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A GONDWANAN PALEONTOLOGICAL JOURNAL



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Submitted: May 24th, 2017 – **Accepted:** October 17th, 2017 – **Published online:** October 26th, 2017

To link and cite this article:

doi: 10.5710/AMGH.17.10.2017.3118

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**CALCAREOUS NANNOFOSSILS FROM LA BARCA FORMATION
(PALEOCENE/EOCENE BOUNDARY), TIERRA DEL FUEGO, ARGENTINA**

NANNOFÓSILES CALCÁREOS DE LA FORMACIÓN LA BARCA (LÍMITE
PALEOCENO/EOCENO), TIERRA DEL FUEGO, ARGENTINA

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14 (catorce) páginas y 3 (tres) figuras

Propuesta para el cabezal: BEDOYA ET AL.: CALCAREOUS NANNOFOSSILS FROM
LA BARCA FORMATION

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Keywords: Austral Basin. Calcareous Nannofossils. Biostratigraphy. Paleocene/Eocene
Boundary. Fuegian Andes.

Deep marine Paleocene to Oligocene turbidites are exposed in several localities along the Atlantic coast of Península Mitre, Tierra del Fuego (Olivero and Malumián, 2008; Torres Carbonell *et al.*, 2009). At Cabo Leticia (Fig. 1), the Paleocene sandstone-conglomerate package of the Cabo Leticia Formation is transitionally covered by the La Barca Formation, which consists of two members; a lower upper Paleocene sandstone-mudstone dominated LB1 Member and an upper organic-rich mudstone-dominated LB2 Member. At Punta Noguera (Fig.1), the La Barca Formation is interpreted to underlie lowermost Eocene turbidites of the Punta Noguera Formation (Olivero *et al.*, 2002; Malumián, *et al.*, 2009). The late Paleocene age of the lower LB1 Member of the La Barca Formation was initially established on the basis of foraminifera and dinocysts (Olivero *et al.*, 2002; Malumián and Caramés, 2002). New studies at Punta Ainol (Fig. 1) have also found a diagnostic late Paleocene assemblage of calcareous benthic foraminifera contained in organic-rich mudstones interpreted as part of the LB2 Member, which suggests a late Paleocene age for the whole formation (Sample PT Sur, Torres Carbonell *et al.*, 2009).

Agglutinated foraminifera are dominant in the La Barca Formation, and only two isolated horizons preserve calcareous benthic foraminifera (Malumián and Jannou, 2010), whereas planktonic foraminifera and calcareous nannofossils have not been previously found in the formation (Malumián and Jannou, 2010). As part of ongoing research devoted to the study of calcareous nannofossils from Tierra del Fuego, we have analyzed samples from the La Barca Formation, both at its type locality in Cabo Leticia and from the mudstones exposed at Punta Ainol. None of the samples processed from the type locality of the La Barca Formation were fertile. Nevertheless, the organic-rich mudstones samples from Punta Ainol are fossiliferous and contain calcareous nannofossils that correlate with other Paleocene-Eocene assemblages from the Southern Hemisphere. Thus, the main goal

of our study is to document the nannofossil assemblages and to interpret their stratigraphic and paleoenvironmental implications.

GEOLOGICAL SETTING

The Austral foreland basin evolved from the Late Cretaceous to the early Neogene in front of the rising Patagonian and Fuegian Andes (Fildani and Hessler, 2005; Olivero and Malumián, 2008). In Península Mitre (Fig. 1), Paleogene sedimentary rocks of the Río Claro and La Despedida groups are present in thrust sheets of the Fuegian fold and thrust belt (Olivero *et al.*, 2002; Torres Carbonell *et al.*, 2009; Torres Carbonell and Dimieri, 2013).

At its type locality (Cabo Leticia), the La Barca Formation consists of a 220 m-thick succession of sandstone and mudstone, divided into a lower member (LB1) and an upper member (LB2). LB1 consists of fine to medium grained, light grey tuffaceous sandstone, interlayered with light gray to black carbonaceous mudstone. LB2 includes thin horizons of fine-grained sandstone in an overall background of thicker beds of light grey to black, organic-rich mudstone with abundant large, subspherical concretions (Olivero *et al.*, 2002).

The exposures of the LB2 member at Punta Ainol (Figs. 1, 2), consist of a minimum of 120 m of predominantly dark mudstone with siliceous sponge spicules and variable proportions of microfossils (agglutinated foraminifera Torres Carbonell *et al.*, 2009, and calcareous nannofossils this study).

[Figure 1]

MATERIALS AND METHODS

Eighteen samples were studied and prepared following the standard smear slide technique (Perch-Nielsen, 1985). We performed qualitative analysis by considering all calcareous nannofossils found in four traverses along the length of the coverslip which

totalized no more than 200 specimens. The analyses were conducted using a polarized light microscope (Leitz DMRXP) with a magnification of 1000×. Two additional traverses were observed in some preparations to search for rare species.

The nanofossils were identified using the taxonomic concepts of Perch-Nielsen (1985), Aubry (1999), and Raffi *et al.* (2005). We followed the standard zonation of Martini (1971); and also compared our results with the zonal scheme proposed by Agnini *et al.* (2014) since some Martini's markers are absent. A similar procedure was followed in the SW Pacific by (Dallanave *et al.*, 2015) and partially by Shepherd and Kulhanek (2016) since they found that some of the key taxa in Agnini's scheme were also missing in their section (See discussion in Shepherd and Kulhanek, 2016). In addition, we used the NP9a/b subzonal boundary introduced by Aubry (1999) and Aubry *et al.* (2000).

Zonal boundaries were placed at the midpoint between samples in which the first occurrence (FO) or last occurrence (LO) of a marker species was recorded. Relative abundances of the species were estimated as follows: abundant, $A \geq 10$ specimens per each field of view; common, $C = 10$ to 1 specimen per each field of view; frequent, $F = 1$ specimen on one to ten fields of view; rare, $R = 1$ specimen on more than ten fields of view, and barren, $B = 0$ specimens on any fields of view. We estimated the preservation state by examining the qualitative degree of dissolution and/or recrystallization, following Pospichal and Wise (1990): good (G), for specimens with little or no dissolution and/or overgrowth; moderate (M), for specimens with little or some dissolution and/or overgrowth, but that are still identifiable; and poor (P), for specimens with considerable dissolution and/or recrystallization. Micropaleontological samples CADIC MIC 1-16 are stored at the Paleontology Collection Repository of CADIC.

RESULTS

Calcareous nannofossil assemblage

The nannofossil assemblage is dominated by small species of *Toweius occultatus* and *Toweius eminens*, with frequent *Chiasmolithus bidens*, and *Coccolithus pelagicus* (Fig. 2). Other taxa, including *Fasciculithus tympaniformis*, *F. involutus*, *Hornibrookina australis*, *Lanternithus* sp., *Sphenolithus* spp., *Toweius pertusus*, *T. rotundus* and *T. tovae* are frequent to rare throughout the section. Rare taxa include *Chiasmolithus solitus*, *Neochiastozygus concinnus*, *N. junctus*, *Prinsius bisulcus* and *Zygrhablithus bijugatus*, *Chiasmolithus nitidus*, *Discoaster araneus*, *Ericsonia subpertusa*, *Fasciculithus* sp. cf. *F. alanii*, *F. mitreus*, *Fasciculithus* sp. cf. *F. richardii*, *F. thomasii* and *Pontosphaera exilis* (Fig. 3). *Heliolithus kleinpellii* and *H. cantabriae*), *Watznaueria* sp. and *Biscutum* sp. are present as reworked nannofossils. The richness of sample CADIC-MIC-09 is remarkable in comparison with other samples of the section. The distribution of taxa is shown in Fig. 2.

Although the overall abundance is rare to common throughout the studied section species richness (34 species identified) is moderate. Nannofossil preservation varies from poor to moderate, with some evidence of dissolution in *Chiasmolithus* shields and nannoliths. Samples LB12 and LB17 resulted barren in nannofossils (Fig. 2). Many of these taxa found in the La Barca Formation are widely known for their resistance to dissolution (e.g. *Toweius* and *Chiasmolithus*) (Crux, 1991; Raffi *et al.*, 2009) so that the variations in abundance and/or scarcity of other taxa probably respond to dissolution. A complete taxonomic list of recorded nannofossil species is included in the online version of this article.

Biostratigraphy

Nannofossil analysis indicates that the sampled section spans the late Paleocene to earliest Eocene and is assigned to Zone NP9, (Martini, 1971) or Zones CNP11 – CNE1 (Agnini *et al.*, 2014).

[Figure 2]

The top of the Zone NP9 of Martini (1971) is marked by the first occurrence (FO) of *Tribrachiatus bramlettei*. However, the latter species was not found in the examined samples, which is consistent with previous studies that documented the absence of *T. bramlettei* in some sediments of the Subantarctic South Atlantic Ocean (e.g. Crux, 1991) and Southern Pacific Ocean (Hollis *et al.*, 2005), preventing the identification of the upper boundary of Zone NP9. Following these authors we used the LO of *Fasciculithus tympaniformis* to indicate the top of NP9, thereby extending the zone into the Eocene. Moreover, the LO of *Fasciculithus* has been reported as late NP9b–NP10 (Hollis *et al.*, 2005; Raffi *et al.*, 2005), and Agnini *et al.* (2014) use it to mark the top of Zone CNE1. Another bioevent considered in the southern ocean to mark the top of the NP9 was the FO of *Discoaster diastypus* (Wise and Wind, 1977; Wei and Wise, 1989), but this species was not found in our samples.

Aubry *et al.* (2000) defined the NP9a/b subzonal boundary using the simultaneous FO of several taxa (i.e., *Rhomboaster*, and *Discoaster* species); later, Aubry and Salem (2013) suggested the LO of *F. alanii* as an additional event to define NP9b. Here, we locate the NP9a/NP9b boundary at sample CADIC MIC-09, which records the LO of *F. alanii*, the FO of *Discoaster* sp. cf. *D. araneus*, the FO of *Rhomboaster* sp. cf. *R. cuspis* and the LO of *Fasciculithus richardii* group (*F. richardii*, *F. mitreus*; s. Agnini *et al.*, 2014).

The LO of *F. alanii* is considered a reliable event to define the top of the Paleocene (Agnini *et al.*, 2007; Youssef Ali, 2015), and thus it can be used as an alternative bioevent

to place this boundary. This event has also been recorded in other South Atlantic sections (Walvis Ridge, Raffi *et al.*, 2009), in different areas of Egypt (Aubry, 1998; Youssef Ali, 2015) and Spain (Monechi *et al.*, 2000). The LO of *F. richardii*, observed at CADIC MIC-09, also occurs at the boundary between the Subzones NP9a/b, and this event has also been used in other areas to define the Paleocene/Eocene boundary (Monechi *et al.*, 2000; Raffi *et al.*, 2009; Agnini *et al.*, 2014).

Some species of *Fasciculithus* survive into the early Eocene, including among others: *F. involutus*, *F. thomasii*, and *F. tympaniformis*, with the last occurrence of this group defining the Zone CNE1/CNE2 boundary (Agnini *et al.*, 2014). Therefore, the presence of *Rhomboaster* in sample CADIC MIC-09 and *Fasciculithus* from samples CADIC MIC-09 to CADIC MIC-16 constrains them to Subzone NP9b (*s.* Aubry *et al.*, 2000) or Zone CNE1 (Agnini *et al.*, 2014). The disappearance of other taxa restricted to Subzone NP9a, such as *P. bisulcus* (Agnini *et al.*, 2007; Self-Trail, 2011; Self-Trail *et al.*, 2012; Youssef Ali, 2015), is not observed here and they seem to extend into the early Eocene as was already recorded for the genus *Prinsius* in the SW Pacific (Hollis *et al.*, 2005).

[Figure 3]

DISCUSSION

Previous studies tentatively established the age of the La Barca Formation as late Paleocene (Olivero *et al.*, 2002; Malumián and Caramés, 2002). The lack of a more precise age assignment resulted from the absence of diagnostic Paleocene macrofaunal elements (Olivero *et al.*, 2002), its complex stratigraphic relationships (Torres Carbonell *et al.*, 2009) and the absence of absolute dating.

Originally this unit was assigned to the late Paleocene based on poorly preserved dinocysts and calcareous foraminifera concentrated in the LB1 member (Olivero *et al.*, 2002; Malumián and Caramés, 2002). The dinocysts of the LB1 member include specimens of *Palaeocystodinium golzowense*, *Glaphyrocysta* sp., and some unidentified taxa, whereas the LB2 member contains an almost monospecific assemblage dominated by *P. golzowense*. The calcareous foraminifera includes *Bullimina karpatika* Szczechura (Malumián and Caramés, 2002). The presence of the calcareous foraminifera *Stensioina beccariformis* White in one sample from the LB2 member at Punta Ainol partially supported the late Paleocene age previously indicated for the whole unit (Torres Carbonell *et al.*, 2009; Malumián and Caramés, 2002). Unfortunately, the sample with *S. beccariformis* (Sample PT Sur of Torres Carbonell *et al.*, 2009) was recovered during preliminary reconnaissance work and cannot be located precisely in our section (Fig. 2). Nonetheless, the late Paleocene age indicated by *S. beccariformis* (Torres Carbonell *et al.*, 2009; Malumian and Jannou, 2010) is not incompatible with our results.

Our new records of calcareous nannofossils in the LB2 member allow correlation with the standard nannofossil biozones and confirm a late Paleocene age, but also extend the age of LB2 member into the earliest Eocene. However, some of the typical late Paleocene and early Eocene nannofossil biomarkers have not been found in the LB2 member as *T. bramlettei*, *Discoaster diastypus* or *Discoaster multiradiatus*. This absence might be caused by the moderately high latitudinal position of the Austral Basin since the standard nannofossil zonations were established using low to mid-latitude located sections (surface and subsurface) and marker taxa are often warmer water species (Aubry, 1998).

Nevertheless, studies of high-latitude calcareous nannofossil assemblages (*e.g.* Wise and Wind, 1977; Wise, 1983; Pospichal and Wise, 1990) including those from the Austral

basin (*e.g.* Pérez Panera, 2013), have helped to improve the biostratigraphic record of the southern high latitudes. Also, the Paleocene/Eocene nannofossils of La Barca Formation have been affected by dissolution and show a similar pattern exhibited by other taxa as *Toweius* spp. and *Chiasmolithus* spp. at southern high latitudes (Perch Nielsen, 1985; Wise and Wind, 1977; Crux, 1991).

CONCLUSIONS

The LO of *Fasciculithus alanii* and *F. richardii* together with the FO of *Rhomboaster* sp. cf. *R. cuspis*, and *Discoaster* sp. cf. *D. araneus*, allow us to assign the age of the LB2 member of La Barca Formation to the late Paleocene to early Eocene NP9 Zone (Thanetian -earliest Ypresian), and we use the LOs of *F. alanii* to define the subzone NP9a/NP9b boundary, as in other South Atlantic sections.

The identification of the P/E boundary in outcrops of the LB2 member of the La Barca Formation in Tierra del Fuego encourages us to perform newly detailed sampling in order to confirm and constrain this stratigraphic boundary.

ACKNOWLEDGMENTS

The results are part of the doctoral research program in progress of ELBA (FCEyN-UBA and CADIC-CONICET), supported by projects PID UE CONICET and PIDUNTdF A-1. This is a contribution R-225 to the Instituto de Estudios Andinos “Don Pablo Groeber”, IDEAN-CONICET. The authors thank the positive review by D. Kulhanek, an anonymous reviewer, and the Editor of *Ameghiniana* J.P. Pérez Panera that help to improve the original MS.

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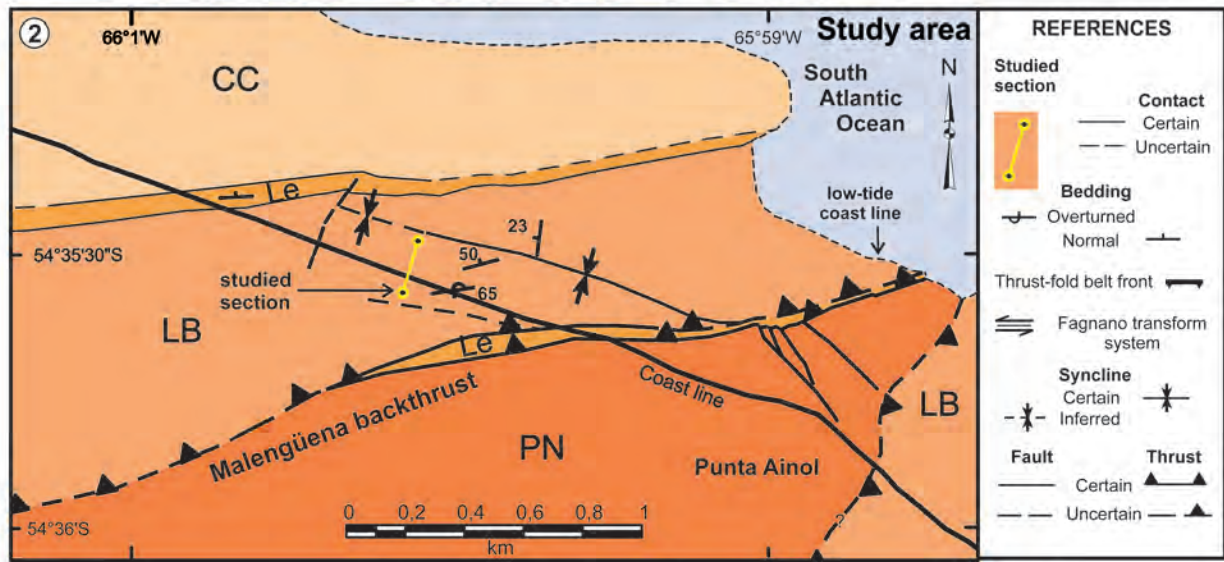
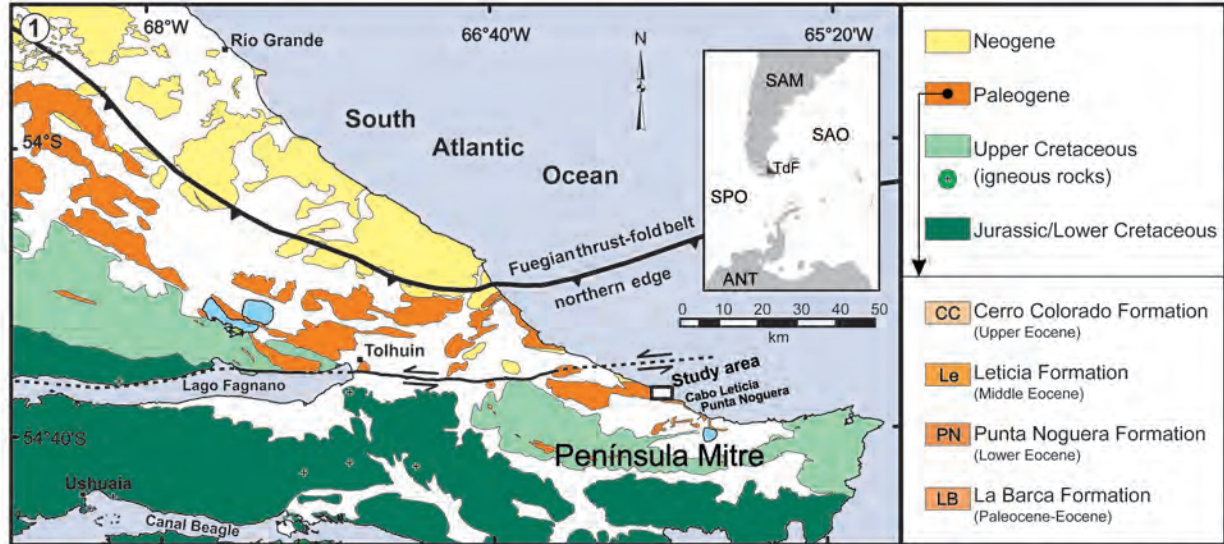
Figure captions

Figure 1. 1. Location maps and geologic sketch of southeastern Tierra del Fuego. **2.**

Geological sketch of the studied outcrops of the La Barca Formation at Punta Ainol. **SAM=** South America; **ANT=** Antarctica; **SPO=** South Pacific Ocean; **SAO=** South Atlantic Ocean; TdF = Tierra del Fuego. Modified from Olivero and Malumián (2008), Torres Carbonell *et al.* (2009), Torres Carbonell and Dimieri (2013).

Figure 2. Distribution of calcareous nannofossils in the LB2 member of the La Barca Formation at Punta Ainol, Tierra del Fuego.

Figure 3. Microphotographs of calcareous nannofossils from the LB2 member of La Barca Formation at Punta Ainol, **1, *Chiasmolithus bidens*; 2, *Hornibrookina australis*; 3, *Toweius eminens*; 4, *T. occultatus*; 5, *T. tovae*; 6, *Prinsius bisulcus*; 7, *Neochiastozygus concinnus*; 8, *Rhomboaster sp.cf. R. cuspis*; 9, *Fasciculithus alanii*; 10, *F. involutus*; 11, *F. tympaniformis*; 12, *Fasciculithus sp. cf. F. mitreus*.** All specimens photographed at 1000× magnification under cross-polarized light. Scale bar = 5 µm.



Thickness (m)	Lithology	Samples CADIC-MIC code	Formation	Epoch	Stage	Eocene		Preservation	Fasciculithus																	
						NP9b	CNE1		Fasciculithus																	
			LA BARCA FORMATION	Paleocene	Thanetian	NP9a	CNP11	M	Fasciculithus																	
									NP9b	CNE1	Fasciculithus															
											Fasciculithus															
120		16	LA BARCA FORMATION	Eocene	Ypresian	NP9b	CNE1	P			Fasciculithus															
110		15							Fasciculithus																	
100		14							Fasciculithus																	
90		13							Fasciculithus																	
80		12							Fasciculithus																	
70		11							Fasciculithus																	
60		10							Fasciculithus																	
50		09							Fasciculithus																	
40		08							Fasciculithus																	
30		07							Fasciculithus																	
20		06							Fasciculithus																	
10		05							Fasciculithus																	
0		04	Fasciculithus																							
		03	Fasciculithus																							
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		01	Fasciculithus																							

References

Mudstone

Sandstone

Covered

Large Concretions

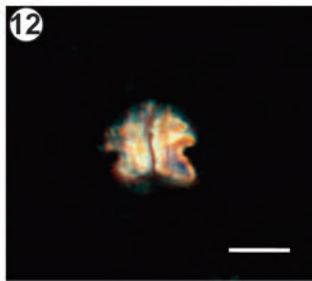
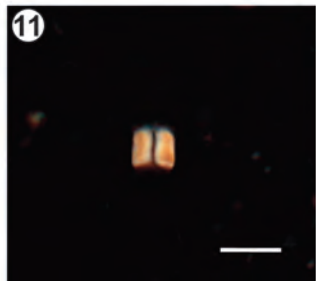
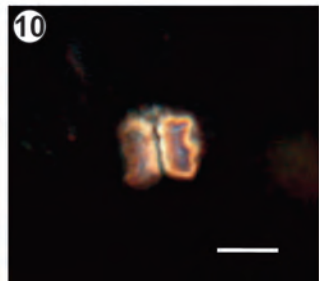
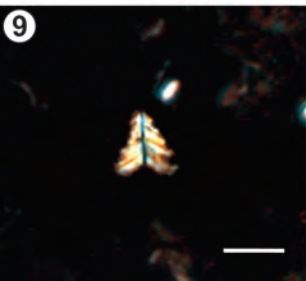
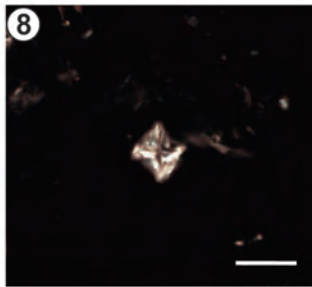
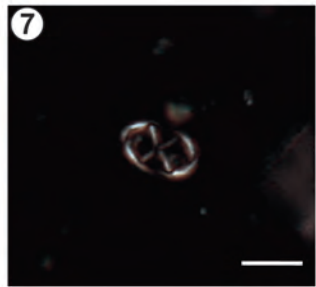
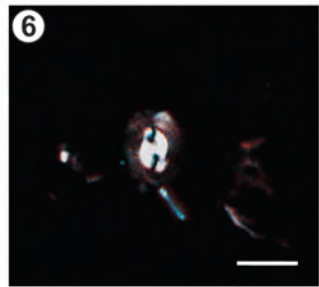
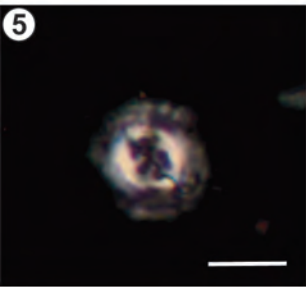
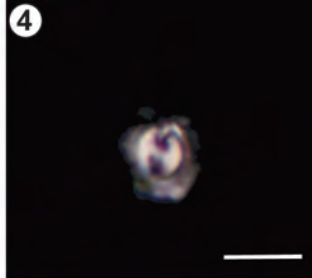
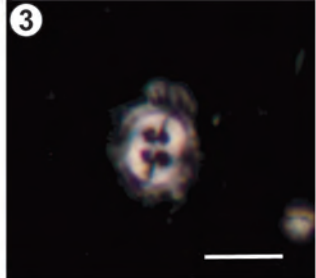
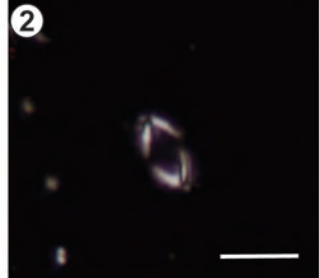
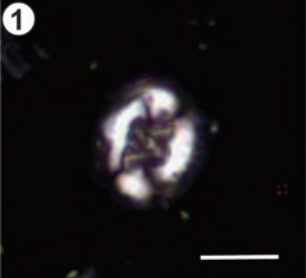
Small Concretions

Preservation

Abundance

P: poor M: moderate

R: rare F: frequent C: common B: barren



SUPPLEMENTARY MATERIAL.

List of species mentioned in the text and figures listed by alphabetical order. The taxonomy and bibliographical references follow Perch-Nielsen (1985) and Nannotax 3.

(<http://www.mikrotax.org/Nannotax3/index.html>)

Biscutum Black, 1959
Braarudosphaera bigelowi (Gran & Braarud, 1935) Deflandre, 1947
Chiasmolithus Hay, Mohler and Wade, 1966
Chiasmolithus bidens Bramlette and Sullivan, 1961
Chiasmolithus nitidus Perch-Nielsen, 1971
C. eograndis Perch-Nielsen, 1971
C. solitus Bramlette and Sullivan, 1961
Coccolithus pelagicus Schiller, 1930
Discoaster Tan Sin Hok, 1927
D. araneus Bukry, 1971
D. diastypus Bramlette & Sullivan, 1961
D. multiradiatus Bramlette and Riedel, 1954
Ericsonia subpertusa Hay and Mohler, 1967
Fasciculithus Bramlette and Sullivan, 1961
Fasciculithus alanii Perch-Nielsen, 1971
Fasciculithus aubertae Haq and Aubry, 1981
F. involutus Bramlette and Sullivan, 1961
F. mitreus Gartner, 1971
F. richardii Perch-Nielsen, 1971
F. thomasi Perch-Nielsen, 1971
F tympaniformis Hay and Mohler, 1967
Helicosphaera Kamptner, 1954
Heliolithus cantabriae Perch-Nielsen, 1971
Heliolithus kleinPELLI Sullivan, 1964
Hornibrookina Edwards, 1973
Hornibrookina australis Edwards and Perch-Nielsen, 1975
Lanternithus Stradner, 1962
Lanternithus simplex Bown, 2005
Neochiastozygus Perch-Nielsen, 1971
Neochiastozygus concinnus Martini, 1961
Neochiastozygus junctus (Bramlette and Sullivan, 1961) Perch-Nielsen, 1971
Neococcolithes protenus Bramlette and Sullivan, 1961
Prinsius bisulcus (Stradner 1963) Hay and Mohler, 1967
Rhomboaster Bramlette and Sullivan, 1961
Rhomboaster cuspis Bramlette and Sullivan, 1961
Sphenolithus Deflandre in Grasse, 1952
Sphenolithus moriformis (Bronnimann and Stradner, 1960) Bramlette and Wilcoxon, 1967
Toweius Hay and Mohler, 1967
Toweius eminens Bramlette and Sullivan, 1961
Toweius pertusus Sullivan, 1965

Toweius occultatus (Locker, 1967) Perch Nielsen, 1971
Toweius rotundus Perch-Nielsen in Perch-Nielsen *et al.*, 1978
Toweius serotinus Bybell & Self-Trail, 1995
Toweius tovae Perch-Nielsen, 1971
Tibrachiatus Kamptner, 1958
Tibrachiatus bramlettei (Brönnimann and Stradner, 1960) Proto Decima *et al.*, 1975
Watznaueria Reinhardt 1964
Zygrhablithus bijugatus Deflandre, 1954