Quantitative Calcareous Nannofossil Biochronology of Middle Eocene through Early Oligocene Sediment from DSDP Sites 522 and 523

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With 12 Figures and 2 Tables

South Atlantic
Calcareous Nannofossils
Eocene
Oligocene
Biochronology

Contents

Zusammenfassung

Mit Hilfe von ausführlichen quantitativen Analysen am ersten und letzten Erscheinen von ausgewählten Arten kalkiger Nannofossilien aus dem Zeitraum mittleres Eozän bis frühes Oligozän im Süd-Atlantik (DSDP Sites 522 und 523) ist die Präzision der Biochronologie dieser Ereignisse verfeinert worden. Das letzte Vorkommen von *R. umbilicus* (33.80 Ma) und *D. saipanensis* (36.72 Ma) ist wegen ihrer geringen Häufigkeit zur Zeit ihres Aussterbens nicht zuverlässig. Für die letztgenannte Art ist eine drastische Abnahme der Häufigkeit kurz vor dem Aussterben um 37.09 Ma zu bemerken, was sich als zuverlässigeres biochronologisches Ereignis als das letzte Vorkommen erweisen kann. Durch ihr letztes Erscheinen bieten sich *E. obruta* (34.35 Ma), *B. serraculoides* (34.79 Ma.), *C. formosus* (34.87 Ma), *D. barbadiensis* (36.96 Ma), *C. grandis* (40.03 Ma) und *Nannotetrina* spp. (44.21 Ma) als deutliche zeitliche Ereignisse an, dies im Hinblick auf ihre Häufigkeit. Das letzte Ereignis kann als Ersatz für das taxonomisch problematische erste Erscheinen von *R. umbilicus* (44.38 Ma; anhand von Exemplaren >14μm) dienen. Sowohl *D. hesslandii* (42.89 Ma) wie auch *E. obruta* (36.07 Ma) nehmen um ihre jeweils vorgeschlagenen Alter deutlich an Häufigkeit zu. Dagegen ist das erste Erscheinen von *I. recurvus* wegen geringer Häufigkeit im frühen Zeitraum kein zuverlässiger biochronologischer Anzeiger; noch dazu ist sein geographisches Auftreten diachron. Seiner Häufigkeit nach ist das letzte Erscheinen von *I. recurvus* (34.93 Ma) deut-
lich, obwohl der Vorgang geographisch diachron ist. Sein Verschwinden aus dem Südatlantik ist frühzeitig, grob korrelierbar mit Schätzungen aus tropischen Regionen. Kurze Intervalle starker Häufigkeit von *C. reticulatum* und *C. protoannula* können darauf hindeuten, daß ihr letztes Erscheinen (jeweils 37.86 Ma und 38.18 Ma) einen begrenzten biochronologischen Wert hat.

Für die Eozän/Oligozän-Grenze wird anhand des Hole 522 und des Aussterbens von *Hantkenina* ein Alter von 36.15 Ma bis 36.20 Ma vorgeschlagen. Das nächstliegende Nannofossilienereignis ist das erste häufige Erscheinen von *E. obruta* (36.07 Ma) oder, regional (?), der scharfe Umschlag im Verhältnis *R. umbilicus/C. formosus* (36.10 Ma).

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Abstract

Detailed quantitative analyses of selected calcareous nannofossil species from middle Eocene through early Oligocene sediment in South Atlantic (DSDP Sites 522 and 523) have refined the biochronologic precision of these events. The last occurrences of *R. umbilicus* (33.80 Ma) and *D. saipanensis* (36.72 Ma) are not reliable due to low abundance at about the time of extinction. The latter species shows a drastic abundance decline shortly before its extinction, at 37.09 Ma, which may prove to be a more reliable biochronologic indication than its absolutely final occurrence. The last occurrences of *E. obruta* (34.35 Ma), *B. serraculoides* (34.79 Ma.), *C. formosus* (34.87 Ma), *D. barbadiensis* (36.96 Ma), *C. grandis* (40.03 Ma) and *Nannotetrina* spp. (44.21 Ma) all provide distinct species events in terms of abundance patterns. The last event may be used as a substitute for the taxonomically problematic first occurrence of *R. umbilicus* (44.38 Ma; as based on specimens >14μm). Both *D.*

D. hesslandii (42.89 Ma) and *E. obruta* (36.07 Ma) show distinct rises in abundance at the suggested age estimates, whereas the first occurrence of *I. recurvus* hardly represents a reliable biochronologic indication due to its low abundances in the early part of the range and diachronous appearance over geographic distance. The last occurrence of *I. recurvus* (34.93 Ma) is distinct in terms of abundance, albeit diachronous over geographic distance, having an early exit at these South Atlantic sites which roughly correlates with estimates from tropical regions. The short intervals with high abundances of *C. reticulatum* and *C. protoannula* may suggest that their last occurrences (37.86 Ma and 38.18 Ma respectively) perhaps are ambiguous from a biochronological point of view.

An age of 36.15 Ma to 36.20 Ma is suggested for the Eocene/Oligocene boundary, as estimated from Hole 522 and using the *Hantkenina* extinction. The nearest nannofossil event is the first abundant occurrence of *E. obruta* (36.07 Ma) or, regionally (?), the sharp change in proportion between *R. umbilicus* and *C. formosus* (36.10 Ma).

1. Introduction

The biostratigraphy of Cenozoic calcareous nannofossils is known to considerable detail (MARTINI, 1971; BUKRY, 1973, 1975; PERCH-NIELSEN, 1985), but yet there is room for substantial improvements. These
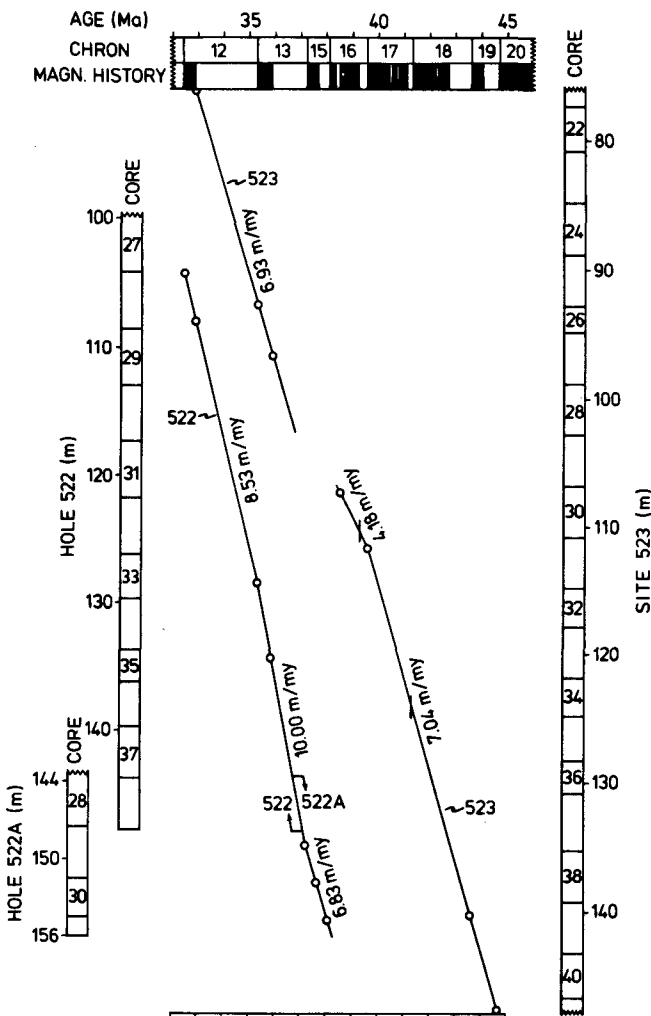

Fig. 1: The age model used in this study.
  See Table 1 for precise age/depth values of the control points. The sediment accumulation rates are expressed as meters/million years (m/m.y.). The arrow at Hole 522 indicates the deepest sample used from that hole, and the arrow at Hole 522A represents the highest sample used from that hole.

can be achieved primarily through quantitative analysis of the accuracy of the species events, but also through determination of additional markers. Direct correlation to magnetostratigraphy transforms a biostratigraphic information to a biochronologic property. The precision of such correlations depends, by and large, on the reliability of the species event as biostratigraphic indication. In turn, this reliability, or accuracy is influenced by factors like the paleoecological preference of the species, changing paleoenvironmental conditions and the taxonomic concept of the biostratigrapher.

There are relatively few Deep Sea Drilling Project (DSDP) sites in which detailed magnetostratigraphy has been established, particularly if considering sequences which are characterised by stratigraphic continuity over longer periods of time. DSDP Leg 73 used the hydraulic piston corer for a drilling program in the southeastern Atlantic Ocean, which was aimed towards the analysis of paleoenvironmental and stratigraphical problems. Subsequent studies of the Leg 73 sediments, (HSÜ, LABRECQUE et al, 1984) revealed the recovery of rather continuous stratigraphic sections from the upper Cretaceous to the Pleistocene, which in many cases yielded magnetostratigraphic results of unusual quality and resolution (TAUXE et al., 1983). The Leg 73 sediments therefore provide near ideal premises for detailed analysis of bio- and magnetostratigraphic correlation from a southern mid-latitude location (25°–29° S, 10°W–3° E).

The purpose of this study has been

1) to determine quantitatively abundance patterns of selected nannofossil species from two Leg 73 sites, in the time interval between about 45 Ma (middle Eocene) and 34 Ma (early Oligocene),

2) to evaluate the accuracy of the species events as biostratigraphic indications
and

3) to establish correlations between the bio- and magneto-stratigraphy.

2. Material and Methods

The two sites studied are Site 522 (26°6.843′S; 5°7.748′W; water depth 4,441 m) and Site 523 (28°33.131′S; 2°15.078′W; water depth 4,562 m). Further information on these sites are given by HSÜ, LABRECQUE et al. (1984). The time control is based on the magnetostratigraphy of TAUXE et al. (1983) and the marine magnetic anomaly time scale of BERGGREN et al. (1986). The magnetostratigraphic control points are presented in Table 1, and these data have been used to calculate sediment accumulation rates (Table 1, Fig. 1). The interpretation of the accumulation rate during Chron 13R-2 of Site 523 is justified by biostratigraphic data presented below.

The counts were made using 20 cm sampling intervals and light microscope techniques. The counting method has been presented by BACKMAN & SHACKLETON (1983) and is further discussed by BACKMAN (1986). In order to account for sediment accumulation rate variations of the different intervals investigated, the plots presented below represent the number of specimens counted per unit area multiplied with the sediment accumulation rate in the pertinent interval, and the plots are therefore expressed as mm^{-2} × **(cm/1000 years)**.

Table 1: Magnetostratigraphic control points for the age model used.

Site	Chron	Depth [m]	Age [Ma]	Rate [m/m.y.]
522	A top C12N	104.30	32.460	
	bottom C12N	108.81*	32.900	
	B top C13N-1	128.45	35.290	A−B = 8.53
	C bottom C13N-2	134.25	35.870	B−C = 10.00
	(C13R-2			10.00[1])
522A	(C13R-2			10.00[2])
	D top C15N-1	148.88	37.240	
	bottom C15N-2	151.80*	37.680	
	E top C16N-1	154.75	38.100	D−E = 6.83
523	F bottom C12N	76.13	32.900	
	top C13N-1	92.70	35.290	
	G bottom C13N-1	96.71*	35.870	F−G = 6.93
	(C13R-2			6.93)
	H top C16N-2[4]	107.40*	38.500	
	bottom C16N-3[4]	110.30*	39.240	
	I top C17N-1	111.71	39.530	H−I = 4.18
	top C18N-1	124.20	41.290	
	top C19N	140.15	43.600	
	J top C20N	147.85	44.660	I−J = 7.04

Depth values are from TAUXE et al. (1983), and those marked (*) are from TAUXE (written communication, 1984). A given depth value represents the midpoint between the two nearest sample levels having different polarity direction. The uncertainty in depth commonly is about ±0.1 m (TAUXE et al., 1983). All reversal boundaries inbetween those used for the sediment accumulation rate calculations fit the suggested age model, except the top of C19N in Site 523. According to TAUXE et al. (1983) this reversal boundary lies between 140.05 and 140.25 m, but the age model used suggests a depth of 140.38 m. The ages of the reversal boundaries are from BERGGREN et al. (1986). The rate marked 10.00[1] in Hole 522 is derived through linear extrapolation from C13N, and the one marked 10.00[2] in Hole 522A is inferred from the corresponding interval in Hole 522. The rate marked 6.93[3] in Site 523 is derived through linear extrapolation from C13N. The identification of the two reversal boundaries marked ([4]) in Site 523 reflects the interpretation of the present writer. A graphical presentation of the age model is shown in Fig. 1.

That is, the plots represent a measure which is roughly proportional to the accumulation of the species. Age is referred to as **Ma** (million years before present) whereas time-intervals are expressed as **m.y.** (million years).

served intact in order to be accounted for as one specimen in the counts. It was noticed that the easiest way to recognise both *B. serraculoides* and *I. recurvus* was to use the combination of interference contrast, gypsum plate and high magnification (×1000).

The characteristic cross-structure of the genus *Chiasmolithus* was lacking in many specimens belonging to this genus, probably due to dissolution. About 10−20 % of the specimens incorporated in the counts of *C. grandis* were lacking the cross in each sample. The size, the optical behaviour between crossed nicols of the placolith rim, and the presence of "teeth" were used to recognise specimens lacking the cross-structure as *C. grandis*.

Dictyococcites scrippsae BUKRY & PERCIVAL, 1971 is considered to be a junior synonym of *D. hesslandii*.

BUKRY (1973) noticed that calcite overgrowth may blur the distinction of *E. obruta, E. fenestrata* (DEFLANDRE & FERT, 1954) STRADNER, 1968 and *E. subdisticha* (ROTH & HAY, 1967) ROTH, 1969. The few specimens observed having pores in the central area were not incorporated in the counts of *E. obruta*.

The species within the *Nannotetrina* spp. concept are not distinguished due to preservational problems (overgrowth). However, the large species *Nannotetrina alata* (MARTINI in MARTINI & STRADNER, 1960) HAQ & LOHMANN, 1976 is not incorporated in the counts of *Nannotetrina* ssp.

Using material from Site 523 BACKMAN & HERMELIN (1986) studied the first appearance of *Reticulofenestra umbilicus* (LEVIN, 1965) MARTINI & RITZKOWSKI, 1968 from a morphometric point of view, and their results indicated that this species should be recognised as having a lower size limit of 14 μm.

BACKMAN (1986) determined the late Eocene abundance patterns of the two rosette-shaped discoasters, *Discoaster barbadiensis* TAN SIN HOK, 1927 and *D. saipanensis* BRAMLETTE & RIEDEL, 1954, using material from site 522.

3. Remarks on Taxonomy

The following species have been studied:

○ *Bramletteius serraculoides* GARTNER, 1969
○ *Calcidiscus formosus* (KAMPTNER, 1963) LOEBLICH & TAPPAN, 1978
○ *Calcidiscus protoannula* (GARTNER, 1971) LOEBLICH & TAPPAN, 1978
○ *Chiasmolithus grandis* (BRAMLETTE & RIEDEL, 1954) RADOMSKI, 1968
○ *Cribrocentrum reticulatum* (GARTNER & SMITH, 1967) PERCH-NIELSEN, 1971
○ *Dictyococcites hesslandii* (HAQ, 1966) HAQ & LOHMANN, 1976
○ *Ericsonia obruta* PERCH-NIELSEN, 1971
○ *Isthmolithus recurvus* DEFLANDRE in DEFLANDRE & FERT, 1954.

In addition to these species, the genus *Nannotetrina* ACHUTAN & STRADNER, 1969 has been studied. Some of these taxonomic categories are commented below.

Complete specimens of *B. serraculoides* were not observed, wherefore this species was identified by the presence of its planar paddle-shaped structure. Many samples contained abundant fragments of the paddle, but at least two thirds of the paddle had to be pre-

4. The Biostratigraphical and Biochronological Significance of the Abundance Patterns

4.1. *Calcidiscus formosus* and *Reticulofenestra umbilicus*

The successive extinctions of *C. formosus* and *R. umbilicus* represent two widely used biostratigraphic indications in the early Oligocene, and both MARTINI (1971) and BUKRY (1973) employed these events in their zonal schemes. Fig. 2 shows that *C. formosus* is characterised by varying but consistently high abundances up to its disappearance shortly above Chron 13. The plots indicate that reworking is negligible at both sites, and that the final occurrences are diachronous, with a younger age (34.87 Ma) at Site 523. Despite this chronological difference of about 0.15 m.y., the extinction of *C. formosus* seems to provide an easily recognisable event in terms of abundance decline.

The abundance pattern of *R. umbilicus* is marked different (Fig. 3), showing an obvious tendency of progressive decline in abundance through most of both records. Considering the absence of reworking of *C. formosus* at both sites, the reduced abundance of *R. um-*
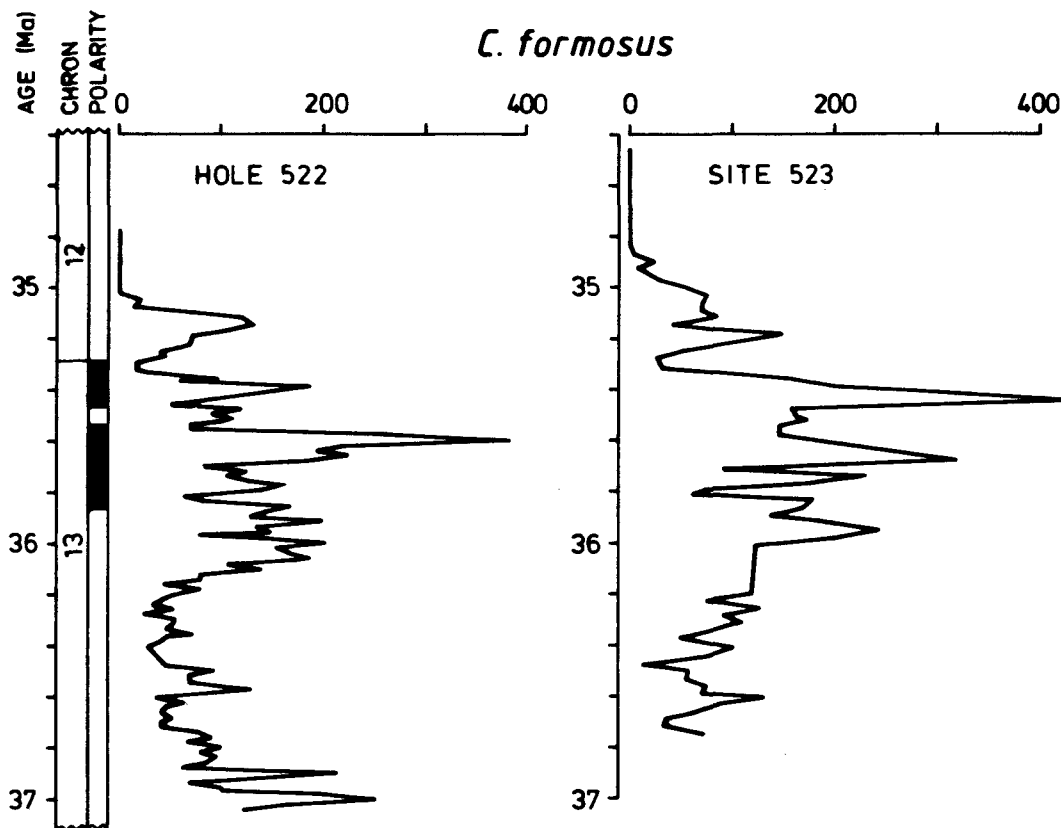
23

Fig. 2: Plots of the abundance of *C. formosus* versus age in Hole 522 and Site 523.
The abundance scale is expressed as number of specimens per square mm times the accumulation rate (cm/1000 years).

bilicus in sediment younger than about 35 Ma seems to represent a true but low accumulation. This interpretation is supported by the known biostratigraphic relationships of these species (e.g. MARTINI, 1971; BUKRY, 1973). The absolutely final occurrence is diachronous (about 0.20 m.y.), and site 523 provides the younger age estimate (33.80 Ma). This suggests that Zone NP 22 of MARTINI (1971) and Subzone CP 16c of OKADA & BUKRY (1980) has a duration of 1.1 m.y., as estimated from Site 523.

HAYS (1971) determined the time of extinction of a (radiolarian) species at a level in the sediment where the abundance falls to 37 percent of the normal. He noticed, however, that it is difficult to establish a firm estimate of the final decline and extinction of a species relative to its normal abundance, and particularly when the species show marked variation in abundance. This idea gains support from the abundance pattern of *R. umbilicus*, because the abundance after 35 Ma (Fig. 3) is rather consistently below 10–15 percent of the abundance before 35 Ma at both sites.

The biochronological property of an extinction to a high degree thus depends on the quantitative concept used of the final abundance decline. At Site 523, for instance, the difficulty of estimating a normal abundance of *R. umbilicus* can be used to argue that its extinction occurs either at 33.80 MA or at 35.06 Ma (Fig. 3), giving an uncertainty of about ±0.6 m.y. In the case of *C. formosus*, the precision is at least one order of magnitude better.

There exists no detailed knowledge about the abundance patterns of *R. umbilicus* from other regions, but the pattern obtained from Sites 522 and 523 suggest that

this species has to be used with considerable caution. The underlying reason for this may be that the paleoenvironmental conditions had an exceptionally strong influence on the abundance variations of *R. umbilicus*.

The proportional relationships of *C. formosus* and *R. umbilicus*

The impression of regularly changing proportions emerged during the counts of *C. formosus* and *R. umbilicus*, and it was thought that this could help solve two problems in the sequence investigated:

1) the problem of diachroneity of their extinctions and
2) the problem of the sediment accumulation rate during Chron 13R-2 at site 523 (Fig. 1).

Fig. 4 shows the time-dependent changes in the proportion of the two species, and the patterns from the two sites are sufficiently similar to allow meaningful comparisons. For instance, the peak and valley marked A and B respectively, are each considered to represent synchronous events. It is also evident that the sharp drop of the striped interval, representing *C. formosus*, occurs at about 35.05 Ma at Site 522 and 34.87 Ma at Site 523. Since the drop occurs across a core boundary (33/32 boundary) in Site 522, this is interpreted to reflect a loss of sediment recovery at precisely that core boundary. Thus, the sediment accumulation rate during Chron 12 of Site 522 probably is somewhat underestimated as shown in Fig. 1. It follows that the age estimated of the species events during that time-interval should be consistently older at Site 522 than those estimated from Site 523, and using the available data the
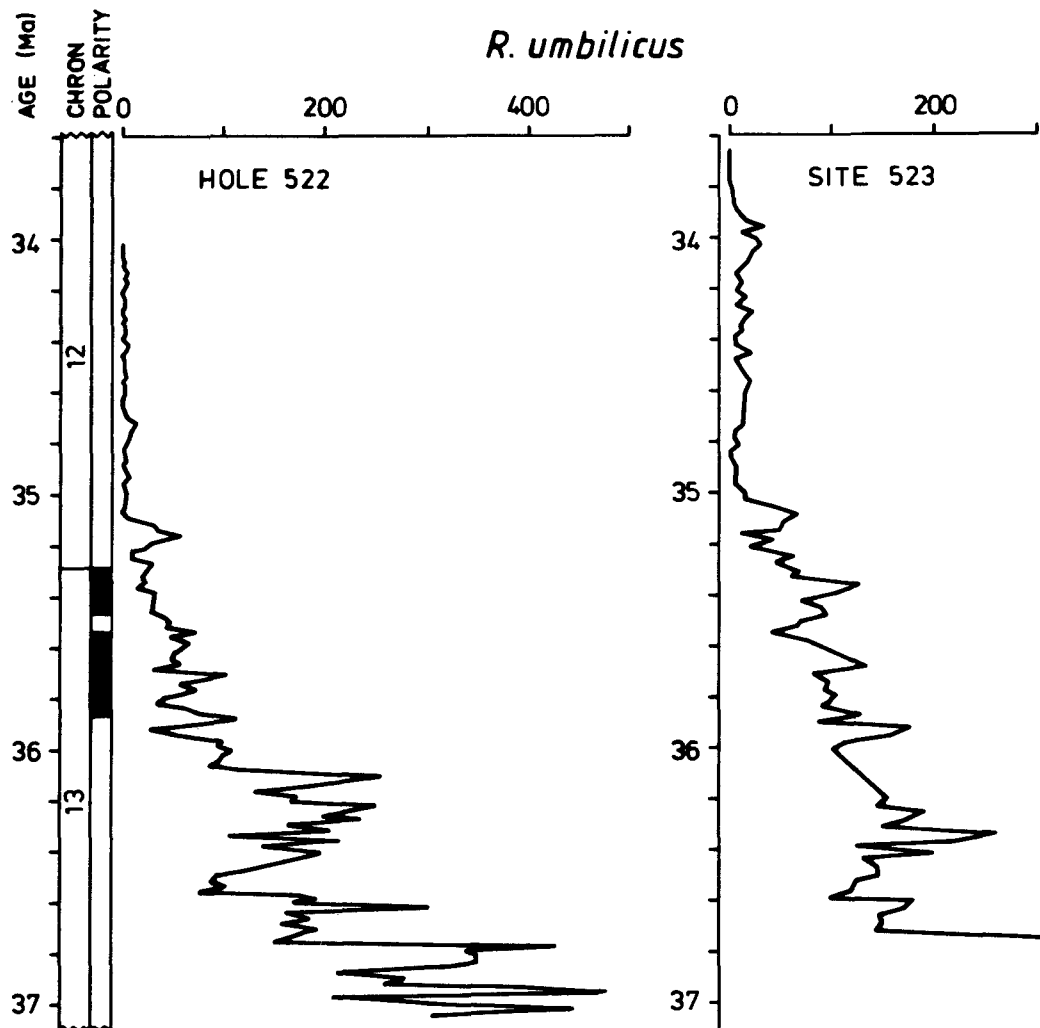
24

Fig. 3: Plots of the abundance of *R. umbilicus* versus age in Hole 522 and Site 523.
The abundance scale is expressed as number of specimens per square mm times the accumulation rate (cm/1000 years).

difference can be calculated to be about 0.15—0.20 m.y. This was the case regarding *C. formosus* and *R. umbilicus*, and also applies for all other events determined in Chron 12, as will be shown below.

At Site 523, the accumulation rate during Chron 13R-2 can be drawn in two ways, either through extrapolation as shown in Fig. 1 or through interpolation between the bottom of Chron 13N-2 and the top of Chron 16N-2. The pattern in Fig. 4 suggests that the levels marked C,D and E each represent a synchronous event. Thus, the extrapolated rate obviously leads to a better estimate of the true rate, because the interpolation would yield an age estimate of nearly 37.3 Ma for the level marked E at Site 523. Furthermore, the rosette-shaped discoasters were still flourishing at 37.3 Ma (BACKMAN, 1986), which is not the case in any of the samples belonging to Chron 13R-2 of Site 523. It is noteworthy how all three levels (C,D,E) have age estimates being about 0.1 m.y. older at Site 523, which probably reflects a misinterpretation of the true subbottom depth of core 28 (top = 98.8 m; 36.17 Ma). The top of core 28 may have been placed too deep because the bottom of core 27 ends at 98.0 m (36.06 Ma).

The cause for the variation in proportion between the two species remains speculative, although changing paleotemperatures of surface waters probably represent a fair guess.

4.2. *Isthmolithus recurvus*

The biostratigraphical value of the entry and exit of *I. recurvus* has to be judged in the light of its paleoenvironmental preferences. In a study using 39 DSDP sites which had sediment recovery from the critical stratigraphic interval, BUKRY (1978) observed that this species occurred only in 23 of the 59 sites. North and south of 30° latitude, *I. recurvus* occurred in all sites investigated, but only in 25 % of the sites located between 20° and 30° latitude (north and south); a percentage which further decreased towards the equator. BUKRY interpreted this pattern of geographic distribution as a paleoecological preference for high latitude environments, that is cooler conditions, since the latitudinal distribution of *I. recurvus* apparently could not be linked to differences in preservational states of the nannofossil assemblages.

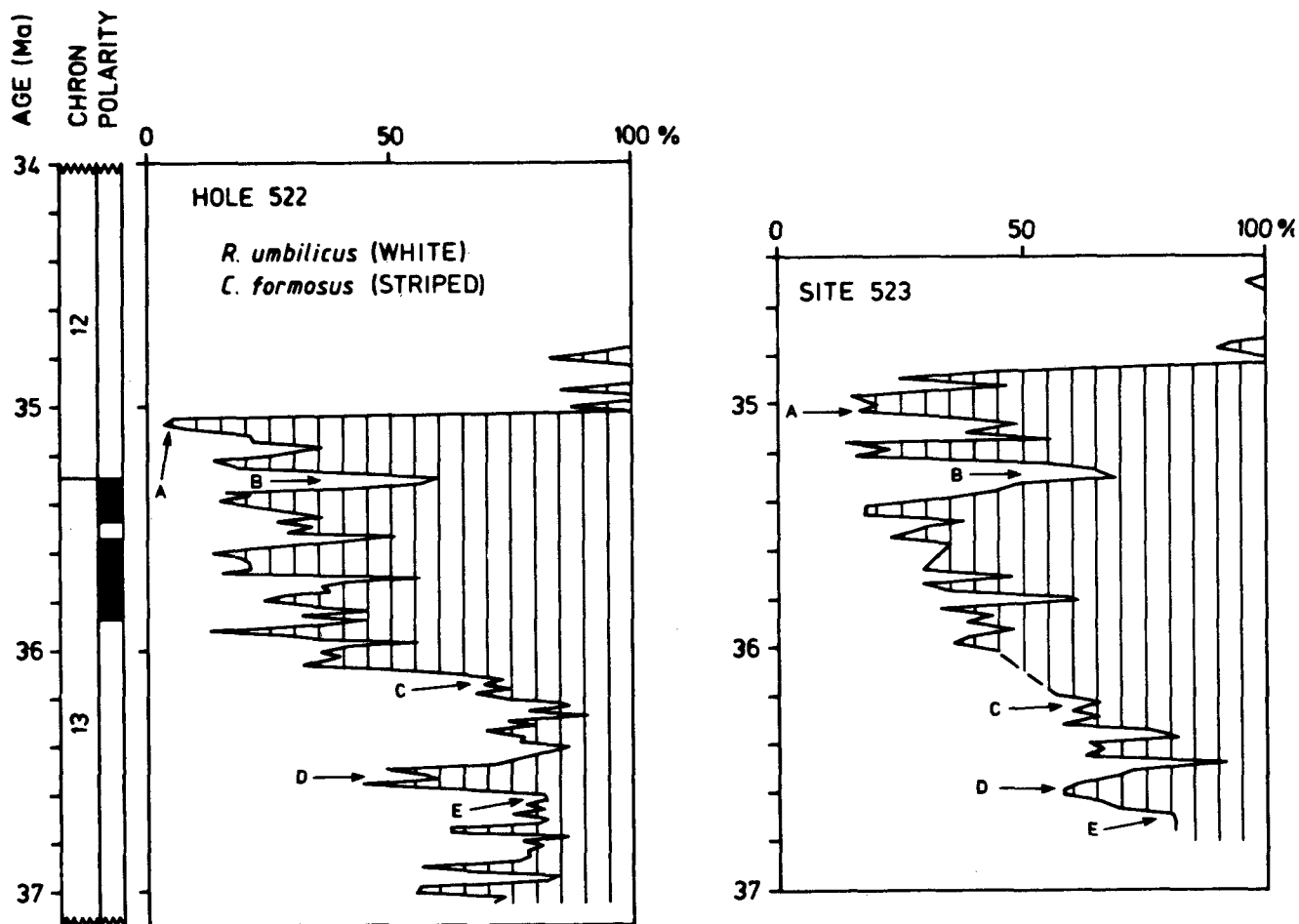The first appearance of *I. recurvus* defines the bottom of both Zone NP 19 (MARTINI, 1971) and Subzone

25

Fig. 4: Plots of the proportional relationship between *R. umbilicus* (Ru) and *C. formosus* (Cf) versus age in Hole 522 and Site 523, calculated as Ru/(Ru + Cf) and expressed in percent.
The sample levels marked A through E are used for correlation between the sites, as discussed in the text.

CP 15b (OKADA & BUKRY, 1980), whereas its disappearance is reported to occur before the extinction of *C. formosus* (top NP 21) at low latitudes (BUKRY, 1973) and at the top of Zone NP 22 at northern mid-latitudes (MARTINI, 1971).

Fig. 5 shows the abundance plots of *I. recurvus* from Sites 522 and 523. Its last occurrence has an age estimated to 34.93 Ma at Site 523 (0.17 m.y. older at site 522). That is, *I. recurvus* disappears two sample levels (<0.1 m.y.) before *C. formosus* at Site 523, and its upper range at these South Atlantic sites therefore agrees with BUKRY's (1973) low-latitude correlation. LOWRIE et al. (1982), however, in using material from one of the Gubbio sections in Italy observed that the final occurrence of *I. recurvus* correlated with MARTINI's (1971) estimate, which was based on material from Germany.

PERCIVAL (1984) suggested that *I. recurvus* has its first appearance close to the bottom of Site 522 (Hole 522A, 37.8 Ma; age estimate from this study), and he did not observe the species below the core recovery gap (core 29, see Fig. 1) in Site 523. Although showing low abundances in Hole 522A, *I. recurvus* is continuously present throughout the drilled sequence of that hole, and is also present below the core recovery gap in Site 523 (Fig. 5). The first appearance is problematic at Site 523, because *I. recurvus* is present in six samples between 40.27 Ma and 40.14 Ma, absent in the next 19 younger

samples and continuously present in sediment younger than 39.46 Ma. For reasons discussed below (see the *C. grandis* section) the latter estimate is interpreted to reflect a more reliable first appearance of *I. recurvus* in Site 523.

Nevertheless, even this younger estimate from immediately above Chron 17 is conceivably older than previously reported. LOWRIE et al. (1982) reported the first appearance of *I. recurvus* from within Chron 15N at Gubbio, whereas MONECHI (1986) observed this event at the very top of Chron 16 from another section in the Gubbio area. In Hungary, however, M. BALDI-BEKE (pers. comm., 1985) has observed this species below Chron 16.

MONECHI (1986) pointed out that the extinction of the planktic foraminifer *Hantkenina*, an event used for recognition of the Eocene/Oligocene boundary, occurs in coincidence with a peak value in the abundance of *I. recurvus* at the Gubbio section. The greatest peak value in Site 522 (Fig. 5) occurs concomitantly with the disappearance of *Hantkenina*, according to the foraminiferal data POORE (1984) presented from this site. Whether or not a cause-and-effect relationship exists between the *I. recurvus* peak, which may be interpreted to represent a short interval of distinctly cooler conditions at northern and southern mid-latitudes, and the *Hantkenina* event is
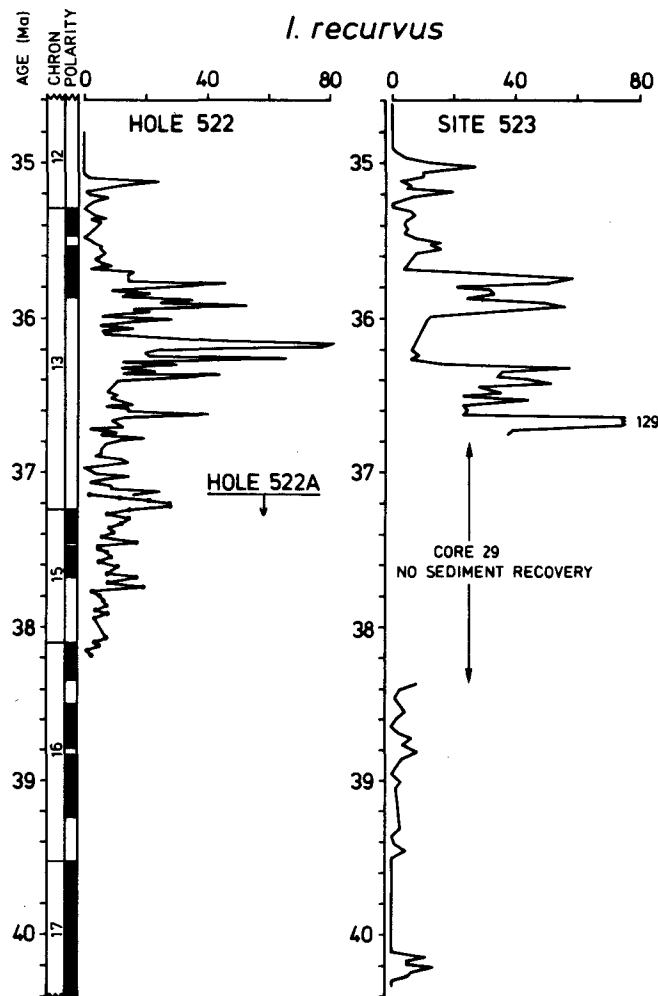
I. recurvus

Fig. 5: Plots of the abundance of I. recurvus versus age in Hole 522, Hole 522A (left) and Site 523 (right).
The abundance scale is expressed as number of specimens per square mm times the accumulation rate (cm/100 years). See Fig. 1 for the sediment recovery gap in Site 523. For reasons discussed in text, the first appearance in Site 523 is suggested at an age of 39.46 Ma rather than the absolutely lowermost occurrence.
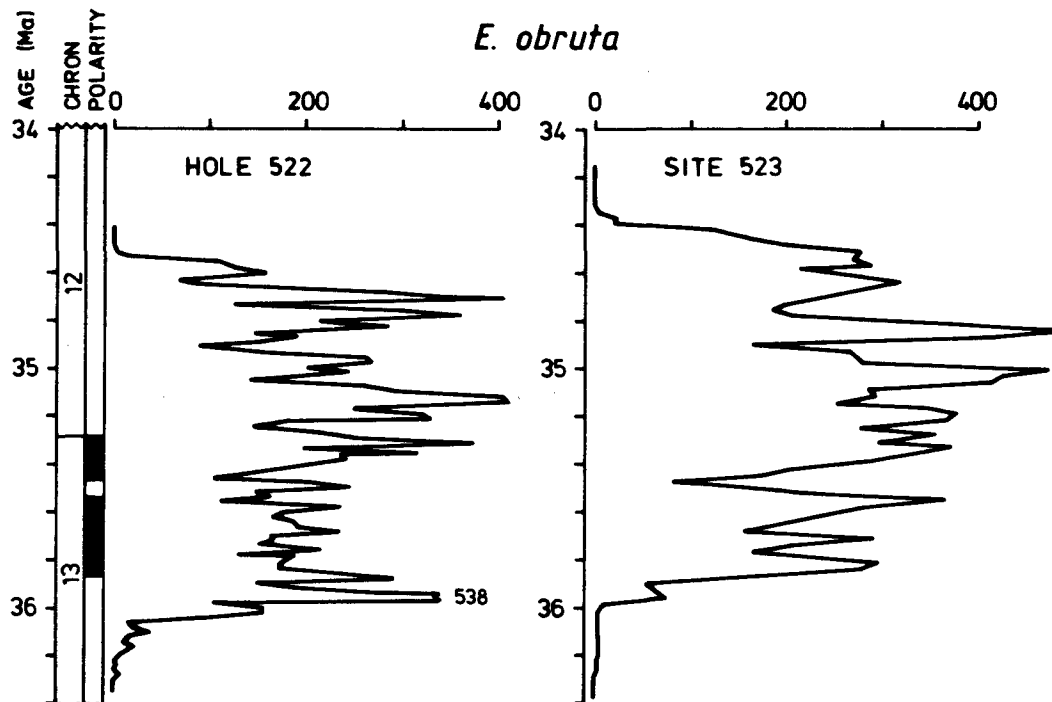
E. obruta

Fig. 6: Plots of the abundance of E. obruta versus age in Hole 522 and Site 523.
The abundance scale is expressed as number of specimens per square mm times the accumulation rate (cm/1000 years).

as yet not known, but the possible connection seems to be an interesting subject deserving further study.

In conclusion, the value of *I. recurvus* apparently seems to be in employing its abundance variations in analysis of paleoenvironmental change, rather than using its first and last occurrence for precise biostratigraphic correlation.

4.3. *Ericsonia obruta*

The species *E. obruta* is a very rare member of the Eocene assemblages until a sharp increase in abundance occurs shortly below Chron 13N, whereafter it is characterised by continuously high, but varying, abundances for about 1.5 m.y. (Fig. 6). The initial sharp rise in abundance does not occur synchronously in the two sites; 36.03–36.07 Ma in Hole 522, 35.87–35.98 Ma in Site 523. This depends either on a true difference in age, in the range of 0.05–0.20 m.y., or a minor error in the correlation of the two sites. The latter explanation seems to be the more plausible one if considering, for instance, the difficulties associated with the determination of exact subbottom depths.

A slightly younger age estimate of the last occurrence of *E. obruta* is obtained from Site 523 (34.35 Ma), as compared to Site 522. The difference amounts to just less than 0.2 m.y., which is in accordance with the previously noticed sediment recovery problem in Chron 12R of Site 522.

Zone NP 21 and NP 22 (MARTINI, 1971) thus may be subdivided into two parts each by using first abundant occurrence, respectively the last occurrence of *E. obruta*. BUKRY (1973) and OKADA & BUKRY (1980) used the end of what they referred to as the acme of *E. subdisticha* (ROTH & HAY, 1967) ROTH, 1959, to subdivide the interval from the last *D. saipanensis* to the last *C. formosus* into Subzones CP 16a and CP 16b which together correspond to Zone NP 21. MARTINI (1971), however, suggested that *E. subdisticha* is common in NP 21 and relatively common in the lower part of NP 22, which presumably implies different ranges of BUKRY's (1973) acme interval of *E. subdisticha* in low and mid-latitude areas.

Taking into account the close taxonomic relationship between *E. subdisticha* and *E. obruta*, it appears tenable to assume that the high abundance interval of *E. obruta* at Sites 522 and 523 represents the interval of "common" to "relatively common" *E. subdisticha* in MARTINI's (1971) sense. Moreover, the fact that BUKRY (1973) explicitly used a broad species concept of *E. subdisticha* suggests

1) that the high abundance interval of *E. obruta* corresponds to BUKRY's acme interval of *E. subdisticha* and
2) that Subzones CP 16a and CP 16b cannot be distinguished in extra-tropical areas.

A weak point in this reasoning, however, is the biased use of the acme concept; of course, a truly recognisable acme interval of *E. obruta/E. subdisticha* may be present in the tropical regions which can be used for subdivision of Zone NP 21 and recognition of the CP 16a/CP 16b boundary. If so, and in order to have any wider application, this acme interval has to be defined quantitatively. An attempt to do this has been made by MONECHI (1986). In using material from the Gubbio area she has observed a sharp rise in abun-

dance of *E. obruta* at a biostratigraphic position which agrees with the results of this study (close to the last occurrence level of *Hantkenina*, in Zone NP 21). A short initial interval of higher abundances of *E. obruta* was followed by an interval of reduced abundances continuing well into Zone NP 22, and MONECHI used the highest abundances for a tentative identification of BUKRY's (1973) acme interval and the two Subzones CP 16a and CP 16b. In doing this she pointed out the close relationship between *E. obruta* and *E. subdisticha*, and treated the high abundances of the former as representing BUKRY's (1973) acme interval of the latter.

In conclusion, the abrupt initial rise in abundance of *E. obruta* appears to represent the best available nannofossil marker for recognition of the Eocene/Oligocene boundary, due to its proximity to the *Hantkenina* event. Both in the South Atlantic sites used here and in Gubbio, these markers subdivide Zone NP 21 into two parts of rather equal duration, while the sharp final abundance decline and extinction of *E. obruta* subdivides Zone NP 22 into two rather equal parts in Sites 522 and 523.

4.4. *Bramletteius serraculoides*

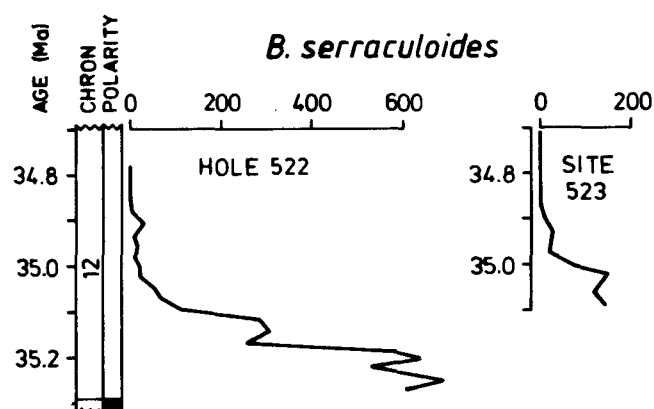The final abundance pattern of *B. serraculoides* is shown in Fig. 7. A sharp drop in abundance occurs at

Fig. 7: Plots of the abundance of *B. serraculoides* versus age in Hole 522 and Site 523.
The abundance scale is expressed as number of specimens per square mm times the accumulation rate (cm/100 years).

the disappearance level of *I. recurvus*, possibly indicating a paleoclimatically caused reduction and disappearance. After this abundance decline, *B. serraculoides* continues with markedly lower abundances for about 0.2 m.y. and again, Site 523 provides a slightly younger age estimate for the absolutely final occurrence level (34.79 Ma). This species event thus is separated from that of *C. formosus* with less than 0.1 m.y. In view of the more distinct abundance decline of the latter species it follows that the last occurrence of *B. serraculoides* provides biostratigraphic and biochronologic information which is of restricted value.

4.5. *Cribrocentrum reticulatum* and *Calcidiscus protoannula*

Cribrocentrum reticulatum has been observed in many

sections of late Eocene age, some of which represent hemipelagic environments, but also from open ocean areas (SHAFIK, 1981). An environmental preference for tropical to temperate conditions was inferred by BUKRY (1977), due to the common occurrences in Zone CP 15 at DSDP Site 366 from the eastern equatorial Atlantic. Zone CP 15 comprises the entire late Eocene according to BERGGREN et al. (1986). SHAFIK (1981) correlated the extinction of *C. reticulatum* to the upper part of Zone P 16 (BLOW, 1969), which encompasses Chron 15 (BERG-GREN et al., 1986), in sections from southern Australia.

Fig. 8 shows the abundance pattern of *C. reticulatum* from Hole 522A. The species has not been observed in Hole 522 which suggests that its highest occurrence is represented in Fig. 8, at the very bottom of Chron 15N-2 (37.65–37.71 Ma). The biostratigraphic position of this extinction consequently agrees with SHAFIK's (1981) results from the Australian section (about 35° to 39°S). However, the high abundance interval of *C. reticulatum* in the South Atlantic site has a markedly short duration (about 0.1 m.y.), which possibly indicates a short period of warmer conditions. It follows that this species event has to be considerably less reliable in terms of accurate biochronology when material from different latitudes is investigated.

The abundance pattern of *C. protoannula* is also shown in Fig. 8. At Site 522 this species has been observed only in the two deepest samples of Hole 522A (38.15 Ma and 38.18 Ma). Occasional rare occurrences were observed in sediment of middle Eocene age at Site 523. GARTNER (1971) noticed that *C. protoannula* was abundant throughout the middle and upper Eocene in the type section but that it was virtually absent in other, adjacent sections covering the same stratigraphic interval, and concluded that its geographic distribution was environmentally controlled.
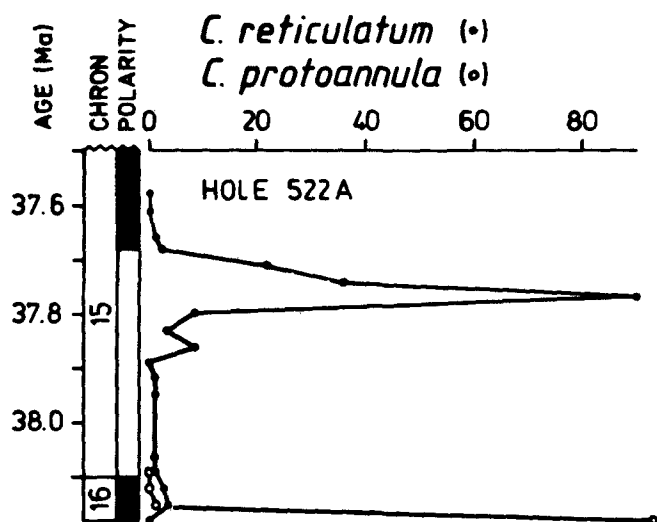

Fig. 8: Plots of the abundance of *C. reticulatum* and *C. protoannula* versus age in Hole 522A.
The abundance scale is expressed as number of specimens per square mm times the accumulation rate (cm/100 years).

4.6. Chiasmolithus grandis and Nannotetrina ssp.

BUKRY (1975) used the extinction of *C. grandis* to define the bottom of the *Chiasmolithus oamaruensis* Subzone

(the CP 14b/CP 15a boundary, OKADA & BUKRY, 1980), and suggested that this zonal boundary represents the NP 17/NP 18 boundary in the zonal scheme of MARTINI (1971). The abundance pattern of *C. grandis* during its final two million years of existence, as derived from Site 523, is shown in Fig. 9. This species shows a drastic abundance decline and highly distinct disappearance which occurs between 40.00 Ma and 40.03 Ma.

In studying *Discoaster/Chiamolithus* percent ratios over latitude, BUKRY (1978) concluded that chiasmoliths preferred cold-water environments. The peaks and valleys in the abundance of *C. grandis* at Site 523 (Fig. 9) therefore may imply changing paleotemperatures of surface waters, the peaks representing relatively cooler conditions and vice versa.

Chiasmolithus grandis is continuously present prior to the extinction except in five samples located immediately below the final abundance peak, and these samples also contain the isolated occurrence of *I. recurvus* (see Fig. 5). This coincidence is interpreted to reflect downhole contamination, partly because the stratigraphic
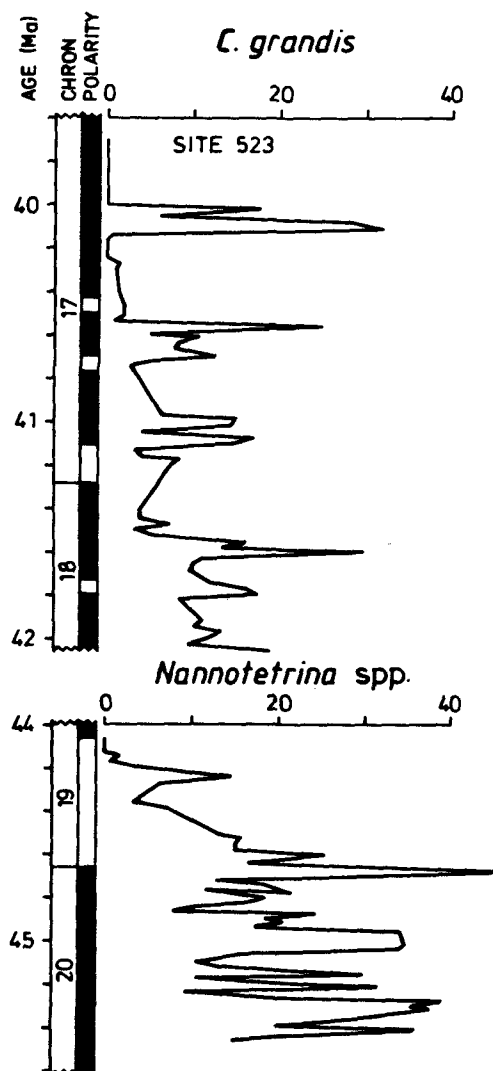

Fig. 9: Plots of the abundance of *C. grandis* and *Nannotetrina* spp. versus age in Site 523.
The abundance scale is expressed as number of specimens per square mm times the accumulation rate (cm/100 years). Notice the zero abundance of the former species immediately below the final abundance peak, which is used in the interpretation of the first appearance of *I. recurvus* (fig. 5).

ranges of these two species are known for being separated.

Fig. 9 also shows that, further downhole in Site 523, the extinction of *Nannotetrina* spp. occurs in the upper part of Chron 19R between 44.14 Ma (absolutely final occurrence) and 44.21 Ma. The extinction of *Nannotetrina* spp. occurs near concomitantly with the problematic first appearance of *R. umbilicus* (BUKRY, 1973). The former event therefore seems to represent a valuable substitute for the first appearance of *R. umbilicus* (about 0.2 m.y. earlier), since the size definition of the latter is so critical for its biostratigraphical and biochronological properties (BACKMAN & HERMELIN, 1986).

4.7. *Dictyococcites hesslandii*

Fig. 10 shows the last species event investigated, namely the first appearance of *D. hesslandii*. The initial rise in abundance is very sharp, occurring across a core boundary (core 37/38 boundary) between 42.86 Ma and 42.89 Ma in Chron 18R-3. After its initial rise in abundance this species becomes an abundant member of the nannofossil assemblages throughout the investigated sequences.

In low latitude areas BUKRY (1973) observed the appearance of the "*Dictyococcites bisectus-D. scrippsae* group", the latter here treated as a synonym of *D. hesslandii*, at a biostratigraphic position which roughly corresponds to the appearance level of *D. hesslandii* at Site 523. The appearance of this easily identified species thus may provide a distinct event which can be applied over wide geographic distances.
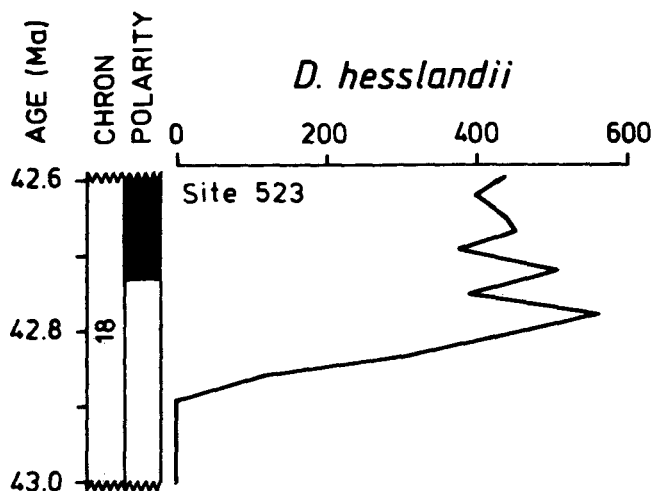

Fig. 10: Plots of the abundance of *D. hesslandii* versus age in Site 523. The abundance scale is expressed as number of specimens per square mm times the accumulation rate (cm/1000 years).

5. The Age of the Eocene/Oligocene Boundary

The Eocene/Oligocene boundary is biostratigraphically recognised by the last occurrences of *Hantkenina* and the *Globorotalia cerroazulensis-G. cocaensis* group (BERGGREN et al., 1986). They used the biostratigraphy of these events as presented by POORE (1984) from Site 522 to derive an age estimate of 36.6 Ma for the
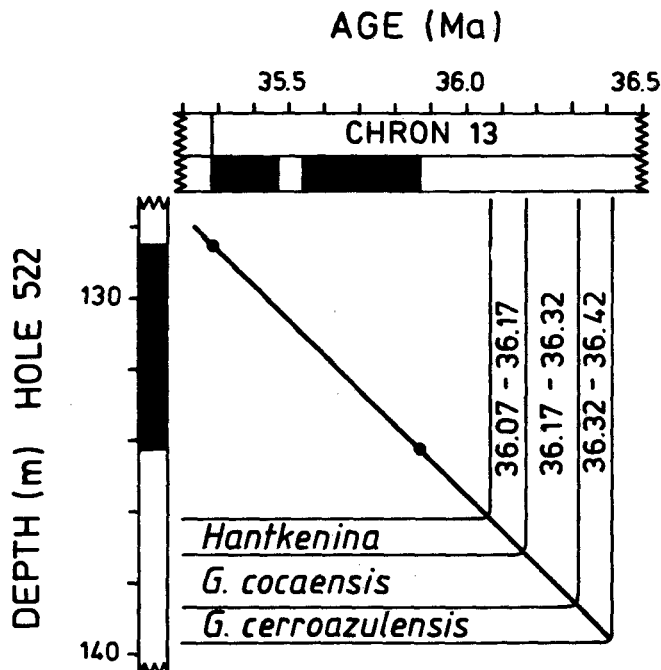

Fig. 11: Depth/age plots of the extinction events of three planktonic foraminiferal species which are critical for the recognition of the Eocene/Oligocene boundary, using the age model of this study (Fig. 1, Table 1). The subbottom depths of these events are taken from POORE (1984). The black interval in the depth column of Hole 522 represents Chron 13N (TAUXE et al., 1983). The *Hantkenina* event is the most critical one for recognition of the Epoch boundary, and the plots thus suggest an age estimate which is about 0.4 m.y. younger than the estimate presented by BERGGREN et al. (1986), which was based on the same criteria as presented here.

Eocene/Oligocene boundary. Meaningful comparisons of such age estimates require identical premises, that is, the use of the same time-scale and the same species event(s). The adoption of the same criteria as BERGGREN et al. (1986) used for definition of the Eocene/Oligocene boundary leads, however, to a younger age estimate of the boundary, according to the age model of this study.

Fig. 11 shows the age estimates of the three critical foraminiferal indications as derived from the age model of this study (Table 1; Fig 1). The *Hantkenina* extinction event, which is the most important one in terms of boundary definition and has an age of about 36.07–36.17 Ma, thus is roughly 0.4–0.5 m.y. younger than the estimate of BERGGREN et al. (1985; 36.6 Ma). It is noteworthy that linear interpolation between the bottom of Chron 13N-2 in Hole 522 and the top of Chron 15N-1 in Hole 522A gives virtually identical age estimates of the *Hantkenina* event (36.05–36.15 Ma).

At least two short intervals of normal polarity have been identified in Hole 522 during the dominantly reversed interval of Chron 13R-2 (TAUXE et al., 1983; fig. 6), and the upper one is associated with the Eocene/Oligocene boundary. Data shown by MONECHI (1986) from the Gubbio area suggest that three normals are present in the reversed interval above Chron 15, and that the boundary is linked with the uppermost one. Linear interpolation in the Gubbio section, from the bottom of Chron 13N-2 to the top of Chron 15, gives an approximative age of 36.18 Ma of the Eocene/Oligocene boundary, as based on the *Hantkenina* event. This event consequently can be considered to have occurred synchronously in the Gubbio area and at the South Atlantic sites.

Using the marine magnetic anomaly time-scale of BERGGREN et al. (1986) therefore suggests an age of the Eocene/Oligocene boundary of about 36.15—36.20 Ma. In nannofossil biostratigraphy this boundary may be recognised by the sharp rise in abundance of *E. obruta* (36.03—36.07 Ma), and perhaps by a marked change in proportion between *R. umbilicus* and *C. formosus*. The former species shows a distinct proportional increase to values in excess of 60 % in sediment being older than 36.10 Ma. If this increase can be applied in other areas is presently not known.

6. Concluding remarks

The biochronology presented in this study is not likely to remain unchanged as sediment from different areas and latitudes are investigated with similar methods. Neither does this study reveal the ultimate biostratigraphical resolution which ist attainable in the pertinent stratigraphic interval. The resolution certainly can be improved, and then particularly in the middle Eocene, in which, for example, several of the zonal markers that were suggested by MARTINI (1971) and BUKRY (1973; 1975) are excluded. Moreover, the question of dia- or syn-chroneity of the species events over geographic distance remains at large unanswered due to the limited spatial distribution of the study material.

Yet it is considered that detailed quantitative studies of the kind presented herein are necessary for accurate evaluation of the species events and their biochronological, biostratigraphical precision in sections lacking magnetostratigraphy. Another obvious strength of the detailed quantitative studies which has been demonstrated in this paper is that they provide the means for accurate correlation between adjacent holes, as well as for revealing the existence of even minor errors in the recovery of sediment caused during the drilling process. A summary of the results is presented in Table 2 and Fig. 12.
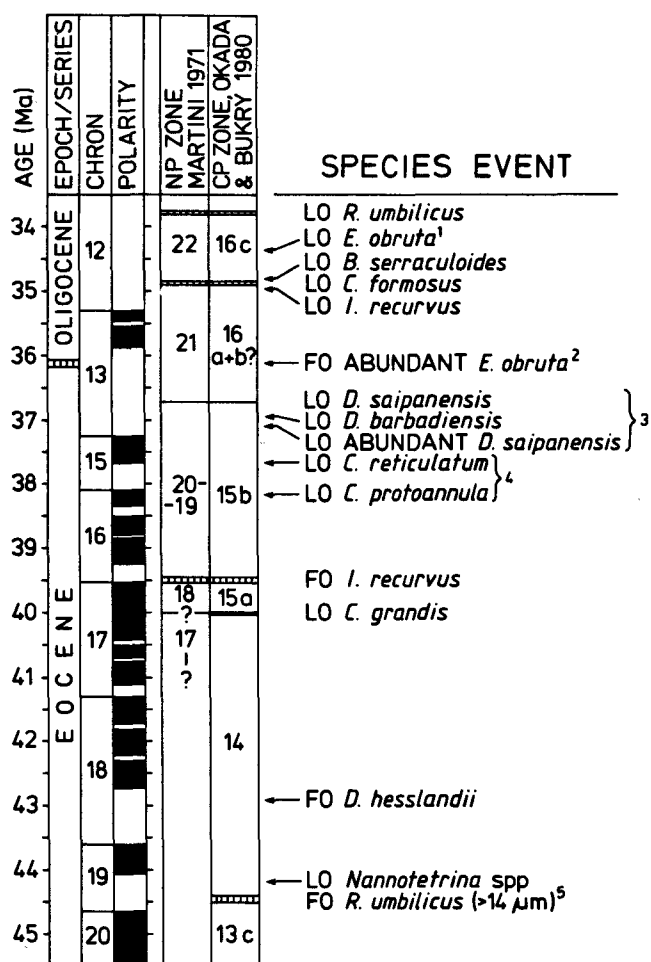

Fig. 12: Summary of the correlation between biostratigraphy and magnetostratigraphy.
LO represents the last occurrence and FO the first occurrence of a species. The Eocene/Oligocene boundary is given a chronological value which is in accordance with the result of this study. The ages of the geomagnetic reversal boundaries are taken from BERGGREN et al. (1986). The tentative correlation of the bottom of Zone NP 18 is based on the suggestion by BUKRY (1975), that the last occurrence of *C. grandis* and the first occurrence of *C. oamaruensis* are approximately synchronous. The absence of NP zonal boundaries below the bottom of NP 18 reflects the fact that several of MARTINI's (1971) middle Eocene zonal markers are not included in this study.
The superscripts in the species event column refer to the following: (1) This species event eventually may represent the end of the acme of *E. subdisticha* in BUKRY's (1973) sense; (2) The correlation is derived from Hole 522; (3) The correlation is derived from Hole 522, according to data presented by BACKMAN (1986); (4) The correlation is derived from Hole 522A; (5) The correlation is valid for specimens >14 μm, according to data presented by BACKMAN & HERMELIN (1986). All other correlations are derived from Site 523. See Table 2 for precise age estimates of these species events.

Table 2: Summary of biochronological properties of the species events investigated.

Species event	Age [Ma]	Zone (top)	Comment
LO *R. umbilicus*	33.80[1]	NP 22/CP 16c	Not reliable; low abundance
LO *E. obruta*	34.35[1]	CP 16a?	Distinct; diachronous?
LO *B. serraculoides*	34.79[1]	—	Rather distinct
LO *C. formosus*	34.87[1]	NP 21/CP 16b	Distinct
LO *I. recurvus*	34.93[1]	—	Distinct but diachronous
FO *E. obruta*	36.07[2]	—	Sharp rise in abundance
R. umbilicus/ C. formosus ratio	36.10[2]	—	Drastic proportional change
LO *D. saipanensis*[3]	36.72[2]	NP 20/CP 15b	Not reliable; low abundance
LO *D. barbadiensis*[3]	36.96[2]	CP 15b	Distinct
D. saipaniensis[3]	37.09[2]	—	Drastic abundance decline
LO *C. reticulatum*	37.68[4]	—	Distinct; use with caution
LO *C. protoannula*	38.18[4]	—	Distinct; use with caution
FO *I. recurvus*	39.46[1]	NP 18/CP 15a	Low abundance; diachronous
LO *C. grandis*	40.03[1]	CP 14b	Distinct
FO *D. hesslandii*	42.89[1]	—	Distinct
LO *Nannotetrina* ssp.	44.21[1]	—	Distinct
FO *R. umbilicus*[5]	44.38[1]	CP 13c	Placolith size >14 μm

LO represents last occurrence and FO represents first occurrence (see species event column). The superscripts in the age column refer to the site from which the age estimate is derived (1) = Site 523, (2) = Hole 522 and (4) = Hole 522A. The superscripts in the species events column refer to data presented by BACKMAN (1986) (3) and by BACKMAN & HERMELIN (1986) (5). The NP zonal system refers to MARTINI (1971) and the CP zonal system refers to OKADA & BUKRY (1980). The comments are based on results as discussed in the text. See Fig. 12 for a graphical presentation of these results.

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