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Benthic $\delta^{18}O$ records in the North Atlantic over the last glacial period (60-10 kyr): Evidence for brine formation

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Abstract. Four high-resolution benthic isotope records from North Atlantic and south Norwegian Sea cores are compared for the past 60 kyr. The benthic records show light $\delta^{18}O$ peaks simultaneously to or following the Heinrich events. The amplitude of these light peaks varies between 1‰ for the most northern core ENAM93-21 and 0.35‰ for the deep North Atlantic cores. The high $\delta^{18}O$ gradient between the North Atlantic cores and the Pacific core V19-30 suggests a regional influence of $\delta^{18}O$-depleted meltwater to deeper depth during periods of iceberg discharges. The most likely process for transferring $\delta^{18}O$-depleted meltwater to depth is sea ice formation induced by brine formation. During Heinrich events 4 and 3 this mecanism was of major importance (compared to open ocean convection) in the southern Norwegian Sea and at the northern boundaries of the Atlantic, leading to intermediate to deep water formation. Other $\delta^{18}O$ excursions appearing in all the records point to the contribution of both brine formation and global changes in the $\delta^{18}O$ of seawater associated with the Heinrich event periods.

1. Introduction

High climatic variability over the last glacial period (60-10 kyr) has been revealed from ice core records [*Dansgaard et al.*, 1993] and North Atlantic sediment cores [*Heinrich*, 1988; *Bond et al*, 1992; *Broecker et al.*, 1992]. Millennial-scale variations refer to the so-called Heinrich events characterized by large iceberg discharges into the North Atlantic. The freshwater signature of these events has been recorded all over the North Atlantic (40°-60°N) [*Bond et al.*, 1993; *Labeyrie et al.*, 1995] and in the Norwegian Sea [*Fronval et al.*, 1995; *Rasmussen et al.*, 1996a], indicating that both the Laurentide and the Fennoscandinavian ice sheets contribute to the iceberg discharges.

The deep circulation response to temperature and salinity perturbations subsequent to the iceberg discharges has been studied [*Maslin et al.*, 1995; *Oppo and Lehman*, 1995; *Sarnthein et al.*, 1994; *Vidal et al.*, 1997; *Zahn et al.*, 1997]. Associated with the Heinrich events, changes in the North Atlantic Deep Water production are observed though the response being different from one event to another. Deep water production seems to be shut down for the HL1 period [*Keigwin and Lehman*, 1994; *Sarnthein et al.*, 1994] while during HL4 there is evidence of well ventilated deep waters in the central Atlantic [*Vidal et al.*, 1997].

In this paper, high-resolution $\delta^{18}O$ benthic records from North Atlantic and south Norwegian Sea cores are compared. The study is focused on the $\delta^{18}O$ variations (light peaks) observed in each record, associated with or lagging the Heinrich events. During these events, $\delta^{18}O$-depleted freshwater tongues extended into the North Atlantic Ocean. To interpret the benthic signal, several hypotheses are considered: global change in the $\delta^{18}O$ of seawater, deep water temperature changes, or more local processes directly associated with the Heinrich events. Particularly, the transfer of light oxygen surface waters from the melting icebergs to deeper depth, induced by brine formation, will be discussed.

2. Methods

This study is based on the comparison between benthic $\delta^{18}O$ records from cores located in the North Atlantic and the south Norwegian Sea (Figure 1). All the cores have been ^{14}C dated and display a resolution better than 500 years for the last glacial period [*Oppo and Lehman*, 1995; *Rasmussen et al.*, 1996a, b; *Vidal et al.*, 1997]. Radiocarbon timescales were used after correcting the ^{14}C dates from the reservoir age [*Bard*, 1988].

Two high-resolution deep-sea cores from the North Atlantic were selected (Figure 1): NA87-22 (55°N, 14°W, 2160 m) and SU90-08 (43°N, 30°W, 3080 m). For both cores, oxygen and carbon isotopes have been performed on the benthic foraminifera species *Cibicides wuellerstorfi*. The stratigraphy is based on ^{14}C datings and the high-resolution benthic $\delta^{18}O$ records (Figures 2 and 3). The chronostratigraphy for isotopic stage 3 was further constrained by the identification of the ice-rafted debris (IRD) peaks (characterizing the Heinrich layers) in both cores and correlation of the $\delta^{13}C$ records, considering core NA87-22 as the reference [*Vidal et al.*, 1997]. Core V29-202 (60°N, 21°W,

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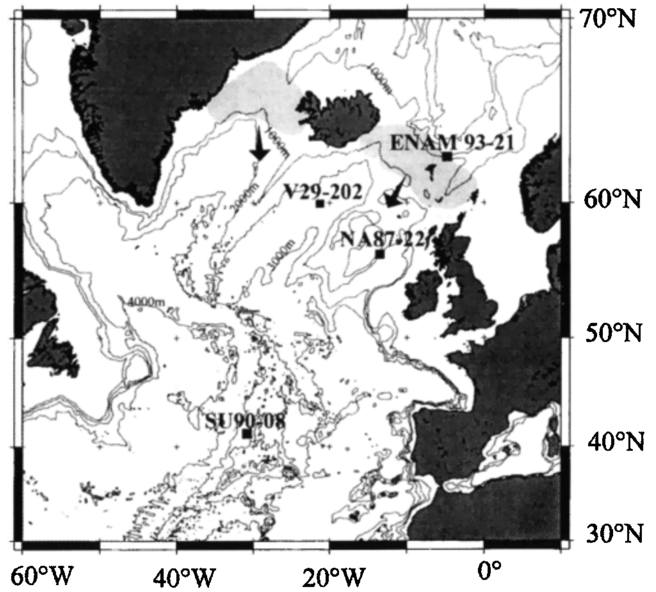

Figure 1. Map of the studied area showing the location of the cores. The shaded areas indicate the possible sites for brine formation during the Heinrich events.

2658 m) was retrieved at the northern boundaries of the Atlantic Ocean [*Oppo and Lehman*, 1995] (Figure 1). For a better comparison the timescale from core V29-202 was slightly reworked by using several time constraints to the original age model based on ^{14}C datings [*Oppo and Lehman*, 1995]: the IRD counts were correlated to the reference cores in this study, NA87-22 and SU90-08 (Figure 4). Age control for the south Norwegian Sea core ENAM93-21 (62°N, 4°W, 1020 m) was achieved by ^{14}C datings [*Rasmussen et al.*, 1996a] and ash layers 1 and 2 [*Mangerud et al.*, 1984; *Ruddiman and Glover*, 1972] (Figure 4). The position of the Heinrich events are characterized by light peaks in the planktonic $\delta^{18}O$ record by analogy with Ocean Drilling Program (ODP) site 609 [*Rasmussen et al.*, 1996a] (Figure 5a). The age model was constrained by adding the ages of the Heinrich events (1-5) obtained from a detailed chronostratigraphic study on North Atlantic cores [*Vidal et al.*, 1997].

3. Results

We will first discuss the major trends in the benthic $\delta^{18}O$ records and the light $\delta^{18}O$ peaks observed in the North Atlantic cores and the implications of the intercore variability of the $\delta^{18}O$ signal. Minima observed in planktonic $\delta^{18}O$ records from the North Atlantic have been interpreted as resulting from large fluxes of glacial meltwater to the sea surface during the Heinrich events [*Bond et al.*, 1993; *Labeyrie et al.*, 1995] (Figure 3). Related to the Heinrich events, the benthic $\delta^{18}O$ records from the North Atlantic show different features from one core to the other, while the $\delta^{13}C$ variations are more similar in the two cores (Figure 3). The covariation in the $\delta^{13}C$ values has been interpreted as resulting from changes in the deep circulation [*Vidal et al.*, 1997].

The major trend of the benthic $\delta^{18}O$ records reflects isotopic changes in the world's ocean water resulting from the variation in global icevolume and changes in deep water temperature [*Duplessy et al.*, 1980; *Labeyrie et al.*, 1987]. Over the last glacial period the general trend of the North Atlantic benthic records was similar to the benthic record from core V19-30, which is considered to reflect global changes in the $\delta^{18}O$ of seawater for the period 60-11 kyr [*Labeyrie et al.*, 1987], indicating that ice-volume changes are governing the large-scale fluctuations in the North Atlantic records (Figure 3). The light $\delta^{18}O$ peaks in the North Atlantic cores could correspond to those appearing in the V19-30 record at ~40 ka and ~30 ka B.P. considering the age uncertainties in this core (Figure 3). The age scale from core V19-30 is obtained from the correlation to the benthic record from core TRI 163-31 [*Shackleton et al.*, 1988] for the period 25-0 kyr B.P. and, for deeper levels, from the spectral tuning [*Shackleton et al.*, 1983]. The accuracy of dating with the spectral tuning method is low for climatic changes with a periodicity less than 5000 years [*Imbrie et al.*, 1992]. However, in the North Atlantic records the light $\delta^{18}O$ peaks are of a larger magnitude with a 0.35‰ lowering compared to the -0.15‰ in the V19-30 record. The differences in amplitude between the areas indicate that regional factors (temperature or local processes) are superimposed on the global signal.

The light $\delta^{18}O$ peaks in the North Atlantic cores do not show the same characteristics from one core to the other; for HL4 and HL3 the light isotope peaks are apparent only in the shallow core NA87-22 and not in the deeper core SU90-08 (Figure 3). There is no characteristic signal observed for HL2. Light benthic $\delta^{18}O$ peaks synchroneous with HL5, HL1, and following HL4 event (at about 33 ka) are observed in both cores (Figure 3). Similar features occur in other benthic records from cores located further

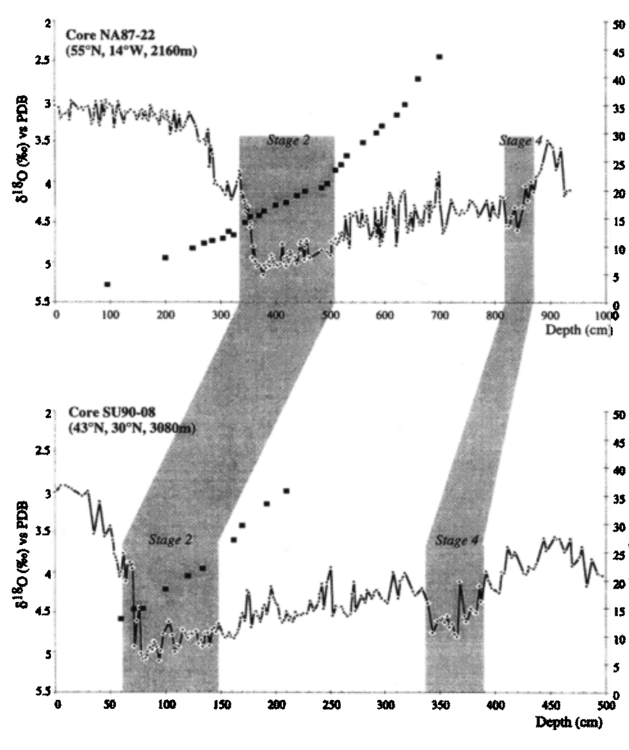

Figure 2. Benthic oxygen and carbon isotopes records versus depth from the North Atlantic cores NA87-22 and SU90-08. (The$\delta^{18}O$ was corrected by +0.64‰ for specific fractionation of *Cibicides wuellerstorfi* [*Duplessy et al.*, 1984]). The solid squares indicate the ^{14}C datings.

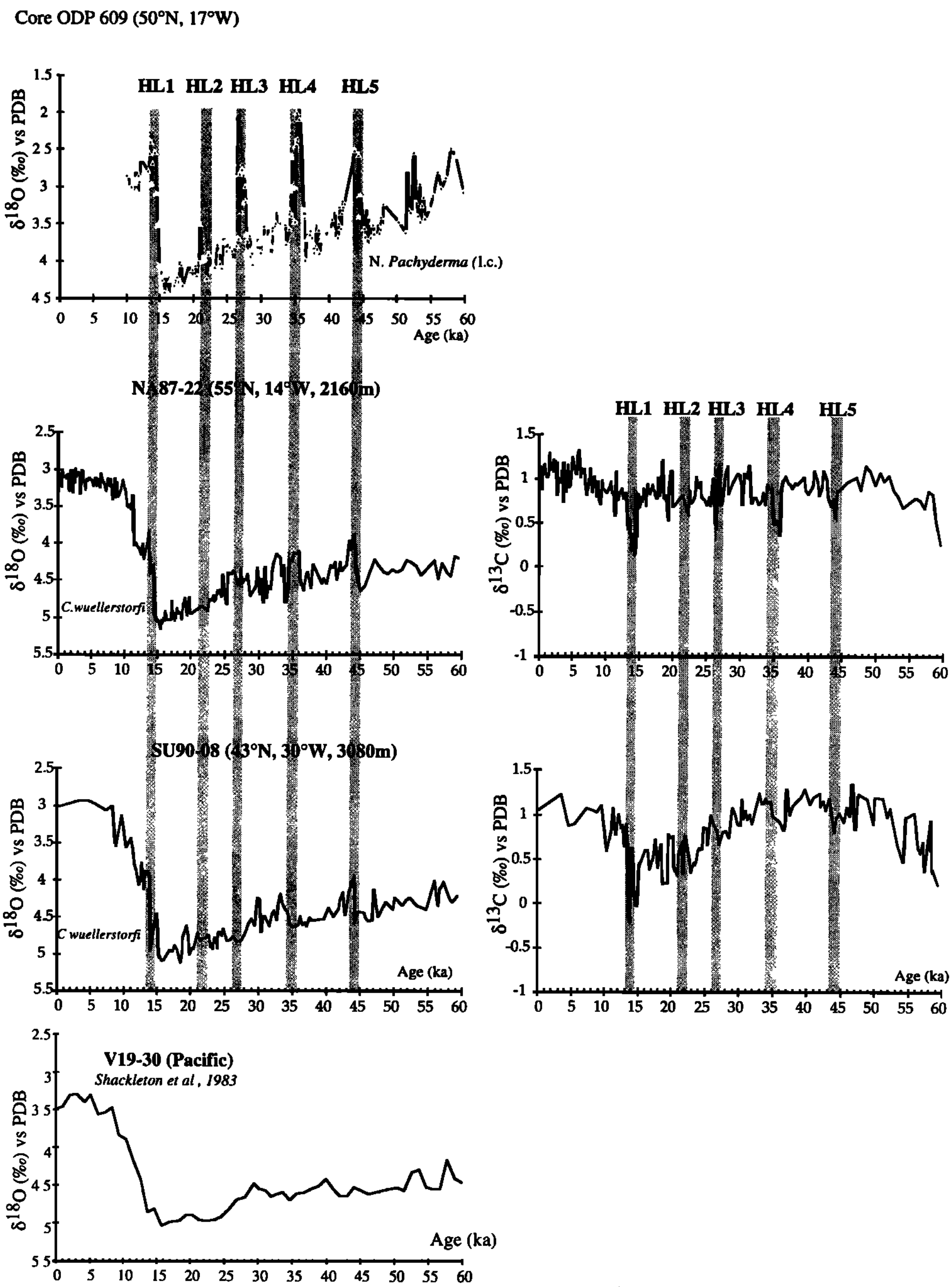

Figure 3. The planktonic $\delta^{18}O$ record from Ocean Drilling Program (ODP) site 609 [*Bond et al.*, 1993]. The shaded lines indicate the Heinrich events. Also given are the benthic oxygen and carbon isotopes records versus age (kyr) from the North Atlantic cores NA87-22 and SU90-08 and benthic oxygen isotope records from east Pacific core V19-30 [*Shackleton et al.*, 1983].

north in the Atlantic (V29-202) and in the south Norwegian Sea (ENAM93-21) (Figure 4). The ENAM93-21 benthic record shows the largest amplitude in light $\delta^{18}O$ peaks during the Heinrich events. As mentioned above, for HL4 and HL3 the amplitude of the light benthic peaks decreases markedly from this shallow core to the deep North Atlantic core V29-202 (2600 m) (Figure 4). Probably, for these events the light benthic $\delta^{18}O$ peaks observed in the shallower cores (ENAM93-21, V29-202, and NA87-22) result from local processes transferring the highly negative $\delta^{18}O$ surface waters downward. For HL5, HL1, and following HL4 the light $\delta^{18}O$ peaks in the North Atlantic cores are in the same range of magnitude (from 2000 to more than 3000 m depth) (Figure 4). This could indicate the contribution of changes in the global $\delta^{18}O$ of seawater and will be discussed later.

Particular interest is focused on the ENAM93-21 core from the margin of the Faeroe-Shetland Channel which shows high-amplitude light peaks (1‰) in the benthic $\delta^{18}O$ record (Figure 4). The interstadial and stadial intervals are defined from the correlation of the ENAM93-21 core to the Greenland ice record [*Rasmussen et al.*, 1996a] (Figure 5a). Related to the iceberg discharges, the benthic record, like the planktonic record,

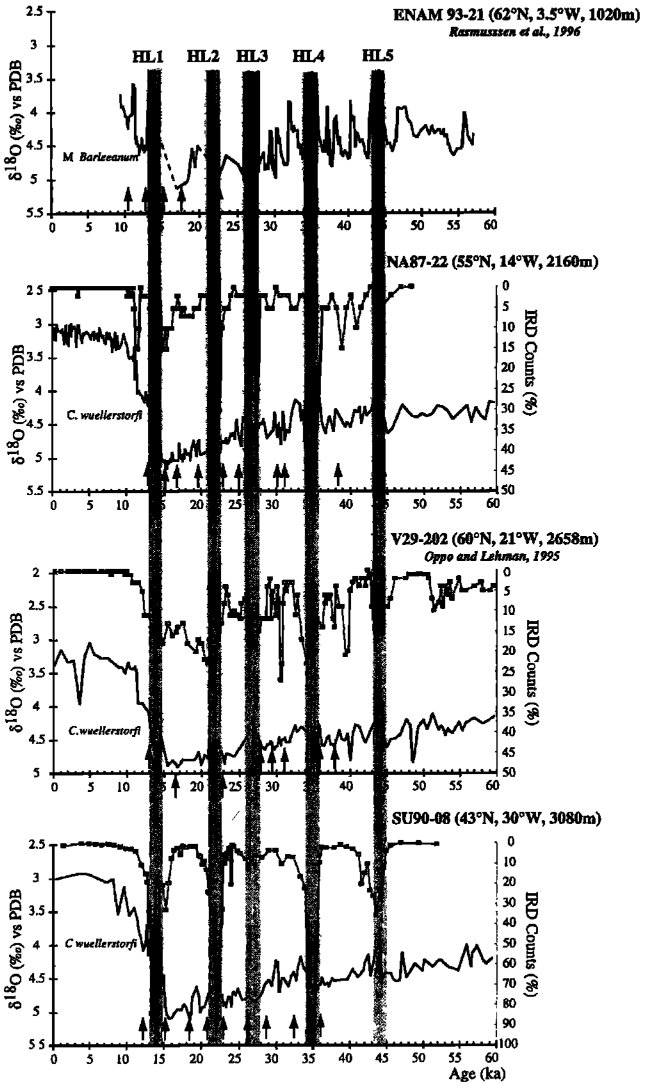

Figure 4. Benthic $\delta^{18}O$ records from a southern Norwegian Sea core (ENAM93-21) and North Atlantic cores (NA87-22, V29-202, and SU90-08). For the ENAM93-21 core the benthic $\delta^{18}O$ values were corrected by 0.4‰ for specific fractionation of *Melonis Barleeanum* [*Shackleton,* 1977]. The data from core V29-202 are from *Oppo and Lehman* [1995]. The IRD counts versus age for the North Atlantic cores are shown. The shaded lines indicate the Heinrich events. The arrows indicate the position of the ^{14}C dated levels in each core

shows a succession of $\delta^{18}O$ depletions (Figure 5a). The larger peaks correspond to the Heinrich events and the smaller peaks correspond to the stadials [*Rasmussen et al.*, 1996a]. Associated with HL5, HL4, and HL3, both planktonic and benthic records show an ~1‰ amplitude, while the amplitude is larger in the planktonic during HL1 (> 2‰). Conversely, for the stadials the $\delta^{18}O$ depletions are larger in the benthic record. The covariation of both records (planktonic and benthic) over the last glacial period shows that surface and deep waters were strongly coupled, suggesting vertical overturn in the water column. The ~1‰ excursion in the planktonic $\delta^{18}O$ record of ENAM93-21 core during the Heinrich events corresponds at least to a ~1‰ decrease in surface water salinity as the freshwater comes from iceberg melting with low $\delta^{18}O$ (-35‰) [*Labeyrie et al.*, 1995].

The low-salinity lid would have prevented deep convection at this area and the transfer of the $\delta^{18}O$-depleted surface waters to deeper depth. Benthic foraminifera fauna studies on the ENAM93-21 core pointed to an influx of Atlantic intermediate

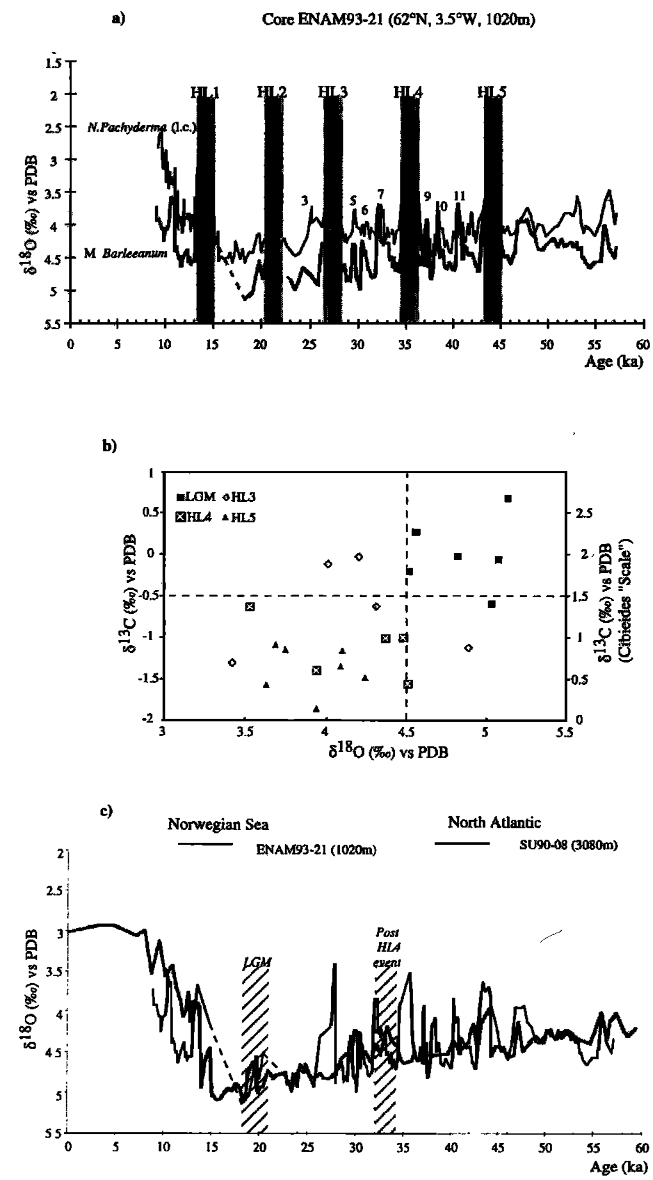

Figure 5. (a) Planktonic and benthic $\delta^{18}O$ records versus age from core ENAM93-21 [*Rasmussen et al.,* 1996b]. The measurements have been made on a Finnigan Mat251 (with an automated kiel device) at Gif/Yvette laboratory and are reported in per mill versus Pee Dee Belemnite (PDB) after calibration with National Bureau of Standards (NBS) 19 [*Coplen*, 1988]. The shaded areas indicate the Heinrich events, and the numbers refer to the stadials defined in the Greenland ice record [*Dansgaard et al.,* 1993]. (b) Benthic foraminifera values of $\delta^{18}O$ versus $\delta^{13}C$ from core ENAM93-21 for different periods: LGM, HL3, HL4, and HL5. The $\delta^{13}C$ values are plotted on two different scales: the raw $\delta^{13}C$ values versus PDB measured on *M. Barleeanum* (left *y* axis) and the raw $\delta^{13}C$ values corrected to a "Cibicides" scale to facilitate comparison with published $\delta^{13}C$ records, $\delta^{13}C_{(Cibicides)} = \delta^{13}C$*(M. Barleeanum)* + 2‰ [*McCorkle and Keigwin,* 1990] (right *y* axis). (c) Benthic $\delta^{18}O$ records versus age from shallow south Norwegian Sea core ENAM93-21 and North Atlantic core SU90-08.

water to the Norwegian Sea during the Heinrich events and the stadials [*Rasmussen et al.*, 1996b]. This water mass has lower $\delta^{18}O$ values than the deeper waters and could cause part of the variability in the benthic $\delta^{18}O$ signal. However, the influence of this newly formed water mass would lead to high $\delta^{13}C$ as observed during the last glacial maximum (LGM) [*Oppo and Lehman*, 1993]. The comparison of the benthic $\delta^{18}O$ and $\delta^{13}C$ values in the ENAM93-21 core shows distinctly lower values during Heinrich events 3, 4, and 5 compared to the values during the LGM (Figure 5b). High $\delta^{13}C$ values are related to the influence of the Atlantic Intermediate Water in the south Norwegian Sea during the LGM, whereas the isotope data show $\delta^{18}O$-depleted and low-ventilated waters associated with the iceberg discharges. Probably, most of the shallow waters were invaded during these periods with ^{13}C-depleted deeper, colder waters [*Vidal et al.*, 1997]. This should introduce a positive $\delta^{18}O$ foraminiferal shift in opposition to what is observed (Figure 4). The most likely explanation for the negative $\delta^{18}O$ shift in the benthic record is the introduction at depth through brine formation of cold, low-$\delta^{18}O$ water spiked by melted continental ice. No fractionation occurs during sea-ice freezing and brine formation [*Craig and Gordon*, 1965], and the $\delta^{18}O$-depleted signal of surface waters is transferred to deeper depth because of the density increase due to salt rejection. A salinity increase of 0.3-0.5 during sea-ice freezing can be reached [*Midttun*, 1985]. Also, the production of this dense water implies cold seawater temperatures (less than -1°C). Isotope data from the ENAM93-21 core point to the frequent influence of brine formation in this area between 50 and 20 kyr whereas the influx of Atlantic Intermediate Water was a minor contribution.

4. Discussion

The high-resolution data set from the ENAM 93-21 core indicates that brine formation occurred frequently during the last glacial period in the southern part of the Nordic Sea (62°N). This has also been proposed for the time spans of HL2 and LGM in other parts of the Nordic Sea [*Veum et al.*, 1992; *Hebbeln et al.*, 1994].

The similarity in amplitude between planktonic and benthic light $\delta^{18}O$ peaks during the Heinrich events suggests that the location of ENAM93-21 was close to one brine formation site (Figures 1 and 5a). The light benthic $\delta^{18}O$ peaks have an equivalent (HL4) or slightly larger (HL5 and HL3) amplitude compared to the planktonic record (Figure 5a). With the breakup of the shelf ice and the sea ice during the Heinrich events, favorable conditions for brine formation could have occurred all along the Nordic Sea margins. There is evidence for a north-south current monitored by the arctic iceberg drift [*Berger and Jansen*, 1995; *Sarnthein et al.*, 1995]. The transport of ice away from the site of production combined with an enhanced easterly wind system (due to the presence of ice caps) leads to maximization of the formation of dense water through brine formation [*Midttun*, 1985]. During the stadials, higher amplitudes in the benthic $\delta^{18}O$ peaks compared to the planktonic peaks in the ENAM93-21 core suggest a site of brine formation further away from the core location than it was during the Heinrich events (Figure 5a). There is no clear signature from the isotopically light intermediate water mass associated with the stadials in the North Atlantic core NA87-22, which has the highest time resolution (~250 years) (Figure 4).

The marked light benthic $\delta^{18}O$ peaks in the North Atlantic cores (NA87-22 and V29-202) point to intermediate to deep water convection due to brine formation relatively close to these sites (Figure 4). This could indicate a source of brines on the Greenland-Iceland shelf. During HL4 and HL3 the light benthic peaks are particularly strong down to 2600 m depth in the North Atlantic (Figure 4). At the location of the NA87-22 core the light benthic $\delta^{18}O$ peaks could result from the contribution of the isotopically light water masses originating from both the Norwegian Sea and the Greenland-Iceland margins (Figure 1). The signal of this isotopically light water mass is not recorded at the location of core SU90-08 (3080 m water depth) in the central Atlantic. Associated with HL4, there is evidence for open ocean convection in the central North Atlantic [*Vidal et al.*, 1997]. The fact that the benthic $\delta^{18}O$ values remain the same as before the event in core SU90-08 could reflect the influence of another water mass originating from a lower latitude [*Vidal et al.*, 1997]. Similar features could account for the HL3 period, although there is no evidence for deep water formation at a lower latitude.

The light peaks related to HL5, HL1, and shortly after HL4 (~33 ka) are observed in the North Atlantic cores down to 3000 m depth (Figure 4). Associated with these events, the benthic $\delta^{18}O$ excursions reach similar values in cores NA87-22, V29-202, and SU90-08. Brine formation as the only cause of these peaks would imply an extreme enhancement of brine formation during these periods with the transfer of an undiluted meltwater signal down to 3000 m southward in the North Atlantic, which is unlikely. After the HL4 the northward migration of the polar front [*Cortijo et al.*, 1997] and the enhanced vertical mixing through the production of well ventilated deep waters in the North Atlantic [*Vidal et al.*, 1997] may have resulted in the translation of the light $\delta^{18}O$ signature to depth. During the HL4 period the benthic $\delta^{13}C$ values in the North Atlantic are higher than in the other basins, indicating that southward deep outflow persisted. The $\delta^{18}O$-depleted water should have been transferred within a few hundred years in the deep North Atlantic. Therefore a delayed transfer of the isotopic signal cannot explain the entirety of the light benthic peaks occurring 1500 years after HL4. However, the restart of deep water formation could lead to warmer and saltier deep waters. The comparison between $\delta^{18}O$ values from the ENAM93-21 and SU90-08 cores enables us to constrain temperature changes from the North Atlantic Deep Water over the last glacial period (Figure 5c). The identical benthic $\delta^{18}O$ values in both cores for the LGM period indicate the cooling of the North Atlantic water to temperatures close to the Norwegian Sea Deep Water for this period (in the range of 0°- -1°C as long as open ocean or brine convection was active somewhere in the Norwegian and Greenland Seas) [*Labeyrie et al.*, 1992], thus assuming that water masses deeper than 1000 m in the Norwegian Sea and in the North Atlantic have about the same $\delta^{18}O$ in the past as in the present [*Labeyrie et al.*, 1987]. After HL4 (~33 ka) the same $\delta^{18}O$ values in both cores indicate that the lowering in the benthic $\delta^{18}O$ from core SU90-08 is not related to deep water warming and suggest a link to global change in the $\delta^{18}O$ of seawater (Figure 5c). Moreover, in the deeper core SU90-08 the light $\delta^{18}O$ peak associated with HL5 appears to be like the one following HL4 (Figure 3). A combined effect of brine formation and global change in ice volume associated with or slightly following the Heinrich events could cause these benthic $\delta^{18}O$

signals. According to the V19-30 record, it should not account for more than half of the signal. Studies on different proxies, able to record sea level changes, indicate high sea stands during stage 3 [*Chappel et al.*, 1986; *Richards et al.*, 1994; *Lindsey*, 1996], but inaccuracy in the datings prevents a precise correlation. For HL1 the benthic $\delta^{18}O$ peak happened during termination I (Figure 3). In addition to the meltwater effect and ice-volume change, the benthic $\delta^{18}O$ is also affected by deep water warming [*Duplessy et al.*, 1980; *Jansen and Veum*, 1990]. The combination of these three factors makes it difficult to figure out which is governing the benthic signal in the North Atlantic cores during Heinrich event 1.

5. Conclusions

High-resolution benthic $\delta^{18}O$ records from North Atlantic deep-sea cores show light peaks linked to the Heinrich events. Intercore variability and interbasin $\delta^{18}O$ gradients point to local processes causing this signal. The light peaks corresponding to the Heinrich events are mainly explained by the transfer of isotopically light water from the surface through brine formation. This process is supported by benthic isotope data ($\delta^{18}O$ and $\delta^{13}C$) from the southern Norwegian Sea core ENAM93-21 which show the occurence the $\delta^{18}O$-depleted and less-ventilated water during Heinrich events 3, 4, and 5. In this area, brine formation was dominant compared to open ocean convection during the Heinrich events and the stadial intervals. Isotopically light signatures recognized in the North Atlantic down to 2600 m during Heinrich events 4 and 3 point to Greenland-Iceland ice margins as other possible areas for brine formation.

Associated with the HL4 event, brine formation in the southern Norwegian Sea and in the northern North Atlantic and open ocean convection in the central North Atlantic [*Vidal et al.*, 1997] corroborates the circulation pattern of the conceptual model proposed by *Imbrie et al.* [1992] for characterizing the preglacial state, when the heat pumped into the high latitudes is at its minimum values.

Light benthic $\delta^{18}O$ peaks recorded in the deep North Atlantic cores (down to 3000 m), like during HL5 and after HL4, suggest that changes in the global $\delta^{18}O$ of seawater associated with or slightly after the Heinrich events could contribute to the $\delta^{18}O$ variability. To point out how dominant this factor is, high-resolution cores from other ocean basins with a detailed chronostratigraphy from oxygen isotope stage 3 are required.

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