

Late Pliocene/Pleistocene calcareous plankton and paleoceanography of the North Atlantic

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ABSTRACT

The calcium carbonate record, abundances and numbers of planktonic foraminifera and coccolithophorids, and the biometry of the foraminifera species *Neogloboquadrina pachyderma* sin. and *Neogloboquadrina atlantica* sin. from DSDP Site 552 have been analyzed for the time interval 3.2 Ma to 0.8 Ma. The different records are used to examine environmental changes in the North Atlantic, especially on the Rockall Plateau, and for comparison in the northern Labrador Sea (ODP Site 646).

The planktonic assemblages in the late Pliocene consisted mainly of subpolar to temperate species; warm-water adapted species were relatively rare. The increase in the influence of polar surface waters at 2.5-2.4 Ma is indicated by an increase in the abundance of cold-water adapted coccolithophore *Coccolithus pelagicus*. However, this corresponds to an increase in subpolar *N. pachyderma* dex., indicating that conditions during this „cold“ phase would be analogous to intermittent interglacials of the late Pleistocene. Today's cold water-adapted *N. pachyderma* sin. first occurred at 1.8 Ma. Relatively high abundances during the interval 1.8-1.35 Ma seem to indicate relatively cold surface temperatures, whereas the absence of *N. pachyderma* sin. during the short interval 1.35-1.2 Ma probably indicates somewhat warmer surface water temperatures. However, using factor analysis, it is shown here that *N. pachyderma* sin. first showed a polar biogeographical distribution at 1.1 Ma, while it is a subpolar indicator between 1.8 Ma and 1.1 Ma.

The biometric data of *Neogloboquadrina* tests at both sites indicate an evolutionary trend from large-sized *N. atlantica* sin. before 2.4 Ma via morphological integrade-forms („*N. atlantica-pachyderma* integrade“) to small-sized *N. pachyderma* sin. between 1.8 Ma and 1.1 Ma.

INTRODUCTION

The circulation system in the North Atlantic has a strong impact on both the climate of the adjacent continents and the storage of carbon in the ocean. Therefore, details about the paleoceanographic development of the surface circulation system are invaluable for understanding the environmental changes of the northern hemisphere climate. The major northern hemisphere climatic cooling in the open North Atlantic is generally observed close to 2.7-2.5 Ma when extreme ice rafting occurred for the first time (Shackleton *et al.*, 1984; Ruddiman *et al.*, 1986a; Raymo *et al.*, 1989). However, Shackleton *et al.* (1984) demonstrated that considerable climatic variability existed during the million year prior

to the initial glacial event. A pattern of regular climate oscillations which become progressively „colder“, more positive in $\delta^{18}\text{O}$, was observed between 3.2 Ma and 2.6 Ma (e.g., Shackleton *et al.*, 1984; Raymo, 1992). This is also shown by sea surface temperature (SST) estimates from planktonic foraminifera using transfer functions (Dowsett & Poore, 1990). The problem in doing this is that the ecologic preferences of extinct species like *Neogloboquadrina atlantica* and *Globorotalia puncticulata* cannot be exactly characterized. To solve this problem a similar but less rigorous transfer function has been used to quantify the ecological niche of extinct species by comparing with stable isotope data (Hooper & Funnell, 1986). Extinct species are

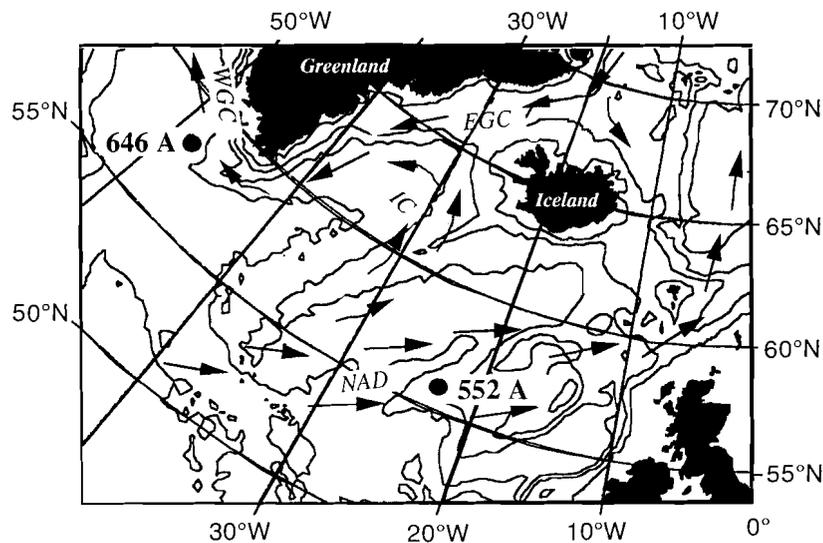


Figure 1. Locations of DSDP Site 552 and ODP Site 646, as well as present-day major surface water circulation (EGC - East Greenland Current, WGC - West Greenland Current, IC - Irminger Current, NAD - North Atlantic Drift).

then substituted by modern analogues, to enable paleotemperatures to be calculated for the Pliocene.

The general evolution of North Atlantic surface water conditions over the last three million years has been described in detail in several key papers (e.g., Shackleton *et al.*, 1984; Zimmerman *et al.*, 1984; Ruddiman *et al.*, 1986a, 1989; Raymo, 1992). Prior to about 1.2 Ma climate variations are characterized by a strong 41 kyr obliquity frequency (Raymo *et al.*, 1989; Ruddiman *et al.*, 1989). For most of the interval from 2.6-1.2 Ma, cold extremes are most analogous to interglaciations (Substage 5d), whereas many warm extremes had more ice and/or probably colder ocean temperatures than are observed today (Raymo, 1992). Thus, except for some low-carbonate spikes during extreme glacial episodes, most of the sediment is of high carbonate content and, therefore, contains planktonic foraminifers (Zimmerman *et al.*, 1984). This is in drastic contrast to both the Norwegian Sea to the north and the Labrador Sea to the west. Here, most of the interval before 1.1 Ma is characterized by glacial conditions, very low productivity of the surface waters, and thus, very low carbonate contents (Henrich & Baumann, 1994; Meggers, 1996; Baumann *et al.*, in press). The most prominent increase in carbonate as well as the change in the number and composition of the calcareous plankton assemblages occurred at approximately 1.1 Ma to 0.9 Ma (Jansen *et al.*, 1989; Henrich & Baumann, 1994; Meggers, 1996; Baumann & Meggers, 1996). It is now well documented that during this interval the climate cyclicity changed, involving a substan-

tial change in mean state and in amplitude of climatic variations (Ruddiman *et al.*, 1986b, 1989; Ruddiman & Raymo, 1988; Raymo, 1992; Berger & Jansen, 1994).

In this study we present records of calcareous plankton assemblages as well as biometrical data of distinct species from Site 552. On the basis of these data we present an overview of the paleoceanographic evolution of the North Atlantic during the late Pliocene - early Pleistocene. These data are combined with existing data from the northeastern Labrador Sea (Site 646) to examine latitudinal variations of the surface current system. In addition, biometric data of *Neogloboquadrina* tests of both sites provide the foundation for a proposed evolutionary trend within this genus.

DATA AND METHODS

DSDP Site 552 was drilled in 2301m water depth on the southwest flank of the Rockall Plateau (Fig. 1). The site is located beneath the diffuse eastern extension of the North Atlantic Current. All cores from Hole 552A were extremely well preserved with the exception of Core 552A-6 (24-29 mbsf). However, despite severe disturbance during core recovery, samples of Core 552A-6 were incorporated in this investigation to compare the test size range of *N. pachyderma* sin. within the lower and upper sediment sections. Interpretations of these samples have to be considered very carefully. Site 646 was drilled on the northern flank of the Eirik Ridge in the northern Labrador Sea and is located beneath the present-day subpolar West Greenland Current in a water depth of 3451m (Fig. 1).

The chronology of the investigated sites is based on oxygen isotope stratigraphies and paleomagnetic data, which have previously been published (e.g., Krumsiek & Roberts, 1984; Shackleton & Hall, 1984; Shackleton *et al.*, 1984). The stratigraphies were updated and/or summarized by Raymo *et al.* (1989) for Site 552, and by Aksu *et al.* (1992) and Baumann & Meggers (1996) for Site 646. All ages were converted to the new time scale of Shackleton *et al.* (1995), proposed for the last 14.8 m.y. (Chron C1 through Chron C5AD). All ages (including previously published ages) used in the following have been converted to this new time scale.

Sediment samples were freeze-dried, weighed and washed on a 63 μ m-mesh sieve, and then further split into subfractions. The total abundance of planktonic foraminifera was determined, and specimens counted for the 125-500 μ m fraction. Samples were split into aliquots of at least 500 specimens. Total foraminifer abundances were converted to „specimens per gram dry weight sediment“ (spec./g).

The identification of individual specimens, especially of *N. pachyderma* sin. and *N. atlantica* sin. was sometimes difficult, and was further complicated by test sizes which were in the size range of both species from 2.75 Ma (in the Labrador Sea) and 2.4 Ma (on the Rockall Plateau) to 1.8 Ma. Therefore, forms which integrate morphologically between *N. atlantica* sin. and *N. pachyderma* sin. in this study were called the „*N. atlantica-pachyderma* integrate“ and were placed together with *N. pachyderma* sin. within the polar planktonic foraminifera group. All other planktonic foraminifera were interpreted as subpolar. Rare numbers of Pliocene species such as *G. puncticulata* or *Globorotalia crassula* were put into „diverse species“.

Coccolith species of 37 samples from Site 552 were counted under the scanning electron microscope (SEM). For quantitative analysis, the <2 μ m fraction was separated, and micrographs of an arbitrarily selected part of the scanned sample were taken (Baumann, 1990). All particles (usually >1000 particles), including up to about 500 coccoliths, were counted in each sample using x2000 magnification. The quantitative data were recorded as particle percent (grain percent of <63 μ m fraction) for coccolith species.

Estimates of factor analysis on the planktonic foraminifer assemblage of Site 646 were calculated with the program SYSTAT. For factor analysis we used *N. atlantica* sin. and dex., *N. pachyderma* sin. and dex., *Globigerina bulloides*, and *Turborotalia quinqueloba*. *Globigerinita glutinata* and *Globigerinita uvula*, as well as *Globorotalia inflata*, *Globorotalia truncatulinoides*, and *Globorotalia scitula* are calcula-

ted as genus (*Globigerinita* and *Globorotalia*).

For biometric analysis of sinistral *Neogloboquadrina*, the maximum diameter of individual *N. atlantica* sin. and *N. pachyderma* sin. tests (in umbilical view) were measured under SEM at a magnification of x150. All maximum diameters were converted into a median diameter per sample. From 61 samples which are counted to determine the planktonic foraminifer assemblage 37 samples were analysed biometrically (with more than 800 individual measurements).

RESULTS

Planktonic foraminifer assemblages from Site 552 are generally characterized by relatively low diversities (Fig. 2). The total numbers range from 200 to 100,000 spec./g sediment. Warmer water indicators such as *G. bulloides*, *T. quinqueloba*, and *Globigerinita* spp. are present in relatively high steady abundances throughout the investigated interval (Fig. 2). However, there are typical faunal changes which can be summarized as follows:

The interval 3.2-2.4 Ma is generally characterized by relatively high numbers of *N. atlantica* sin. (up to 18,000 spec./g) and *N. pachyderma* dex. (up to 10,000 spec./g). Polar planktonic foraminifer species were not found during this interval. The mean sizes of *N. atlantica* sin. are in the range 275-300 μ m (compare also with Fig. 5). However, the extreme range in its maximum diameter (200-450 μ m) possibly indicate that species of „*N. atlantica-pachyderma* integrate“ were already present within this interval. A drastic decrease in maximum test size to generally <250 μ m at around 2.4 Ma corresponds well with counting results. *N. atlantica* sin. is nearly absent from the planktonic foraminifer assemblage, while *N. pachyderma* dex. is the most dominant species (numbers >75,000 spec./g) and forms around 50% of the fauna. In addition, the amount of *Globorotalia* spp. increased.

A significant change within the planktonic foraminifer assemblage at 1.8 Ma is indicated by the first occurrence of the modern polar species *N. pachyderma* sin. (Fig. 2). Until 1.4 Ma *N. pachyderma* sin. dominated the assemblage, while the number of *N. pachyderma* dex. decreased to <10,000 spec./g, and *N. atlantica* sin. as well as „*N. atlantica-pachyderma* integrate“ disappeared from the assemblage. *N. pachyderma* sin. can only be differentiated from the „*N. atlantica-pachyderma* integrate“ by its smaller size and not by its ultrastructure. The maximum test sizes are in the range from 150 μ m to 250 μ m. These small sizes lead to the impression that this species is more encrusted than the older *Neogloboquadrina* species or than the modern type of *N. pachyderma* sin.

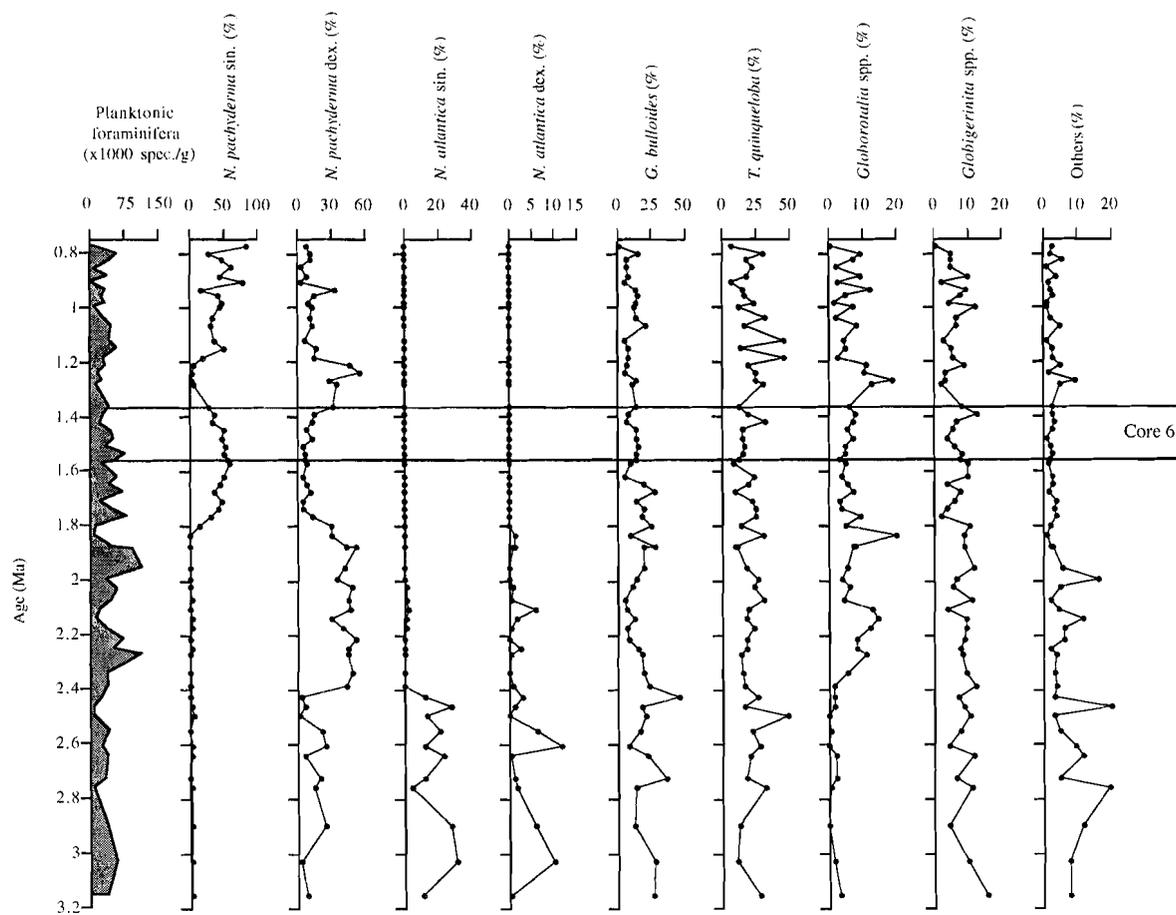


Figure 2. Number of planktonic foraminifera (specimens per gram sediment) and percent-abundance of the main species and species groups of DSDP Site 552 in the interval 3.2 Ma to 0.8 Ma.

Another shift within the planktonic foraminifer assemblage occurred between 1.4 Ma and 1.2 Ma (Fig. 2). *N. pachyderma sin.* nearly disappeared from the assemblage (<10%), whereas *N. pachyderma dex.* increased and formed >30% of the fauna (up to 13,000 spec./g). The sparse tests of *N. pachyderma sin.* only show maximum sizes in the range from 200 μm to about 250 μm , indicating that *N. pachyderma sin.* is the only sinistral *Neogloboquadrina* species which is present during this interval. After 1.2 Ma, the mean size obviously increased and is up to about 350 μm in maximum (compare also with Fig. 5). The foraminifer assemblage again is dominated by *N. pachyderma sin.*, but subpolar species such as *G. bulloides*, *T. quinqueloba* (up to 50%) and *N. pachyderma dex.* are also present.

The total abundance of calcareous nannofossils at Site 552 varied strongly and was between 5 and about 60 grain-% in the investigated interval (Fig. 3). The assemblage was generally dominated by few species, usually of *Gephyrocapsa* spp. or *Reticulofenestra* spp.. However, individuals of warmer

water-adapted species such as *Helicosphaera carteri*, *Pontosphaera* spp., *Calcidiscus leptoporus*, *Umbilicosphaera sibogae*, *Oolithotus fragilis*, and *Discoaster* spp. were present in low numbers in most of the samples. The development of the assemblage can be summarized as follows:

The total amount of nannofossils was about >40 grain-% prior to 2.5 Ma, and reticulofenestrids (*R. minuta*, *R. minutula*, *R. productella*) dominate the assemblage (Fig. 3). In addition, warmer water-adapted species were also present in moderate abundances. Species of *Gephyrocapsa* as well as *Coccolithus pelagicus*, which is related to cold surface-water temperatures, only occurred in very low numbers.

The total number of nannofossils decreased between 2.5 Ma to 2.4 Ma, and the following interval until 1.1 Ma was characterized by moderate abundances of nannofossils (10-40 grain-%). *Gephyrocapsids* dominated the assemblage except for the interval 2.5-2.3 Ma and between 2.0-1.7 Ma. Here, cold-water adapted *C. pelagicus* formed up to

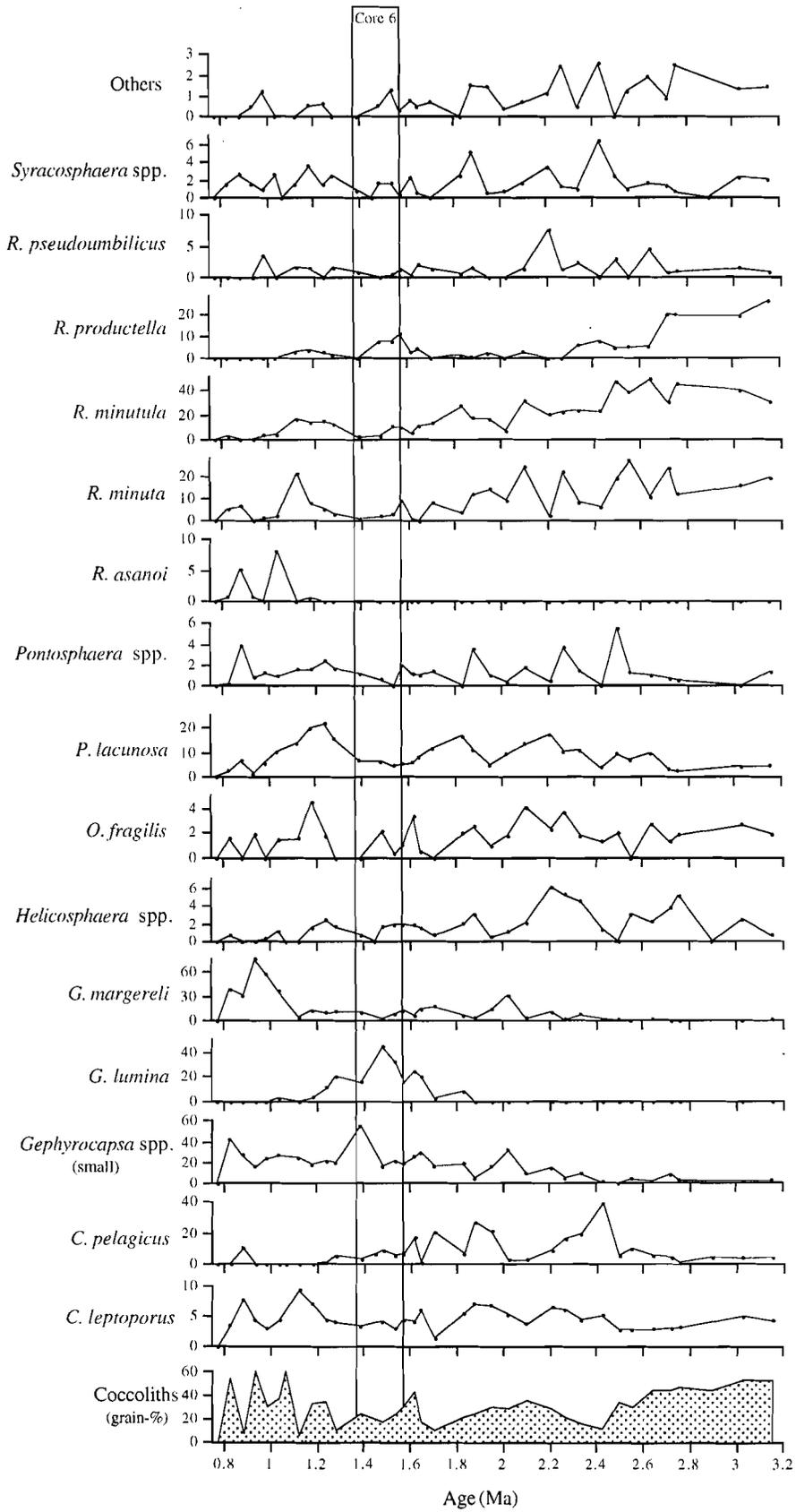


Figure 3. Number of coccolithophores (grain-%), and composition of the coccolithophore assemblage (%) at DSDP Site 552 in the interval 3.2 Ma to 0.8 Ma.

40% of the floral assemblage.

The interval after about 1.1 Ma was characterized by large fluctuations in the abundance of calcareous nannofossils (Fig. 3). They were abundant especially in interglacial stages, whereas during glacials the number drastically decreased. Generally, abundance peaks are higher (up to >60 grain-%) during this interval than observed before. *Gephyrocapsa* species dominated the assemblage while other species reached less than 10%.

PREVIOUSLY PUBLISHED RESULTS

Results of ODP Site 646 in the Labrador Sea have previously been published by Aksu *et al.* (1989, 1992), Aksu & Kaminski (1989), and Baumann & Meggers (1996). In general, the calcareous plankton assemblages are less diverse than the assemblage of the Rockall Plateau. This is most probably due to the influence of cold surface waters as well as the closer proximity of Site 646 to the Greenland ice-shield. In addition, carbonate in the Labrador Sea is far less well preserved than observed on the Rockall Plateau (Meggers, 1996; Baumann & Meggers, 1996). The development of calcareous plankton and the surface water paleoceanography at Site 646 can be summarized as follows:

Relatively low numbers of calcareous nannofossils and planktonic foraminifera, dominated by subpolar species, indicate that the northern Labrador Sea was weakly influenced by warm Atlantic surface waters during parts of the interval 3.1 Ma to 2.8 Ma. The calcareous plankton assemblages indicated an increase in the influence of polar surface waters 2.8 Ma ago. The assemblages were characterized by very low numbers of strongly corroded, cold-water adapted species (*C. pelagicus*, *N. pachyderma* sin.) until 2.3 Ma. Subpolar foraminifera species *T. quinqueloba* and *N. atlantica* sin. temporarily occurred between 2.3 Ma and 1.8 Ma, indicating an episodic inflow of relatively warm surface waters into the northern Labrador Sea. The interval 1.8 Ma to 1.5 Ma was marked by a series of strong environmental shifts in the surface water regime. Relatively high amplitudes in the biogenic calcareous records and abundant warm-adapted species indicate the presence of relatively warm surface waters during climatic optima, although cold-adapted species dominated throughout this interval. A significant decrease in the numbers of calcareous nannofossils and planktonic foraminifera at 1.5 Ma was related to another cooling that lasted until about 1.1 Ma. During the last 1.1 m.y., abundant warm-adapted species indicate the presence of relatively warm surface waters during interglacials, while scarce polar assemblages are related to variable conditions dominated by at least seasonal sea-ice cover during glacials.

In addition, a morphological transformation from large *N. atlantica* via median-sized „*N. pachyderma* integrate“ to modern *N. pachyderma* sin. was evident at Site 646 between 2.4 Ma and 1.8 Ma.

Based on the high-resolution faunal data of Site 646 a factor analysis has been carried out. Factor analysis indicate two different paleoecological interpretations of the *Neogloboquadrina* taxon. Two factors (polar and subpolar) are statistically relevant for Site 646 within the limits of confidence by the Kaiser-criterion (compare with Backhaus *et al.*, 1994). Over 80% of the variance can be explained by the two varimax rotated factors.

While *N. pachyderma* sin. scores highly on the polar factor after the mid-Pleistocene transition, it shows high factor loadings on the subpolar factor before 1.1 Ma (Table 1). Within the time-period between 3.2 Ma and 1.1 Ma *N. atlantica* sin., the „*N. atlantica-pachyderma* integrate“ and the small individuals of *N. pachyderma* sin. (between 1.8 Ma and 1.1 Ma) were combined with species like *G. bulloides*, *T. quinqueloba*, *G. inflata*, *G. glutinata* in the subpolar group.

Table 1. Factor matrix for the samples of ODP Site 646.

Factor matrix Site 646	3.2 Ma -1.1 Ma	1.1 Ma - 0 Ma
	"subpolar"	"polar"
<i>N. pachyderma</i> sin.	0.871	-0.522
<i>N. pachyderma</i> dex.	0.866	0.469
<i>N. atlantica</i>	-0.034	
<i>G. bulloides</i>	0.643	0.444
<i>T. quinqueloba</i>	0.793	0.654
<i>Globorotalia</i>	0.635	0.608
<i>Globigerinita</i>	0.776	0.575
Variance	50.820	30.274

DISCUSSION

Surface-water paleoceanography: Comparison of Sites 552 and 646 calcareous plankton data

The fluctuations in Pliocene/Pleistocene calcareous faunal and floral data at Site 552 suggest periodic changes in surface water conditions, although the sampling resolution was not high enough to demonstrate cyclicity. However, as previously shown, variations in high-resolution records of $\delta^{18}\text{O}$ and CaCO_3 at Site 552 were dominated by the 41 kyr component of the orbital obliquity during most of the late Pliocene/early Pleistocene (Shackleton & Hall, 1984; Raymo *et al.*, 1989). A development of the calcareous plankton and surface water paleoceanography as observed at Site 646 could not be determined. It seems reasonable to suggest that over the time-scale con-

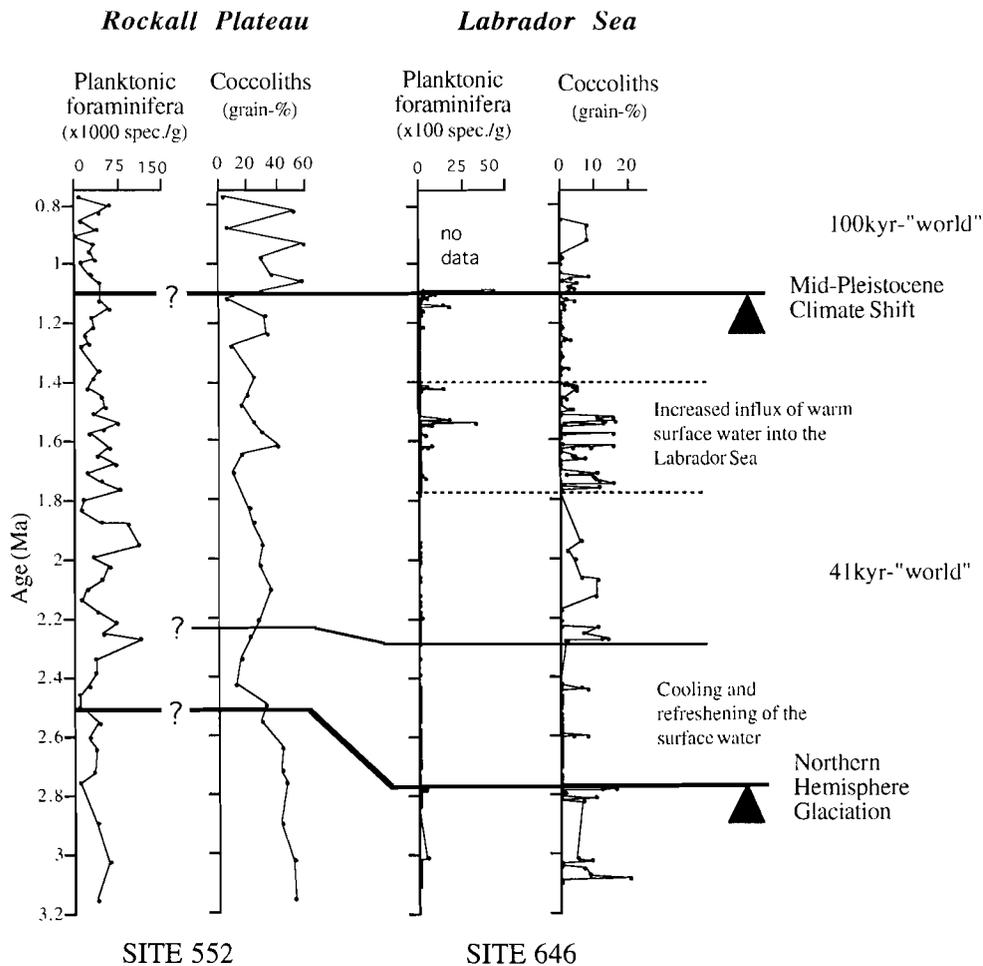


Figure 4. Comparison of the absolute abundances of both coccolithophores and planktonic foraminifera at Sites 646 and 552. Main palaeoceanographic events are indicated by horizontal lines.

sidered here the ecological conditions during interglacials did not change appreciably on the Rockall Plateau. Only spikes of low coarse fraction carbonate associated with glacial stages suggest particularly intense cold periods during which surface productivity was reduced (Zimmerman *et al.*, 1984).

Thus, between 3.2 Ma and 0.8 Ma strong gradients in the number of calcareous planktic organisms were present between the Rockall Plateau and the northern Labrador Sea (Fig. 4). The number of planktonic foraminifers is several times higher in the northeastern North Atlantic compared to the area south of Greenland. In addition, the latter area is characterized by long-lasting intervals nearly barren in foraminifers and calcareous nannofossils, whereas on the Rockall Plateau the calcareous fauna and flora is present throughout the investigated interval. These differences are not only due to strong carbonate dissolution in the

Labrador Sea (Baumann & Meggers, 1996), but are probably caused by drastic differences in the productivity of calcareous plankton. Although there is no clear evidence for a strong cooling trend in the latest Pliocene to Pleistocene calcareous plankton record at Site 552, it is notable that *N. atlantica* and the reticulofenestrads nearly disappeared in the latest Pliocene-earliest Pleistocene. The last appearance as well as the drastic decrease in abundance of these taxa must also be interpreted as a response to changed environmental conditions. Similar regional extinctions, which were also described for other planktonic organisms in the study area (e.g. dinoflagellates, de Vernal & Mudie, 1992), probably suggest the onset of harsh environmental conditions and may be attributed to surface water cooling. At Site 552, this is also shown by the increase in abundance of cold-water adapted coccolithophore species *C. pelagicus* during the interval 2.4–2.2 Ma. Nevertheless, a disappearance of most of

the taxa in response to the development of an extensive sea ice cover and to cooling and/or refreshing of the surface water as observed in the Labrador Sea are not inferred for the northeastern North Atlantic.

These data indicate that the thermal gradient between the two areas was strong throughout most of the late Pliocene to early Pleistocene interval. Site 552 is located beneath the diffuse eastern extension of the North Atlantic Current, whereas Site 646 is influenced by the subpolar West Greenland Current which is fed by both the polar East Greenland Current and the subpolar Irminger Current, a branch of the North Atlantic Drift. Hence, the Labrador Sea was heavily influenced by polar, ice-laden surface water after the northern hemisphere cooling started. The calcareous fauna and flora indicate that surface paleoceanographic conditions off southern Greenland were mostly very different compared to that in the Rockall Plateau area. The assemblages are characterized by very low numbers of cold-water adapted species during most of the interval until about 1.1 Ma. Almost monospecific assemblages of *N. pachyderma* sin. at Site 552 are first observed in the upper Pleistocene (Hooper & Funnell, 1986). Thus, repeated migrations of the polar front across this site did not occur before 1.1 Ma when amplitudes of glacial / interglacial cycles drastically increased (Jansen *et al.*, 1989; Ruddiman *et al.*, 1986a). These changes indicate the initiation of warmer interglacials with warmer surface water influx not only into the Labrador Sea (Aksu *et al.*, 1989; Baumann & Meggers, 1996) but also into the Norwegian-Greenland Sea (Henrich *et al.*, 1989; Jansen *et al.*, 1989; Baumann *et al.*, in press).

Despite all these gradients, there are similarities in the biometrical evolution of *Neogloboquadrina* species indicating a convergent biometrical evolution of this genus in both the northeastern North Atlantic and the northwestern North Atlantic.

Surface water temperature in the Pliocene - early Pleistocene North Atlantic: The possibility of a reconstruction

All paleoecological work on plankton is based on the fundamental assumption that the pelagic ecosystem being sampled today has remained unchanged during the examined time period. The most common technique used with planktonic foraminifers is the transfer-function pioneered by Imbrie & Kipp (1971). The downcore use of different transfer functions to calculate SST back in the early Pleistocene and in the Pliocene has been carried out by various working groups (Thunell, 1979; Hooper & Funnell, 1986; Dowsett & Poore, 1990;

Dowsett, 1991). Thunell (1979) used the Imbrie & Kipp (1971) model to calculate paleotemperatures for the last 5.0 m.y. in the Mediterranean area, making the basic assumption that evolving lineages of planktonic foraminifera retain nearly the same ecological requirements throughout their history. Dowsett & Poore (1990) and Dowsett (1991) used such a technique to calculate Pliocene to Pleistocene SST in the North Atlantic. Mostly extinct Pliocene species were assumed to be ecologically equivalent to closely related modern forms. For example the extinct planktonic foraminifer *G. puncticulata* is compared with the modern related species *G. inflata* (Dowsett & Poore, 1990). In the Pliocene *N. atlantica* was substituted for sinistral *N. pachyderma* to enable paleotemperatures for this time period by Hooper & Funnell (1986). From the results of Hooper & Funnell (1986), we consider *N. atlantica* sin. to be a polar species, since it shows highest abundances during glacial intervals. In contrast to this, *N. atlantica* sin. was regarded as a subpolar species by Poore & Berggren (1975) and by Kennett & Srinivasan (1980) by morphological comparison between *N. atlantica* sin. and *Neogloboquadrina dutertrei*.

In the present study we have concentrated on both the planktonic foraminifer assemblage and the morphological characteristics of key-species. Although there are strong thermal gradients in surface water between the Labrador Sea and the Rockall Plateau (see above) the comparison of the biometrical record with assemblage and isotope data (compare Ruddiman *et al.*, 1986b) indicate that the calculation of Pliocene - early Pleistocene SST by using transfer functions is very difficult and should be performed with caution.

A similarity between both sites is the time-transgressive disappearance of *N. atlantica* sin. after the intensification of the northern hemisphere cooling at 2.4 Ma (Fig. 5). The number of sinistral *Neogloboquadrina* decreased between 2.4 Ma and 1.8 Ma within the sediments of both the northern Labrador Sea and the Rockall Plateau. In the North Atlantic the last appearance of *N. atlantica* sin. provides a useful biostratigraphic datum. Several analyses indicate a last occurrence of this species between 2.4 Ma and the Pliocene/Pleistocene boundary. Hooper & Weaver (1987) give an extinction point of 2.3 Ma at ODP Sites 609, 610 and 611. This agrees well with the extinction points in this study and in the investigations of Spiegler & Jansen (1989) for the Vøring-Plateau, Pujol & Duprat (1985) for the Goban Spur, and Zachariasse *et al.* (1990) for the Mediterranean. Further investigations on test sizes of *N. atlantica* sin. and *N. pachyderma* sin. may help to distinguish these species in the upper Pliocene to lower Pleistocene sediment

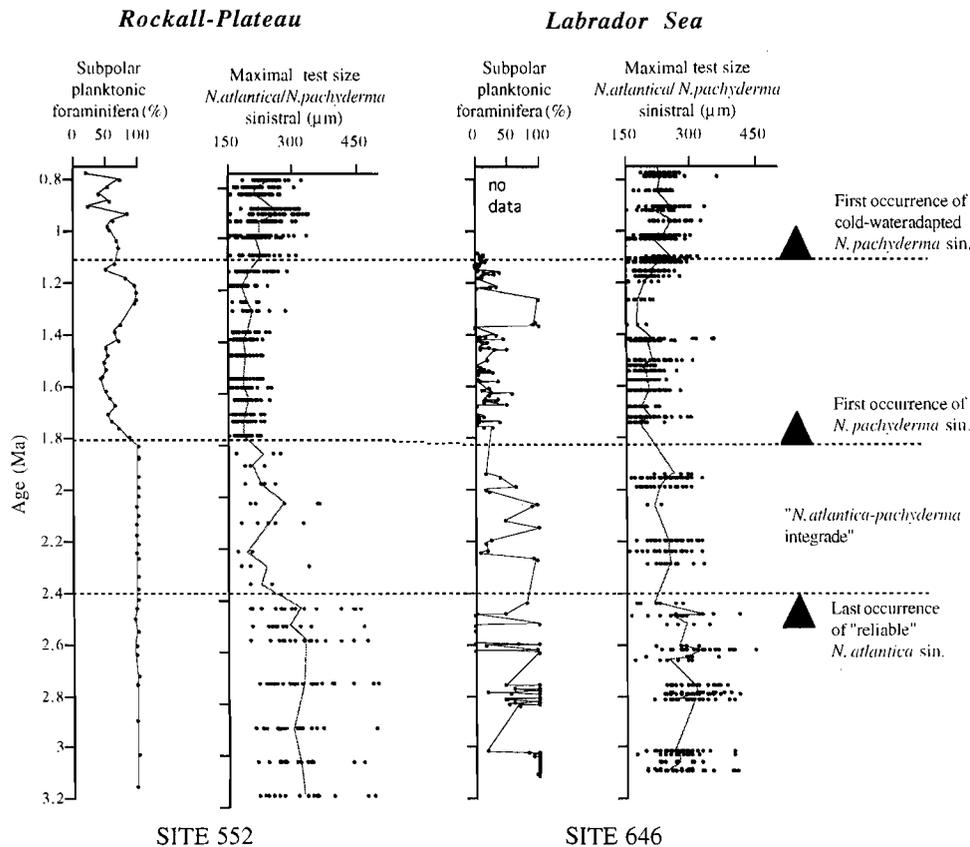


Figure 5. Biometrical measurements of *N. pachyderma* sin./*N. atlantica* sin. (maximum diameter) as well as the amount of subpolar planktonic foraminifera during the time interval 3.2-0.8 Ma for DSDP Site 552 and ODP Site 646. Median test size of each sample is indicated by the traced line. Note that *N. pachyderma* sin. in the abundance-plots is used as a polar species although this interpretation is not supported by the results presented in this paper.

sections of the North Atlantic

The second synchronous event is the appearance of the small *N. pachyderma* sin. at 1.8 Ma. The small size of *N. pachyderma* sin. in this interval gives the impression that this species are more heavily encrusted (compare Hooper & Weaver, 1987) than *N. atlantica* sin. or the „*N. atlantica-pachyderma* integrate“. Also synchronous is the redisappearance of *N. pachyderma* sin. from the planktonic foraminifer assemblage between 1.35 Ma and 1.2 Ma. This may indicate that there are morphological changes in the taxon *Neogloboquadrina* due to the drastic climatic and ecological changes of the Northern Hemisphere in this time. Also the last synchronous pattern, the trend to larger sized *N. pachyderma* sin. in the whole North Atlantic, suggests an evolutionary trend in cold-water adapted *Neogloboquadrina* (Fig. 5). This evolution influenced the temperature preferences of the species *N. atlantica* sin. and *N. pachyderma* sin. Due to the strong similarities in the biometrical

evolution of *Neogloboquadrina*, it could be stated that the cooling of the Northern Hemisphere influenced the planktonic foraminifer assemblages, as it is shown for the lineage *Neogloboquadrina acostaensis* - *Neogloboquadrina humerosa* - *N. dutertrei* by Biolzi (1991), for the lineage *G. puncticulata* - *G. inflata* by Wei (1994) and for the lineage *Globorotalia crassaformis* - *Globorotalia tosaensis* - *G. truncatulinoides* by Lazarus *et al.* (1995). In all these lineages changes in the oceanographic conditions triggered the disappearance of ancient species followed by a first appearance of new species. The coincidence between paleoceanographic events and biometrical/morphometrical changes suggest that paleoenvironmental changes cause developmental perturbations. Oceanic conditions influence the size, the shape and the developmental timing of planktonic foraminifera (Wei, 1994). The different planktonic foraminifer lineages responded to the Northern Hemisphere cooling events by morphological variations and by diversification.

In Site 552 a no-analogue assemblage (compared with the isotope record of benthic foraminifers) precludes making credible SST estimates in the interval 1.3-1.2 Ma (Ruddiman *et al.*, 1986b). Only the record above 1.1 Ma is suitable for SST estimates and related time-series analysis. Low numbers of *Globigerinoides ruber* and other low-latitude species indicate that warm subtropical conditions did not develop during this interval. The fauna in this time-period consisted of *N. pachyderma* dex. (see also Ruddiman *et al.*, 1986b). Within this interval, there are three brief pulses of heavier benthic foraminiferal oxygen isotopic values, suggesting a greater ice-volume on the surrounding continents (Shackleton & Hall, 1984; Shackleton *et al.*, 1984). Also the CaCO₃-record shows synchronous minima (Zimmerman *et al.*, 1984), implying dissolution of carbonate particles on the sea-floor, increased dilution by IRD, or suppression of productivity in surface waters. Analyses concerning the carbonate dissolution on the Rockall Plateau indicate a relatively good carbonate preservation over the whole time period from 3.2 Ma to 0.8 Ma (Diester-Haass & Schnitker, 1989; Meggers, 1996). Investigations of the benthic foraminifer assemblage also indicate that the main body of benthic species are characteristic of North Atlantic Deep Water (NADW) (Murray, 1984). It may therefore be assumed that either non-corrosive NADW has occupied the Rockall Plateau area throughout most of the Neogene. While the northern Labrador Sea is a very sensitive area for NADW-production, depending on the establishment of meridional circulation, the Rockall Plateau was influenced by relatively warm Atlantic surface water for the whole time. Therefore, the out-of-phase link between SST and oxygen isotope record at Site 552 could not be explained with the preservation of carbonate.

Dilution by IRD is much more important in the interpretation of carbonate minima on the Rockall Plateau. For example, after 1.3 Ma, inputs of IRD to the Norwegian Sea generally increased, which is supposed to be due to an intensified glaciation (Jansen *et al.*, 1988). In addition, Spiegler (1989) showed that redeposition of microfossils from the shelf areas increased during glacials after 1.2 Ma. This suggests that continental ice-sheets expanded much further onto the continental shelves after 1.2 Ma than during the interval between 2.5 Ma and 1.35 Ma. Therefore, the explanation for the non-analogue link between SST and oxygen isotope data could be more easily seen in several significant coolings of the North Atlantic ocean that occurred between 1.3 Ma and 1.2 Ma. These coolings are registered in an anomalous way in the genus *Neogloboquadrina* because of a fundamental change in environmental responses of *N. pachyderma* sin.,

which is the polar end-member in the planktonic foraminifer assemblage. The same pattern of a low-frequency oscillation toward warm SST values near the interval 1.35-1.2 Ma was also seen at Site 607 (Ruddiman *et al.*, 1989). In both cases there are out-of-phase links between SST and benthic oxygen isotope records which are probably artifacts caused only by the absence of the species *N. pachyderma* sin. The speculations of Ruddiman *et al.* (1986b, 1989) are confirmed by the biometrical/paleoceanographical results of this study. In addition, factor analysis of Site 646 planktonic foraminifer data shows that from 1.1 Ma *N. pachyderma* sin. first exhibits a polar adaptation. Raymo *et al.* (1986) have shown that *N. pachyderma* sin. did not take on a distinct „cold-indicator“ role in the North Atlantic until 1.7 Ma. This role was abandoned by *N. pachyderma* sin. from 1.3 Ma to 1.2 Ma and finally reacquired at 1.2 Ma to 1.1 Ma with the mid-Pleistocene transition (Ruddiman *et al.*, 1986b). Late Pliocene to Holocene biometrical analyses in the Labrador Sea clearly indicate an increase in maximum diameter of *N. pachyderma* sin. after 1.1 Ma, most probably related to a better adaptation of this species to the extreme glacial conditions (Baumann & Meggers, 1996).

Next to changing surface water conditions between 1.3 Ma and 1.1 Ma changes in deep water chemistry can be detected from carbon isotope studies (Raymo *et al.*, 1990). Raymo *et al.* (1990) concluded that a significant decrease in NADW-production occurred between 1.2 Ma and 1.1 Ma. During the same interval poor carbonate preservation could be seen in the Labrador Sea (Baumann & Meggers, 1996) and in the Norwegian-Greenland Sea (Henrich & Baumann, 1994; Meggers, 1996). It is generally believed that the thermohaline circulation is largely driven through the production of NADW (Johnson, 1982; Raymo *et al.*, 1990). Therefore, the breakdown of this thermohaline circulation cannot only be seen within carbonate preservation patterns and $\delta^{13}\text{C}$ -values, but also in its influence on the planktonic foraminifer assemblage (Meggers, 1996; Baumann & Meggers, 1996) and on the ecological niches of benthic foraminifers (Schönfeld, 1996), which showed several extinctions in the middle Pleistocene.

CONCLUSIONS

The planktonic assemblages in the upper Pliocene at Site 552 consist mainly of subpolar to temperate species. The increase in the influence of polar surface waters at about 2.5 Ma is indicated mainly by an increase in the abundance of the cold-water adapted coccolithophore species *C. pelagicus*. However, this corresponds to an increase in subpolar *N. pachyderma* dex., indicating that conditions

during this „cold“ phase would be analogous to intermittent interglacials of the late Pleistocene. The drastic decrease in abundance of „Pliocene“ taxa is interpreted as a response to the onset of harsh environmental conditions and may be attributed to surface water cooling. In general, the calcareous faunal and floral data indicate that the thermal gradient between Sites 552 and 646 was strong throughout most of the late Pliocene to early Pleistocene interval.

The biometric data of *Neogloboquadrina* tests at both sites indicate an evolutionary trend from large-sized *N. atlantica* sin. before 2.4 Ma via morphological integrate-forms („*N. atlantica-pachyderma* integrate“) to small-sized *N. pachyderma* sin. between 1.8 Ma and 1.1 Ma. Therefore, the use of transfer functions on cold-water adapted *Neogloboquadrina* in sediment sections of the northern North Atlantic older than about 1.1 Ma should be treated with caution. From factor analyses it can be shown that *N. pachyderma* sin. first becomes a cold-water adapted species at 1.1 Ma, while it is a subpolar indicator between 1.8 Ma and 1.1 Ma.

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