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12. SEA-SURFACE GRADIENTS BETWEEN THE NORTH ATLANTIC AND THE NORWEGIAN SEA DURING THE LAST 3.1 M.Y.: COMPARISON OF SITES 982 AND 985[1]

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ABSTRACT

Records of bulk carbonate content, ice-rafted detritus (IRD), planktonic foraminifers, and coccolithophores of Ocean Drilling Program Site 982 from the Rockall Plateau and Site 985 from the Norwegian Sea are compared to determine the variability of the south-north gradients in surface water since ~3.1 Ma.

The onset of the major Northern Hemisphere glaciation appears time-transgressively between the sites, as indicated by both a noticeable increase in IRD and marked decrease in carbonate. Thus, each site is recording a somewhat different manifestation of the larger processes that occurred in the interval 2.8 to ~1.1 Ma. Although the interval since ~2.5 Ma was a climatically unstable time interval in the North Atlantic, sedimentation is largely composed of calcareous biogenics at Site 982. Minimum carbonate contents, however, result primarily from dilution by IRD during glacials. In contrast, at Site 985 glacial conditions, probably with discontinuous sea-ice cover, dominated throughout until 1.1 Ma as shown by the nearly carbonate-free sediments. Thus, during most of this time interval the North Atlantic surface water did not enter the Norwegian Sea. Nevertheless, increased carbonate contents and relatively abundant coccoliths indicate increasingly northward penetrations of comparatively warm Atlantic water into the Norwegian Sea during short phases at ~1.9 and 1.4 Ma.

The gradient between the North Atlantic and the Norwegian Sea became less distinct after ~1.1 Ma and even less pronounced after 0.65 Ma. Short but warm interglacials with relatively high biogenic carbonate accumulation occurred in the Norwegian Sea, alternating with longer glacial-dominated intervals with high inputs of IRD. However, glacial–interglacial contrast was subdued in the Norwegian Sea as opposed to the North Atlantic. Thus, a pronounced increase in the meridional circulation of the northern North Atlantic is inferred for the Brunhes Chron.

INTRODUCTION

One of the central goals of Ocean Drilling Program (ODP) Leg 162 was to investigate the role of the Iceland-Faeroe Ridge as a critical gateway for the thermohaline circulation system in the North Atlantic. Today, warm saline surface water flows from the Atlantic via the Iceland-Faeroe Ridge into the Norwegian Sea. The advection of these temperate surface waters into the area provides a strong heat source for eastern subarctic Europe and causes the recent favorable warm climatic conditions. As a consequence of the cooling and sinking of the advected waters, deep-water formation takes place, especially in the Iceland and Greenland Seas. Much of the world's deep water is formed in this region. The northward inflow of temperate surface waters into the Norwegian Sea and southward outflow of deep, well-oxygenated waters from this area into the North Atlantic must pass the Iceland-Faeroe Ridge. Oceanographic as well as climatic changes on each side of the gateway are therefore closely related to each other.

The flow pattern via the Iceland-Faeroe Ridge as well as the surface-water circulation system in the northern North Atlantic has consistently changed over time with shifting climate regimes. Many recent studies have shown that variations in surface-water conditions and thermohaline circulation in the North Atlantic during the last glacial cycle are linked to the rapid and significant oscillations in air temperature (e.g., Lehman and Keigwin, 1992; McManus et al., 1994; Bond and Lotti, 1995; Oppo and Lehman, 1995). The present circulation pattern, which probably has been operating since ~10 ka (Baumann and Matthiessen, 1992; Koç Karpuz and Jansen, 1992; Sarnthein et al. 1995), is different from the unstable pattern of the glacials (e.g., Veum et al., 1992; Duplessy and Labeyrie, 1994; Sarnthein et al., 1995). The North Atlantic Drift changed its northward position considerably during the late Quaternary without extending far into the Norwegian Sea during glacials (CLIMAP, 1981). Although there is no evidence that the thermohaline circulation was totally hampered during cold stages, much of the heat loss occurred farther south in the North Atlantic. This is shown by sea-surface temperature reconstructions along south-north transects from the North Atlantic to the Norwegian Sea/northwest Europe (Sejrup and Larsen, 1991; Veum et al., 1992; Koç et al., 1996).

Direct comparisons between North Atlantic and Norwegian-Greenland Sea records, nevertheless, are usually not attempted. Evidence from both the Norwegian Sea and the North Atlantic suggests that the major intensification in Northern Hemisphere glaciation, which generally is defined by an abrupt increase in the amount of IRD, occurred at ~2.75 Ma (Raymo et al., 1989; Jansen et al., 1990; Jansen and Sjøholm, 1991; Fronval and Jansen, 1996). Climatic variations are characterized by a strong 41-k.y. obliquity frequency (Raymo et al., 1989; Ruddiman et al., 1989). Thermal gradients between the Norwegian Sea and the North Atlantic can certainly be observed by comparing the differences in carbonate records. Differences in carbonate content of the sediments have often been used to distinguish the surface-water masses in the Norwegian-Greenland Sea (Kellogg, 1975, 1976; Henrich et al., 1989; Henrich and Baumann, 1994). High carbonate contents reflect sediments underlying the warm inflowing Atlantic water, whereas low carbonate contents in sediments indicate cold, usually ice-covered surface-water masses. The North Atlantic record is, however, generally quite dissimilar to that of the Norwegian-Greenland Sea (Jansen et al., 1988). Especially in the interval 3.1–1.1 Ma, strong discrepancies are reflected by low-to-zero carbonate deposition in the Norwegian Sea compared with highly fluctuating but continuous carbonate deposition in the North Atlantic. Previous works (Jansen et al., 1988, 1989; Henrich, 1989) tried to interpret these differences in carbonate sedimentation as a result of low carbonate productivity and flux, combined with increased bottom-water pCO_2 resulting from decreased deep-water ventilation rates in the Norwegian Sea. In the North Atlantic, on the other hand,

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carbonate distribution is primarily controlled by dilution by IRD during glacials. Here, cold extremes are most analogous to interglaciations (Substage 5d), whereas many warm extremes had more ice and/or (probably) colder surface-water temperatures than are observed today (Raymo, 1992). Thus, except for some low-carbonate spikes during extreme glacial episodes, most of the sediment has high carbonate content. Henrich and Baumann (1994) and Baumann et al. (1996) proposed at least some phases of warmer Atlantic water intrusions into the Norwegian Sea between 1.65 and 1.3 Ma, although the stronger influence of warmer surface waters should be restricted to the easternmost Norwegian Sea. These authors observed relatively high amplitudes in the percent of biogenic carbonate and in the abundance of warm-adapted species that indicate the short-term presence of relatively warm surface waters. In addition, the nannoplankton and foraminifer assemblages are characterized by well-preserved species during climatic optima between 1.65 and 1.3 Ma.

At ~1 Ma, a major shift toward more extensive glaciations of longer duration and warmer interglacials, most likely with less continental ice (Ruddiman et al., 1989; Raymo, 1992; Berger and Jansen, 1994; Henrich and Baumann, 1994; Fronval and Jansen, 1996), is also reflected by the transition from carbonate-free/-poor to carbonate-bearing sediments in the Norwegian Sea. In general, interglacials are associated with the enhanced influx of Atlantic surface water to the Norwegian-Greenland Sea. Therefore, high carbonate contents covaried with warm stages in the interglacial–glacial cycles in both the Norwegian-Greenland Sea and the North Atlantic.

In this paper, we present medium- to high-resolution records of bulk carbonate content, calcareous plankton assemblages (planktonic foraminifers and coccolithophores), and sedimentological proxy data. Continuous recovery and comparable sedimentation rates of Pliocene/Pleistocene sediments provided the opportunity to compare the records of Sites 982 and 985. We investigated both sites to reconstruct the interactions between the Norwegian Sea and the North Atlantic over the last 3 m.y. Our main objectives were to reconstruct the history of mid-term evolution of the Northern Hemisphere climate as well as the exchange of surface-water masses between the North Atlantic and the Norwegian Sea across the Iceland-Faeroe Ridge.

MATERIALS AND METHODS

Samples were collected from the composite sections of Leg 162 Sites 982 and 985 (see Jansen, Raymo, Blum, et al., 1996). Site 982 is located in the North Atlantic on the Rockall Plateau (57°31′N, 15°52′W) in a water depth of 1134 m; Site 985 was drilled in the Norwegian Sea on the western slope of the Iceland Plateau into the Norway Basin (66°56.5′N, 6°27′W) at a 2788-m water depth (Fig. 1). The sedimentation rate at both sites varied between 1.5 and 3 cm/k.y. (Jansen, Raymo, Blum, et al., 1996). Samples were usually taken every 10- to 20-cm depth interval for bulk calcium carbonate measurements and at 20- to 30-cm depth intervals for faunal, floral, and sedimentological analysis. The stratigraphic resolution of these samples is relatively similar between the sites, usually between 3000 and 6000 yr for bulk carbonate measurements and ~10,000–15,000 yr for faunal, floral, and sedimentological data.

A LECO CS-125 infrared analyzer was used to determine calcium carbonate contents. This device measures only total carbon (TC) contents. In a subsequent analysis, the samples were therefore treated with hydrochloric acid to allow the determination of total organic carbon (TOC) content. The bulk carbonate content can be calculated from the weight percentage of the bulk sediment with the following equation:

$$CaCO_3 \text{ wt\%} = (\text{TC wt\%} - \text{TOC wt\%}) \times 8.33.$$

For the studies of the coarse fraction (planktonic foraminifers, IRD = all lithogenic particles, as well as all other biogenic and volcanic components), the samples were freeze-dried using a FINN-AQUA (lyvotac GT2). Part of the freeze-dried sample was weighed and then washed on a 63-µm sieve and further separated into 63- to 125-, 125- to 500-, 500- to 1000-, and >1000-µm fractions using an ATM-SONIC-Sifter. The 125- to 500-µm fraction was chosen for particle count procedure. A split of 300 to 1000 grains, depending on the amount of biogenic particles, was separated with a microsplitter and counted for biogenic and terrigenous components. Total foraminifer abundances and IRD data were converted to numbers per gram dry weight sediment. In this study, only numbers of total planktonic foraminifers and abundances of subpolar species—mainly *N. pachyderma* dex., *Globigerina bulloides*, *Turborotalita quinqueloba*, and species of *Globigerinita* and *Globorotalia*—are presented.

Coccolith species were counted under the scanning electron microscope (SEM). For preparation, a combined dilution/filtering technique as described by Andruleit (1996) was used. A small amount of sediment was weighed and brought into suspension. After dilution with a rotary splitter, the suspension was filtered through polycarbonate membrane filters (Schleicher and Schuell, 50-mm diameter, 0.4-µm pore size). A monolayer of all sediment particles was produced for investigation under the SEM. All coccoliths were recorded in numbers per gram dry sediment. Here, only numbers of total coccoliths as well as abundances of the cold water–adapted species *Coccolithus pelagicus* (Wallich) Schiller are shown. Subsequently, numbers and abundances of all species will be presented elsewhere.

STRATIGRAPHY

The stratigraphic framework for both sites was based initially on magnetostratigraphy from the Leg 162 IR volume (Jansen, Raymo, Blum, et al., 1996). Refining the time scale of the Brunhes Chron was possible for Site 985 (Fig. 2). We cross-correlated the typical shape patterns of the carbonate record with those of ODP Site 643 from the Vøring Plateau and with those of Site 907 from the Iceland Plateau. The carbonate and oxygen isotope data from Site 643 are from Henrich and Baumann (1994), whereas the ages for Site 643 are from

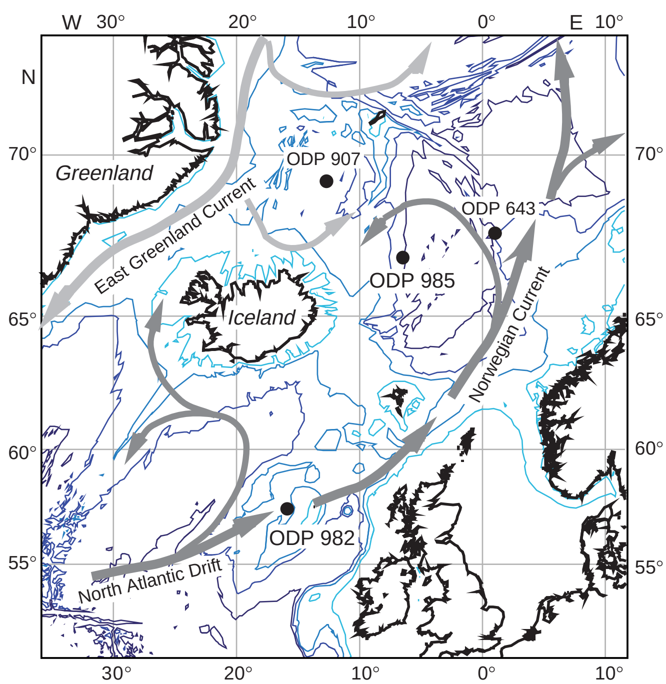

Figure 1. Location map for Sites 982, 985, and other referenced sites and the main surface ocean circulation pattern currently prevailing in the northern North Atlantic and Norwegian-Greenland Sea. Contour interval is 500 m.

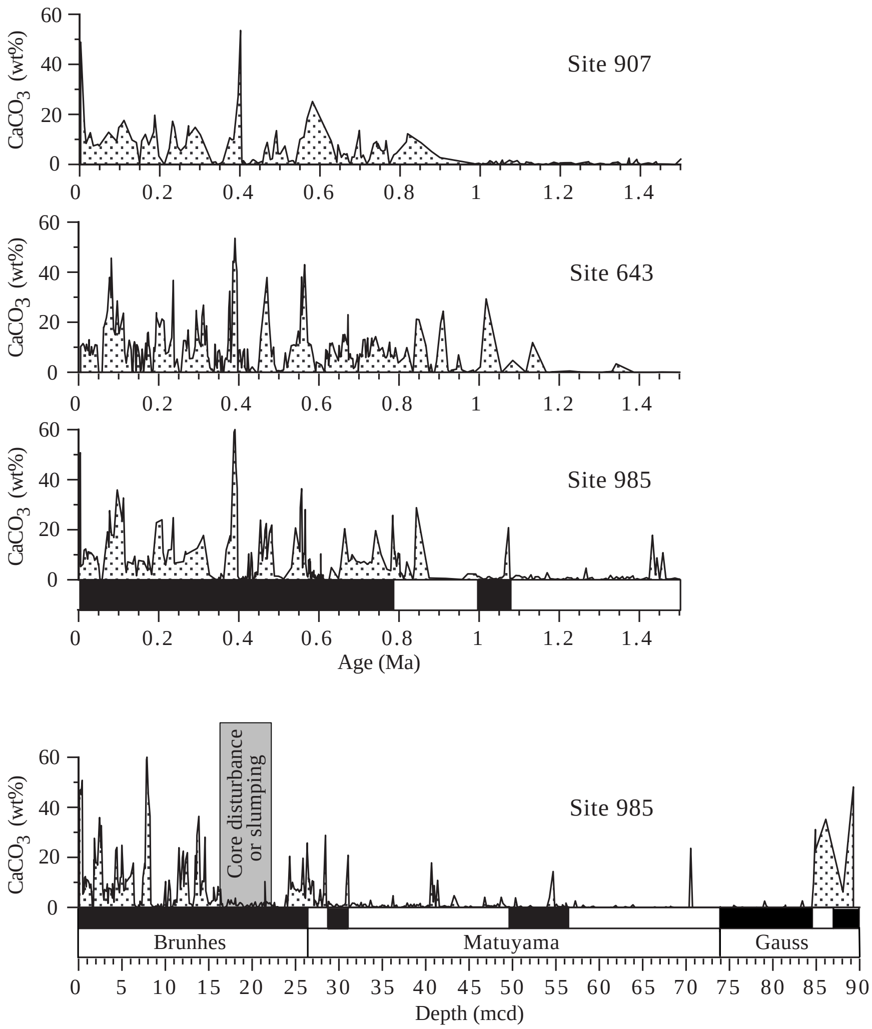

Figure 2. Carbonate records from Sites 643, 907, and 985. The δ[18]O records from Sites 643 and 907 are plotted to corrected sub-bottom depth (Sites 643 and 907) or to composite sub-bottom depth (mcd: Site 985). The carbonate and δ[18]O data for Site 643 are from Henrich and Baumann (1994), and the ages for Site 643 are from Fronval and Jansen (1996) and T. Fronval (pers. comm., 1997). Carbonate data for Site 907 are from Baumann et al. (1996), and the δ[18]O data and age interpretations are from Fronval and Jansen (1996). Typical shape patterns for the Site 985 carbonate record are cross-correlated to those for Sites 643 and 907.

Fronval and Jansen (1996) and T. Fronval (pers. comm., 1997). Carbonate data from Site 907 are from Baumann et al. (1996), whereas the oxygen isotope stratigraphy is from Fronval and Jansen (1996). Oxygen isotope Stages 1 to 15 and, thus, age interpretations could be determined relatively easily and correlated at all of these sites. An almost carbonate-barren interval from 16.2 to ~22.0 mcd (meters composite depth) at Site 985 (Fig. 2) was described as a disturbed interval, or slumping, in the initial core descriptions (see Jansen, Raymo, Blum, et al., 1996). Therefore, this interval was regarded as strongly extended either by drilling effects or by slumping. The following carbonate peaks in the depth interval from 24 to 26 mcd are placed in the Brunhes Chron.

For Site 982, an excellent high-resolution carbonate record provided the opportunity to create a time scale by the application of the orbital-tuning technique first proposed by Imbrie et al. (1984). For the tuning target, the summer insolation at 65°N (Berger, 1978) was used. We tuned the unfiltered carbonate record under the assumption that high carbonate contents are closely related to high summer insolation (Shackleton et al., 1995). This tuning as well as the correlations between the sites were performed with *ANALYSERIES* (Paillard et al., 1996).

RESULTS

Site 982

The carbonate contents at Site 982 vary strongly between 15 and 95 wt% (Fig. 3). The deepest section studied is characterized by continuously high contents of carbonate with maximum values exceeding 90 wt%; only three minor excursions to lower values <55 wt% appear at 52.3, 59.5, and 62.9 mcd. Relatively high numbers of coccoliths display the general trend of the carbonate contents. In contrast to these high carbonate concentrations, rather low numbers of planktonic foraminifers, which are dominated by subpolar species, are observed in the depth interval of >60–52.3 mcd (Fig. 3). The first input of IRD appears at ~59.5 mcd, as also indicated by a first noticeable peak of the >500-µm fraction (Fig. 4), which consists exclusively of large rock fragments. Maxima with relatively high amounts of IRD are present until 38.6 mcd.

A significant change appears at ~55.0 mcd. Relatively high-amplitude and high-frequency fluctuations of the carbonate record are observed. The carbonate contents range from 15 to 90 wt% accompanied by varying numbers of planktonic foraminifers. A general trend to higher numbers of planktonic foraminifers is observed from 55 to 42 mcd. This tendency is also reflected by increasing percentages of the 125- to 500-µm fraction (Fig. 4). The total number of coccoliths is relatively low but is dominated by high percentages of the cold water–adapted species *Coccolithus pelagicus* in the depth interval 52.8–39.3 mcd. A short interval with intensified frequencies and amplitudes of carbonate contents varying between 15 and 90 wt% at 40.5 to 38.5 mcd marks the next sedimentary transition. This interval is accompanied by high amounts of IRD and an abrupt change in planktonic foraminifer composition. Strongly decreasing percentages of subpolar planktonic foraminifers indicate the appearance of the polar species *Neogloboquadrina pachyderma* sin. (Fig. 3). This obvious change persists in the following 8 mcd.

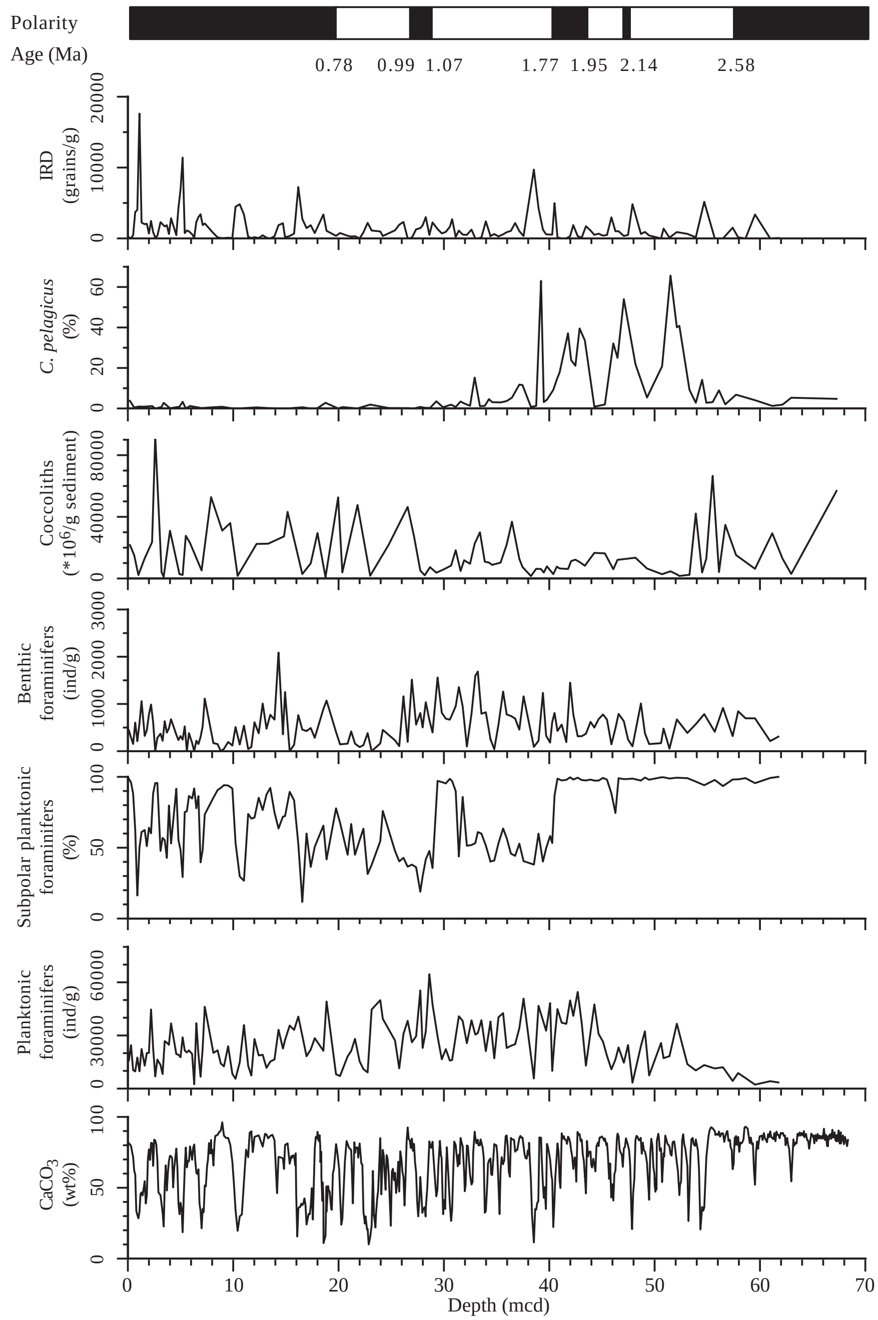

Figure 3. Carbonate, bulk faunal and floral data, and IRD contents for Site 982 plotted to composite sub-bottom depth. Magnetic polarity scale and ages of magnetic reversals are indicated.

Carbonate contents fluctuate strongly from 38.5 to 16 mcd. The two-step decrease of minimum carbonate contents at ~24 mcd is remarkable. In addition, in the section from 40.5 to 32 mcd, the total numbers of coccoliths reach values of up to 40,000 × 10^6 per gram of sediment with low but significant percentages of *C. pelagicus*. At 32 mcd, a short peak of again-high percentages of subpolar planktonic foraminifer species leads to a short phase in which subpolar species again dominate the assemblage at >90%. On the other hand, the total number of planktonic foraminifers and also coccoliths decreases (Fig. 3). This phase ends abruptly at 29 mcd, where high percentages of polar planktonic foraminifers reappear and the total number of planktonic foraminifers increases to maximum values of more than 60,000 individuals per gram (ind/gram). At 26 mcd, the amount of benthic foraminifers decreases suddenly. The subpolar planktonic foraminifer percentage curve generally follows the pattern of the strongly fluctuating carbonate record. The total number of coccoliths increases significantly at 29 mcd.

A remarkable change in the structure of the carbonate record is obvious at the last 16 mcd of the record (Fig. 3). Depressed frequency and increased amplitude are characteristic for the carbonate record and also for the record of the subpolar planktonic foraminifer percentage. The curve of the total number of planktonic foraminifers does not seem to follow a regular pattern. There is apparently no correlation between the total number of foraminifers and the carbonate record. This effect is not present for the total abundance of coccoliths. Coccolith peaks match the major carbonate peaks. The highest total numbers of coccoliths can be observed at 2.5 mcd with more than 90,000 × 10^6 coccoliths per gram of sediment. The highest amounts of IRD, with as much as 18,000 grains/gram, were also counted in this last section.

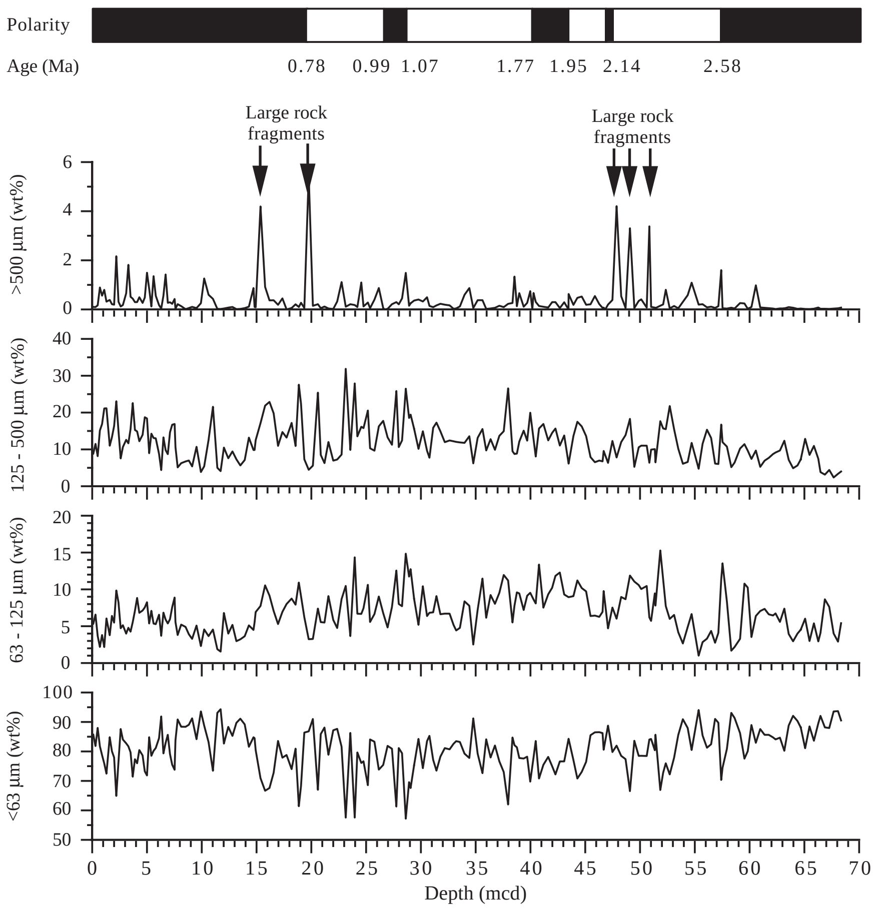

Figure 4. Grain-size data for Site 982 plotted to composite sub-bottom depth. Magnetic polarity scale and ages of magnetic reversals are indicated.

Site 985

From high carbonate contents ranging from 10 to 50 wt% and correspondingly high contents of coccoliths from 90 to 85 mcd, the total carbonate sedimentation decreases sharply to almost zero. Little to no carbonate was deposited in the interval from 85 to 65 mcd (Fig. 5). Carbonate contents vary between 0 and 2.6 wt%, and only one isolated peak at 70.5 mcd reaches 23.6 wt%. Long carbonate-barren sections are predominant, with sporadic low values of total planktonic foraminifers below five individuals per gram observed. The first input of IRD occurs in this section at 83.5 mcd. Following the high percentages of the 63- to 125- and the 125- to 500-µm fractions at 83–81 mcd, the grain-size distribution is characterized by high percentages of the <63-µm fraction until 49 mcd (Fig. 6).

Carbonate contents increase slightly in the section from 65 to 31 mcd (Fig. 5). Two maxima at 54.5 and 41 mcd reach 14 and 18 wt%, respectively. Except for these maxima, carbonate values never exceed 5 wt%. Correspondingly, two small peaks in the total amount of coccoliths are obvious. Coccolith assemblages are dominated by *Coccolithus pelagicus*. The numbers of total planktonic foraminifers do not exceed 26 individuals per gram. IRD input generally increases in this section. Maximum values at 35 mcd reach 16,000 grains/gram. Despite the low numbers of planktonic foraminifers, dominant percentages of subpolar planktonic foraminifers are present from 66 to 64 mcd and from 56 to 53.5 mcd. High percentages also occur from 39 to 34 mcd.

The first significant amount of planktonic foraminifers is from 31 to 24 mcd, fluctuating between zero and maximum numbers of more than 29,000 ind/gram (Fig. 5). The assemblage is clearly dominated by polar species. Analogously, carbonate values increase to generally higher values, varying between 0 and 22 wt%. An almost carbonate-barren interval from 22 to 17 mcd was identified as highly disturbed or slumping in the core descriptions (Jansen, Raymo, Blum, et al., 1996), so we regard this interval as extremely extended.

The last section is characterized by strongly fluctuating carbonate contents as well as greatly varying amounts of planktonic foraminifers and coccoliths. Highest values of carbonate occur to >60 wt%. The highest numbers of planktonic foraminifers range to 50,000 ind/gram; those of coccoliths, as much as $13,000 \times 10^6$/g of sediment. Benthic foraminifers also reach higher numbers, with more than 1000 ind/gram. Percentages of subpolar species coincide with the varying carbonate and total planktonic foraminifer records, whereas the generally high IRD input fluctuates anticyclically with the carbonate measurements.

DISCUSSION

Onset of the Major Northern Hemisphere Glaciation

A comparison of the records plotted to age for the Norwegian Sea and the North Atlantic sites is shown in Figures 7–9. An abrupt decrease in the carbonate contents at Site 985 at 3.05 Ma indicates a distinct change toward severe glacial conditions, probably with a relatively continuous sea-ice cover. This pattern may possibly be interpreted as the culmination of a gradual long-term cooling trend in the Northern Hemisphere with significant intensification of glaciation since ~6 Ma (Jansen and Sjøholm, 1991; Larsen et al., 1994; Fronval and Jansen, 1996). The intensification of the glacial regime occurred almost synchronously in the Iceland Sea (Baumann et al., 1996; Fronval and Jansen, 1996) and possibly documents the influence of an earlier and/or larger Greenland Ice Sheet. However, >125-µm IRD at Site 985 occurs only in relatively small quantities until ~2.5 Ma

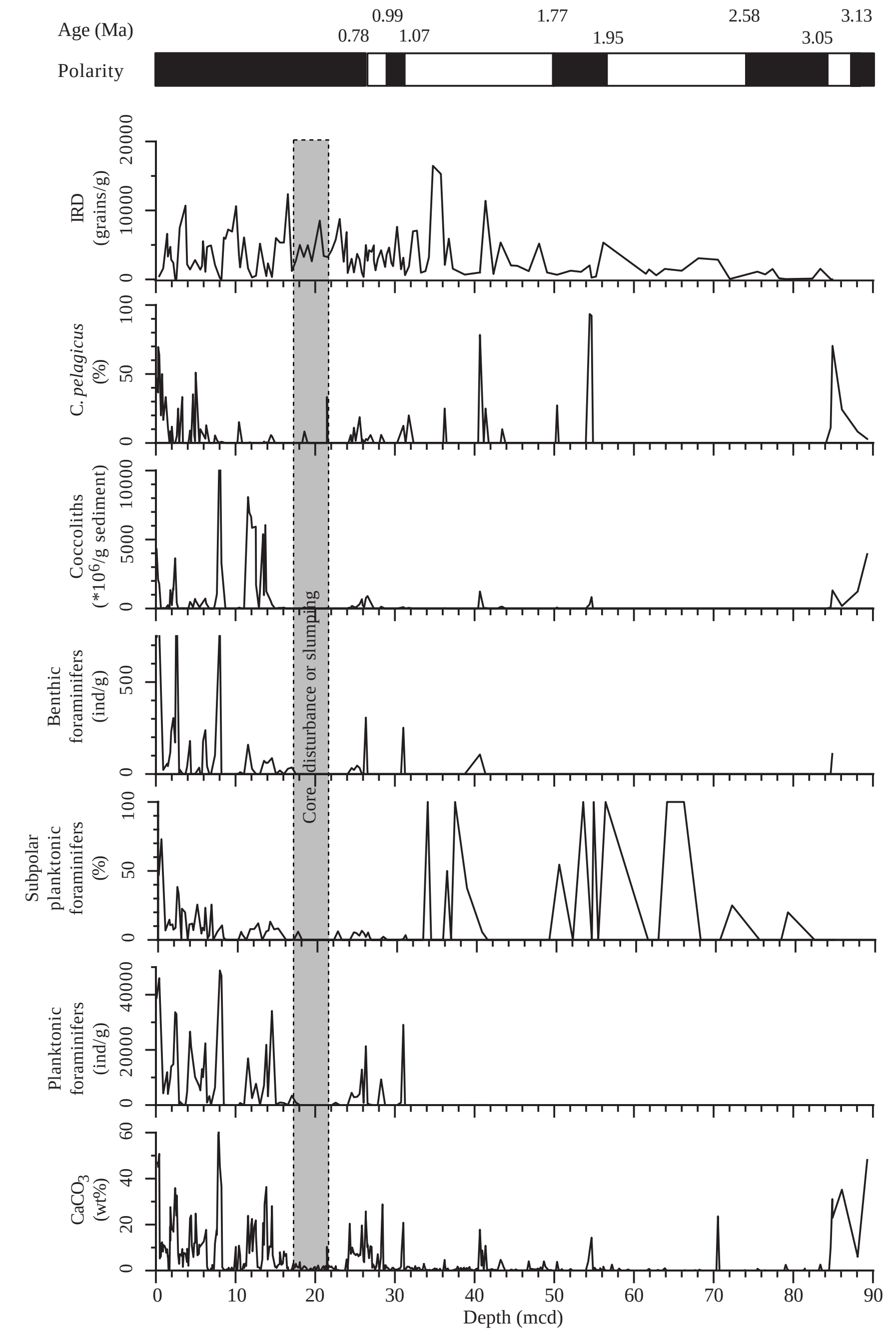

Figure 5. Carbonate, bulk faunal and floral data, and IRD contents for Site 985 plotted to composite sub-bottom depth. Magnetic polarity scale and ages of magnetic reversals are indicated.

(and subsequently). The IRD, however, forms nearly 100% of this size fraction, and the amount of silt-sized particles is >90% throughout most of this interval (Figs. 7, 9). This may have resulted from weak ice rafting and little continental erosion. The major onset of the Scandinavian glaciation occurred somewhat later in comparison with the Greenland Ice Sheet. The Vøring Plateau, which is strongly influenced by the Norwegian Current, initially shows a significant increase in IRD input at 2.75–2.6 Ma (Jansen et al., 1988; Henrich et al., 1989; Wolf and Thiede, 1991). Correspondingly, a sudden and strong decrease in carbonate contents at the Vøring Plateau also occurred at ~2.75 Ma (Baumann et al., 1996).

In comparison, indications of the increased glaciation do not occur in the North Atlantic until 2.8 Ma, the time of a first and significant increase in IRD (Fig. 7). The North Atlantic Drift would probably have turned straight eastward without entering the Norwegian Sea, but heat flux transport to the Rockall Plateau area was not reduced. Besides, between 2.8 and 2.5 Ma, glacial intervals became progressively more drastic as reflected by short but extreme decreases in carbonate contents and numbers of coccoliths (Figs. 7, 8). These findings are in good accord with results of isotope and IRD studies of the North Atlantic (Shackleton et al., 1984; Shackleton and Hall, 1984; Keigwin, 1987; Jansen et al., 1988; Raymo et al., 1989; Raymo, 1994). There is strong evidence for this progressive cooling from the increase in the percentage of cooler living planktonic foraminifers (Loubere and Moss, 1986). Also, Backman et al. (1986) and Backman and Pestiaux (1987) reported both marked variability of warm-adapted discoaster abundances and significantly decreasing accumulation rates of discoasters in Deep Sea Drilling Project (DSDP) Hole 552A before 2.5 Ma. Sea-surface temperature estimates, however, are not easy to reconstruct because the assemblages are not completely analogous to modern faunas (Ruddiman and Raymo, 1988).

In addition, the carbonate curve from Site 982 looks quite similar to those of Sites 552, 607, and 609 (Shackleton et al., 1984; Raymo et al., 1989; Ruddiman et al., 1989). In particular, the high values in

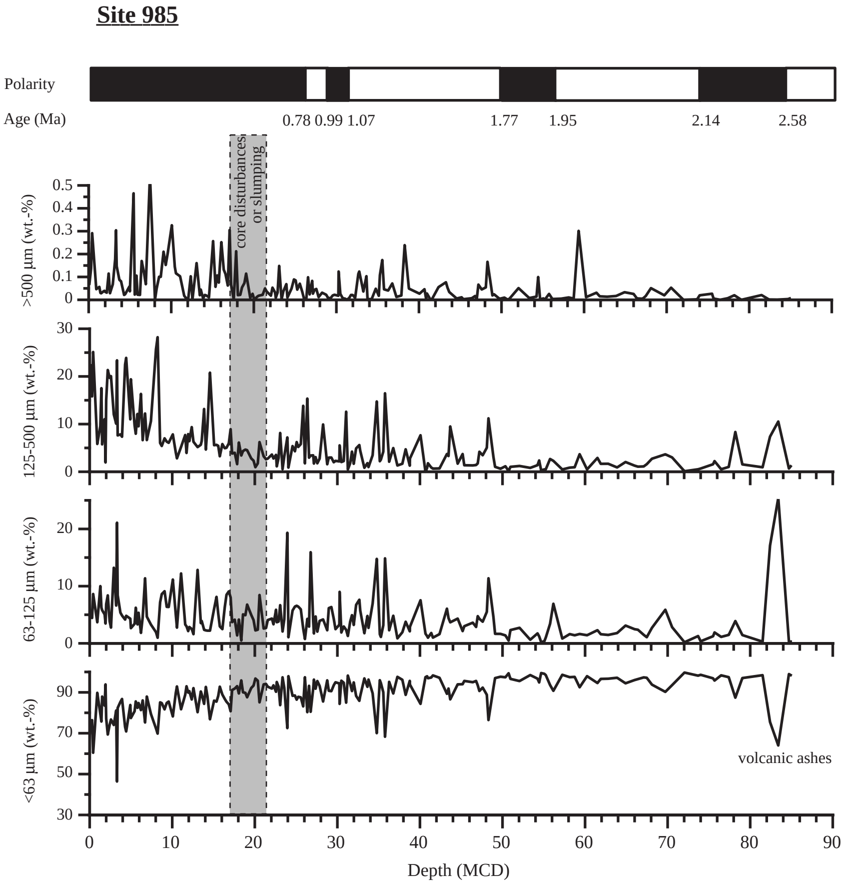

Figure 6. Grain-size data for Site 985 plotted to composite sub-bottom depth. Magnetic polarity scale and ages of magnetic reversals are indicated.

the late Gauss interrupted by small carbonate minima, which are caused by IRD input, can be well correlated between the sites. These short-termed carbonate decreases are not well documented at Sites 552 and 609, probably because significant amounts of sediment are missing at core breaks at these sites (Raymo et al., 1989). Correlation is thus best with Site 607 as well as in the Pleistocene sequences of all sites. These short but synchronous intervals, however, probably reflect progressively increased glacial conditions during the late Gauss.

The causes of the initiation and intensification of the Northern Hemisphere glaciation remain essentially unresolved. This is a very controversial topic and not a basic part of this study. A variety of causes were discussed. These included changes in orbital forcing as well as tectonic explanations, such as the emergence of the Panama Isthmus (e.g., Keigwin, 1982; Keller et al., 1989) or the progressive uplift of the Tibetan-Himalayan regions (Ruddiman and Raymo, 1988; Ruddiman et al., 1989; Ruddiman and Kutzbach, 1991).

Gradients in Sea-Surface Conditions between 2.8 and 1.1 Ma

In the time interval from ~2.8 to 1.1 Ma, very low to zero carbonate production is suggested for the Norwegian Sea. Thus, siliciclastic fine-grained sediments (constantly >90%) and coarse IRD (Fig. 9) characterize most of the sediments of this period. Similar record patterns have also been found at Site 907 on the Iceland Plateau (Baumann et al., 1996; Fronval and Jansen, 1996) although the pattern at Site 644 farther east is slightly different (Baumann et al., 1996). Here, at least periodic intrusions of warmer waters into the easternmost Norwegian Sea were reported by Henrich and Baumann (1994) and Baumann et al. (1996). Nonetheless, only sparse evidence for relatively warm surface-water intrusions can be found at Site 985. Low carbonate contents and numbers of planktonic foraminifers are characteristic for the whole interval. Only at 1.9 and 1.45 Ma do carbonate contents and the total numbers of coccoliths reach higher values. Another indication for Atlantic water inflow during this interval possibly comes from the IRD record. Strong terrigenous input is reported to be restricted to the flanks of the isotope curves, indicating that the occurrence of IRD displays rapid melting after warm periods (Wolf and Thiede, 1991; Baumann et al., 1996). High IRD contents in the period until ~1.1 Ma therefore indicate at least temporary open-water conditions before melting and deposition of ice-rafted material in the Norwegian Sea.

In the North Atlantic, the high carbonate values of the Pliocene are relieved by highly fluctuating carbonate contents since 2.5 Ma and are accompanied by relatively strong IRD peaks. Thus, the cold glacial phases had diminished surface-water productivity but also increased IRD supply. In addition, especially in the interval 2.5–1.65 Ma, colder sea surface-water temperatures in the North Atlantic are indicated by the coccolith assemblage. The numbers of total coccoliths significantly decreased after 2.5 Ma and, contemporaneously, the cold water–adapted species *C. pelagicus* reached very high abundances. The occurrence of *C. pelagicus* could also be controlled by different ecological factors and not by temperature alone. Nonetheless, these findings indicate somewhat similar conditions in the surface waters of the North Atlantic in the interval 2.5–1.65 Ma compared to the sea-surface conditions in the Norwegian Sea during interglacials of the late Pleistocene. This holds true both for numbers of total coccoliths and for relative abundances of *C. pelagicus*. Further evidence comes from biometric analyses of *C. pelagicus* placoliths (Baumann, 1995; Baumann and Meggers, 1996; K.-H. Baumann, unpubl. data). Today, this species is dominant with small-sized placoliths (7–12 µm) in plankton and surface sediments of the Greenland and Iceland Seas (Samtleben et al., 1995). Large placoliths (>10 µm), however, are observed in the northern North Atlantic, which probably indicate unfavorable conditions for *C. pelagicus* (Baumann, 1995). However, during the interval 1.6–2.5 Ma, small-sized placoliths of *C. pelagicus* were also observed in sediments of the north-

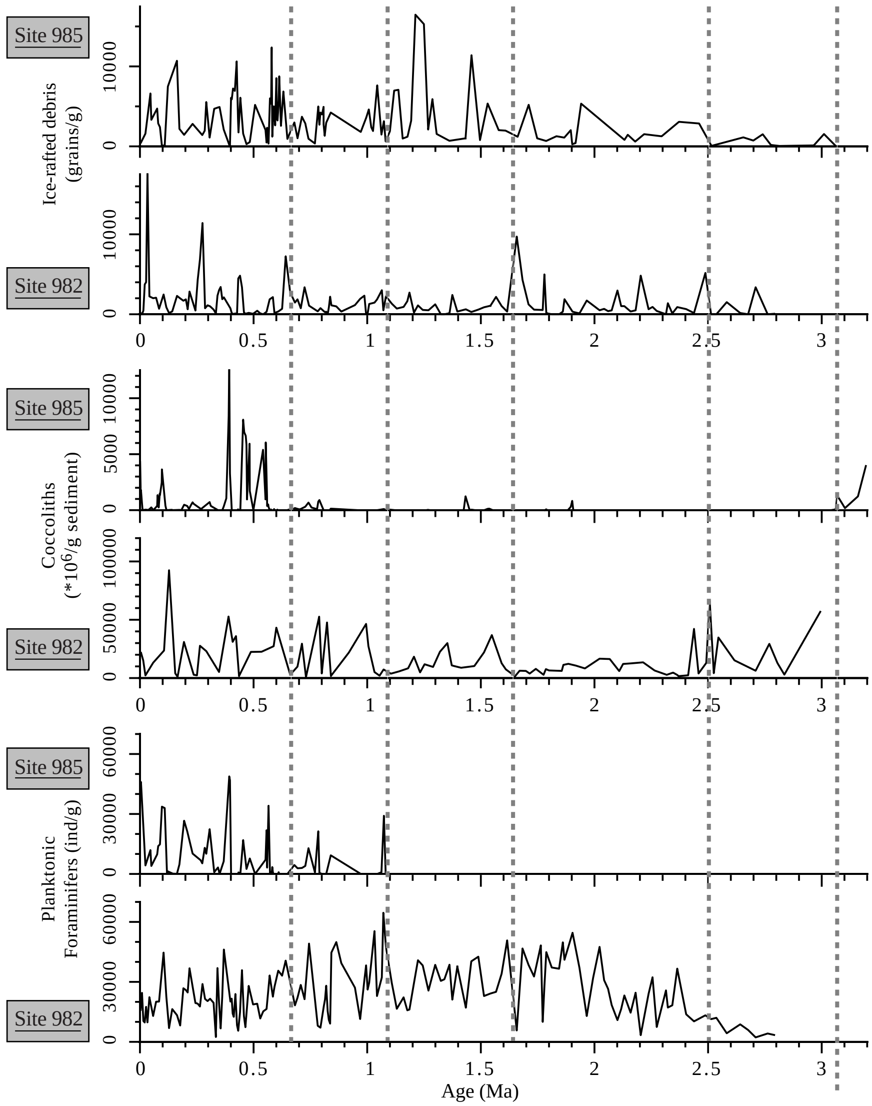

Figure 7. Comparison of planktonic foraminifer, coccolith, and IRD contents between Sites 982 and 985 plotted to the age models described in the text.

ern North Atlantic and of the Labrador Sea (Baumann and Meggers, 1996). Thus, the preferred ecological requirements of this species seem to be stable through the Matuyama and Gauss Chrons.

Colder surface-water conditions in the North Atlantic significantly reduced the potential heat export to the Norwegian Sea. Consequently, carbonate sedimentation in the Norwegian Sea was extremely reduced. The gradient in sea-surface temperature must have been extremely strong, however, and probably no Atlantic water entered the Norwegian Sea. Hence, the circulation type was different from that of the present-day ocean. Jansen et al. (1988) has already proposed a stronger thermal gradient than at present caused by a more zonal circulation system with deflected North Atlantic surface-water currents. In addition, benthic foraminifer $\delta^{13}C$ values (Raymo et al., 1990, 1992; Sikes et al., 1991) show a constantly present but significantly reduced production of northern source deep water. Reduced deep-water formation in the Norwegian Sea must have been coupled to decreased advection and weakened northward flow of Atlantic surface waters. Since the Atlantic surface waters were strongly cooled (Sikes et al., 1991), the resulting low carbonate production in the Norwegian Sea and the persistent glacial conditions are not surprising.

This interval is also characterized by consistently present IRD. Visual inspection of the >500-µm fraction additionally shows the presence of larger dropstones between 2.4 and 2.1 Ma. In the period from 2.5 to 2.1 Ma, Jansen et al. (1989) and Sikes et al. (1991) found surprisingly low-amplitude fluctuations of oxygen isotope records after the glaciation events. Hence, Sikes et al. (1991) concluded that the magnitude of glacial events from 2.5 to 2.1 Ma was no more than one-half or two-thirds of the last Pleistocene glacial. The ice volume was estimated to be less than one-half of Pleistocene glaciation. Despite generally low ice volume, ice rafting as far as into the southern North Atlantic (as documented at Site 607 by Raymo et al., 1989) could be explained by surface waters that have cooled much more in response to Pliocene ice volume changes than in the late Pleistocene (Sikes et al., 1991).

After ~1.65 Ma, the relative IRD input to the North Atlantic decreased significantly (Fig. 9). In addition, total numbers of coccoliths increase, whereas the dominance of the cold water–adapted *C. pelagicus* declines (Figs. 7, 8). Thus, a considerable warming of the surface waters in the North Atlantic during interglacials is indicated after 1.65 Ma. In the easternmost Norwegian Sea, an appreciable warming occurred synchronously during short interglacial-like phases (Henrich and Baumann, 1994; Baumann et al., 1996). As shown by these data, however, the interval from 1.65 to 1.1 Ma seems to be glacial-dominated north of the Iceland-Faeroe Ridge, in strong contrast to the high potential heat export of the North Atlantic recorded in high carbonate contents during interglacials. Jansen et al. (1988) and Henrich and Baumann (1994) explained low carbonate contents in the Norwe-

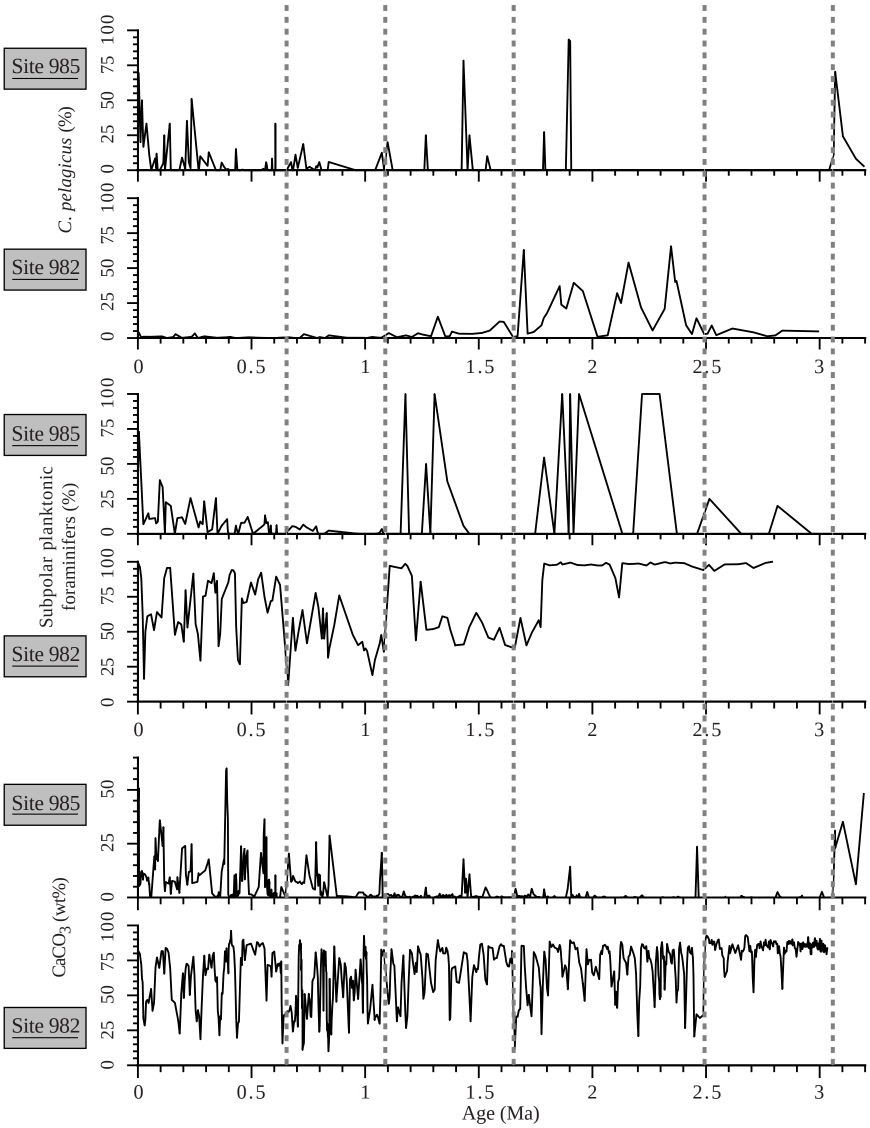

Figure 8. Comparison of bulk carbonate data, amount of subpolar planktonic foraminifers, and abundance of cold water–adapted *Coccolithus pelagicus* between Sites 982 and 985 plotted to the age models described in the text.

gian Sea in this interval with dissolution as a result of low carbonate productivity and decreased deep-water ventilation. More recent investigations at Iceland and Norwegian Sea Sites 907 and 644 (Baumann et al., 1996) have revealed high carbonate contents and a relatively high abundance of planktonic foraminifers on the Vøring Plateau (Site 644) in contrast to significantly diminished carbonate production in the Iceland Sea (Site 907). Such an extreme gradient could possibly be explained by extensive sea-ice cover and an extremely eastward-situated polar front between Sites 644 and 643, as earlier proposed by Henrich and Baumann (1994). On the other hand, ice-rafted material on the Iceland Plateau (Baumann et al., 1996) and at Site 985 reflects occasional melting and thus warming.

An explanation for these extreme south-north and east-west gradients in carbonate sedimentation could be given by faunal data. In the North Atlantic, *N. pachyderma* sin. is described to have first appeared 1.8 m.y. ago. The observed decrease in subpolar foraminifer numbers at Site 982 between 1.8 and 1.2 Ma, thus, would indicate cooling in contrast to the previously explained trend toward warmer surface water conditions, as reflected by coccolith assemblages. Raymo et al. (1987), however, showed 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 to 1.2 Ma and recurred at 1.2 to 1.1 Ma with the mid-Pleistocene transition (Ruddiman et al., 1986). Other authors, however, suggested that *N. pachyderma* sin. did not attain its role as a cold-water indicator before 0.9 Ma (Ruddiman et al., 1986; Jansen et al., 1988). Biometric analysis of this species clearly indicated an increase in the maximum diameter of *N. pachyderma* sin. after 1.1 Ma, which is most likely related to a better adaptation to a polar habitat (Baumann and Meggers, 1996). Additionally, factor analysis showed that *N. pachyderma* sin. was first a polar indicator at 1.1 Ma (Meggers, 1996; Meggers and Baumann, 1997). In conclusion, this might be an important reason for the little faunal response to a possible sea-surface heat export from the North Atlantic to the Norwegian Sea, especially between 1.85 and 1.35 Ma. Except for the cold water–adapted *C. pelagicus*, there was no other polar-adapted carbonate secreting species and thus only limited (coccolith) carbonate accumulation.

Gradients in Sea-Surface Conditions during the Last 1.1 m.y.

For the last 1.1 m.y., a strong reaction of the Norwegian Sea carbonate production to heat export from the North Atlantic is obvious roughly each 100 k.y. During this time, the periodicity in the variation of the ice-sheet volume increased from a 41-k.y. to a 100-k.y. periodicity (Ruddiman et al., 1986, 1989; Raymo, 1992; Imbrie et al.,

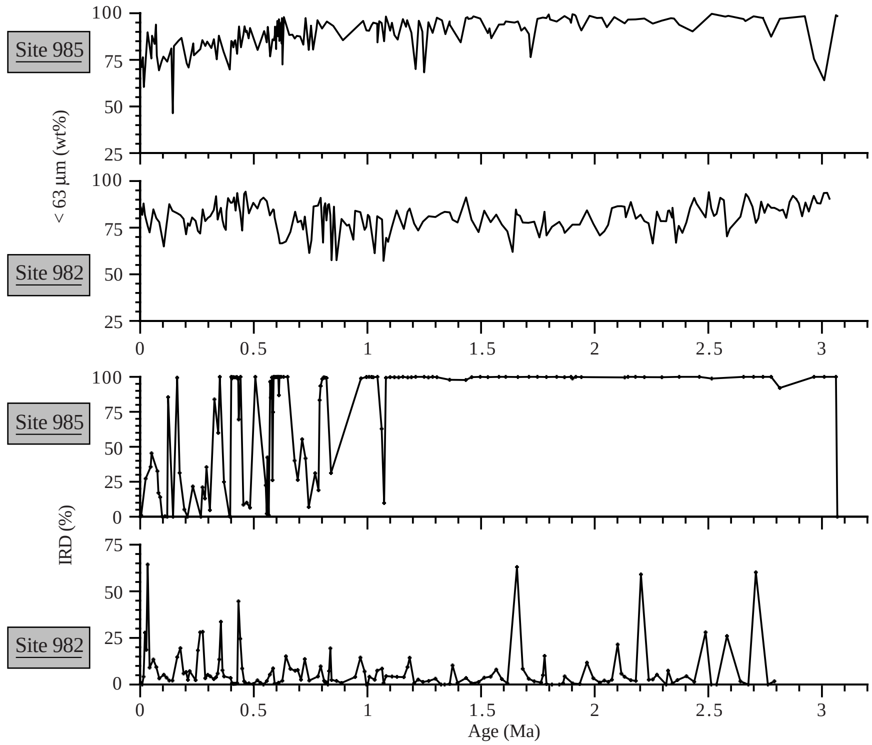

Figure 9. Comparison of IRD contents and <63 µm between Sites 982 and 985 plotted to the age models described in the text.

1993; Berger and Jansen, 1994). The gradient between the two observed sites, however, is strong. A comparison of the carbonate maxima of the two sites shows differences of 30–55 wt%. North Atlantic carbonate records are strongly influenced by varying productivity and IRD dilution (Ruddiman et al., 1986; Raymo et al., 1989), caused by ice-sheet control on sea-surface temperature. High carbonate productivity fluctuations in the Norwegian Sea were probably caused by variations in the intensity and extension of warm Atlantic water inflow (Henrich, 1989). In general, a somehow synchronous development of carbonate sedimentation between the Norwegian Sea and the North Atlantic can be observed during the last 1.1 m.y., which became more pronounced during the last 0.65 m.y. Strong gradients in surface-water temperatures existed, however, reflected by much lower carbonate contents and lower percentages of subpolar planktonic foraminifer species at Site 985 compared with Site 982.

A striking difference between the Norwegian Sea and the North Atlantic sites can also be observed in the composition of the planktonic foraminifer assemblages. At Site 985, the total abundance of planktonic foraminifers generally mirrors the shape of the carbonate record; this does not happen at Site 982 (Fig. 10). This difference may be explained by the fact that the cold water–adapted *N. pachyderma* sin. contributes as much as 80% of the total planktonic foraminifer assemblage in the North Atlantic during glacials. As a result, many planktonic foraminifers appear in glacials as well as in interglacials, whereas in the Norwegian Sea planktonic foraminifers reach high numbers only during interglacials. High abundances of polar foraminifers in the North Atlantic, however, should be restricted to glacials, where they found optimal environmental conditions. This is partly confirmed by the strong relationship between the carbonate record and subpolar foraminifer abundance in the youngest section until 0.65 Ma, when a highly significant correlation ($r^2 = 0.62$) occurs (Fig. 10). In contrast, in the interval older than 0.6 Ma this relationship is strongly weakened, and the correlation coefficient is close to zero ($r^2 = 0.001$). This also supports the previously discussed ecological meaning of *N. pachyderma* sin., which did not have a clear cold-water preference and cannot be considered as a polar-adapted species before ~0.65–0.8 Ma. In addition, these data confirm the general conclusion of Meggers and Baumann (1997) that a change in the life habitat of *N. pachyderma* sin. occurred. The optimum adaptation of the species to the polar environment, however, seems to have happened after ~1.1 Ma. As indicated by regression analysis, *N. pachyderma* sin. reached its optimum adaptation at ~0.65 Ma.

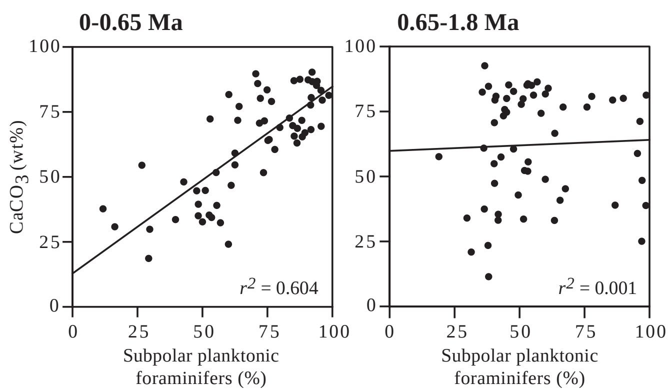

Figure 10. Relationship between carbonate record and subpolar foraminifer abundances in the intervals 0–0.65 and 0.65–1.8 Ma.

During the past 0.65 Ma, highest amplitude oscillations in biogenic carbonate records can be seen in the Norwegian Sea. This indicates that short but warm interglacials with presumably intensive deep-water formation occurred between relatively long-lasting glacials characterized by high inputs of IRD. It is known that the rates of ice decay are clearly faster than the rates of ice growth during the last 0.65 m.y. (Ruddiman et al., 1986; Raymo, 1992). Significant Atlantic water intrusions, especially during interglacials, reached far up into the Fram Strait (Baumann et al., 1996; Hevrøy et al., 1996). Hence, the surface circulation pattern probably occurred with only minor variations during the interglacials of the late Pleistocene. In addition, planktonic isotope data document the fact that glacial periods became colder and more pronounced (Fronval and Jansen, 1996). Carbonate preservation further improved, during both glacials and interglacials (Henrich and Baumann, 1994). Hence, continuous formation of

North Atlantic deep water may have also occurred during glacials. A major precondition is sufficient salt supply by temperate Atlantic surface-water intrusions (e.g., Hebbeln et al., 1994).

CONCLUSIONS

In general, carbonate sedimentation in the Norwegian Sea is closely related to heat export from the North Atlantic. However, a strong front between the North Atlantic and the Norwegian Sea was present throughout most of the last 3.1 m.y. Thus, the circulation type was different from that of the late Pleistocene interglacials, without extending into the Norwegian Sea.

The onset of major Northern Hemisphere glaciation was time-transgressive between the studied sites. In the North Atlantic, a first drop in carbonate coeval with an increase in IRD was observed at 2.8 Ma, although the interval since ~2.5 Ma was dominated by carbonate sedimentation. In contrast, at Site 985 glacial conditions (most likely with discontinuous sea-ice cover) occurred as early as 3.05 Ma and lasted until ~1.1 Ma.

At Site 982, long-term cooling culminated at 2.5 Ma, leading to a more glacial-dominated period until 1.65 Ma. In this interval, heat export from the North Atlantic to the Norwegian Sea was possibly restricted by cold surface temperatures of the North Atlantic. Increased northward penetrations of relatively warm Atlantic water to the Norwegian Sea were restricted to short phases at ~1.9 and 1.4 Ma.

In addition, the faunal response to sea-surface heat import from the North Atlantic was weak; thus, only limited production of carbonate was possible. A stepwise adaptation of *N. pachyderma* sin. to the polar environment from 1.1 to 0.65 Ma increased carbonate production. The optimum adaptation of *N. pachyderma* sin. after 0.65 Ma leads to enhanced carbonate production, reflecting the intensity of heat import from the North Atlantic, especially during interglacials.

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