Quaternary
Coccoliths
Northern hemisphere
Stratigraphy
Spatio-temporal distribution

Quaternaire
Coccolithes
Hémisphère Nord
Stratigraphie
Déplacement spatio-temporel

Spatio-temporal distribution of some Quaternary coccoliths

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Received 4/3/87, in revised form 24/9/87, accepted 5/10/87.

ABSTRACT

Calcareous nannofossil assemblages have been studied in sediments of six Quaternary cores from the northern hemisphere (between 1°S and 60°N) in the Atlantic, and the equatorial Pacific and Indian Oceans. Most of the sections penetrated sediments of the whole Quaternary; they have been dated using paleomagnetism, isotopic measurements and variation of total nannofossil abundance. Nannofossils are counted, and their acmes as well as their highest/lowest occurrences (HO and LO) are considered as stratigraphic markers. This geographical and time study shows the spatio-temporal distribution of nannofossils. The distribution of 9 species or specific groups of coccoliths shows that some events have a world-wide stratigraphic significance. These events are synchronous (top of acme of *Gephyrocapsa caribbeanica* at 0.268 m.y.; HO of the "small" *Gephyrocapsa* at 0.050–0.020 Ma). Others are time-transgressive (LO of *Umbellosphaera irregularis* between 0.320 and 0.020 Ma; LO of *G. ericsonii* between 1.240 and 0.200 Ma; LO of *G. oceanica* s. str. between 1.140 and 0.480 Ma; LO of *G. caribbeanica* between 1.220 and 0.550 Ma; HO of *Cyclococcolithina macintyrei* between 1.700 and 1.450 Ma; HO of *G. doronicoides* between 0.600 and 0.480 Ma; HO of *G. ericsonii* between 0.020 and 0.150 Ma; HO of *Helicopontosphaera sellii* between 1.040 and 1.420 Ma; LO of *G. oceanica* "W" between 0.270 and 1.200 Ma; top of acme of "small" *Gephyrocapsa* between 0.650 and 1.000 Ma). These time-lags have to be kept in mind when assigning ages to LOs and HOs in different oceans and latitudes.

Oceanol. Acta, 1988, **11**, 1, 65-77.

RÉSUMÉ

Distribution spatiale et temporelle de quelques coccolithes quaternaires

Les associations de nannofossiles calcaires ont été étudiées dans des sédiments de six carottes quaternaires prélevées en hémisphère Nord (entre 1°S et 60°N) dans l'Atlantique, ainsi que dans le Pacifique équatorial et l'Océan Indien. La plupart des coupes ont fourni des sédiments correspondant à l'ensemble du Quaternaire; leur datation est basée sur des mesures paléomagnétiques et isotopiques, ainsi que sur les variations de l'abondance totale des nannofossiles. Les coccolithes, comptés avec précision, fournissent des repères considérés comme marqueurs stratigraphiques : ce sont des apparitions/disparitions (=LO et HO) ou des acmés des divers taxa. Il s'avère que la plupart de ces repères sont décalés d'une coupe à l'autre. L'étude des nannofossiles dans le temps et dans l'espace permet de suivre ces décalages au cours du Quaternaire en fonction des aires climatiques. L'étude de la distribution de 9 espèces ou groupes spécifiques de coccolithes montre que certains événements ont une signification stratigraphique mondiale. Ces événements peuvent être synchrones (fin de l'acmé de *Gephyrocapsa caribbeanica* à 0,268 Ma; HO des « petites » *Geophyrocapsa* à 0,050-0,020 Ma). D'autres se déplacent en fonction de la latitude au cours du temps (LO de *Umbellosphaera irregularis* entre 0,320 et 0,020 Ma; LO de *G. ericsonii* entre 1,240 et 0,200 Ma; LO de *G. oceanica* s.str. entre 1,140 et 0,480 Ma; LO de *G. caribbeanica* entre 1,220 et 0,050 Ma; HO de *Cyclococcolithina macintyrei* s.str. entre 1,700 et 1,450 Ma; HO de *G. doronicoides* entre 0,600 et 0,480 Ma; HO de *G. ericsonii* entre 0,020 et 0,150 Ma; HO de *Helicopontosphaera sellii* entre 1,400 et 1,420 Ma; LO de *G. oceanica* « W »

entre 0,270 et 1,200 Ma; fin de l'acmé des « petites » *Gephyrocapsa* entre 0,650 et 1,000 Ma). Dans de futures études portant sur la stratigraphie du Quaternaire basée sur les coccolithes, il faudra tenir compte de ces décalages dans les HO et LO en fonction de la localisation des sections considérées.

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INTRODUCTION

The unquestionable importance of nannofossils throughout their geological record is due to their presence in the upper layer of almost all the oceans and to the cosmopolitanism of most of the species. This is why calcareous nannofossils have been extensively used in the past thirty years for precise stratigraphic delineations within the Mesozoic and the Cenozoic. In contrast, the use of coccoliths for the reconstruction of the Quaternary histories is much more recent.

Various biostratigraphic zonations have been established with nannofossils (Tab. 1); the best-known is by Martini (1971) and the most recent one is by Okada and Bukry (1980). Different criteria have been employed. Besides the classical appearance or disappearance of taxa (LO=lowest occurrence and HO=highest occurrence, according to Gartner, 1973), some authors have used the somewhat controversial concept of taxa acme (Bukry, 1978; Gartner, 1977), while some others have attempted to find world-wide synchronous events (Thierstein *et al.*, 1977).

Most of the papers concerning Quaternary nannofossils deal with rather limited areas, and global trends are note usually drawn. The detailed study of global chronostratigraphy of Thierstein *et al.* (1977) is therefore exemplary. Such world-wide events seem to be the best for interpreting the stratigraphy of areas; the resulting scheme is more realistic than the classical and rigid stratigraphic zonations for the past two millions years. In this context, paleoecology and biostratigraphy of nannofossils are complementary concepts in the study of time-transgressive coccolith events. This explains the choice of cores used in my study.

A datum s.str. reflects a biological event that is synchronous over large areas, or even everywhere. Traditional biostratigraphic zonations (*e.g.* Martini, Worsley, 1970; Okada, Bukry, 1980) and datums are exclusively based on HO and LO of species. However, in several instances, the absence of some datums has been demonstrated; *e.g.*, the frequent absence of the *Isthmolithus recurvus* datum in the late Eocene at low latitudes (Bukry, 1973), or the disappearance of discoasters occurring much earlier than the Plio-Pleistocene boundary at high- and mid-latitudes. These two "anomalies" are due to the influence of the environment and climate. In spite of these absences, the *I. recurvus* and discoasters datums are unquestionably useful in higher latitudes.

From a biological point of view, it is aberrant to assume *a priori* that any species could appear or disappear at the same time in the world ocean. The duration of a species is conditioned by the good or bad quality of its environment. Then, through time, it will be able to adapt to a wider environment, sometimes as a slightly different species or variant. Thus, its geographical distribution will not be the same at different times.

Table 1
Some published zonations and chronology for Quaternary nannofossils.
Quelques zonations précédemment publiées et chronologie pour les coccolithes quaternaires.

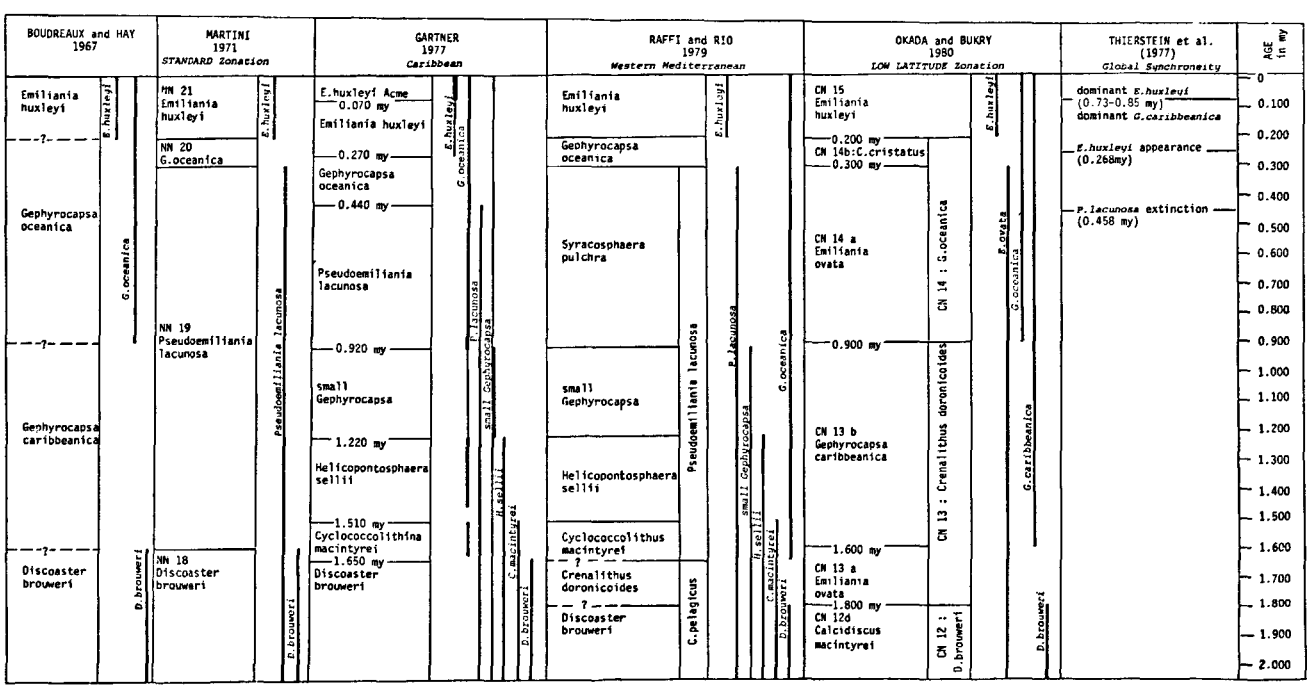

Table 2
Location of sites.
Situation des sites.

Core N°	Cruise	Latitude	Longitude	Water depth
IGBA 7705	Faegas II (Grousset *et al.*, 1978)	60°23.3'N	26°00.0'W	2140 m
Holes 548 and 549 A	DSDP Leg 80 (de Gracianski *et al.*, 1984)	48°54.95'N	12°09.84'W	1251 m
IGBA 74215	Midlante B (Pujol *et al.*, 1976)	28°52.2'N	25°25.2'W	4789 m
IGBA 74206	Midlante B (Pujol *et al.*, 1976)	19°36.0'N	27°25.0'W	4662 m
Hole 573	DSDP Leg 85 (Mayer *et al.*, 1985)	00°29.91'N	133°18.57'W	4311.5 m
MD 77158	Osiris III-MD 13 (Valet *et al.*, 1979)	01°16,0' S	89°09,0'E	2530 m

PURPOSE OF THE STUDY

A high-resolution chronostratigraphic scale for the Quaternary has not yet been established with nannofossils. Published studies have led to the recognition of only 4 or 5 zones (Tab. 1). It is well known that nannofossil associations and major events (=LO, HO and acmes) are scarcely synchronous in different areas (Thierstein *et al.*, 1977). However, there is no comprehensive published study of such spatio-temporal variations of nannoplankton assemblages. The present one is the beginning of such a study, with some selected cores and some selected nannofossil species. I have used quantitative data for documenting the nannofossil events chronologically and geographically. After correlating the cores, I noticed that some of these events were evidently diachronic; therefore, I have attempted to decipher whether the supposed diachronisms are artifacts or not.

MATERIAL AND METHODS

Six deep-sea cores were selected for this study (Fig. 1). The locations ranged from 60°N latitude to 1°S, thus covering the climatic province fan described by McIntyre and Be (1967). Four of these cores were located in the Atlantic Ocean (60°N-20°N), one in the Pacific (1°N) and one in the Indian Ocean (1°S; Tab. 2). The boundaries of five major provinces of living coccoliths (McIntyre, Be, 1967, for the Atlantic Ocean) and of living planktonic foraminifera (Be, 1977, for the world ocean) were taken into account in selecting the core locations. The southernmost cores (DSDP 573 and MD 77158) are considered as "equatorial", because their nannofossil associations are different from, and indicate a warmer regime than those of the "tropical" core IGBA 74206.

Physical, geochemical and paleontological techniques were applied to date all six cores. For most cores, the magnetostratigraphical dating of Ness *et al.* (1980) was used. Oxygen-isotopic measurements on planktonic foraminifera were also used to determine the paleoclimatic stages, using the scale of Morley and Hays (1981) for the last 700 000 years, and of Van Donk (1976) for the earlier Pleistocene. Curves of nannofossil total abundance indicate paleoclimatic changes in low– as well as in mid-latitudes, as already shown (Pujos, 1985 for DSDP Leg 85 and 1984 for Leg 80). For the Pacific, I used the variations of the carbonate content of sediments for dating the Quaternary from DSDP Leg 85, as done by some earlier workers (*e.g.*, Arrhenius, 1952; Gardner, 1982).

Different schemes of Quaternary zonation based on calcareous nannofossils (Tab. 1) include a few marker planes that are commonly considered as datums by stratigraphers: 1) the HO (=Highest Occurrence) of *Pseudoemiliania lacunosa* at 0.458 Ma (Thierstein *et al.*,

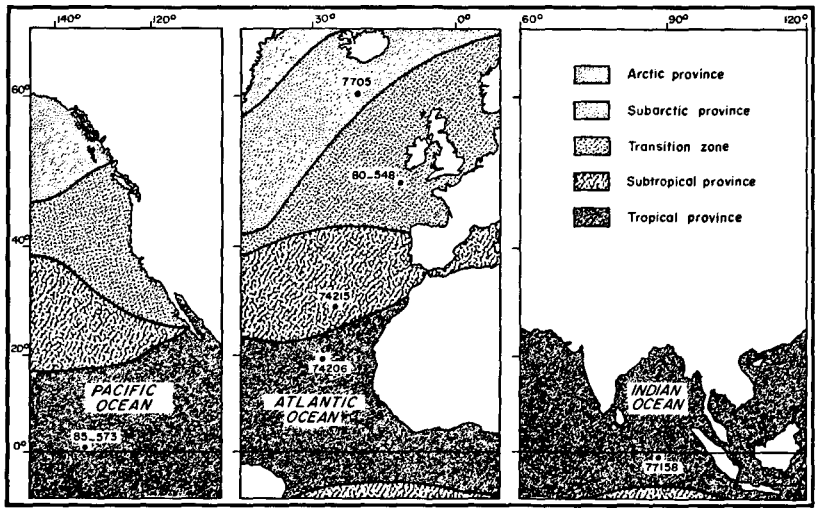

Figure 1
Location of sites in relation to five major provinces of nannoplankton (McIntyre, Bé, 1967) and of planktonic foraminifera (from Bé, 1977).
Situation des sites en relation avec les cinq provinces climatiques du nannoplancton (McIntyre, Bé, 1967) et des foraminifères planctoniques (d'après Bé, 1977).

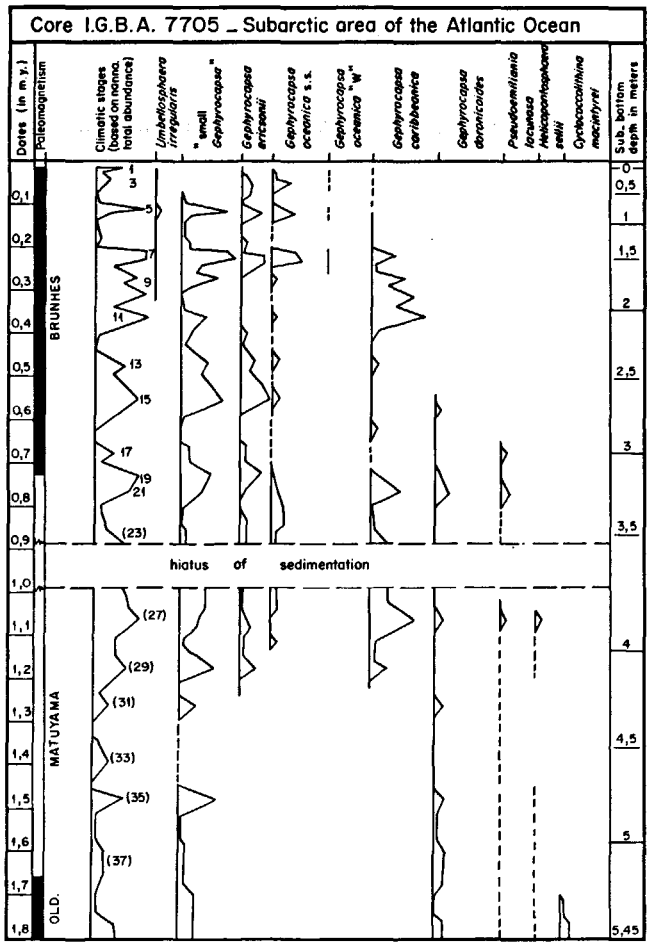

Figure 2

Distribution of some coccoliths and total abundance of nannofossils in core IGBA 7705 (subarctic Atlantic Ocean). Number of coccoliths:

1 10 20 40

5 15 >40

in a single field of view (for total abundance) X 1200; in 5 fields of view (for species abundance) X 1200.

Distribution de quelques coccolithes et abondance totale des nannofossiles dans la carotte IGBA 7705 (Océan Atlantique subarctique). Nombre de coccolithes:

1 10 20 40

5 15 >40

estimé dans un seul champ (pour l'abondance totale) X 1200; estimé dans cinq champs (pour l'abondance des espèces) X 1200.

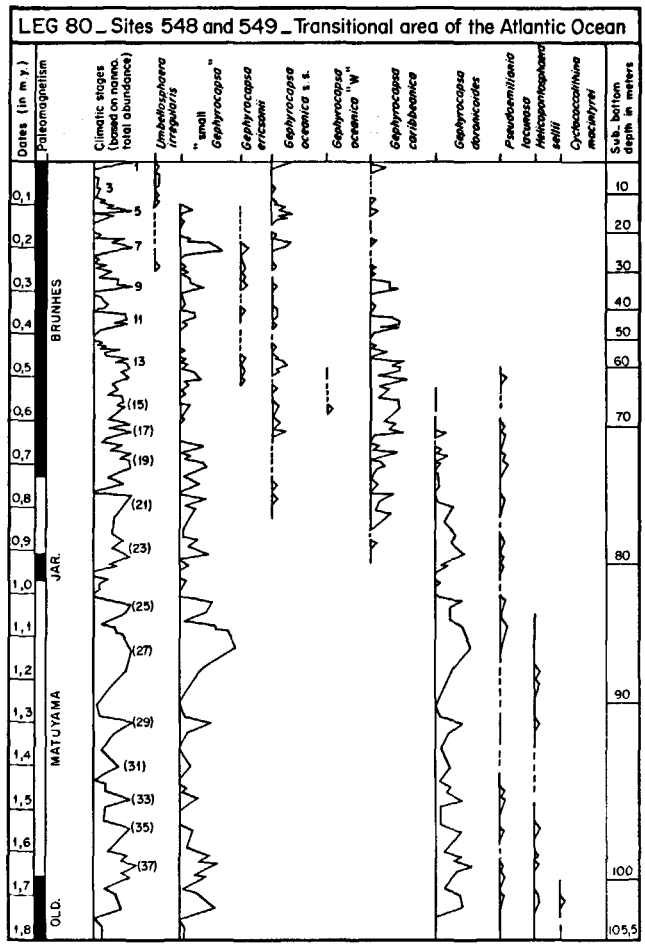

Figure 3

Distribution of some coccoliths and total abundance of nannofossils at site 548 of DSDP Leg 80 (transitional area of the Atlantic Ocean; scales: see Fig. 2)

Distribution de quelques coccolithes et abondance totale des nannofossiles au site 548 du Leg 80 des DSDP (aire transitionnelle de l'Océan Atlantique; échelles sur la fig. 2).

1977); 2) the acme of *Gephyrocapsa caribbeanica* during climatic stage 9, at 0.270-0.280 Ma (Thierstein *et al.*, 1977); 3) the LO (=Lowest Occurrence) of *Emiliania huxleyi* in stage 8, at about 0.268 Ma; unfortunately, because of the small size of *E. huxleyi* and its scarcity between stages 8 and 5 (about 0.125 Ma), it is often excluded from stratigraphic analyses; 4) a similar situation exists for the "point of maximum abundance difference between *E. huxleyi* and *G. caribbeanica*", that Thierstein *et al.* (1977) date at about 0.073 Ma for cores in the transitional zone, at 0.083 Ma in low latitudes and at 0.012 Ma in the tropics. It is, in fact, difficult to distinguish under a light microscope *E. huxleyi* from *G. aperta* in samples from stages 4 and 5 in which both taxa may be present. Thierstein *et al.* (1977) note that there is "a limitation in the recognition of the reversal in the high southern latitudes" and in a subpolar core with high dissolution. For this reason, I opted for the use of the easily discernible and less ambiguous taxa.

Using the foregoing information, time scales were determined for all six cores. It has been possible to establish that the six cores cover almost the entire Quaternary era. For the cores with a Pliocene base, the present study has been limited to the last 1 800 000 years [=climatic stages 38/39 and Olduvai base (Van Donk, 1976)]. Some of these cores display minor sedimentary hiatuses (7705 and 74215). The sedimentation rates are even during the Brunhes and the Matuyama; in most cases (except for core 77158), they are lower during the Matuyama than during the Brunhes event.

The samples studied are regularly spaced, with 60 to 160 samples per core. The nannofossils were examined on smear-slides with a light microscope, and quantitative estimates were made at 1200 magnification. The rarest specimens were searched within 10 fields of view and their number was homogenized with the rest of the nannoflora; this technique is similar to that described by Backman and Shackleton (1983).

Brief descriptions of the cores, from highest to lowest latitudes, are given below.

- IGBA 7705 (Fig. 2) core was raised south of Iceland during the Faegas II cruise. It is located in the subarctic

province which corresponds to the northern limit of present day nannoplankton. In this core, the following paleomagnetic reversals have been observed: Brunhes/Matuyama and Olduvai top (Weinreich, pers. comm., 1983); but the Jaramillo chron was not identified. This attests to a hiatus at 0.9-1.05 Ma. The top of the section represents the present climatic stage 1.

Coccoliths are, on the whole, of average abundance, their number dropping in the period prior to 1 Ma ago, probably because of dissolution. Nevertheless, climatic stages are easily identified on the total abundance curve. The sedimentation rate is distinctly higher for the last 200 000 years.

- Sites 548 and 549 of DSDP Leg 80 (Fig. 3) are located south of Ireland in the transitional climatic area. The two sections complement one another: middle- and late-Pleistocene samples (= Brunhes epoch) were taken at site 548 and early Pleistocene samples (= Matuyama epoch) at site 549. The magnetostratigraphy (Townsend, 1984) is hampered by problems in the interpretation of the Jaramillo chron, but it can still be satisfactorily interpreted (Pujos, 1984). Nannofossils are consistently abundant and well diversified. They characterize climatic stages that have previously been correlated with isotopic stages established with planktonic foraminifera (Vergnaud-Grazzini *et al.*, 1984; Pujos, 1984).

- The IGBA 74215 core, recovered from the subtropical province during the Midlante B cruise, is located off Mauritania. It is the only section in this study that lacks paleomagnetic stratigraphy (Fig. 4). Nannofossils are consistently abundant; the species composition of the nannoflora permitted the identification of climatic stage 9 and of stage 7 which is at the top of the core. The $\delta^{18}O$ curve for *Globorotalia truncatulinoides* (measured by Duplessy, pers. comm., 1976; personal interpretation in comparison with Van Donk's curve, 1976) shows all climatic stages from 7 to 35, according to the scale of Van Donk (1976). Isotopic values were not obtained for the lower part of the core, but the variations in the total abundance of nannofossils suggest that stages 35-37 are also represented.

- The IGBA 74206 core (Fig. 5) is located in the northern part of the tropical province, off the coast of Casamance. The paleomagnetic measurements were unreliable, because of drilling problems; it is possible to determine the chrons but not the exact positions of reversals. Nannofossils are abundant and the various assemblages indicate well the climatic stages. This section not only includes the Quaternary, but also the underlying Pliocene which is rich in discoasters; they disappear at a subbottom depth of 7.40 m which corresponds to the Plio-Pleistocene boundary.

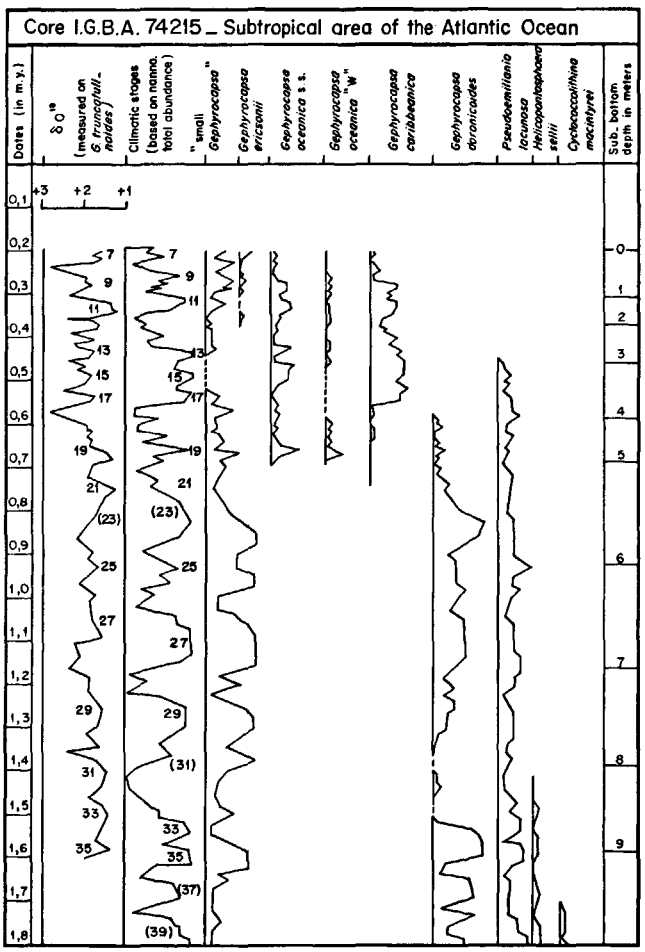

Figure 4

Distribution of some coccoliths and total abundance of nannofossils in core IGBA 74215 (subtropical Atlantic Ocean; scales: see Fig. 2).

Distribution de quelques coccolithes et abondance totale des nannofossiles dans la carotte IGBA 74215 (Océan Atlantique subtropical; échelles sur la fig. 2).

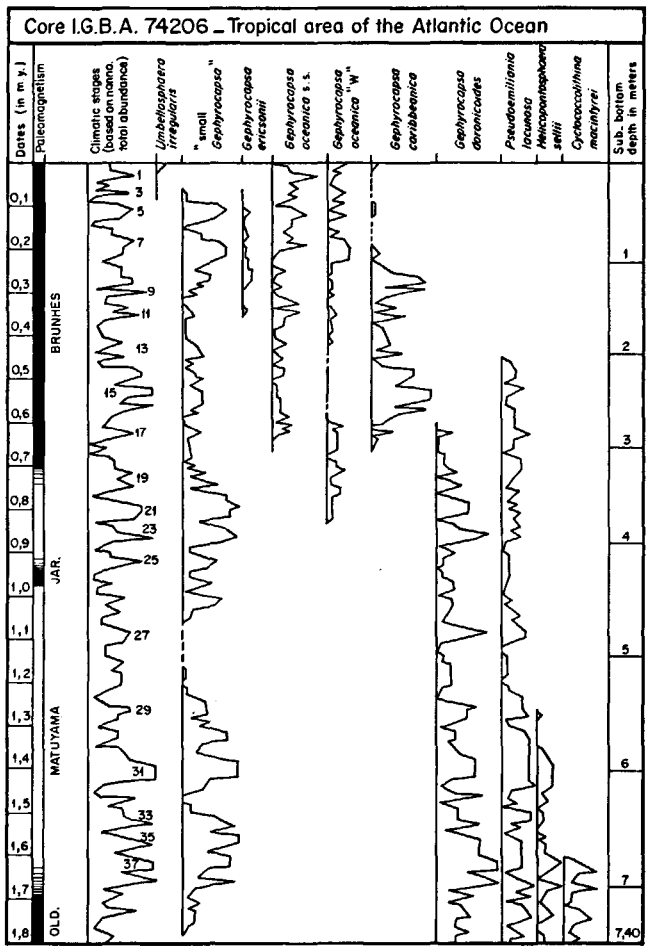

Figure 5

Distribution of some coccoliths and total abundance of nannofossils in core IGBA 74206 (tropical Atlantic Ocean; scales: see Fig. 2).

Distribution de quelques coccolithes et abondance totale des nannofossiles dans la carotte IGBA 74206 (Océan Atlantique subtropical; échelles sur la fig. 2).

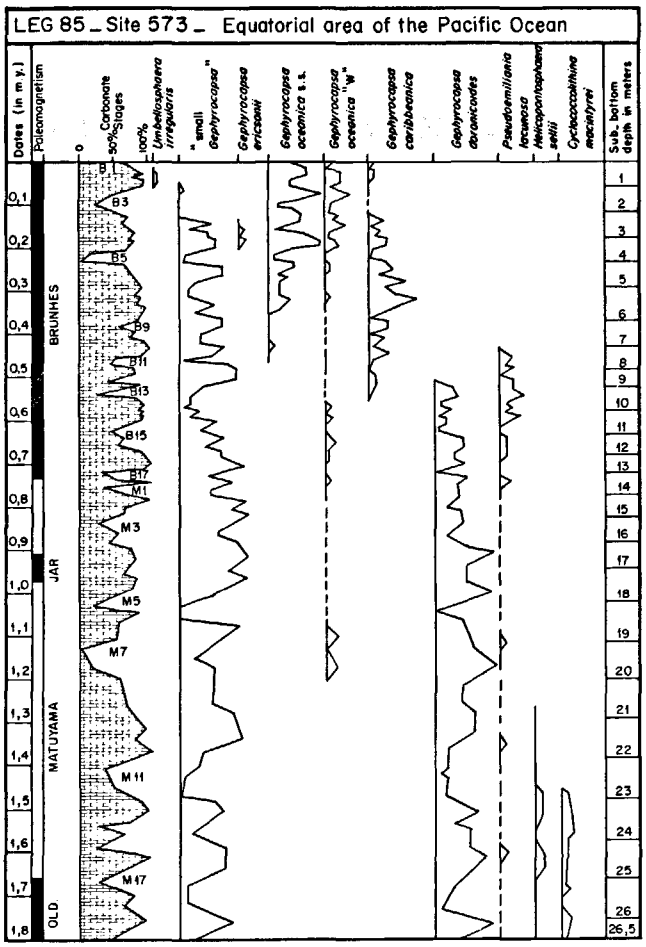

Figure 6

Distribution of some coccoliths and total abundance of nannofossils at site 573 of DSDP Leg 85 (equatorial Pacific Ocean; scales: see Fig. 2).

Distribution de quelques coccolithes et abondance totale des nannofossiles au site 573 du Leg 85 des DSDP (Océan Pacifique équatorial; échelles sur la fig. 2).

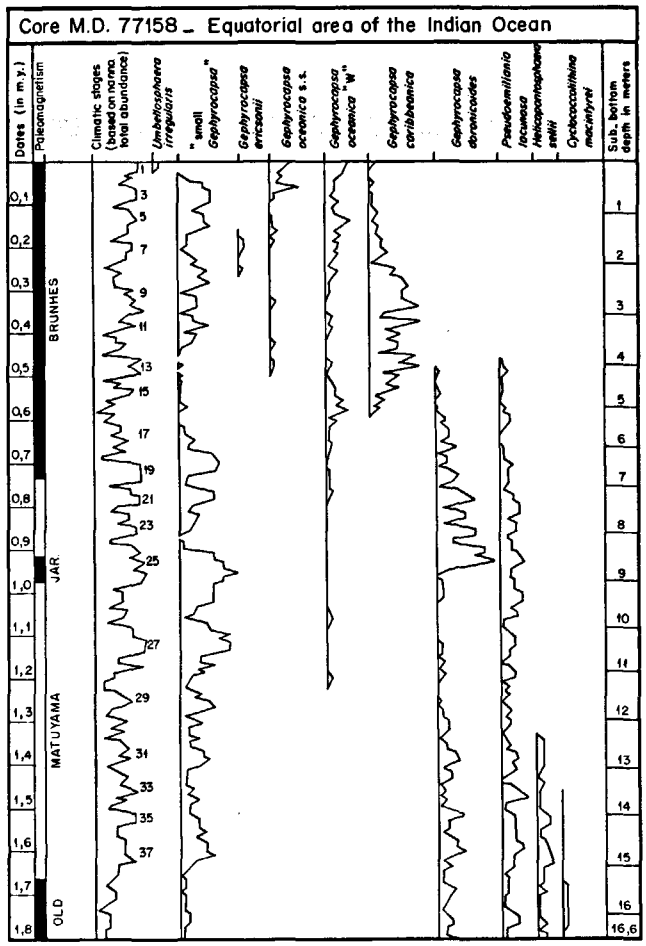

Figure 7

Distribution of some coccoliths and total abundance of nannofossils in core MD 77158 (equatorial Indian Ocean; scales: see Fig. 2)

Distribution de quelques coccolithes et abondance totale des nannofossiles dans la carottes MD 77158 (Océan Indien equatorial; échelles sur la fig. 2).

• Site 573 of DSDP Leg 85 is located north of the equator, in a highly productive area of the Central Pacific (Fig. 6). The magnetostratigraphy of this region has been established by Weinreich and Theyer (1984). Paleoclimatic stages have been determined using the CaCO3 fluctuations in the sediments; and thus the time scale established by Gardner (1982) can be used. The total abundance curve of nannofossils is very similar to that of the carbonate curve (Pujos, 1985) at least in this core. Therefore, the fluctuations in the abundance of coccoliths are not only a function of phytoplanktonic productivity but also of increased dissolution during warmer periods.

• The MD. 77158 core (Fig. 7) of the Osiris III cruise is located in the Indian Ocean, slightly to the south of the equator. Paleomagnetic reversals (Valet *et al.*, 1977) and climatic stages, marked by changes in the total abundance of nannofossils, give dates to this section. It is the only section, out of six, to have a constant sedimentation rate throughout the Pleistocene and consequently lends itself to an accurate nannofossil study.

TAXONOMIC OBSERVATIONS

Two thirds of the species used in this study belong to the genus *Gephyrocapsa* which can be considered as a Pleistocene taxon. Almost all the coccoliths I have placed within this genus have a cross-bar. However, I have also included in *Gephyrocapsa* a few specimens that do not always have this morphological characteristic; these belong to the species *G. doronicoides* which I previously split into several variants (Pujos, 1984; 1985; Pujos-Lamy, 1976) belonging to the same evolutionary trend, and showing the appearance of the cross-bar from closed or open coccoliths. This generic ambiguity has to be closely scrutinized and clarified in future studies.

The following taxa have been investigated; they are presented with a brief description (for detailed descriptions, *see* Pujos 1984; 1985) :

Gephyrocapsa oceanica s. str. (Fig. 8, n° 1)

– *Gephyrocapsa oceanica* Kamptner, 1943, Pl. 1, Fig. 16-17;

– *Gephyrocapsa oceanica* s.str. in Pujos 1985.

This medium-sized species has a large central opening and an oblique cross-bar, easy to observe. Maximum length: 2.4 – 3.2 µm.

Gephyrocapsa oceanica "W" (Fig. 8, n° 2)

– *Gephyrocapsa oceanica* "W" in Pujos (1984; 1985).

This large variant (maximum length: 4 µm) has a larger central opening than *G. oceanica* s.str. It can be considered as an ecophenotypic variant of the species s.str., corresponding to *G. omega* Bukry and *G. oceanica* Kamptner var. *californiensis* Kamptner. Like these two taxa, *G. oceanica* "W" has to be taken as a warm water variant.

***Gephyrocapsa caribbeanica* (Fig. 8, n° 3)**

– *Gephyrocapsa caribbeanica* Boudreaux and Hay (*in* Hay *et al.*, 1967, Pl. 12-13, Fig. 1-2).

It is a medium-sized closed *Gephyrocapsa* (maximum length = 3-3.7 µm), with a cross-bar more or less well developed.

***Gephyrocapsa doronicoides* (Fig. 8, n° 4)**

– *Gephyrocapsa doronicoides* (Black, Barnes, 1961) Bukry 1973, Pl. 1, Fig. 13-15.

I have already distinguished five variants within *G. doronicoides* (Pujos, 1984; 1985); they seem to be ecotypes, without a wide stratigraphical use. *G. doronicoides* is a closed *Gephyrocapsa*, with or without a cross-bar; its greatest length varies from 2.8 to 9 µm.

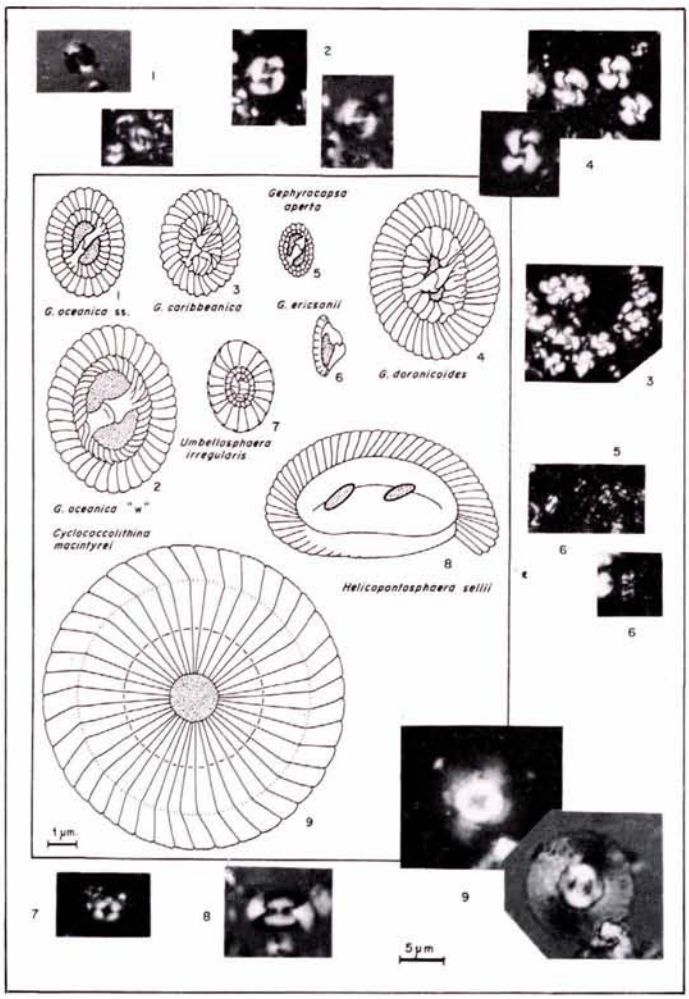

Figure 8

The nine species groups of nannofossils discussed in this paper.

Morphologie schématisée des neuf groupes spécifiques dont il est question dans la présente étude.

"Small *Gephyrocapsa*" (Fig. 8, n° 5)

This denomination was given by Gartner (1977). The group consists of coccoliths usually smaller than 2 µm, many of them are even ≦1 µm. The most frequent species are:

– *G. aperta* Kamptner 1963, Pl. 6, Fig. 32-35.

– *G. kamptneri* Deflandre and Fert, 1954, Pl. 6, Fig. 4*a*; Pl. 8, Fig. 4.

– *G. sinuosa* Hay and Beaudry, 1973, Pl. 1, Fig. 13-14.

***Gephyrocapsa ericsonii* (Fig. 8, n° 6),**

– *Gephyrocapsa ericsonii* McIntyre and Be, 1976, Pl. 10 and 12 B.

This species can be distinguished from the other "small *Gephyrocapsa*" by its cross-bar which is very refringent between crossed nicols. Maximum length: 2.2-2.4 µm.

***Umbellosphaera irregularis* (Fig. 8, n° 7)**

– *Umbellosphaera irregularis* Paasche, 1955, *in* Markali and Paasche, 1955, Pl. 3, *Fig. a-f*; Pl. 4, Fig. *a-b*; Pl. 5, Fig. *a-c*; Pl. 6, Fig. *a-c*.

U. irregularis has round-elliptical coccoliths, the outer shield of them is not refringent between crossed nicols (maximum length: 3.5 µm).

***Helicopontosphaera sellii* (Fig. 8, n° 8)**

– *Helicopontosphaera sellii* Bukry and Bramlette, 1969, Pl. 2, Fig. 3-7.

H. sellii is 8.5 µm in length, and it has two small oblique central holes. I have justified the choice of the genus *Helicopontosphaera* (instead of *Helicosphaera*) in Pujos (1984).

***Cyclococcolithina macintyrei* (Fig. 8, n° 9)**

I use the generic name of *Cyclococcolithina* for *C. macintyrei* (Bukry and Bramlette) as Wilcoxon did (1970, p. 82).

RESULTS

The spatio-temporal distribution of the 9 species or morphologic groups involved is shown in Figures 9 and 10; the main results can be summarized as follows:

1/*Gephyrocapsa oceanica* s.str. (Fig. 9). Several authors have attempted to determine the LO of this species. Shafik (1978) examined the most informative data (0.900 Ma from Bukry, 1973; 1.510 to 1.650 Ma from Gartner, 1977; about 1.571 Ma from Haq *et al.*, 1977) and suggested that the difference in the ages given is partly due to different species concepts. I agree with Shafik. For this reason, I have described (see above in the taxonomic observations) and figured (Fig. 8-1) *G. oceanica* s.str. according to my own species concept. In my study, the LO of *G. oceanica* s.str. can be dated 1.200 Ma in high latitudes and 0.480 Ma. in low latitudes. The abundance of coccoliths increases gradually

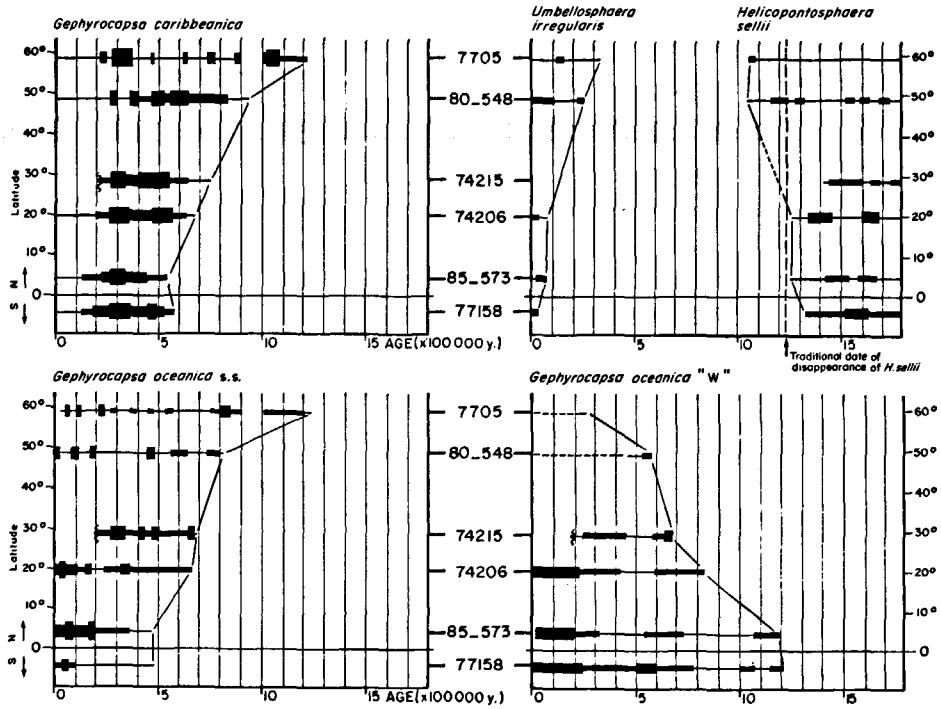

Figure 9

Quaternary spatiotemporal distribution of Gephyrocapsa caribbeanica, Umbellosphaera irregularis, Gephyrocapsa oceanica *s.str.*, Gephyrocapsa oceanica "*W*" *and* Helicopontosphaera sellii. ▮ >40 *coccoliths (in 5 fields of view X* 1200)*;* ▪ 15 *to* 39 *coccoliths;* ▬ 5 *to* 14 *coccoliths;* — 2 *to* 4 *coccoliths;* ---- 1 *coccolith.*

Distribution spatio-temporelle au Quaternaire de *Gephyrocapsa caribbeanica, Umbellosphaera irregularis, Gephyrocapsa oceanica* s.str., *Gephyrocapsa oceanica* "W" et *Helicopontosphaera sellii.* ▮ >40 coccolithes (dans 5 champs X 1200); ▪ 15 à 39 coccolithes; ▬ 5 à 14 coccolithes; — 2 à 4 coccolithes; ---- 1 coccolithe.

from high to low latitudes. Such a distribution allows the reconstruction of the invasion of the northern hemisphere by this taxon. It occurs at about 1.200 Ma at 60°N latitude in the Atlantic Ocean, and persists until today. However, it never dominates the assemblages. *G. oceanica* s.str. is primarily a "cold water" form, and its colonization of all latitudes has taken approximatively 0.700 m.y. It invaded the tropical Atlantic around 0.500 Ma and the equatorial Pacific and Indian Ocean waters around 0.200 Ma. Its present day distribution in both the tropical and equatorial provinces is, therefore, a rather recent phenomenon.

2/ *Gephyrocapsa oceanica* "W" (Fig. 9). The *G. oceanica* "W" group comprises several species and variants encountered in low-latitude waters (=*G. omega, G. oceanica* var. *californiensis*). These are therefore undoubtedly warm-water species. In high latitudes, the group occurs sporadically but becomes progressively abundant towards the equator. Furthermore, *G. oceanica* "W" makes a very early appearance in low latitudes at about 1.200 Ma but occurs for the first time at 60°N latitude only at about 0.270 Ma.

3/ *Gephyrocapsa caribbeanica* (Fig. 9). *G. caribbeanica* is commonly considered as a "cold-water" species (Roth, Coulborn, 1982, Recent sediments; Geitzenauer *et al.*, 1977, Recent sediments; Steinmetz, Anderson, 1983, middle and late Pleistocene sediments), because it is proportionately more abundant in cold than in warm regions and periods. The studies that led to this conclusion, however, are based on species percentages which tend to over-estimate certain species because, during past cold periods, and in high latitudes, the assemblages of nannoplankton were very poor and were dominated by the species that were the most tolerant to unfavorable climates. In computing percentages, the proportions of such resistant species will be artificially increased. This can be the case with *G. caribbeanica* which is almost always present in sediments at cold periods. In fact, it would be more realistic to consider *G. caribbeanica* as a cosmopolitan form.

This species flourished during odd-numbered isotopic climatic stages at high and middle latitudes, especially during stage 9, and between 0.600 and 0.130 Ma in the tropics and the equatorial region. In addition to its world-wide prevalence throughout stage 9 (Thierstein *et al.*, 1977), the species shows an interesting LO ranging between 1.300 Ma in high latitudes and 0.550 Ma at the equator.

4/ *Gephyrocapsa doronicoides* (Fig. 10). This species group dominates the nannofossil assemblage of the middle and early Pleistocene. It survived from the late Pliocene and is consequently found at the base of all sections studied. Its extinction has been dated by Bukry (1970) at 0.900 Ma and at about 0.800 Ma by Perch-Nielsen (1972) who gave it the name *C. jaramillensis.* The complexity of the HO of this species is enhanced by its complex morphology. It is likely that its extinction was not synchronous: between 0.480 and 0.600 Ma Nevertheless, it appears to be extinct slightly earlier at 60°N latitude (=0.480 Ma) than at the equator.

The *G. doronicoides* abundance reaches its maximum in the tropical province s.s. (=towards 20-30°N latitude). Its abundance drops considerably at high latitude, which suggests that it is a tropical species.

5/ *Gephyrocapsa ericsonii* (Fig. 10). No information is yet available on the distribution of this species. This is

due to the difficulty in distinguishing the species among various small *Gephyrocapsa*. However, its spatio-temporal distribution is of great interest. The LO of *G. ericsonii* varies between 1.240 Ma at 60°N latitude and 0.200 Ma at the equator. Its HO changes within the same geographic limits from 0.020 to 0.150 Ma. Furthermore, this species is present during a much shorter time period at low latitudes (=0.080 m.y.) than at high latitudes (=1.200 m.y.). It is thus a "cold-water" species and could contribute considerably to stratigraphic and climatic studies of the late Quaternary.

6/ "Small" *Gephyrocapsa* (Fig. 10). This group occurs as early as the earliest Pleistocene and thrives throughout most of the last 2 million years. In my study, its extinction is estimated at 0.050±0.020 Ma depending on geographical location of the section, and correlated with that of *G. aperta* s.str., since at this time, the latter is the only species present among the "small" *Gephyrocapsa*, except for *G. ericsonii* which I exclude from the group of small forms.

The "small" *Gephyrocapsa* were first described by Gartner (1977) who has established a "small *Gephyrocapsa* zone" and assigned it an age of 1.220 Ma to 0.920 Ma. According to Gartner (1977) "This datum... does not correspond to the concept of datum as commonly perceived... It is impossible to find a specimen of *Gephyrocapsa* of normal size." In spite of these problems, this zone is considered reliable by many authors (*e. g.*, Rio, 1982). The long and significant acme of the "small" *Gephyrocapsa* throughout the Pleistocene is stratigraphically useful, although it can be dated differently according to latitude. Its spatio-temporal distribution shows a shift from high (from 1.000 to 1.300 Ma) to low latitudes (from 0.650 to 1.000 Ma). South of the equator, changes in the abundance of this group are so frequent that no acme can be determined. SEM studies have revealed the complex morphological characteristics of the group within this "zone". Thus, at site 548 of DSDP Leg 80, it is a "*G. sinuosa* zone" that can be distinguished, while *G. aperta* is almost the only *Gephyrocapsa* species to be present in this zone at site 573 of DSDP Leg 85 and in cores IGBA 7705 and IGBA 74206. Core MD 77158 shows an assemblage with particularly small coccoliths (<1 μm; especially between 0.670 and 0.780 Ma) represented by variants of *G. aperta*, *G.* aff. *kamptneri* and possible variants of *G. producta*. The same diversity among the *Gephyrocapsa* species was also noticed by Gartner (1977) who concluded that it is not important to determine them "since none of these small species can be distinguished with a light microscope".

The complex aspects of this group and the very small size of the coccoliths handicap their use in stratigraphy, even if at certain latitudes (especially towards 50-60°N latitude) the "small" *Gephyrocapsa* zone is stratigraphically useful. But, as soon as warmer latitudes are reached, small *Gephyrocapsa* are more and more abundant, with more species and variants; the successive acmes are so long that they join one another, which renders accurate dating of this zone impossible.

Determination of the zone in the lower Pleistocene should be useful but is ambiguous in the present state of information.

7/ *Umbellosphaera irregularis* (Fig. 9). Gartner and Emiliani (1976) have located the LO of this species in stage 14 in the Colombian Basin at 11°N latitude. Gartner (1977) added information on a site at 32°S latitude and on an equatorial site, where *U. irregularis* occurs only at the top of the sections. These results are not

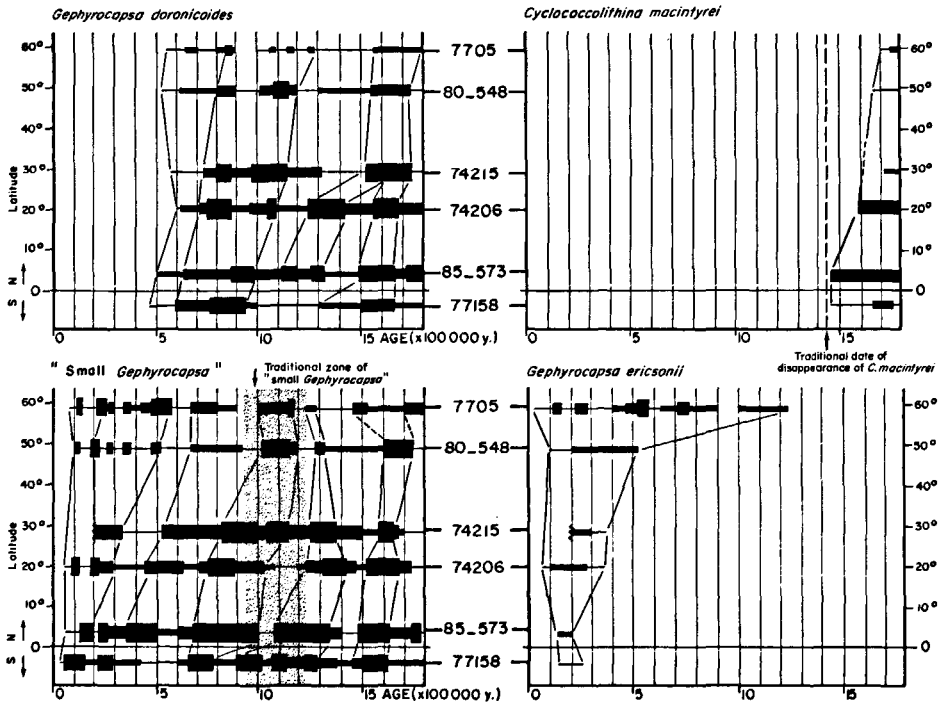

Figure 10

Quaternary spatiotemporal distribution of Gephyrocapsa doronicoides, Cyclococcolithina macintyrei, *the "small"* Gephyrocapsa *and* Gephyrocapsa ericsonii.

Distribution spatio-temporelle au Quaternaire de *Gephyrocapsa doronicoides, Cyclococcolithina macintyrei,* les « petites » *Gephyrocapsa* et *Gephyrocapsa ericsonii.*

very precise: they are complicated by a possible confusion with the LO of another species (*U. tenuis*) located in stage 7 in the Colombian basin by Gartner and Emiliani (1976).

The present study shows that *U. irregularis* occurs at about 0.320 Ma (=base of stage 9) in high latitudes. At the equator, it first appears at the base of the last warm climatic stage, at about 0.020 Ma. It is still extant at all latitudes. In contrast to *G. ericsonii*, which has a similar LO extent, *U. irregularis* is no more abundant in high than in low latitudes. Therefore, it colonized the warm provinces recently without preferring any particular climatic province. This recent adaptation to warmer areas corresponds well with the distribution observed by Geitzenauer *et al.* (1977) who noted its highest relative abundance from south of the Sargasso Sea to the Colombian coasts. This may be the region that this species prefers.

8/ *Helicopontosphaera sellii* (Fig. 9). Gartner (1977) established the *H. sellii* zone and calibrated it between 1.220 Ma (where he placed the HO of the species) and 1.510 Ma (considered by Gartner as the HO of *C. macintyrei*). This zone was adopted by other micropaleontologists, such as Rio (1982). Backman and Shackleton (1983) dated the HO of *H. sellii* at 1.370 Ma and stated in the abstract of their paper that it is diachronous and occurs earlier outside the equatorial zone. Unfortunately, these authors made no further comment on this matter; they merely mentioned the disappearance of *H. sellii* slightly later than that of *C. macintyrei* and plotted its relative abundance on diagrams without a detailed time scale. They concluded that "this taxon disappears from mid-latitudes (=1.320 m.y.) well before its extinction from a narrow latitudinal band in the equatorial Pacific (=1.100 m.y.)". So were they suggesting that this Pacific equatorial band is anomalous?

The results I have obtained are in disagreement with those of Backman and Shackleton (1983), but I also observed that the coccoliths of *H. sellii* are abundant at low latitudes, whereas at higher latitudes (=50-60°N) their presence is often sporadic and the species is difficult to detect. On this point, I agree with Backman and Shackleton when they wrote: "the datum should only be used biostratigraphically with extreme caution".

9/ *Cyclococcolithina macintyrei* (Fig. 10). The HO of *C macintyrei* is an often used datum. Okada and Bukry (1980), Gartner (1977) and Raffi and Rio (1979) generally agree on the usefulness of the HO of this species in zonations, but disagree on the age of this event. The most recently published dates range from 1.510 Ma (Gartner, 1976) to 1.450 Ma (Backman, Shackleton, 1983). The latter consider the extinction of *C. macintyrei* as... "a reliable and easily recognizable datum event". In spite of this conclusion, this datum level must be used with caution as a result of its diachronism.

DISCUSSION

The detailed analysis of nannofossils from 6 Quaternary sections shows the diverse spatio-temporal distribution of the 9 taxa at different latitudes of the Northern Atlantic and the equatorial Pacific and Indian Oceans. They have to be placed into 4 groups according to their synchronism or diachronism:

Synchronous ranges

Some taxa show synchronous geologic events regardless of latitude ranges. Two of them are well known and they are taken as world-wide datums; so they are commonly used and they are only mentioned here:

– HO of *Pseudoemiliania lacunosa* at 0.450 Ma ± 0.010 Ma (Gartner, 1977; Thierstein *et al.*, 1977)

– top of acme of *Gephyrocapsa caribbeanica* and dominance change between *G. caribbeanica* and *Emiliania huxleyi* at 0.268 Ma (Thierstein *et al.*, 1977) which corresponds to the top of isotopic stage 9. The top of acme of *G. caribbeanica* is easy to recognize with a light microscope, which is not the case for the appearance of the very small *E. huxleyi*.

I have dated a third synchronous event in the present study:

– HO of the small *Gephyrocapsa* at 0.050±0.020 Ma (=during isotopic stage 3); at this time, the small *Gephyrocapsa* belong almost entirely to *G. aperta*.

Diachronous ranges

There are two time-transgressive trends:

• Events occurring at increasingly later dates from high to low latitudes:

– LO of *Umbellosphaera irregularis*: between 0.320 Ma (in high latitudes) and 0.020 Ma (in low latitudes);

– LO of *Gephyrocapsa ericsonii*: between 1.240 Ma (in high latitudes) and 0.200 Ma (in low latitudes);

– LO of *Gephyrocapsa oceanica* s.str.: between 1.200 Ma (in high latitudes) and 0.480 Ma (in low latitudes);

– LO of *Gephyrocapsa caribbeanica*: between 1.300 Ma (in high latitudes) and 0.550 Ma (in low latitudes);

– HO of *Cyclococcolithina macintyrei*: between 1.700 Ma (in high latitudes) and 1.450 Ma (in low latitudes);

– HO of *Gephyrocapsa doronicoides*: between 0.600 Ma (in high latitudes) and 0.480 Ma (in low latitudes).

Most of the events described are related to the lowest occurrences of species, except for *C. macintyrei* and *G. doronicoides*. The time gradient is generally long (between 0.300 and 1.000 Ma).

• Events occurring at increasingly earlier dates from high to low latitudes:

– HO of *Gephyrocapsa ericsonii*: between 0.020 Ma (in high latitudes) and 0.150 Ma (in low latitudes).
– HO of *Helicopontosphaera sellii*: between 1.100 Ma (in high latitudes) and 1.420 Ma (in low latitudes).
– LO of *Gephyrocapsa oceanica* "W": between 0.270 Ma (in high latitudes) and 1.200 Ma (in low latitudes).

It must be noted that two of these three events are associated with highest occurrence of species and their time gradient is short (0.130 and 0.380 m.y.).

Small *Gephyrocapsa*

This group has a distinct spatio-temporal distribution. These coccoliths are generally less abundant in high latitudes than in low latitudes. They were living throughout the Quaternary, with one or two main time-transgressive acmes dated as follows:

– in high latitudes: one acme from 1.300 to 1.000 Ma;
– in low latitudes: two acmes:
- early acme from 1.650 to 1.080 Ma;
- late acme from 1.000 to 0.650 Ma.

The "small *Gephyrocapsa* zone" was dated between 1.220 and 0.920 Ma by Gartner (1977). So, because of this diachronism, this group is of limited stratigraphical use except for the top of the late acme which occurs at about 1.000 Ma in high latitudes and at 0.650 Ma in low latitudes.

All these stratigraphical markers are plotted and summarized on Figure 11, to facilitate use.

SPATIO-TEMPORAL DISTRIBUTION PATTERNS

The distribution of dominant nannofossil species shows pronounced spatio-temporal gradients, especially for lowest occurrences of species. The time-lag is great between 60°N latitude and the equator and may be as long as 1 m.y. This phenomenon cannot be explained by the influence of glacial climates as is the case for many organisms during the Quaternary. Ruddiman and McIntyre (1973) concluded that the time-lag for glacial waters was no more than 7.000 yr between high- and mid-latitudes, which is much shorter than the species occurrence lags recorded in the present study. How can we explain this phenomenon? Perhaps by a progressive adaptation of nannoplankton to various environments, leading to colonization of larger areas, or by specific mutations furthering moving of some assemblages to a different climatic area.

In contrast, the extinction events are nearly synchronous, the time-lag not exceeding 0.300 m.y. Nevertheless, they should be used with caution because they may be misinterpreted (as too young) when the material is reworked. Can these extinctions, therefore, be considered totally synchronous? The time difference of 0.300 m.y. may have been caused by the latitudinal time-lag of large-scale climate phenomena.

CONCLUSIONS

All the nannofossil species and species groups discussed in the present paper can be considered to be strati-

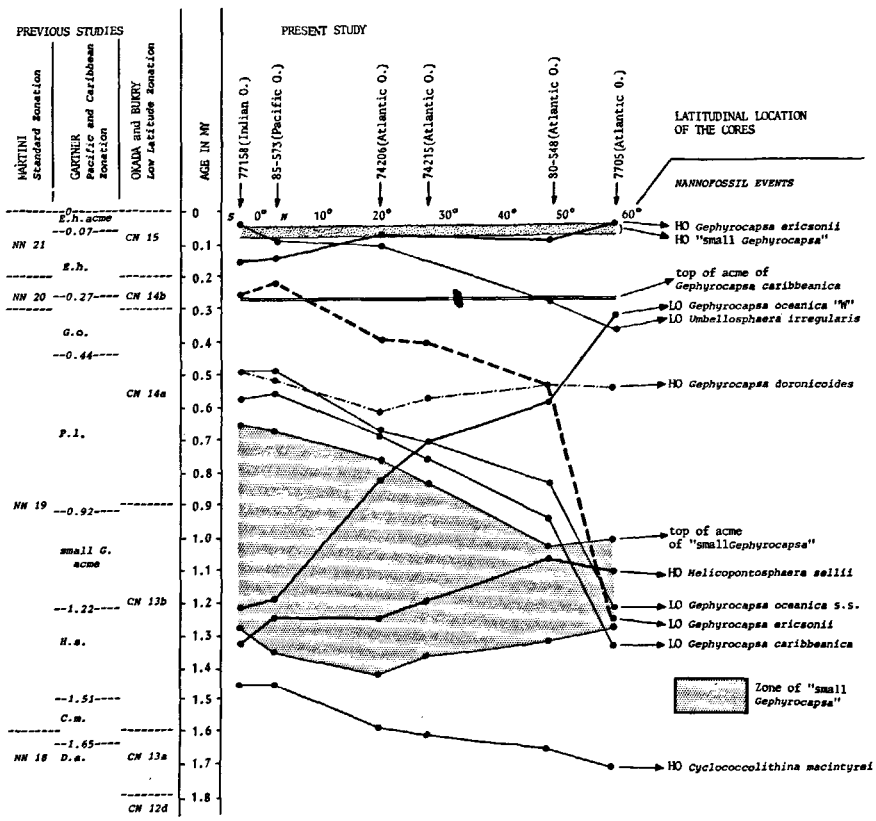

Figure 11

Comparison between results in the present paper and previous Pleistocene nannofossil zonations: E.h. = Emiliania huxleyi; *G.o.* = Gephyrocapsa oceanica; *P.l.* = Pseudoemiliania lacunosa; *H.s.* = Helicopontoshaera sellii; *small G.acme* = *acme of "small* Gephyrocapsa"; *C.m.* = Cyclococcolithina macintyrei; *D.a.* = Discoaster *spp.*

Comparaison entre les résultats de la présente étude et les zonations précédentes basées sur les nannofossiles pléistocènes : E.h. = *Emiliania huxleyi;* G.o. = *Gephyrocapsa oceanica;* P.l. = *Pseudoemiliania lacunosa;* H.s. = *Helicopontosphaera sellii;* small G.acme = acmé des "petites *Gephyrocapsa*"; C.m. = *Cyclococcolithina macintyrei;* D.a. = *Discoaster* spp.

graphic markers. Some nannofossil events are truly synchronous and the corresponding taxa (*Pseudoemiliania lacunosa, Gephyrocapsa caribbeanica* and "small" *Gephyrocapsa*) mark real datums (Fig. 11). All the other taxa show spatio-temporal distribution patterns that I have interpreted as a latitudinal effect. It will be possible to use these diachronous events in chronostratigraphy for local sedimentary sections. Thus, different nannofossil associations will be found at the same time in sections from different oceanic areas (Tab. 3).

This phenomenon of time-transgressive distribution is evident when studying Quaternary nannofossils from low to high latitudes. The present study shows their ability for colonizing various climatic provinces.

Table 3

Dates of the main events in high and low latitudes.

Dates des principaux événements aux hautes et basses latitudes.

	High latitudes (Ma)	Low latitudes (Ma)
HO of *G. ericsonii*	0.020	0.150
HO of small *Gephyrocapsa*	0.50±0.020	
Top of acme of *G. caribbeanica*	0.268	
HO of *G. oceanica* "W"	0.270	1.200
LO of *U. irregularis*	0.320	0.020
HO of *P. lacunosa*	0.450±0.010	
HO of *G. doronicoides*	0.600	0.480
Top of acme of small *Gephyrocapsa*	1.000	0.650
HO of *H. sellii*	1.100	1.420
LO of *G. oceanica* s.tr.	1.200	0.480
LO of *G. ericsonii*	1.240	0.200
LO of *G. caribbeanica*	1.300	0.550
HO of *C. macintyrei*	1.700	1.450

Acknowledgements

The samples I studied were taken on several cruises: Faegas II with M. Pujos as chief scientist, Midlante B and Osiris III with J.-C. Duplessy as chief scientist. Samples from Legs 80 and 85 were supplied through the assistance of the International Ocean Drilling Programme. I thank all the chief scientists and participants of these cruises and Legs, as well as the two anonymous reviewers for their useful reviews and suggestions. Many thanks to B. Sen Gupta who was kind enough to revise the English of most of my paper.

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