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Rapid changes in surface and deep water conditions at the Faeroe Margin during the last 58,000 years

Tine L. Rasmussen,¹ Erik Thomsen,² Tjeerd C.E. van Weering,³ and Laurent Labeyrie⁴

Abstract. A high-resolution piston core, ENAM93-21, from a water depth of 1020 m near the Faeroe-Shetland Channel is investigated for variations in magnetic susceptibility, surface oxygen isotopes, grain size distribution, content of ice-rafted detritus (IRD), and distribution of planktonic and benthic foraminifera. The core, covering the last 58,000 years, is correlated with the Greenland ice cores and compared with paleorecords from the Norwegian Sea and the North Atlantic Ocean. All fifteen Dansgaard-Oeschger climatic cycles recognized from the investigated time period in the Greenland ice cores have been identified in the ENAM93-21 core. Each cycle is subdivided into three intervals on the basis of characteristic benthic and planktonic faunas. Interstadial intervals contain a relatively warm planktonic fauna and a benthic fauna similar to the modern fauna in the Norwegian Sea. This indicates thermohaline convection as at present, with a significant contribution of deep water to the North Atlantic Deep Water (NADW). Transitional cooling intervals are characterized by more cold water planktonic foraminifera and ice-related benthic species. The benthic fauna signifies restricted bottom water conditions and a reduced contribution to the NADW. The peak abundance of *N. pachyderma* (s.) and the coldest surface water conditions are found in the stadial intervals. The benthic fauna is dominated by species with an association to Atlantic Intermediate Water, suggesting an increased Atlantic influence in the Norwegian Sea, and there was probably no contribution to the NADW through the Faeroe-Shetland Channel. The three different modes of circulation can be correlated to paleoceanographic events in the Norwegian Sea and the North Atlantic Ocean.

Introduction

In the North Atlantic Ocean and the Norwegian-Greenland Seas a direct relation exists between ocean circulation and climate. Warm saline Atlantic surface water flows from the Atlantic Ocean via the Faeroe-Shetland Channel into the Norwegian Sea, where it cools and sinks during the winter, releasing heat to the atmosphere. The inflow of Atlantic surface water is vital for the mild winter climate of northwest Europe.

The deep water generated flows south through the Denmark Strait, across the Iceland-Scotland Ridge, and through the Faeroe-Shetland Channel. It contributes to the formation of the North Atlantic Deep Water (NADW), which forms part of the global circulation system [Gordon, 1986; Broecker, 1987, 1991]. The Faeroe-Shetland Channel is the main gate-

way between the North Atlantic Ocean and the Norwegian-Greenland Seas [Dooley and Meincke, 1981; Hopkins, 1991]. The present circulation pattern, which has been operating since the end of the last deglaciation 9,000-10,000 years ago [Koç Karpuz and Jansen, 1992; Sarnthein et al., 1994, 1995], is apparently very different from the unstable pattern of the foregoing glacial period [Duplessy et al., 1988, 1992, 1993; Duplessy and Labeyrie, 1994; Labeyrie and Duplessy, 1985; Labeyrie et al., 1987, 1992; Veum et al., 1992; Sarnthein et al., 1994, 1995].

The last glacial maximum (LGM) marked the culmination of an orbitally controlled cooling trend [Hays et al., 1976; Imbrie et al., 1984; Imbrie et al., 1992] with increasing ice volume on the continents. Superposed on the general cooling trend were numerous rapid climatic oscillations on a millennial scale. These oscillations were first described from the Greenland ice cores by Dansgaard et al. [1982] and Johnsen et al. [1992], and they are often called Dansgaard-Oeschger cycles [Broecker and Denton, 1989; Broecker et al., 1990]. Broecker et al. [1985, 1990], Broecker and Denton [1989], Birchfield and Broecker [1990], and Broecker [1991] have proposed that the oscillations can be explained by changes in the mode of operation of the circulation system in the Norwegian-Greenland Seas and the North Atlantic Ocean. The models involve a change in position of convection sites [Broecker, 1991; Rahmstorf, 1994, 1995].

Fluctuations in the abundance of planktonic faunas and in the composition of surface isotopes during the last glacial

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period have been described by Koç Karpuz and Jansen [1992], Bond et al. [1993], Bond and Lotti [1995], Fronval et al. [1995], and Hafliðason et al. [1995]. The fluctuations are associated with changes in the surface circulation in the North Atlantic Ocean and the Norwegian Sea and are correlated with Dansgaard-Oeschger cycles in the Greenland ice cores. Changes in deep-sea sedimentation and possible changes in deep water circulation have been discussed by Streeter and Shackleton [1979], Schnitker [1980, 1982], Jansen et al. [1983], Jansen and Erlenkeuser [1985], Jansen and Veum [1990], Boyle and Rosener [1990], Veum et al. [1992], Sarnthein et al. [1994], Keigwin and Lehman [1994], and Labeyrie et al. [1995]. In the North Atlantic Ocean Oppo and Lehman [1995] were able to show that the influence of NADW was reduced in cold periods during the last glaciation. Reduced deep water circulation has also been suggested for the Younger Dryas cold event [Boyle and Keigwin, 1987; Keigwin et al. 1991; Lehman and Keigwin, 1992; Labeyrie et al., 1992; Duplessy et al., 1993].

The Dansgaard-Oeschger cycles appear in larger 7,000- to 10,000-year cycles of successively colder intervals culminating with Heinrich events [Bond et al., 1993]. Heinrich events are deposits rich in ice-rafted detritus (IRD). They are related to collapses of the Laurentide Ice Sheet releasing numerous icebergs into the North Atlantic [Ruddiman, 1977; Ruddiman and McIntyre, 1981; Heinrich, 1988; Bond et al., 1992, 1993; Bond and Lotti, 1995; Broecker et al., 1992, Broecker, 1994; Grousset et al., 1993].

This study focuses on a high-resolution sedimentary record from the margin of the Faeroe-Shetland Channel in order to reconstruct the paleoceanography of the area and establish a correlation with the Greenland temperature record. The site was chosen because the Faeroe-Shetland Channel forms a major connection between the North Atlantic and the Norwegian Sea (Figure 1).

The study is based on investigations of planktonic and benthic foraminifera, foraminiferal oxygen isotopes, grain size distribution, and magnetic susceptibility. The results are discussed in relationship to paleorecords from the Norwegian Sea and the North Atlantic Ocean, as well as to records of previously investigated cores from the Faeroe-Shetland Channel area [Rasmussen et al., 1996].

Material and Methods

The results presented below are based mainly on a study of an 11-m-long piston core, ENAM93-21, taken at a water depth of 1020 m on the continental margin northeast of the Faeroe Islands (Figure 1)¹.

Magnetic susceptibility was measured manually at intervals of 5 cm with a Bartington magnetometer before opening the core. The core was opened, split, and subsampled at 5-cm intervals, taking samples with fixed volumes of 6 cm³

¹ Supporting data are available on diskette or via Anonymous FTP from kosmos.agu.org, directory APEND (Username=anonymous, Password=guest). Diskette may be ordered from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009 or by phone at 800-966-2481; \$15.00. Payment must accompany order.

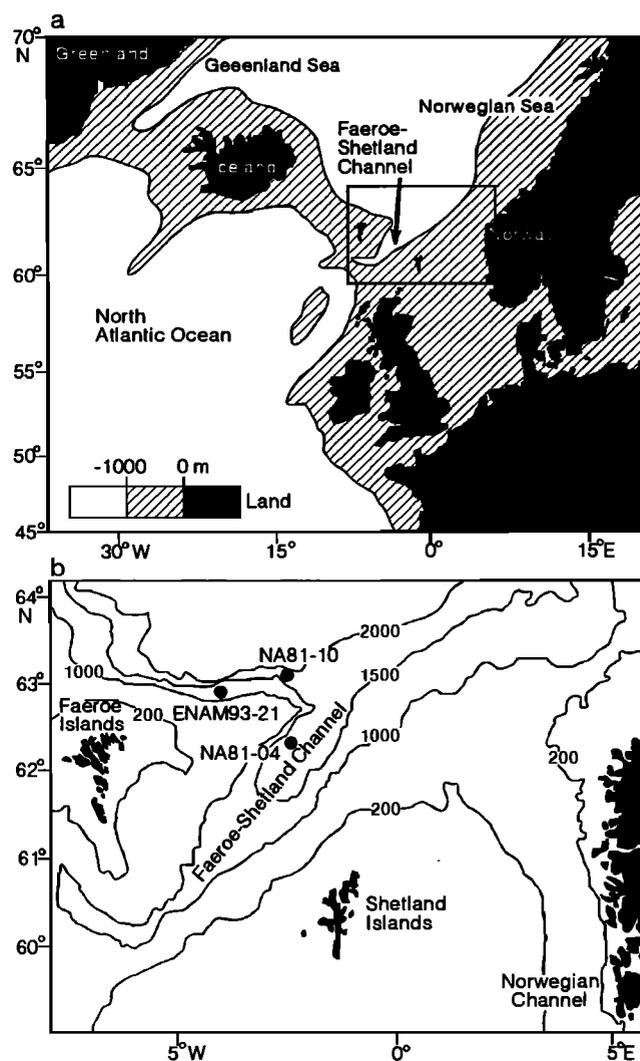


Figure 1. (a) Map of the North Atlantic Ocean and the Norwegian Sea showing the Scotland-Iceland-Greenland Ridge and location of study area. (b) Map of the Faeroe-Shetland Channel and the Faeroe Margin showing the bathymetry of the Faeroe-Shetland Channel and position of investigated cores.

each. Samples were washed through sieves with mesh sizes of 0.1 mm and 0.063 mm. The grain size of the sediment was measured as the weight of the residue larger than 0.1 mm and 0.063 mm. The content of ice-rafted detritus was measured as the weight of the 0.5- to 5-mm fraction. This fraction was chosen in order to exclude foraminifera.

Approximately 300 benthic and 150-300 planktonic foraminifera were picked from the 0.1-mm fraction and identified. However, in a few samples, it was only possible to obtain about 150 benthic specimens. Absolute abundances were calculated as the number of specimens per cubic centimeter of wet sediment. Relative abundances in percentage were calculated within each group separately. Selected samples were ¹⁴C dated by accelerator mass spectrometry (AMS). Oxygen isotopic ratios of *Neogloboquadrina pachyderma* (sinistral) (expressed as δ¹⁸O versus Pee

Dee belemnite (PDB)) were measured on an automated carbonate reaction line coupled to a Finnigan MAT 251 mass spectrometer. The external reproducibility of powdered carbonate standards is $\pm 0.05\%$. Data are reported using as a reference NBS-19 $\delta^{18}\text{O}$ of -2.20% versus PDB.

Magnetic Susceptibility and Lithology of the ENAM93-21 Core

The magnetic susceptibility curve of the ENAM93-21 core shows a characteristic asymmetrical sawtooth pattern (Figures 2, 3, and 4). The increases in magnetic susceptibility are mostly abrupt, while the decreases are typically more gradual (Figures 4c and d).

The content of calcium carbonate varies opposite to the magnetic susceptibility, although sometimes with a slight offset (Figure 2). The magnetic susceptibility values are also closely linked with the grain size distribution (Figure 2). Intervals with low magnetic susceptibility readings are fine grained, composed mainly of clay- and silt-sized material, whereas intervals with high readings are more coarse grained with a higher proportion of particles in the 0.063- to 0.1-mm fraction (very fine sand). The sand-sized material consists mainly of grains of basalt. The clayey and silty intervals may contain thin layers of IRD with sand and gravel-sized particles (Figure 2). The IRD consist mostly of quartz, but grains of chalk and limestone are also present.

The sandy intervals with high magnetic susceptibility readings and a low content of calcium carbonate are generally dark, olive green. The more fine grained intervals with low

magnetic susceptibility and a higher content of calcium carbonate appear as light, grey-brown.

Stratigraphy and Age Control

The position of ash I near the top of the core and of ash II near the bottom frames the investigated interval (Figure 3e). Ash I is dated at 10.6-10.3 ka by Mangerud et al. [1984] and Bard et al. [1994]. Ash II is dated at approximately 55 ka by Ruddiman and Glover [1972] (Table 1).

The $\delta^{18}\text{O}$ record for ENAM93-21 was compared with the $\delta^{18}\text{O}$ record for deep-sea core ODP609 from the North Atlantic Ocean (Figure 3) [Bond et al., 1992, 1993]. We have identified Heinrich events H5-H1 in the ENAM93-21 core by the very pronounced light oxygen isotope values, in combination with an increase in the relative abundance of *N. pachyderma* (sinistral) and a higher content of IRD. Note that the Heinrich events and the high relative abundances of *N. pachyderma* (s.) correlate with intervals of low magnetic susceptibility.

In addition to the ages of ash I and II, ages have been obtained for seven events in the ENAM93-21 core (Table 1). Four samples from the upper part of the core have been dated by AMS ^{14}C (Figure 3e, Table 1). Termination IA [Duplessy et al., 1981] is dated to 15.5-13.24 kyr. The Bølling-Allerød interstadial complex is framed by an ^{14}C date of 13.24 ka and the Younger Dryas ash I. The ages of Heinrich events 3 and 4 are from the North Atlantic timescale [Bond et al., 1992, 1993].

The ages of other events were calculated by interpolation assuming a constant sedimentation rate between dating

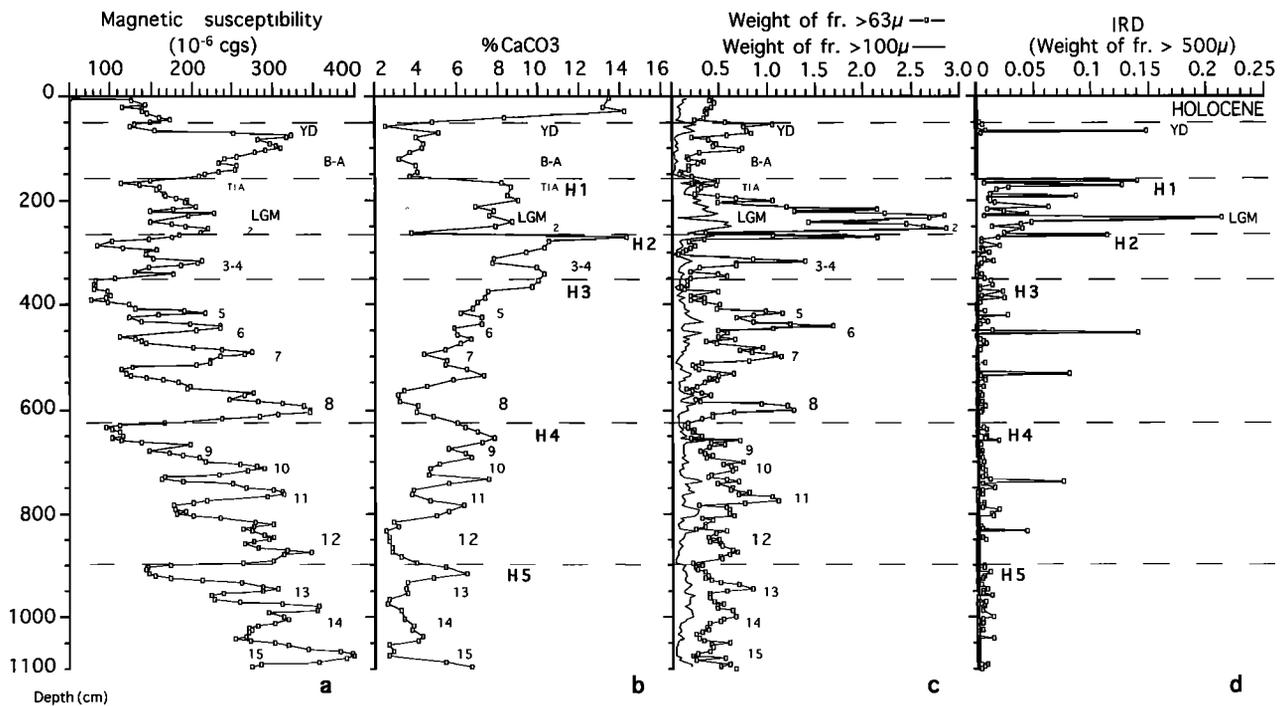


Figure 2. (a) Magnetic susceptibility, (b) percentage of calcium carbonate, (c) grain size distribution, and (d) amount of ice-rafterd detritus (IRD) for ENAM93-21. Position of Heinrich events H5-H1 and interstadials (Dansgaard-Oeschger cycles) are indicated (see Figure 4). Horizontal dashed lines show boundaries between Bond cycles.

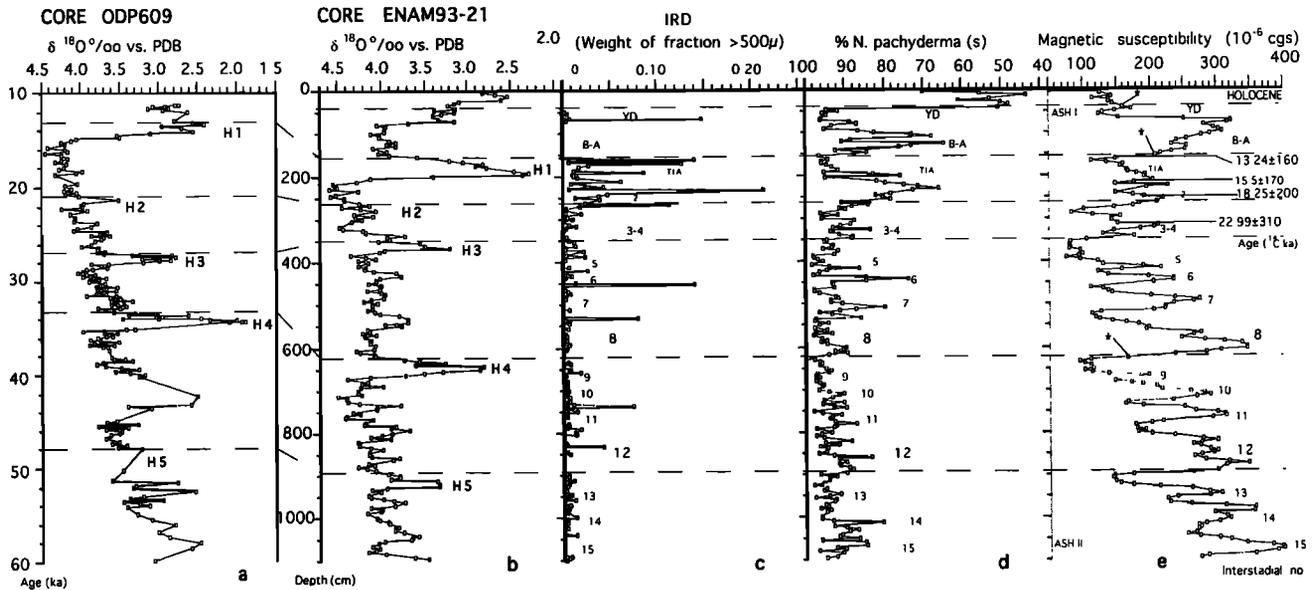


Figure 3. Comparison of (a) $\delta^{18}\text{O}$ of planktonic foraminifera *N. pachyderma* (s.) for deep-sea core ODP609 [Bond et al., 1992, 1993] with (b) $\delta^{18}\text{O}$ of *N. pachyderma* (s.), (c) IRD, (d) percentage of *N. pachyderma* (s.), and (e) magnetic susceptibility record, for core ENAM93-21. Position of Heinrich events H5-H1 and interstadials (Dansgaard-Oeschger cycles) are indicated (see Figure 4). Horizontal dashed lines show boundaries between Bond cycles. The position of ash layers and ^{14}C datings in the ENAM93-21 core are indicated.

points. The sedimentation rate is about 24 cm/kyr in the lower part of the core. It decreases from H3 to H2 and in the LGM interval to about 14 cm/kyr. It is again higher from termination IA to the beginning of the Holocene (30 cm/kyr).

Correlation With the Greenland Ice Cores

The configuration of the magnetic susceptibility curve of the ENAM93-21 core is very similar to the configuration of the $\delta^{18}\text{O}$ curve from the equivalent parts in the Greenland GRIP (Greenland Ice-core Project) and GISP2 (Greenland Ice Sheet Project 2) ice cores (Figure 4) [Johnsen et al., 1992; Dansgaard et al., 1993; Grootes et al., 1993].

The shorter cycles in ENAM93-21 appear in larger cycles with progressively lower magnetic susceptibility. Each of these larger cycles ends with a minimum magnetic susceptibility record correlating with a Heinrich event (Figure 3). The larger cycles resemble the Bond cycles in the ice core [Lehman, 1993; Broecker, 1994], i.e. successively smaller $\delta^{18}\text{O}$ cycles bundled into 7,000- to 10,000-year cycles [Bond et al., 1993].

The $\delta^{18}\text{O}$ cycles in the ice cores, the so-called Dansgaard-Oeschger cycles, are related to temperature fluctuations. Each of the Dansgaard-Oeschger cycles begins with an abrupt increase in temperature [Johnsen et al., 1992; Dansgaard et al., 1993]. After a relatively shortlasting maximum in the early part of the cycle (the interstadial), a period with gradually decreasing temperatures follows, and the cycle ends with a very cold period (the stadial). The magnetic susceptibility

cycles in the ENAM93-21 core follow a similar pattern, with a sharp increase to a maximum value in the lower part of the cycles followed by a gradual decrease to a minimum in the upper part (Figure 4).

The numbering of the interstadials in the GRIP ice core [Dansgaard et al., 1993] and the correlation of the ice core with the ENAM93-21 core is shown in Figure 4. The lower part of the investigated interval from interstadial 15 to interstadial 3 is easily correlated. The correlation is less straightforward from interstadial 3 to the end of the LGM (between 23 and 16 kyr), and this interval will only be briefly considered in the present paper. We note also that interstadial 14 and the Bølling-Allerød interstadial complex differ from the other interstadials by showing lower values of magnetic susceptibility instead of higher (Figure 4).

The close correlation of the magnetic susceptibility cycles in the ENAM93-21 core with the Dansgaard-Oeschger cycles in the Greenland ice cores allows us to use the Dansgaard-Oeschger temperature cycles as the basal stratigraphic and paleoclimatic framework for the interpretations of the faunistic data presented below. Thus each of the cycles in the ENAM93-21 core is subdivided into an interstadial interval, a transitional cooling interval, and a stadial interval.

Distribution of Foraminifera

Abundance and Preservation

The absolute abundance of benthic foraminifera is high in the Holocene and in most of the interstadials and low in the

Table 1. Position of Heinrich Events, Dansgaard-Oeschger Interstadial Events, Diatom Layers, and Ash Layers in Core ENAM93-21

Event/Period	Depth in core, cm		Age, ka	Dated interval cm
	Bottom	Top		
Holocene	40	0	-	-
Diatom layer	45	40	-	-
Younger Dryas	70	45	-	-
Ash layer I	60	50	10.3-10.6*	-
Allerød	110	75	-	-
Bølling	155	125	-	-
Diatom layer	160	150	13.24±160†	160.5-159.5
Heinrich event H1	195	155	-	-
Transition H1-LGM	215	200	15.5±170†	215.5-214.5
Last glacial maximum	250	220	18.25±200†	245.5-244.5
D-O interstadial 2	270	250	-	-
Heinrich event H2	300	270	-	-
D-O interstadial 3	325	305	22.99±310†	310.5-309.5
D-O interstadial 4	350	345	-	-
Heinrich event H3	400	355	26.0‡	-
D-O interstadial 5	420	405	-	-
D-O interstadial 6	450	435	-	-
D-O interstadial 7	515	480	-	-
D-O interstadial 8	620	545	-	-
Heinrich event H4	665	625	35.2-33.5‡	-
D-O interstadial 9	685	670	-	-
D-O interstadial 10	725	700	-	-
D-O interstadial 11	785	745	-	-
D-O interstadial 12	895	815	-	-
Heinrich event H5	930	895	-	-
D-O interstadial 13	955	930	-	-
D-O interstadial 14	1035	975	-	-
Ash layer II	1070	1055	55§	-
D-O interstadial 15	1085	1050	-	-

D-O, Dansgaard-Oeschger.

* From Mangerud *et al.* [1984] and Bard *et al.* [1994].

† Accelerator mass spectrometry ¹⁴C dates measured on *N. pachyderma* (s.) and corrected for a 400-year reservoir.

‡ From Bond *et al.* [1992, 1993] and Labeyrie *et al.* [1995].

§ From Ruddiman and Glover [1972].

stadials (Figure 5). The absolute abundance of planktonic foraminifera is, in contrast, highest in the stadials.

The planktonic/benthic ratio (P:B ratio) is generally high in the stadials (Figure 5), although exceptions are found from H3 to the end of the LGM (28-16 kyr). In the interstadial intervals and in the Holocene the P:B ratio is around 1.

The preservation of the foraminifera is mostly very good in the stadials with high concentrations of planktonic foraminifera. Numerous small transparent specimens are preserved. In the interstadials and in the Holocene the preservation is only moderate, with a slight etching of most of the specimens and a tendency toward increased pore size in the planktonic forms. The transitional cooling intervals are generally poor in foraminifera. The preservation of the planktonic forms varies, ranging from heavily corroded and fragmented individuals to well-preserved and transparent specimens. The benthic forms are mostly better preserved than the planktonic, and the very low P:B ratios (0.3-0.7) found in these intervals may in some cases be due to preferential dissolution of planktonic specimens.

Relative Abundance of Benthic Species

Nonion zaandamae, *Cassidulina teretis*, *Elphidium excavatum*, *Stainforthia fusiformis*, and *Epistominella vitrea* are widespread throughout the ENAM93-21 core. *Pullenia bulloides* and a group of "Atlantic species" comprising *Sigmoilopsis schlumbergeri*, *Eggerella bradyi*, and *Epistominella decorata/Alabaminella weddellensis* are also ubiquitously present (Figures 6, 7, and 8).

The most distinct overall tendency in the distribution of the benthic species is a decrease in the relative abundance of *N. zaandamae* from interstadial 15 to the top of termination IA (58-13 kyr) (Figure 6b). It increases again abruptly at the base of the Bølling interstadial and at the base of the Holocene.

The relative abundance of *N. zaandamae* is closely correlated with the interstadial-stadial climatic cycles. It is relatively common in the interstadials and rare in the stadials. *N. zaandamae* cooccurs with *E. vitrea* and/or *S. fusiformis* (Figures 7b and c).

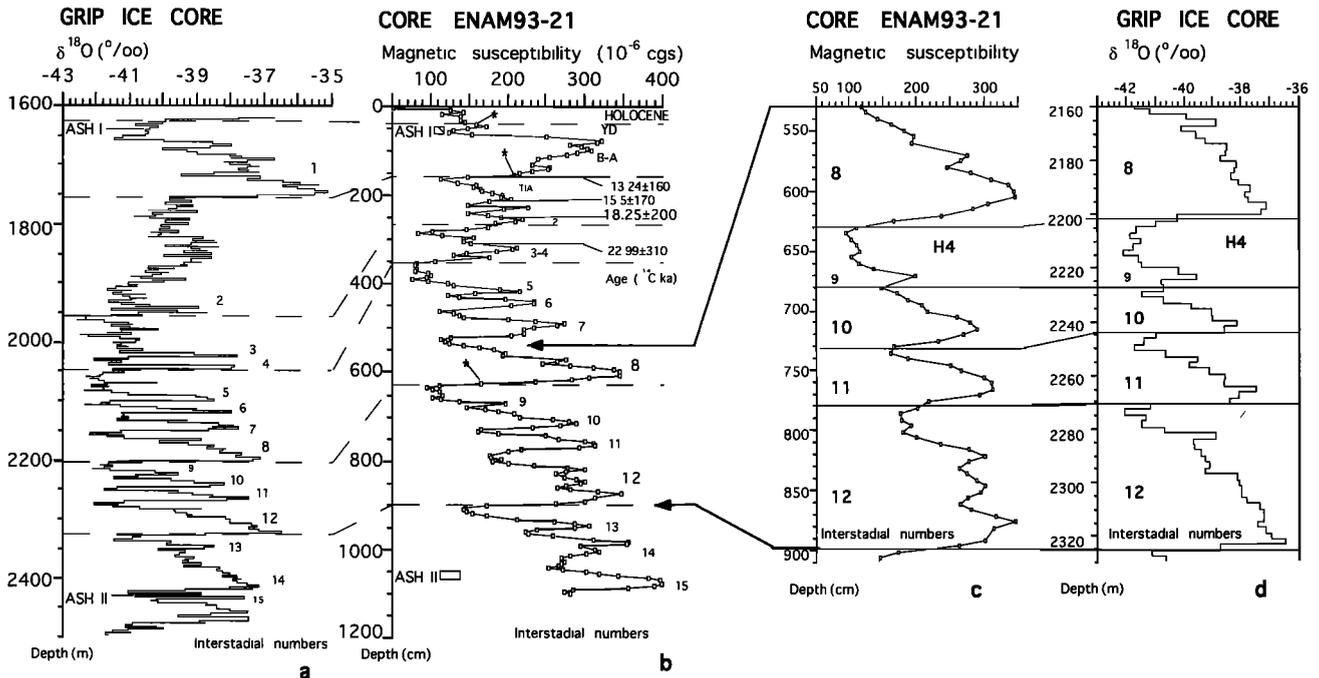


Figure 4. Comparison of (a) $\delta^{18}\text{O}$ record for the GRIP (Greenland Ice-core Project) ice core with (b) magnetic susceptibility record for the ENAM93-21 core. Positions of interstadials (Dansgaard-Oeschger cycles) are indicated. Horizontal dashed lines show boundaries between Bond cycles. The position of ash layers I and II in the GRIP core is from *Grønbold et al.* [1995]. Figures 4c and 4d are details of Figures 4a and 4b, respectively, showing the $\delta^{18}\text{O}$ record and the magnetic susceptibility record of Dansgaard-Oeschger cycles 8-12.

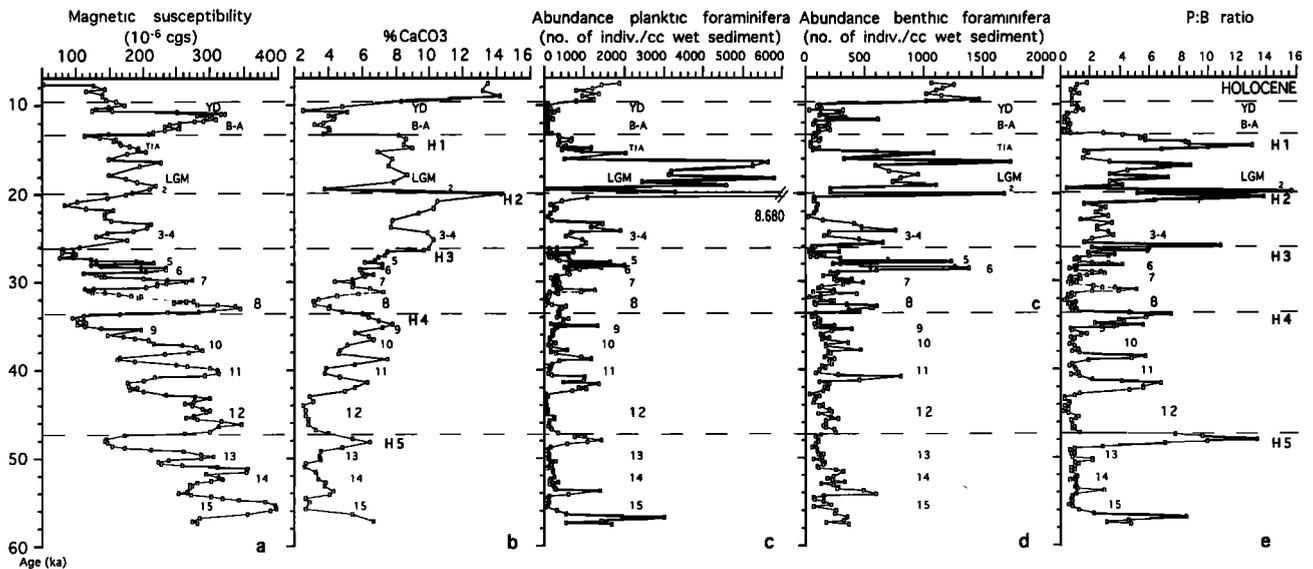


Figure 5. Comparison of (a) magnetic susceptibility for the ENAM93-21 core with (b) content of calcium carbonate, (c) concentration of planktonic and (d) benthonic foraminifera, and (e) ratio of planktonic to benthonic foraminifera (P:B ratio). Position of Heinrich events H5-H1 and interstadials (Dansgaard-Oeschger cycles) are shown. Horizontal dashed lines show boundaries between Bond cycles. The depth scale has been converted to age (see Table 1).

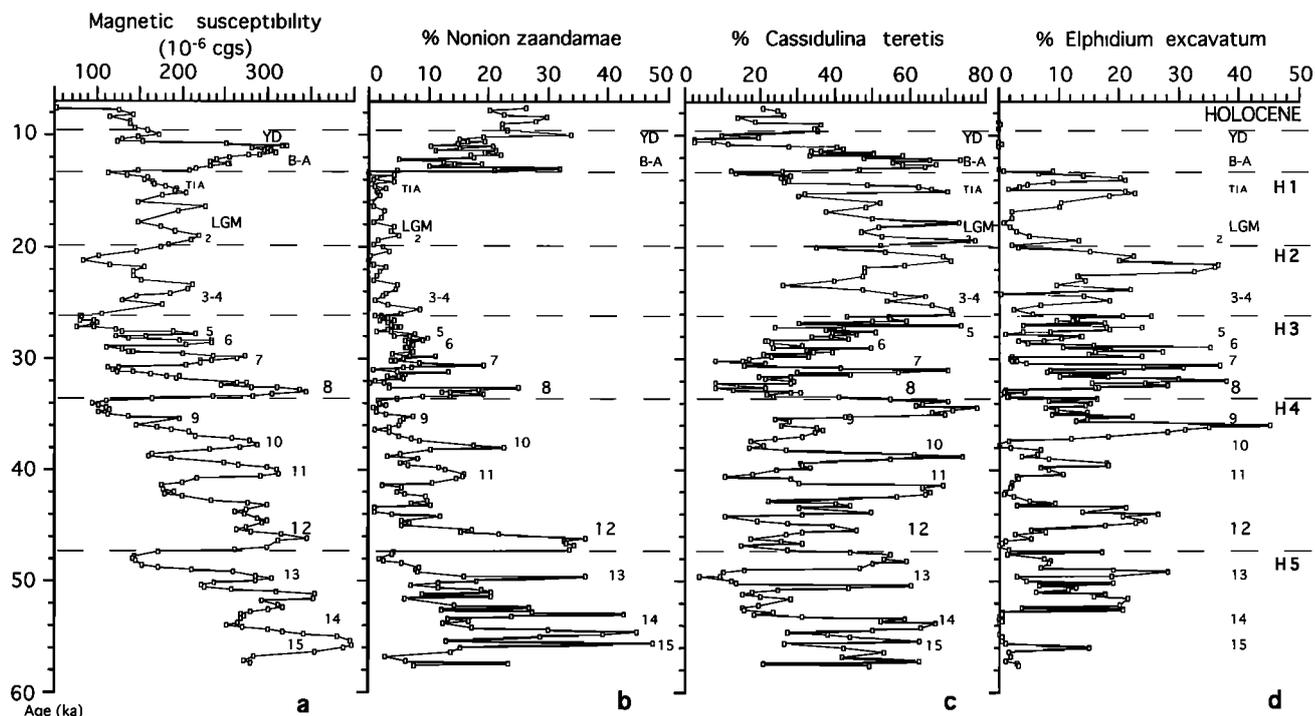


Figure 6. Comparison of (a) magnetic susceptibility for the ENAM93-21 core with (b) relative abundance of benthonic foraminifera *Nonion zaandamae*, (c) relative abundance of benthonic foraminifera *Cassidulina teretis*, and (d) relative abundance of benthonic foraminifera *Elphidium excavatum*. Position of Heinrich events H5-H1 and interstadials (Dansgaard-Oeschger cycles) are shown. Horizontal dashed lines show boundaries between Bond cycles.

Pullenia bulloides is relatively abundant in the middle Holocene deposits. Minor peaks occur at the base of the Bølling interstadial and at the base of the Younger Dryas (Figure 7d). Otherwise, the species is present only in very low numbers in the interstadial deposits.

Elphidium excavatum occurs in most samples below the Bølling interstadial (Figure 6d). The species is common in the transitional cooling intervals and in a thin zone between the stadials and the interstadials. It is rare in the stadial and interstadial intervals (Figures 6c and 8e).

The relative abundance of *Cassidulina teretis* (Figures 6c and 8e) increases gradually upward through the core to a maximum in the interval 28-11 kyr. *C. teretis* is the dominating species in the stadial intervals, whereas it is nearly absent in the interstadials. *C. teretis* occurs together with species like *S. schlumbergeri*, *Eggerella bradyi*, *Cibicides* aff. *C. floridanus*, *Cibicides* spp., *Gyroidinoides neosoldanii*, *Gyroidina umbonata*, *Uvigerina* sp., *Globobulima* sp., *Anomalinoidea minimus*, and *Epistominella decolata/Alabaminella weddellensis*. Together, this association constitutes more than 90% of the stadial faunas (Figures 6c and 7e).

Relative Abundance of Planktonic Species

The upper part of the core above the base of the LGM is characterized by large fluctuations in the relative abundance of the planktonic species (Figures 8 and 9). However, *N. pachyderma* (s.) is always the dominating form. *N.*

pachyderma (s.) is common in the LGM, the Bølling-Allerød, and the Holocene intervals, but totally dominant in the termination IA and Younger Dryas deposits (Figure 9b). The relative abundance of *Globigerina quinqueloba* varies generally opposite to that of *N. pachyderma* (s.) (Figure 9c). *G. quinqueloba* is most abundant in the LGM interval and in the lower Holocene. *N. pachyderma* (d.) is relatively rare in most of the core. The highest relative abundance is found in the Holocene deposits (Figure 9d).

The relative abundance of the various planktonic species is less fluctuating below the LGM interval (Figure 9). The most apparent changes here are small decreases in the abundance of *N. pachyderma* (s.) in most of the interstadials and corresponding increases in the abundance of *G. quinqueloba* and *N. pachyderma* (d.) (Figure 8).

Interpretation of Distribution Patterns

Bottom Water Conditions

Interstadial intervals. The benthic faunas of the Holocene and the interstadials between 58 and 30 kyr are very similar and almost identical to the recent faunas of the Norwegian Sea [see Mackensen *et al.*, 1985]. The most important species is *N. zaandamae*. At present, *N. zaandamae* is very abundant in the Norwegian Sea at water depths between 600 and 1200 m, where it occurs together with *P. bulloides* in a generally very rich fauna [Belanger and Streeter, 1980; Sejrup *et al.*, 1981; Mackensen *et al.*, 1985].

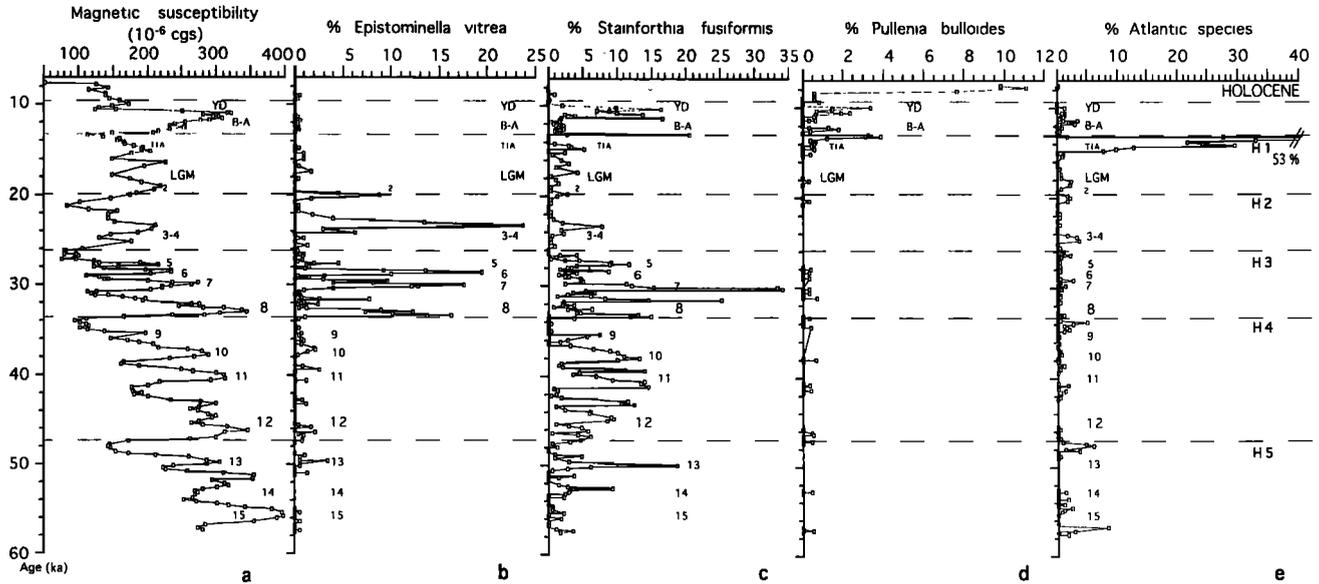


Figure 7. Comparison of (a) magnetic susceptibility for the ENAM93-21 core with (b) relative abundance of benthonic foraminifera *Epistominella vitrea*, (c) relative abundance of benthonic foraminifera *Stainforthia fusiformis*, (d) relative abundance of benthonic foraminifera *Pullenia bulloides*, and (e) relative abundance of a group of so-called "Atlantic species" comprising *Sigmoilopsis schlumbergeri*, *Epistominella decorata*/*Alabaminella weddellensis*, *Uvigerina* sp., *Globululimina* sp., *Eggerella bradyi*, a.o. Position of Heinrich events H5-H1 and interstadials (Dansgaard-Oeschger cycles) are shown. Horizontal dashed lines show boundaries between Bond cycles.

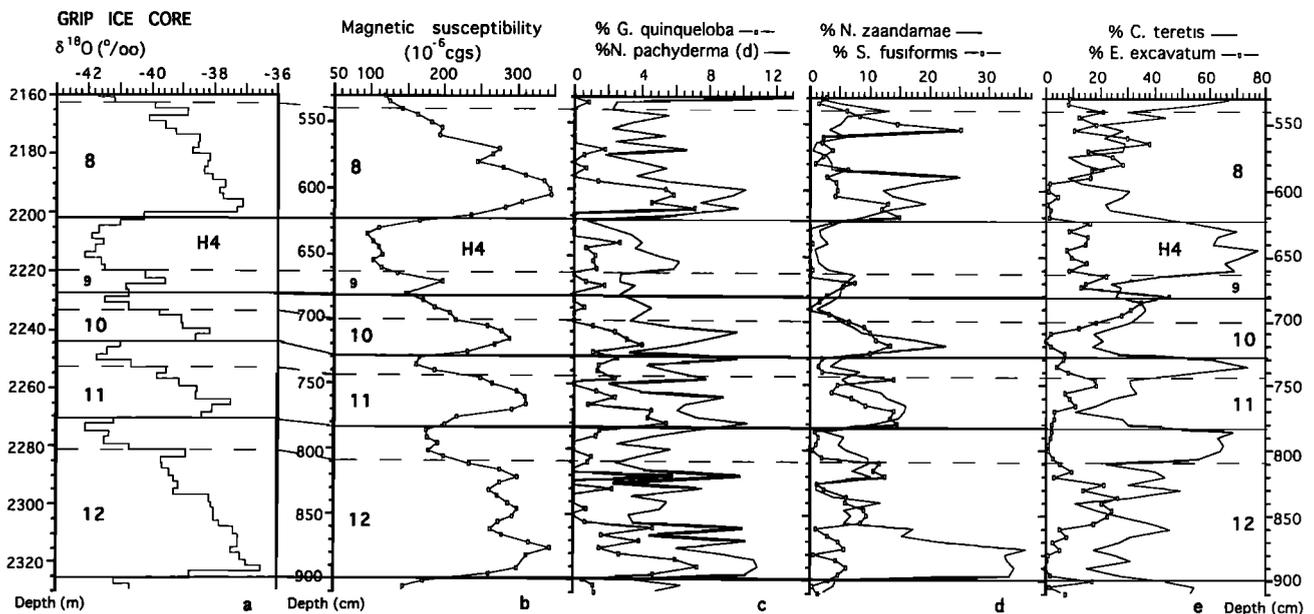


Figure 8. Detailed presentation and comparison of (a) Dansgaard-Oeschger cycles 8-12 in the GRIP ice core with selected parameters from the corresponding cycles in the ENAM93-21 core. The parameters are (b) magnetic susceptibility, (c) relative abundance of planktonic foraminifera *G. quinqueloba* and *N. pachyderma* (d) (accumulated percentages), (d) relative abundance of benthonic species *N. zaandamae* and *S. fusiformis*, and (e) relative abundance of benthonic species *C. teretis* and *E. excavatum*. Horizontal lines show boundaries between Dansgaard-Oeschger cycles. Dashed lines show transitional cooling intervals and stadial intervals.

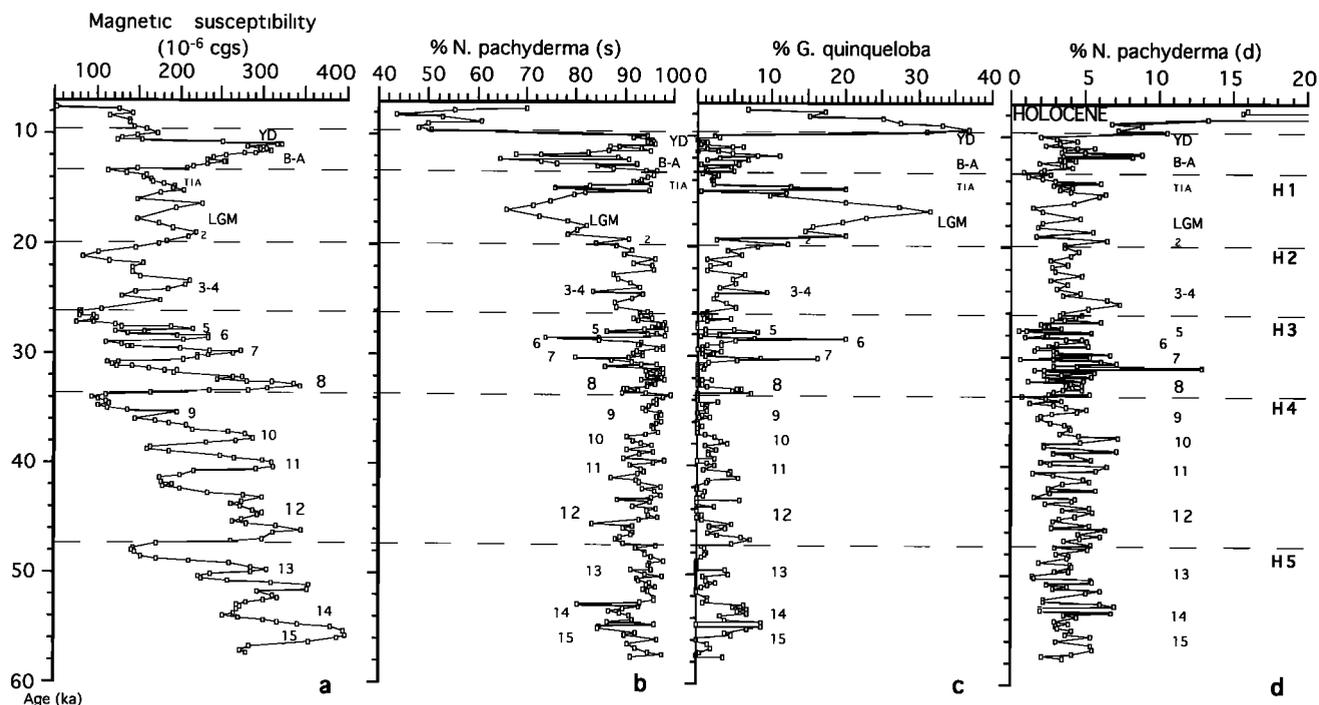


Figure 9. Comparison of (a) magnetic susceptibility for the ENAM93-21 core with (b) relative abundance of planktonic foraminifera *Neogloboquadrina pachyderma* (s.), (c) relative abundance of planktonic foraminifera *Globigerina quinqueloba*, and (d) relative abundance of planktonic foraminifera *N. pachyderma* (d.). Position of Heinrich events H5-H1 and interstadials (Dansgaard-Oeschger cycles) are shown. Horizontal dashed lines show boundaries between Bond cycles.

N. zaandamae is an infaunal species related to high-productivity regions, and it requires a steady flux of food [Corliss and Chen, 1988; Gooday, 1993]. The distribution of *N. zaandamae* indicates that the bottom water conditions in the interstadial periods in the Norwegian Sea probably were as today with a deep convection.

N. zaandamae cooccurs with *E. vitrea* and *S. fusiformis* (Figures 6b, 7b, c, and 8), both of which are absent in the Holocene and modern sediments. *E. vitrea* is presumably an opportunistic phytodetritus feeder like the very similar species *E. exigua* [Gooday and Lamshead, 1989; Gooday, 1993; Smart et al., 1994]. *S. fusiformis* tolerates relatively low levels of oxygen and high amounts of organic matter in the sediment [Alve, 1990].

The presence of *E. vitrea* in the interstadial periods indicates that the food supply was more unstable and more seasonal [see Thomas et al., 1995] than at present, especially in the interstadials between 33 and 20 kyr. The presence of *S. fusiformis* indicates further that the bottom water currents were not quite as intense as they are today. The relative abundance of *S. fusiformis* tends to increase from 58 to 30 kyr, suggesting a gradual weakening of the deep water renewal during that period (Figure 7d).

Today in the Norwegian Sea, *P. bulloides* is most abundant at water depths of about 1000 m [Belanger and Streeter, 1980; Sejrup et al., 1981; Mackensen et al., 1985]. This is the level of maximum water movement out of the Faeroe-Shetland Channel [Peterson and Rooth, 1976; Thiel, 1983]. In the Labrador Sea, *P. bulloides* is associated with

contour currents [Schafer et al., 1981], and it is interpreted as an indicator of strong bottom currents. The distribution of *P. bulloides* in the ENAM93-21 core suggests that maximum current velocity in the bottom water at this site occurred during the middle Holocene.

Transitional cooling intervals. *Elphidium excavatum* is the most important species in the transitional cooling intervals (Figures 6 and 8e). *E. excavatum* is extremely adaptable and tolerant of large variations in temperature, salinity, and food supply [Mudie et al., 1984; Scott et al., 1984; Vilks, 1989; Linke and Lutze, 1993; Conradsen et al., 1994]. Numerous studies have shown that the species has a wide depth range. It is often passively transported from shallower areas but is able to survive in the deep sea [Phleger, 1942; Culver and Buzas, 1980; Streeter and Lavery, 1982; Corliss and Emerson, 1990; Corliss, 1991; Bergsten, 1994]. *E. excavatum* dominates under polar conditions, with low salinity, low productivity, and extensive ice cover [Scott et al., 1984; Vilks, 1989; Schroeder-Adams et al., 1990]. The species is characteristic of ice-rafted sediments in the Norwegian Sea [Hald and Vorren, 1987]. The occurrence of *E. excavatum* indicates that the transitional cooling intervals were periods with fluctuating polar conditions [Vilks, 1969, 1989; Aksu, 1983; Scott et al., 1984, 1989a, b; Schroeder-Adams et al., 1990; Scott and Vilks, 1991] and probably variable deep water convection.

Stadial intervals. The stadial intervals are dominated by *C. teretis* in almost monospecific faunas of low concentrations (Figures 6c and 8e). *C. teretis* is an arctic species

[Green, 1960; Feyling-Hanssen, 1964; Lagoe, 1977, 1979], which tolerates low and unstable food supplies [Gooday and Lambshead, 1989]. *C. teretis* is abundant in the Arctic Ocean in the Atlantic Intermediate Water mass at water depths from about 700 to more than 1000 m [Green, 1960; Lagoe, 1979, 1980; Scott and Vilks, 1991; Bergsten, 1994]. *C. teretis* is considered to be an indicator of Atlantic Intermediate Water with temperatures above 0 °C [Jennings and Helgadottir, 1994; Jennings and Weiner, 1996]. In the ENAM93-21 core, *C. teretis* is nearly always found in association with the group of Atlantic species (*S. schlumbergeri* a.o.) (Figures 6c and 7e). At present this fauna occurs in the Atlantic Ocean at intermediate water depth [Phleger et al., 1953; Caralp et al., 1970; Pujos-Lamy, 1973; Lutze, 1979; Cole, 1981; Caralp, 1984].

The stadial intervals are further distinguished by good preservation of foraminifera, a high content of calcium carbonate, and the presence of IRD. These characteristics are typically glacial.

The large difference between the stadial and the interstadial benthic faunas on the Faeroe Margin points to great changes in the deep water circulation with an increasing influence of Atlantic Intermediate Water during the stadials. This influence culminated with the migration of the Atlantic fauna into the southeastern part of the Norwegian Sea shortly after the start of each stadial period. The entry of Atlantic Intermediate Water and of Atlantic foraminifera into the Norwegian Sea indicates a diminished outflow of deep water through the Faeroe-Shetland Channel and a reduced deep convection north of the Faeroe Islands.

The faunas of the Younger Dryas stadial provide rather conflicting evidence. The benthic fauna shows rapid interchanges between *N. zaandamae*, *P. bulloides*, and *S. fusiformis*, while *C. teretis* is nearly absent (Figures 6 and 7). The presence of *S. fusiformis* indicates a less efficient ventilation and a weakened convection as compared with the Holocene.

Surface Water Conditions

N. pachyderma (s.), a cold water indicator [Bé and Tolderlund, 1971; Kellogg, 1976, 1980], is the dominant planktonic species throughout the record of the ENAM93-21 core, except for a brief interval during the Holocene (Figure 9). *N. pachyderma* (s.) is particularly dominating in the stadial periods. In the interstadials the relative importance of the boreal form *N. pachyderma* (d.) increases slightly, suggesting a greater inflow of Atlantic surface water from the south (Figure 8c) [Kellogg, 1976, 1980, 1984; Johannessen et al., 1994]. The relative abundance of *G. quinqueloba* also increases in the interstadials (Figure 8c). In recent sediments, *G. quinqueloba* is most abundant close to the arctic front in mixed polar and Atlantic high-productivity waters [Kellogg, 1976; Johannessen et al., 1994].

The distribution of the planktonic species suggests that the surface water temperatures in the Norwegian Sea were higher in the interstadial periods as compared with the stadial and that the inflow of Atlantic surface water was greater.

Discussion

The ENAM9-21 core contains a remarkably detailed record covering the last 58,000 years. All Dansgaard-

Oeschger climatic cycles recognized from the equivalent time period in the Greenland ice cores have been identified. Below we will discuss the environmental changes during a typical cycle in the ENAM93-21 core and compare the results with observations from the North Atlantic Ocean, the Norwegian Sea, and the deeper parts of the Faeroe-Shetland Channel.

Interstadial Intervals

Interstadial conditions are most clearly seen in the benthic foraminifera, where high abundances of *N. zaandamae* indicate deep water conditions and convection very similar to today (Figures 6c and 8d). This implies that deep water is generated by thermohaline convection in the Norwegian-Greenland Seas contributing to the formation of NADW. This conclusion is supported by the planktonic/benthic ratio, which is about 1 and is the same as in the Holocene sediments (Figure 5) [see Berger and Diester-Haass, 1988; Gibson, 1989; Graf, 1989; Sarnthein and Altenbach, 1995].

In the planktonic foraminifera the interstadials are distinguished by a small increase in the relative importance of the boreal species *G. quinqueloba* and *N. pachyderma* (d.). However, the proportions of the two species are low compared with the proportions found in the North Atlantic Ocean. The main reason for this may be the northerly position of ENAM93-21 site outside the main current of the Atlantic surface water inflow into the Norwegian Sea (Figure 1) [see Dooley and Meincke, 1981; Hopkins, 1991]. Boreal species are generally rare in the glacial deposits from the Norwegian-Greenland Seas [see, for example, Kellogg, 1976; Kellogg et al., 1978; Haake and Pflaumann, 1989; Fronval et al., 1995], and at present they usually dominate only in areas directly overflowed by the Atlantic Current [see Kellogg, 1976; Johannessen et al., 1994; Hafliðason et al., 1995]. The interstadial periods probably correlate with phases in the North Atlantic Ocean with warm surface conditions and associated NADW flow [Bond et al., 1993; Oppo and Lehman, 1995; Bond, 1995].

Transitional Cooling Intervals

In the temperature cycles of the Greenland ice cores the warm interstadial periods are very short. They are followed by relatively long periods characterized by gradual cooling [Cuffey et al., 1995; Johnsen et al., 1995]. The same sequence of events can be observed in the ENAM93-21 core. In the core, however, the cooling intervals are seen only in the benthic foraminifera and in the magnetic susceptibility records. In the planktonic faunas the change from warm to cold faunas is abrupt.

With low concentrations and often poor preservation the benthic and planktonic faunas of the cooling intervals are typical of polar environments. The occurrence of *E. excavatum* indicates fluctuating bottom conditions, and it is probable that the vertical circulation was greatly reduced and the renewal of the deep water irregular. The relative abundance of *N. pachyderma* (d.) is very variable, suggesting great fluctuations in the inflow of warmer surface water from the North Atlantic Ocean. The ENAM93-21 site was probably close to the polar front, and shifting positions of the polar front and corresponding rapid changes in surface conditions could account for the fluctuating signals.

The ratio of planktonic to benthic foraminifera is 0.3-0.7. This low ratio may in some cases be affected by preferential dissolution of planktonic foraminifera [see *Berger*, 1968, 1973, 1979; *Malmgren*, 1983], but, in general, it probably reflects a low planktonic production rate (Figure 5). The reason for this is not fully understood, as several factors may be involved. However, low planktonic production and low P:B ratios seem to be characteristic of polar regions with extensive winter sea ice cover and unstable conditions [*Vilks*, 1969, 1970, 1975, 1989; *Lagoe*, 1980; *Gibson*, 1989; *Scott et al.*, 1989a, b; *Scott and Vilks*, 1991].

The transitional cooling intervals apparently correlate with the phases of surface water cooling that precede the Heinrich events and IRD events in the North Atlantic records [*Bond et al.*, 1993; *Bond and Lotti*, 1995]. These cooling phases are apparently associated with a very reduced NADW [*Oppo and Lehman*, 1995]. The cooling intervals may also correlate with the periods of increased ice rafting observed in the Norwegian Sea by *Fronval et al.* [1995].

Thus the Norwegian Sea, Faeroe-Shetland area, and North Atlantic regions all experienced polar coolings after the peak warm periods. This suggests that the events are closely linked and probably in phase.

Stadial Intervals and Heinrich Events

The stadial intervals including the Heinrich events in the ENAM93-21 core are primarily distinguished by low values of magnetic susceptibility, high concentrations of IRD, and distinct depletions of ^{18}O . They are further characterized by an increase in the relative abundance of *N. pachyderma* (s.), a high ratio of planktonic to benthic tests, and an assemblage of benthic species with an affinity to Atlantic Intermediate Water. The benthic faunas of the various stadials are very similar and totally different from those of the interstadials and transitional cooling intervals. Comparable changes in the level of $\delta^{18}\text{O}$, the content of IRD, and the proportion of *N. pachyderma* (s.) have been observed in the ODP-644 core taken northeast of the ENAM93-21 site in the Norwegian Sea [*Fronval et al.*, 1995], and they are apparently typical of the Faeroe-Shetland Channel and the southern part of the Norwegian Sea.

The ^{18}O depletions during the Heinrich events in the North Atlantic Ocean are generally ascribed to low salinity and the presence of meltwater from icebergs [see *Bond et al.*, 1992, 1993; *Grousset et al.*, 1993; *Labeyrie et al.*, 1995]. The icebergs are associated with the breakdown of primarily marine ice shelves [*Bond et al.*, 1992, 1993; *Koç and Jansen*, 1994; *Fronval et al.*, 1995], and they are considered to be the main agent for the distribution of IRD. The higher number of depletion events in the Faeroe-Shetland Channel as compared with the North Atlantic Ocean may be due to the more northerly position of this site, closer to the Fennoscandian ice sheet.

Several lines of evidence in the ENAM93-21 core indicate that the Norwegian Sea during the stadial intervals was characterized by a reduced convection and slow deep water circulation as compared with the interstadials. The main indications are the ratio of planktonic to benthic specimens and the presence of Atlantic benthic species in all stadials and Heinrich events.

With more than 90% planktonic specimens the planktonic/benthic ratios of the stadial periods are very high as compared with the interstadial and transitional intervals (Figure 5e). The high ratios coincide with an increase in the concentration of planktonic specimens and a decrease in the concentration of benthic. Therefore it probably reflects both an increase in the surface productivity and a decrease in the bottom productivity. The difference between the surface and the deep water productivity points to a decoupling of the surface and bottom environments and a stop in the deep convection north of the Faeroe Islands [see *Sarnthein et al.*, 1995; *Sarnthein and Altenbach*, 1995].

This inference concurs with the presence of Atlantic benthic species in the stadials and Heinrich events (Figure 7e). A strongly reduced deep convection north of the Faeroe Islands and a diminished outflow of deep water through the Faeroe-Shetland Channel would allow for the entry of Atlantic Intermediate Water and Atlantic benthic foraminifera into the Norwegian Sea.

The second indication of a slower deep water circulation during the stadials is from a comparison of the ENAM93-21 core with cores from the deeper parts of the Faeroe-Shetland Channel. A comparison of the ENAM93-21 core with the NA81-10 and NA81-04 cores [*Rasmussen et al.*, 1996], taken at a water depth of 1750 m (Figure 1), reveals a distinct change in bottom water conditions related to depth. In ENAM93-21, all stadials including the Heinrich events contain a well-preserved foraminiferal fauna. In the two deeper cores the stadials, in general, contain a poorly preserved fauna marked by dissolution. This difference suggests that during the stadial periods the bottom water was well oxygenated, with good circulation at a water depth of 1020 m, but corrosive with reduced circulation at 1750 m.

Reduced circulation in deep waters in the Norwegian-Greenland Seas during glacial periods has previously been suggested by *Kellogg et al.* [1978], *Streeter et al.* [1982], *Jansen and Erlenkeuser* [1985], *Haake and Pflaumann* [1989], and *Ramm* [1989].

In the North Atlantic Ocean, there is increasing evidence for a reduced NADW influence [*Streeter and Shackleton*, 1979; *Curry et al.*, 1988; *Duplessy et al.*, 1988; *Keigwin and Lehman*, 1994; *Oppo and Lehman*, 1995] and an enhanced circulation in the intermediate water during the glacial period [*Boyle and Keigwin*, 1982, 1987; *Boyle*, 1992; *Oppo and Lehman*, 1993; *McCave et al.*, 1995]. *Labeyrie et al.* [1985] and *Duplessy et al.* [1988] indicate that during the LGM, convection moved south to the subpolar Atlantic Ocean. Our results suggest that this happened in all stadial periods during the last glaciation. Thus the locus of deep water formation apparently shifted back and forth between the Norwegian-Greenland Seas and the Atlantic Ocean, concurring with the Dansgaard-Oeschger cycles.

Conclusions

The ENAM9-21 core, taken near the northern outlet of the Faeroe-Shetland Channel, contains a detailed record of planktonic and benthic parameters covering the last 58,000 years. All 15 Dansgaard-Oeschger climatic cycles recognized

from the equivalent time period in the Greenland ice cores have been identified. Each cycle consists of a warm interstadial interval, a transitional cooling interval, and a cold stadial interval.

Interstadial conditions are most clearly seen in the benthic foraminifera, where high abundances of *N. zaandamae* indicate deep water conditions and a circulation that is very similar to that of today. Deep water generated by thermohaline convection in the Norwegian-Greenland Seas probably contributed to the formation of NADW. The interstadial periods seem to correlate with phases in the North Atlantic Ocean with warm surface conditions and associated NADW flow.

The short interstadial periods are followed by relatively long periods characterized by gradual cooling. The cooling intervals are seen only in the benthic foraminifera and in the magnetic susceptibility records. In the planktonic faunas the change from warm to cold faunas is abrupt. The faunas of the cooling intervals are typical of polar environments with low concentrations and often poor preservation. The occurrence of *E. excavatum* indicates variable bottom conditions, and it is probable that the vertical circulation was greatly reduced with a slow renewal of the deep water. The transitional cooling intervals seem to correlate with the phases of surface water cooling that precede the Heinrich events and IRD events in the North Atlantic records. These cooling phases are apparently associated with a very reduced NADW [Oppo and Lehman, 1995].

The stadial intervals including the Heinrich events are distinguished by low values of magnetic susceptibility, high concentrations of IRD, distinct depletions of ^{18}O , a small increase in the relative abundances of *N. pachyderma* (s.), and an assemblage of benthic species with an affinity to Atlantic Intermediate Water. The benthic faunas of the various stadials are very similar and totally different from those of the interstadial and transitional cooling intervals. The presence of "Atlantic species" during the stadial intervals suggests that the outflow of deep water through the Faeroe-Shetland Channel was diminished and the convection north of the Faeroe Islands had stopped or was strongly reduced. Convection probably shifted to the subpolar Atlantic south of the Faeroe Islands. The oceanographical changes during the last glacial period in the Faeroe-Shetland Channel and the North Atlantic Ocean are clearly closely connected and generally in phase.

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