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CALCAREOUS NANNOFOSSILS AND THE $<25\mu$ FRACTION IN QUATERNARY SEDIMENTS OF THE SUBTROPICAL NE ATLANTIC OCEAN

CONTENTS

Key words: *Calcareous nannofossils, Diatoms, Pleistocene, Paleoecology, Paleohydrology, Productivity, Estimated temperatures and salinities, Silica, African western margin, Organic matter.*

ABSTRACT

The fine fraction ($<25\mu$) is observed on smear slides of sediments from the last 700 Ky of the Site 658, ODP Leg 108, from the western African margin, and from core Mid 06 from the open ocean. Nannofossils and other components of this fraction are studied.

Nannofossils are used for (1) establishing a precise chronological scale of the period and for specifying the limits of the 17 last climatic stages; (2) estimating winter and summer paleotemperatures and paleosalinites using a transfer function; (3) localizing some a-priori aberrant maxima of the nannofossil cold species *Coccolithus pelagicus*, of the warm genus *Rhabdosphaera* and of *Helicopontosphaera*.

The other components of the fine fraction observed at ODP Site 658 are silts, diatoms and silica/organic matter colloids. Their maxima are always located at the same periods, in relation to the glacial and/or interglacial climatic stages. They are absent from the oceanic core Mid 06.

Information from both nannofossils and other components make it possible to reconstruct the hydrological, atmospherical and environmental history of the area of the sections (and more generally the western African margin) for the last 700 Ky.

RIASSUNTO

Viene analizzata in "*smear slides*" la frazione fine ($<25\mu$) dei sedimenti degli ultimi 700 Ky del Site 658, ODP Leg 108, margine occidentale africano, e della carota di oceano aperto Mid 06 e ne vengono studiati i nannofossili e gli altri componenti.

I nannofossili sono utilizzati per: (1) stabilire una scala cronologica precisa dell'intervallo di tempo e per definire con precisione i limiti degli ultimi 17 cicli climatici; (2) fare una stima delle paleotemperature e paleosalinità invernali ed estive usando una funzione transfer; (3) localizzare alcuni massimi a priori aberranti della specie fredda di nannofossili *Coccolithus pe-*

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lagicus e dei generi caldi *Rhabdosphaera* e *Helicopontosphaera*.

Gli altri componenti della frazione fine, osservati al Site 658 ODP, sono silts, diatomee e materia colloidale silico/organica. I loro massimi si collocano sempre negli stessi intervalli di tempo, in relazione ai cicli climatici glaciali e/o interglaciali. Essi sono assenti nella carota oceanica Mid 06.

Le informazioni ricavate, sia dai nannofossili che dagli altri componenti, hanno reso possibile la ricostruzione della storia idrologica, atmosferica ed ambientale dell'area in esame (e più in generale del margine occidentale africano) per gli ultimi 700 Ky.

INTRODUCTION

Several legs (DSDP, ODP and others) took place in the easter part of the tropical and equatorial Atlantic Ocean. Many sites have been cored, most of which recovered Quaternary sediments with abundant and diverse nannofossils. The study area (North-eastern subtropical Atlantic ocean, facing Africa, (Fig. 1) is partly subject to seasonal and permanent upwelling, which cause high productivity. Two sections were chosen in order to compare sedimentation in this high productivity area with sedimentation in the adjacent open ocean.

The first step of the present study was to date sediments as precisely as possible with nannofossils, using markers previously determined for "the northern hemisphere" (Pujos, 1988), and isotope measurements on tests of benthic and planktonic foraminifera. The second step was to link nannofossil associations and paleoenvironment; for this purpose, various organic and inorganic elements of the $<25\mu$ fraction were used and an attempt

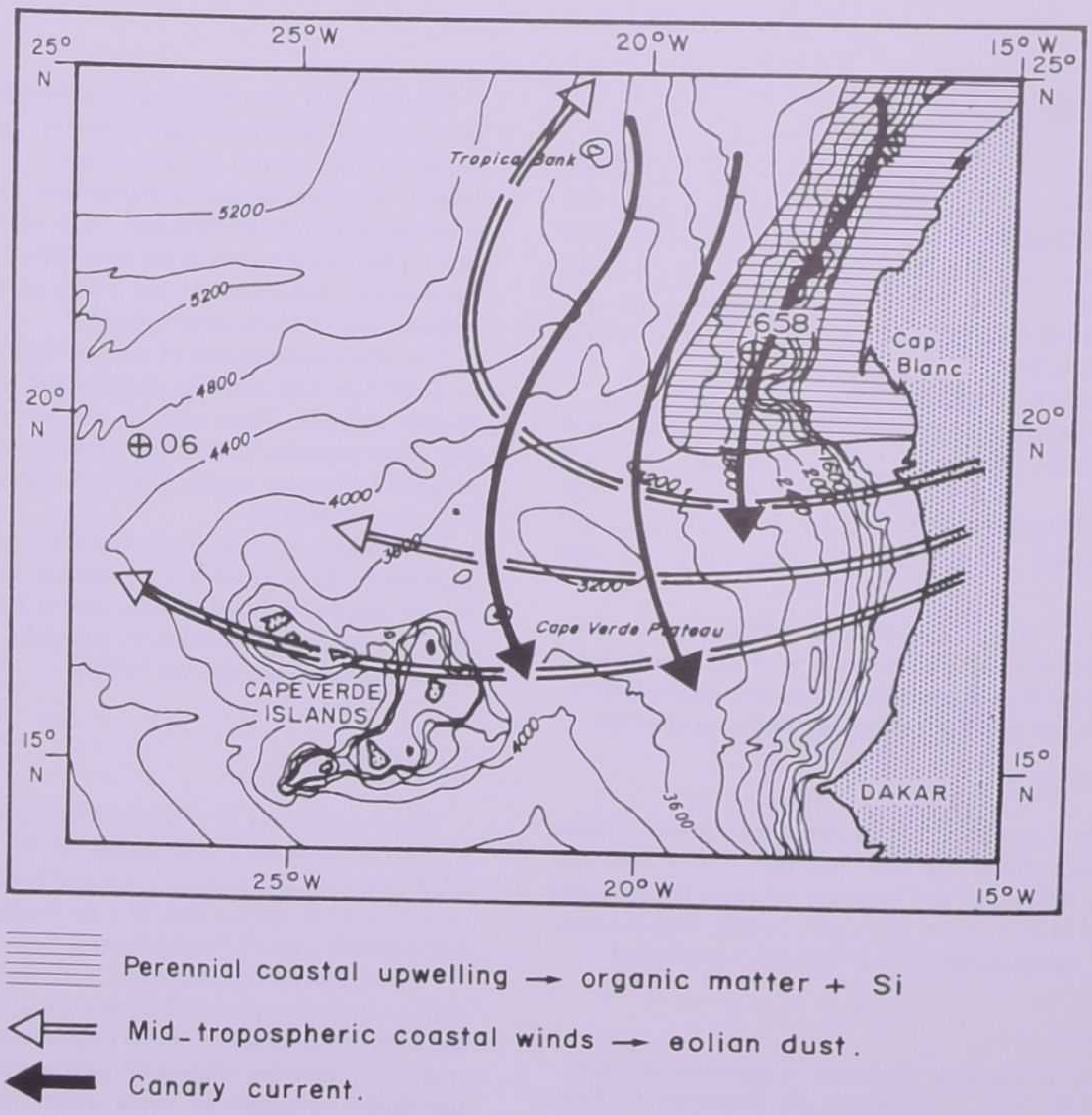

Fig. 1 - Location of ODP Site 658 and of core Mid 06. General hydrological and atmospherical sketch of the studied area.

was made to quantify physical parameters of the surface layers of the past ocean. Given the complexity of the area and the abundance of coccoliths, the study was limited to the last 700,000 years.

THE AREA

The high-productivity area is located West of tropical Africa; its influence is limited to the continental shelf and slope, between 0 and about 3,000 m deep (Fig. 1). It is related to a complex atmospherical and hydrological system, further complicated by seasonal influences:

— *In situ* tropical waters supplied by the warm water reservoir located, according to McIntyre *et al.* (1989), in the western equatorial Atlantic.

— "Cooler" NAW (= North Atlantic water) of the Canary current.

— SAW (= South Atlantic water) of the Benguela current and the South equatorial current.

— A double system of upwellings: a perennial coastal upwelling induced by the Canary current and a seasonal upwelling induced by the South Atlantic central waters.

— African rivers (the Niger, Congo and smaller rivers) which bring low salinity water and fresh water organisms (diatoms) to the ocean. Seasonal rises in river levels increase this flux and may stimulate biogenic opal and organic matter production.

— Mid-tropospheric coastal winds which bring eolian dust from the Sahara.

These climatic and oceanic factors bring chemical (dissolved silica; low salinity water), inorganic (silts from the continent and from the continental shelf; eolian dust) and organic components (organic matter; freshwater diatoms) to the study area, adding to the autochtonous sedimentation (Kassens and Sarnthein, 1989; Morzadec-Kerfourn, 1988; Gasse *et al.*, 1989).

This outline describes the recent environment of the study area briefly. Core samples make it possible to follow its changes in relation to the glacial and interglacial alternation.

MATERIAL

Two sections were chosen, based on their location and sedimentation history (Tbl. 1 and Fig. 1):

ODP Site 658 was located on the oceanic slope, about 150 km offshore, within the well-known high-productivity area (Sarnthein *et al.*, 1989; Kassens and Sarnthein, 1989; Gasse *et al.*, 1989). The recovered cores record almost continuous sedimentation at least during the last 0.7 My. The sedimentation rate is almost constant (except for two short hiatus between the isotopic stages 3 and 5, and within stage 11), and the sediments are rich in calcareous organisms (nannofossils, benthic and planktonic foraminifera) and siliceous organisms (diatoms, silicoflagellates and radiolarians); there are also abundant inorganic elements.

Table 1 - Location of the two sections

CORE	LATITUDE	LONGITUDE	WATER DEPTH
ODP Site 658	20°45′N	18°35′W	2575m
Mid 06	19°36′N	27°25′W	4662m

Core Mid. 06 was recovered at a similar latitude to ODP Site 658 but about 1,100 km offshore (Pujol *et al.*, 1976). This core has been taken as a reference of hydrologically undisturbed open ocean sedimentation, contrasting with ODP Site 658. It has a lower sedimentation rate, which may act as an artifact and disturb the regularity of the distribution of some components. There is no obvious hiatus; but stage 11 at least does not seem to be complete. Nannofossils are abundant and the assemblages are diverse during the last 700 Ky. Isotope data are available for the last 500 Ky. Inorganic components and siliceous organisms are rare.

93 Core top samples were selected, for use in the first step of the transfer function (see below: methods). They were located in the northeastern Atlantic ocean (5°S to 66°N, 0°W to 50°W, fig. 2). The tropical samples were used for a previous tropical nannofossil transfer function (Pujos, 1988 b); but because episodic intrusions of the Canary current bring cooler waters to the area, it was necessary to add further samples from the northern Atlantic; tropical core tops from ODP Leg 108 were also used.

METHODS OF STUDY

The abundances of nannofossils and other organic and inorganic components of the $<25\mu$ fraction were studied (Pujos, 1989 a and b), by counting and/or estimate on smear slides with an optical microscope. Selected samples were also studied by SEM.

NANNOFOSSILS

Nannofossils were identified (list of species, Appendix) using the same criteria as previously for DSDP studies (PUJOS, 1984 and 1985) and for study of spatio-temporal distribution (PUJOS, 1988a). No additional species were found.

Count matrices of nannofossils were established for dating and for estimating physical parameters of the past superficial water layers via mathematical functions; there are two kinds of matrices: statigraphical and paleoecological.

The "stratigraphical" nannofossil taxa

This initial group of species is used solely to establish a high-resolution biostratigraphy. For these coccoliths, it is not necessary to make very precise counts. As previously (PUJOS, 1988a), three kinds of stratigraphical events are used: lowest occurrence (= "LO"), highest occurrence (= "HO") and acmes ("lowest" bottom of acme = "LA", and "highest" top of acme = "HA"). For locating these events on a section, semi-quantitative estimates are sufficient; they are made in about 5 fields of view, X 1,200, and about 13 ranges of abundance are used (1, 2; 3-5, 6, 7-8, 9-10, 11-12, 13-16, 17-20, 21-25, 26-30, 31-35 coccoliths).

Although they are established on estimates, these "counts" are converted into percentages, 100% corresponding to the sum of the counts of all the stratigraphical coccoliths (Fig. 4).

The nannofossil taxa used as stratigraphical markers are:

Emiliania huxleyi
Gephyrocapsa aperta
G. ericsonii
G. oceanica s.s.
G. oceanica "W"
G. caribbeanica
G. lumina
G. producta
G. doronicoides (with 4 variants)
Pseudoemiliania lacunosa
Umbellosphaera irregularis

The "ecological" nannofossil taxa

21 "ecological" taxa are determined (Appendix), which are all the coccoliths other than the "stratigraphical" ones; they are:

Ceratolithus div. sp.
* *Coccolithus pelagicus*
* *Cyclococcolithina leptopora* s.s.
* *Cyclococcolithina leptopora* var.
Cyclolithella annula
Emiliania annula
** *Florisphaera* div. sp.
* *Helicopontosphaera* div. sp.
Pontosphaera alboranensis
Pontosphaera distincta
Pontosphaera japonica
Pontosphaera messinae
Pontosphaera multipora
Pontosphaera pacifica
* *Rhabdosphaera clavigera* and *Discosphaera tubifera*
* *Scapholithus fossilis*
Scyphosphaera div. sp.
* *Syracosphaera* div. sp.
Thoracosphaera var. 1
Thoracosphaera var. 2
* *Umbilicosphaera sibogae*

Nine taxa were selected for detailed paleoenvironmental analysis, because they are present in most of the pleistocene samples, which is not the case for the other ecological taxa. Eight of the ecological taxa (marked* on the list above) were counted until their sum reached 150 coccoliths. The ninth (*Florisphaera*, marked ** on the list) was counted apart, because its cells bear considerably more coccoliths than the other genera (about 200 coccoliths for *Florisphaera*, between 9 and 40 for the others); it is counted on an area corresponding to a 1/2 slide field of an optical microscope X 1 200.
The number of coccoliths per cell varies depending on the genus, species, variety, and the environment. Thus, coccolith counts have to be transformed into cell (= organism) counts to be taken as a population of Coccolithophoridae. (The technique used for converting coccolith counts into cell counts is described by GIRAUDEAU and PUJOS, 1990, and by GIRAUDEAU, same book).

INORGANIC AND OTHER ORGANIC COMPONENTS

Organic components other than nannofossils

Several kinds of siliceous organisms are present and often abundant; they are not all detailed: only broken radiolarians appear on smear slides, and the distribution of silicoflagellates does not show obvious changes. Only the frustules of Diatoms are abundant and small enough to be identified and counted on smear slides quantitatively: they were used for paleoenvironmental interpretations.

Inorganic components

Study of inorganic components is restricted to semi-quantitative estimate of silt and eolian dust <25μ. Several observations of the <25μ sediment and semi-quantitative analyses were made by SEM at strategic locations down the cores for specifying the size and morphology of various sediment components.

On some smear slides (mainly from ODP Site 658), observation of coccoliths is hindered by cloud of structureless matter <0.5μ; it appears as a thick, dense, more or less homogenous and yellowish glue, which coats almost everything.

An attempt was made to analyse this "glue", which is neither calcareous, nor organic. It is not made of clay, and usually shows no precise structure when observed with either a Transmission Electron Microscope (N. MAILLET, 1988, personal communication) or a Scanning Electron Microscope (semi-quantitative SEM analyses by P. LEGIGAN, 1989, to be published). In some of these samples, this colloidal matter is slightly different, and seems to have an imprecise structure, a kind of reticulum, which could be interpreted as strongly dissolved diatom frustules. It was concluded that this matter is, in most cases, a siliceous/organic colloidal gel, sometimes with dissolved diatoms. Thus, is is totally or in part silica, controled by the sedimentation of abundant organic matter[1]. This agrees well with conclusions of the study of diagenetic cementation by KASSENS and SARNTHEIN (1989).

ISOTOPE MEASUREMENTS

At ODP Site 658, measurements have been made on shells of selected benthic (*Cibicides wuellerstorfi*) and planktonic Foraminifera (*Globorotalia inflata*), enabling identification of Quaternary isotopic stages and sub-stages (SARNTHEIN and TIEDEMAN, 1989).

For core Mid.06, they were made in shells of *Globigerinoides sacculifer*; the curve obtained makes location of the main climatic stages possible, providing a basic chronological framework for the study, and defining the limits of the climatic stages.

THE TRANSFER FUNCTION

The IMBRIE and KIPP (1971) transfer function was chosen; it is made with cell transformed coccolith matrices (see above). The method has three mathematical stages:

Cabfac

In *Cabfac*, count matrices of recent nannofossils are used; samples from North-eastern Atlantic 103 core tops were chosen (Fig. 2). Cabfac is a factor analysis program which provides two matrices: matrix A with the proportional representation of the factor in all the samples; matrix B with the proportional representation of the taxa in the factors.

Regress

In *Regress,* it is necessary to introduce matrix A from Cabfac and a matrix with environmental data for all the samples (core tops) already used in Cabfac. These data were derived from an oceanographic atlas (U.S. Naval Atlas, 1967); for this study, the winter (February) and summer (August) temperatures, and the winter and summer salinities were introduced. Regress uses a curvilinear regression, that enables a statistical correlation between recent organisms and the environmental parameters (matrix C).

Thread

In *Thread*, coccolith counts of fossil samples (here: ODP Site 658 and core Mid 06) are compared to the matrices B) (from Cabfac) and C (from Regress), that leads to paleoenvironmental estimates (here of winter and summer temperatures and salinities).

A transfer function was established for the sections and produced the estimates given in figures 8 and 9.

DATA PRESENTATION

Graphs were drawn with the absolute counts or percentages of the organic and inorganic components, the SEM analyses and the paleoenvironmental estimates. There is strong background for some samples; to reduce it, all the numbers (except the isotopic measurements) are smoothed by the 3 point-running average method.

STRATIGRAPHY

Two techniques were used for establishing the stratigraphy of the studied sections:

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(1) The organic matter was grouped with the inorganic components because of its amorphous appearance and because it is neither possible to separate the inorganic part (silica, and other chemical elements...) from the organic part (= siliceous organisms) nor to specify what kind and amount of siliceous organisms (diatoms, but also perhaps pieces of radiolarians and silicoflagellates) are held by the inorganic net.

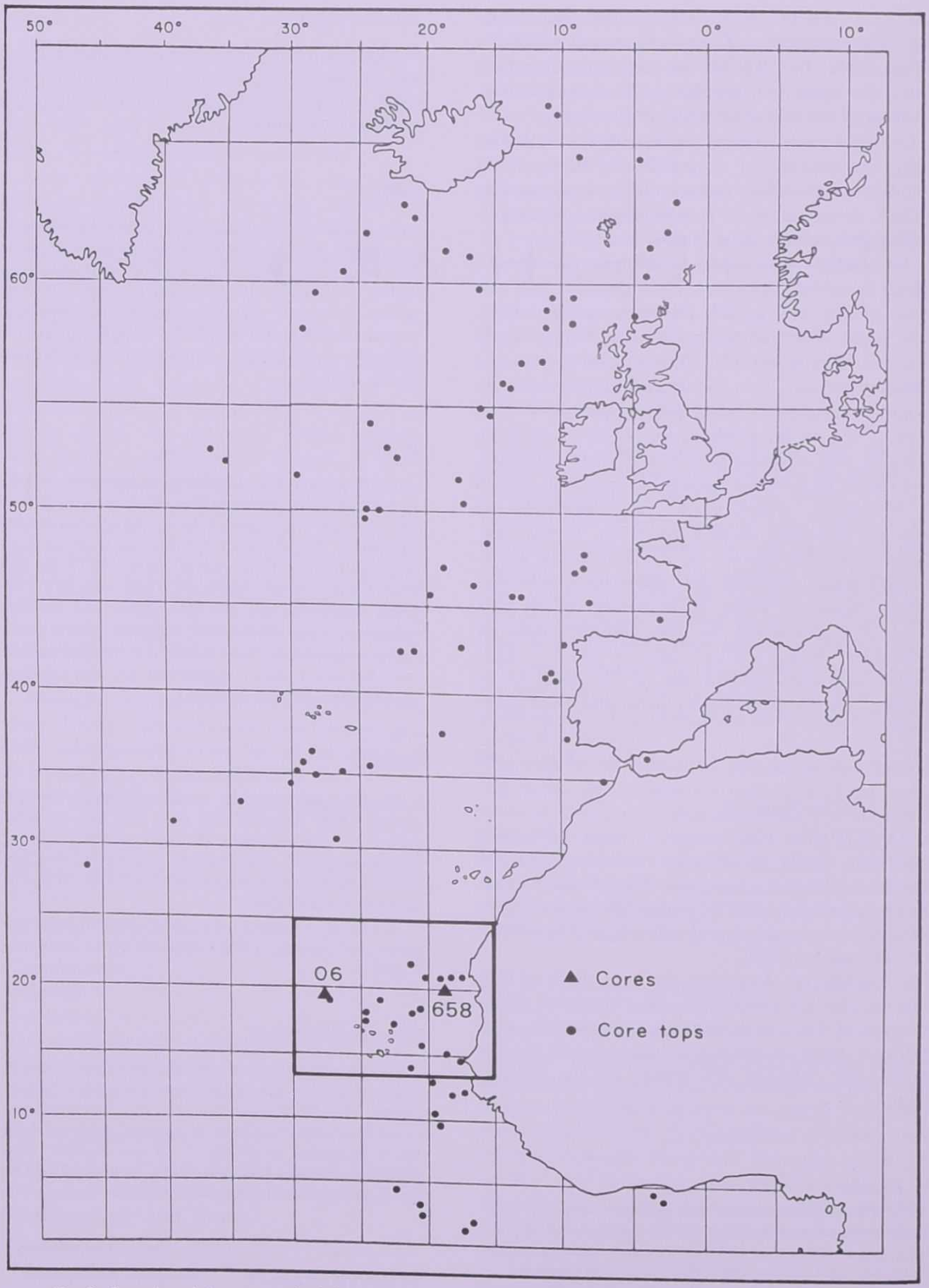

FIG. 2 - Location of the cores and of the core tops used in the transfer function. (Box = area of Fig. 1).

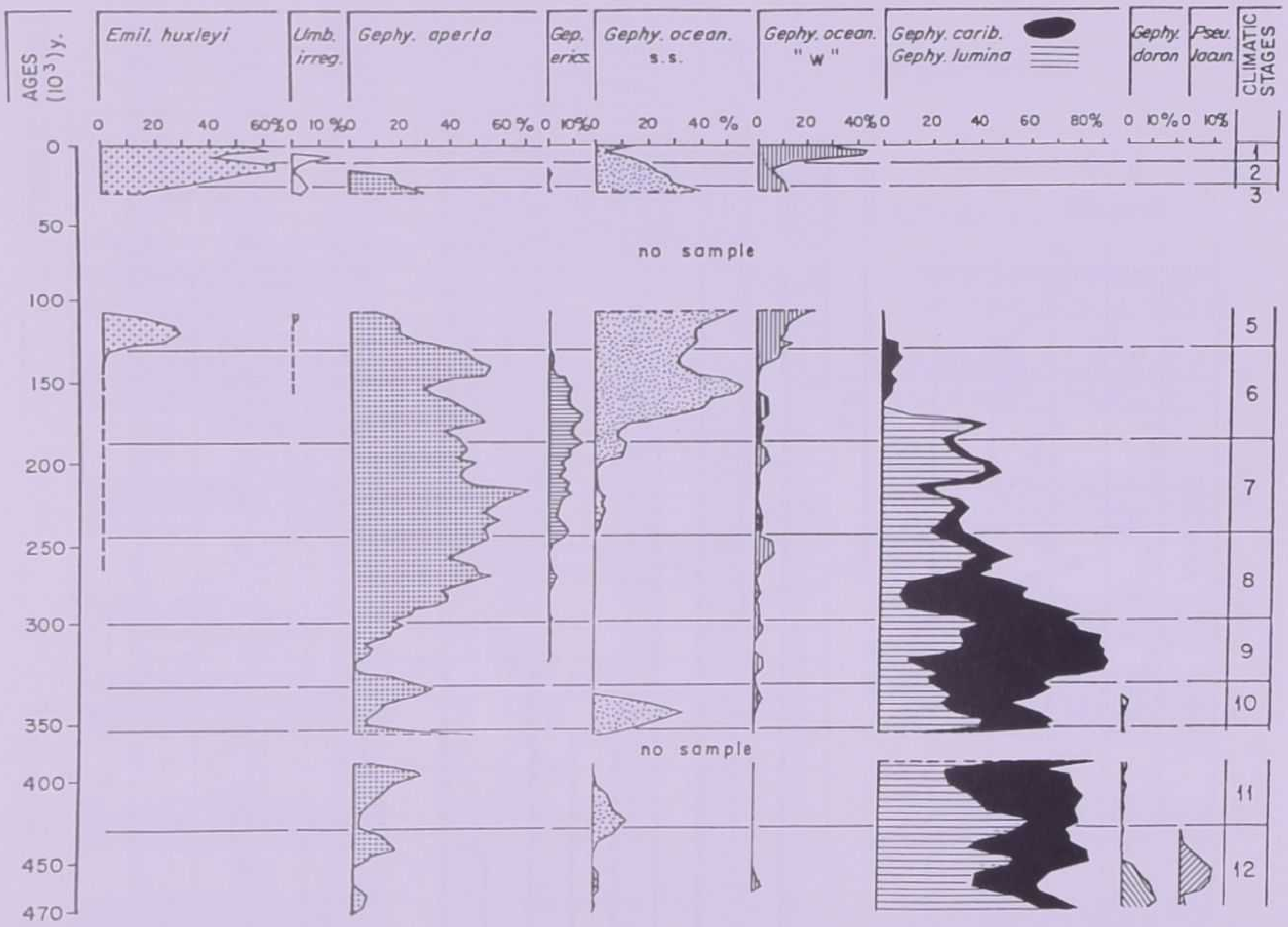

FIG. 3 - Distribution of the stratigraphical taxa at ODP Site 658 for the last 470,000 years.

NANNOFOSSIL CHRONO-STRATIGRAPHY (Figs. 3 and 4):

Ages are attributed to the main nannofossil stratigraphical events (appearances and disappearances of taxa, beginnings and ends of acmes). The two well-known nannofossil datums of the Quaternary are LO (= lowest occurrence) of *Emiliania huxleyi* and HO (= highest occurrence) of *Pseudoemiliania lacunosa*; supplementary criteria are necessary, that change the classical concept of "datum" into a concept of "marker": it has been argued (PUJOS, 1988a) that some "secondary markers", influenced by a spatio-temporal gradient, can be used as stratigraphical markers in Quaternary sections, providing that the geographical/climatological location of the studied section is well known. An attempt was made to apply this method to ODP Site 658 and core Mid. 06. The "stratigraphical" events that lend themselves to dating should be found in the following succession, according to PUJOS (1988a):

HO *Gephyrocapsa aperta*
HO *Gephyrocapsa ericsonii*
LO *Umbellosphaera irregularis*
LA (= bottom of acme) of *Emiliania huxleyi*
HA (= top of last small acme) of *Gephyrocapsa caribbeanica* and *G. lumina*
HA (= top of last acme) of *G. aperta*
LA (= bottom of last acme) of *G. aperta*
HA (= top of acme) of *G. caribbeanica*/*G. lumina*
LO *G. ericsonii*
HO *Pseudoemiliania lacunosa*
HO *Gephyrocapsa doronicoides* div. var.

Almost all these events were found in this succession at ODP Site 658 and in core Mid. 06, except for the HO of *Gephyrocapsa doronicoides* s.l., which occurs later than predicted. This reconfirms the value of the technique in the northern hemisphere (PUJOS, 1988a), even in an area with complex hydrology and ecology. The problem of *G. doronicoides* has to be related to the earlier populations which have not been yet studied in this geographical area, but it is perhaps linked to the special hydrology of the area at this time.

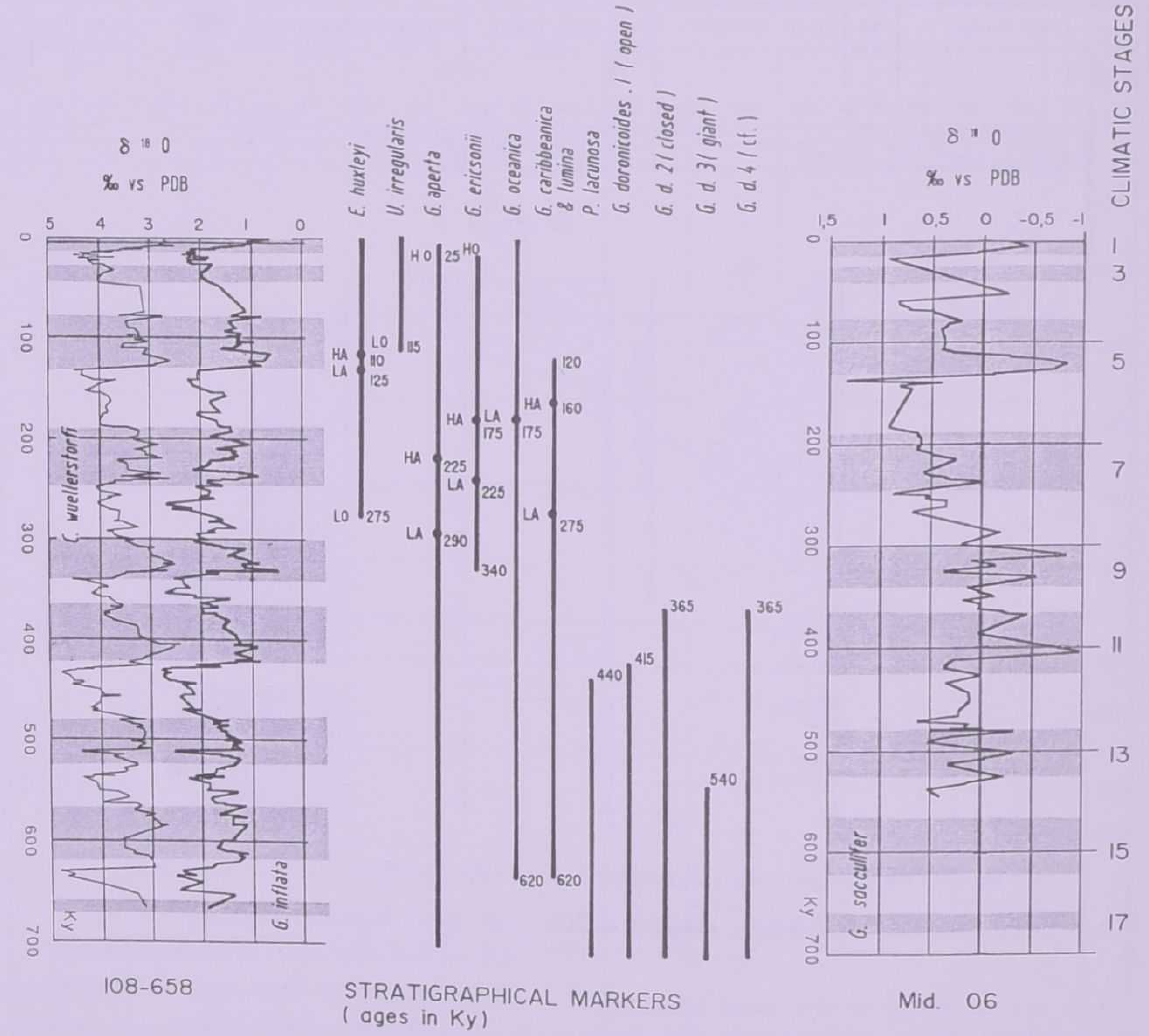

FIG. 4 - Stratigraphy of the last 700,000 years throughout both sections: - ∂180 measured in shells of Foraminifera (isotopes of ODP Site 658 are from SARNTHEIN and TIEDEMAN, 1989).
Nannofossil markers: HO = highest occurrence; LO = lowest occurrence; HA = highest top of acme; LA = lowest bottom of acme.

The markers make it possible to calibrate and complete the chronological scale sketched out by the isotopic events (see below). They are shown on figures 3 and 4.

ISOTOPIC AND CLIMATIC STAGES (Fig. 4)

A chronological scale from the last 700,000 years at ODP Site 658 and in core Mid 06 was obtained by using the position of the isotopic stages and sub-stages and the ages provided by the nannofossil stratigraphical taxa; the last 17 climatic stages can be identified and dated by comparison with the SPECMAP Stack curve (IMBRIE *et al.*, 1984): this chronology is used as a framework throughout the present study. The alternation of the glacial and interglacial stages is used as a mean of interpreting variations in the studied organic and inorganic components.

PALEOECOLOGY AND PALEOHYDROLOGY

The objective of the study is to reconstruct the climate and hydrology of the North-eastern tropical Atlantic for the last 700,000 years, using the

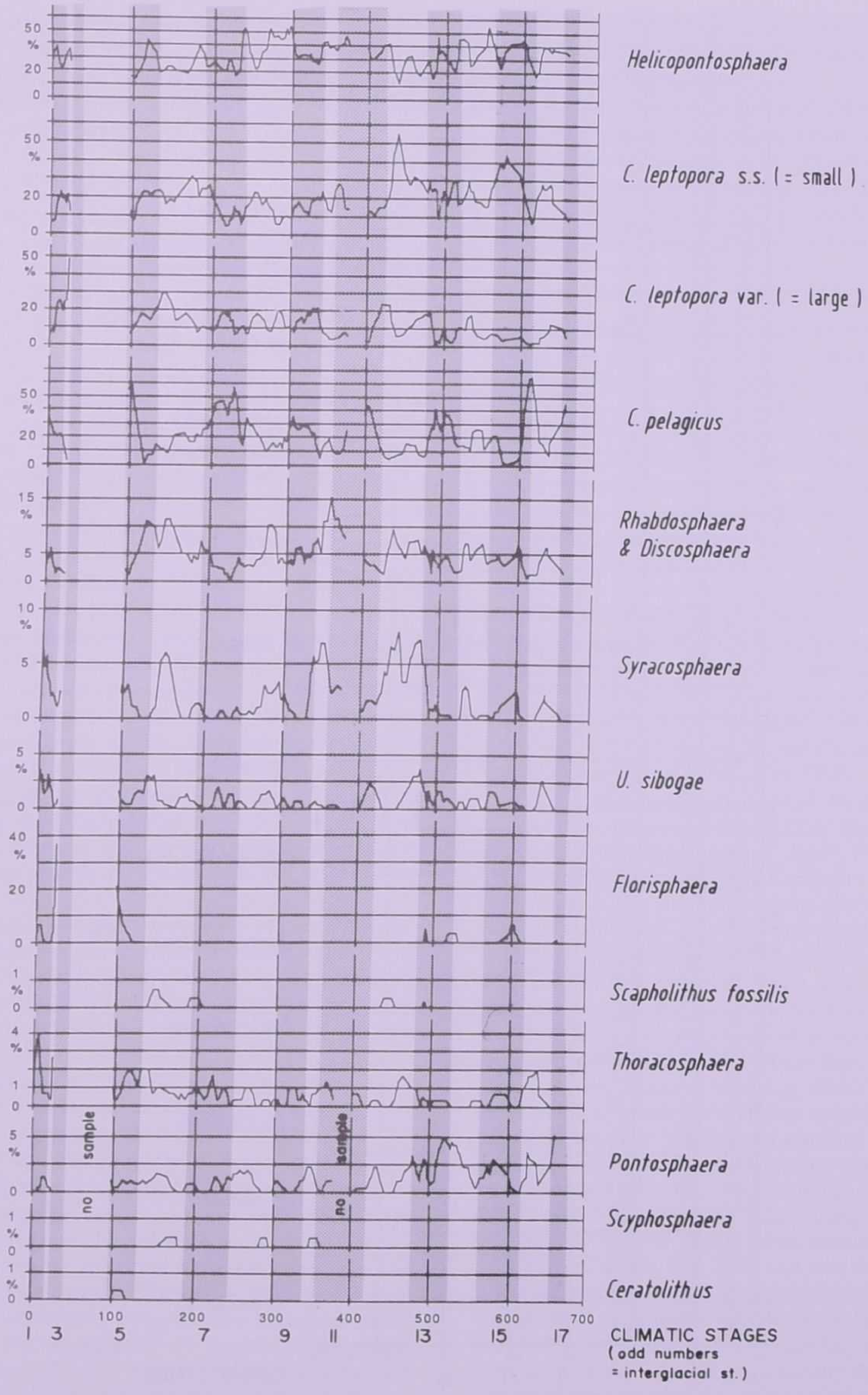

FIG. 5 - Distribution of the ecological taxa at ODP Site 658.

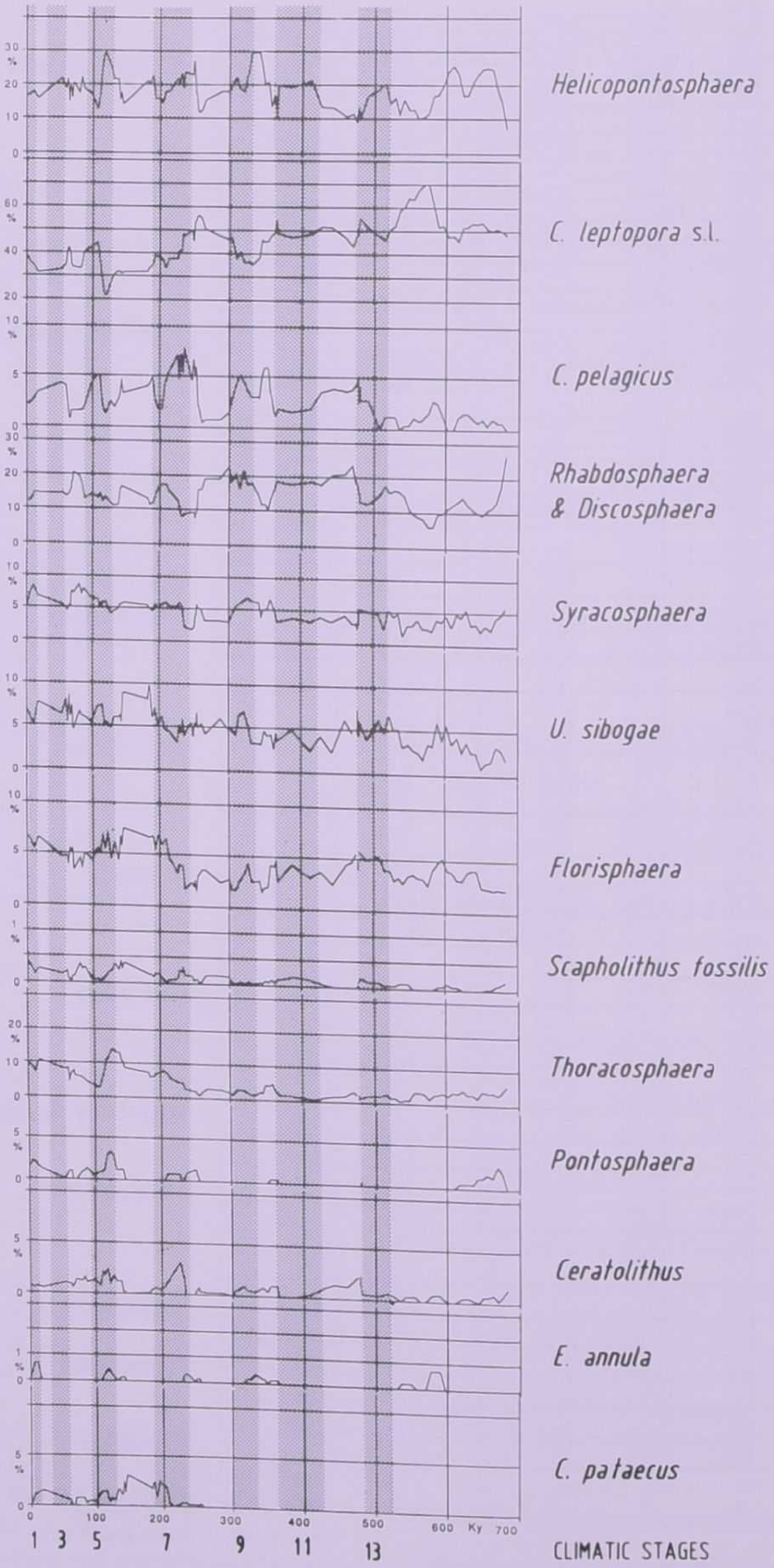

FIG. 6 - Distribution of the ecological taxa in core Mid 06.

Coccolithophores, and other organic and inorganic elements in the <25μ fraction; among these elements, three categories are distinguished: calcareous organisms, siliceous organisms, and inorganic components.

CALCAREOUS ORGANISMS

These are represented by the Coccolithophoridae. Paleoecological studies based on nannofossils are not numerous; other than the floral distribution of MCINTYRE and BE (1967) and the influence of the polar front on some species MCINTYRE *et al.,* 1972), their interpretation is often limited to general considerations of some of their variations, interpreted as "more or less warm or cold" (*e.g.* WEAVER and PUJOL, 1988; NOEL and PANIGEL, 1985). The strong variations affecting the surface water in the studied area provide a good opportunity for an environmental interpretation of some nannofossil taxa.

The distribution of these "ecological" taxa is drawn in percentages (100% = sum of the nine ecological taxa) on figures 5 and 6.

Some preliminary results can be given, from their distribution, according to the climatic stages:

— *Helicopontosphaera* div. sp.: short and marked peaks of abundance at or near the oxygen isotopestage limits which are the main climatic changes (both cores).

— *Coccolithus pelagicus*: maxima of abundance during the interglacial (= odd) stages (both cores), when it reaches up to 60% at ODP Site 658, but usually no more than 5% in core Mid. 06.

— *Cyclococcolithina leptopora* s.l.: maxima during most of the glacial (= even) stages (both cores). *Syracosphaera* (ODP Site 658), *Rhabdosphaera* (ODP Site 658) and *Scapholithus fossilis* (both cores) show similar distribution, but less strongly.

— *Florisphaera*: usually sparse, this genus has a marked maximum during stage 5 at ODP Site 658; it is present throughout core Mid. 06 (between 2 and 5% of all the ecological taxa).

— no special distribution for the other taxa.

Although no categorical statement can be made at this stage of the study, it is possible to note *a priori* unusual relations between some taxa and the climatic stages. Thus, the well known cold species *Coccolithus pelagicus* has abundance peaks during the interglacial (= warm) stages, while coccoliths of the warm *Rhabdosphaera* are abundant during the glacial (= cold) stages (at ODP Site 658). This phenomenon will be tentatively explained below, on the assumption that the "cold-warm" concept is too simplistic for interpreting the distribution of *Coccolithus pelagicus* and *Rhabdosphaera*.

In spite of different surroundings, most of the nannofossil taxa have similar distribution patterns in the two sections; differences lie basically in the fact that they can be much more abundant in one of the sections, which is the case for *Coccolithus pelagicus, Rhabdosphaera* and *Florisphaera*.

RESULTS OF THE NANNOFOSSIL TRANSFER FUNCTION

Some attempts have been made to use nannofossils with greater precision, for example in a transfer function, as has been done with planktonic foraminifera (IMBRIE and KIPP, 1971; IMBRIE *et al.,* 1973; PUJOL 1980; DUPRAT, 1983), radiolarians (MORLEY, 1989) and diatoms (PICHON *et al.*, 1987). Transfer functions with nannofossils are due mostly to some Climap Project Members, and are limited to estimates of temperature for the last 20,000 years (ROCHE *et al.,* 1975) or to isotopic stage 5 (Climap Project Members, 1984) in selected cores. Satisfactory estimates of temperature and salinity were obtained with coccoliths of Caribbean cores, for almost the whole Quaternary (PUJOS, 1987 and 1988b; GIRAUDEAU and PUJOS, 1990), for the Caribbean Site DSDP 502 (GIRAUDEAU, this volume), and for the last climatic cycle in the Mediterranean (GIRAUDEAU, 1986).

For the North-eastern tropical Atlantic, a transfer function different from that of the Caribbean study is used (PUJOS, 1987 and 1988 a and b), because, in the Caribbean, nannofossil associations are much more diverse, and there is no influence of cooler water currents.

No paleoenvironmental estimates of the study area exist in the litterature. PRELL *et al.* (1976) published results obtained from planktonic foraminifera, from equatorial cores from the eastern Atlantic but they are located farther South, in an area with very different hydrology; PRELL's study gives maps of winter and summer temperatures, for the Recent and 18,000 years ago; they will be useful for comparing with the results presented here. Climap Project Members (1984) have made estimates of temperature for stage 5 using various organisms worldwide, except in the eastern tropical Atlantic; in this area, they said that they had many problems due to of the complex hydrology, and obtained temperature variations 4°C above or below those predicted, which was too imprecise.

In spite of these problems, a transfer function was established with the Coccolithophoridae of the ODP Site 658 and of core Mid 06; estimates were obtained and curves were drawn (Figs. 8 and 9).

Temperature estimates

Temperature estimates must clearly be taken with circumspection. In comparison with the estimates from Prell *et al.* (1976), for the period 18,000 years ago, there are some differences, but never in excess of 2°C (Tbl. 2); such results are in a very acceptable range, especially matching Climap's conclusions (for the glacial stages: see below). For older climatic stages, the seasonality (= SST-SWS) increases at ODP Site 658 to a maximum during the stages 7 and 8. This is much less acceptable; it is due mostly to very low estimated temperatures when they are the lowest in the African margin area (In fact, it is likely that this strong seasonality is due to a parameter other than temperature occurring during the glacial stages. This parameter would appear to be so strong and influence the nannofossil associations so much that nannofossils would be unable to record the temperature variations correctly). Fluctuations of these estimates are interesting for interpretation of the hydrological variations of the area, but so far they cannot be taken as exact paleotemperatures. They will be interpreted and used for the general sketch of the hydrological paleoreconstitution of the area.

Table 2 - Comparison of some estimated temperatures and salinities at the ODP Site 658 and at Mid. 06 with temperatures and salinities from Prell *et al.* (1976) and from the U.S. Naval Atlas (1967)

ODP SITE 658	WINTER TEMPERATURE		SUMMER TEMPERATURE	
	Recent	18,000 y BP	Recent	18,000 y BP
Prell *et al.*	18.5°	14.5°	23.0°	18.5°
U.S. Naval Atlas	18.6°		23.4°	
present study	18.1°	13.5°	23.2°	20.6°
MID 06	**WINTER TEMPERATURE**		**SUMMER TEMPERATURE**	
	Recent	18,000 y BP	Recent	18,000 y BP
Prell *et al.*	22.7°		24.2°	
U.S. Naval Atlas	19.7°		24.2°	
present study	21.0°	(21.1°)	26.0°	(26.1°)
ODP SITE 658	**WINTER SALINITY**		**SUMMER SALINITY**	
	Recent		Recent	
U.S. Naval Atlas	36.45‰		36.25‰	
present study	36.4‰		36.29‰	
Mid 06	**WINTER SALINITY**		**SUMMER SALINITY**	
	Recent		Recent	
U.S. Naval Atlas	36.35‰		36.30‰	
present study	36.80‰		37.40‰	

Temperature estimates of core Mid 06 have a very small variation (between winter and summer, and between glacial and interglacial stages), which agrees well with what is commonly assumed for tropical oceanic areas (Prell *et al.*, 1976).

Salinity estimates

Quaternary winter and summer salinities have not previously been estimated in this area. Thus, the estimates obtained cannot be compared with anything, but the recent ones (Tbl. 2): estimates are the same as those from the U.S. Naval Atlas (1967) at ODP Site 658 and 1‰ too high in core Mid 06, which would appear to be acceptable. Salinity fluctuations in winter and in summer are very close to each other, which is the case at the present time. It is interesting to note that during interglacial (= odd) stages, the derived summer salinities are lower than the winter ones; this phenomenon exists in both cores, but it is more important at ODP Site 658 than in core Mid 06.

Siliceous organisms

Study of siliceous organisms was not the main purpose of this study but they were occasionally so abundant on smear slides at ODP Site 658, that they cannot be ignored. In core Mid 06, siliceous organisms were not found.

At ODP Site 658, the siliceous organisms are often diatoms, the abundance of which was estimated in one field of view (X 1 200); this total abundance is assimilated to diatom productivity, which is usually linked to upwelling (Blasco *et al.,* 1981; Richert, 1977) or to freshwater influx (Gasse *et al.,* 1989). The total abundance estimate is shown on figure 7; the peaks of maximum abundance all straddle the limit between glacial-interglacial stages. Some genera and species (always $<25\mu$) were determined; they are detailed below (Interpretation A-1-c).

$<25\mu$ Inorganic components

Calcareous and siliceous organisms are usually so abundant that inorganic elements are difficult

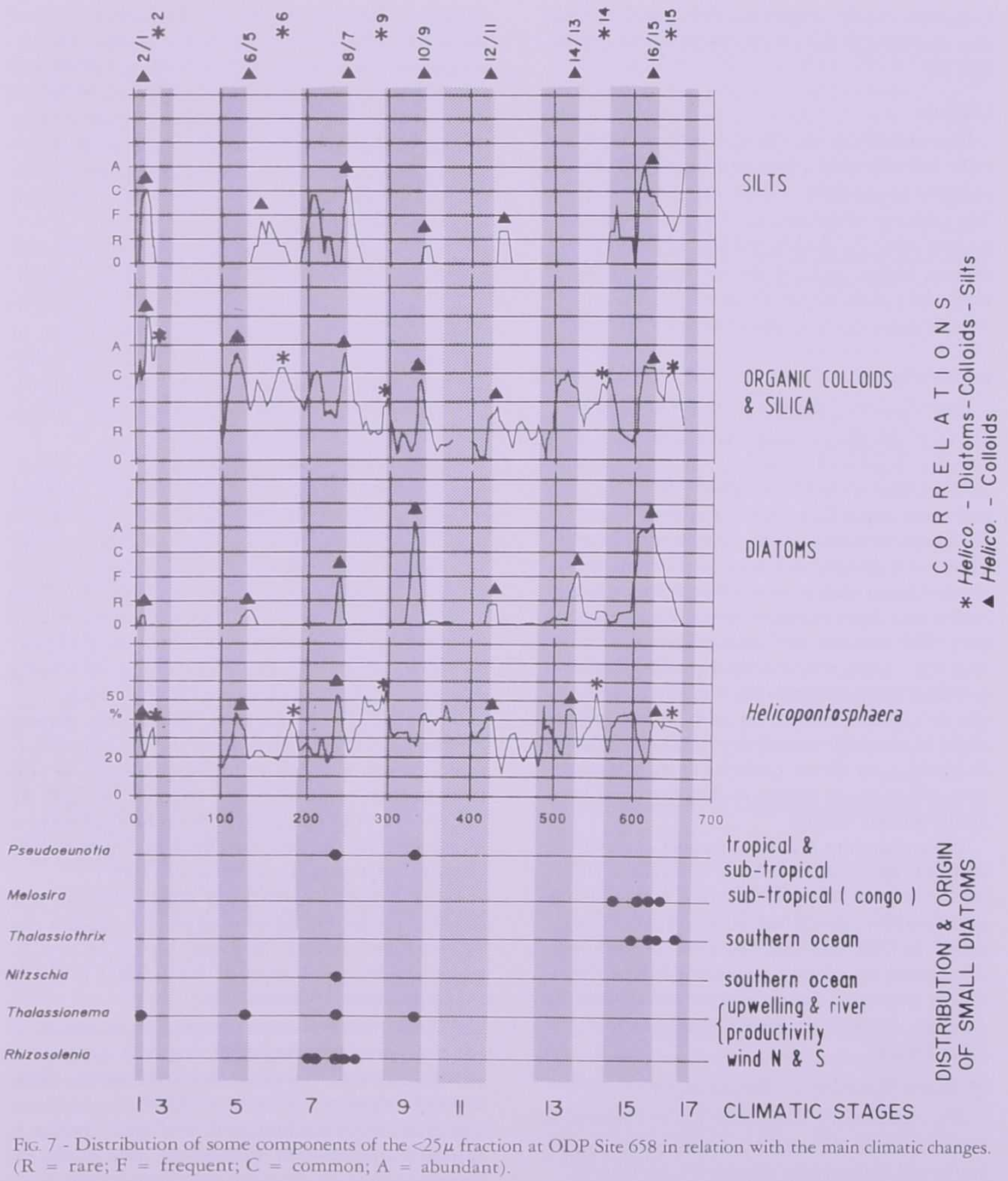

FIG. 7 - Distribution of some components of the $<25\mu$ fraction at ODP Site 658 in relation with the main climatic changes. (R = rare; F = frequent; C = common; A = abundant).

to see, determine and count. Nevertheless, in some samples at ODP Site 658, they are noteworthy; they belong to two categories.

Silts

Some sporadic samples contain very small ($<6\mu$), regular sized and abundant elements of quartz. According to their morphology observed by SEM, most of them have been reworked by water currents; few of them seem to have been transported by wind. Their distribution is evaluated in a semi-quantitative way in one slide field of the optical microscope (x 1200) (Fig. 7). Silt maxima are located at the upper part of the even

(= glacial) climatic stages at ODP Site 658. They are too scattered and rare to be estimated in core Mid 06.

Colloids

The abundance of the colloidal material at ODP Site 658 was estimated from the surface it occupied in one field of view (X 1 200) (Fig. 7). The peaks of abundance are located at the limit between even (= glacial) and odd (= interglacial) climatic stages, and also in the lower parts of most of the even (= glacial) stages.

Colloids are totally absent from core Mid 06.

INTERPRETATION

ODP Site 658 is located at 20°45′ N, about 150 km from the African coast. This area has a very complex superficial hydrology; it is a marging area between a northern region (20-25°N) with permanent upwelling and a southern one (12-20°N) with a winter-spring upwelling (GUILCHER, 1977); it is complicated by the presence of the coastal Canary current to the North which brings cold waters from northern areas to the tropical ones. The seasonal and local influence of river level rises is also very strong. Upwelling and river inflow bring nutrient-rich, hyposaline, cold waters to the surface layer; so an attempt has been made to establish correlations between unusual distributions of the components of the <25μ fraction and the water masses as they may have been during the last 700 Ky.

In contrast, core Mid 06 is located at about the same latitude as the ODP Site 658 (about 20°N) but is far from the African coast, so upwellings and river flows should not affect planktonic organisms. At ODP Site 658, two kinds of hydrological patterns were found, depending on their position in relation to climatic stages, and influencing different inorganic/organic components of the <25μ fraction.

A: At the beginning of climatic stages

The components concerned are the inorganic elements (silts and organic/siliceous colloids), diatoms and *Helicopontosphaera* div. sp. (Fig. 7).

(A-1) the beginning of the interglacial stages

The four components quoted above succeed each other, always in the same order, in less than 10,000 years. This succession starts at the glacial-interglacial transition and continues into the beginning of the interglacial stages. It is found at the limits 12/11, 10/9, 8/7, 6/5, and less markedly at the limit 2/1, because of the lower rate of sedimentation. There are three stages:

(A-1-a) Peak of the silts at the later period of the glacial stages (= arid episodes in this area, according to GASSE *et al.,* 1989). This is usually the glacial maximum, the sea level is at its lowest and the sea has withdrawn partially or totally from the shelf; sediment from the shelf and/or the continent is displaced to deeper areas, but not far away from the shelf so that reworked silts can reach ODP Site 658.

At the same time, increased aridity results in eolian dust being brought from the Sahara by various winds (Harmattan in winter and monsoon in summer) (MORZADEC-KERFOURN, 1988). Thus, at the location of the ODP Site 658, silts are introduced from two areas and by two means of transport: from the continental shelf by river influx, and from the Sahara by winds.

(A-1-b) Peak of organic matter. At the beginning of the interglacial stages, climate changes strongly on the continent: it becomes very humid; large river influx increases introducing nutrient and silicate rich water to the ocean. Climate changes strengthen the Canary current which brings cooler water to the African margin area (see also the distribution of *Coccolithus pelagicus* on Fig. 8) triggering coastal upwelling, increasing productivity in the oceanic superficial waters.

(A-1-c) Peak of diatoms. Maximum diatom abundance occurs slightly after the increase of organic matter. It is linked to the presence of still large quantities of siliceous colloids brought by the rivers and by upwelled waters. Environmental interpretations can be given for some diatom taxa (PICHON, pers. comm.; GASSE *et al.,* 1989):

* the tropical/sub-tropical *Pseudoeunotia* was found at the beginning of interglacial stages 9 and 7. *Pseudoeunotia* can be taken as an *in situ* (= tropical/subtropical) diatom. Its increase is linked to increased local productivity.

* *Thalassionema nitzschioides* is abundant at the beginning of interglacial stages 9, 7, 5 and 1. It is linked to upwelled waters (ABRANTES, 1988) and to freshwater (GASSE *et al.* 1989).

* *Melosira* is a subtropical freshwater genus. It is especially abundant throughout the whole interglacial stage 15. It is brought here by the Congo influx (GASSE *et al.,* 1989).

* *Thalassiothrix* was found in the same samples as *Melosira* (stage 15). *Thalassiothrix* comes from the southern ocean (PICHON, pers. comm.); it arrived here within the subpolar water masses migrating from the southern Atlantic.

Stage 15 is also characterized by especially abundant silts and colloidal organic matter. It is likely that, between 650 and 615 Ky BP, the climate was more humid, with a much more substantial large river influx than during the other interglacial stages of the middle and middle-late Quaternary. Using dinocysts, MORZADEC-KERFOURN (1988) also suggested that restricted humid environments extended along the African margin at this period.

* *Nitzschia kerguelensis* is a dominant species of the southern ocean (PICHON, pers. comm.). It was found at the beginning of stage 7; it was reworked by subpolar southern water masses following the Benguela current.

* *Rhizosolenia styliformis* is a windblown species (GASSE *et al*, 1989). It is abundant only at the 8/7 limit and throughout stage 7, which may reflect exceptionally arid and windy conditions during stage 7 (GASSE *et al.,* 1989).

(A-1-d) Peak of *Helicopontosphaera*. There are peaks of *Helicopontosphaera* at the same time as the peaks of diatoms. This genus is considered by some authors to be linked to lower salinities (NOEL and PANIGEL, 1985) or more convincingly to upwelled waters (ABRANTES, 1988). It has also been shown that *Helicopontosphaera* abundance varies with ∂13C and local productivity (PUJOS, submitted). Here, *Helicopontosphaera* increases with organic matter at ODP Site 658. It also increases at the beginning of the interglacial stages in core Mid 06, an area without upwelling that is not considered as being reached by river inflows (GASSE *et al.,* 1989). This suggests:

— either that *Helicopontosphaera* is not directly influenced by the productivity variations, or by low-salinity waters;

— or that, at the beginning of the sudden rise of river level, some of the fresh water reaches the open ocean area of the core Mid 06, which has not been detected before.

(A-2) the beginning of the glacial stages (Fig. 7).

At the beginning of stages 8, 6 and 2 in particular, there is almost no silt or diatoms; these periods are marked by peaks of abundance in the distribution of silica and of *Helicopontosphaera*.

Silts are not abundant during most glacial stages, due to the aridity of climate, a high sea level and a decrease of the river influx. When present (stage 8), silts can be linked to the presence of windblown diatoms: dust and diatoms are transported by wind from the Sahara during some glacial stages (GASSE *et al.,* 1989).

During the earlier period of glacial stages, colloidal material is abundant but seems to be composed largely of extremely dissolved diatoms. It is the beginning of the arid period. River flow diminishes, as well as the amount of silica brought to the ocean. Diatoms were perhaps still abundant, but their frustules met waters undersaturated in silica, dissolving them during their fall to the bottom, or even on reaching the bottom. Even if diatoms were living at that period, the majority of them were too dissolved to be identified on smear slides.

There is also a peak of *Helicopontosphaera* during the earlier period of the glacial stages in both cores. This peak has no close relation with organic matter abundance. At that time, an arid climate was well established on the continent. There was no longer productive freshwater provided by rivers. The distribution of *Helicopontosphaera* strengthens the interpretation put forward at the end of the paragraph above (A-1-b): it is related to local productivity, but not always to exceptionally productive phenomena.

(A-3) Conclusion on the beginning of the stages

There is no continuation between successive "glacial-interglacial" and "interglacial-glacial" transitions. These periods of maximum climatic changes and the following earlier periods of the climatic stages are the seat of complex hydrological and/or atmospherical phenomena that induce disturbances in organic and inorganic deposits.As soon as the climate becomes firmly established, it would appear that perturbations stop and the middle periods of glacial and interglacial stages are quiet.

B: Interpretation of inferred temperature and salinity fluctuations

Some components of the <25μ fraction can also be linked to the infered temperature and salinity parameters: silts, the *Rhabdosphaera-Discosphaera* group, and *Coccolithus pelagicus* (Figs. 8 and 9).

(B-1) Estimated temperatures

At ODP Site 658, the peaks of silts can easily be correlated with the minima of temperatures as well as with strong river inflows (see the above paragraph), while the maxima of the warm taxum *Rhabdosphaera* occur during maxima of temperatures.

Winter and summer temperatures fluctuate in parallel but they cannot be correlated with the "glacial-interglacial" alternation, as is usually the case, which underlines once again the complexity of the area. In fact, both temperature curves show a maximum in the middle of the glacial stages, then are periods of quiet hydrology, when the cool current and upwelling are weak, and the *in situ* warm tropical superficial water can dominate the African margin area.

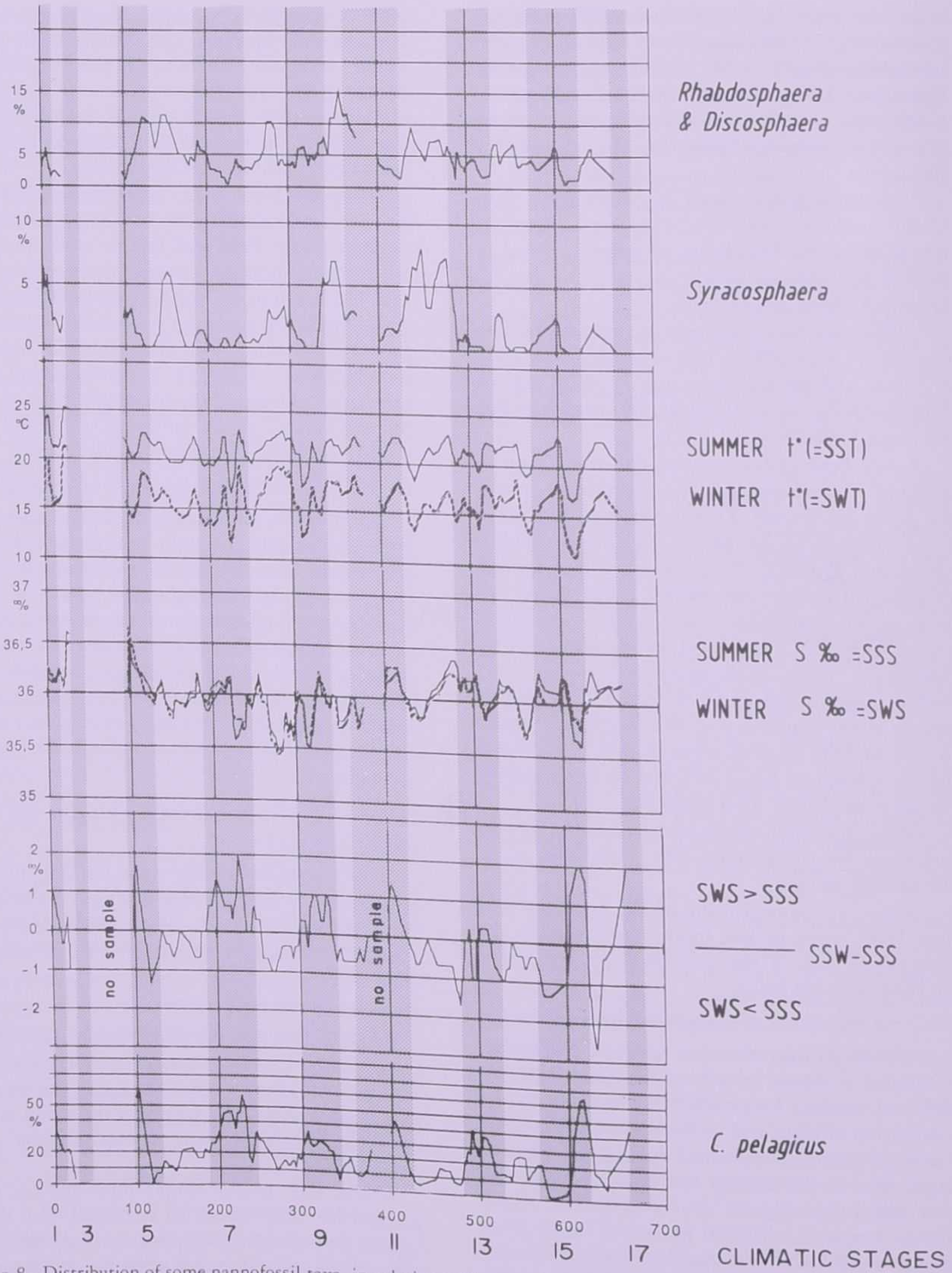

FIG. 8 - Distribution of some nannofossil taxa, in relation with nannofossil estimates of winter and summer temperatures and salinities at ODP Site 658.
T° = temperature; SWT = sea winter temperature; SST = sea summer temperature; S‰ = salinity; SWS = sea winter salinity; SSS = sea summer salinity.

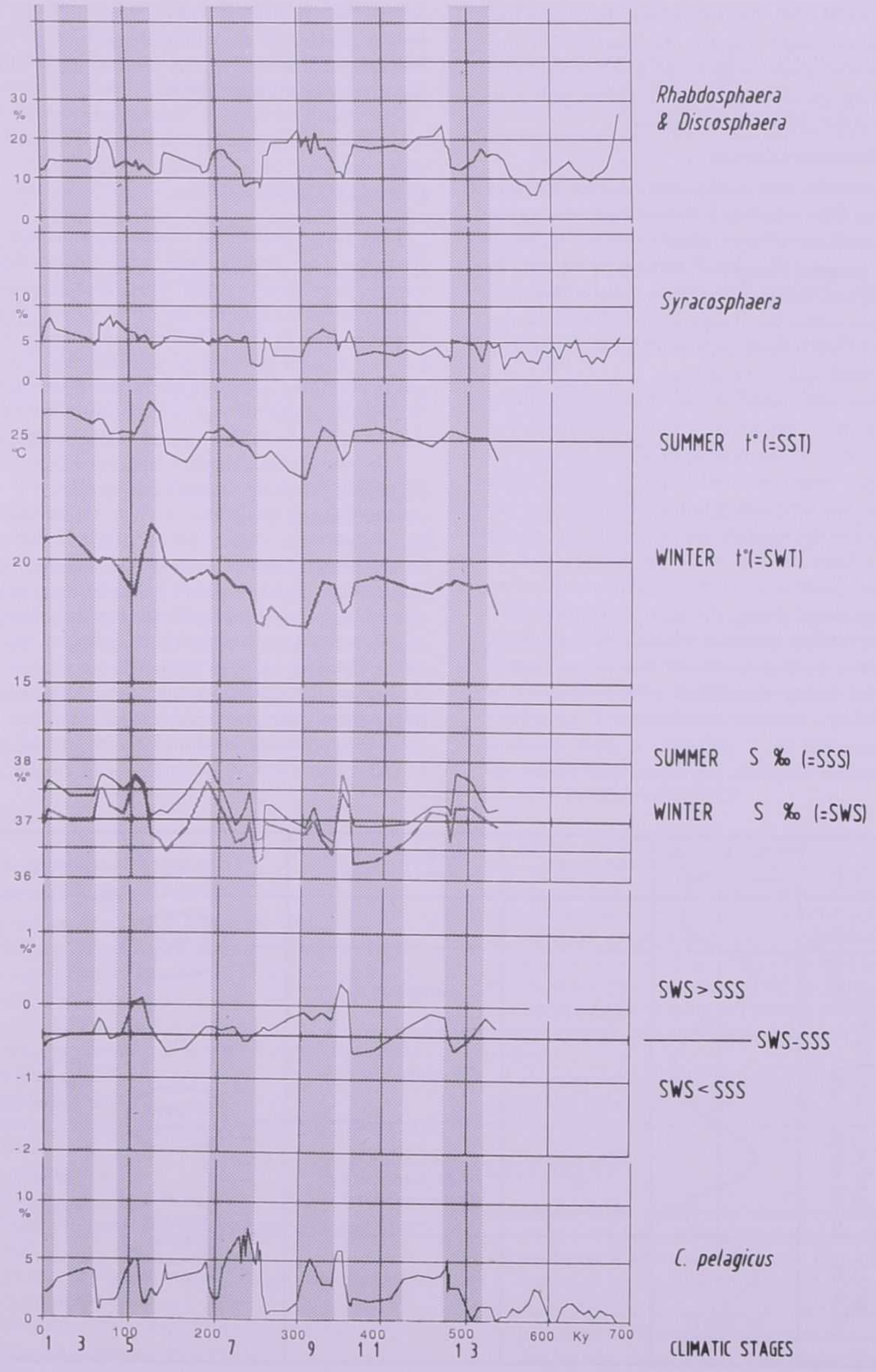

FIG. 9 - Distribution of some nannofossil taxa, in relation with nannofossil estimates of winter and summer temperatures and salinities in core Mid 06.

In core Mid 06, *Rhabdosphaera* fluctuates like the climatic stages (Fig. 6): abundant (20%) during the interglacial stages and much less (10%) during the glacial stages, which agrees well with the usual distribution of the genus.

(B-2) Estimated salinities

At ODP Site 658, winter salinities are not very different from summer salinities and their variation amplitude is very small (36‰ ± 0,25‰), which suggests that river influences (shown in the previous paragraph) are not recorded by nannofossils, unless the temperature influence is too strong to allow these organisms to be influenced by the weak salinity variations.

As has been noted above, the peaks of abundance of the "cold-water" species *Coccolithus pelagicus* occur in the middle of all the interglacial (= warm) stages at ODP Site 658. At the same periods, the estimated summer salinities become lower than the winter ones, while the rest of the time salinity is the same in winter and in summer. GASSE *et al.* (1989) established that during interglacial stages, the summer tropical African river inflow increases strongly. Consequently, freshwater coming to the African ocean margin increases during interglacial summers, which is recorded by a maximal abundance of *C. pelagicus*.

In core Mid 06, *C. pelagicus* is most abundant and summer salinities are lower than winter salinities at the earlier interglacial periods, which means that some continental freshwater reaches the area of this core at the beginning of the sudden river rise during summer.

CONCLUSION

This study shows the importance of the <25μ fraction. The preparation and observation of smear slides require little time, and the data are sufficient for reconstituting much of the past history of an area (Fig. 10). The utility of nannofossilts in stratigraphy is well known, but their use in obtaining precise ages in the determination of climatic stages of the middle and late Quaternary is new, and the technique is not widespread.

This work also suggests environmental interpretations for some nannofossil species:

— *Coccolithus pelagicus* is not really a "cold" species as often stated. It is obvious that a cold environment does not disturb this species, but the label: "*C. pelagicus* = cold" is not always accurate. After interpreting the African western margin, it seems better to associate *C. pelagicus* with some salinity events, such as salinity inversions (here: during interglacial stages, the summer salinity becomes lower than the winter salinity).

— *Rhabdosphaera* is abundant in glacial stages of ODP Site 658, and in interglacial stages in the

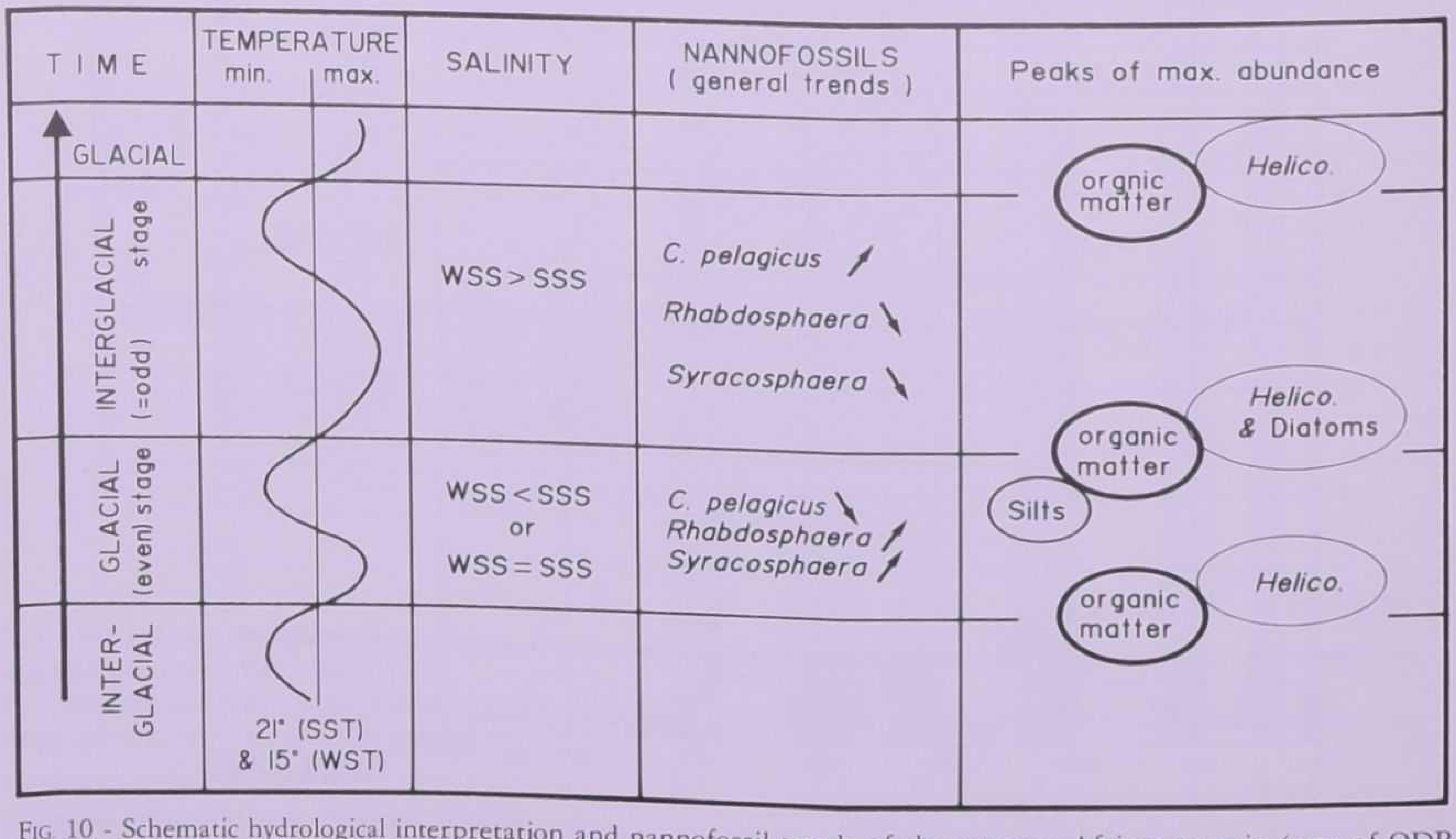

FIG. 10 - Schematic hydrological interpretation and nannofossil trends of the western African margin (area of ODP Site 658) during the glacial and interglacial stages.

core Mid 06; in fact, *Rhabdosphaera* follows the temperature fluctuations well: the relation "*Rhabdosphaera* = warm" can still be used. The same may be true for *Syracosphaera*.

— "*Helicopontosphaera* = higher productivity" is confirmed but only for a "normal" productivity. When productivity increases in relation with large arrivals of fresh and silicated water, there is no special effect on the distribution of *Helicopontosphaera*, the exact cause of which is still unknown. "*Helicopontosphaera* = low salinity" is also confirmed; it was useful to prove that the freshwater flow extended to the open ocean at the beginning of the interglacial stages.

In addition, it is not difficult to note the maxima of abundance of other components of the fine fraction. Diatoms, silts and colloids of silica/organic matter are easy to distinguish on smear slides and, can supplement nannofossil data for paleoenvironmental interpretation (here: alternation of glacial-arid and interglacial-humid stages, coastal upwelling, African river sudden rise, winds coming from the Sahara, Canary and Benguela currents). A transfer function made with few taxa of nannofossils (in this case: 9 taxa) makes it possible to estimate winter and summer paleotemperatures and paleosalinities, which helps to complete the history of an oceanic area.

APPENDIX

List of Quaternary species
ODP Site 658 and core Mid 06

Ceratolithus cristatus KAMPTNER, 1950
Coccolithus pelagicus (WALLICH) SCHILLER, 1930
Cyclococcolithina leptopora (MURRAY and BLACKMAN) WILCOXON, 1970
Cyclococcolithina leptopora var.
Cyclolithella annula (COHEN) COHEN and REINHARDT, 1968
Discosphaera spp
Emiliania huxleyi (LOHMANN) HAY and MOHLER, 1967
Florisphaera div. sp.
Gephyrocapsa aperta KAMPTNER, 1963
Gephyrocapsa caribbeanica BOUDREAUX and HAY, 1967
Gephyrocapsa doronicoides (BLACK and BARNES) PUJOS, 1984
Gephyrocapsa ericsonii MCINTYRE and BÉ, 1967
Gephyrocapsa lumina BUKRY, 1973
Gephyrocapsa oceanica KAMPTNER, 1943
Gephyrocapsa oceanica "W"
Helicopontosphaera kamptneri HAY and MOHLER, 1967
Helicopontosphaera wallichi (LOHMANN) BOUDREAUX and HAY, 1969
Pontosphaera alboranensis BARTOLINI, 1970
Pontosphaera distincta (BRAMLETTE and SULLIVAN) ROTH and THIERSTEIN, 1972
Pontosphaera japonica (TAKAYAMA) BURNS, 1973
Pontosphaera messinae BARTOLINI, 1970
Pontosphaera multipora (KAMPTNER) ROTH, 1970
Pontosphaera pacifica BURNS, 1973
Pseudoemiliania lacunosa KAMPTNER, 1963, ex GARTNER, 1969
Rhabdosphaera clavigera MURRAY and BLACKMAN, 1898
Scapholithus fossilis DEFLANDRE, 1954
Scyphosphaera div. sp.
Syracosphaera div. sp.
Thoracosphaera var. 1*
Thoracosphaera var. 2*
Umbellosphaera irregularis PAASCHE, 1955
Umbilicosphaera sibogae (WEBER and VAN BOSSE) GAARDER, 1970

(*) The genus *Thoracosphaera* is not a coccolithophore, but a Dinophyte (TANGEN *et al.*, 1982); nevertheless specimens of *Thoracosphaera* can be observed and counted on slides made for the nannofossil observation.

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