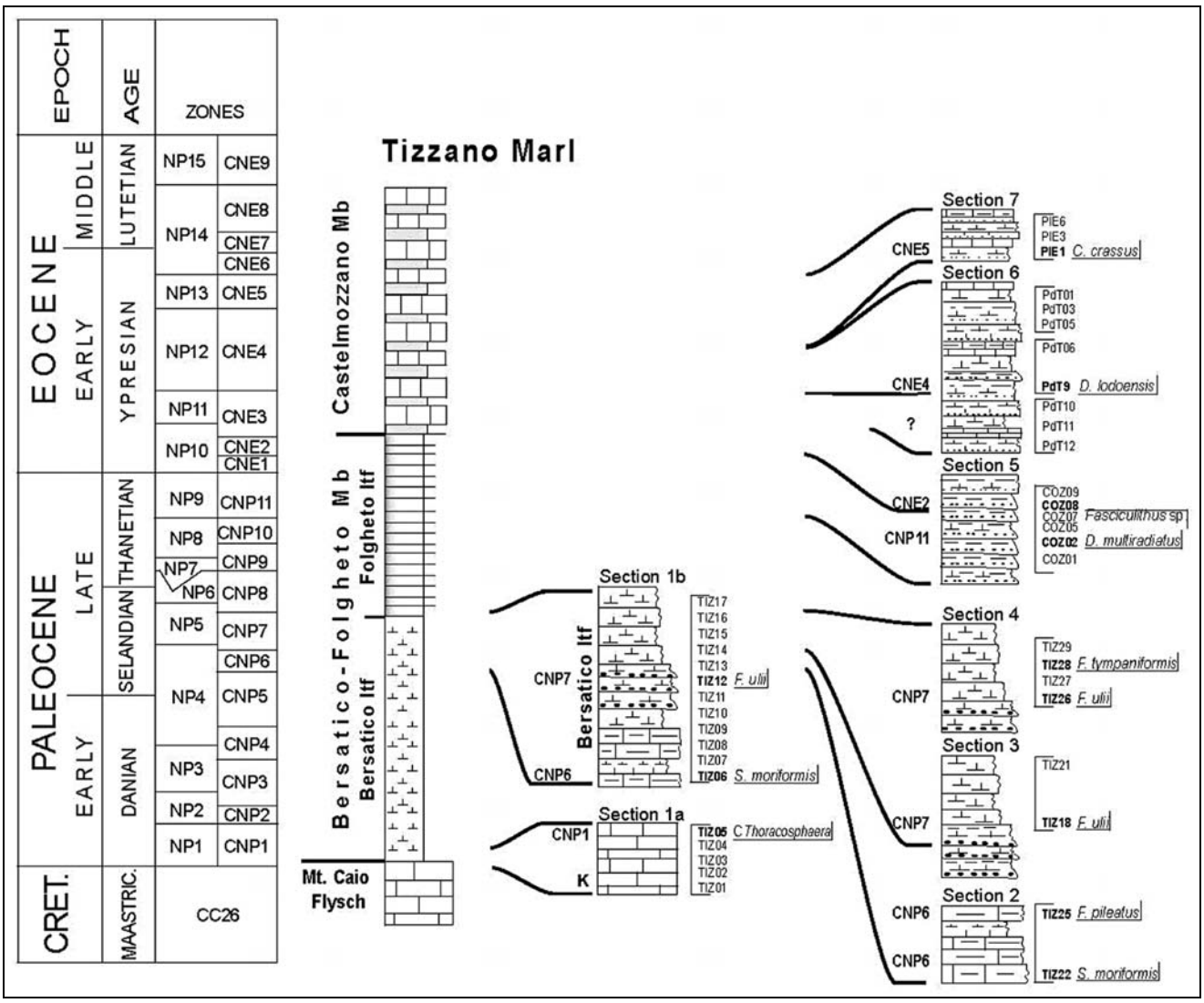

Fig. 3 - Biostratigraphy of the Tizzano Marl sections 1-7 sampled in the Parma Valley. Detailed calcareous nannofossil abundances are reported in Tabs 2-8 and Figs 9-12. Zone CC26 of Sissingh (1977), NP Zones of Martini (1971), CNP-CNE Zones of Agnini et al. (2014). For symbols see legend in Fig. 2. Mb = Member, ltf = lithofacies, K = Cretaceous.

Valleys (Barbieri & Petrucci 1966; Rizzoli 1988). The pelitic-arenaceous Rio Brugnara Mb. is overlaid by the marly-calcareous Armorano Mb., which is composed of thick to very thick megaturbidites (up to 5 m in thickness), and pelitic-arenaceous turbidites. The overlying thick Calestano Mb. shows marly-calcareous to calcareous lithological features.

Penice Unit - The bulk of the Penice Unit, the Mt. Penice Flysch crops out in the Trebbia, Nure and Aveto Valleys. It consists of a very thick monotonous marly-calcareous lithofacies interposed between a pelitic-arenaceous and a shaly-calcareous lithofacies. The marly-calcareous lithofacies shows intercalations of pelitic-arenaceous turbidites and, in its upper part, black pelites with siliceous limestones. The basal pelitic-arenaceous lithofacies is thin (about 70 m) and characterized by marly pelitic interbeds. The disrupted upper shaly-calcareous lithofacies is made up of black pelites with intercalations of thin to medium thick marly-calcareous to calcareous turbidites, and siliceous limestones.

Materials and methods

We analysed 267 samples collected from successions 1a to 7 of the Tizzano Marl Unit (Fig. 3), successions 8 to 12 of the Farini d'Olmo Unit (Fig. 4), successions 13 to 16 of the Mt. Sporno Unit (Fig. 5), and succession 17 referable to the Penice Unit (Fig. 6). The calcareous nannofossils analyses were carried out on smear slides prepared from unprocessed materials following standard methods (Bown & Young 1998). A total of 160 taxa (see Appendix) were identified following the taxonomy proposed by Aubry (1984, 1988, 1989, 1990, 1999) and Perch-Nielsen (1985). Nannofossil specimens are generally poorly to moderately preserved, and have etching and overgrowth that sometimes prevent their identification. Semi-quantitative data were collected using the following methods: by counting for each taxon the number of specimens *vs*. 300 observed specimens to obtain percent of the taxon in the total assemblage; by counting the taxa observed in 200 fields of views (roughly corresponding to 5 mm^2) to obtain the number of tax-

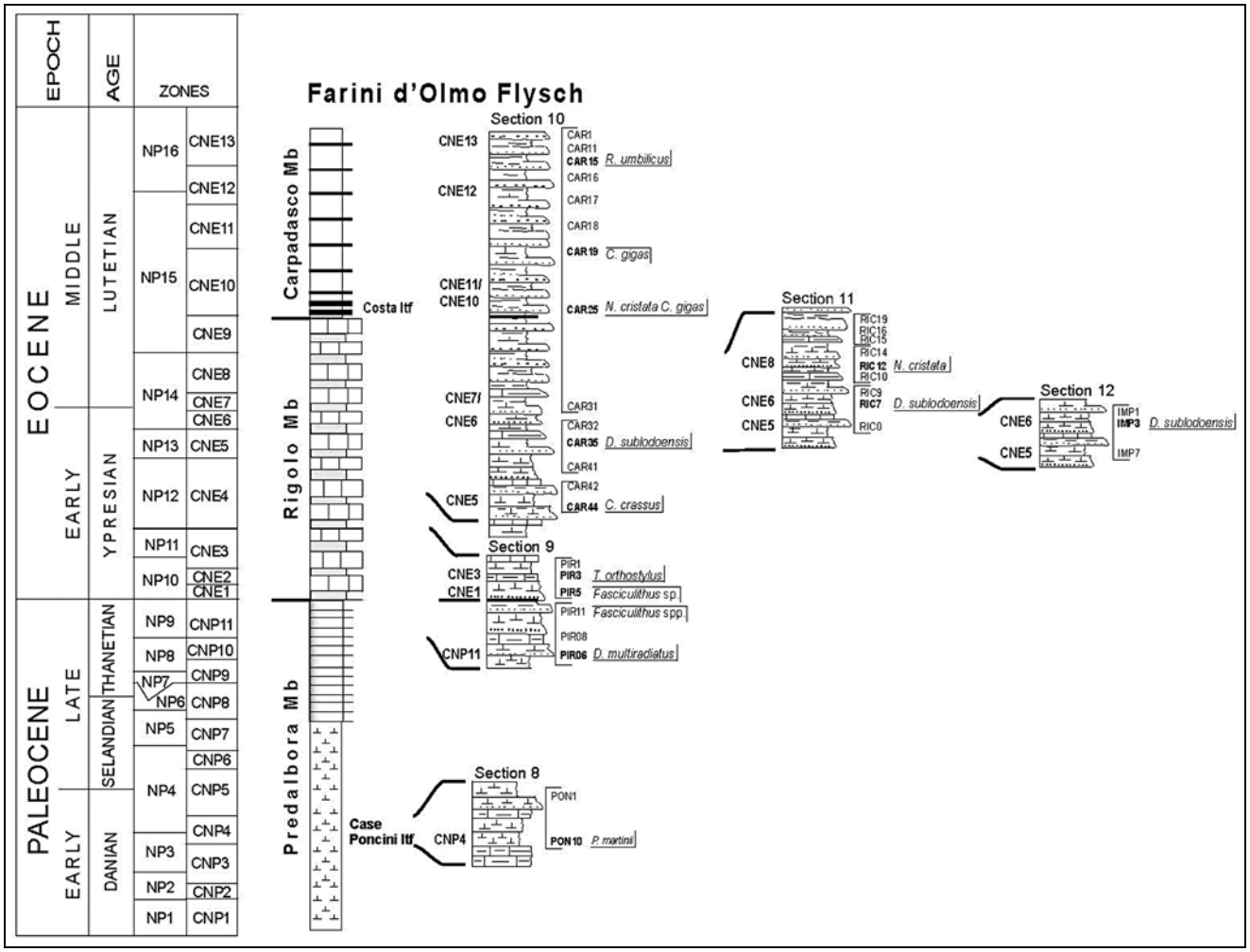

Fig. 4 - Biostratigraphy of the Farini D'Olmo Flysch sections 8-11 sampled in the Nure and Ceno Valleys. Farini D'Olmo Flysch = Mt. Dosso Flysch Fm. of Venzo (1966). Detailed calcareous nannofossil abundances are reported in Tabs 9-13 and Figs 13-17. NP Zones of Martini (1971), CNP-CNE Zones of Agnini et al. (2014). For symbols see legend in Fig. 2. Mb = Member, ltf = lithofacies.

on/mm^2. The numeric data are reported in Tabs 2-18 as supplementary material (link of website), and the distribution patterns of the recognised calcareous nannofossil taxa are shown in Figs 7a-c.

Results

Two well-known and widely utilized biozonation schemes, the Martini (1971) NP Zonation and the Okada & Bukry (1980) CP Zonation, are used for Paleogene calcareous nannofossils biostratigraphy. The use of these schemes for dating the Cenozoic sedimentary successions of the Northern Apennines is difficult as shown in several studies (*i.e.* Fornaciari & Rio 1996; Fornaciari et al. 1996; Catanzariti et al. 1997; Fornaciari et al. 2010). The recent Paleogene biozonation of Agnini et al. (2014) gives us the opportunity of testing the biohorizons of this new biostratigraphic scheme in our successions, reported and correlated to the biostratigraphic schemes of Martini (1971) and Okada & Bukry (1980) in Fig. 8. In the studied sections, we recognized CNP (Calcareous Nannoplankton Paleocene) and CNE (Calcareous Nannoplankton Eocene) biozones through the presence of the taxa reported below. Their abundance patterns are shown in Figs 9-25.

The Coccolithaceae are represented by the genera *Campylosphaera*, *Coccolithus*, *Chiasmolithus*, *Cruciplacolithus*, and *Ericsonia*.

In the genus *Campylosphaera*, only *C. dela* occurs with rare and sporadic specimens in sections 6, 7 (Fig. 3, Tabs 7-8), 9, 10, 12 (Fig. 4, Tabs10, 11, 13), 14 and 15 (Fig. 5, Tabs 15-16), from Zone CNP11 (NP9/CP8a) to Zone CNE8 (NP14 *p.p.*/CP12b).

The genus *Coccolithus* is predominantly represented by *C. pelagicus*, which has high abundance percentages in all the investigated samples, reaching 66% of the assemblages in section 5 (Fig. 3, Tab. 6; CNE2 Zone -NP10 *p.p.*/CP8b *p.p.*). *Coccolithus eopelagicus* was recorded in very low percentages and discontinuously in sections 6, 7 (Fig. 3, Tabs 7 and 8), 9, 10 and 11 (Fig. 4, Tabs 10, 11-12), within Zones CNE4-CNE13 (NP12-NP16 *p.p.*/CP10-CP14a *p.p.*). *Coccolithus crassus* is present in sections 7 (Fig. 3, Tab. 8), 10-12 (Fig. 4, Tabs 11-

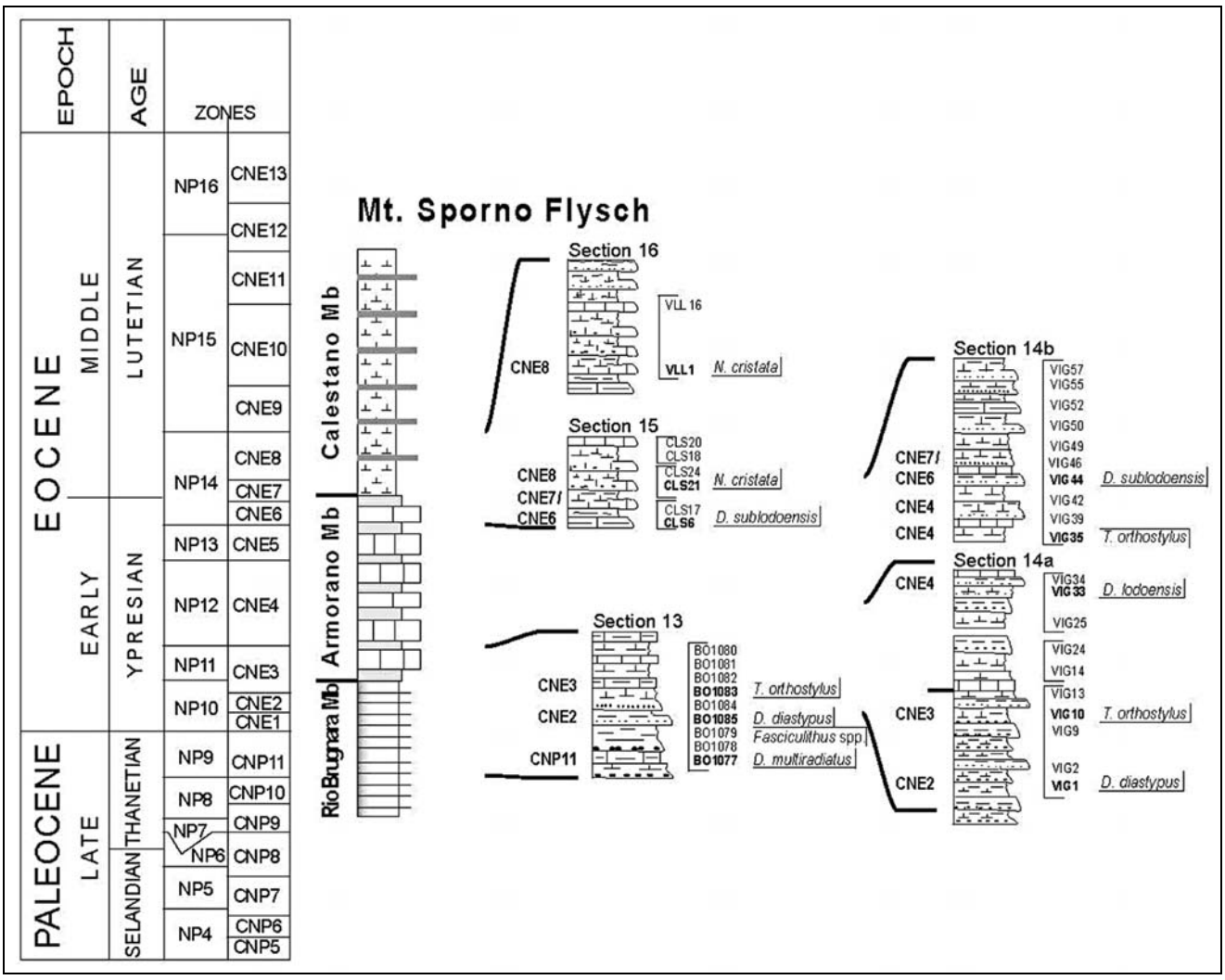

Fig. 5 - Biostratigraphy of the Mt. Sporno Flysch sections 13-16 sampled in the Ceno Valley. Detailed calcareous nannofossil abundances are reported in Tabs 14-16 and Figs 18-23. NP Zones of Martini (1971), CNP-CNE Zones of Agnini et al. (2014). For symbols see legend in Fig. 2. Mb = Member.

13), 14 (Fig. 5, Tab. 15) and 17 (Fig. 6, Tab. 18). In the Castelmozzano Mb. of the Tizzano Marl (section 7, Fig. 6/3, Tab. 8), in the Rigolo Mb. of the Farini d'Olmo Flysch (sections 10, 12; Fig. 4; Tabs 11, 13), and in the marly-calcareous lithofacies of the Mt. Penice Flysch (section 17, Fig. 6, Tab. 18), the biohorizon top of *T. orthostylus* is not clearly delineated. Therefore in those sections we used the base of *C. crassus*, that occurs close to the top of *T. orthostylus,* to recognize Zone CNE5 (NP13/CP11 *p.p.*). The highest occurrence of *C. crassus* was detected in sections 10, 11, 14 and 17 (Tabs 11, 12, 15, 18), within Zone CNE7 (NP14 *p.p.*/CP12a *p.p.*).

The genus *Chiasmolithus* was recorded in all the investigated sections, even though it is not always continuous and common. The most common species are *C. bidens, C. californicus, C. consuetus*, *C. danicus, C. gigas, C. grandis, C. eograndis C. expansus*, *C. medius*, *C. solitus* and *C. titus*. *Chiasmolithus bidens* occurs in sections 1, 3, 5, 6 (Fig. 3; Tabs 2, 4, 6-7), 9 (Fig. 4, Tab. 10), 13, 14a-b (Figs 5, 20; Tabs 14-15) and 17 (Fig. 6, Tab. 18), from Zone CNP6 (NP4/CP3) to Zone CNE4 (NP12/CP10-CP11 *p.p.*). *Chiasmolithus californicus* occurs in section 10 (Fig. 8/4; Tab. 11) from Zone CNE6 to Zone CNE7 (NP14 *p.p.*/CP12a). *Chiasmolithus consuetus* occurs in sections 5-7 (Figs 3, 20; Tabs 6-8), 9, 10, 12 (Fig. 4; Tabs 10-11, 13), and 16 (Fig. 5; Tab. 17), from Zone CNP11 (NP9/CP8a) to Zone CNE11 (NP15 *p.p.*/CP13b *p.p.*). *Chiasmolithus danicus* was recorded in sections 1b-4 (Figs 3, 10; Tabs 2-5), 8 and 9 (Fig. 4; Tabs 9-10), from Zone CNP4 (NP2 *p.p.*-NP3 *p.p.*/CP1b *p.p.*-CP2 *p.p.*) to Zone CNP11 (NP9/CP8a). *Chiasmolithus gigas* is present only in section 10 (Figs 4, 15; Tab. 11), indicating the biostratigraphic interval CNE10-CNE11 (NP15 *p.p.*/CP13a-CP13b) in the Carpadasco Mb. of the Farini d'Olmo Flysch. *Chiasmolithus grandis* is present in sections 7 (Fig. 3; Tab. 7), 9, 11 (Figs 4, 15; Tabs 10, 12), 13-16 (Fig. 5; Tabs 14-17) and 18 (Fig. 6; Tab. 18), with the highest number of specimens (20 on 5 mm^2) in section 10 (Fig. 4, Tab. 11), from Zone CNE3 (NP10 *p.p.*-NP11/CP9a *p.p.*-CP9b) to Zone

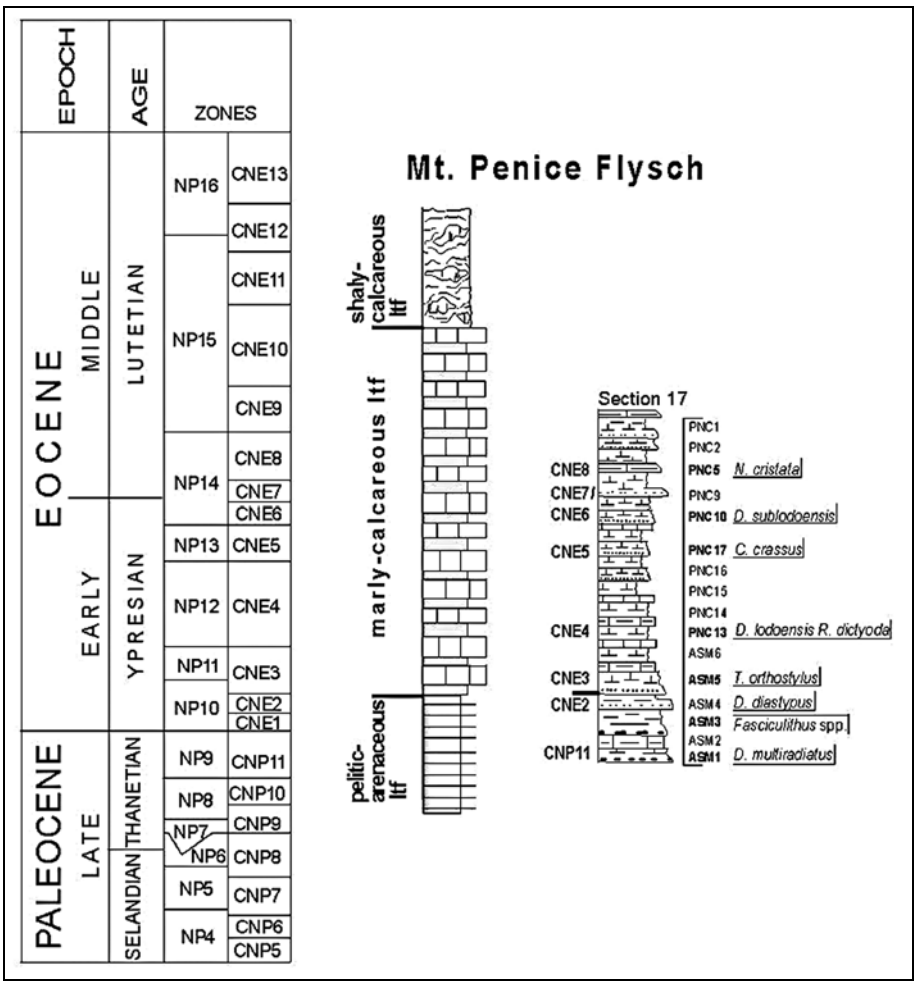

Fig. 6 - Biostratigraphy of the Mt. Penice Flysch section 17 sampled in the Nure Valley. Detailed calcareous nannofossil abundances are reported in Tab. 18 and Figs 24-25. NP Zones of Martini (1971), CNP-CNE Zones of Agnini et al. (2014). For symbols see legend in Figure 2. ltf = lithofacies.

CNE13 (NP16 *p.p.*/CP14a *p.p.*). *Chiasmolithus solitus* occurs in sections 6, 7, 9, 10-17 (Figs 3, 4-6; Tabs 7-8, 10, 11-18), and 12 (with the highest number of specimens, *i.e.* 2 on 5 mm^2, Fig. 4; Tab. 13), from Zones CNE2 (NP10 *p.p.*/CP8b *p.p.*-CP9a *p.p.*) to CNE13 (NP16 *p.p.*/CP14a *p.p.*). *Chiasmolithus eograndis, C. expansus*, *C. medius*, and *C. titus* occur in sections 14-16 (Fig. 5; Tabs 15-17), from Zone CNE5 (NP13/CP11 *p.p.*) to Zone CNE11 (NP15 *p.p.*/CP13b *p.p.*).

Several species of the genus *Cruciplacolithus* occur in the studied sections. *Cruciplacolithus primus* is present in sections 1, 2 (Fig. 3; Tabs 2-3) and 8 (Fig. 4; Tab. 9), characterizing Zone CNP4 (NP3/CP2). *Cruciplacolithus tenuis* was recorded in sections 1b-4 (Fig.3; Tabs 2-5), 8, 9 (Fig. 4; Tabs 9-10), 13, 14 (Fig. 5; Tabs 14-15) and 17 (Fig. 6; Tab. 18), from Zone CNP4 (NP3/CP2) to Zone CNE3 (NP10 *p.p.*-NP11/CP9a *p.p.*-CP9b). *Cruciplacolithus asymmetricus* occurs in sections 1b-3, 5 (Fig. 3; Tabs 2-4, 6, 9) and 8 (Fig. 4, Tab. 9), from Zone CNP4 (NP3/CP2) to Zone CNP11 (NP9/CP8a), and *C. frequens* that occurs in sections 5, 6 (Fig. 3, Tabs 6-7), and 14 (Fig. 5, Tab. 15), co[illegible]e CNP11 (NP9/CP8a) to Zone CNE4 (NP12/CP10-CP11 *p.p.*).

In the genus *Ericsonia* we recognized *E. formosa, E. robusta, E. subdisticha* and *E. subpertusa*. *Ericsonia subpertusa* is abundant and continuously present in sections 1b-6 (Fig. 3, 9, 11, 13; Tabs 2-7), 8-9 (Fig. 4; Tabs 9-10), and 14a (Figs 5, 20; Tab. 15) from Zone CNP4 (NP3/CP2) to Zone CNE4 (NP12/CP10-CP11 *p.p.*). *Ericsonia formosa* is common and continuously present in sections 6, 7 (Figs 3, 12; Tabs 7-8), 10-12 (Figs 4, 16; Tabs 11-13), 14b-16 (Figs 5, 21; Tabs 15-17) and 17 (Fig. 6, 25; Tab. 18), from Zone CNE4 (NP12/CP10-CP11 *p.p.*) to Zone CNE13 (NP16 *p.p.*/CP14a *p.p.*). *Ericsonia robusta* occurs with ambiguous specimens (*E.* cf *robusta*) in sections 1-4 (Fig. 3; Tabs 2-5), 9 (Fig. 4; Tab. 10) and 13 (Fig. 5; Tab. 14). *Ericsonia subdisticha* is recorded as scarce in few samples of sections 6, 7 and 10-17 (Tabs 7-8 and 11-18).

The Noelaerabdaceae are represented by the genera *Cyclicargolithus* with the species *C. floridanus*, *Dictyococcites* with small elliptical forms (5 μm in diameter) labeled *Dictyococcites* sp. and *Reticulofenestra*, with the species *R. dictyoda* and *R. umbilicus*. These taxa are concomitantly present in sections 7 (Fig. 3, Tab. 8), 10-12 (Figs 4, 15; Tabs 11-13), 14b-16 (Figs 5, 21, 22, 23; Tabs 15-17), and 17 (Figs 6, 25; Tab. 18), show different abundances, with *Cyclicargolithus* that is the most abundant (up to 60% of the assemblage, Tab. 18), and *Reticulofenestra*, that is more abundant than

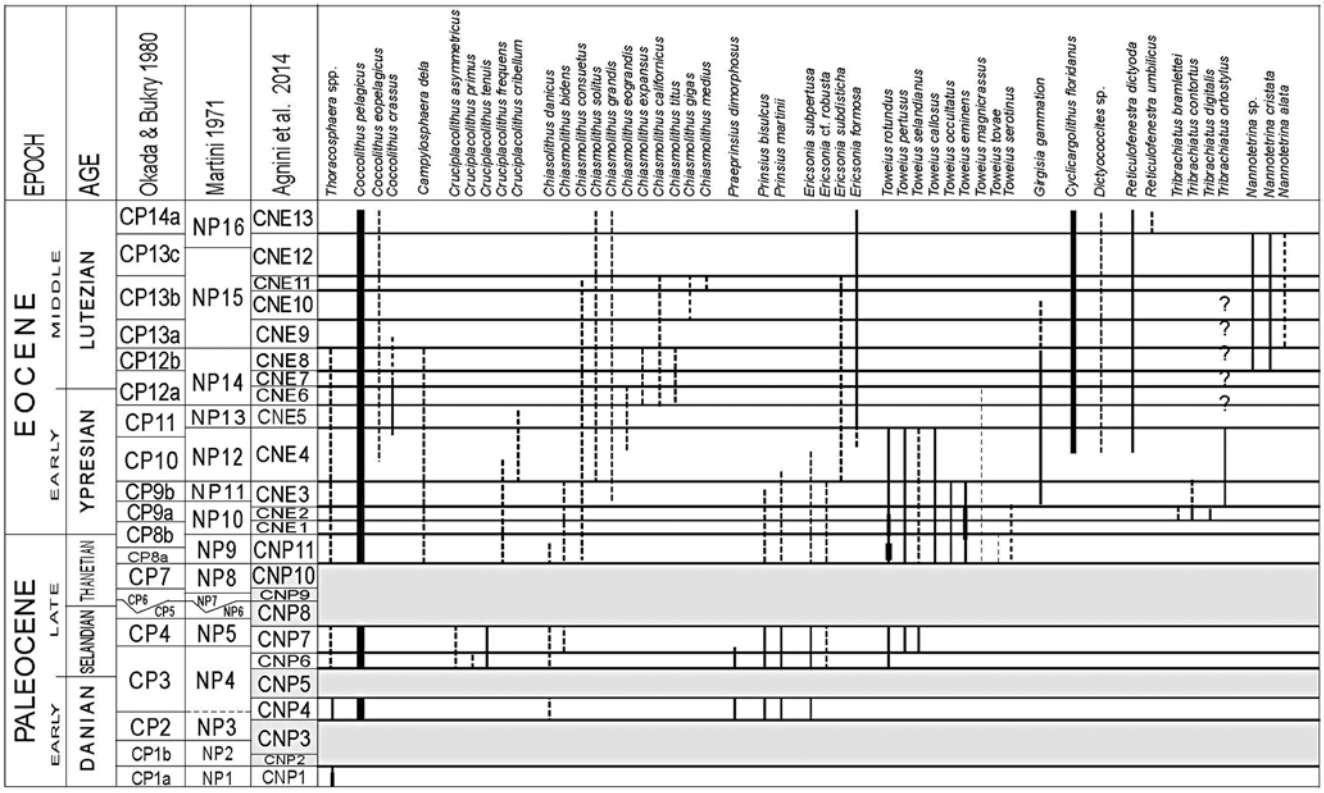

Fig. 7a - Range chart of the calcareous nannofossil taxa recovered from the Paleocene-middle Eocene successions of the Northern Apennine Caio, ~~Bettola, Antola,~~ Farini, Cerrogno and Penice Units. Chronostratigraphic schema from Fig. 8. In grey zones that were not studied.

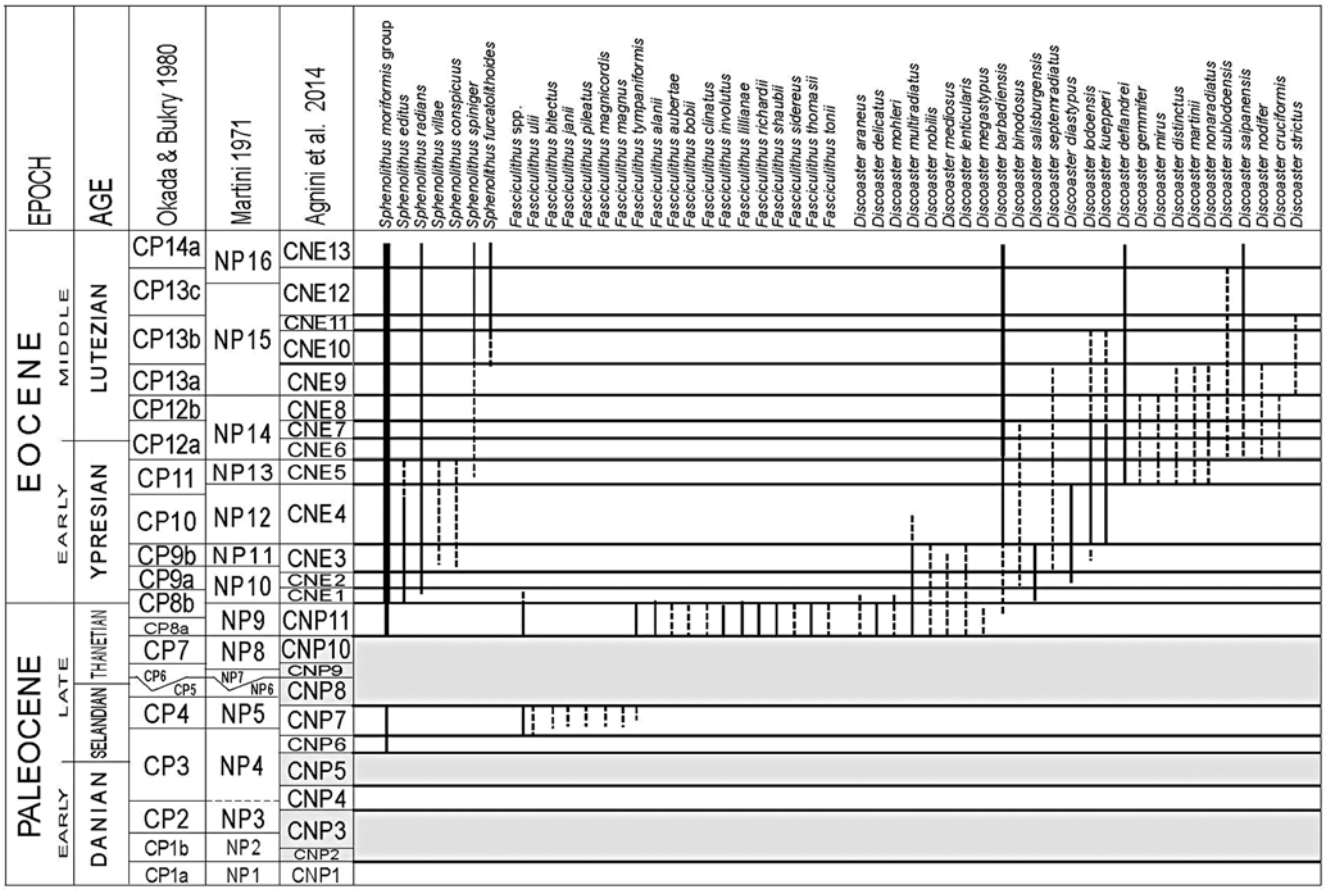

Fig. 7b - continued.

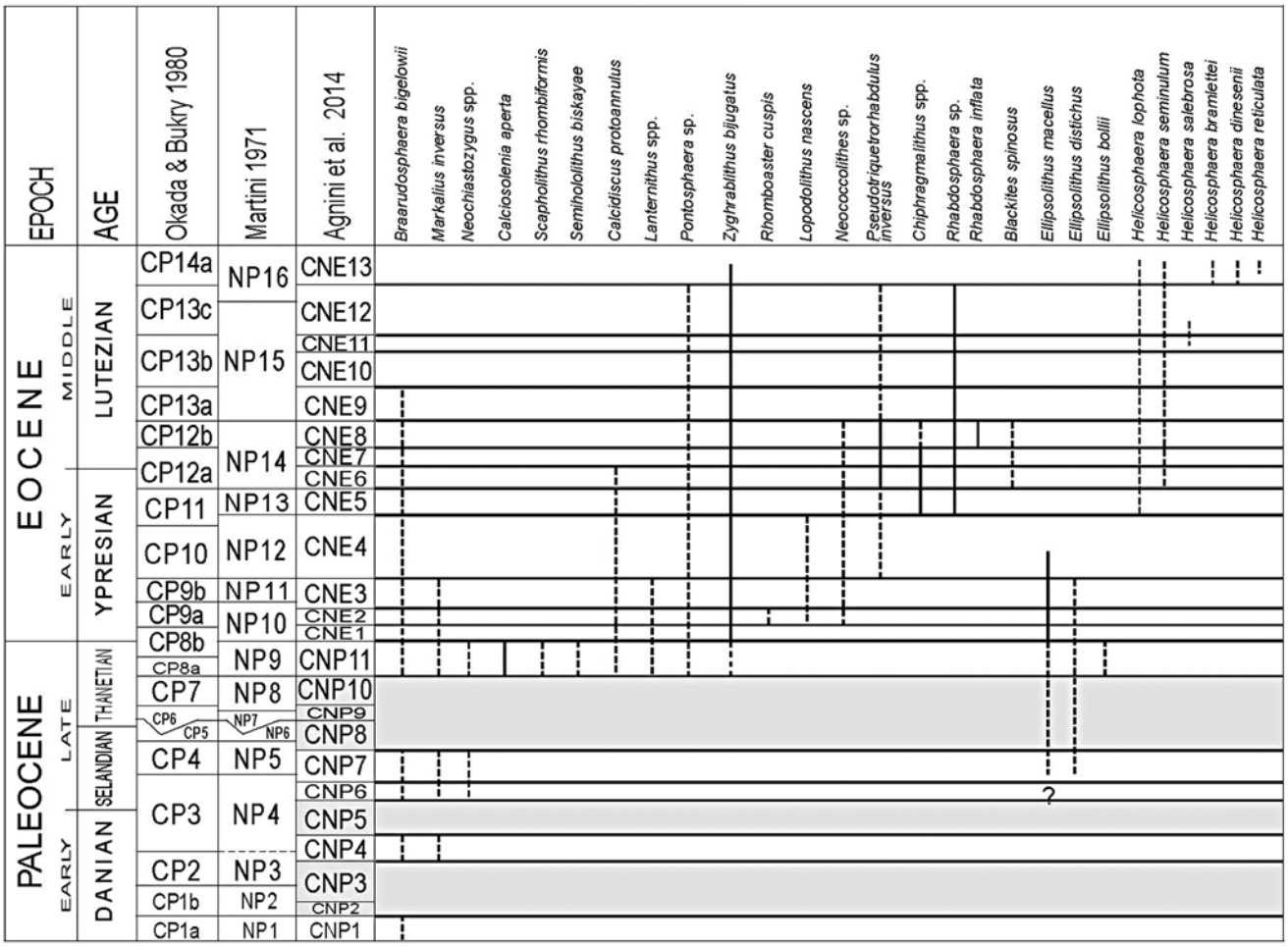

Fig. 7c - continued.

Dictyococcites. These three genera characterize the middle Ypresian-middle Lutetian assemblages, and suddenly occur from the upper part of Zone CNE4 (NP12/CP10) to Zone CNE13 (NP16 *p.p.*/CP14a *p.p.*), that was recognized for the occurrence of specimens of *R. umbilicus* (*sensu* Backmann & Hermelin 1986).

The Prinsiaceae present with the genera *Praeprinsius*, *Prinsius*, *Toweius* and the species *Girgisia gammation*. The latter taxon occurs in sections 6, 7 (Figs 3, 12; Tabs 7-8), 9-12 (Figs 4, 14, 15, 16,17; Tabs 10-13), 14b-15 (Figs 5, 21, 22; Tabs 15-16), and 17 (Figs 6, 25; Tab. 18) from Zone CNE3 (NP11/CP9b) to Zone CNE8 (NP14 *p.p.*/CP12b).

The genus *Prinsius* comprises the species *P. bisulcus*, and *P. martinii* that with *Praeprinsius dimorphosus* are commonly and continuously present in sections 1b-4 (Figs 3, 9, 10; Tabs 2-5) and 8 (Fig. 4, 13; Tab. 9), delineating Zones CNP4 (NP3 *p.p.*/CP2 *p.p.*), CNP6 (NP4 *p.p.*/CP3 *p.p.*) and CNP7 (NP4 *p.p.*-NP5 *p.p.*/CP3 *p.p.*-CP4 *p.p.*), recognized in the Predalbora Mb. of the Farini d'Olmo Flysch (Case Poncini lithofacies, Fig. 4).

The genus *Toweius* includes the species T. *callosus*, *T. eminens*, *T. magnicrassus*, *T. occultatus*, *T. pertusus*, *T. rotundus T. selandianus*, *T. serotinus*, and *T. tovae*. These species are present in sections 1b-6 (Figs 3, 9-12; Tabs 2-7), 9 (Figs 4, 14; Tab. 10), 13-14 (Figs 5, 18, 20; Tabs 14-15), and 17 (Figs 6, 25; Tab. 18), from Zone CNP6 (NP4 *p.p.*/CP3 *p.p.*) to Zone CNE4 (NP12/CP10-CP11 *p.p.*). *Toweius callosus*, *T. rotundus* and *T. pertusus* display the highest abundances in sections 5, 9, 13, 14a and 17 (Figs 3, 8/4-10/6, 11, 14, 18, 20, 25; Tabs 6, 10, 14, 15, 18), from Zone CNP11 (NP9/CP8a) to Zone CNE3 (NP11/CP9b).

The Discoasteraceae were represented by many species (see Fig. 7b and the Taxonomic Appendix for the complete list) that were variably continuous and common throughout the studied sections. Diagenetic modification of the morphology often hampers the identification of some species, therefore the unidentified specimens were counted as *Discoaster* sp. and "star shaped *Discoaster* with terminal nodes", in the numerical tables. The recognized species characterize the assemblages of zones CNP11 (NP9/CP8a) to CNE13 (NP16 *p.p.*/CP14a *p.p.*) (*i.e.* sections 5-7, Fig. 3, Tabs 6-8; sections 9-17, Figs 4-10/6, Tabs 10-18). The number of specimens varies from low number in section 5 (Figs 3, 11; Tab. 6) within Zone CNP11 (NP9 /CP8a), to

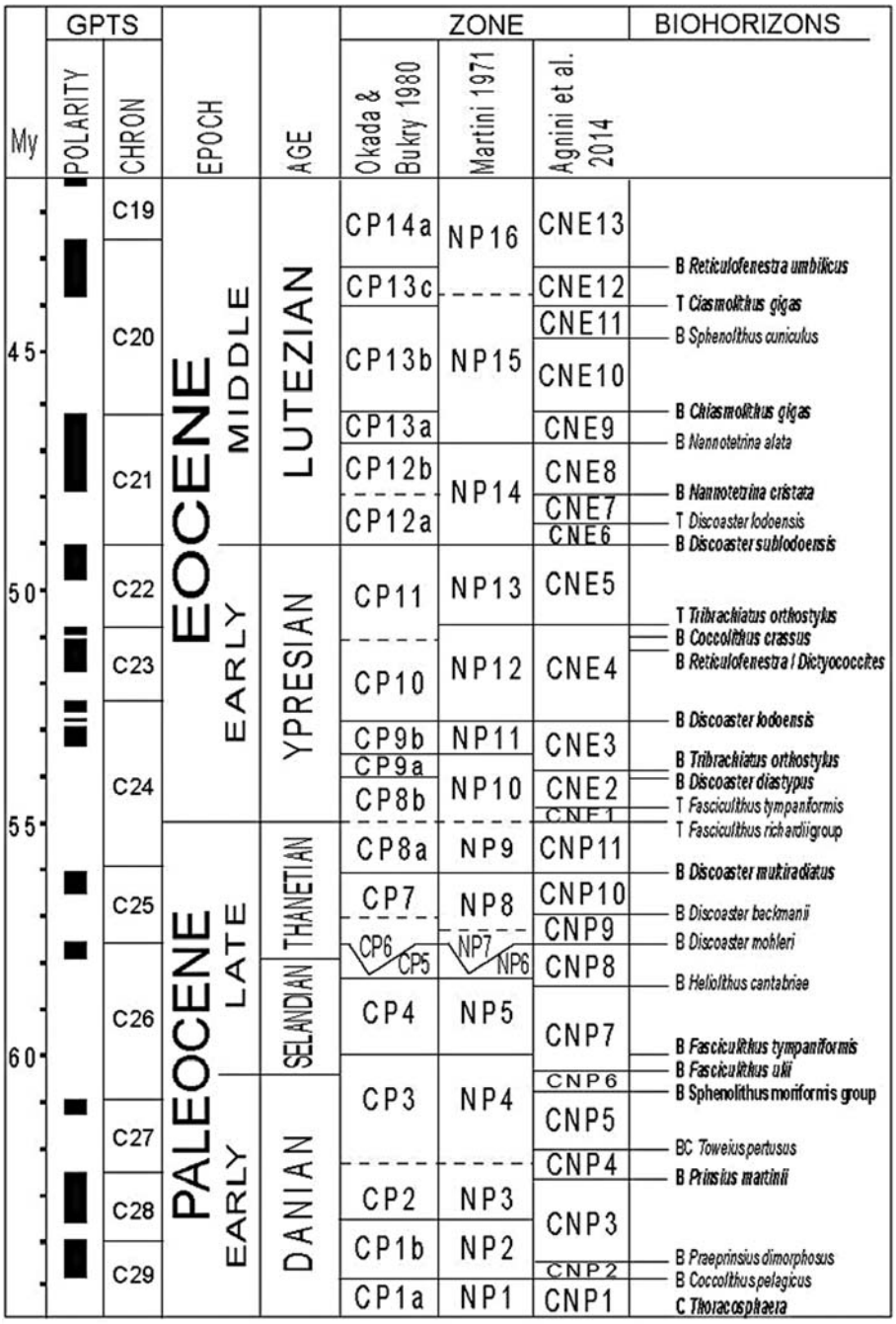

Fig. 8 - Calcareous nannoplancton biozonation for the early Paleocene-middle Eocene after Agnini et al. (2014). In bold are the events used to date the "Tertyiary Flysch *Auctt.*" successions.

hundreds in sections 10-12 (Figs 4, 15-17; Tabs 11-13) and 14-16 (Figs 5, 19, 21; Tabs 15-17) within Zone CNE5 (NP13/CP11 *p.p.*) to Zone CNE8 (NP14 *p.p.*/ CP12b). *Discoaster multiradiatus*, the CNP11 (NP9/ CP8a) marker, was recognized in the Folgheto lithofacies of the Tizzano Marl in section 5 (Figs 3, 11; Tab. 6), the Predalbora Mb. of the Farini d'Olmo Flysch in section 9 (Figs 4, 14; Tab. 10), the Brugnara Mb. of the Mt. Sporno Flysch in section 13 (Figs 5, 18; Tab. 14) and the pelitic-arenaceous lithofacies of the Mt. Penice Flysch in section 17 (Fig. 6, Tab. 18). The species *D. delicatus*, *D. falcatus*, *D. lenticularis*, *D. mohleri*, *D. megastypus*, *D. nobilis, D. salisburgensis* occur in sections 5 (Fig. 3, Tabs 6), 9 (Fig. 4, Tab. 10), 13 (Fig. 5, Tab. 14) and 17 (Fig. 6, Tab. 18), within Zone CNP11 (NP9/CP8a). Zone CNE2 (NP10/CP9 *p.p.*) is recognized by the first specimens of *D. diastypus* in sections 13, 14a (Figs 5, 18-19; Tabs 14-15) and 17 (Figs 6, 24; Tab. 18), in the Brugnara Mb. of the Mt. Sporno Flysch (Fig. 5, Tab. 15) and in the Mt. Penice Flysch (Fig. 6, Tab. 18). The appearance of *D. lodoensis* in section 6 (Figs 3, 12; Tab. 7), 14a (Figs 5, 19; Tab. 15), and 17 (Figs 6, 24; Tab. 18) indicates Zone CNE4 (NP12/CP10-CP11 *p.p.*) in the Castelmozzano Mb. of the Tizzano Marl, in the Armorano Mb. of Mt. Sporno Flysch and in the marly-calcareous lithofacies of the Mt. Penice Flysch. *Discoaster sublodoensis* was difficult to recognize due to poor preservation of the rare broken specimens encountered. In

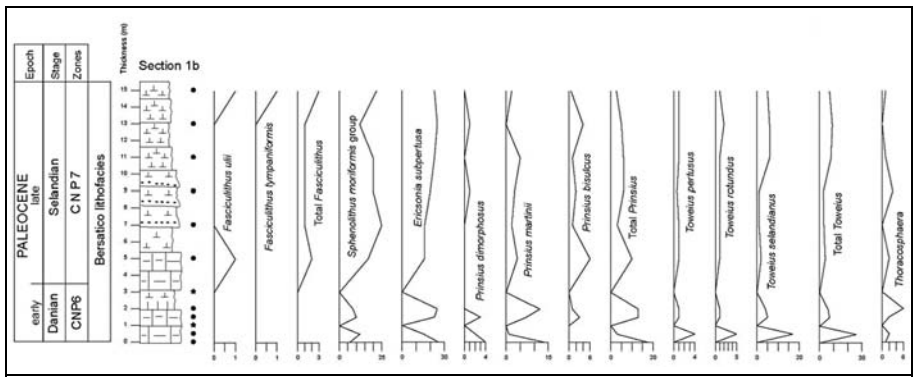

Fig. 9 - Section 1b. Abundance patterns of selected calcareous nannofossils recovered in the Bersatico lithofacies (Tizzano Marl), species plotted against lithostratigraphy and biostratigraphy. Dot = Sample, Star = Barren sample.

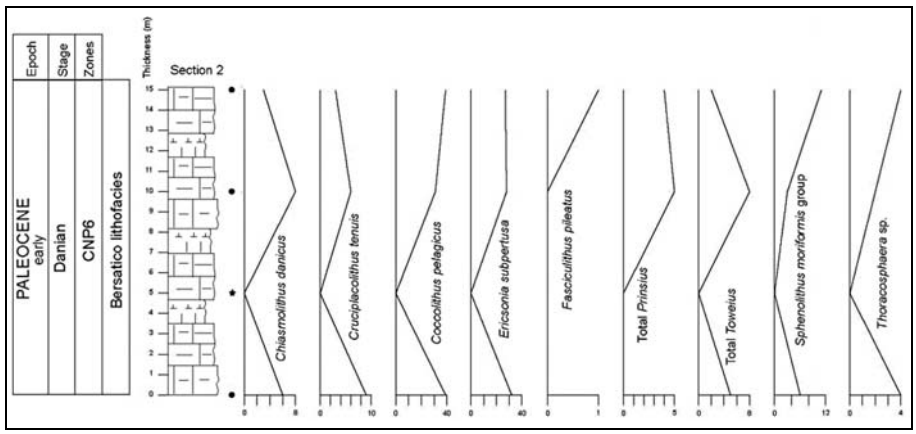

Fig. 10 - Section 2. Abundance patterns of selected calcareous nannofossils recovered in the Bersatico lithofacies (Tizzano Marl), species plotted against lithostratigraphy and biostratigraphy. Dot = Sample, Star = Barren sample.

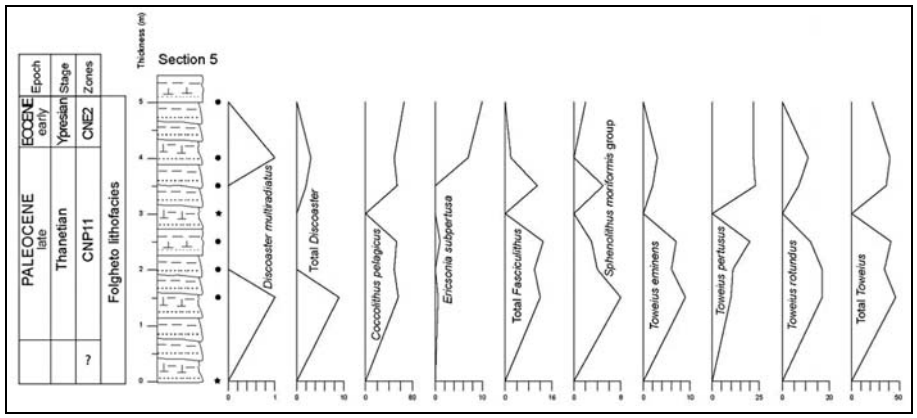

Fig. 11 - Section 5. Abundance patterns of selected calcareous nannofossils recovered in the Folgheto lithofacies (Tizzano Marl), species plotted against lithostratigraphy and biostratigraphy. Dot = Sample, Star = Barren sample.

some cases, the appearance of the species was indirectly established by the presence of specimens recognized as *D.* cf *sublodoensis* (Tabs 11-12). Therefore Zone CNE6 (NP14 *p.p.*/CP12a *p.p.*) was recognized on the occurrence of *D.* cf *sublodoensis* in sections 10-12 (Figs 4, 15-17; Tabs 11-13), 14b, 15 (Fig. 5, 21-22; Tabs 15-16) and 17 (Figs 6, 24; Tab. 18), in the Rigolo Mb. of the Farini d'Olmo Flysch, the Armorano Mb. of the Mt. Sporno Flysch and the marly-calcareous lithofacies of the Mt. Penice Flysch.

The genus *Sphenolithus* is common and continuous in most of the investigated sections. The occurrence of the first specimen of *S. primus* and *S. moriformis*, lumped together in the *S. moriformis* group in sections 1b, 2 (Figs 3, 9-10; Tabs 2-3), indicates Zone CNP6 (NP4 *p,p.*/CP3 *p.p.*), in the Bersatico lithofacies of the Tizzano Marl. *Sphenolithus radians* was recorded in the sections 6, 7 (Figs 3, 12; Tabs 7-8) and 10-17 (Figs 5-6, 18, 20; Tabs 11-18). Its lowest occurrence ranges from Zone CNE1 (NP10 *p.p.*/CP8a) in section 9 (Fig. 4, Tab. 10) to Zone CNE2 (NP10 p.p./CP8b *p.p.*-CP9a *p.p.*) in section 14 (Fig. 5, Tab. 15). In section 17 (Fig. 6, Tab.18), the first specimens of S. *radians* were observed in the lower part of Zone CNE3 (NP10 *p.p.*-NP11/CP9a *p.p.*-CP9b). The presence of *Sphenolithus spiniger* in sections 10-12 (Fig. 4, Tabs 11-13), 15 and 16 (Fig. 5, Tabs 16-17), indicates Zone CNE7 (NP14 *p.p.*/CP12b) to Zone CNE13 (NP16 *p.p.*/CP14a *p.p.*). *Sphenolithus furcato-*

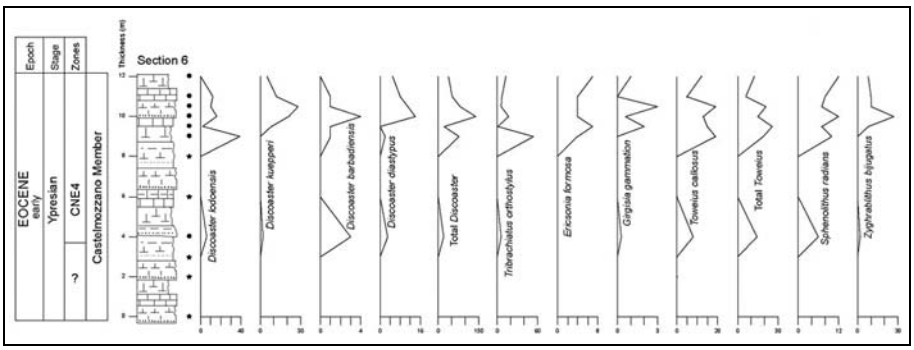

Fig. 12 - Section 6. Abundance patterns of selected calcareous nannofossils recovered in the Castelmozzano Member (Tizzano Marl), species plotted against lithostratigraphy and biostratigraphy. Dot = Sample, Star = Barren sample.

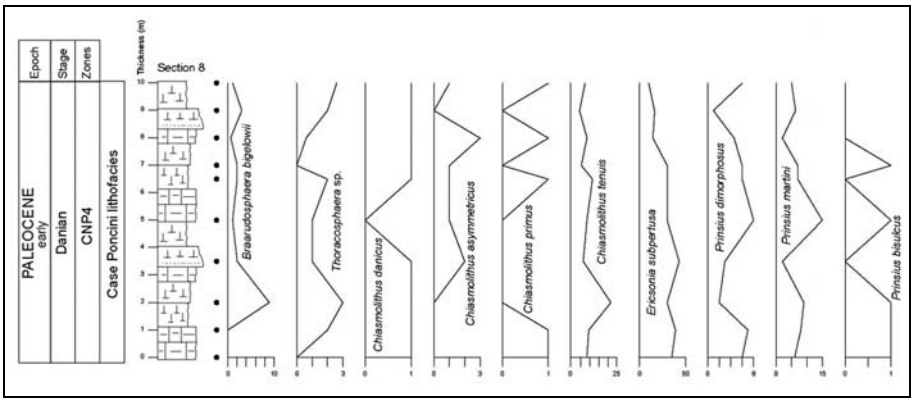

Fig. 13 - Section 8. Abundance patterns of selected calcareous nannofossils recovered in the Case Poncini lithofacies (Farini d'Olmo Flysch), species plotted against lithostratigraphy and biostratigraphy. Dot = Sample.

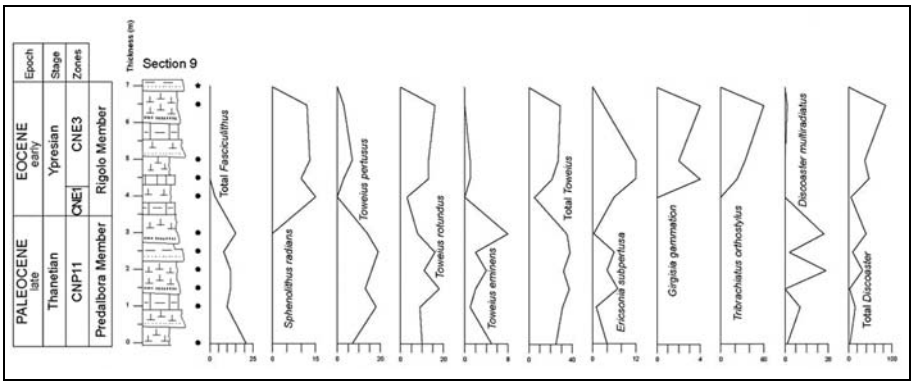

Fig. 14 - Section 9. Abundance patterns of selected calcareous nannofossils recovered in the Predalbora and Rigolo Members (Farini d'Olmo Flysch), species plotted against lithostratigraphy and biostratigraphy. Dot = Sample, Star = Barren sample.

lithoides has been observed in section 10 (Figs 4, 15; Tab. 11) from Zone CNE7 (NP14 *p.p.*/CP12b) to Zone CNE13 (NP16 *p.p.*/CP14a *p.p.*). Other subordinate species of *Sphenolithus* are *S. editus* (*i.e.* Tabs 7, 10, 13-15, 18; sections 6, 9, 12-14; Figs 3-5), *S. cospicuus* (*i.e.* Tabs 7, 10, 13; sections 6, 9, 12), and *S. villae* (*i.e.* Tabs 7, 10, 14-15, 18; sections 6, 9, 13-14, 17; Figs 3-5).

The genus *Fasciculithus* occurs in sections 1b, 3 and 4 (Fig. 3, Tabs 2, 4-5) with the species *F. bitectus*, *F. jani, F. magnicordis, F. magnus, F. pileatus, F. tympaniformis* and *F. ulii*, within Zone CNP7 (NP4 *p.p.*-NP5 *p.p.*/CP3 *p.p.*-CP4 *p.p.*) *Fasciculithus ulii* indicates Zone CNP7 (NP4 *p.p.*-NP5 *p.p.*/CP3 *p.p.*-CP4 p.p.) in section 1b (Figs 3, 9; Tab. 2), in the Bersatico lithofacies of the Tizzano Marl. The presence of other *Fasciculithus* (*F. alanii, F. aubertae, F. clinatus, F. lilianiae, F. richardii, F. shaubi, F. thomasii* and *F. tonii*) in sections 5 (Fig. 6, Tab. 6), 9 (Fig. 8, Tab. 10), 13 (Fig. 5, Tab. 14) and 17 (Fig. 6, Tab. 18), indicates Zone CNP11 (NP9/CP8a). The top of this zone is marked by the LCO of *Fasciculithus* spp., corresponding to the top of *F. richardii* group in sections 5 (Figs 3, 11; Tab. 6), 13 (Figs 5, 18; Tab. 14), 17 (Figs 6, 24; Tab. 18), within the Folgheto lithofacies of the Tizzano Marl, of the Rigolo Mb. of the Farini d'Olmo Flysch, the Brugnara Mb. of the Mt. Sporno Flysch and the pelitic-arenaceous lithofacies of the Mt. Penice Flysch, with zones CNE1-CNE2 (NP10 *p.p.*/CP8b-CP9a *p.p.*) above.

The genus *Tribrachiatus* includes the species *T. bramlettei*, *T. contortus, T. digitalis* and *T. orthostylus*. The first three species are generally rare (*i.e.* sections 13, 17; Figs 5-6; Tabs 14, 18), except for section 14a (Figs 5, 22; Tab. 15, s), in which they are common; specimens with intermediate morphologic features are also present

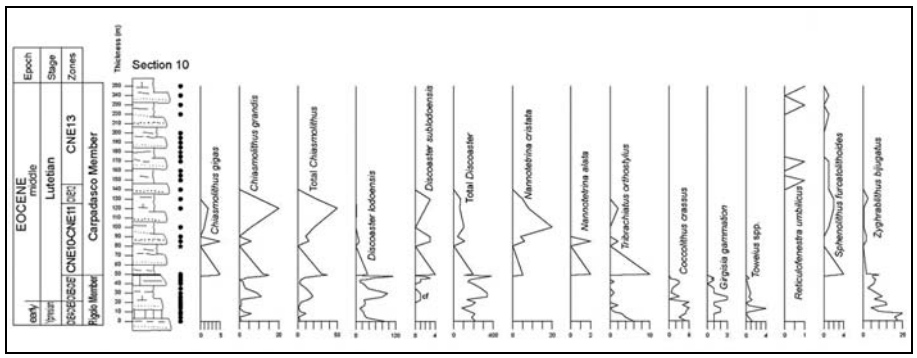

Fig. 15 - Section 10. Abundance patterns of selected calcareous nannofossils recovered in the Rigolo and Carpadasco Members (Farini d'Olmo Flysch), species plotted against lithostratigraphy and biostratigraphy. Dot = Sample, Star = Barren sample.

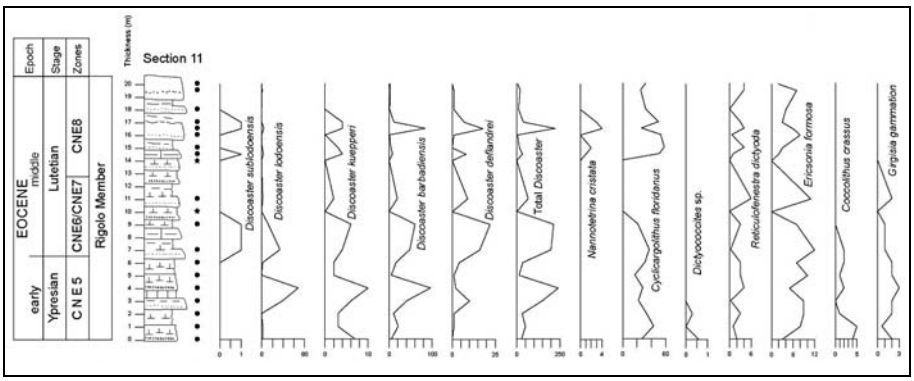

Fig. 16 - Section 11. Abundance patterns of selected calcareous nannofossils recovered in the Rigolo Member (Farini d'Olmo Flysch), species plotted against lithostratigraphy and biostratigraphy. Dot = Sample, Star = Barren sample.

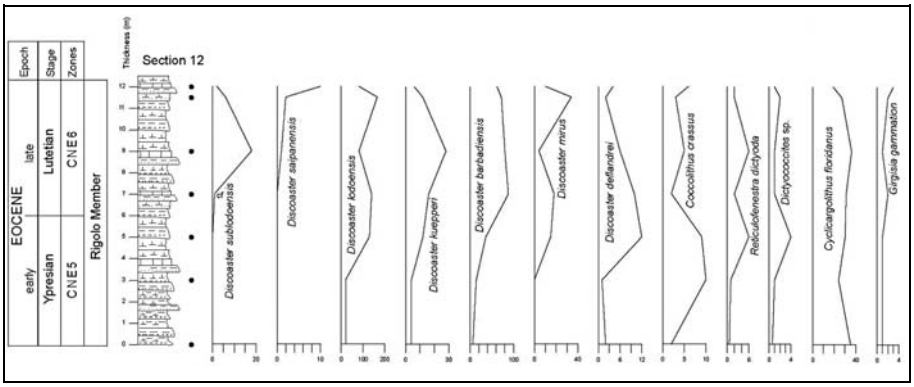

Fig. 17 - Section 12. Abundance patterns of selected calcareous nannofossils recovered in the Rigolo Member (Farini d'Olmo Flysch), species plotted against lithostratigraphy and biostratigraphy. Dot = Sample.

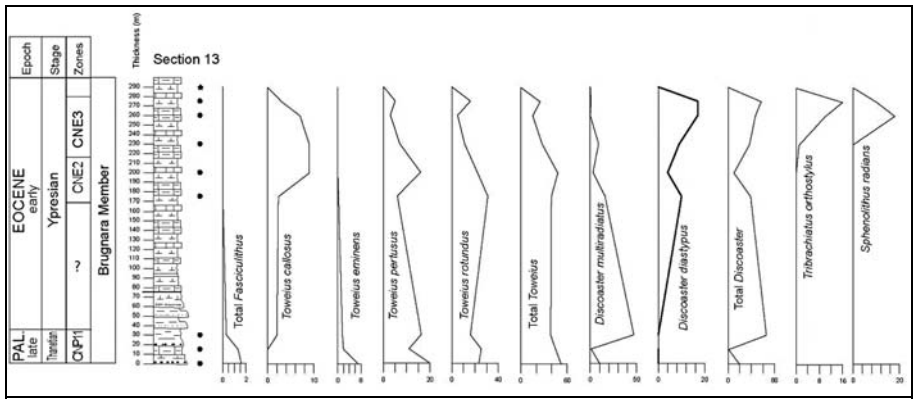

Fig. 18 - Section 13. Abundance patterns of selected calcareous nannofossils recovered in the Brugnara Member (Mt. Sporno Flysch), species plotted against lithostratigraphy and biostratigraphy. Dot = Sample, Star = Barren sample.

(section 13; Figs 5, 22; Tab. 15). *Tribrachiatus orthostylus* occurs in section 6, 7 (Figs 3, 12; Tabs 7-8), 10, 12 (Figs 4, 18; Tabs 11,13), 14a (Figs 5, 19; Tab. 15) and 17 (Figs 6, 24; Tab. 18) and is very common (up to 60 specimens on 5 mm^2) in section 9 (Figs 4, 14; Tab. 10). Its occurrence indicates Zone CNE3 (NP10 *p.p.*-NP11/CP9a *p.p.*-CP9b) in sections 7 (Fig. 3, Tab. 8), 9 (Figs 4, 14; Tab. 10) and 14a (Figs 5, 19; Tab. 15), namely in the Rigolo Mb. of the Farini d'Olmo Flysch, the Brugnara Mb. of the Mt. Sporno Flysch and the

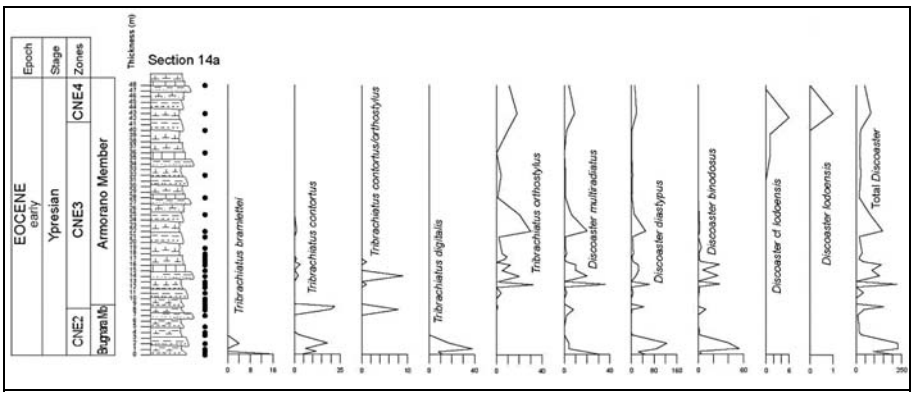

Fig. 19 - Section 14a. Abundance patterns of selected calcareous nannofossils recovered in the Brugnara and Armorano Members (Mt. Sporno Flysch), species plotted against lithostratigraphy and biostratigraphy. Dot = Sample.

marly-calcareous lithofacies of the Mt. Penice Flysch. The LO of *T. orthostylus* is, instead, useless for biostratigraphic classification, due to the reworking of the taxon repeatedly observed in sections 7 (Fig. 3, Tab. 8), 10, 12 (Fig. 4, Tabs 11, 13) and 16 (Fig. 5, Tab. 17).

The genus *Nannotetrina* includes *N. cristata* and *N. fulgens*. *Nannotetrina cristata* is present in sections 10 (Figs 4, 15; Tab. 11), 15, 16 (Figs 5, 22, 23;Tabs 16-17) and 17 (Figs 6, 24; Tab. 18), placing the Carpadasco Mb. of the Farini d'Olmo Flysch, the Calestano Mb. of the Mt. Sporno Flysch and the marly-calcareous lithofacies of the Mt. Penice Flysch in Zone CNE8 (NP14 *p.p.*/CP12b). *Nannotetrina alata* occurs only in section 10 (Figs 4, 15; Tab. 11).

The genus *Thoracosphaera* has been recorded with the highest percentage (10%) in section 1a (Fig. 3, Tab. 2), and allows to place the lowermost part of the Tizzano Marl, above the Cretaceous Mt. Caio Flysch within Zone CNP1. Forms of *Thoracosphaera* continuously occur in the lower Paleocene sections 1b-4 (Figs 3, 9-10; Tabs 2-5) of the Tizzano Marl, and 8 (Figs 4, 13; Tab. 9) of the Farini d'Olmo Flysch. In most of the other sections *Thoracosphaera* is rare and discontinuously in the interval from Zone CNP11 (NP9/CP8a) to Zone CNE8 (NP14 *p.p.*/CP12b) (*i.e.* sections 6- 7, Fig. 3, Tabs 7- 8; sections 10-11, Fig. 4, Tabs 9-10; section 14, Fig. 5, Tab. 15; section 17, Fig. 6, Tab. 18).

The genus *Ellipsolithus*, with the species *E. bollii E. distichus* and *E. macellus*, occurs as rare and scattered in sections 4-6 (Fig. 3, Tabs 5- 7), and more common and continuous in sections 9 (Fig. 4, Tab. 10), 13 and 14a (Figs 5, 20; Tab. 14-15), in intervals corresponding to Zone CNP7 (NP4 *p.p.*-NP5 *p.p.*/CP3 *p.p.*-CP4 *p.p.*) up to Zone CNE4 (NP12/CP10-CP11 *p.p.*).

The genus *Helicosphaera* is represented by rare and sporadic specimens of *H. lophota* (*i.e.* sections 7, 10-12, 14-16, 17; Figs 3-6; Tabs 8, 11-13, 15-17, 18) and of *H. seminulum* (sections 10-12, 14-16; Figs 4-5; Tabs 11-13, 15-17), from Zone CNE5 (NP13/CP11 *p.p.*) to Zone CNE13 (NP16 *p.p.*/CP14a *p.p.*). *Helicosphaera salebrosa* occurs in section 10 (Fig. 4, Tab. 11), from Zone CNE11 (NP15 *p.p.*/CP13 *p.p.*) to Zone CNE12 (NP15 *p.p.*-NP16 *p.p.*/CP13c), *H. bramlettei*, *H. dinesenii* and *H. reticulata* are present in sections 10 (Fig. 4, Tab. 11), in Zone CNE13 (NP16 *p.p.*/CP14a *p.p.*).

The genus *Rhomboaster* with *R. cuspis* was recorded in section 17 (Fig. 6, Tab. 18).

The genus *Rhabdosphaera* is present in sections 10, 12 (Fig. 4, Tabs 11, 13), 15 and 16 (Fig. 5, Tabs 16-17). The marker species *R. inflata* has been observed only in sections 15 and 16 (Fig. 5, 23; Tabs 16-17) and delineates Zone CNE8 (NP14 *p.p.*/CP12b). *Blackites spinosus* is present in section 15 (Fig. 5, Tab. 16) indicating the interval from Zone CNE6 (NP14 *p.p.*/CP12a *p.p.*) to Zone CNE8 (NP14 *p.p.*/CP12).

The Zygodiscaceae are represented by the genera *Chiphragmalithus*, *Lophodolithus*, *Neochiastozygus* and *Neococcolithes*, that discontinuously occur in the studied sections (*i.e.* sections 10, 14, 15, 16; Figs 4-5; Tabs 11, 15, 16-17).

The Holococcoliths include the taxa *Lanthernitus minutus* and *L. simplex*, *Semihololithus biskayae* and *Zyghrablithus bijugatus*. *Lanthernitus minutus* and *L. simplex* are present in section 13 (Fig. 5, Tab. 14), from Zone CNP11 to Zone CNE3 (NP10 *p.p.*-NP11 (CP9a *p.p.*-CP9b *p.p.*) in the Mt. Sporno Flysch. *Semihololithus biskayae* is present in section 9 (Fig. 4, Tab. 10) and characterizes Zone CNP11 (NP9/CP8a) in the Predalbora Mb. of the Farini d'Olmo Flysch. *Zighrablythus bijugatus*, the most common species of holococcoliths (Figs 12, 15, 20, 25), ranges from the uppermost part of Zone CNP11 (NP9/CP8a) in section 9 (Fig. 4, Tab. 10), up to Zone CNE13 (NP16 p.p./CP14a p.p.) in section 10 (Fig. 4, Tab. 11).

A peculiar presence of *Calciosolenia aperta* has been recorded in section 13 (Fig. 5, Tab. 14) with 18% of specimens in the observed assemblage (in sample BO1079), in the Brugnara Mb. of the Mt. Sporno Flysch. This occurrence marks the uppermost part of Zone CNP11 (NP9/CP8a).

Other taxa that are discontinuously present with very low percentages include *Braarudosphaera bigelowii* (*i.e.* sections 1, 2, 4, 8, 14; Figs 3-5; Tabs 2, 3, 5, 9, 15), *Markalius inversus* and *M. apertus* (*i.e.* sections 2, 3,

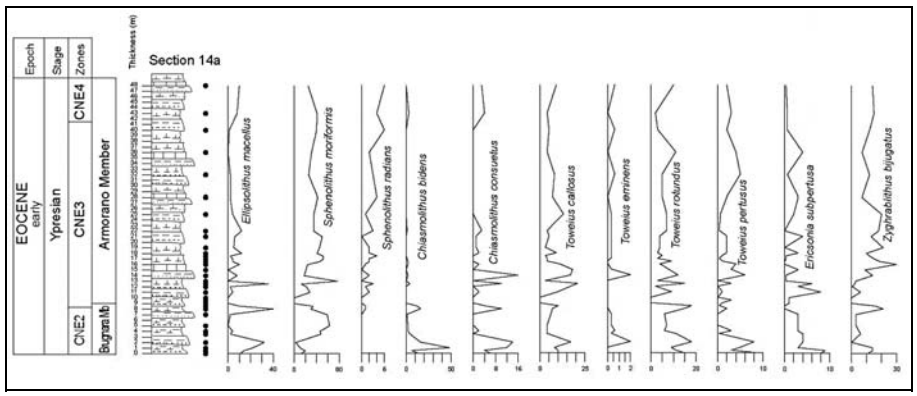

Fig. 20 - Section 14a. Abundance patterns of selected calcareous nannofossils recovered in the Brugnara and Armorano Members (Mt. Sporno Flysch), species plotted against lithostratigraphy and biostratigraphy. Dot = Sample.

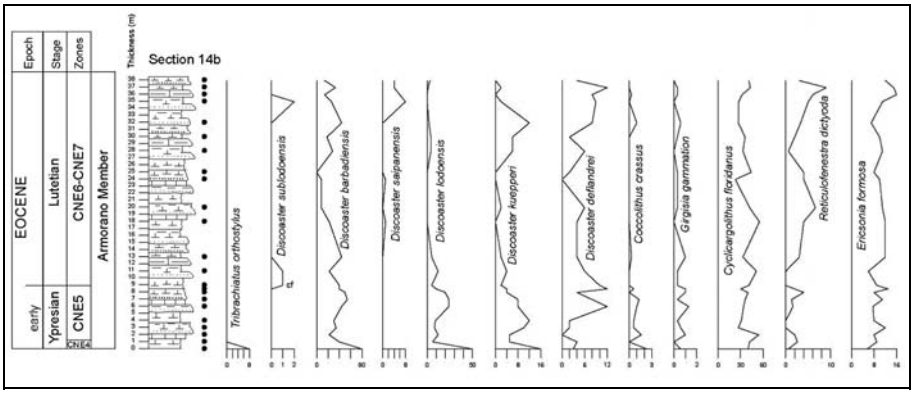

Fig. 21 - Section 14b. Abundance patterns of selected calcareous nannofossils recovered in the Armorano Member (Mt. Sporno Flysch), species plotted against lithostratigraphy and biostratigraphy. Dot = Sample.

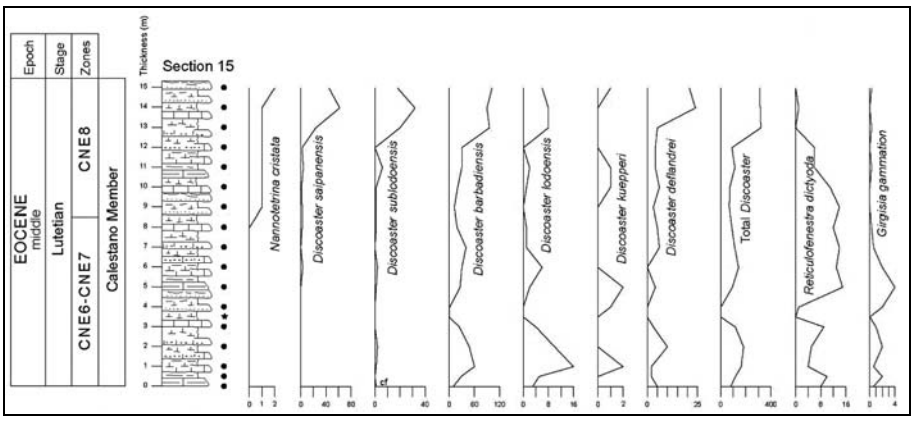

Fig. 22 - Section 15. Abundance patterns of selected calcareous nannofossils recovered in the Calestano Member (Mt. Sporno Flysch), species plotted against lithostratigraphy and biostratigraphy. Dot = Sample, Star = Barren sample.

8, 9; Figs 3-4; Tabs 3, 4, 9, 10), *Pontosphaera* (*i.e.* sections 9, 16; Tabs 10, 17) and very rare *Scapholithus rhombiformis* (section 9; Fig. 4; Tab 10).

Biostratigraphy and dating

As reported in Figure 26, we recognized 15 on 18 biozones of Agnini et al. (2014), 7 on 12 biozones of Martini (1971) and 11 on 17 bio-zones/subzones of Okada & Bukry (1980).

The biozones of Agnini et al. (2014), as reported in the follow, were recognized on events that occur in the successions of Caio, Farini, Sporno and Penice Units, and allow an accurate dating of the early Paleocene-middle Eocene "Tertiary Flysch *Auctt.*".

The early Danian CNP1 Zone was recognized on the common occurrence of *Thoracosphaera* (Tab. 2), in assemblage with abundant reworked Cretaceous specimens. The Danian CNP4 Zone was identified on the presence of *P. martinii* (Fig. 13). The late Danian CNP6 Zone was recognized on the occurrence of *S. moriformis* group (Fig. 10). The Selandian CNP7 Zone was recognized on the occurrence of *F. ulii* (Fig. 9). The Thanetian CNP11 Zone was easily recognized on the occurrence of *D. multiradiatus* and common *Fasciculithus* spp. (Figs 11, 14, 18). The earliest Ypresian CNE1 Zone was identified on the sharply decrease in abundance of *Fasciculithus* sp., as *F. tympaniformis* was not clearly identified (Fig. 14). The early Ypresian CNE2 Zone was recognized on the occurrence of *D. diastypus* and *T. digitalis*

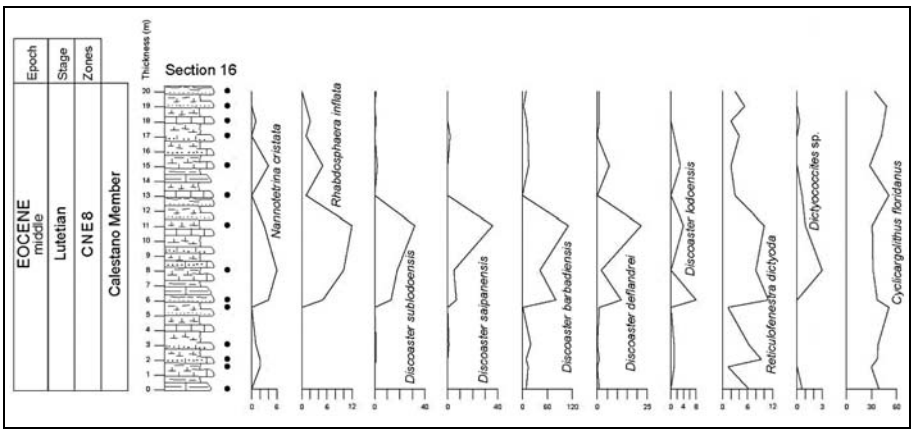

Fig. 23 - Section 16. Abundance patterns of selected calcareous nannofossils recovered in the Calestano Member (Mt. Sporno Flysch), species plotted against lithostratigraphy and biostratigraphy. Dot = Sample.

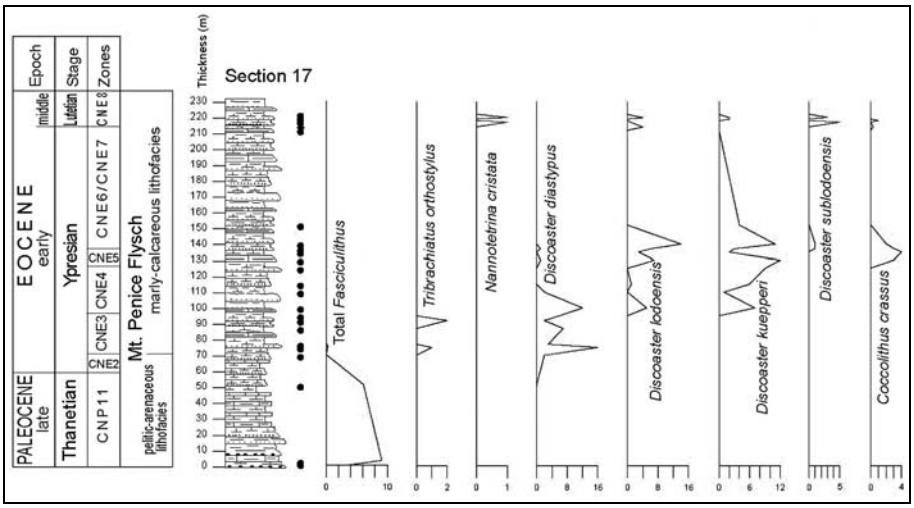

Fig. 24 - Section 17. Abundance patterns of selected calcareous nannofossils recovered in the Mt. Penice Flysch, species plotted against lithostratigraphy and biostratigraphy. Dot = Sample, Star = Barren sample.

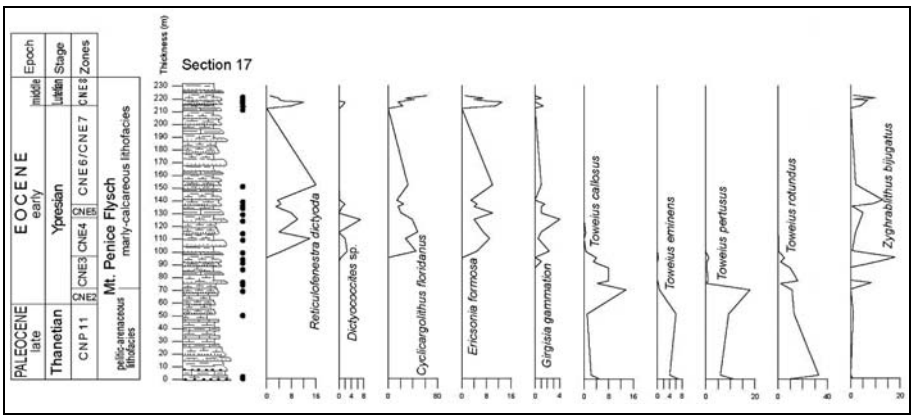

Fig. 25 - Section 17. Abundance patterns of selected calcareous nannofossils recovered in the Mt. Penice Flysch, species plotted against lithostratigraphy and biostratigraphy. Dot = Sample, Star = Barren sample.

(Figs 18, 19; Tabs 14, 15a) or on the disappearance of *Fasciculithus* (Fig. 11). The Ypresian CNE3 Zone was recognized on the occurrence of *T. orthostylus* (Figs 14, 18, 19, 24). The middle Ypresian CNE4 Zone, was recognized on the occurrence of *D. lodoensis* (Figs 12, 15, 20, 24). The resolution of Zone CNE4 was increased by the appearance of *R. dictyoda*, *Dictyococcites* and *C. floridanus* (Figs 21, 25). The late Ypresian CNE5 Zone was identified on the disappearance of *T. orthostylus* only in section 14b (Fig. 21). In other sections, the ambiguous behaviour of this species, that rarely occurs (Tab. 18) or unexpectedly reappears above its "normal" stratigraphic range (Figs15; Tabs 12, 13, 16, 17), led us to use the occurrence of *C. crassus* to recognize Zone CNE5 (Figs 15, 16, 17, 24). The earliest Lutetian CNE6 Zone was recognized on the occurrence of *D. sublodoensis* (Fig. 17) and gathered with Zone CNE7, because *D. lodoenis*, the marker of Zone CNE7, persists above its normal range (Figs 15, 16, 21, 22, 24). The early Lutetian CNE8 Zone was recognized on the oc-

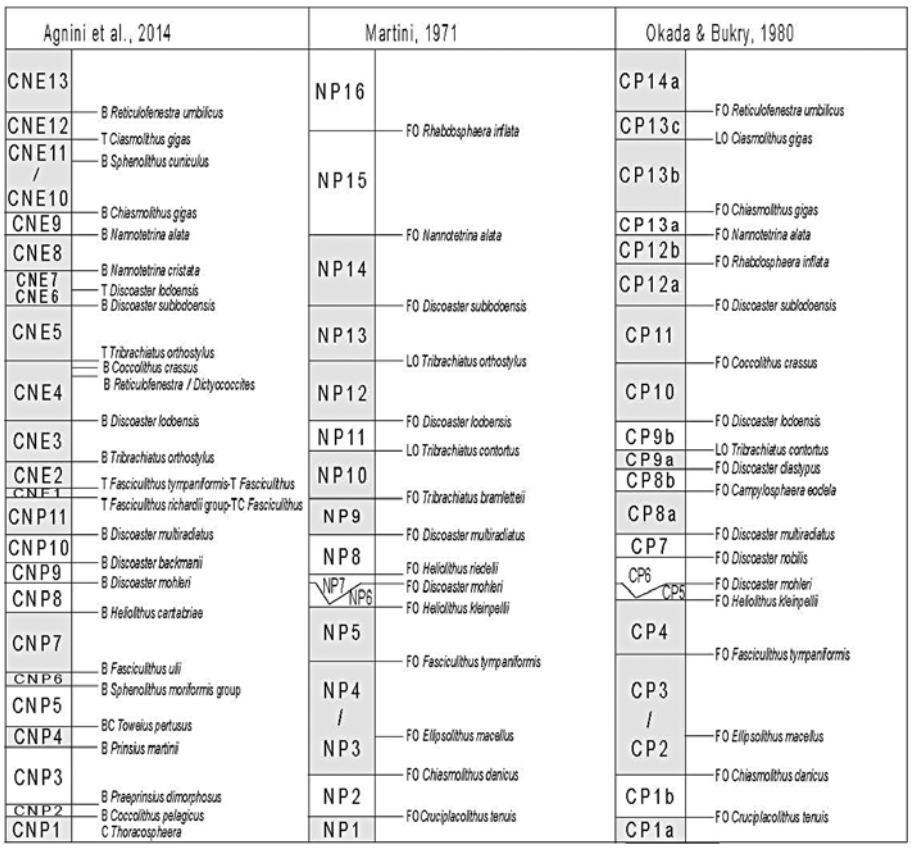

Fig. 26 - Comparison between the recognized zones of Agnini et al. (2014) and the zones of Martini (1971) and of Okada & Bukry (1980). In grey, the zones recognized in this paper.

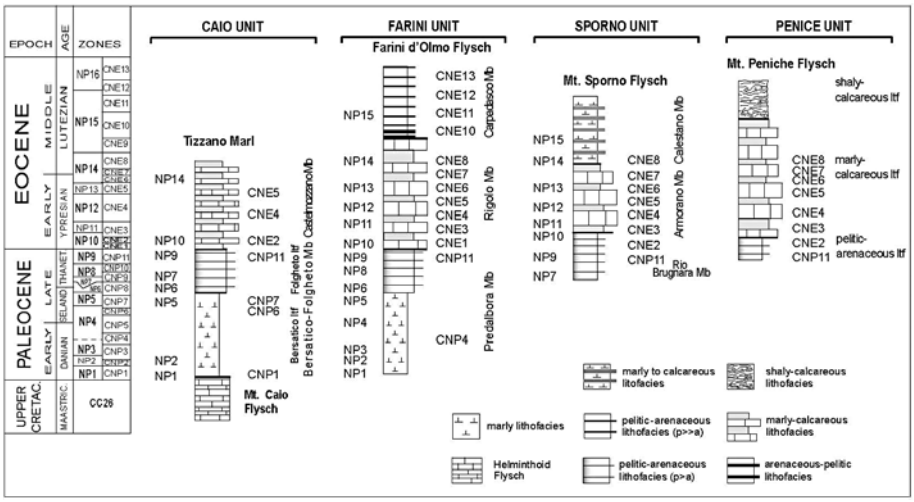

Fig. 27 - Ages and calcareous nannofossil zones of the Caio, Farini, Sporno and Penice Units. NP zones for the Caio Unit are from Cerrina Feroni et al., (1991, 1994a); NP zones for the Farini d'Olmo Unit are from Rio & Archilli (1980), Cerrina Feroni et al. (1994b), Ottria (1997) and Martini & Zanzucchi (2000); NP zones for the Sporno Unit are from Rio (1987) and Cerrina Feroni et al. (1991). CNP and CNE zones were recognized in this paper. Mb = Member, ltf = lithofacies.

currence of *N. cristata* (Figs 16, 22, 23, 24), and the appearance of *R. inflata* improves (Fig. 23) the resolution of the zone. The middle Lutetian CNE10 and CNE11 Zones were assembled as *S. cuniculus* was not recorded, on the contrary we easily recognized *S. furcatolithoides* that could replace *S. cuniculus*. This interval was determined on the total range of *C. gigas* (Fig. 15). The lattermost Lutetian CNE12 and CNE13 Zones were recognized using the first rare and scattered occurrence of *R. umbilicus* (Fig. 15).

On the contrary the biozones of Martini (1971) and Okada & Bukry (1980) are not always applicable for the dating of the "Tertiary Flysch *Auctt*.". For example, *E. macellus*, marker for Zone NP3/NP4 and Zone CP2/CP3 boundary, is rare and scattered (*i.e.* Tabs 2b, 5, 6). *Fasciculithus tympaniformis*, marker for Zone NP4/NP5 and Zone CP3/CP4 boundary, is discontinuous in its initial range and less reliable than *F. ulii* (*i.e.* Tabs 4,5). *Tribrachiatus bramlettei*, marker for Zone NP9/NP10 boundary, has a sporadic distribution (Tabs 14-15a), and *C. eodela*, marker for Zone CP8a/CP8b boundary, was not recorded. *Tribrachiatus contortus*, marker for Zone NP10/NP11 and Zone CP9a/CP9b boundary, is discontinuous and rare in its final range (Fig. 20). *Rabdosphaera inflata*, marker for Zone CP11/CP12a boundary, is rare (Tab. 16) or not recorded

in the early Lutetian sections, excluding section 16 (Fig. 23), and *N. alata*, marker for Zone NP14/NP15 and Zone CP12b/CP13a boundary, co-occurs with *N. cristata* (Fig. 15), or was not recorded.

Taking into account the reconstructed lithostratigraphic frame, the dating of the successions investigated in this study (Figs 3-6), and the dating reported in literature (Tab. 1), the ages of the "Tertiary Flysch *Auctt.*" are described below and summarized in Figure 27.

In the uppermost part of the Mt. Caio Flysch we recorded Zone CNP1, that corresponds to the *Biantolithus sparsus* Zone of Romein (1979), to which Rio et al. (1983) ascribed the Mt. Caio Flysch. In the Bersatico-Folgheto Mb. of the Mt. Caio Unit we recognized Zones CNP6, CNP7, CNP11 and CNE2, that confirm and improve ages previously assigned to Zones NP2, NP5 to NP7 and NP9 by Cerrina Feroni *et al.* (1991). In the Castelmozzano Mb. we recorded Zones CNE4 and CNE5, that improve the ages ascribed to Zones NP10 and NP14 by Cerrina Feroni *et al.* (1991).

We dated the lower part of the Predalbora Mb. of the Farini Unit to Zone CNP4, and the upper part to Zone CNP11. In this member Rio & Archilli, (1980), Ottria (1997), Martini & Zanzucchi (2002) recognized Zones NP1 to NP10. In the Rigolo Mb. we documented Zones CNE1 to CNE8, that agree with ages ascribed to Zones NP10 to NP14 by Rio & Archilli (1980) and Martini & Zanzucchi (2002). In the Carpadasco Mb. we recognized Zones CNE10 to CNE13, that improve the age assigned to Zone NP15 by in Rio & Archilli (1980) and Martini & Zanzucchi (2000).

In the uppermost part of the Rio Brugnara Mb. of the Mt. Sporno Unit, we recognized Zones CNP11, CNE2 and CNE3 that improve the ages previously assigned to Zones NP7 and NP9 by Cerrina Feroni *et al.* (1991). In the overlying Armorano Mb. we recognized Zones CNE3, CNE4 and CNE6-CNE7, that confirm the ages referable to Zones NP10 to NP14, documented in Rio (1987) and Cerrina Feroni *et al.* (1991). In the Calestano Mb. we recorded Zone CNE8 on the occurrence of *N. cristata* that was also used by Rio (1987) and Cerrina Feroni *et al.* (1991) to identify Zone NP15. We also documented for the first time a succession of zones, from CNP11 to CNE 8, for the Mt. Penice Flysch. In particular, Zones CNP11 to CNE2 were recorded in the pelitic-arenaceous lithofacies, and Zones CNE3 to CNE8 were recorded in the marly-calcareous lithofacies.

Conclusions

This study is part of a multidisciplinary work aimed at constraining the tectono-sedimentary evolution of the External Ligurides of the Northern Apennines, and reconstructing the geodynamic evolution of the External Ligurian domain, a key sector of the Western Tethys, located between the Ligurian-Piedmont ocean and the continental margin of the Adria Plate. Our effort focused on refining the biostratigraphy and the chronostratigraphy of the Northern Apennines "Tertiary Flysch *Auctt.*" (External Ligurides). Although the sampled sedimentary record was fragmented, the recovered rich calcareous nannofossils assemblages allowed us to recognize most of the Paleocene-middle Eocene events proposed by Agnini et al. (2014).

From the early Paleocene to the middle Eocene we used the following primary events: Base *Prinsius martinii*, Base *Sphenolithus moriformis* group, Base *Fasciculithus ulii*, Base *Discoaster multiradiatus*, Base *Tribrachiatus orthostylus*, Base *Discoaster lodoensis*, Top *Tribrachiatus orthostylus*, Base *Discoaster sublodoensis*, Base *Nannotetrina cristata*, Base and Top *Chiasmolithus gigas,* and Base *Reticulofenestra umbilicus*. Taking into account the features of the studied assemblages, we substituted the Top *Fasciculithus richardii* group with the Top common *Fasciculithus* and the Top *Fasciculithus tympaniformis* with the Top *Fasciculithus*.

We also used some additional events: common occurrence of *Thoracosphaera* to identify Zone CNP1, Base *Discoaster diastypus* to identify Zone CNE2, and Base *Coccolithus crassus* to identify Zone CNE5. In addition, the appearance of the genera *Dictyococcites*, *Reticulofenestra* and *Ciclycargolithus*, the appearance of *Rabdosphaera inflata* and the occurrence of *Sphenolithus furcatolithoides* seems useful to increase the biostratigraphic resolution of the late Ypresian-early Lutetian time span. On the contrary, we had to group Zones CNE6 and CNE7, as Top of *Discoaster lodoensis* revealed biostratigraphic problem, and we also grouped Zones CNE10 and CNE11, as *Sphenolithus cuniculus* was not recognized in the assemblages.

The features of the assemblages investigated in this study and the recognized markers refined the biostratigraphic and chronostratigraphic frame of the Paleocene-middle Eocene formations of the Caio, Farini, Sporno and Penice Units, that belong to the "Tertiary Flysch *Auctt.*". In the Caio Unit Zones CNP6 and CNP7 partially covered the gap between Zones NP2 and NP5, and Zones CNE2 to CNE5 close the gap between Zones NP9 and NP14. Zone CNE13 recorded at the top of the Carpadasco Mb. provided age younger than that previously recorded for the Farini Unit, and Zones CNP11 to CNE8 recognized in the Penice Unit, allowed a correlation of this unit with the "Tertiary Flysch *Auctt.*".

Appendix

Taxonomic list

- *Blackites* Hay and Towe 1962
  B. spinosus (Deflandre and Fert 1954) Hay and Towe 1962
- *Braarudosphaera* Deflandre 1947
  B. bigelowii (Gran and Braarud 1935) Deflandre 1947
- *Calcidiscus* Kamptner 1950
  C. protoannulus (Gartner 1971) Loeblich & Tappan 1978
- *Calciosolenia* Gran 1912
  C. aperta (Hay and Mohler 1967) Bown 2005
- *Campylosphaera* Kamptner 1963
  C. dela (Bramlette and Sullivan 1961) Hay and Mohler 1967
- *Chiasmolithus* Hay Mohler and Wade 1966
  C. bidens (Bramlette and Sullivan 1961) Hay and Mohler 1967
  C. californicus (Sullivan 1964) Hay and Mohler 1967
  C. consuetus (Bramlette and Sullivan 1961) Hay and Mohler 1967
  C. danicus (Brotzen 1959) Hay and Mohler 1967
  C. gigas (Bramlette and Sullivan 1961) Radomski 1968
  C. grandis (Bramlette and Riedel 1954) Radomski 1968
  C. eograndis Perch-Nielsen 1971
  C. expansus (Bramlette and Sullivan 1961) Gartner 1970
  C. medius Perch-Nielsen 1971
  C. solitus (Bramlette and Sullivan 1961) Locker 1968
  C. titus Gartner 1970
- *Chiphragmalithus* Bramlette and Sullivan 1961
- *Coccolithus* Schwarz 1894
  C. crassus Bramlette and Sullivan 1961
  C. eopelagicus (Bramlette and Riedel 1954) Bramlette and Sullivan 1961
  C. pelagicus Schiller 1930
- *Cruciplacolithus* Hay and Mohler in Hay et al. 1967
  C. asymmetricus van Heck & Prins 1987
  C. cribellum (Bramlette and Sullivan 1961) Romein 1979
  C. frequens (Perch-Nielsen 1977) Romein 1979
  C. primus Perch-Nielsen 1977
  C. tenuis (Stradner 1961) Hay and Mohler in Hay et al. 1967
- *Cyclicargolithus* Bukry 1971
  C. floridanus (Roth and Hay in Hay et al. 1967) Bukry 1971
- *Dictyococcites* Black 1967
- *Discoaster* Tan Sin Hok 1927
  D. araneus Bukry 1971
  D. barbadiensis Tan Sin Hok 1927
  D. binodosus Martini 1958
  D. cruciformis Martini 1958
  D. deflandrei Bramlette and Riedel 1954
  D. delicatus Bramlette and Sullivan 1961
  D. diastypus Bramlette and Sullivan 1961
  D. distinctus Martini 1958
  D. gemmifer Stradner 1961
  D. kuepperi Stradner 1959
  D. lenticularis Bramlette and Sullivan *1961*
  D. lodoensis Bramlette and Riedel 1954
  D. martinii Stradner 1959
  D. mediosus Bramlette and Sullivan 1961
  D. megastypus Bramlette and Sullivan 1961
  D. mirus Deflandre in Deflandre and Fert 1954
  D. mohleri Bukry and Percival 1971
  D. multiradiatus Bramlette and Riedel 1954
  D. nobilis Martini 1961
  D. nodifer (Bramlette and Riedel 1954) Bukry 1973
  D. nonaradiatus Klumpp 1953
  D. saipanensis Bramlette and Riedel 1954
  D. salisburgensis Stradner 1961
  D. septemradiatus (Klumo 1953) Martini 1958
  D. strictus Stradner 1961
  D. sublodoensis Bramlette and Sullivan 1961
- *Ellipsolithus* Sullivan 1964
  E. bollii Perch Nielsen 1977
  E. distichus (Bramlette and Sullivan 1961) Sullivan 1964
  E. macellus (Bramlette and Sullivan 1961) Sullivan 1964
- *Ericsonia* Black 1964
  E. formosa (Kamptner 1963) Haq 1971
  E. robusta (Bramlette and Sullivan 1961) Edwards and Perch-Nielsen 1975
  E. subdisticha (Roth and Hay in et al. 1967) Roth in Baumann and Roth 1969
  E. subpertusa Hay and Mohler 1967
- *Fasciculithus* Bramlette and Sullivan 1961
  F. alanii Perch-Nielsen 1971
  F. aubertae Haq and Aubry 1981
  F. bitectus Romein 1979
  F. bobii Perch-Nielsen 1971
  F. clinatus Bukry 1971
  F. involutus Bramlette and Sullivan 1961
  F. janii Perch-Nielsen 1971
  F. lilianiae Perch-Nielsen 1971
  F. magnicordis Romein 1979
  F. magnus Bukry and Percival 1971
  F. pileatus Bukry 1973
  F. richardii Perch-Nielsen 1971
  F. shaubii Hay and Mohler 1967
  F. sidereus Bybell and Self-Trail 1995
  F. thomasii Perch-Nielsen 1971
  F. tonii Perch-Nielsen 1971
  F. tympaniformis Hay and Mohler in Hay Mohler et al. 1967
  F. ulii Perch-Nielsen 1971
- *Girgisia* Varol 1989
  G. gammation Bramlette and Sullivan 1961
- *Helicosphaera* Kamptner 1954
  H. bramlettei Muller 1970
  H. dinesenii Perch-Nielsen 1971
  H. lophota Bramlette and Sullivan 1961
  H. reticulata Bramlette and Wilcoxon 1967
  H. salebrosa Perch-Nielsen 1971
  H. seminulum Bramlette and Sullivan 1961
- *Lanternithus* Stradner 1962
  L. minutus Stradner 1962
  L. simplex Bown 2005
- *Lopodolithus* Deflandre in Deflandre and Fert 1954
  L. nascens Bramlette and Sullivan 1961
- *Markalius* Bramlette and Martini 1964
  M. apertus Perch-Nielsen 1979
  M. inversus (Deflandre in Deflandre and Fert 1954) Bramlette and Martini 1964
- *Nannotetrina* Achuthan and Stradner 1969
  N. cristata (Martini 1958) Perch-Nielsen 1971
  N. alata (Martini 1960) Haq & Lohman 1976
- *Neochiastozygus* Perch-Nielse 1971
  *N. junctus (*Bramlette and Sullivan 1961) Perch-Nielsen 1971
  N. modestus Perch-Nielsen 1971
  N. perfectus Perch-Nielsen 1971
- *Neococcolithes* Sujkowski 1931
- *Pontosphaera* Lohmann 1902
- *Pseudotriquetrorhabdulus* Wise in Wise and Constans 1976
  P. inversus (Bukry and Bramlette 1969) Wise in Wise and Constans 1976
- *Praeprinsius* Varol and Jakubowski 1989
  P. dimorphosus (Perch-Nielsen 1981) Varol and Jakubowski 1989

- *Prinsius* Hay and Mohler 1967
  P. bisulcus (Stradner 1963) Hay and Mohler 1967
  P. martinii (Perch-Nielsen 1969) Haq 1971
- *Reticulofenestra* Hay Mohler and Wade 1966
  R. dictyoda (Deflandre in Deflandre and Fert 1954) Stradner in Stradner and Edwards 1968
  R. umbilicus (Levin 1965) Martini and Ritzkowski 1968
- *Rhabdosphaera* Haeckel 1894
  R. inflata Bramlette and Sullivan 1961
- *Rhomboaster* Bramlette and Sullivan 1961
  R. cuspis Bramlette and Sullivan 1961
- *Scapholithus rhombiformis* Hay and Mohler 1967
- *Semihololithus* Perch-Nielsen 1971
  S. biskayae Perch-Nielsen 1971
- *Sphenolithus* Deflandre in Grassé 1952
  S. conspicuus Martini 1976
  S. editus Perch-Nielsen in Perch-Nielsen et al. 1978
  S. furcatolithoides Locker 1967
  S. moriformis (Brönnimann and Stradner 1960) Bramlette and Wilcoxon 1967
  S. radians Deflandre in Grassé 1952
  S. spiniger Bukry 1971
  S. villae Bown 2005
- *Thoracosphaera* Kamptner 1927
- *Toweius* Hay and Mohler 1967
  T. callosus Perch-Nielsen 1971
  T. eminens (Bramlette and Sullivan 1961) Perch-Nielsen 1971
  T. magnicrassus (Bukry 1971) Romein 1979
  T. occultatus (Locker 1967) Perch-Nielsen 1971
  T. pertusus (Sullivan 1965) Romein 1979
  T. rotundus Perch-Nielsen in Perch-Nielsen et al. 1978
  T. selandianus Perch-Nielsen 1979
  T. serotinus Bybell and Self-Trail 1995
  T. tovae Perch-Nielsen 1971
- *Tribrachiatus* Shamrai 1963
  T. bramlettei (Brönnimann and Stradner 1960) Proto Decima et al. 1975
  T. contortus (Stradner 1958) Bukry 1972
  T. digitalis Aubry 1996
  T. orthostylus Shamrai 1963
- *Zygrhablithus* Deflandre 1959
  Z. bijugatus (Deflandre in Deflandre and Fert 1954) Deflandre 1959

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