Middle Eocene to early Oligocene calcareous nannofossil stratigraphy at Leg 177 Site 1090

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Abstract

Semi-quantitative and quantitative analyses on nannofossil assemblages were carried out on the middle Eocene to early Oligocene interval of Site 1090 Hole B; several biozones were recognized according to the schemes of Martini (1971), Okada and Bukry (1980) and Wei and Wise (1990a), between the FO of Reticulofenestra reticulata and the LO of Reticulofenestra umbilica. Based on nannofossil biostratigraphy, our proposed interpretation of shipboard magnetic inclination data recognizes magnetic chronos from C12 to C19, according to the geomagnetic polarity time scale of Berggren et al. (1995). The Eocene/Oligocene boundary is placed between the last occurrences of Reticulofenestra oamaruensis and Discoaster saipanensis, within Chron C13r. On the basis of the correlation between magnetostratigraphy and biostratigraphy, a new biochronology is proposed for some nannofossil events. The age of FO of Reticulofenestra circus was estimated at 33.39 Ma; no previous biochronology is available in the literature for this event. An age–depth curve is constructed on the basis of the correlation between nannofossil biostratigraphy and the GPTS of Berggren et al. (1995). A very low value of sedimentation rate (0.5 m/Ma) characterizes the upper part of the study site, from the last occurrence of Ericsonia formosa to the last occurrence of R. umbilica. The presence of a hiatus or a condensed interval may occur at this level. It may be related to the mid-Oligocene Marshall Paraconformity and the inception of the Antarctic Circumpolar Current, which contributed to the modification of the nannoflora composition and sedimentation in this sector of the South Ocean. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Southern Ocean; Eocene; Oligocene; calcareous nannofossils; biostratigraphy

1. Introduction

Site 1090 is located in the central part of the Subantarctic Zone on the northern flank of the Agulhas Ridge (42°54’S, 8°53’E) (Fig. 1). The water depth (3702 m) places Site 1090 near the boundary between the North Atlantic deep water and underlying circumpolar deep water, and above the carbonate compensation depth (CCD). Hole 1090B was drilled to 397.5 mbsf and recovered Holocene to middle Eocene sediments. The recovery of the Eocene to lower Oligocene sequence is generally good even though the cores were drilled using the extended core barrel system (XCB) (Shipboard Scientific Party, 1999). Both, nannofossil events and geomagnetic inclination recorded in this interval enabled us to refer sediments to biostratigraphic and geomagnetic polarity zones. In particular the Eocene/Oligocene transition seems to be well documented at

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Hole 1090B. Site 1090 represents a reference record to improve knowledge about this critical period of the Earth’s history, which is characterized by significant changes in climate, sea level, global oceanic circulation patterns as well as in marine biota. A detailed biostratigraphy and an accurate chronostratigraphy of the sedimentary record provide the basis for such understanding. Therefore, we analyzed the calcareous nannofossil assemblages of the middle Eocene to lower Oligocene interval, focusing especially on the Eocene/Oligocene transition with quantitative investigations of nannofossil assemblages. Our results include recognition of both, low and high latitude standard biozones (Martini, 1971; Okada and Bukry, 1980; Wei and Wise, 1990a) and allow the development of a stratigraphic interpretation of shipboard magnetic inclination data available from Site 1090 (Shipboard Scientific Party, 1999) based on nannofossil biostratigraphy.

2. Materials and methods

Cores 177-1090B-23X to 1090-43X were examined for calcareous nannofossil biostratigraphy. Quantitative analyses were carried out on one to two samples per section collected from upper Eocene to lower Oligocene sediments (Cores 23X–31X) between the first occurrence (FO) of Isthmolithus recurvus and the last occurrence (LO) of Reticulofenestra umbilica, in order to obtain detailed abundance patterns of marker species through the Eocene/Oligocene transition. Semi-quantitative analyses were performed on one to two samples per section of the middle-low-
er upper Eocene cores 32H to 43X to improve the biozonal attribution presented by the Shipboard Scientific Party (1999).

Smear slides were prepared according to standard technical preparation from unprocessed sediment. Analyses were performed using a light microscope (Zeiss ‘Axioskop’) with 1000 X magnification. One hundred and fifty fields of view of each smear slide (about 2.64 mm²) were examined both to determine semi-quantitative abundances of middle-early upper Eocene species and to count a significant number of specimens of the marker species whose quantitative distributions are useful to improve the nannofossil biostratigraphy through the Eocene/Oligocene transition. Such a quantitative method allows the examination of a large number of nannofossils and thus provides important abundance patterns of rare species as Reticulofenestra oamaruensis, Discoaster saipanensis and Ericsonia formosa, the presence of which would have been difficult to detect by counting only a total of 300–500 nannofossils. Moreover, two additional traverses of each slide were scanned in order to recognize the presence of very rare species. Rare to very rare reworked Cretaceous nannofossils were found in some samples (see range chart in Marino and Flores, in press). Quantitative abundance patterns of marker species were plotted as number of specimens per unit area of smear slide according to the counting technique proposed by Backman and Shackleton (1983) and Rio et al. (1990a, b). On the basis of these quantitative analyses we defined primary biostratigraphic events such as the FO and LO of taxa, as well as the range of acmes.

3. Biostratigraphy

The standard schemes of Martini (1971) and Okada and Bukry (1980) were adopted for biostratigraphic study in the Southern Ocean (Fig. 2). Moreover, the high latitude zonal scheme of Wei and Wise (1990a) proved to be suitable for a detailed biozonal attribution of nannofossil assemblages of Hole 1090B. In fact, both classical biozonal events of low latitude (Martini, 1971; Okada and Bukry, 1980) and high latitude (Wei and Wise, 1990a) schemes were recognized at Hole 1090B, thus defining all biozones from the

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<td></td>
<td>37</td>
<td>C17b</td>
<td>CP15a</td>
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<td>NP17</td>
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<td>C. grandis</td>
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Fig. 2. Chronostratigraphy according to Berggren et al. (1995) and biostratigraphy of the study interval.
middle Eocene to lower Oligocene interval. The only deficiency represents the lack of the determination of the LO of *Chiasmolithus solitus*, which marks the top of the middle Eocene CP14a zone, due to poor preservation and taxonomic problems (see below). The CP14a/CP14b boundary was tentatively approximated by the LO of *Discaster bifax* according to the suggestions of Bukry (1973).

### 3.1. Biostratigraphic results

Nannofossil range chart of Site 1090 is available in *Marino and Flores (in press)* to whom the
reader is referred for more details on distribution and abundance of calcareous nannofossils. Below, we discuss the nannofossil events recognized on the basis of semi-quantitative and quantitative analyses. The biostratigraphic discussion will refer to the zones of Okada and Bukry. However, all zones of the schemes of Martini (1971) and Wei and Wise (1990a) are also shown in Fig. 3, in order to make possible an easy comparison with the literature. 

Reticulofenestra umbilica, which has its FO at the base of the middle Eocene CP14 zone, is present at the bottom of the hole and its extinction occurs at the top of the studied interval. Semi-quantitative analyses allowed us to recognize the FO and LO of Reticulofenestra reticulata, the LO’s of Discoaster bifax and Chiasmolithus grandis, and the FO of Chiasmolithus oamaruensis. Some of these events should not be considered highly reliable since poor preservation or rarity of index species prevented us from recognizing their continuous or significant distribution.

The lowest occurrence of Reticulofenestra reticulata is recorded at 372.84 mcd. The species is characterized by specimens 5–6 µm in size in its lower range. An increase in the size, up to 8–9 µm, has been observed upward in the section, which is in accordance to the morphometric evolution of this taxon proposed by Wei and Wise (1990b). Moreover, the basal range of R. reticulata is characterized by very rare and scattered specimens; on the other hand the distribution of the species is continuous from 361 mcd to its LO at 308.977 mcd. Discoaster bifax is very rare in the middle Eocene interval at Hole 1090B and was recorded only in three samples; the highest occurrence of the species is tentatively placed at 371.415 mcd, where the last rare specimens were recorded. At the same level the abundance of Chiasmolithus solitus, the distribution of which is almost continuous from the bottom of the hole, drops from few to rare, very rare and scattered presence. Nevertheless, this marker is not reliable to zone middle Eocene sediment of Hole 1090B. In this interval several poorly preserved specimens of Chiasmolithus show curved bars in the central X cross like C. solitus. However, and in accordance with Perch-Nielsen (1985), the poor preservation prevented us from identifying the overlapping of the distal cycle elements that would have allowed us to attribute the Chiasmolithus specimens to C. solitus. The zonal boundary CP14a/CP14b is defined as uncertain at Hole 1090B, based on considerations about the distribution of D. bifax and C. solitus (Fig. 3). The FO of Reticulofenestra bisecta is recorded just above

<table>
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<th>Event</th>
<th>Depth (mbsf)</th>
<th>Sample interval (cm)</th>
<th>mcd</th>
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<td>R. umbilica</td>
<td>212.74</td>
<td>221.14</td>
<td>23X-7, 30/23X-7, 130</td>
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<tr>
<td>C. abisectus</td>
<td>212.74</td>
<td>221.14</td>
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<tr>
<td>I. recurvus</td>
<td>213.49</td>
<td>221.89</td>
<td>23X-7, 130/23X-CC, 26–36</td>
</tr>
<tr>
<td>E. formosa</td>
<td>213.49</td>
<td>221.89</td>
<td>23X-7, 130/23X-CC, 26–36</td>
</tr>
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<td>C. abisectus</td>
<td>219.1</td>
<td>230.06</td>
<td>24X-4, 30/24X-4, 130</td>
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<td>Blackites</td>
<td>223.97</td>
<td>234.81</td>
<td>24X-CC, 18–24/25X-1, 120</td>
</tr>
<tr>
<td>R. umbilica</td>
<td>223.97</td>
<td>234.81</td>
<td>24X-CC, 18–28/25X-1, 120</td>
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<td>O. oamaruensis</td>
<td>246.7</td>
<td>258.69</td>
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<td>D. saipanensis</td>
<td>250.4</td>
<td>262.39</td>
<td>27X-5, 120/27X-6, 120</td>
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<td>O. oamaruensis</td>
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<td>289.96</td>
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<td>R. reticulata</td>
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<td>308.97</td>
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<td>353.65</td>
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<td>F. bisecta</td>
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<td>368.43</td>
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<td>371.41</td>
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<td>C. oamaruensis</td>
<td>360.85</td>
<td>372.84</td>
<td>40X-1, 130/40X-2, 130</td>
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</tbody>
</table>

Table 1 Interval samples and depth of calcareous nannofossil events at Hole 1090B
the LO of *D. bifax* where the first rare specimens of the species are found. However, the presence of just one doubtful specimen of *R. bisecta* should be noted at the same level where *R. reticulata* first occurs, within the zone CP14a.

The LO of *Chiasmolithus grandis* is tentatively placed at 353.65 mcd even though the species is scattered and rare in the uppermost portion of its range (Marino and Flores, in press). The FO of *Chiasmolithus oamaruensis* occurs just above the extinction of *C. grandis*. The two events are used to define the base of CP15 and NP18 (Bukry, 1973, Okada and Bukry, 1980; Martini, 1971). At Hole 1090B we used the FO of *C. oamaruensis* to zone this interval because the stratigraphically youngest occurrence of *C. grandis* could not be discerned clearly (Fig. 3). The LO of *Reticulofenestra reticulata* is recorded to occur below the FO of *Isthmolithus recurvus* by Wei et al. (1992), Madile and Monechi (1991) and Wei and Thierstein (1991) and above this event by Madile and Monechi (1991) and Coccioni et al. (1988). In Hole 1090B we found the LO of *R. reticulata* below the FO of *I. recurvus*, thus in the upper part of CP15a. The occurrence of *R. reticulata* in the uppermost portion of its stratigraphic range is discontinuous. The low recovery rate of core 33X prevents denser and continuous sampling of this interval (Fig. 3).

Quantitative analyses were performed for the recognition of the events in the upper Eocene–lower Oligocene interval between the FO of *Isthmolithus recurvus* and the LO of *Reticulofenestra umbilica*. The abundance patterns of most index species are shown in Fig. 4. The patterns show significant variation in the species abundance pattern. Very low abundance characterizes the distribution of *Reticulofenestra oamaruensis*, *Discoaster saipanensis* and *Ericsonia formosa*. Despite this, all important LO and FO events may be determined and a biostratigraphic zonation can be established according to the classical definition of the standard zonation (Figs. 3, 4). The FO of *Reticulofenestra circus* (8–9 μm), which occurs in the upper part of NP22 (De Kaenel and Villa, 1996), is recorded at 234.81 mcd. *R. circus* shows a relatively high abundance value between 232.56 and 215 mcd and becomes rare and scattered above this section, up to the top of the studied interval. The LO of the species, which occurs within the NP23 (De Kaenel and Villa, 1996) was not discerned in the studied sediment interval. We also noted the presence of *R. circus*-like circular *Reticulofenestra* sp., which are 5–7 microns in size, between 303.17 mcd and the FO of *R. circus*. We considered these circular reticulofenestrids to be related to the taxon *R. circus*, which according to De Kaenel and Villa (1996) are generally 8–9 microns in size. We found a similar morphometric evolution, recorded as the increase of size, for *Reticulofenestra reticulata* in Hole 1090B, a pattern that has also been documented by Wei and Wise (1990a). High abundance intervals (acmes) of *Clausicoccus* spp. and *Blackites* spp. were found between 234.81 mcd and 230.06 mcd (Figs. 3, 4). *Clausicoccus* spp. includes taxa such as *Clausicoccus fenestratus*, *Clausicoccus abruptus*, and *Clausicoccus subdistichus* because the poor preservation of nannoflora in many samples prevented us from discriminating the different species. Also Wise (1983), Wei and Thierstein (1991) and Madile and Monechi (1991) noted the problematic identification of diagnostic features used to define at species level the *Clausicoccus* specimens when studied with the light microscope. However, these taxa seem to have a similar stratigraphic distribution at Hole 1090B and *C. fenestratus* generally seems to represent the main component of the *Clausicoccus* taxa. We used the upper level of the *Clausicoccus* spp. acme to define the base of CP16b. The acme of *Blackites* spp. can be correlated to the lower Oligocene acme of the *Blackites spinosus* group at Site 1123 (McGonigal and Di Stefano, submitted) and at Sites 511 and 513 (Wei and Wise, 1990b), where acmes of both, the *B. spinosus* group and the *C. fenestratus* group, occur at the same stratigraphic interval as in Hole 1090B.

The LO’s of *Ericsonia formosa*, *Isthmolithus recurvus* and *Reticulofenestra umbilica* occur very closely between 221.89 and 221.14 mcd (Figs. 3, 4, Table 1). This pattern indicates that lower Oligocene zone CP16c has a very short range in Hole 1090B in comparison to the underlying zones CP16b and especially CP16a. The very short range of CP16c indicates strongly condensed sed-
Fig. 4. Abundance patterns of selected calcareous nannofossil taxa.
imentation and/or the occurrence of one or more disconformities in this section. This interval is also marked by a significant change in the nannofossil assemblage composition indicated by a drop of the number of species from more than 15 to less than 10, coincident to an enhancement of carbonate dissolution (Marino and Flores, in press).

Above this interval *Reticulofenestra bisecta*, *Cyclicargolithus floridanus*, *Coccolithus pelagicus* and *Reticulofenestra daviesi* group (according to Wei and Wise, 1990b) become the main components of the preserved nannoflora. We also mark the FO of *Cyclicargolithus abisectus* (> 10 microns, according to Rio et al., 1990a) at 221.14 mcd, oc-

Fig. 5. Interpretation of shipboard geomagnetic inclination and age-depth curve based on correlation between calcareous nannofossil biostratigraphy and GPTS of Berggren et al. (1995).
occurring however with very rare specimens. A co-
occurance of the LO of *R. umbilica* and the FO
of *C. abisectus* has been recorded by Wei (1991)
from the southern high latitude ODP Site 703.
However, Martini and Müller (1986) place the
FO of *C. abisectus* at the bottom of NP24, thus
about 3 Myr above the LO of *R. umbilica*.
Moreover, the FO of *C. abisectus* has also been
reported from NP22 (De Kaenel and Villa, 1996),
thus from a period stratigraphically older than the
LO of *R. umbilica*. Moreover, the FO of *C. abisectus*
as been reported from NP22 (De Kaenel and Villa, 1996),
thus from a period stratigraphically older than the
LO of *R. umbilica*, as well as from within NP23
by Fornaciari et al. (1990). These reports might
indicate that the FO of *C. abisectus* has a diachro-
nous occurrence in the lower portion of the Oli-
gocene. However, also the rarity of the taxon in the
lowermost portion of its stratigraphic range might
have caused different age assignments of its FO.

4. Correlation of nannofossil bioevents with
shipboard geomagnetic data

Based on calcareous nannofossil biostratigra-
phy an interpretation of the shipboard magnetic
inclination data (Shipboard Scientific Party, 1999)
is proposed for Hole 1090B (Fig. 5). Most nan-
nofossil bioevents recorded from the interval be-
 tween 221.14 mcd (the LO of *Reticulofenestra
umbilica*) and 304.51 (the FO of *Isthmolithus
recurvus*) could be correlated to the shipboard
magnetic data in close correspondence with the
time relationship between nannofossil bioevents
and the geomagnetic time scale (GMTS) pre-
 sented by Berggren et al. (1995) (Table 2). The
LO of *Reticulofenestra reticulata*, identified at
308.97 mcd, was correlated to C16n, according
to Wei (1991) and Wei and Wise (1992). The cor-
relation of nannofossil bioevents identified below
the LO of *R. reticulata* to the GMTS was more
problematic because no quantitative analyses have
been performed on this interval and the shipboard
gemagnetic data are discontinuous or show un-
clear polarities. A new nannofossil biochronology
is proposed for some events from C17n to the mid
C13n by means of interpolation between chron
boundaries according to the geomagnetic polarity
time scale of Berggren et al. (1995). Brief com-
ments on nannofossil bioevents and the proposed
correlation to the geomagnetic polarity time scale
are in the following.

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<th>Site 1090 Hole B</th>
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<td>Latitude Ma Chron</td>
<td>Ma Chron</td>
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<tr>
<td>FO <em>C. abisectus</em></td>
<td>mid-low 32.3 early C12r</td>
<td>late C12r</td>
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<td>LO <em>R. umbilica</em></td>
<td>northern high 31.3 C12r</td>
<td>late C12r</td>
</tr>
<tr>
<td>LO <em>I. recurvus</em></td>
<td>31.8 to 33.1 C12r diachronous</td>
<td>early C12r</td>
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<td>LO <em>E. formosa</em></td>
<td>low-mid 32.8 C13n–C12r diachronous</td>
<td>early C12r</td>
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<td>End acme <em>Claudiscus</em></td>
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<td>33.39 C13n</td>
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<td>FO <em>R. circus</em></td>
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<td>LO <em>D. saipanensis</em></td>
<td>low-mid 34.2 C13r</td>
<td>34.09 C13r</td>
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<td>LO <em>R. oamaruensis</em></td>
<td>northern high 35.4 C16n diachronous</td>
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<td>36 C16n.2n</td>
<td>36 C16n.2n</td>
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<tr>
<td>LO <em>R. reticulata</em></td>
<td>low-mid 36.1 C15 diachronous</td>
<td>36.1 C16n.2n</td>
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<td>LO <em>C. oamaruensis</em></td>
<td>37 C17n1n</td>
<td>37 C17n1n early C17r</td>
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<td>LO <em>C. grandis</em></td>
<td>37.1 C17n.1n (C18n, Italian sections)</td>
<td>C18n</td>
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<td>FO <em>R. bisecta</em></td>
<td>38 C17n.3n (C18n, C18r, Italian sections)</td>
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Table 2
Comparison between magnetoboichronology according to Berggren et al. (1995) (central column) and this study (right column)
4.1. FO of Reticulofenestra reticulata

This event occurs within the C19r or at the C19n/C18r boundary up to C18n (see discussion in Berggren et al., 1995). In Hole 1090B the FO of *Reticulofenestra reticulata* seems to occur at a geomagnetic polarity boundary that could be interpreted to represent the C19n/C18r boundary. If this interpretation is correct the interpolated age assignment of the FO of *R. reticulata* in Hole 1090B is ca. 41.2 Ma.

4.2. LO of Discoaster bifax

This event was not yet correlated to the GMTS. The *Discoaster bifax* extinction is not a reliable event at Hole 1090B because the species was found in just a few samples. However, the position of the LO of *D. bifax* seems to be correlative with the lowermost part of the reversed polarity that could be interpreted to represent C18r (Fig. 5) and its age should range from 40.13 to 41.257 Ma.

4.3. FO of Reticulofenestra bisecta

The FO of *Reticulofenestra bisecta* is considered to be diachronous because it is reported as occurring within either C17n.3n (Hole 523), C18n (Contessa Highway section), or C18r (Bottaccione section); however some problems seem to arise from a miscorrelation between the Italian section normal polarity and seafloor anomalies around chron C19n–C16n (see discussion in Berggren et al., 1995). At Hole 1090B the FO of *R. bisecta* occurs in the lower part of the reversed polarity C18r (Fig. 5). If our magnetic interpretation is correct, this datum is not in agreement with the age assignment of 38 Ma proposed by Berggren et al. (1995). The age of the FO of *R. bisecta* should be older than 38 Ma, between 40.13 Ma (base of C18n.2n) and 41.257 Ma (base of C18r) (Fig. 5).

4.4. LO of Chiasmolithus grandis

This event is reported as occurring within C17n.1n at Site 523 (Poore et al., 1983; Berggren et al., 1995) and at Site 516 (Wei and Wise, 1989; Berggren et al., 1995). At southern high latitudes (Sites 689 and 690) the event occurs earlier (Wei and Wise, 1990a), in the lower part of C17, even if some doubts exist about the magnetic interpretation and stratigraphic continuity at these sites (see discussion in Berggren et al., 1995). The event is not reliable at Hole 1090B because the species is represented by rare and scattered specimens. The LO is tentatively placed at 347.73 mcd, which is in a section with an unclear geomagnetic polarity record. Considering that the expanded normal polarity interval between ca. 321 and 340 mcd should represent C17n, based on the age assignments obtained from the overlying biostratigraphic events and the pattern of the geomagnetic record, we assume that the FO of *Chiasmolithus oamaruensis* falls also at Hole 1090B in the lower reversed portion of C17.

4.5. FO of Chiasmolithus oamaruensis

This datum is reported as falling in C17n.1n at Site 523 (Poore et al., 1983; Berggren et al., 1995) and at Site 516 (Wei and Wise, 1989; Berggren et al., 1995). At southern high latitudes (Sites 689 and 690) the event occurs earlier (Wei and Wise, 1990a), in the lower part of C17, even if some doubts exist about the magnetic interpretation and stratigraphic continuity at these sites (see discussion in Berggren et al., 1995). The event is not reliable at Hole 1090B because the species is represented by rare and scattered specimens. The LO is tentatively placed at 347.73 mcd, which is in a section with an unclear geomagnetic polarity record. Considering that the expanded normal polarity interval between ca. 321 and 340 mcd should represent C17n, based on the age assignments obtained from the overlying biostratigraphic events and the pattern of the geomagnetic record, we assume that the FO of *Chiasmolithus oamaruensis* falls also at Hole 1090B in the lower reversed portion of C17.

4.6. LO of Reticulofenestra reticulata

This event is considered to be diachronous between low-mid and high latitudes, occurring between the C15n/C15r boundary and within C16n.1n (Contessa Highway section, Hole 522, Massignano section) or in the middle part of C16n at high latitudes (Aubry, 1992; Wei, 1991; Wei and Thierstein, 1991). At Hole 1090B the LO falls within the lower portion of a normal polarity interval that may represent the C16n.2n. The estimated age for the LO of *Reticulofenestra reticulata* is 36.1 Ma.
4.7. FO of Isthmolithus recurvus

This event occurs within C16n.2n at Hole 1090B as reported in Berggren et al. (1995) from several sections (Contessa Highway, Massignano section). This datum correlates well with the magnetic interpretation for Hole 744A, Hole 703A, Sites 748 and 689 (see Berggren et al., 1995). The estimated age for the FO of *Isthmolithus recurvus* is 36 Ma.

4.8. FO of Reticulofenestra oamaruensis

This taxon, which is restricted to the southern high latitudes, has its FO close to the C15r/C16n boundary in C16n.1n (see discussion in Aubry, 1992 and Berggren et al., 1995). The event occurs at the top of C16n.1n in Hole 1090B and this indicates that the polarity reversal at ca. 289 mcd represents the C15r/C16n boundary. The estimated age for the FO of *Reticulofenestra oamaruensis* in Hole 1090B is ca. 35.36 Ma.

4.9. LO of Discoaster saipanensis

This event is considered highly diachronous (see discussion in Berggren et al., 1995) because it is correlated to chron C13r (low-mid latitude) and C16n.1n or C16n (high latitude). In Hole 1090B the event falls within a reversed polarity interval, that we interpret to represent an expanded chron C13r, just above a short normal polarity event within C13r (Fig. 5). In the Massignano section the LO occurs in C13r (Coccioni et al., 1988), below and not above the short normal polarity within C13r (Fig. 6) (Bice and Montanari, 1988). This discrepancy could be due to the rarity of *Discoaster saipanensis*, the presence of which may be difficult to detect in a short time-consuming analysis. The abundance pattern of *D. saipanensis* recorded from Hole 1090B does not suggest a reworked presence of the species in its uppermost occurrence range (Fig. 4). The estimated age for the LO of *D. saipanensis* is 34.09 Ma; our data confirm the diachronous character of the event. The species is probably ecologically controlled, according to the suggestions of Aubry (1992) and Monechi et al. (2000) who consider the genus *Discoaster* as indicative of oligotrophic condition.

4.10. LO of Reticulofenestra oamaruensis

The LO of *Reticulofenestra oamaruensis* is a reliable event according to many authors (see discussion in Berggren et al., 1995), falling within C13r. The position of the LO of *R. oamaruensis* in Hole 1090B is in close correspondence with the geomagnetic reinterpretation of Wei (1992) proposed for Hole 703A where the event occurs within the C13r just above a short normal polarity event in Core 114-703A-13, previously referred to C13n by Hailwood and Clement (1991) and Madile and Monechi (1991). This short normal polarity was also recorded at Site 748, within C13r according to the magnetic interpretation of Wei et al. (1992). We estimate an absolute age for the LO of *R. oamaruensis* in Hole 1090B of 34.0 Ma.

4.11. FO Reticulofenestra circus (8–9 microns)

This event has not been considered by Berggren et al. (1995). According to our interpretation of shipboard geomagnetic data this event falls within C13n. An age of 33.39 Ma is proposed for the FO of *Reticulofenestra circus* by interpolation between the base of C13n and the end acme of *Clausicoccus* spp. at 33.3 Ma.


This event (LO of *Clausicoccus subdistichus*) occurs in C13n at the Contessa and Massignano sections (Italy) at 33.3 Ma (Berggren et al., 1995) and thus indicates that the normal polarity interval between ca. 223 and 242 mcd represents chron C13n at Hole 1090B.

4.13. LO of Ericsonia formosa

This event is considered to be diachronous between low-mid and southern high latitudes (Table 2) occurring from the uppermost C13n and lower C12r (low-mid latitude) to chron C18 (high latitude) in Sites 748 Hole C, 749 and Hole 689B.
Fig. 6. Comparison between the inferred magnetostratigraphy at Hole 1090B and the magnetostratigraphy at Italian stratotype sections. Foraminiferal events in the Massignano section are according to Coccioni et al. (1988). *Globigerinatheka index* event at Hole 1090B is according to Galeotti et al. (this issue).
where the magnetic record is not sufficiently documented or not available (see discussion in Berggren et al., 1995). At Hole 1090B the event occurs, together with the LO of *Isthmolithus recurvus*, within a reversed polarity interval that may represent the C12r. The estimate age of 32.8 Ma for the LO of *Ericsonia formosa* (Berggren et al., 1995) is considered consistent with the age model at Hole 1090B (Fig. 5).

### 4.14. LO of *Isthmolithus recurvus*

This event is one of the most inconsistent Oligocene nannofossil data ranging from upper chron C12r to upper C13n. The LO of *Isthmolithus recurvus* falls in the early C12r at Site 1090B, close to the magnetic polarity reversal interpreted to represent the C12r/C13n boundary. This datum is in accordance with the reinterpretation of magnetostratigraphy at Site 703A (Wei, 1992).

### 4.15. LO of *Reticulofenestra umbilica*

This event is diachronous between low-middle and southern high latitudes. It falls in southern high latitudes in the upper portion of C12r (Berggren et al., 1995). In Hole 1090B the LO of *Reticulofenestra umbilica* is in C12r.

### 4.16. FO of *Cyclicargolithus abisectus*

This event has not been considered by Berggren et al., 1995. The FO of *Cyclicargolithus abisectus* is recorded as contemporaneous with the LO of *Reticulofenestra umbilica* in the late C12r according to Wei (1992). It similarly occurs within C12r at Hole 1090B, together with the LO of *R. umbilica*, as at Site 703A (Wei, 1991).

### 5. Discussion

Our interpretation of the geomagnetic inclination requires some comment concerning the sedimentation rates and the location of the Eocene/Oligocene boundary. The occurrence of several events in a short interval around 220 mcd seems to indicate very low sedimentation rates up to 0.5 m/Myr between the LO of *Ericsonia formosa* and the LO of *Reticulofenestra umbilica* (Fig. 5). A hiatus close to this interval may be inferred. However, all biozones were recognized (Figs. 3, 5) and a condensed stratigraphic interval can be thought as very probable near the above-mentioned nannofossil events. On the other hand, the presence of a hiatus at this level was found in the South Ocean at Site 703 by Wei (1991) and at Sites 1123–1124 by McGonigal and Di Stefano (submitted); the latter authors correlate this hiatus to the known regional mid-Oligocene Marshall Paraconformity (Fulthorpe et al., 1996, and reference therein). A high sedimentation rate occurs below the end acme of *Clausicoccus* spp. down to the Chron C17n: 38.6 m/Ma in the C13r, 9.8 m/Ma in the C15, 17.6 m/Ma in the C17n (Fig. 5). The large difference in the sedimentation rate from chron C13 to C12 seems to suggest a significant variation in the paleoceanography of the South Ocean, possibly also in relation to the middle Oligocene Marshall Paraconformity and inception of the Antarctic Circumpolar Current (Fulthorpe et al., 1996, and reference therein). This current could have contributed to the modification of the middle Oligocene nannoflora composition and have affected the sedimentation in the studied sector of the South Ocean, resulting in the presence of a hiatus or a condensed section.

Fig. 6 shows a comparison between magnetostratigraphy at Hole 1090B and at the Italian sections which represent the stratotype area for the Eocene/Oligocene boundary. A short ‘normal’ signal of magnetic inclination within C13r was found both at the high southern latitude Sites 703A (Wei, 1992) and 748 (Wei et al., 1992) as well as at the Massignano quarry section (Fig. 6). In the latter section the global stratotype section and point for the Eocene/Oligocene boundary was located just above the short normal chron (Bice and Montanari, 1988), close to the extinction of the foraminifer *Hantkeninidae*. This short normal chron also occurs at Hole 1090B; it could be interpreted as a cryptochron (short intensity fluctuation of the geomagnetic field) according to Cande and Kent (1992) and may be correlative with the short normal signal recorded within...
C13r at Sites 703A and 748, and at the Massignano section. However, it is noteworthy that neither Lowrie and Lanci (1994), in their intensive re-examination of the Massignano section, nor Lanci et al. (1996) in their new study of the Massicore core (Fig. 6) were able to confirm the presence of the short chron. Consequently the problem of the interpretation of the occurrence of short polarity events or cryptochrons within C13r is open. A critical discussion of the problem is made in Lanci et al. (1996). The age assignment of the boundary is 33.7 Ma (Montanari et al., 1988) or 33.5 ± 0.3 Ma (Lanci et al., 1996). According to our interpretation, which is mainly based on biostratigraphic results, the Eocene/Oligocene boundary at Hole 1090B can be placed between the LO of Discoaster saipanensis, considered the classical nannofossil event for the approximation of this boundary, and the LO of Reticulofenestra oamaruensis whose age assignment is 33.7 Ma according to Berggren et al. (1995). The last event has not been recognized in the Italian sections where the GSSP for the E/O boundary was established (Coccioni et al., 1988; Premoli Silva and Jenkins, 1993). However, the age of the LO of R. oamaruensis is the closest to the dating of the boundary according to both Montanari et al. (1988) and Lanci et al. (1996). Such a chronostratigraphical boundary at Hole 1090B results in a location near the CP15b/CP16a, NP19–20/NP21, within the inferred chron C13r (Figs. 3, 5, 6).

6. Conclusion

Semi-quantitative and quantitative analyses on nannofossil assemblages allowed us to zone the middle Eocene to lower Oligocene interval of Hole 1090B according to the schemes of Martini (1971), Okada and Bukry (1980) and Wei and Wise (1990a). Based on nannofossil biostratigraphy an interpretation of shipboard geomagnetic inclination is proposed and magnetic chrons from C12 to C19 were recognized according to the GPTS of Berggren et al. (1995). The correlation between most nannofossil events and the inferred magnetostratigraphy at Hole 1090B correlates closely to the GPTS. Revised ages of some nannofossil events are proposed on the basis of the correlation between biostratigraphy and magnetostratigraphy in the interval from the base of Chron C13n to the top of C19n. Some events confirm their slightly diachronous character (LO of Isthmolithus recurvus, LO of Ericsonia formosa, LO of Discoaster saipanensis), though the correlation to the inferred magnetostratigraphy at Hole 1090B shows that they are closely comparable to the chron reported by Berggren et al. (1995) for mid latitude sites. On the other hand, the LO of Reticulofenestra reticulata occurs within C16n.2n just as it does at other high latitude sites.

An age–depth curve is based on the correlation between the nannofossil biostratigraphy and the GPTS of Berggren et al. (1995). Very low value of the sedimentation rate (0.5 m/Myr) characterizes the upper part of the study site where all biozones were recognized according to standard schemes. At the very least this interval could represent a condensed section; however the presence of a hiatus cannot be excluded because data of Wei (1991) and McGonigal and Di Stefano (submitted) indicate a hiatus at the same level in some high latitude sites. This hiatus or condensed interval may be correlative with the middle Oligocene Marshall Paraconformity and inception of the Antarctic Circumpolar Current.

The Eocene/Oligocene boundary is placed between the last occurrences of Reticulofenestra oamaruensis and Discoaster saipanensis; these events fall within Chron C13r at Hole 1090B above a short normal magnetic signal known in the literature as a cryptochron (?) and the interpretation of which is ambiguous.

Acknowledgements

We are grateful to J. Firth, K. McGonical and S. Monechi for their careful reviews of the manuscript. Many thanks to R. Gersonde, N. Ciaranfi and A. Girone for their encouragement and suggestions. Financial support for this study was provided by M.U.R.S.T. Grant 40% (1999) to N. Ciaranfi.
**Taxonomic appendix**

Calcareous nannofossils considered in this study are listed by alphabetical order of generic epithet. Bibliographic references for most of taxa can be found in Perch-Nielsen (1985). Any references not cited therein are included in the bibliography. Biometric definitions on problematic species adopted in this study are also reported.

*Blackites spinosus* (Deflandre and Fert, 1954) Hay and Towe, 1962

*Chiasmolithus grandis* (Bramlette and Riedel) Radomski, 1978

*Chiasmolithus oamaruensis* (Deflandre, 1954) Hay, Molher and Wade, 1966

*Chiasmolithus solitus* (Bramlette and Sullivan) Locker, 1968

*Clausicoccus fenestratus* (Deflandre and Fert, 1954) Prins, 1979

*Clausicoccus obruptus* (Perch-Nielsen, 1971) Prins, 1979

*Clausicoccus subdistichus* (Roth and Hay, in Hay et al., 1967) Prins, 1979

*Coccolithus pelagicus* (Wallich, 1977) Schiller, 1930


*Discoaster bifax* Bukry, 1971

*Discoaster saipanensis* Bramlette and Riedel, 1954

*Ericsonia formosa* (Kamptner, 1963) Haq, 1971

*Isthmolithus recurvus* (Deflandre in Deflandre and Fert) Bramlette and Martini, 1964

*Reticulofenestra bisecta* (Hay, Mohler and Wade, 1967) Roth, 1970

*Reticulofenestra circus* De Kaenel and Villa, 1996

*Reticulofenestra daviesi* (Haq, 1968) Haq, 1971

*Reticulofenestra oamaruensis* (Deflandre in Deflandre and Fert) Stradner and Edwards, 1968

*Reticulofenestra reticulata* (Gartner and Smith, 1967) Roth and Thierstein, 1972

*Reticulofenestra umbilica* (Levin and Joerger, 1967) Varol, 1989

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