Deep sea records from the southeast Labrador Sea: Ocean circulation changes and ice-rafting events during the last 160,000 years

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[1] Results from two deep sea cores from northeast of Newfoundland at 1251 and 2527 m water depth, respectively, indicate that during the time period from 160,000 to 10,000 years BP, ice rafting events in the Labrador Sea were accompanied by rapid variations in deep and surface water circulation. Twelve ice-rafting events occurred, each coinciding with high concentrations of detrital carbonate and oxygen isotopic depletion of both surface and bottom waters. Eleven of these can be correlated with the North Atlantic Heinrich events H1–H11. The remaining very conspicuous ice-rafting event took place early in MIS substage 5e, at a time when the planktic faunal assemblage suggests marked warming of the sea surface. In the shallower core, benthic $\delta^{13}C$ values rise from a minimum during the deglaciation to peak substage 5e values following the last ice-rafting event, indicating that the ventilation of intermediate depths was renewed after the deglaciation was complete and continued throughout substage 5e. The benthic foraminifera suggest that this well-ventilated water mass was comparable to the modern Labrador Sea Water (LSW). The benthic faunas suggest that a relatively warm intermediate water mass entered the SE Labrador Sea during Heinrich events. Generally low benthic $\delta^{13}C$ values indicate that this water mass was poorly ventilated and rich in inorganic nutrients. Isotope data and benthic faunal distributions indicate that North Atlantic Deep Water (NADW) formed in the Norwegian-Greenland Sea reached the SE Labrador Sea between the Heinrich events. *INDEX TERMS:* 4267 Oceanography: General: Paleoceanography; 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3030 Marine Geology and Geophysics: Micropaleontology; *KEYWORDS:* Paleoceanography, Labrador Sea, ice rafting, foraminifera, last climate cycle

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1. Introduction

[2] The Norwegian-Greenland Sea and the Labrador Sea are the main areas for deep water formation in the North Atlantic Ocean today. Both regions are fed by warm surface water derived from the Gulf Stream system, and the deep water is formed by convection during the cold winter seasons. The deep water created in the Norwegian-Greenland Sea overflows the Greenland-Scotland Ridge as the Norwegian Sea Overflow Water (NSOW) and the Greenland Sea Overflow Water (GSOW), respectively. Both water masses are very cold and dense with temperatures of about $-1°C$. In the North Atlantic they mix with warmer Atlantic intermediate water and become the NADW. This water mass flows into the Labrador Sea at a water depth of approximately 1700 to 3500 m [*Lucotte and Hillaire-Marcel*, 1994].

[3] The Labrador Sea is the source area for the Labrador Sea Water (LSW), also called the Upper NADW. The LSW is warmer, less saline, and less dense than the overflow water from the Norwegian-Greenland Sea. It flows above NADW roughly between 800 and 1700 m water depth. The LSW contributes to the Atlantic intermediate water together with Mediterranean Overflow Water and Central Water. At present, deep water is formed in both the Norwegian-Greenland Sea and the Labrador Sea, although their relative importance varies on decadal timescales [*Sy et al.*, 1997; *Dickson*, 1997]. Both Upper and Lower NADW are relatively nutrient-depleted because they contain a significant component of nutrient-poor surface waters. This is reflected in their relatively high $\delta^{13}C$ values [*Kroopnick*, 1985].

[4] High resolution studies of deep sea cores from the Norwegian-Greenland Sea and North Atlantic Ocean covering the last 150,000 years have demonstrated that the circulation pattern and deep water formation in the Norwegian-Greenland Sea underwent profound changes during the last glacial period [e.g., *Keigwin and Lehman*, 1994; *Oppo and Lehman*, 1995; *Rasmussen et al.*, 1996a, 1996b, 1999; *Vidal et al.*, 1997; *Labeyrie et al.*, 1999]. The changes are on a millennium timescale, and they were especially prominent during the so-called Heinrich events, when massive discharges of icebergs from surrounding ice sheets apparently restricted the formation of deep water north of the

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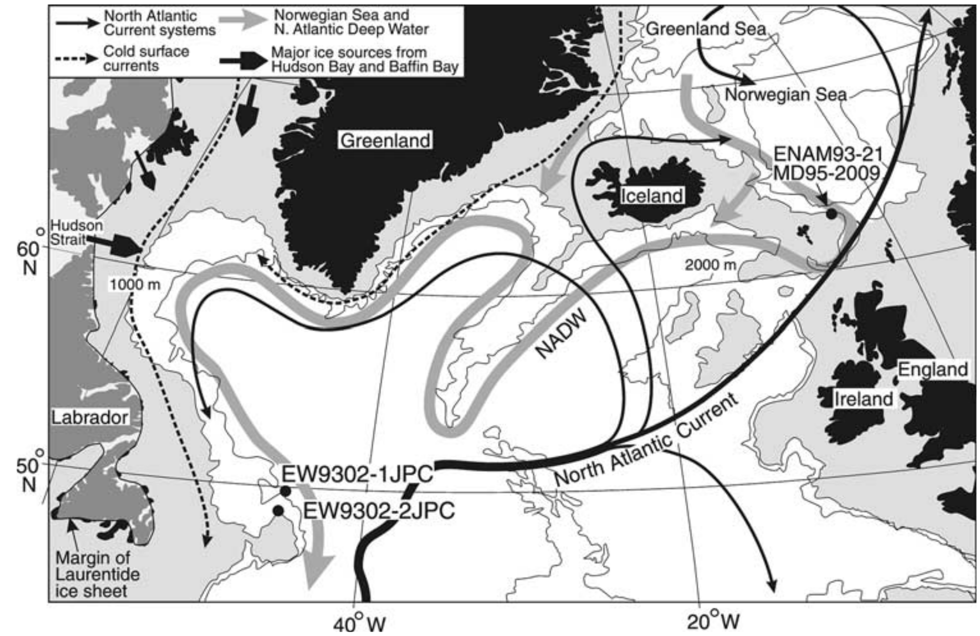

Figure 1. Map of the northern Atlantic Ocean and Norwegian-Greenland Sea showing the locations of the investigated cores EW9302-1JPC and EW9302-2JPC from northeast of Newfoundland and of cores ENAM93-21 and MD95-2009 from the southeastern Norwegian Sea. Main features of present surface currents and deep currents, maximum extent of Laurentide ice sheet and major ice sources in the Hudson Bay [*Dowdeswell et al.*, 1995] are also indicated.

Greenland-Scotland Ridge. In the eastern North Atlantic Ocean the Lower NADW was replaced by deep water originating from the Antarctic region [e.g., *Duplessy et al.*, 1988; *Oppo and Lehman*, 1993; *Sarnthein et al.*, 1994].

[5] The purpose of the present investigation is to study variations in the formation and properties of the North Atlantic intermediate and deep water over the last ~160,000 years in relation to ice rafting events and past climate changes, and, further, to explore the relationship between deep water formed in the Greenland-Norwegian Sea, in the Labrador Sea, and elsewhere. The interpretations are based on the abundance of planktic and benthic foraminifera, lithic fragments, and oxygen and carbon isotopes measured on both benthic and planktic foraminifera.

2. Study Area

[6] The study is based on two piston cores from the Flemish Cap in the southeastern Labrador Sea (Figure 1). The two cores (EW9302-1JPC, pos. 49°14.30′N, 45°05.34′W) and (EW9302-2JPC, pos. 48°47.70′N, 45°05.09′W) were taken at water depths of 2527 and 1251 m, respectively. The deeper site lies within NADW whereas the shallower site lies within LSW. Both cores are situated above the strongest currents of the Western Boundary Undercurrent (WBUC), which today flows at a water depth of 2700–3300 m [e.g., *Carter and Schafer*, 1983; *Hillaire-Marcel et al.*, 1994]. The cores lie in the direct pathway of the icebergs produced by the Laurentide ice shelves during the glacial period [*Bond et al.*, 1992; *Broecker et al.*, 1992; *Andrews and Tedesco*, 1992; *Grousset et al.*, 1993; *Dowdeswell et al.*, 1995; *Andrews*, 1998].

[7] The present hydrography near the coring sites is shown in Figure 2. The CTD profile generally confirms the water mass structure inferred from earlier studies in the Labrador Sea [e.g., *Lee and Ellett*, 1967; *Wright and Worthington*, 1970; *Carter and Schafer*, 1983; *Lucotte and Hillaire-Marcel*, 1994; *Bilodeau et al.*, 1994]. The surface water consists of the southward flowing Labrador Current. It is recognized by variable temperatures and salinities and extends down to a water depth of about 400 m (Figure 2) [*Carter and Schafer*, 1983; *Lucotte and Hillaire-Marcel*, 1994]. The underlying LSW continues to a depth of about 1800 m. It is identified by temperatures of 3.5–3.7°C and a salinity of approximately 34.85‰ (Figure 2). NADW resides below LSW down to a depth of about 3500 m. In the Labrador Sea, the NADW can be subdivided into an upper part from 1800 to 2200 m composed of NSOW, and a lower part from about 2200–3500 m composed of GSOW. The NSOW is distinguished by higher temperature than both the LSW above and the GSOW below. The GSOW has a temperature between 2 and 3°C and a salinity near 34.90‰ (Figure 2) [*Lucotte and Hillaire-Marcel*, 1994]. The deepest part of the central Labrador Sea below a depth of about 3500 m contains some Southern Ocean Water (SOW) generated in the Antarctic region. This water mass has the lowest temperatures in the area (<2°C) (Figure 2). However, along the southwestern slope, the SOW rises to depths of about 2700 m [*Lucotte and Hillaire-Marcel*, 1994].

3. Material and Methods

[8] The two piston cores, EW9302-1JPC and EW9302-2JPC, henceforth will be referred to as 1JPC and 2JPC.

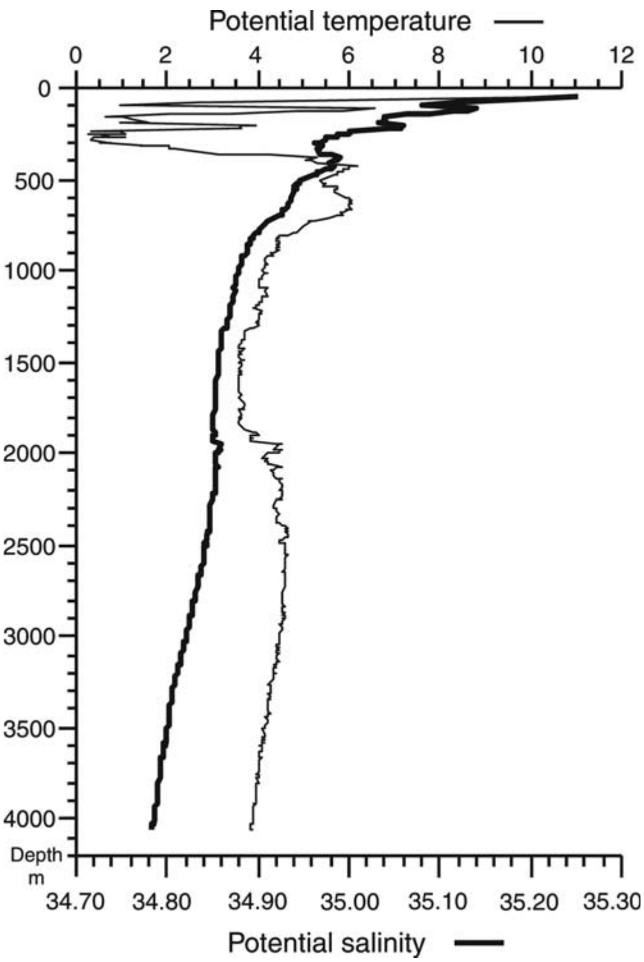

Figure 2. CTD-station 3 from EW9302 CTD-1 (pos. 49°54.12′ N, 44°27.85′ W, water depth 4082 m) showing potential temperature (°C) and potential salinity (‰) profiles from the Labrador Sea.

Core 2JPC from 1251 m water depth is 11.91 m long. It consists of relatively fine-grained, homogenous sediments throughout. Core 1JPC from 2527 m water depth is 13.20 m long. It consists of alternating beds of fine-grained clayey and more coarse-grained sandy deposits. Individual beds are generally between 0.15 m and 1.0 m thick. Some of the sandy beds are fining upwards, but the boundaries between the beds are normally sharp. The sediments are probably drift deposits. The contrasting sediment types most likely reflect varying bottom-current regimes and the different position of the two cores on the continental margin.

[9] The cores were sampled at 8 cm intervals except for certain critical intervals in which the sampling distance was reduced to 4 cm. The total number of samples was 202 from core 1JPC and 175 from core 2JPC. The samples were dried, weighed, and washed through a 63-μm sieve. The residues were dried and weighed again. The samples were subsequently dry sieved through a 106-μm sieve for the foraminiferal analyses. Approximately 300 planktic and 300 benthic foraminifera were picked, counted, and identified in each sample. The concentration of planktic and benthic foraminifera was calculated as number of specimens per gram dry weight sediment. Relative abundance was calculated within each group separately. All foraminifera were well preserved and we have seen no indications of significant transportation.

[10] Counts of ice rafted detritus (IRD) were done on the >150 μm size fraction. At least 300 grains were counted in each sample. In core 2JPC detrital carbonate was visually identified and counted separately. The concentration of IRD was calculated as the number of grains per gram dry weight sediment. The percentage of IRD was calculated relative to the concentration of total entities including benthic and planktic foraminifera and mineral grains. In addition to the sampling described above, core 1JPC was sampled every 4 cm for bulk carbonate analyses using methods described by *Ostermann et al.* [1990].

[11] Oxygen isotope measurements were performed using standard techniques [*Ostermann and Curry*, 2000]. The analyses were performed on the planktic foraminifera *Neogloboquadrina pachyderma* sinistral (*N. pachyderma* s) and the benthic foraminifera *Cibicidoides wuellerstorfi*. However, due to discontinuous distribution of the benthic species in core 2JPC it was necessary to use 2 additional taxa (*Melonis barleeanum*, and *Cibicides* spp.). Where the species overlap the isotope values are similar ensuring no significant offsets. Radiocarbon dates were obtained on *N. pachyderma* s using the Accelerator Mass Spectrometry (AMS) technique (Table 1).

4. Results

4.1. Stratigraphy and Age Control

[12] Seventeen AMS radiocarbon dates and several tephra layers provide important stratigraphic constraints in the younger section of the cores. The AMS ^{14}C datings range from 13.77 to 36.95 ka BP in core 2JPC, and from

Table 1. AMS-^{14}C Dates for Cores EW9302-1JPC and EW9302-2JPC[a]

Core	Depth, cm	AMS,[b] ^{14}C	Error, 1ß	Laboratory Number
EW9302-1JPC				
	16	7.52	±40	OS-6696
	24	7.26	±40	OS-7428
	80	16.55	±70	OS-6697
	104	17.1	±60	OS-7429
	160	19.1	±110	OS-7430
	192	20.2	±65	OS-7431
	224	21.2	±150	OS-7432
	320	21.2	±80	OS-7433
	368	23.9	±120	OS-7434
	416	26.7	±160	OS-14543
	480	37.9	±460	OS-14542
EW9302-2JPC				
	32	13.77	±130	AAR-4675
	64	17.09	±120	AAR-4676
	161	20.78	±150	AAR-4677
	200	24.28	±240	AAR-4678
	240	26.71	±240	AAR-4679
	336	36.95	±700	AAR-4680

[a]Core EW9302-1JPC was dated at WHOI NOSAMS, Woods Hole Oceanographic Institution, core EW9302-2JPC at the AMS-Laboratory, University of Aarhus.

[b]Correction: 400 years.

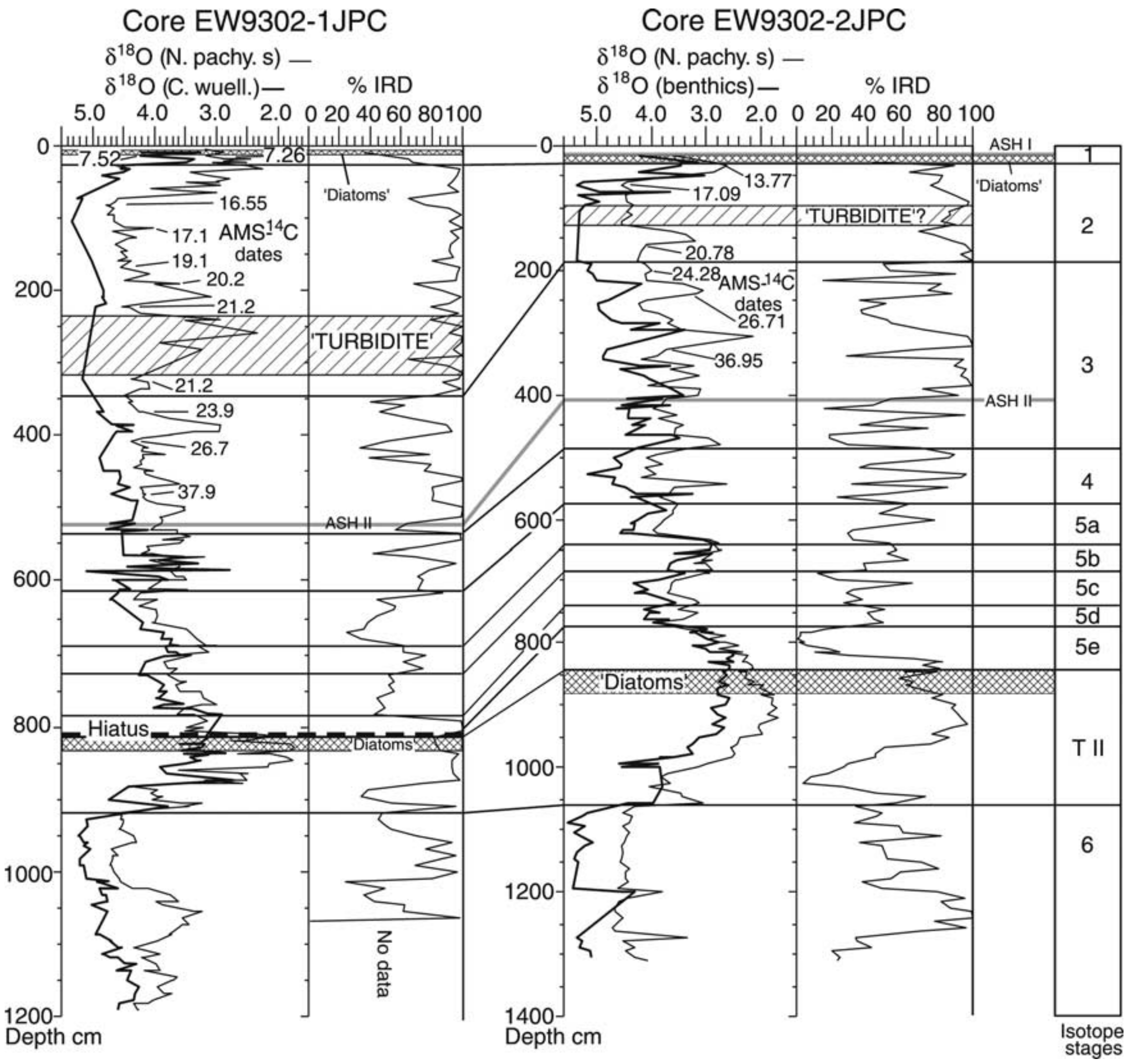

Figure 3. (left) Benthic $\delta^{18}O$ record measured on *C. wuellerstorfi*, planktic $\delta^{18}O$ record measured on *N. pachyderma* sinistral and percentage of IRD for core EW9302-1JPC. (right) Benthic $\delta^{18}O$ record combined from measurements on *C. wuellerstorfi*, *Cibicides* spp., and *M. barleeanum*, planktic $\delta^{18}O$ record measured on *N. pachyderma* sinistral and percentage of IRD for core EW9302-2JPC. Position of tephra layers and AMS-C14 dates are indicated. Diatom beds and turbidite layers are marked. Marine isotope stages 1–6 are indicated to the far right.

7.52 to 37.9 in core 1JPC (Table 1; Figure 3). Abundant basaltic and rhyolithic ash grains at 408 cm in core 2JPC have been chemically analyzed and identified as ASH II [*Kvamme et al.*, 1989; *Fillon and Duplessy*, 1980; S. Wastegaard, personal communication, 2000] (Figure 3). A number of basaltic ash grains at 524 cm in core 1JPC probably also belong to the ASH II event. However, this identification is based purely on visual inspection. ASH II is dated to ~53,000 calendar years [*Grönvold et al.*, 1995; *van Kreveld et al.*, 2000]. High amounts of rhyolitic tephra grains occurring 16 cm below the top of core 2JPC (Figure 3) may relate to ASH I dating 10,300^{14}C years [*Mangerud et al.*, 1984]. This tephra layer has been recognized in a core from southwest of Greenland [*Hillaire-Marcel et al.*, 1994]. Diatom layers have been identified at 12 cm and 808–830 cm depth in 1JPC. Similar layers are present at 24 cm and 640–680 cm depth in 2JPC (Figure 3).

[13] Both cores contain a distinct reddish clay layer (Figure 3). Such layers are often reported from Labrador Sea records, and they are generally interpreted as turbidites originating from the Gulf of St. Lawrence [*Hillaire-Marcel et al.*, 1994; *Stoner et al.*, 1996]. The layers from the JPC cores contain very little material coarser than 63 μm. A few foraminifera and mineral grains covered with red material appear reworked. AMS ^{14}C datings in core 1JPC give an age of 21.2 ka BP just below and just above the turbidite, thus closely constraining the age of the event (see Table 1). The reddish layer in 2JPC seems to be younger, and the two events are probably not related.

[14] Identification of isotope stage boundaries follows generally accepted practice [e.g., *Martinson et al.*, 1987],

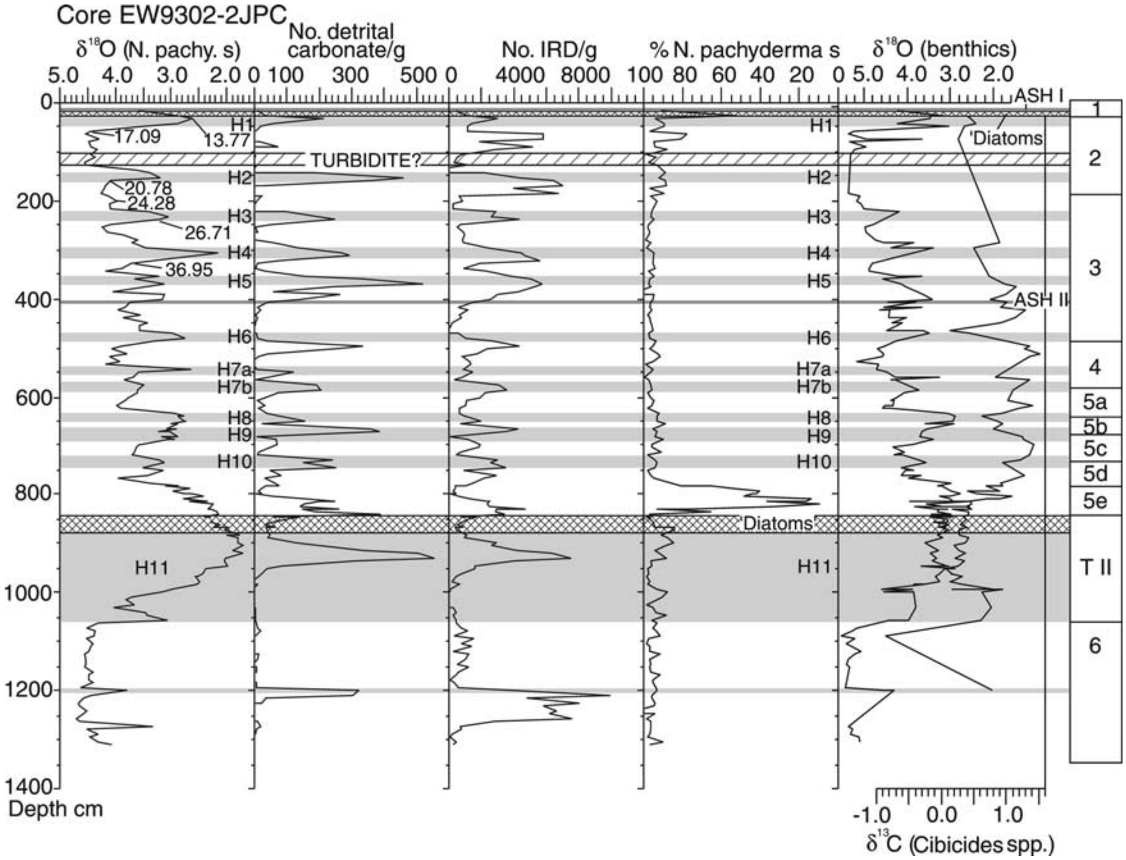

Figure 4. From left to right: Planktic δ^{18}O record measured on *N. pachyderma* sinistral, number of IRD and detrital carbonate grains per gram dry weight sediment (note differences in scales), relative abundance of *N. pachyderma* sinistral, benthic δ^{18}O record measured on *C. wuellerstorfi*, *Cibicides* spp., and *M. barleeanum* and benthic δ^{13}C record measured on *C. wuellerstorfi* and *Cibicides* spp. for core EW9302-2JPC. Marine isotope stages are indicated to the far right. Bars indicate the position of Heinrich events H1–H11. Legend otherwise as in Figure 3.

except for MIS 5, where low δ^{18}O values that ordinarily signal interstadial substages occur in association with glacial indicators such as elevated concentrations of IRD and detrital carbonate. This is undoubtedly due to proximity of the core sites to sources of ^{18}O-depleted deglacial meltwater. To overcome this limitation we use a combination of δ^{18}O and lithology to guide selection of substages 5d-5a based on the expectation that glacial lithologic indicators occur at relative minimum concentration during interstadial substages 5a and 5c.

[15] A similar problem prohibits a conventional designation of the MIS 6/substage 5e transition based on the midpoint of the δ^{18}O decrease from maximum values of MIS 6. In fact, the first half of the interval marked by lowest δ^{18}O values ordinarily corresponding to the period of minimum ice volume and maximum surface temperature within MIS 5e is associated in both cores with glacial lithologic indicators. We take the interval of elevated detrital carbonate (designed as H11 in section 4.2; Figure 4) to be extralimital to substage 5e and set its onset to coincide with the decrease in the abundance of the polar planktic foraminifera *N. pachyderma* s, indicating an increase in sea surface temperatures. The decrease coincides with the top of a diatom mat corresponding to the onset of substage 5e in the Norwegian Sea [*Rasmussen et al.*, 1999]. Termination II is designated as the interval between the onset of ^{18}O depletion from maximum values of MIS 6 and the onset of MIS 5e based on the above criteria (Figure 4). The absence of an interval with low abundance of *N. pachyderma* s in 1JPC indicates that substage 5e is missing from 1JPC and signifies a hiatus in the core.

4.2. Ice-Rafting Events (IRD, Detrital Carbonate, and δ^{18}O)

[16] Twelve large IRD events have been identified in core 2JPC (Figure 4). The IRD grains include a considerable amount of detrital carbonate up to 0.5–2 mm in size, and often with columnals of crinoid stems embedded. Each IRD event is associated with low planktic and benthic δ^{18}O values (Figures 3–5).

[17] The combination of high concentrations of IRD and detrital carbonate and low δ^{18}O values define the North Atlantic Heinrich events [see *Heinrich*, 1988; *Bond et al.*, 1992; *McManus et al.*, 1994]. Similar events are also well known from the Labrador Sea area [e.g., *Fillon and Duplessy*, 1980; *Andrews and Tedesco*, 1992; *Hillaire-*

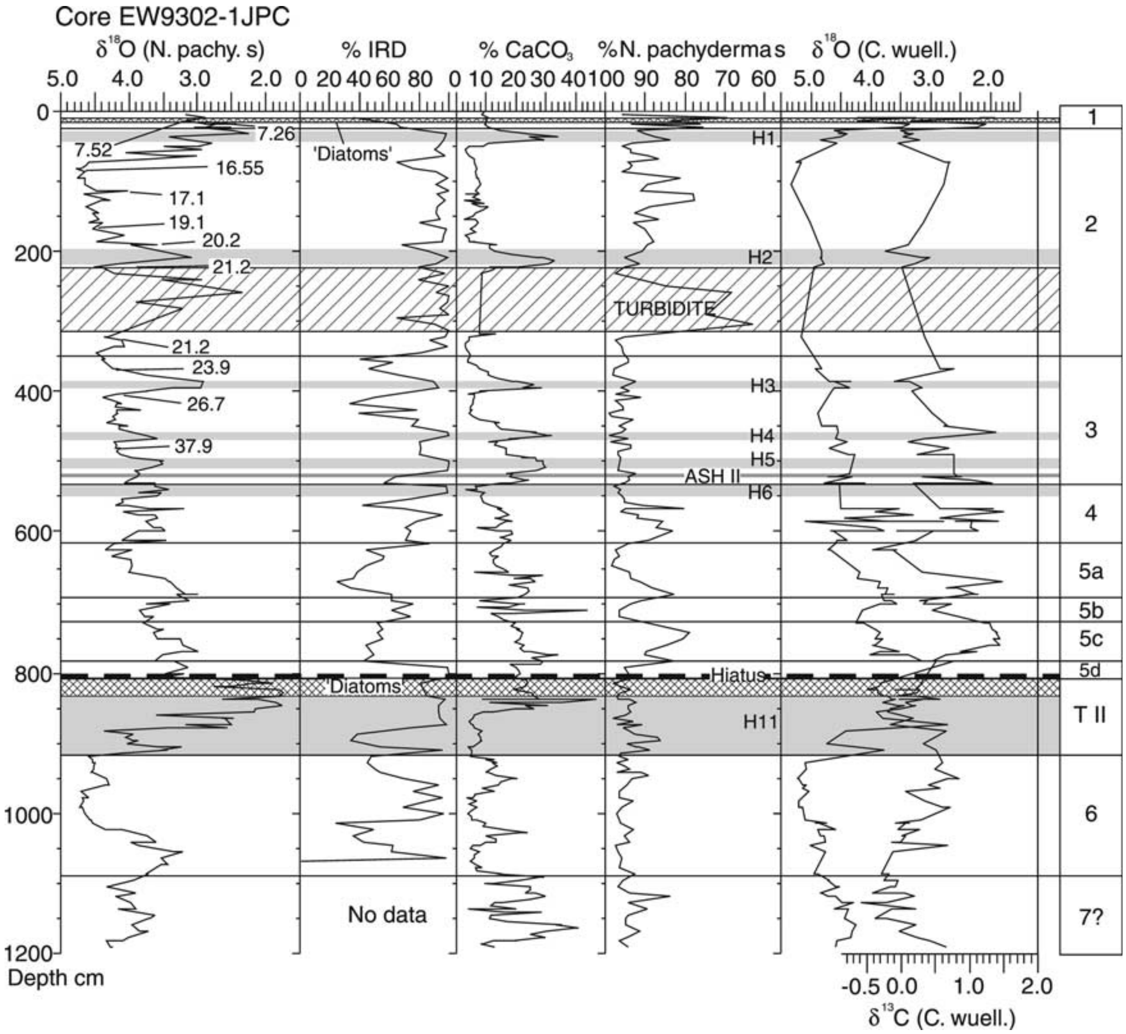

Figure 5. From left to right: Planktic δ^{18}O record measured on *N. pachyderma* sinistral, percent IRD, carbonate content, relative abundance of *N. pachyderma* sinistral, benthic δ^{18}O record measured on *C. wuellerstorfi* and benthic δ^{13}C record measured on *C. wuellerstorfi* for core EW9302-1JPC. Marine isotope stages are indicated to the far right. Bars indicate the position of Heinrich events H1–H6 and H11. Legend otherwise as in Figure 3.

Marcel et al., 1994; *Andrews et al.*, 1994; *Stoner et al.*, 1996; *Jennings et al.*, 1996], where they are characterized primarily by the presence of detrital carbonate [*Andrews and Tedesco*, 1992]. Several studies have shown that the events in the two areas can be reliably correlated and are of the same age [*Andrews et al.*, 1994; *Hillaire-Marcel et al.*, 1994; *Bond and Lotti*, 1995; *Stoner et al.*, 1996, 1998; *Veiga-Pires and Hillaire-Marcel*, 1999; *Kirby and Andrews*, 1999; *Clarke et al.*, 1999; *Hillaire-Marcel and Bilodeau*, 2000; *Hiscott et al.*, 2001].

[18] Heinrich events H1–H6 are easily identified in both of our records and their timing is in good agreement with the timing of H1–H6 elsewhere in the North Atlantic [see, e.g., *Bond et al.*, 1992; *Stoner et al.*, 1996; *Elliot et al.*, 1998]. For reasons that are unclear the ^{18}O depletion associated with H6 appears after the peak of detrital carbonate (Figures 4 and 5) [see also *Bond et al.*, 1999; *Hiscott et al.*, 2001]. Heinrich event 6 is described as a low detrital carbonate event in the SE Labrador Sea by *Stoner et al.* [1996, 1998]. H7–H11 have been identified in 2JPC only (Figure 4). They follow the same distinctive pattern as H1–H6 with high concentrations of IRD and detrital carbonate and low values of δ^{18}O. H7 consists of two peaks labeled H7a and H7b (Figure 4).

[19] The most prominent increases in IRD and detrital carbonate occur during H11 in the upper part of Termination II, H5, and H2 (Figure 4). Termination II is almost 2 m thick in 2JPC. IRD and detrital carbonate concentrations are generally low during the Termination, except for the prominent peaks corresponding to H11. Another conspicuous peak occurs in association with the marked decrease in abundance of *N. pachyderma* s marking the onset of MIS 5e. A ~40 cm thick diatom layer occurs between the two IRD peaks (Figure 4).

[20] The oxygen isotope values of MIS 3 and 4 fluctuate strongly reflecting the episodic influence of meltwater

during Heinrich events. Benthic δ^{18}O values closely follow the planktic isotope values throughout the study interval with large jumps of similar magnitude (Figures 3–5) [see also *Fillon and Duplessy*, 1980]. This is most clearly seen in the continuous record of 2JPC. It is less evident in 1JPC, which has large gaps in the record (Figures 3 and 5).

4.3. Benthic δ^{13}C Records

[21] The δ^{13}C record of benthic species *C. wuellerstorfi*, and *Cibicides* spp. is incomplete due to low abundance of these taxa. They were most abundant during Termination II and during MIS 5. The two records show significant variations in δ^{13}C with lowest values during Termination II (Figures 4 and 5), as has been seen in several other middepth and deep cores [*Adkins et al.*, 1997; *Oppo et al.*, 1997, 2001; *Lototskaya and Ganssen*, 1999]. This δ^{13}C minimum and the associated Cd/Ca maximum [*Adkins et al.*, 1997] are generally attributed to a replacement of nutrient-poor North Atlantic source waters by nutrient-rich waters of southern origin [*Adkins et al.*, 1997; *Oppo et al.*, 1997, 2001; *Lototskaya and Ganssen*, 1999]. However, a Norwegian Sea source cannot be ruled out [*Bauch et al.*, 2000; *Oppo et al.*, 2001]. Although the δ^{13}C record is patchy, the available data suggest that the deglaciation and Heinrich events are generally associated with lower values than are times of reduced IRD.

4.4. Distribution of Benthic Foraminifera

[22] The difference in water depth between the cores 1JPC and 2JPC is nearly 1300 m. Their benthic faunas are, therefore, very different, and below they will be presented separately.

[23] In core 1JPC (2527 m), benthic foraminifera are essentially confined to the intervals between the Heinrich events. The Heinrich events themselves are either barren or contain only few individuals (Figure 6). Two clearly separate species groups can be recognized from the intervals between the Heinrich events (Figure 6). The first group is diverse and dominated by *C. wuellerstorfi*, *Epistominella exigua*, *Uvigerina peregrina*, *Oridorsalis umbonatus*, and *Pullenia bulloides*, but the group includes also a number of less common species such as *Gyroidinoides neosoldanii*, *Cibicides* spp., *Epistominella* spp., *Melonis barleeanum*, *M. pompiliolides*, *Hoeglundina elegans*, and *Rupertina stabilis*. The species of group 1 are typical of the Atlantic Ocean at water depths exceeding ~2000 m [*Streeter*, 1973; *Schnitker*, 1974, 1979; *Schafer et al.*, 1981, 1985; *Thomas et al.*, 1990; *Bilodeau et al.*, 1994; *Harloff and Mackensen*, 1997; *Schmiedl et al.*, 1997]. In core 1JPC, the group is particularly abundant in the samples taken immediately above the Heinrich events (Figure 6).

[24] The second group consists of only two species, namely *Alabaminella weddellensis* and *Pullenia* sp. (Figure 6). *A. weddellensis* is common in the central North Atlantic Ocean today at water depths from about 1000 m to more than 3500 m [*Gooday and Lambshead*, 1989; *Thomas et al.*, 1995; *Loubere*, 1996]. *Pullenia* sp. is a small, thin-shelled form with five chambers in the last whorl resembling *P. osloensis* described from the Oslofjord area [*Feyling-Hanssen*, 1964]. Its ecology is poorly known, although it seems to populate areas with a high organic supply, which is typical for *Pullenia* species [*Schnitker*, 1979; *Kaiho*, 1994]. In core 1JPC, this group shows a tendency to increase in abundance upward approaching the Heinrich events (Figure 6). It is particularly abundant in MIS 2.

[25] Core 2JPC (1251 m) contains a much richer benthic fauna than core 1JPC (Figures 7 and 8). The single most abundant benthic species is *Elphidium excavatum* (Figure 7). It generally constitutes more than 20% of the benthic fauna, and often more than 60%. In the modern Labrador Sea *E. excavatum* is very abundant on the middle slope between 1500 and 2000 m water depth. According to *Schafer et al.* [1981], *Streeter and Lavery* [1982], and *Corliss* [1991] the species is down-transported passively from the shelf areas, but able to survive on the slope [see also *Jennings et al.*, 1996]. In core 2JPC, *E. excavatum* is most abundant near the MIS 4/3 and 3/2 transitions (Figure 7). In stage 5, the highest concentrations are between Heinrich events, whereas in MIS 4, 3 and 2, it peaks in the Heinrich events (Figure 7).

[26] Most of the remaining species can be referred to two clearly separated fauna groups (Figure 8). The first group, termed "the Atlantic species group," is dominated by *Eggerella bradyi* (often referred to as *Tosaia hanzawaia*), *Sigmoilopsis schlumbergeri*, *Bulimina costata*, *Bolivina pygmaea*, *Sagrina subspinescens*, *Gyroidinoides neosoldanii*, *G. umbonata*, and *Epistominella decorata*/*A. weddellensis*. More rare species are *Gavelinopsis praegeri*, *Anomalinoides minimus*, *Valvulineria* spp., and *Bolivina pseudoplicata*. Most of the species assigned to the "Atlantic species group" are relatively common in the modern Labrador Sea at water depths between 1000 and 2500 m [*Cole*, 1981; *Schafer et al.*, 1981; *Schafer and Cole*, 1982]. However, they occur at the same depth off west Africa, along the western European seaboard, in the Mediterranean Sea (see references of *Rasmussen et al.* [1996a]), and on the midoceanic Ridge [*Hermelin and Scott*, 1985]. In core 2JPC, the "Atlantic species group" is most abundant in oxygen isotope substage 5e and in the Heinrich events (Figure 8).

[27] The second group consists of *M. barleeanum* (=*Nonion zaandamae*) and *Islandiella norcrossi*. Two species, *Cassidulina teretis* and *Nonionellina labradoricum*, are often found together with *M. barleeanum* and *I. norcrossi*, but they are not included in the group. *M. barleeanum* does not seem to be a dominant species in the Labrador Sea today [e.g., *Bilodeau et al.*, 1994]. Generally it is especially abundant in areas with a high food supply [*Sejrup et al.*, 1981; *Mackensen et al.*, 1985, 1993; *Caralp*, 1989; *Schmiedl et al.*, 1997]. *I. norcrossi* is a widespread cold water species living on the arctic shelves and slopes [*Vilks*, 1989; *Mudie et al.*, 1984; *Schröeder-Adams et al.*, 1990]. It is also found on the slopes of the Norwegian-Greenland Sea [*Belanger and Streeter*, 1980]. *C. teretis* is relatively abundant in the Labrador Sea today. It lives mainly on the upper to the lower slope. *N. labradorica* is mostly found on the shelf and upper slope [*Schafer and Cole*, 1982; *Mudie et al.*, 1984; *Bilodeau et al.*, 1994].

[28] In core 2JPC, *M. barleeanum* and *I. norcrossi* are most abundant in the intervals between Heinrich events

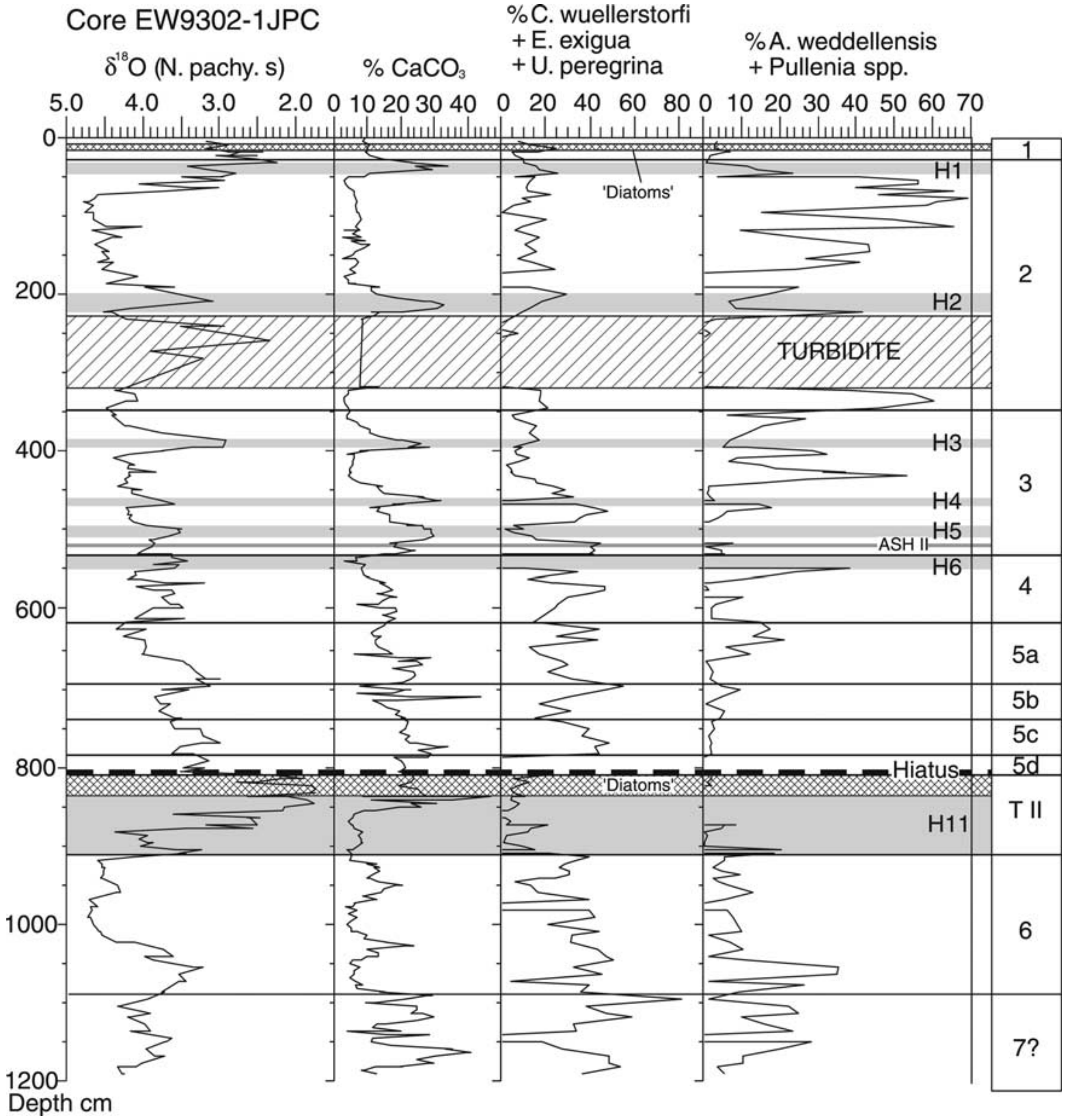

Figure 6. From left to right: Planktic $\delta^{18}O$ record measured on *N. pachyderma* sinistral, carbonate content, relative abundance of the benthic species *C. wuellerstorfi*, *E. exigua*, *U. peregrina* a.o. (see text for explanation), and *A. weddellensis* and *Pullenia* sp. added together for core EW9302-1JPC. Marine isotope stages are indicated to the far right. Bars indicate the position of Heinrich events H1–H6 and H11. Legend otherwise as in Figure 3.

(Figure 8). The somewhat lower relative abundance of *M. barleeanum* and *I. norcrossi* in MIS 5 is in part due to the presence of numerous specimens of *E. excavatum* in this interval.

[29] A correlation between core 1JPC at 2527 m water depth and core 2JPC at 1257 m water depth reveals large faunal differences between the two sites (Figure 3). At 1257 m, the intervals between the Heinrich events contain a fauna dominated by *M. barleeanum* and *I. norcrossi*. At 2527 m, the same intervals are characterized by *C. wuellerstorfi*, *Epistominella exigua*, *Uvigerina peregrina* in the lower parts, and *A. weddellensis* and *Pullenia* sp. in the upper parts. At 1257 m the Heinrich events are dominated by the group of Atlantic species, whereas at 2527 m, the Heinrich events are either barren or contain only few specimens (Figures 6 and 8).

[30] In both cores, the relative abundance of the benthic species fluctuates strongly in the intervals between Heinrich events. The oscillations are particularly pronounced in *M. barleeanum* and *I. norcrossi* during MIS 3 in core 2JPC (Figures 8 and 9) and in *A. weddellensis* and *Pullenia* sp. in core 1JPC (Figure 6).

5. Discussion

[31] Since the record of 1JPC is incomplete with a distinct hiatus in MIS 5 and missing benthic oxygen isotope values

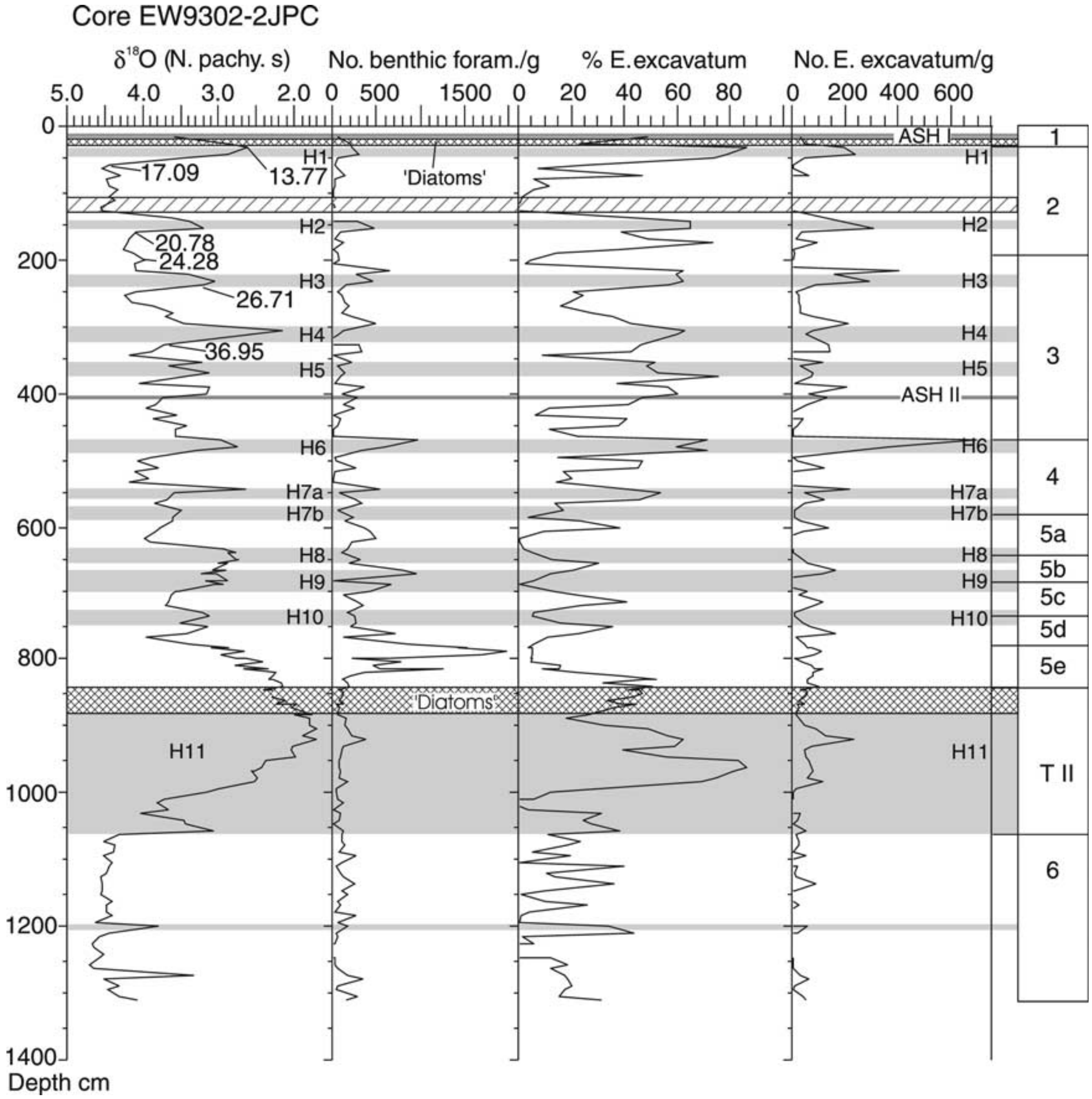

Figure 7. From left to right: Planktic $\delta^{18}O$ record measured on *N. pachyderma* sinistral, number of benthic foraminifera >100 μm per gram dry weight sediment, relative abundance of *Elphidium excavatum*, and number of specimens of *E. excavatum* per gram dry weight sediment for core EW9302-2JPC. Marine isotope stages are indicated to the far right. Bars indicate the position of Heinrich events H1–H11. Legend otherwise as in Figure 3.

in particular in stages 3 and 2, we will in the following focus mostly on 2JPC at 1251 m water depth. The results on 2JPC will then be compared with 1JPC.

5.1. Deep Water Circulation During Termination II and the Interglacial Substage 5e

[32] The transition between MIS 6 and 5 (Termination II) shows some significant differences throughout the North Atlantic realm. The transition is marked everywhere by a decrease in the $\delta^{18}O$ values. However, in cores from North Atlantic locations the decrease takes place over a few centimeters to decimeters [e.g., *McManus et al.*, 1994; *Oppo et al.*, 1997, 2001; *Adkins et al.*, 1997; *Labeyrie et al.*, 1999; *Hillaire-Marcel et al.*, 2001; *Hiscott et al.*, 2001], whereas in the Norwegian-Greenland Sea it generally occurs over several meters [*Fronval and Jansen*, 1997; *Rasmussen et al.*, 1999]. The amount of IRD in the transitional zone also varies significantly. The problems of interpreting these differences are compounded by the fact that the corresponding interval in the Greenland ice cores is disputed and unresolved. We will therefore pay special attention to this transition.

[33] The sediments associated with Termination II are almost 2 m thick in 2JPC and more than 4 times thicker than MIS 5e, thus resembling the transition in the Norwegian-Greenland Sea. The content of IRD is low except for a prominent peak, H11, in the upper part. The high content of detrital carbonate indicates a significant source in the

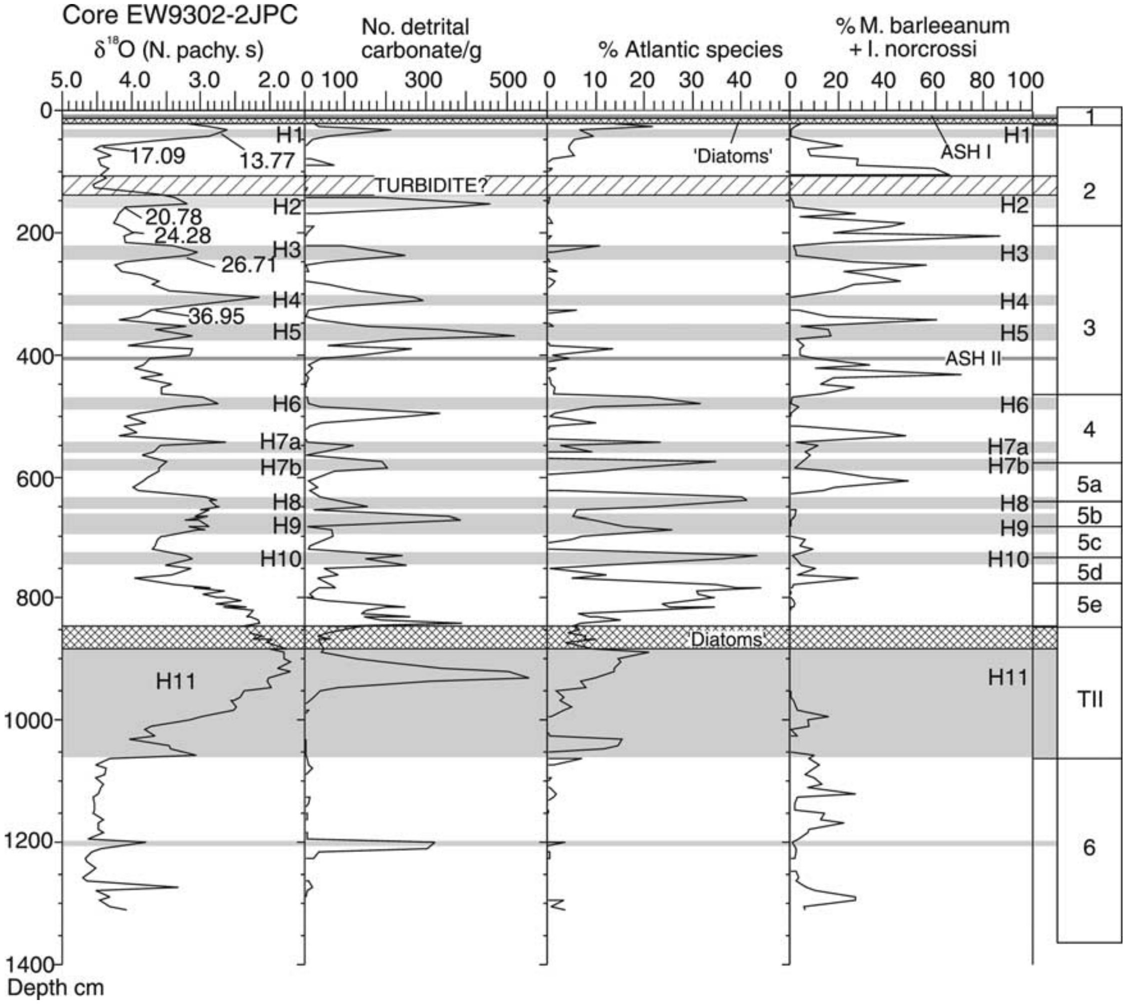

Figure 8. From left to right: Planktic $\delta^{18}O$ record measured on *N. pachyderma* sinistral, the number of detrital carbonate grains per gram dry weight sediment, relative abundance of the benthic "Atlantic species group" (see text for explanation), and relative abundance of the two benthic foraminifera *M. barleeanum* and *I. norcrossi* added together for core EW9302-2JPC. Marine isotope stages are indicated to the far right. Bars indicate the position of Heinrich events H1–H11. Legend otherwise as in Figure 3.

Hudson Strait area [e.g., *Bond et al.*, 1992; *Andrews and Tedesco*, 1992; *Andrews et al.*, 1994; *Andrews*, 1998; *Hemming et al.*, 1998; *Hiscott et al.*, 2001]. The evidence of decreasing values of $\delta^{18}O$ prior to the H11 event suggests that considerable amounts of deglacial meltwater had already entered the North Atlantic before the massive iceberg discharge from the Laurentide ice sheet first arrived north of the Flemish Cap, and we suggest that the greatly increased thickness of Termination II, both in 2JPC and in the Norwegian Sea, is due to locally enhanced sedimentation rates during the deglaciation.

[34] A diatom layer (predominantly *Coscinodiscus* spp. > 106 μm) follows the first deglacial IRD event. Unusually large blooms of diatoms are often seen in upwelling zones or in the mixing zone between warm and cold surface water, where high amounts of nutrients are available [see *Bodén and Backman*, 1996]. In the Late Quaternary North Atlantic, diatom layers are often associated with major transitions between cold and warm isotope stages [*Aksu and Mudie*, 1985; *Jennings et al.*, 1996], and in the Norwegian Sea diatom beds have been observed both at the base of MIS 5 and 1 [*Koç and Jansen*, 1992; *Rasmussen et al.*, 1996a, 1996b, 1999].

[35] Just above the diatom layer, the composition of the planktic foraminifera changes abruptly, and it is evident that the layer marks a major change in the paleoceanographic conditions. The decreasing relative abundance of the polar planktic foraminifera *N. pachyderma* s indicates a rapid increase of the temperature in the upper water column (Figure 4). Subpolar planktic species such as *N. pachyderma* d, *Globigerina bulloides*, *Turborotalia quinqueloba*, *Globorotalia inflata* become abundant. Nevertheless, a second prominent IRD peak containing coarse detrital carbonate coincides with the rise in SST (Figure 4) and large-scale ice rafting apparently continued well after the sea surface first warmed. The presence of detrital carbonate indicates that many of these icebergs likewise came from the Hudson Strait area suggesting that the Laurentide Ice

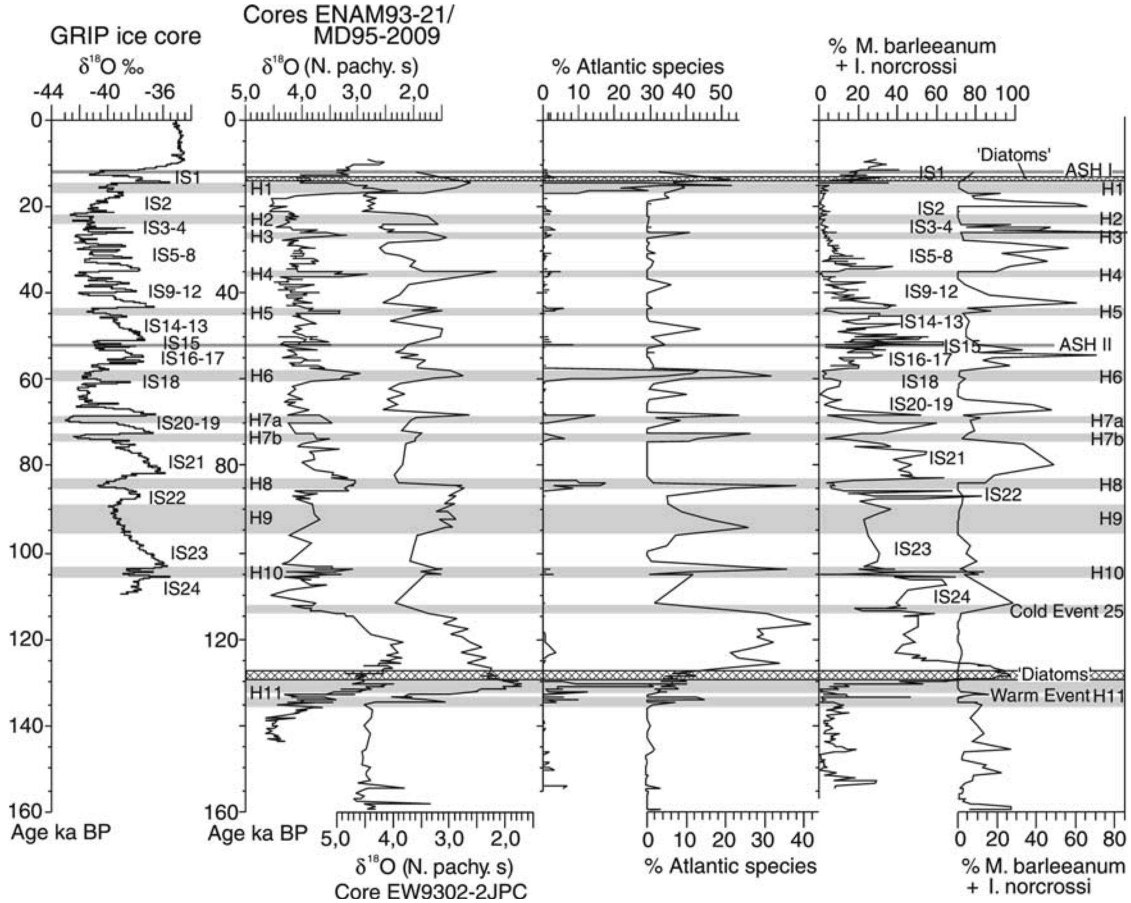

Figure 9. Comparison of records from GRIP Greenland ice core, EW9302-2JPC, and ENAM93-21/MD95-2009 on ice core/calendar timescale. From left to right: Oxygen isotope record from the GRIP Greenland ice core [*Johnsen et al.*, 1992; *Dansgaard et al.*, 1993], planktic δ^{18}O record measured on *N. pachyderma* sinistral for ENAM93-21/MD95-2009, and EW9302-2JPC, relative abundance of the benthic "Atlantic species group" (see text for explanation) for ENAM93-21/MD95-2009, and EW9302-2JPC, and relative abundance of *M. barleeanum* and *I. norcrossi* added together for ENAM93-21/MD95-2009, and EW9302-2JPC, respectively.

Sheet deglaciated late and sea surface warmth may have supported the final melting phase of the deglaciation. An alternative explanation could be a lake outbreak through the Hudson Strait as is known to have occurred during the early Holocene at 8.2 ka BP [*Barber et al.*, 1999; *Labeyrie et al.*, 1999].

[36] The benthic δ^{13}C values were high during the early part of Termination II (Figures 4 and 5), suggesting that an intermediate water mass formed at this time and that thermohaline circulation played a role in the early melting. Concurrent with the ice rafting event registered at 1000 cm (c. 135 ka BP) in core 2JPC δ^{13}C values decreased and remained low for the remainder of the deglaciation and earliest MIS 5e. Only, when the surface waters were nearly free of debris carrying icebergs did δ^{13}C increase again (Figure 4). The low benthic δ^{13}C values during the late Termination II and early MIS 5e indicate the presence of a poorly ventilated intermediate-depth water mass, rich in inorganic nutrients. In fact, the consistent association of low δ^{13}C values with high IRD suggests that the production of intermediate-depths water was strongly reduced whenever extensive layers of icebergs and meltwater were present at the surface. The low benthic δ^{18}O values suggest that this poorly ventilated water mass contained some deglacial meltwater [e.g., *Lehman et al.*, 1993].

[37] The changes in the benthic foraminifera assemblages generally support the interpretations based on isotope data. The foraminifera faunas in 2JPC during both Termination II and MIS 5e were dominated by the "Atlantic species group" with the addition of abundant *E. excavatum* during Termination II and the early part of MIS 5e (see Figures 7 and 8). The "Atlantic species group" has a high affinity to the present fauna in the area at water depths between 1000 and 1500 m [see, e.g., *Cole*, 1981; *Schafer et al.*, 1981] suggesting a somewhat similar benthic situation with relatively warm bottom water. However, conditions clearly comparable to the modern situation did not arise until after the increase in the δ^{13}C values in the early part of MIS 5e (Figure 4). The improvements in the benthic conditions is indicated by the higher concentration of benthic foramin-

ifera, the maximum relative abundance of the "Atlantic species group," and the decline in *E. excavatum* in the late part of MIS 5e (Figures 7 and 8).

[38] We conclude that the surface and bottom water conditions during the peak of MIS 5e at 2JPC were comparable to the modern conditions in the area indicating that the intermediate water mass at 1251 m was fairly similar to the modern Labrador Sea Water. This suggests that LSW was generated throughout the peak of MIS 5e, although, perhaps, at a more northerly position than today (Figure 1). The benthic faunas indicate that the intermediate water mass that occupied the area during late Termination II and early MIS 5e also was fairly LSW-like. However, the low $\delta^{13}C$ values suggest that the water was poorly ventilated, and the flow was probably much weaker than during peak MIS 5e. We suggest that this water mass was formed outside of the Labrador Sea, probably to the south of the Heinrich belt, and that it entered the SE Labrador Sea from an eastern direction.

[39] Our conclusion regarding peak MIS 5e contrasts with that of *Hillaire-Marcel et al.* [2001] who suggest that LSW did not form during this time period and that a water mass resembling the overflow water from the Greenland Sea occupied the entire water column below a thin low-density surface layer. This conclusion was derived by estimating density of surface, subsurface, middepth, and deep water from dinocyst assemblages, and the oxygen isotope values of the planktic foraminifera *G. bulloides*, *N. pachyderma* s, and the benthic foraminifera *C. wuellerstorfi*, respectively, during MIS 5e and the Holocene. They conclude that the upper density contrast was too large to permit overturning during MIS 5e. However, the "Atlantic species group" found at 1251 m water depth in our core 2JPC does not appear to be linked to overflow water from the Nordic Seas (see references of *Rasmussen et al.* [1996a]). The two studies rely on different assumptions, and further investigations are needed to reconcile our different interpretations.

5.2. Water Circulation During the Glacial Period

5.2.1. Heinrich Events

[40] The high abundance of *N. pachyderma* s during Heinrich events (Figures 4 and 5) suggests that the surface water was cold. Large amounts of IRD indicate the presence of numerous icebergs over the investigated sites, and the low $\delta^{18}O$ values at the surface are attributed to iceberg melting.

[41] The benthic faunas at 1251 m are generally dominated by the "Atlantic species group" and *E. excavatum* (Figures 7 and 8). This indicates that the bottom conditions during Heinrich events H10–H1 were fairly similar to those of Termination II (H11) and early MIS 5e with relatively warm, intermediate bottom water. The low $\delta^{13}C$ values at 2JPC (Figure 4) suggest that the water was poorly ventilated and rich in inorganic nutrients. Low $\delta^{13}C$ values at middepth during Heinrich events have been recorded both at subpolar North Atlantic Ocean sites [*Curry et al.*, 1999], at a shallow ($\sim$1100 m) subtropical site [*Zahn et al.*, 1997], and from the Norwegian Sea [*Dokken and Jansen*, 1999]. At 1JPC at 2527 m conditions during Heinrich events were too severe for benthic foraminifera (Figure 6), suggesting that there was very little circulation of the deep water masses at about 2.5 km water depth.

5.2.2. Intervals Between Heinrich Events

[42] The intervals between Heinrich events are characterized by low IRD content and relatively high benthic and planktic $\delta^{18}O$ values and high benthic $\delta^{13}C$ values (Figures 3–5). The high surface $\delta^{18}O$ values combined with the high abundance of *N. pachyderma* s suggest cold near-surface conditions (Figures 4 and 5). Although poorly resolved, the high $\delta^{13}C$ values suggest improved ventilation of deep waters.

[43] In core 2JPC, the benthic fauna is dominated by *M. barleeanum*, *I. norcrossi* together with *C. teretis* and *N. labradorica* (Figure 8). These species are well known from the Northwestern Labrador Sea, where *M. barleeanum* (as *N. zaandamae*), *C. teretis*, and *N. labradorica* dominate during MIS 2 and 3 [*Aksu and Mudie*, 1985; *Jennings et al.*, 1996]. *M. barleeanum*/*N. zaandamae* has also been noted to increase during interglacials and larger interstadials in deep sea records from the South Atlantic [*Schmiedl and Mackensen*, 1997]. Both *I. norcrossi* and *M. barleeanum* are very abundant in the interstadial and interglacial sediments in the SE Norwegian Sea at comparable water depth (1020 m) [*Rasmussen et al.*, 1996b, 1999]. The fauna is here attracted to ample and sustained food supply and connected to outflow water (NSOW) from the Norwegian Sea through the Faeroe-Shetland Channel [*Rasmussen et al.*, 1996a, 1996b, 1999]. The NSOW is here characterized by high $\delta^{18}O$ values [*Rasmussen et al.*, 1996b, 1999; *Balbon*, 2000], and produced during interstadial and interglacial periods [*Rasmussen et al.*, 1996a, 1996b, 1999]. In the North Atlantic, the NSOW is an important contributor to the NADW, which is recognized by its high $\delta^{13}C$ values [*Kroopnick*, 1985]. Today the NADW passes close to the investigated sites, and we suggest the faunal and isotopic similarity between the interstadials in the Norwegian-Greenland Sea and the intervals between the Heinrich events in 2JPC is due to this common water mass.

[44] The benthic faunas of 1JPC (2527 m water depth) are different from those of 2JPC. However, *C. wuellerstorfi*, *E. exigua*, *O. umbonatus* a.o., dominating the lower parts of the intervals between Heinrich events in 1JPC are typical NADW species (Figure 6). This group is replaced later by *Pullenia* sp. and *A. weddellensis* indicating a change to more food rich and less oxygenated conditions. The change probably signifies a reduction in NADW-flow. *Pullenia* species are often recorded in glacial North Atlantic records deeper than about 2000 m [*Schnitker*, 1979; *Scott et al.*, 1989; *Bilodeau et al.*, 1994, *Thomas et al.*, 1990, 1995].

6. Conclusions and Comparison of the SE Labrador Sea and the SE Norwegian Sea

[45] Isotope, IRD, and faunal distributions in two deep sea cores from the SE Labrador Sea at water depths of 1251 m and 2527 m, respectively, demonstrate that during the time period from 160,000 to 10,000 years BP there were several IRD events recorded in the Labrador Sea. This interval was characterized by rapid variations in deep and surface water circulation.

[46] We have identified all Heinrich events H1–H11 by high concentrations of IRD and detrital carbonate and strong depletions in both surface and benthic ^{18}O. A conspicuous IRD and detrital carbonate event occurring during the early part of MIS 5e was associated with warm near-surface waters, suggesting that oceanic warmth may have contributed to the final melting of the Laurentide ice sheet. Alternatively, the event was the result of a lake outbreak [e.g., *Barber et al.*, 1999; *Labeyrie et al.*, 1999]. The composition of the benthic foraminifera faunas combined with the benthic carbon isotopes indicate that bottom water conditions were fairly similar to the present conditions and Labrador Sea Water was apparently generated throughout peak MIS 5e. A hiatus precludes evaluation of MIS 5e at the deeper site 1JPC at 2527 m water depth. However, other evidence suggests that NSOW was formed in the Nordic Seas during MIS 5e [e.g., *Fronval and Jansen*, 1997; *Rasmussen et al.*, 1999]. NSOW/NADW may therefore also have been present in the deep Labrador Sea as suggested by *Hillaire-Marcel et al.* [2001].

[47] The Heinrich events were characterized at both sites by a cold, fresh surface water mass and numerous icebergs. The benthic foraminifera, dominated by the "Atlantic species group," and the oxygen and carbon isotopes indicate that the icy surface water was overlaying a relatively warm, poorly ventilated and nutrient rich intermediate water mass down to a water depth of at least 1251 m. We propose that this water mass was generated south of the Heinrich belt and entered the SE Labrador Sea from the east. The paucity of benthic foraminifera at 2527 m water depth suggests that this depth was also poorly ventilated.

[48] During the time periods between Heinrich events the surface water probably was derived from the Gulf Current system as today. However, the planktic fauna was dominated by *N. pachyderma* s indicating that the near-surface water was colder than today. The benthic foraminifera in both cores were dominated by species that are typical of the NSOW/NADW system [*Rasmussen et al.*, 1996a, 1996b] and it is probable that the deep water at both sites consisted of NADW. Isotope and fauna changes in the deeper core at 2527 m water depth indicate a reduction in the NADW flow prior to the Heinrich events.

[49] The isotope and faunal records of the SE Labrador Sea have many features in common with the records from the SE Norwegian Sea. The surface and benthic δ^{18}O records are very similar. The values were low during Heinrich/stadial events and high during the intervening time intervals [*Rasmussen et al.*, 1996b, 1999; *Balbon*, 2000]. Furthermore, some distinctive characteristics have been recorded in both areas. For example, H7 and H11 show double peaks in IRD, isotopes and faunas in both the SE Norwegian Sea and in the SE Labrador Sea.

[50] Heinrich events in both areas are characterized by low benthic δ^{18}O values, a planktic fauna totally dominated by *N. pachyderma* s [see also *Rasmussen et al.*, 1996b, 1999; *Balbon*, 2000], and the presence of the "Atlantic species group" in the benthic fauna. This suggests that the water column in both areas was stratified with a cold, icy surface water of reduced salinity overlaying a warmer, intermediate water mass, rich in inorganic nutrients. The intermediate water masses may have had the same origin south of the Heinrich Belt.

[51] During the periods in between Heinrich events (interstadials) the surface water in both areas originated from the Gulf Stream system. However, dominance of *N. pachyderma* s shows that the sea surface temperatures were lower than today [see also *Rasmussen et al.*, 1996a, 1996b, 1999]. *M. barleeanum* and *I. norcrossi* dominate the benthic faunas in both areas. They are typical of the NSOW/NADW system, and it is probable that during these periods this water mass formed a direct physical connection between the two areas.

[52] During MIS 5e *N. pachyderma* s was rare in both the SE Labrador Sea and the SE Norwegian Sea, and surface water in both areas consisted of relatively warm water from the Gulf Stream system [see also *Rasmussen et al.*, 1996a, 1996b, 1999]. The composition of the benthic faunas suggests that deep water was generated by convection in both the northern Norwegian-Greenland Sea [*Rasmussen et al.*, 1999] and the Labrador Sea, largely as today.

[53] Finally, it should be noted that the smaller stadial events between Heinrich events that are so conspicuous in the Greenland ice cores and in the Norwegian Sea records have not been directly observed in the investigated cores from the Labrador Sea [see also *Andrews and Barber*, 2002]. They may be reflected in the strongly fluctuating relative abundance of the benthic foraminifera *M. barleeanum* and *I. norcrossi* during MIS 3 in core 2JPC and of *A. weddellensis* and *Pullenia* sp. in core 1JPC. Nevertheless, their oceanographic and ecological impact must have been smaller in the Labrador Sea than in the Norwegian Sea.

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