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# Current Tertiary and Quaternary calcareous nannoplankton stratigraphy and correlations

by ERLEND MARTINI and CARLA MÜLLER*

with 7 tables

**Zusammenfassung.** Die Standard Nannoplankton Zonierung wird vorwiegend aufgrund von Ergebnissen des Tiefseebohrprogramms (DSDP) auf den neuesten Stand gebracht. Da einige Arten, die als Leitformen benutzt wurden, durch paläoklimatische Einflüsse oder durch Paläowassertiefen in ihrem Leitwert begrenzt sind, werden als Ersatz zusätzliche Arten für die Bestimmung der NP- und NN-Zonen aufgeführt. Korrelationen zu den planktonischen Foraminiferen Zonen, zu der paläomagnetischen Zeiteinteilung und zu anderen kalkigen Nannoplankton Zonierungen (OKADA & BUKRY 1980) werden angegeben und diskutiert. Verbreitungstabellen für die wichtigsten Nannoplankton-Arten im Tertiär und Quartär sind beigegeben.

**Abstract.** The nannoplankton zonation is updated on basis of new information mainly from the Deep Sea Drilling Project (DSDP). Because certain species used as datum indicators are restricted by paleoclimatic or paleodepth conditions additional species for identifying the NP- and NN-zones are mentioned as substitutes. Correlations to planktonic foraminiferal zones, the paleomagnetic time scale, and other calcareous nannoplankton zonations (OKADA & BUKRY 1980) are indicated and discussed. Range charts for most of the important species in the Tertiary and Quaternary are given.

## Introduction

Based on numerous investigations by the micropaleontological working group on the Mediterranean Neogene and paleontologists participating in the Deep Sea Drilling Project, the correlations between planktonic foraminiferal zones (BLOW 1969, BERGGREN et al. 1984) and nannoplankton zones (MARTINI 1971, OKADA & BUKRY 1980) are rather well established for the Tertiary and Quaternary (Tables 1, 2).

Unfortunately correlation schemes as published by BERGGREN et al. (1983) and BERGGREN et al. (1984) may rise some confusion (Table 3). Great progress was achieved during the last years concerning the correlation of biozones and paleomagnetic anomalies (RYAN et al. 1974, BERGGREN et al. 1983, 1984). The callibration to absolute ages, however, is still under discussion, and it is necessary to gather as many data as possible. The quality of these data

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Table 1 Correlation of Paleogene foraminiferal zones (Blow 1969) and calcareous nannoplankton zones (Martini 1971; Okada & Bukry 1980).

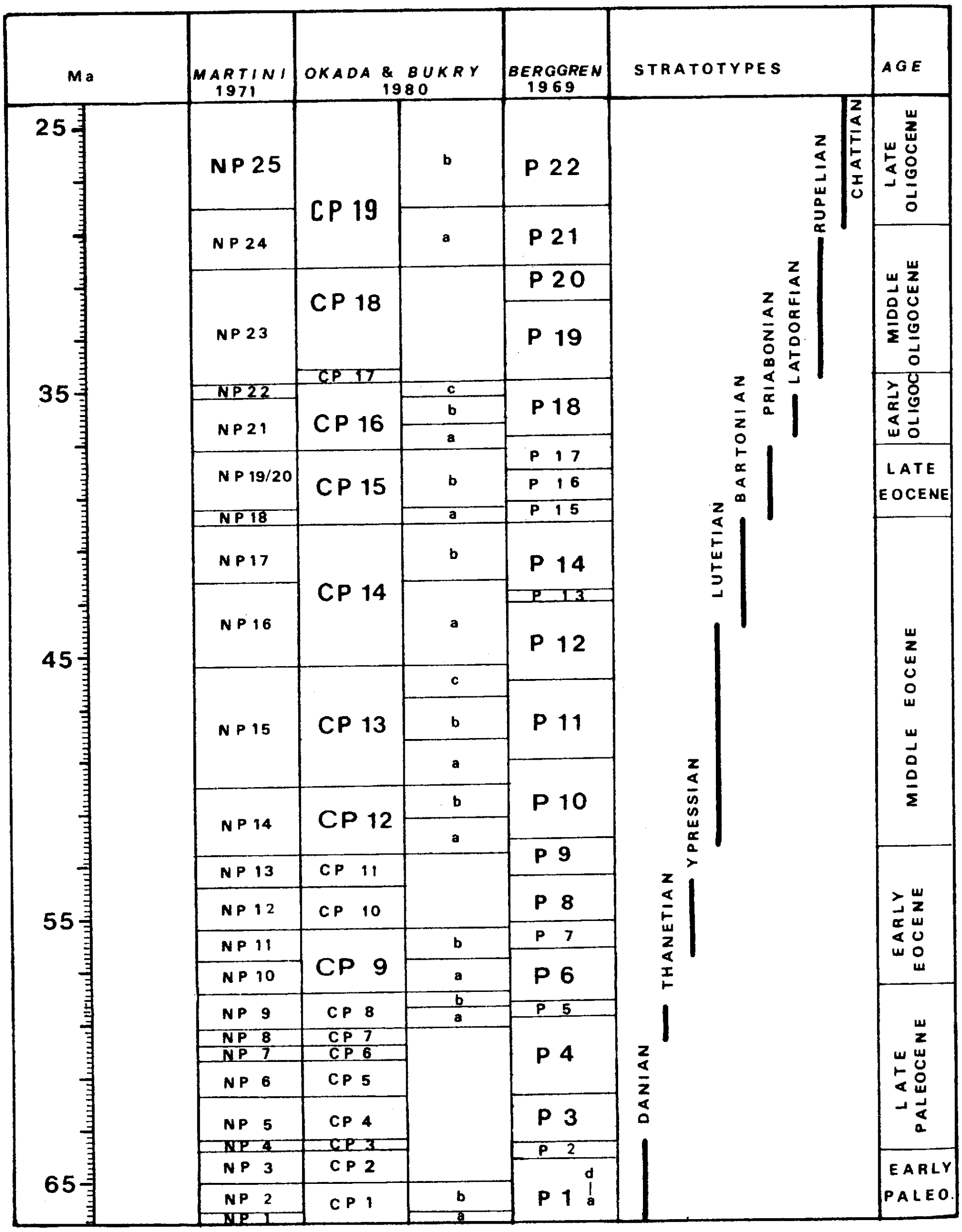


Table 2 Correlation of Neogene and Quaternary foraminiferal zones (Blow 1969) and calcareous nannoplankton zones (Martini 1971; Okada & Bukry 1980).

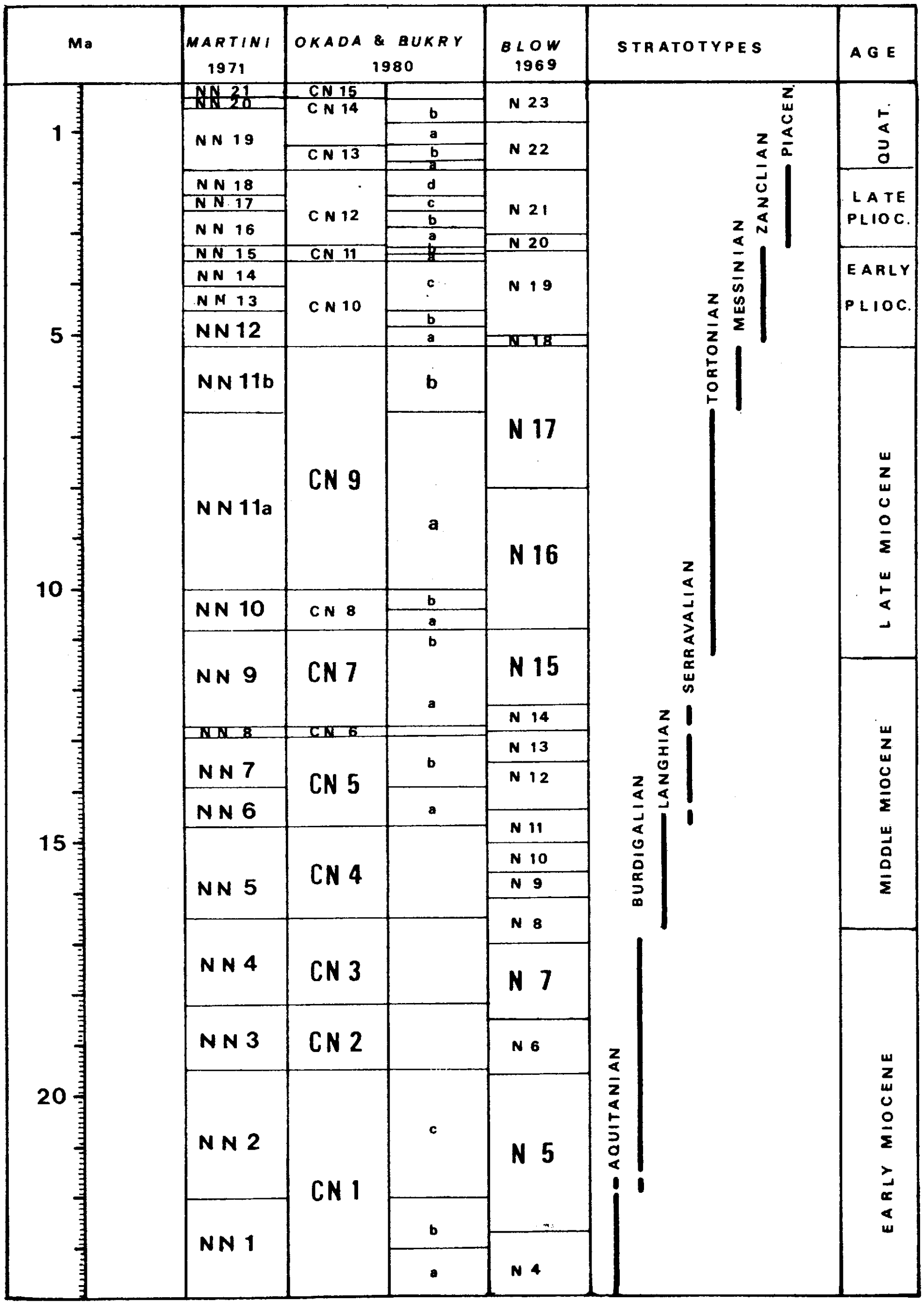
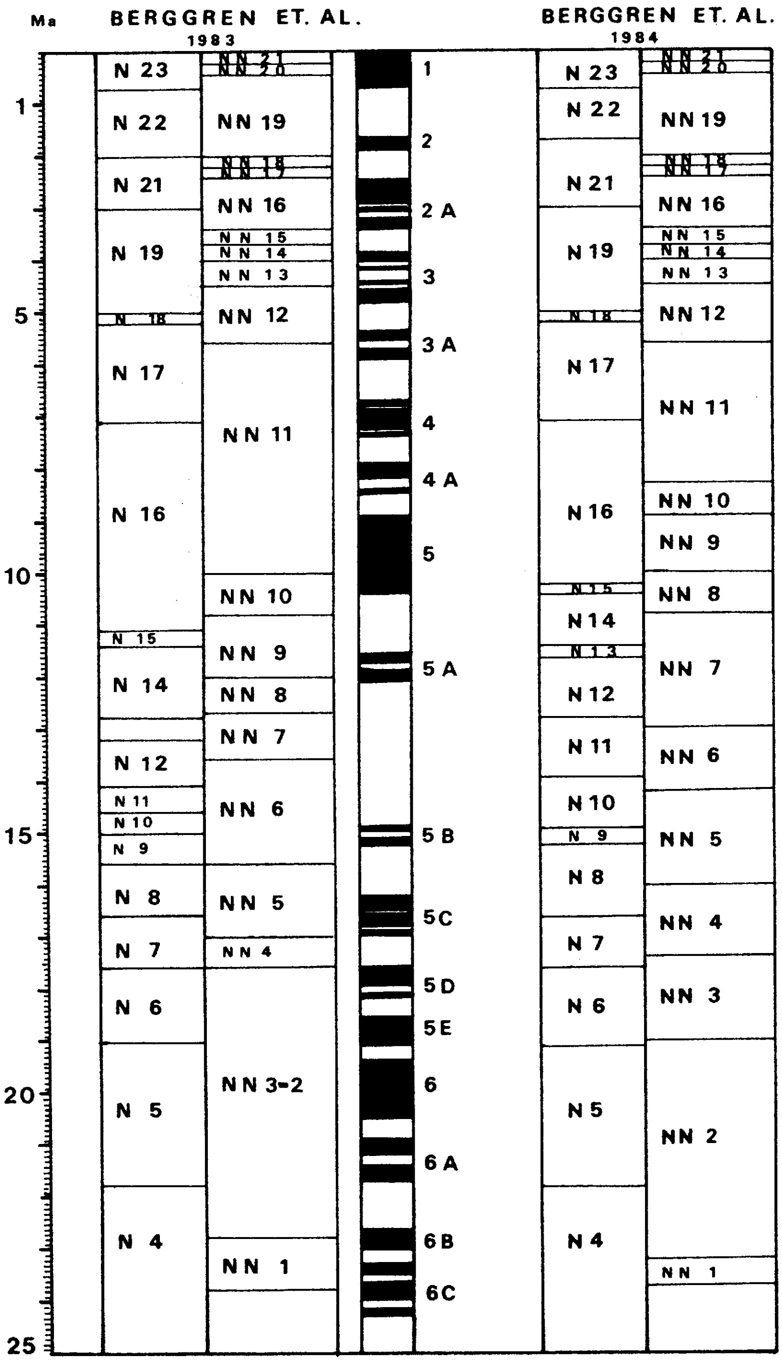


Table 3 Comparison of the correlation schemes published by BERGGREN et al. 1983 and BERGGREN et al. 1984.



depends on the paleomagnetic and biostratigraphic resolution which can be obtained from a section. Particularly in condensed sequences it seems difficult to obtain sufficient paleomagnetic resolution.

Determination of some biozones by the first or last occurrence of the zonal markers may be unreliable due to paleoecological conditions influencing the stratigraphic ranges of the utilized species. This fact may explain why often considerable differences are to be observed for the time interval assumed for the same biozone between certain correlation schemes. Unsufficient biostratigraphic resolution diminishes considerably the data published recently by Hsü et al. (1984), because only a few zonal boundaries were determined exactly.

## Comments on the standard nannoplankton zonation

The Standard Zonation was introduced and discussed in detail by MARTINI in 1971, following short preliminary notes by MARTINI & WORSLEY (1970) and MARTINI (1970) subdividing the Paleogene into 25 zones (NP 1 to NP 25) and the Neogene-Quaternary into 21 zones (NN 1 to NN 21). The boundaries are well defined by the first or last occurrence of zonal markers. The most typical species for each zone are listed and biostratigraphic events within the zones are discussed. This zonation is partially based on a compilation of zones earlier established for certain stratigraphic intervals (HAY & MOHLER 1967; HAY et al. 1967, BRAMLETTE & WILCOXON 1967, GARTNER 1969), and can be used for worldwide correlations, as has been proved during the Deep Sea Drilling Project. It is particularily applicable for dating landsections and well-cuttings.

BUKRY (1973) established the "low-latitude coccolith biostratigraphic zonation". Most of the zonal markers are the same as used in the standard zonation. But for some intervals additional subzones allow more precise dating in some areas. OKADA & BUKRY (1980) added code numbers for the zones and subzones (CP = Paleogene, CN = Neogene) and gave a correlation with the standard zonation of 1971.

Results gathered during 15 years of the Deep Sea Drilling Project and other studies make it necessary to revise slightly the standard zonation and the range of several species. Additional species turned out to be useful markers whereas other ones have shown to be of only limited value.

More detailed informations have been obtained concerning the paleogeographic distribution of the species and their value for paleoenvironmental interpretations. However, most of the index fossils are the same as used before. This is the case especially in the Paleogene, when latitudinal differentiations were less pronounced due to more uniform climate. The continuous evolution and creation of oceanic basins by sea floor spreading led to the etablishment of bottom currents, stratification of water masses and more differentiated climatic zones. This resulted in a distinct latitudinal zonation of the oceans since the end of the Paleogene.

### Paleogene

According to the standard zonation the Cretaceous/Tertiary boundary is defined by the extinction of *Arkhangelskiella cymbiformis* and other Cretaceous species. The most significant horizon separating the Cretaceous-Paleocene series is characterized by an almost monospecific assemblage of *Thoracosphaera* combined with a distinct drop in $CaCO_3$ content as observed in deep sea as well as in land sections (PERCH-NIELSEN 1977, 1981, THIERSTEIN & OKADA 1979, MÜLLER 1979) and which seems to indicate a worldwide event. The first occurrence of *Biantholithus sparsus* is only of limited value. The species is generally very rare (PERCH-NIELSEN 1977, MÜLLER 1985) and occurs already in an interval with only Cretaceous species below the *Thoracosphaera*-horizon (MÜLLER 1985).

PERCH-NIELSEN (1979) subdivided the Danian into a number of short subzones which can be recognized only by using the electronmicroscope, and which are not discussed here. The *Discoaster gemmeus* zone (NP 7) is changed to *Discoaster mohleri* zone since the two species are synonymous. No other changes are necessary for the Paleocene. BUKRY (1973) used the same species as zonal markers. Additionally he subdivided the *Discoaster multiradiatus* zone (NP 9) by the first occurrence of *Campylosphaera eodela* into two subzones. The latter species differs from *Campylosphaera dela* only by its smaller size and is here considered as ancestor of *C. dela.* The evolution from small ancestors of a species to those of normal size is an often observed phenomenon. *Rhomboaster cuspis* was used by EDWARDS (1971) to introduce the *Rhomboaster cuspis* zone within the uppermost Paleocene (part of NP 9). This species can be a good marker in near-shore areas (MÜLLER 1978).

The Lower Eocene nannoplankton zones (NP 10 to NP 13) are well defined by widely distributed species which are also used by BUKRY (1973). *Imperiaster obscurus* mentioned from zones NP 11 and NP 12 seems to be restricted to the North European epicontinental basins and to the Ural street (MARTINI 1970, 1971).

Some difficulties exist for the Middle Eocene (zones NP 14 to NP 17). The *Discoaster sublodoensis* zone (NP 14) is subdivided by BUKRY (1973) into a lower *Discoasteroides kuepperi* and an upper *Rhabdosphaera inflata* Subzone by the first occurrence of *Rhabdosphaera inflata.* This species turned out to be a good marker with a rather wide distribution. Zone NP 15 (*Chiphragmalithus alatus* zone) is defined as interval from the first occurrence of *Chiphragmolithus alatus* to the last occurrence of *Blackites (= Rhabdosphaera) gladius.* However, the latter species seems to have only a local distribution. It is well known from the NW European basins but it was not found in other regions. The first occurrence of *Discoaster tani nodifer* is therefore proposed to subdivide zones NP 15 and NP 16 (MÜLLER 1974, 1979). BUKRY (1973) used the first appearance of *Reticulofenestra umbilica* and *Discoaster bifax* to mark the top of zone NP 15. The same biostratigraphic event is used by HAQ (1984). However, typical forms of *Reticulofenestra umbilica* are known already from zone NP 14 (MÜLLER 1979) whereas the smaller and more rounded ancestral forms of *Reticulofenestra umbilica* are known from zone NP 13. Generally *Discoaster bifax* seems to be less common than *Discoaster tani nodifer* so that its value as zonal marker is more limited. *Chiasmolithus gigas* is restricted to the lower-middle part of zone NP 15. *Discoaster martinii* is typical for this zone, but it never becomes frequent.

The determination of the Middle/Upper Eocene boundary (NP 17/NP 18) and the subdivision of the Upper Eocene are difficult in tropical areas, where the zonal markers (*Chiasmolithus oamaruensis* and *Isthmolitus recurvus* are rare or missing. These species are common in temperate and cold water. MARTINI (1976) proposed the last occurrence of *Chiasmolithus grandis* for the determination of the boundary between zones NP 18–NP 19. But this species may be also rare in some areas. Zones NP 19–NP 20 have to be combined as also indicated

Table 4 Standard calcareous nannoplankton zonation in the Paleogene and correlation to the zonation of Okada & Bukry (1980).

| AGE | STANDARD ZONATION (MARTINI 1971) | | |
|---|---|---|---|
| | | | H. recta + |
| Late Oligocene | NP 25 | Sphenolithus ciperoensis | |
| | | | S. distentus + |
| Middle Oligocene | NP 24 | Sphenolithus distentus | |
| | | | S. ciperoensis * |
| | NP 23 | Sphenolithus predistentus | |
| | | | R. umbilica + |
| Early Oligocene | NP 22 | Helicosphaera reticulata | |
| | | | C. formosus + |
| | NP 21 | Ericsonia subdisticha | |
| | | | D. saipanensis + |
| Late Eocene | NP 20 | Sphenolithus pseudoradians | |
| | | | S. pseudoradians * |
| | NP 19 | Isthmolithus recurvus | |
| | | | I. recurvus * |
| | NP 18 | Chiasmolithus oamaruensis | |
| | | | C. oamaruensis * |
| Middle Eocene | NP 17 | Discoaster saipanensis | |
| | | | C. solitus + |
| | NP 16 | Chiasmolithus solitus | |
| | | | R. gladius +<br>D. tani nodifer * |
| | NP 15 | Chiphragmalithus alatus | |
| | | | C. alatus * |
| | NP 14 | Discoaster sublodoensis | |
| | | | D. sublodoensis * |
| Early Eocene | NP 13 | Discoaster lodoensis | |
| | | | M. tribrachiatus + |
| | NP 12 | Marthasterites tribrachiatus | |
| | | | D. lodoensis * |
| | NP 11 | Discoaster binodosus | |
| | | | M. contortus + |
| | NP 10 | Marthasterites contortus | |
| | | | M. bramlettei * |
| Late Paleocene | NP 9 | Discoaster multiradiatus | |
| | | | D. multiradiatus * |
| | NP 8 | Heliolithus riedeli | |
| | | | H. riedeli * |
| | NP 7 | Discoaster mohleri | |
| | | | D. mohleri * |
| | NP 6 | Heliolithus kleinpellii | |
| | | | H. kleinpellii * |
| | NP 5 | Fasciculithus tympaniformis | |
| | | | F. tympaniformis * |
| | NP 4 | Ellipsolithus macellus | |
| | | | E. macellus * |
| Early Paleoc. | NP 3 | Chiasmolithus danicus | |
| | | | C. danicus * |
| | NP 2 | Cruciplacolithus tenuis | |
| | | | C. tenuis * |
| | NP 1 | Markalius inversus | |
| | | | A. cymbiformis + |

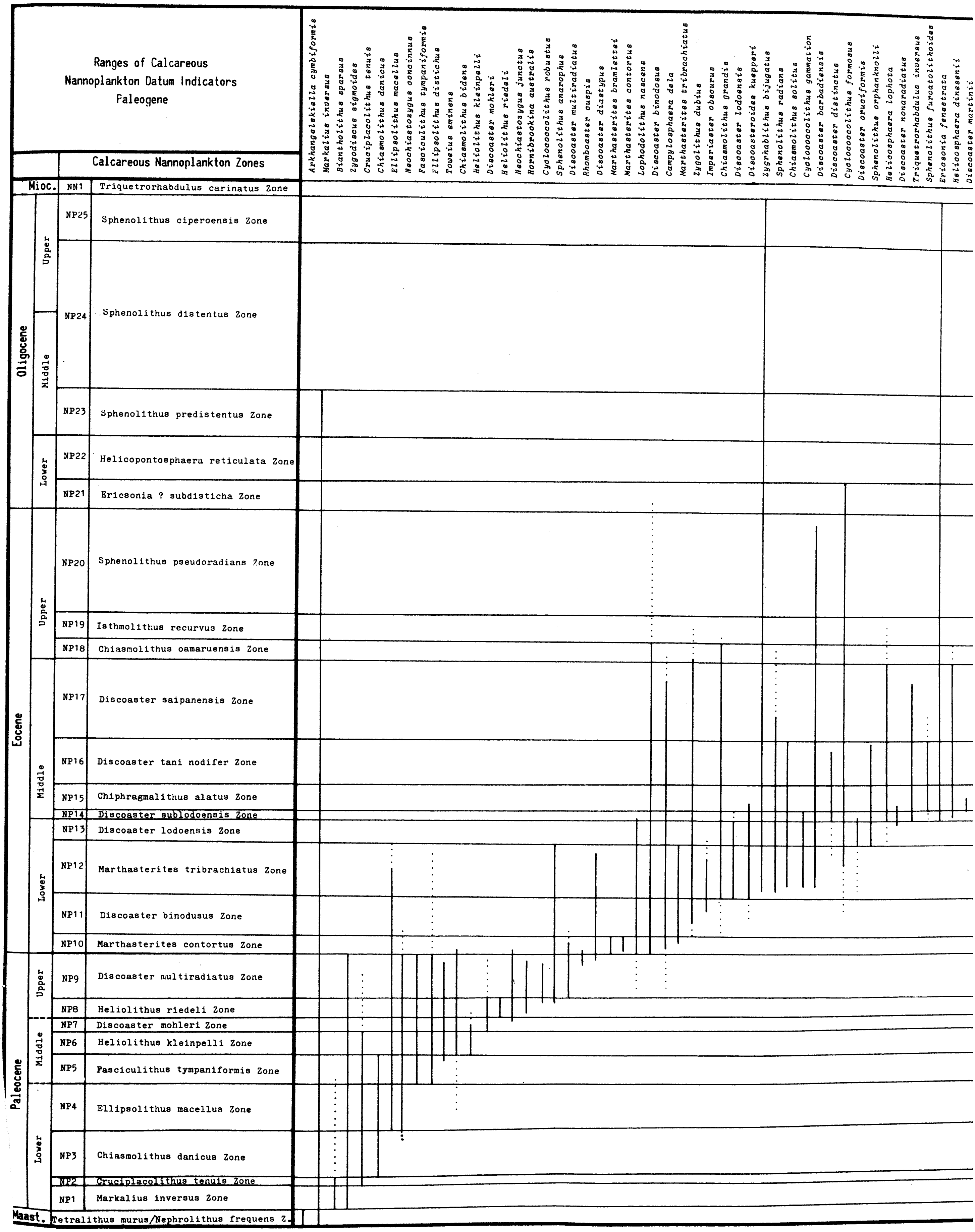
| ZONATION (OKADA & BUKRY 1980) ZONES | | SUBZONES | | |
|---|---|---|---|---|
| | | | | S. ciperoensis +, D. bisctus + |
| CP 19 | Sphenolithus ciperoensis | CP 19b | Dictyococcites bisectus | |
| | | | | S. distentus + |
| | | CP 19a | Cyclicargolithus floridanus | |
| | | | | S. ciperoensis * |
| CP 18 | Sphenolithus distentus | | | |
| | | | | S. distentus * |
| CP 17 | Sphenolithus predistentus | | | |
| | | | | R. hillae, R. umbilica + |
| CP 16 | Helicosphaera reticulata | CP 16c | Reticulofenestra hillae | |
| | | | | C. formosus + |
| | | CP 16b | Coccolithus formosus | |
| | | | | C. subdistichus A + |
| | | CP 16a | Coccolithus subdistichus | |
| | | | | D. barbadiensis +, D. saipanensis + |
| CP 15 | Discoaster barbadiensis | CP 15b | Isthmolithus recurvus | |
| | | | | I. recurvus * |
| | | CP 15a | Chiasmolithus oamaruensis | |
| | | | | C. grandis +, C. oamaruensis * |
| CP 14 | Reticulofenestra umbilica | CP 14b | Discoaster saipanensis | |
| | | | | C. solitus +, D. bifax + |
| | | CP 14a | Discoaster bifax | |
| | | | | R. umbilica *, D. bifax * |
| CP 13 | Nannotetrina quadrata | CP 13c | Coccolithus staurion | |
| | | | | C. gigas + |
| | | CP 13b | Chiasmolithus gigas | |
| | | | | C. gigas * |
| | | CP 13a | Discoaster strictus | |
| | | | | N. quadrata *, R. inflata + |
| CP 12 | Discoaster sublodoensis | CP 12b | Rhabdosphaera inflata | |
| | | | | R. inflata * |
| | | CP 12a | Discoasteroides kuepperi | |
| | | | | D. sublodoensis * |
| CP 11 | Discoaster lodoensis | | | |
| | | | | C. crassus * |
| CP 10 | Tribrachiatus orthostylus | | | |
| | | | | D. lodoensis * |
| CP 9 | Discoaster diastypus | CP 9b | Discoaster binodosus | |
| | | | | T. contortus + |
| | | CP 9a | Tribrachiatus contortus | |
| | | | | D. diastypus *, T. contortus * |
| CP 8 | Discoaster multiradiatus | CP 8b | Campylosphaera eodela | |
| | | | | C. eodela * |
| | | CP 8a | Chiasmolithus bidens | |
| | | | | D. multiradiatus * |
| CP 7 | Discoaster nobilis | | | |
| | | | | D. nobilis * |
| CP 6 | Discoaster mohleri | | | |
| | | | | D. mohleri * |
| CP 5 | Heliolithus kleinpellii | | | |
| | | | | H. kleinpellii * |
| CP 4 | Fasciculithus tympaniformis | | | |
| | | | | F. tympaniformis * |
| CP 3 | Ellipsolithus macellus | | | |
| | | | | E. macellus * |
| CP 2 | Chiasmolithus danicus | | | |
| | | | | C. danicus * |
| CP 1 | Zygodiscus sigmoides | CP 1b | Cruciplacolithus tenuis | |
| | | | | C. tenuis * |
| | | CP 1a | Cruciplacolithus primus | |
| | | | | M. mura + |

Table 5 Standard calcareous nannoplankton zonation in the Neogene and Quaternary and correlation to the zonation of OKADA & BUKRY (1980).

| AGE | STANDARD ZONATION (MARTINI 1971) | | | |
|---|---|---|---|---|
| Quaternary | NN 21 | Emiliania huxleyi | | E. huxleyi * |
| | NN 20 | Gephyrocapsa oceanica | | P. launosa + |
| | NN 19 | Pseudoemiliania lacunosa | b | C. macintyrei + |
| | | | a | D. brouweri + |
| Late Pliocene | NN 18 | Discoaster brouweri | | D. pentaradiatus + |
| | NN 17 | Discoaster pentaradiatus | | D. surculus + |
| | NN 16 | Discoaster surculus | | R. pseudoumbilica + |
| Early Pliocene | NN 15 | Reticulofenestra pseudoumbilica | | A. tricorniculatus + |
| | NN 14 | Discoaster asymmetricus | | D. asymmetricus * |
| | NN 13 | Ceratolithus rugosus | | C. rugosus * |
| | NN 12 | Amaurolithus tricorniculatus | | D. quinqueramus + |
| Late Miocene | NN 11 | Discoaster quinqueramus | b | A. delicatus * |
| | | | a | D. quinqueramus * |
| | NN 10 | Discoaster calcaris | | D. hamatus + |
| Middle Miocene | NN 9 | Discoaster hamatus | | D. hamatus * |
| | NN 8 | Catinaster coalitus | | C. coalitus * |
| | NN 7 | Discoaster kugleri | | D. kugleri * |
| | NN 6 | Discoaster exilis | | S. heteromorphus + |
| | NN 5 | Sphenolithus heteromorphus | | H. ampliaperta + |
| Early Miocene | NN 4 | Helicosphaera ampliaperta | | S. belemnos + |
| | NN 3 | Sphenolithus belemnos | | T. carinatus + |
| | NN 2 | Discoaster druggii | | D. druggii * |
| | NN 1 | Triquetrorhabdulus carinatus | | |

| AGE | ZONATION (OKADA & BUKRY 1980) ZONES | | SUBZONES | | |
|---|---|---|---|---|---|
| Quaternary | CN 15 | Emiliania huxleyi | | | E. huxleyi * |
| | CN 14 | Gephyrocapsa oceanica | CN 14b | Ceratolithus cristatus | E. ovata +, E. annulata + |
| | | | CN 14a | Emiliania ovata | G. oceanica * |
| | CN 13 | Crenalithus doronicoides | CN 13b | Gephyrocapsa caribbeanica | G. caribbeanica * |
| | | | CN 13a | Emiliania annula | D. brouweri + |
| Late Pliocene | CN 12 | Discoaster brouweri | CN 12d | Calcidiscus macintyrei | D. pentaradiatus + |
| | | | CN 12c | Discoaster pentaradiatus | D. surculus + |
| | | | CN 12b | Discoaster surculus | D. tamalis + |
| | | | CN 12a | Discoaster tamalis | R. pseudoumbilica +, S. neoabies + |
| Early Pliocene | CN 11 | Reticulofenestra pseudoumbilica | CN 11b | Discoaster asymmetricus | D. asymmetricus A * |
| | | | CN 11a | Sphenolithus neoabies | C. primus +, A. tricorniculatus + |
| | CN 10 | Amaurolithus tricorniculatus | CN 10c | Ceratolithus rugosus | C. rugosus *, C. acutus + |
| | | | CN 10b | Ceratolithus acutus | C. acutus *, T. rugosus + |
| | | | CN 10a | Triquetrorhabdulus rugosus | D. quinqueramus + |
| Late Miocene | CN 9 | Discoaster quinqueramus | CN 9b | Amaurolithus primus | C. primus * |
| | | | CN 9a | Discoaster berggrenii | D. berggrenii *, D. surculus * |
| | CN 8 | Discoaster neohamatus | CN 8b | Discoaster neorectus | D. neorectus *, D. loeblichii * |
| | | | CN 8a | Discoaster bellus | D. hamatus + |
| Middle Miocene | CN 7 | Discoaster hamatus | CN 7b | Catinaster calyculus | C. calyculus * |
| | | | CN 7a | Helicosphaera carteri | D. hamatus * |
| | CN 6 | Catinaster coalitus | | | C. coalitus * |
| | CN 5 | Discoaster exilis | CN 5b | Discoaster kugleri | D. kugleri *, C. floridanus + |
| | | | CN 5a | Coccolithus miopelagicus | S. heteromorphus + |
| | CN 4 | Sphenolithus heteromorphus | | | C. macintyrei *, D. deflandrei A + |
| Early Miocene | CN 3 | Helicosphaera ampliaperta | | | S. heteromorphus * |
| | CN 2 | Sphenolithus belemnos | | | S. belemnos * |
| | CN 1 | Triquetrorhabdulus carinatus | CN 1c | Discoaster druggii | D. druggii * |
| | | | CN 1b | Discoaster deflandrei | C. abisectus A + |
| | | | CN 1a | Cyclicargolithus abisectus | |

Table 6 Stratigraphic range of important calcareous nannoplankton species in the Paleogene. Dotted lines indicate very rare or locally restricted occu



Paleogene. Dotted lines indicate very rare or locally restricted occurrences, in some cases also cf.identifications.

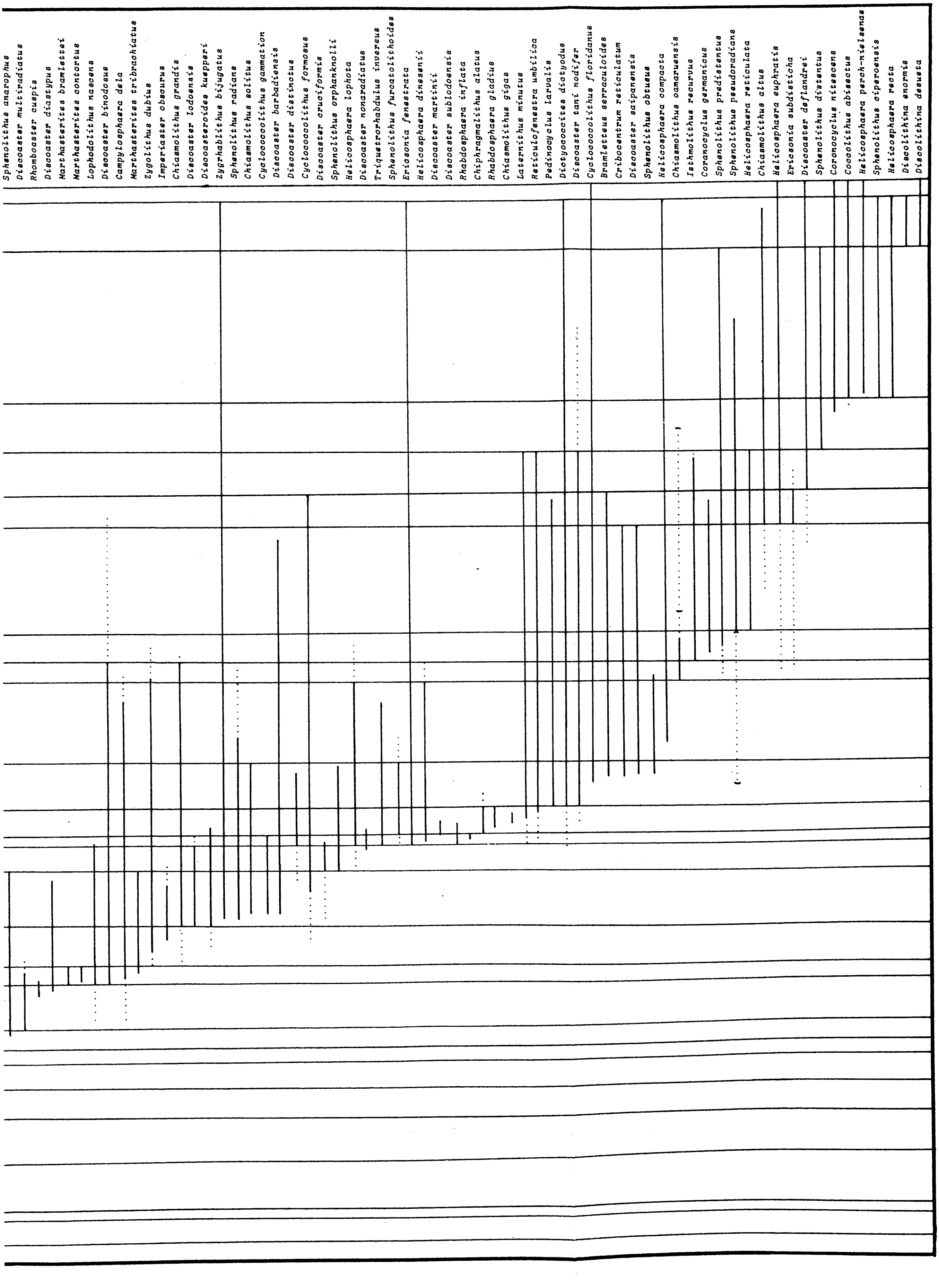
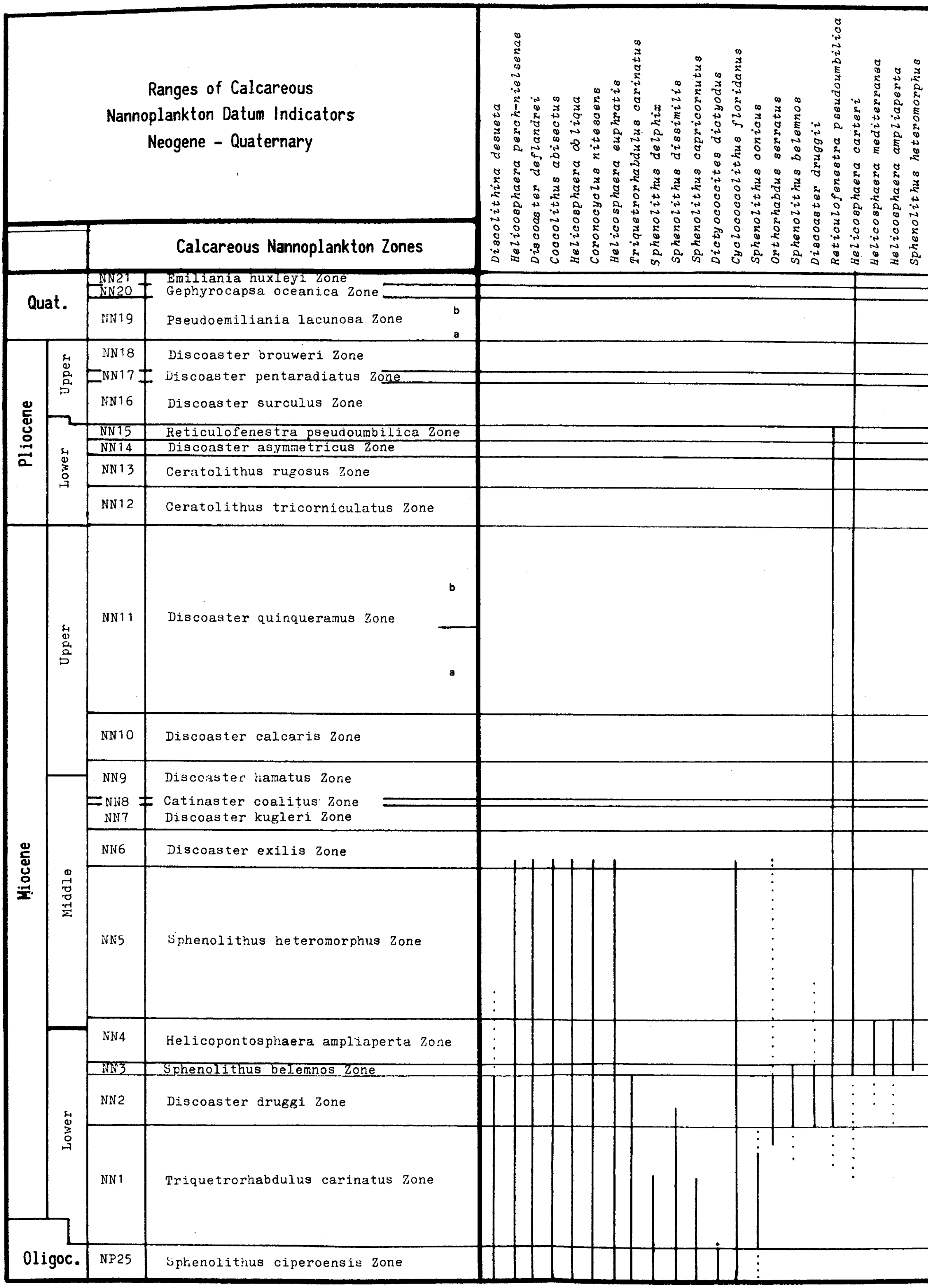
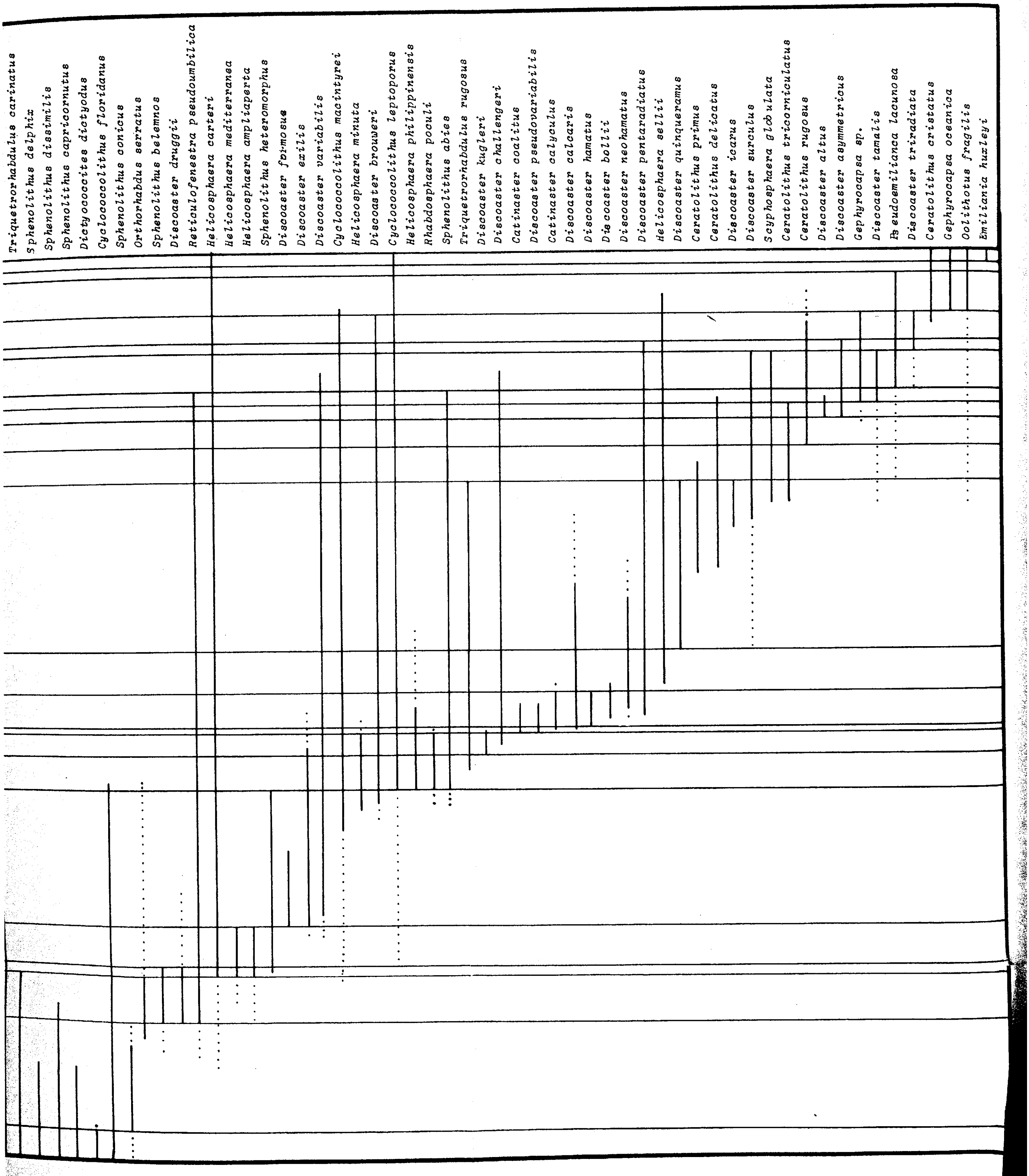


Table 7 Stratigraphic range of important calcareous nannoplankton species in the Neogene and Quaternary. Dotted lines indica



eogene and Quaternary. Dotted lines indicate very rare or locally restricted occurrences, in some cases also cf. identifications.



by BUKRY (1973). The first occurrence of *Sphenolithus pseudoradians* proposed for the subdivision of this interval, is not a time consistent event. Results obtained from many areas have shown that this species has either an earlier appearance (Middle Eocene, BUKRY 1971, MARTINI 1976) or it is rare or absent in the Upper Eocene and Lower Oligocene. It seems possible to use the occurrence of *Helicosphaera reticulata* to recognize zone NP 20. But in most areas this species is also too rare to be of real stratigraphic value.

The top of the Eocene is defined by the extinction of rosette-shaped discoasters like *Discoaster saipanensis* and *Discoaster barbadiensis*. *Discoaster saipanensis* seems to have a slighty longer range. Generally the discoasters become rare within the uppermost Eocene particularily at higher latitudes. This might be related to a general cooling during this time which reaches its maximum within the lowermost Oligocene (NP 21). In the regions where the discoasters are absent either due to low surface water temperature or to shallow environment *Cribrocentrum reticulatum* can be used for the determination of the Eocene/Oligocene boundary (MÜLLER 1970, 1979), because its last occurrence is just shortly prior to the extinction of *D. saipanensis*.

The Oligocene nannoplankton zones (NP 21 to NP 25) can be recognized without difficulties. They are mainly based on the last or first occurrence of Sphenoliths, which are typical warm water species. They are rare or absent in the higher latitudes. In those areas the boundary between zones NP 23 and NP 24 can be determined by the first occurrence of *Cyclicargolithus abisectus* and/or *Helicosphaera recta*. It is more difficult to separate the zones NP 24 and NP 25 by the use of *Discolithina enormis*. This species is more common in shallow environments.

The top of zone NP 25 is considered as the Oligocene/Miocene boundary. It is characterized by the extinction of *Sphenolithus ciperoensis*, *Zygrhablithus bijugatus*, *Ericsonia fenestrata* and *Helicosphaera recta* (MÜLLER 1982). The order of their extinction levels can vary from one area to another. *Dictyococcites dictyodus* (*Reticulofenestra bisecta* of some authors) seems to disappear earlier in the Equatorial Pacific, in the Philippines and Australia (NP 23–NP 24). On the other hand this species is reported by MARTINI (1986) from the lowermost Miocene in the SW Pacific. The disappearance and reoccurrence of *Sphenolithus ciperoensis* within the uppermost Oligocene (NP 25) was described from the Indian Ocean (BIZON & MÜLLER 1981). Climatic fluctuations are most probably the reason for this phenomenon.

A characteristic change in size of the nannoplankton exists between the Oligocene and Miocene (MÜLLER 1979, 1980). They are smaller in the lowermost Miocene and generally the assemblages are less diversified.

## Neogene

Related to the continuous climatic deterioration during the Neogene, particular since the Middle Miocene, the application of the standard zonation becomes more difficult. This is true especially at higher latitudes. The subdivision of zones NN 1 and NN 2 is not always possible due to the scarcity or absence of *Discoaster druggii* in certain areas. Also *Triquetrorhabdulus carinatus* which disappears at the top of zone NN 2 can not be found always. Its presence seems to be controlled not only by water temperature but also by water depth. In those cases the top of zone NN 2 may be determined by the first occurrence of *Sphenolithus belemnos* as proposed by BUKRY (1973). Zones NN 3 to NN 5 are easily to recognize even at higher latitudes. This is related to a general warming of the surface water and the penetration of warm water masses into higher latitudes (HAQ 1980, MÜLLER 1985). No changes of the standard zonation are necessary in tropical and subtropical zones for the Neogene and Quaternary sequences. It is possible to subdivide the long *Discoaster quinqueramus* zone (NN 11) of late Miocene age into subzones NN 11 a and NN 11 b by the first occurrence of *Amaurolithus delicatus* at about 6.2 m. y. BUKRY (1973) proposed *Amaurolithus primus* as zonal marker. But this species is less common. Since the first occurrence of the two species is time equivalent it is prefered to use *Amaurolithus delicatus* (= *Ceratolithus delicatus*).

The top of zone NN 11 corresponds to the Miocene/Pliocene boundary at 5.2 m. y. It can be recognized by the extinction of *Discoaster quinqueramus* and *Triquetrorhabdulus rugosus*. In the Pliocene the same zonal markers are used for the standard zonation and for the zonation given by BUKRY (1973). At higher latitudes only a rough subdivision in lower and upper Pliocene is possible by the extinctions of *Reticulofenestra pseudoumbilica* and *Sphenolithus abies*; however, the latter is a rare species. Discoasters are more common within the lower part of zone NN 12 due to an increase of water temperature. They are rare up to zone NN 16 (lower part) 2.5–2.7 m. y. After that they are missing at the higher latitudes (PERCH-NIELSEN 1972, BIZON & MÜLLER 1977, MÜLLER 1978, MARTINI 1979). This event corresponds to the beginning of the glaciation in the northern hemisphere (BERGGREN 1972, BIZON & MÜLLER 1977, 1978, MÜLLER 1978, 1985, DRIEVER 1984). The zone NN 15 is the only one which can be determined more precisely by the presence of a small *Gephyrocapsa* and *Pseudoemiliana lacunosa* together with *Reticulofenestra pseudoumbilica*.

The top of the Pliocene is defined by the extinction of *Discoaster brouweri*. In those areas where discoasters have an earlier extinction, *Cyclococcolithus macintyrei* is proposed as index fossil (BIZON & MÜLLER 1977, 1978). This biostratigraphic event lies near the top of the Olduvai event (about 1.6 m. y.) and is almost contemporary with the extinction of the discoasters in tropical regions. According to GARTNER (1973) there is an interval of 0.14 m. y. between these two events.

The Pleistocene zonation (NN 19 to NN 21) was revised by GARTNER (1977) who discribed 7 zones. He subdivided zone NN 19 into 4 zones which, however, ware not easy to apply worldwide. For the lowermost part of the Pleistocene he introduced the *Cyclococcolithus macintyrei* zone of 0.14 m. y. which correspond to the lowermost part of the zone NN 19 = NN 19 a (MARTINI & JENKINS 1986).

## Stratotypes and major boundaries

Stratotype sections important for internationally applicable subdivisions of the Tertiary system contain in most cases calcareous nannoplankton suitable to define the position of the stratotype, if well defined, within the nannoplankton zonation. There is a good coverage in the Oligocene and Neogene, but in the Paleocene and Eocene unfavourable conditions for the calcareous nannoplankton in several stratotype sections hamper determinations of the ranges of the proposed international stratigraphic units with this fossilgroup. The correlations presented here accordingly are based mainly on calcareous nannoplankton data, and on discussions and conclusions of the sixth congress of the Regional Committee on Mediterranean Neogene Stratigraphy held in Bratislava, 1975, and of the meeting of the International Subcommission on Paleogene Stratigraphy held in Paris 1981. However, HARDENBOL & BERGGREN (1978) extended several chronostratigraphic units rather arbitrarily beyond the limits of their supposed type-section or -area, some of them on basis of cross-correlations and rather dubious evidences (e. g. CAVELIER 1979), including the Thanetian and Rupelian, which cannot be accepted, because they are entirely misleading.

On basis of the nannoplankton found in the type-section and -area the Danian ("Lower Paleocene") can be placed into nannoplankton zones NP 1 to NP 3 (PERCH-NIELSEN 1969, MARTINI 1971). Nannoplankton data are rather sparse in the remaining Paleocene, but at least zone NP 8 was identified in the type Thanetian (BRAMLETTE & SULLIVAN 1961, MARTINI 1971, AUBRY 1984). In the Lower Eocene (Ypresian) at least nannoplankton zones NP 11 and NP 12 were found in the type Ypresian (HAY & MOHLER 1967, MARTINI 1971, MÜLLER & WILLEMS 1981). In the Middle Eocene the type Lutetian nannoplankton assemblage (BOUCHÉ 1967) belongs to zone NP 14 (HAY et al. 1967, MARTINI 1971), but zone NP 16 was also identified in this stage (AUBRY 1983). The type Bartonian, generally considered to represent the upper part of the Middle Eocene yielded only nondiagnostic nannoplankton species in most samples with the exception of the Barton H, which contains a typical assemblage of zone NP 17 (MARTINI 1971). The type Priabonian and the Possagno section can be placed in the interval containing zones NP 18 to NP 20, considered as the Upper Eocene (MARTINI 1971, ROTH, BAUMANN & BERTOLINO 1971).

The Lower Oligocene (Latdorfian) includes nannoplankton zones NP 21 and NP 22 (MARTINI 1971, BENEDEK & MÜLLER 1976), the Middle Oligocene (Rupelian) comprises zone NP 23 and part of zone NP 24 (MÜLLER 1970, MARTINI 1971), and the Upper Oligocene (Chattian) includes part of nannoplankton zone NP 24 and zone NP 25 (MARTINI & MÜLLER 1975). The Paleogene/Neogene boundary is identified at the NP 25/NN 1 boundary of the standard nannoplankton zonation.

For the Lower Miocene (Aquitanian and Burdigalian), nannoplankton data are rather sparse but indicate a correlation of the interval from nannoplankton zone NN 1 to part of zone NN 4 (MÜLLER 1974, BIZON & MÜLLER 1977, MÜLLER & PUJOL 1979). The base of the Middle Miocene (Langhian and Serravallian) is in the upper part of nannoplankton zone NN 4 and the top of the Middle Miocene lies within zone NN 9 (MARTINI 1968, 1971, MÜLLER 1975). The top of the type Langhian seems somewhat difficult to define because meager foraminiferal assemblages and massive reworking. It is just above the last common occurrence of *Sphenolithus heteromorphus* (top of zone NN 5), which is here taken for convenience to define the top of the Langhian. The Langhian is certainly misplaced in tables by BERGGREN et al. (1984), HAQ (1984, Fig. 8; totally within NN 4), which need correction.

The base of the Upper Miocene (Tortonian and Messinian) is in the upper part of zone NN 9 (MARTINI 1975). The Tortonian/Messinian boundary can be placed approximately with the first occurrence of ceratoliths (MAZZEI 1977, CHERCHI & MARTINI 1981), which can be also used to subdivide zone NN 11 into a lower (NN 11 a) and upper part (NN 11 b).

Because the Lower Pliocene is a transgressive phase following the Upper Miocene salinity crises in the Mediterranean, there is still some discussion about the exact position of the Miocene/Pliocene boundary in the nannoplankton zonation (MARTINI 1975, D'ONOFRIO et al. 1975, CITA et al. 1973), however, a position at the top of zone NN 11b seems most convenient and is adopted here. Accordingly, the Lower Pliocene (Zanclean) includes nannoplankton zone NN 12 and reaches to zone NN 15 (CITA & GARTNER 1973). The Upper Pliocene (Piacenzian) contains zones NN 16 to NN 18 and is considered to terminate with the last occurrences of *Discoaster brouweri* in the open ocean in low and middle latitudes.

Major boundaries are commonly defined by marked lithologic and/or faunistic changes. Different fossilgroups used to define such a boundary may give rise to extensive discussion and confusion.

The Cretaceous/Tertiary (Maastrichtian/Danian) boundary is marked by an extinction of most Cretaceous nannoplankton species (BRAMLETTE & MARTINI 1964); although this event according to recent investigations is not as spectacular as formerly thought (PERCH-NIELSEN 1981). The boundary is placed nowadays at a clay-enriched layer with an abnormal high iridium content (e. g. ALVAREZ et al. 1984). Shortly above a mass occurrence of *Thoracosphaera* can be noted in the basal part of zone NP 1, which serves as a good marker for the boundary in terms of calcareous nannoplankton, although it is considered to represent a calcareous dinoflagellate cyst (FÜTTERER 1976). It is widespread in oceanic as well as in land-sections.

The Paleocene/Eocene boundary is tentatively placed between zones NP 9 and NP 10, which is approximately between the *Morozovella velascoensis* and *M. subbotinae* zones in the planktonic foraminiferal zonation (HARLAND et al. 1982), and at present is no subject to controverse discussion.

The Eocene/Oligocene boundary identified by means of the calcareous nannoplankton is commonly placed at last occurrence of rosette-shaped discoasters which dominate in the Eocene, especially at the last occurrence of *Discoaster saipanensis* (top of zone NP 20, MARTINI 1971) in deep sea sediments as well as in landbased sections of low and middle latitudes. There are several articles discussing the time equivalence of the Eocene/Oligocene boundary using calcareous nannoplankton and foraminifera (e. g. BOMBITA & RUSU 1981, SNYDER, MÜLLER & MILLER 1984, MARTINI, 1986), which may be summarized in that the boundary by means of the planktonic foraminifera (commonly at the last occurrence of *Globorotalia cerroazulensis*) is slightly younger than the boundary drawn with calcareous nannoplankton, and is in the lower part of zone NP 21. The time span between the two boundary "events" is about 0.4 m. y. as deduced from the sedimentation rate at DSDP Site 592 in the Southwest Pacific (MARTINI, 1986). At high latitudes discoasters are generally rare or missing and not reliable to indicate the Eocene/Oligocene boundary. However, *Cribrocentrum reticulatum* was shown to have its last occurrence just below the Eocene/Oligocene boundary (top of zone NP 20, last occurrence of *Discoaster saipanensis*) at low and middle latitudes, and also can be used as reliable substitute species at high latitudes (MÜLLER 1978b).

The Lower Oligocene (Latdorfian), including standard nannoplankton zones NP 21 and NP 22, was clearly deposited prior to the Rupelian (= Middle Oligocene), which includes the standard calcareous nannoplankton zones NP 23 and part of NP 24, although a quite misleading version was recently published in HARLAND et al. (1982), which has some forerunners in papers by BERGGREN (e. g. HARDENBOL & BERGGREN 1978), and is also used in a few DSDP-papers.

The Oligocene/Miocene boundary in terms of calcareous nannoplankton generally is placed at the top of nannoplankton zone NP 25 (MÜLLER 1981, STEININGER 1982) where several nannoplankton species have their last occurrence, e.g. *Sphenolithus ciperoensis*, *Helicosphaera recta*, and *Zygrhablithus bijugatus*. *Dictyococcites dictyodus* (*Reticulofenestra bisecta* of some authors) which may be used in certain areas as additional boundary indicator is not very reliable because of its varying last occurrences, e.g. in the Central Pacific top of zone NP 23 (DSDP Site 317), Southwest Pacific well within zone NN 1 (DSDP Site 593). In some papers (e.g. OKADA 1980) BUKRY's *Cyclicargolithus abisectus*-acme zone is used as last zone of the Oligocene. Despite the fact that *C. abisectus* ranges up to the lower part of zone NN 6 (*Discoaster exilis* Zone), it has several acmes up to this level and can not be used to define a reliable zone near the Oligocene/Miocene boundary.

The Miocene/Pliocene boundary is taken at the top of zone NN 11 as discussed above.

The Pliocene/Pleistocene boundary is commonly placed with the extinction of discoasters at the top of zone NN 18 in tropical and subtropical regions. Difficulties occur at high latitudes where discoasters as well as diagnostic planktonic foraminifera are missing or have different last or first occurrences. BIZON & MÜLLER (1977, 1978) proposed the extinction of *Cyclococcolithus macintyrei* as biostratigraphic event to determine the Pliocene/Pleistocene-boundary in these areas. MÜLLER (1979, 1985) demonstrated that the last occurrence of *C. macintyrei* is near the top of the Olduvai event, which was dated as 1.6 to 1.8 m.y. (HAQ et al. 1977) and 1.72 to 1.88 m.y. in HARLAND et al. (1982) and which seems at or close to the extinction level of discoasters. Other authors (GARTNER 1977, MARTINI & JENKINS, 1986) use the extinction of *C. macintyrei* to subdivide the Pleistocene zone NN 19 into a small lower (NN 19a) and large upper part (NN 19b, without *C. macintyrei*). The last occurrence of *C. macintyrei* was recently dated as 1.45 m.y. by BACKMAN & SHACKLETON (1983), above the last occurrence of *Discoaster brouweri* dated 1.88 m.y. in the same paper.

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