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Evidence for an additional Heinrich event between H5 and H6 in the Labrador Sea

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[1] An additional Heinrich ice-rafting event is identified between Heinrich events 5 and 6 in eight cores from the Labrador Sea and the northwest Atlantic Ocean. It is characterized by sediment rich in detrital carbonate (40% $CaCO_3$) with high concentration of floating dropstones, high coarse-fraction (% > 150 μm) content, and has a sharp contact with the underlying but grades into the overlying hemipelagic sediment. It also shows lighter $\delta^{18}O_{Npl}$ values, indicating freshening due to iceberg rafting and/or meltwater discharge. This event is correlated with Dansgaard-Oeschger event 14 and interpreted as an additional Heinrich event, H5a. The thickness of H5a in the Labrador Sea reaches up to 220 cm. This additional Heinrich event has also been reported in cores PS2644 and SO82-5 from the northern North Atlantic. With the recognition of H5a the temporal spacing between Heinrich events 1 to 6 becomes more uniform (~7 ka). *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 4267 Oceanography: General: Paleoceanography; *KEYWORDS:* Heinrich events, nepheloid flow deposits, GISP2, Dansgaard-Oeschger cycle, Labrador Sea

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1. Introduction, Background, and Purpose

[2] Deep-sea sediment cores from the North Atlantic provide evidence for the occurrence of short-lived episodes of sudden, intensified iceberg discharge between 70 and 10 ka, which deposited lithologically distinct layers of ice-rafted detritus known as Heinrich layers [*Heinrich*, 1988; *Bond et al.*, 1992; *Broecker et al.*, 1992]. During these episodes, very large numbers of icebergs were discharged from the Northern Hemisphere ice sheets into the North Atlantic and were picked up by the North Atlantic Current (Gulf Stream), drifting eastward along the 40–50°N latitude band [*Bond et al.*, 1992]. Surging of the Hudson Strait and Laurentian Channel ice streams during Heinrich events led to repeated collapse of the ice dome of the Laurentide Ice Sheet (LIS) that was centered over the Hudson Bay Lowlands between 70 and 10 ka [*Alley and MacAyeal*, 1994; *Clark et al.*, 1996]. Ice-rafting events older than 70 ka have been documented [*Heinrich*, 1988], but are normally not penetrated by piston cores in high sedimentation-rate areas such as the Labrador Sea.

[3] Heinrich events are correlated with climatic cycles [*Bond et al.*, 1993] recorded in the Greenland Summit ice cores GISP2 and GRIP [*Dansgaard et al.*, 1993] that consist of asymmetric cooling and warming cycles termed Bond cycles [*Broecker*, 1994]. Superposed on the Bond cycles are the higher frequency millennial-scale Dansgaard-Oeschger (D-O) temperature oscillations. These D-O oscillations are characterized by progressive cooling, leading within a few hundred years to stadial episodes, followed by rapid warming to interstadials. The coldest D-O oscillation is a Heinrich event terminating a Bond cycle. In North Atlantic sediment cores, Heinrich layers are characterized by a sudden increase in the coarse lithic fraction (% of particles >150 μm), reduced concentration of foraminifera, and light $\delta^{18}O$ values in planktonic foraminifera [*Heinrich*, 1988; *Bond et al.*, 1992]. The presence of detrital carbonate within the lithic layers and the geochemical signature of the noncarbonate fraction have led to the conclusion that the major source of icebergs during these ice-rafting events was the LIS [*Andrews and Tedesco*, 1992; *Bond and Lotti*, 1995; *Gwiazda et al.*, 1996; *Hemming et al.*, 2000].

[4] In the northwest Labrador Sea, detrital carbonate events (DC events) were identified by *Andrews and Tedesco* [1992] by their creamy-yellow color and high detrital carbonate content (up to 50–60% by weight) predominantly contained in the silt-and-clay size fractions [*Hesse and Khodabakhsh*, 1998]. These DC events are equivalent but not entirely identical to Heinrich events in the North Atlantic, because the DC events may include carbonate-turbidite intervals at the top and bottom that do not contain ice-rafted debris (IRD) and are not part of Heinrich events [*Rashid et al.*, 2003a]. DC-1 and DC-2 in cores from the

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continental slope in front of the Hudson Strait have been correlated with H1 and H2 on the basis of ^{14}C-AMS dates [*Andrews and Tedesco*, 1992].

[5] Various mechanisms have been proposed for the origin of Heinrich events. *Heinrich* [1988] in his original paper related the ice-rafting events with the half period of the precessional cycle (11,000 years). However, by precision dating of the six most recent Heinrich layers, *Broecker et al.* [1992] and *Bond et al.* [1993], found no correlation with any component of Milankovitch insolation cycles. Sea level rise and global temperature changes [*Bond and Lotti*, 1995; *Grousset et al.*, 2000] have also not been substantiated as external forcing mechanisms. In contrast, *MacAyeal* [1993] proposed that basal melting due to the accumulation of geothermal heat under the LIS caused ice stream surging through major ice outlets leading to Heinrich events. According to this "binge-purge" model the accumulated geothermal heat together with pressure melting caused the thawing of the basal ice and the underlying subglacial till that, once water-soaked, acted as a lubricant, triggering sudden ice stream surging in the Hudson Strait and Gulf of St. Lawrence outlets [*Alley and MacAyeal*, 1994]. Once the surging started frictional heat would contribute to the ice melting. The phase of fast ice flow ended when the geothermal and frictional heat was dissipated as the ice thinned. The water-charged subglacial till would then refreeze onto the underlying bedrock, effectively terminating its lubricating function. Once the ice surges stopped, the ice sheet once again began to thicken, initiating another cycle. However, *Clarke et al.* [1999] and *Marshall et al.* [2000] reported that in order to simulate fast ice streamflow through the Hudson Strait, climatic perturbations such as changes in surface temperature, and the mass balance of the ice sheet need to be considered in addition to internal glaciomechanical properties of ice sheet. However, the model simulations produced inadequate amounts of meltwater required for fast flow at the base of the ice sheet. On the other hand, *Verbitsky and Saltzman* [1995] proposed that the combined effects of diffusion of atmospheric temperature changes to the ice bottom and internal friction in the bottom boundary layer of ice sheet are more critical to produce basal melting than the geothermal heating, thus reintroducing an element of the external forcing hypotheses.

[6] The binge-purge model explains the inferred short duration of the events (~750 years) [*Alley and MacAyeal*, 1994] and the large amount of detritus transported to the open ocean in each episode. However, a crucial aspect of the binge-purge model, the predicted apparent ~7 ka cyclicity for the recurrence of Heinrich events was not confirmed by the North Atlantic data. In particular, the interval of ~15 ka between H5 (generally dated between 50 and 52 ka) and H6 (between 66 and 67 ka) is twice as long as the average recurrence interval. Although this does not necessarily cast doubts on the validity of the proposed binge-purge mechanism, because ice sheet growth conditions, especially net accumulation rate, but also ice sheet configurations may have varied considerably prior to the various Heinrich events [e.g., *Kirby and Andrews*, 1999], a more even spacing would eliminate the necessity of numerous additional assumptions and make the model easier to work with. In this context, the hint at the occurrence of a possible additional Heinrich event between H5 and H6 in cores PS2644 and SO82-05 from the Icelandic and Irminger seas [*van Kreveld et al.*, 2000] is significant. This would reduce the recurrence period between the two events to the average value. In a reexamination of Labrador Sea cores, we have found further evidence for the presence of an additional Heinrich event between H5 and H6 here called H5a in a number of cores with sufficient stratigraphic penetration.

2. Samples and Methods

2.1. Samples

[7] The samples used in this study come from eight cores; four (Hu90-013-28, -29, Hu88-024-11, and MD99-2233; hereafter Hu90-28, -29, Hu88-11, and MD99-33) retrieved from the Labrador Slope in front of the Hudson Strait and from the deep Labrador Basin, three from Orphan Basin (Hu77-14-04, MD95-2024 and MD95-2025, hereafter Hu77-04, MD95-24 and MD95-25), and one from the northwest Atlantic Ocean (MD95-2022, hereafter MD95-22) (Figure 1; Table 1).

[8] Core MD99-33 was retrieved from the slope off the Saglek Bank southeast of the Hudson Strait and contains the longest stratigraphic record from this region (Figure 1). Core Hu90-29 has been collected from the Labrador continental rise (Figures 1 and 2), core Hu90-28 from the rise on the left (northern) levee of the EA tributary of the Northwest Atlantic Mid-Ocean Channel (NAMOC) [*Hesse et al.*, 1996], and Hu88-11 from the deep basin on the right (southern) levee of the DB tributary, sites not influenced by turbidity current spill-over from the NAMOC. Core Hu77-04 was retrieved from Orphan Basin. Data for cores MD95-24 and 25, which are located within 100 km of Hu77-04, were taken from *Stoner et al.* [2000] and *Hiscott et al.* [2001], respectively. Core MD95-22 is located on the right levee of the NAMOC in the northwest North Atlantic Ocean.

2.2. Laboratory Methods

[9] Cores were subsampled at 2.5 to 5 cm intervals and 0.5 g of dry sample material were used to determine calcium carbonate ($CaCO_3$) by coulometry measuring total carbonate from the CO_2 liberated by 10% phosphoric acid. Since smear slides show that most of the carbonate is in fact detrital in origin, we refer to this measurement as "detrital carbonate" although it contains a small proportion of biogenic carbonate. The remaining sample was dried in an oven at 63°C for 24 hours and weighed and then disaggregated and washed through 63-μm sieves. The >150 μm fraction was used to pick foraminifera.

[10] Stable oxygen and carbon isotope analyses of planktonic foraminifera were performed on *Neogloboquadrina pachyderma* (sinistral) (hereafter Nps) in the 150–250 μm fraction. All measurements were carried out by the stable isotope labs at Woods Hole Oceanographic Institution on a Finnigan MAT252 mass spectrometer equipped with a

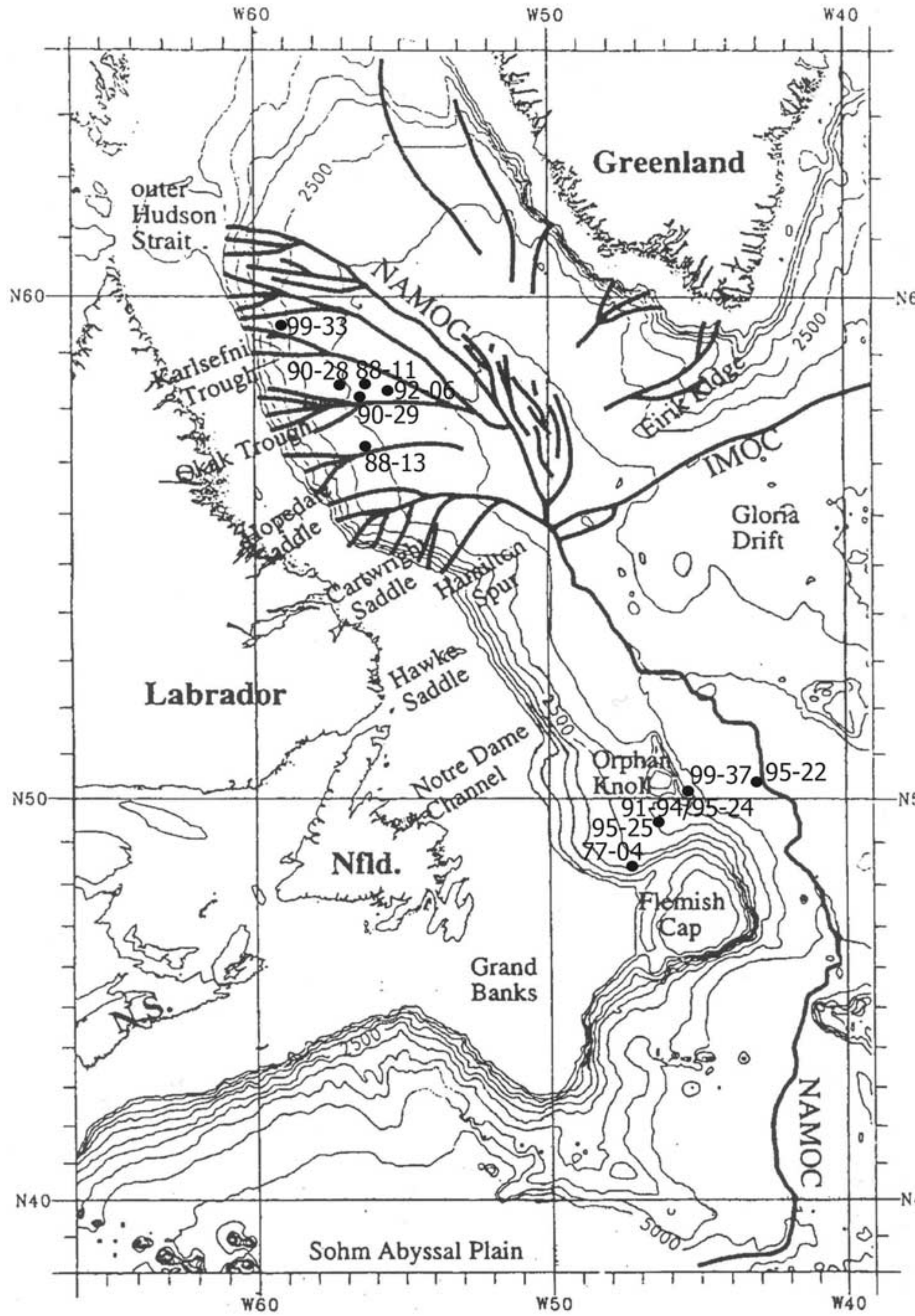


Figure 1. Location map of cores used in this study. NAMOC, Northwest Atlantic mid-ocean channel.

"Kiel" device and at GEOTOP, Université de Québec à Montréal, on a VG-PRISM^{TM} mass spectrometer with an automated carbonate extraction device. Results were converted to the V-PDB scale [*Coplen*, 1996] after the usual corrections [*Craig*, 1957]. The overall analytical reproducibility, as determined from replicate measurements on the standard material (Carrara Marble), is routinely better than ± 0.05‰ (±1σ) for both $\delta^{18}O$ and $\delta^{13}C$.

[11] Chronostratigraphic control for all cores is based on accelerator mass spectrometry (AMS) ^{14}C dating of foraminifera. Approximately 800–1200 shells/sample of *N. pachyderma* (s) were handpicked under the binocular microscope. AMS ^{14}C dates have been obtained by the NSF Arizona-AMS and NOSAMS-WHOI facilities, and the Iso-Trace Laboratory of the University of Toronto (Table 2). All ages reported here were calculated after isotopic normalization (i.e., for a $\delta^{13}C$ value of −25‰) using Libby's ^{14}C half-life as provided by the laboratories. A reservoir age of 450 years was subtracted to account for the apparent age of dissolved inorganic carbon in high-latitude sea surface

Table 1. Location of Cores Used in the Study

Core ID	Latitude, N	Longitude, W	Water Depth, m	Length, cm	Location	Reference
SO82-5	59°	31°	1416		Irminger Sea	*van Kreveld et al.* [2000]
PS2644	67°52.02	21°45.92	777	918	Icelandic Sea	*Voelker et al.* [2000]
Hu77-14-04	48°43.60	47°32.50	2359	1062	Orphan Knoll	this study
Hu88-24-11	58°47.70	56°21.51	3027	1081	Labrador Basin	this study
Hu90-13-28	58°45.80	57°06.75	2913	1175	Labrador Slope	this study
Hu90-13-29	58°23.61	56°45.76	2918	1402	Labrador Slope	this study
MD95-2022	50°34.38	43°03.51	4245	1837	North Atlantic Ocean	this study
MD95-2024	50°12.40	45°41.21	3536	2615	Orphan Knoll	*Stoner et al.* [2000]
MD95-2025	49°47.64	46°41.85	3009	3512	Orphan Basin	*Hiscott et al.* [2001]
MD99-2233	59°49.46	59°09.35	2350	2462	Saglek Bank	this study

waters of the northwest Labrador Sea [*Bard*, 1988]. The bias of bioturbational mixing can largely be ignored at these subpolar sites since the low organic carbon (and nutrient) flux characteristic for this environment and the high sedimentation rate reduce the bioturbational mixing depth to 2 cm or less [*Trauth et al.*, 1997].

[12] Radiographs of 1 cm thick sediment slabs taken from the split cores proved to be an invaluable tool for visually identifying different sedimentary facies and deducing the positions of Heinrich layers. The time-consuming preparation of the slabs is paid off by the resolution in the identification of sedimentary structures and textures unmatched by any other technique.

2.3. Core Hu90-29

[13] Core Hu90-29 was selected as the principal reference core for identifying the complete set of Late Pleistocene Heinrich layers in the Labrador Sea because of the great stratigraphic range penetrated with its sediments, the completeness of the stratigraphic record and its proximal location, but not too close to the Hudson Strait outlet. The upper ~80 cm of missing sediment from the top of the piston core (PC) are preserved in the trigger weight core (TWC). The sediment comprises nepheloid flow deposits, hemipelagic sediments with and without ice-rafted debris, contourites, and thin, parallel-laminated, carbonate-rich, mud-turbidites (Figure 2) [*Wang and Hesse*, 1996; *Rashid*, 2002].

3. Results and Interpretations

3.1. Problems of Stratigraphic Correlation in Ice-Proximal Regions and Strategy for Importing Established Stratigraphies to Core Hu90-29

[14] Establishing a reliable Heinrich event stratigraphy beyond H4 in core Hu90-29 from the ice-proximal region of the northwest Labrador Sea is a formidable task as outlined below. The strategy of how to tie the stratigraphy of this core to the established Late Pleistocene stratigraphies for Marine (oxygen) Isotopic Stages (MIS) 1–5 in the North Atlantic has to deal with the specific problems encountered in ice-proximal regions especially in the northwest Labrador Sea. In the region close to a former major ice outlet such as the Hudson Strait, significant meltwater and sediment discharges, typically in the form of nepheloid-flow layers [*Rashid et al.*, 2003a], distort the familiar shape of the oxygen isotope curve. Detrital carbonate concentration and coarse-fraction (% of particles >150 μm) content, which are other parameters used to identify Heinrich layers and thereby to establish a stratigraphy, show distortions of their profiles compared to corresponding profiles from distal regions.

[15] The strategy chosen to overcome these difficulties is to use core MD95-24 from the Orphan Knoll area of the southern Labrador Sea, where some of the disturbing influences of the vicinity of the Hudson Strait ice outlet such as meltwater and detrital carbonate fluxes are weaker, and nepheloid-flow layers have not been detected. The stratigraphy of core MD95-24 was constructed by *Stoner et al.* [2000] using a variety of tools including the geomagnetic paleointensity and its inverse correlation with the flux of cosmogenic isotopes such as ^{36}Cl and ^{10}Be (in ice cores). This enabled them to establish a firm correlation of this core with the revised chronology of the GISP2/GRIP ice cores [*Alley et al.*, 1997; *Meese et al.*, 1997]. These authors extended into the southern Labrador Sea the previously achieved correlation in the North Atlantic between Heinrich events [*Bond et al.*, 1993] and Dansgaard-Oeschger ice-rafting events [*Bond and Lotti*, 1995] with the GISP2 ice core chronology of *Meese et al.* [1994]. The correlation is further constrained by the position of ash zone 2 (AZ2) which was reported both in core MD95-24 and in the GISP2 ice core. Correlating the detrital carbonate concentration, coarse fraction content, and $\delta^{18}O_{Npl}$ between MD95-24 and Hu90-29 (Figure 3), our aim is to import the GISP2 chronology to ice-proximal regions of the northwest Labrador Sea. The advantage of using the GISP2 ice core chronology [*Meese et al.*, 1997] is that down to 50 ka BP it is based on annual ice layer counting. Beyond 50 ka calendar (cal) years BP, trace gas concentrations were used to correlate the Vostok ice core chronology of *Sowers et al.* [1993] from Antarctica with the GISP2 ice core [*Bender et al.*, 1994]. However, we are aware of the uncertainties associated with the older parts of the GISP2 timescale (for details regarding these uncertainties, see *Meese et al.* [1997]).

3.2. Procedure to Identify Heinrich Layers in Ice-Proximal Cores

[16] For practical purposes four criteria were used to identify Heinrich layers: (1) the occurrence of nepheloid-flow deposits, (2) the presence of high-carbonate concentration layers, (3) high but variable contents of coarse-fraction, and (4) characteristic light O- and C- isotope anomalies. The first step in this procedure was to delineate the position of Heinrich layers in the cores with the help of X-radiographs. This tool allows determining the position

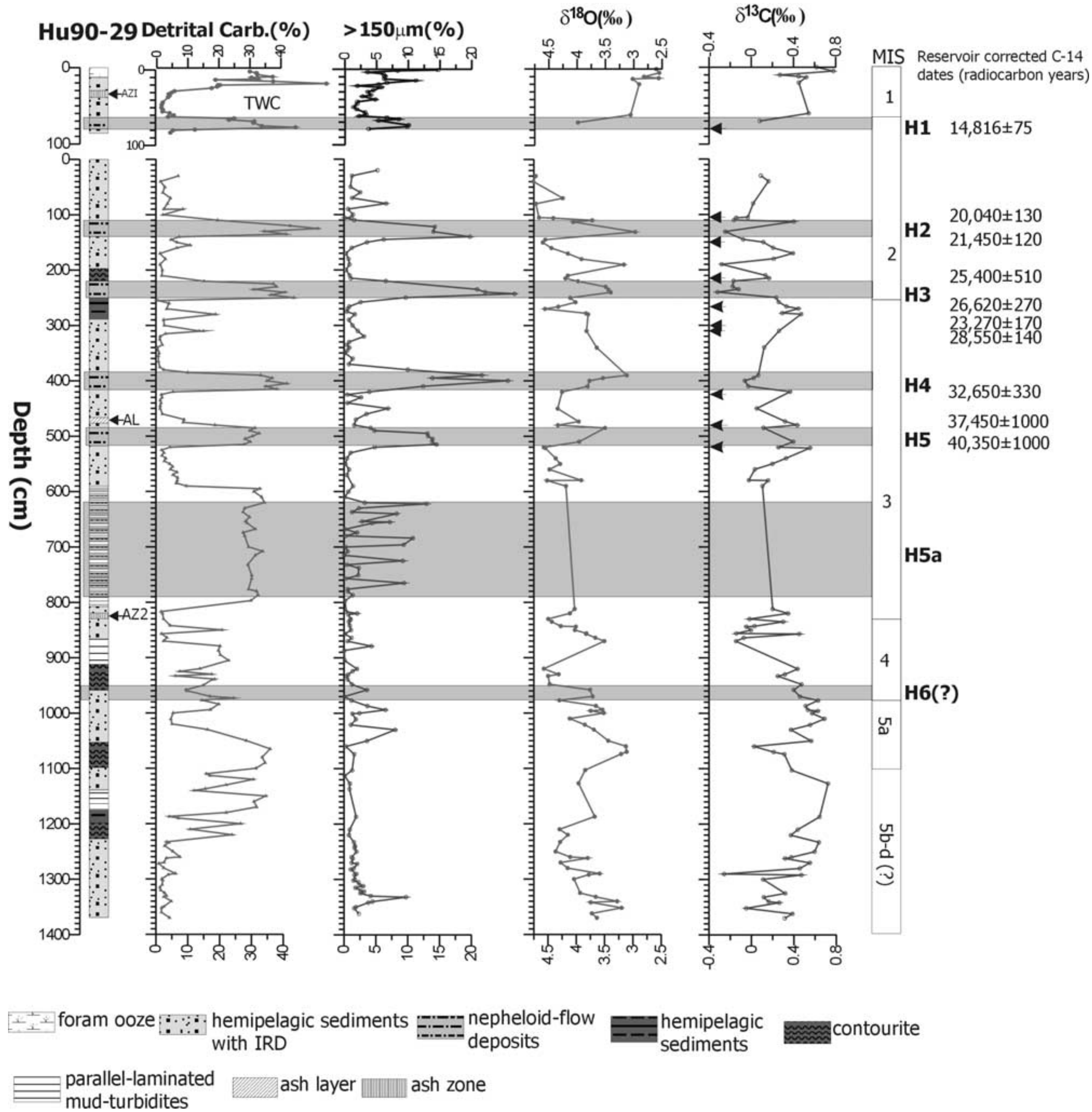


Figure 2. Isotope stratigraphy based on *N. pachyderma* (s) (Nps), facies distribution, detrital carbonate (bulk weight) and ice-rafted debris (%) content of core Hu90-29 from the Labrador continental rise. There are no $\delta^{18}O$ data between 590 and 812 cm due to insufficient numbers of foraminifera caused by dilution of the background sediment by nepheloid flow layers and parallel-laminated mud turbidites. Seven Heinrich events (H1–H6, including H5a) are identified. Note that three minor carbonate peaks at 155, 280, and 310 cm are due to high concentrations of foraminifera. Ages of younger Heinrich events are constrained by ^{14}C-AMS. Ages >40 ka are constrained by tie-points obtained by matching with GISP2 via core MD95-24 (see Figure 3), by comparison with the marine isotope stratigraphy curve of *Martinson et al.* [1987] and identification of AZ-2. Data for GISP2 are from *Stuiver and Grootes* [2000] and *Grootes and Stuiver* [1997].

of Heinrich layers in ice-proximal cores with high accuracy and precision, as they are characterized by nepheloid flow deposits with their unique sedimentary structures, which are restricted to Heinrich events. They do not occur in the time intervals between the events, when normal ice rafting continues. This rapid method is infallible for most Heinrich events. In the next step the Heinrich layer positions established in this way are compared with

Table 2. Radiocarbon Ages Determined From the Polar Planktonic Foraminifera *Neogloboquadrina Pachyderma* (Sinistral) for Hu90-29

Laboratory	Depth, cm	Planktonic Species, 150–250 μm	Amount of Material, mg	Radiocarbon Convention Age, Years	Error ± 1σ, Years	Corrected ^{14}C-AMS Age,[a] Years	*Stuiver et al.* [1998]	*Beck et al.* [2001]
AA-43075	80T	Nps		15,266	75	14,816	17,600	18,000
AA-43076	105	Nps		21,490	130	20,050	23,500	24,400
OS-27249	150	Nps	8.36	21,900	120	21,450		25,900
AA-43077	215	Nps		25,850	510	25,400		30,700
TO-2994	267	Nps	106	27,070	270	26,620		31,300
AA-43078	300	Nps		23,720	170	(23,270)		(28,800)
OS-33016	310	Nps	6.52	29,000	140	28,550		33,500
TO-2995	426	Nps	26	33,100	330	32,650		39,400
AA-41999	480	Nps		37,900	1000	37,450		43,500
AA-43079	520	Nps		40,800	1000	40,350		44,800
TO-2996	858	Nps	317	48,810	1130	48,360		
TO-2997	1009	Nps	81	54,530	2090	54,080		

[a]Radiocarbon convention age, −450 years for surface ocean reservoir age, is corrected according to *Bard* [1988] back to 20 ka [*Bard et al.*, 1993] and back to 50 ka according to the scheme of *Laj et al.* [2000]. Ages in parentheses appear too young to be considered real and were discarded. Radiocarbon dates younger than 24 ka are converted to calendar age according to the CALIB4.3 program [*Stuiver et al.*, 1998] and ages between 24 and 40 ka BP are calibrated according to the scheme of *Beck et al.* [2001], respectively.

carbonate concentration and the content of IRD, because in the northwest Labrador Sea Heinrich layers are rich in detrital carbonate, as mentioned earlier. By necessity they contain IRD whose concentrations, however, are lower than in distal regions because of the dilution by sediment discharged in nepheloid flows and low-density turbidity currents [*Rashid et al.*, 2003a]. In the final step the set of identified Heinrich layers is correlated stratigraphically with the known Heinrich events with the aid of the marine oxygen isotope stratigraphy, radiocarbon dating and basin-wide marker horizons (ash layers). The ages of Heinrich events younger than ~40 ka are constrained by ^{14}C-AMS dates (Figure 2, Table 2). Individual Heinrich layers are then numbered stratigraphically and missing or additional events can be detected, which is the objective of this contribution.

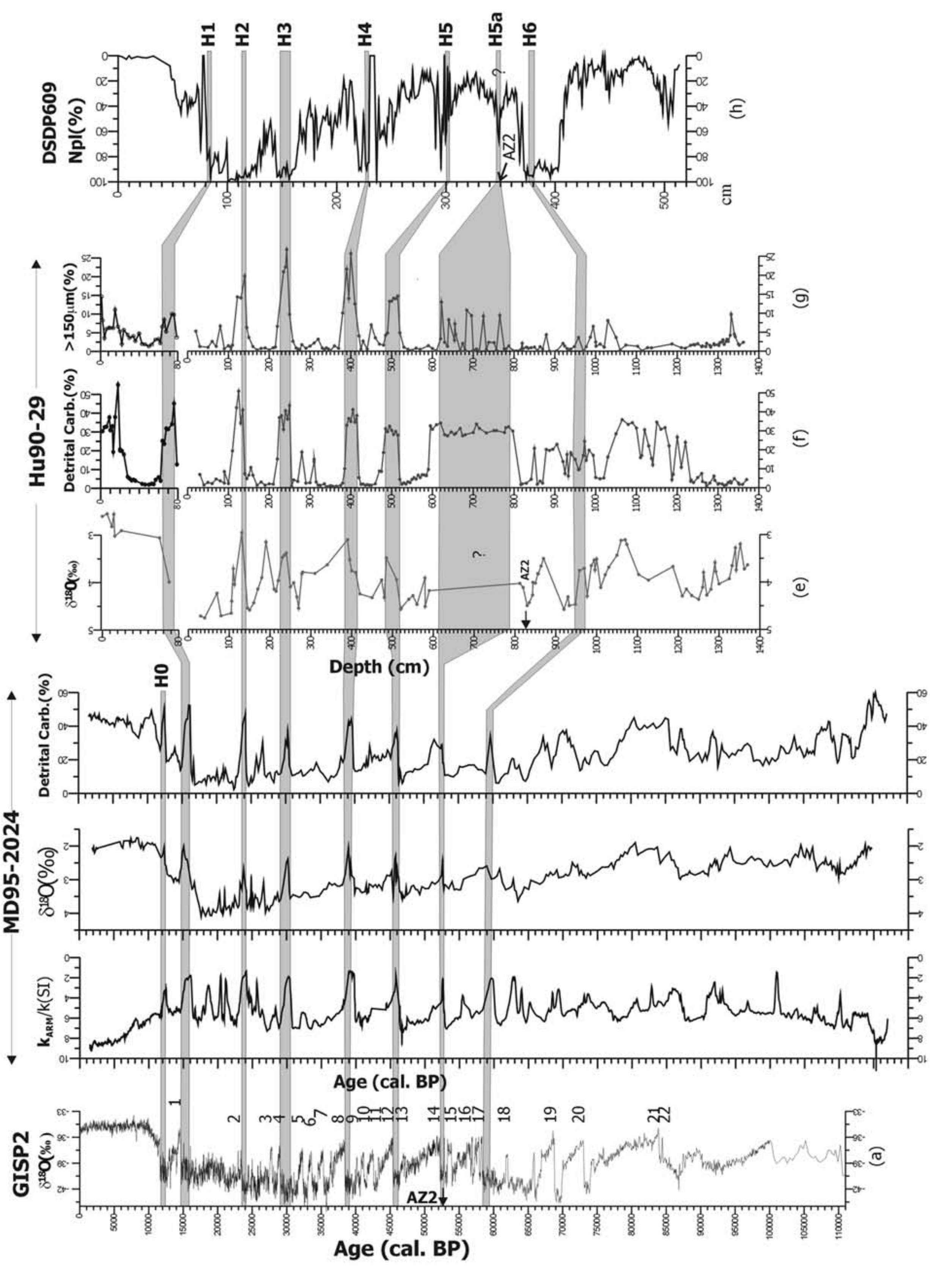
3.3. Set of Heinrich Layers in Core Hu90-29 and Tentative Stratigraphic Correlation

[17] The outstanding characteristic of the carbonate content curve of core Hu90-29 (Figure 2) is the fact that above 800 cmbsf the carbonate concentration rises at 6 different levels (i.e., between 62 and 78 in TWC, 110 and 140, 220 and 250, 385 and 415, 485 and 515, and 590 and 800 cmbsf) abruptly from the Labrador Sea background level to a maximum of up to 50%. Without exception, these high carbonate levels, which show elevated coarse-fraction contents (Figure 2) and low δ^{18}O peaks, correspond to Heinrich layers as confirmed by the X-radiographs and verified by the marine isotope stratigraphy (section 3.4). Between these levels few minor carbonate peaks made up of foraminifera occur at 155, 280 and 310 cmbsf, but none of these is coupled with increased coarse-fraction content and only the latter two are coupled with light δ^{18}O values (Figure 2). These peaks correspond to very thin layers with no relationship to Heinrich events. As mentioned, most events were accompanied by a drop in δ^{18}O values of *N. pachyderma* (s), which occasionally form discrete peaks, either matching exactly the peak in coarse-fraction content or occurring immediately above. Between 40 cm (TWC) and 600 cm, only a few light δ^{18}O peaks (such as that at 190 cmbsf) were neither associated with an increase in carbonate concentration nor an increase in coarse-fraction content.

[18] During the initial stage of Heinrich events, the δ^{13}C values remain high but drop rapidly to the lightest values during the peak of the events and gradually return to the average Labrador Sea δ^{13}C values at the end, except during H1. In HL-1, a high δ^{13}C value of 0.544‰, is coupled with a low δ^{18}O peak of 3.06‰ at 60 cmbsf. Heinrich layer 6 is associated with a ~1.7‰ δ^{18}O drop whereas the δ^{13}C values remain relatively low during this interval (Figure 2).

[19] The shallowest Heinrich layer, clearly HL-1, occurs between 64 and 78 cm in the TWC. It is made up of nepheloid flow deposits with high carbonate concentration (up to 45%), and has a basal age of 14,816 ± 75 ^{14}C years at

Figure 3. (opposite) Correlation of cores Hu90-29, MD95-24, and DSDP Site 609 from the Labrador rise, Orphan Knoll, and North Atlantic with GISP2 Greenland Summit ice core. Data for core MD95-24 are from *Stoner et al.* [2000], for DSDP Site 609 from *Bond et al.* [1993], and for GISP2 ice core from *Stuiver and Grootes* [2000] and *Grootes and Stuiver* [1997]. (a) Oxygen isotopes in GISP2 plotted against cal years BP [*Meese et al.*, 1994; *Bender et al.*, 1994]. (b) k_{ARM}/k (anhysteretic remanent magnetization/magnetic susceptibility ratio) from core MD95-24 correlated with GISP2 δ^{18}O assuming association of detrital carbonate layers with cold stadials by *Stoner et al.* [2000]. (c) $\delta^{18}O_{NPl}$ [*Stoner et al.*, 2000]. (d) Detrital carbonate (%) [*Stoner et al.*, 2000]. (e) δ^{18}O values in *N. pachyderma* (s) in core Hu90-29. (f) Comparison of high detrital carbonate (nepheloid-flow deposits). (g) High IRD peaks from core Hu90-29 with core MD95-24 and correlation with GISP2 δ^{18}O values. (h) Concentration (%) of *N. pachyderma* (s) in core DSDP 609 is also correlated with cores MD95-24 and Hu90-29 and GISP2 ice core (see text for detail).


DSDP609
Npl(%)
cm
(h)
H1
H2
H3
H4
H5
H5a
H6
AZ2
Hu90-29
$\delta^{18}O$(‰)
Detrital Carb.(%)
>150μm(%)
(e)
(f)
(g)
Depth (cm)
MD95-2024
k_{ARM}/k(SI)
Detrital Carb.(%)
(b)
(c)
(d)
H0
Age (cal. BP)
GISP2
(a)

80 cm depth. It has a sharp erosional basal contact and a gradual transition to the overlying sediments.

[20] A second Heinrich layer, clearly HL-2, occurs between 110 and 140 cm and consists also of nepheloid flow deposits. It is characterized by a high carbonate concentration (up to 51%), a light peak of 2.96‰ at 131 cmbsf in $\delta^{18}O$ values, a coarse-fraction content of up to 20% and bracketing ages of 20,040 ± 130 ^{14}C years and 21,450 ± 120 ^{14}C years. HL-2 is 30 cm thick and also has a sharp basal erosional contact and the top grades into the overlying hemipelagic sediments with IRD, like HL-1.

[21] The next stratigraphically deeper Heinrich layer between 220 and 250 cm consists of carbonate-rich, nepheloid flow deposits and has ages of 25,400 ± 510 ^{14}C years at the top (at 215 cm) and 26,620 ± 270 ^{14}C years at the base (at 267 cm), respectively. This is Heinrich layer 3 (Table 2) [*Rashid et al.*, 2003b]. A light $\delta^{18}O$ value of 3.43‰ (at 235 cmbsf), a corresponding $\delta^{13}C$ peak of −0.12‰, the high carbonate concentration of 43%, and the highest coarse-fraction content of all Heinrich layers of 27% are additional characteristics of this Heinrich layer. An age reversal of 23,270 ± 170 ^{14}C years (AA-43078), which occurs at 300 cm and may be due to trace contamination, e.g., by tap-water bicarbonate during sample preparation [*Thompson et al.*, 2000], was disregarded.

[22] The next Heinrich layer occurs between 385 and 415 cm which is characterized by high carbonate concentration (10 to 41%) in nepheloid flow deposits, an increase in coarse-fraction content (varying between 10 and 26%) and a light $\delta^{18}O$ value of 3.11‰ at 390 cmbsf. The basal contact is sharp and the transition at the top with the overlying hemipelagic sediments with IRD is gradual. A ^{14}C-AMS date of 32,650 ± 330 ^{14}C years was obtained at the base of this layer at 426 cm.

[23] Between 485 and 515 cmbsf, a sequence of nepheloid flow deposits, which exhibits high carbonate concentrations (19 to 32%), a marked increase in coarse-fraction content (5 to 15%), and a relatively light $\delta^{18}O$ value of 3.45‰ at the top of the layer, is identified as the next stratigraphically older Heinrich layer. It has a sharp erosional basal contact and a gradual transition at the top to the overlying hemipelagic sediments with IRD. Two dates of 37,450 ± 1000 and 40,350 ± 1000 ^{14}C years were obtained at the top and base of the layer at 480 and 520 cmbsf, respectively.

[24] Stacks of nepheloid flow deposits between 600 and 790 cm are underlain by 10 cm of parallel-laminated, carbonate-rich mud-turbidites (Figure 2). Typical for nepheloid flow deposits of the northwest Labrador Sea, they are rich in carbonate (27 to 34%) and show variable coarse-fraction content (3 to 13%). There were few foraminifera for isotopic analyses within this interval. This interval is another Heinrich layer.

[25] The deepest Heinrich layer in the core was tentatively identified between 950 and 975 cm by a preceding carbonate peak at 970 cm in conjunction with a relatively light $\delta^{18}O$ value of 3.71‰ and a minor peak in coarse-fraction content. This Heinrich layer is different from other Heinrich layers in the Labrador Sea in that it lacks sedimentary structures characteristic of nepheloid-flow deposits, but rather contains foraminiferal sand. Therefore much of the carbonate is not of detrital origin. The detrital portion of the coarse-fraction (% of >150 μm) is comprised of limestone and dolomite fragments. This Heinrich layer shows similarities to H6 in core Hu90-013-13 from the West Greenland Rise in the Labrador Sea which lacks detrital carbonate [*Hillaire-Marcel et al.*, 1994]. *Stoner et al.* [1996, 1998] also reported the presence of a low detrital carbonate event associated with H6 from core Hu91-045-94 from the Orphan Knoll area of the SE Labrador Sea which also contains foraminiferal sand. Recently, *Rasmussen et al.* [2003] have also reported a similar finding in cores EW9302-1 and 2 JPC from the Flemish Cap in the SE Labrador Sea.

3.4. Marine Oxygen Isotope Stratigraphy for Core Hu90-29

[26] The oxygen isotope profile of core Hu90-29 was matched with that of core MD95-24 (Figures 3 and 4). This allowed identification of major boundaries of the marine isotope stratigraphy on the $\delta^{18}O$ profile of core Hu90-29 (Figure 2). The carbonate content provided another parameter for correlation (Figures 2 and 5). Twelve ^{14}C-AMS dates from core Hu90-29 and twenty one radiocarbon dates reported by *Stoner et al.* [1996, 2000] for cores MD95-24 and Hu91-94 and the presence of two ash horizons made this correlation robust between 0 and 830 cm (Figure 3; Table 2). The correlation between 830 and 1370 cm was achieved by establishing the MIS boundaries by matching the oxygen isotope curve with that of *Martinson et al.* [1987]. We are aware of the differences between the data set of *Martinson et al.* [1987] and core Hu90-29, where the record of core Hu90-29 is highly influenced by meltwater discharge and its perturbation of the salinity and $\delta^{18}O$ profile close to an ice margin as opposed to the records of *Martinson et al.* [1987]. We have developed an age model in two ways: (1) using the correlation of MD95-24 to the GISP2 ice chronology proposed by *Stoner et al.* [2000], and (2) using the chronology of *Martinson et al.* [1987] to date the oxygen isotope stratigraphic boundaries. The oxygen isotope stratigraphy of core Hu90-29 covers the MIS 1 to 5, including a thin, condensed Holocene section (Figure 2).

[27] The Holocene consists of 14 cm of light brown oxidized foraminiferal ooze at the top of the TWC displaying low $\delta^{18}O$ values between 2.60 and 2.91‰ and underlain by 49 cm of early Holocene dark grey hemipelagic sediments with IRD. Ash zone I, hereafter referred to as AZ1, occurs between 30 and 40 cm. AZ1 in the North Atlantic was dated 10.6 to 11.1 ka ^{14}C by *Bard et al.* [1994]. The boundary between MIS 1 and 2 was tentatively placed at 63 cm in the TWC on the limb of the $\delta^{18}O$ curve that rises to higher values in and below Heinrich layer 1 (as outlined above in section 3.3).

[28] MIS 2 comprises the lower 22 cm of the TWC and the top 250 cm of the PC. High $\delta^{18}O$ values of 4.70‰ typical of the Last Glacial Maximum were measured between 30 and 110 cm of the PC. As observed in most high sedimentation-rate cores, the planktonic oxygen-isotope

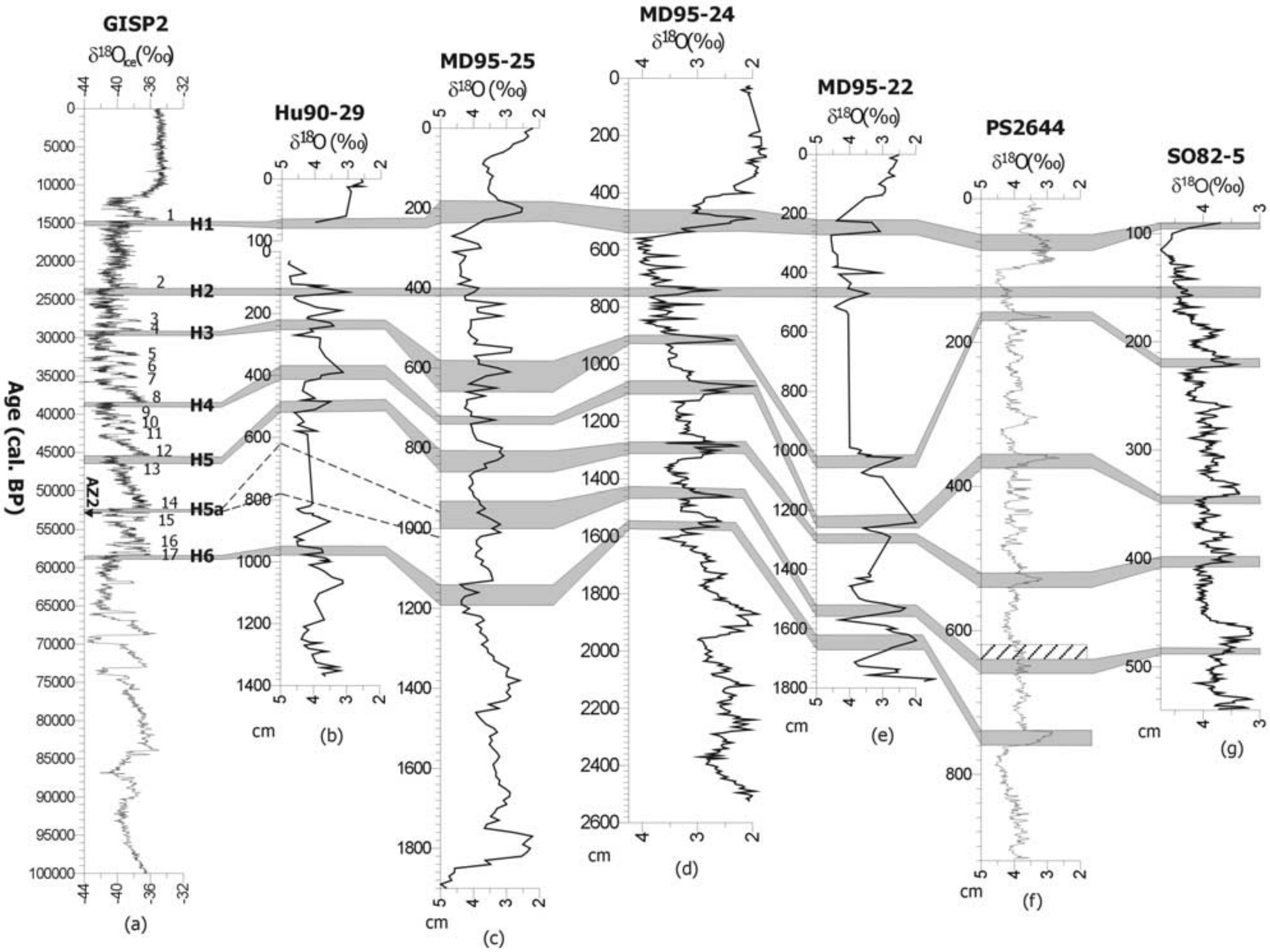


Figure 4. Oxygen isotope profile of GISP2 ice core compared to oxygen isotope stratigraphy in deep-sea sediment cores based on *N. pachyderma* (s) (Nps). (a) 20-year spacing of $\delta^{18}O$ of GISP2 ice core data [*Stuiver and Grootes*, 2000] up to 66,000 cal years BP. Beyond 66 ka, resolution is ~100 years [*Grootes and Stuiver*, 1997]. (b) Hu90-29, (c) MD95-25 [*Hiscott et al.*, 2001], (d) MD95-24 [*Stoner et al.*, 2000], (e) MD95-22, (f) PS2644 [*Voelker et al.*, 2000], and (g) SO82-05 [*van Kreveld et al.*, 2000]. Note that the vertical scale on GISP2 is in calendar years BP, while sediment cores are plotted against depth subbottom. Note also the absence of oxygen isotope data between 600 and 800, and 542 and 980 cm in cores Hu90-29 and MD95-22, respectively. Stippled interval in Figure 4f indicates H5.2 according to *van Kreveld et al.* [2000].

record of the MIS 2 is not regular but interrupted by lighter $\delta^{18}O$ peaks. As discussed above, two of the three prominent light $\delta^{18}O$ peaks at 131 and 235 cmbsf are associated with Heinrich events, i.e., the peaks at 131, 190, and 235 cmbsf with events 2 and 3, respectively. The boundary between MIS 2 and 3 was placed at 255 cmbsf, just above the minor light $\delta^{18}O$ and $\delta^{13}C$ peaks at 260 cm which overlie a date of 26,620 ± 270 ^{14}C years at 267 cm.

[29] Between 267 and 830 cm, an expanded isotopic stage 3 occurs with three distinct lighter $\delta^{18}O$ peaks two of which (3.11‰ at 390, and 3.45‰ at 485 cmbsf) are associated with Heinrich events, the third one (3.92‰) occurring at 579.5 cmbsf. The gap in the oxygen isotopic record between 590 and 810 cm is due to the foraminifera-barren section of thick nepheloid-flow deposits that are interbeded by thin, graded finely laminated mud turbidites.

[30] One rhyolitic ash layer and one ash horizon with minor basaltic shards, hereafter referred to as AL5 and AZ2 were identified between 470 and 480 cm [*Khodabakhsh*, 1997], and 820 and 830 cm, respectively. The AL5 in core Hu90-29 is tentatively correlated to the AL of core PS2644 from the Icelandic Sea [*Voelker et al.*, 2000] based on the similarity in their abundance of basaltic shards and their geochemistry [*Khodabakhsh*, 1997]. An age of 45.19 ka ^{14}C years 5 cm below the base of this ash layer was reported by *Voelker et al.* [2000], which was considered to occur in the upper part of HL-5 (Figure 3). In Hu90-29, a radiocarbon age of 37.45 ka, which gives a calibrated age of 43.50 ka, was obtained 10 cm above the ash layer suggesting that AL5 may correlate with the ash layer of core PS2644.

[31] The predominantly rhyolitic composition of the shards between 820 and 830 cm indicates a correlation with

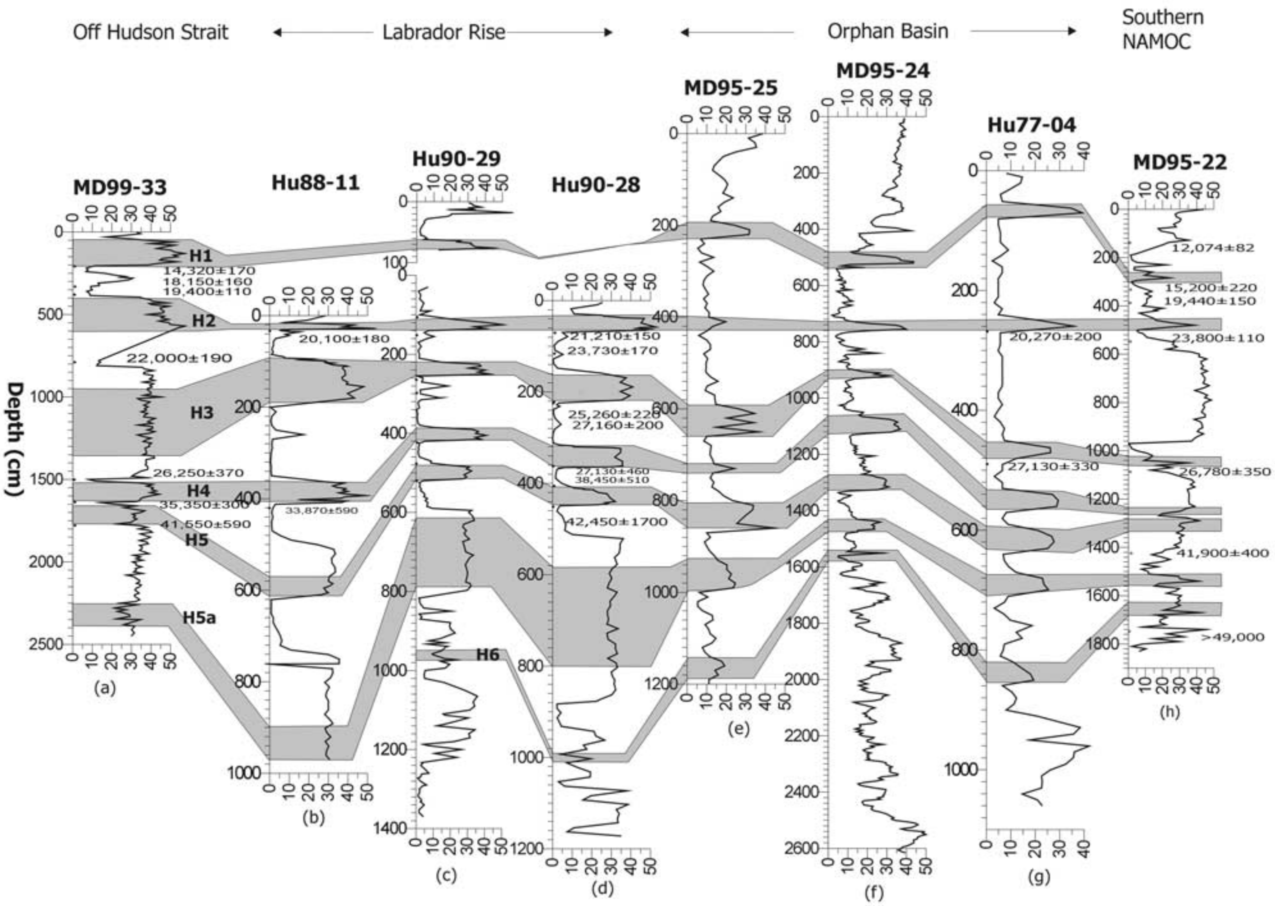


Figure 5. Detrital carbonate profiles from deep-sea sediment cores. (a) MD99-33, (b) Hu88-11, (c) Hu90-29, (d) Hu90-28, (e) MD95-25 [*Hiscott et al.*, 2001], (f) MD95-24 [*Stoner et al.*, 1994], (g) Hu77-04, and (h) MD95-22. Note that high detrital carbonate in Figures 5a and 5h above and below H3 are due to the presence of detrital carbonate-rich mud turbidites; likewise the high detrital carbonate in Figures 5c and 5d above and below H5a reflects detrital carbonate-rich mud turbidites as does the high DC content above H5a in Figure 5b. Note that the sediment record equivalent to H1 in core Hu90-28 was lost during coring.

AZ2 of both the Labrador Sea [*Fillon and Duplessey*, 1980; *Stoner et al.*, 2000] and the North Atlantic Ocean [*Ruddiman and Glover*, 1972; *Bond et al.*, 1993]. In the GRIP/GISP2 ice cores, the AZ2 was identified as multiple visible bands of predominantly rhyolitic composition between 52 and 53 ka cal BP [*Grönvold et al.*, 1995; *Zielinski et al.*, 1997], which is younger than the earlier age of 57.5–65 ka BP reported by *Ruddiman and Glover* [1972] and *Fillon and Duplessey* [1980]. The presence of AZ2 has also been reported in DSDP Site 609 between H5 and H6 [*Bond et al.*, 1993].

[32] The boundary between MIS 3 and 4 was tentatively placed at 830 cm, just below AZ2, based on the presence of lighter δ^{13}C values ranging between 0.30 and −0.2‰ from 830 to 870 cmbsf. Light δ^{13}C values are a well-known marker for stage 4 in the North Atlantic Ocean [*Labeyrie and Duplessy*, 1985]. Since the turbidite interval between 870 and 910 cm is probably a more or less instantaneously deposited sediment unit, stage 4 appears to be a condensed section in the Labrador Sea. *Hillaire-Marcel et al.* [1994] envisaged the reduced thickness of MIS 4 as a general feature of the Labrador Sea. Sedimentation rates apparently were low during MIS 4 in the Labrador Sea coinciding with low organic carbon productivity during this time [*Hillaire-Marcel et al.*, 1994]. A heavy δ^{18}O peak at 977 cm subsurface depth is taken as the lower boundary of MIS 4 against MIS 5a.This boundary was also reported by *Hiscott et al.* [2001] at 1135 cm in core MD95-25 from the Orphan Basin in the southwestern Labrador Sea.

[33] One warmer substage of MIS 5, 5a was resolved between 975 and 1100 cm since the δ^{18}O values within this interval show values closer to Holocene values observed in the TWC section of this core decreasing from 4.30‰ at 977 cmbsf to 3.11‰ at 1070 cmbsf. Three relatively light δ^{18}O spikes of 3.20, 3.28 and 3.59‰ were observed at 1290, 1340, and 1352 cmbsf, respectively, within the combined substages 5b-d (?) (Figure 2). For this section of the core, preference was given to ages of oxygen isotope stages [*Martinson et al.*, 1987] for the purpose of establishing a chronology because of the lack of reliable markers (Figure 2). Cores Hu91-94 [*Hillaire-Marcel et al.*, 1994]

and MD95-24, which are from the Orphan Knoll [*Hillaire-Marcel and Bilodeau*, 2000; *Stoner et al.*, 2000], show a similar shape of the oxygen isotope curve for substage 5a and the MIS 4/5a transition to that of core Hu90-29.

4. Discussion

4.1. Correlation of the Deeper Heinrich Layers in Hu90-29 With MD95-24

[34] We now use the correlation of core Hu90-29 via MD95-24 with the GISP2 record and the ages of Heinrich events summarized in Table 3 to correlate the identified deeper Heinrich layers in core Hu90-29 stratigraphically. Heinrich layers H1 to H3 were identified with confidence based on radiocarbon dating and correlation with numerous other cores in the Labrador Sea [*Rashid et al.*, 2003b; *Rasmussen et al.*, 2003; *Hillaire-Marcel et al.*, 1994; *Andrews and Tedesco*, 1992]. Below H3, four Heinrich layers were identified in those sections of the core that correspond to MIS 3 through 4. Thus there is one Heinrich layer in addition to those that have been traditionally recognized in the North Atlantic Ocean.

[35] There is little doubt concerning the stratigraphic correlation of the Heinrich layer between 385 and 415 cm with H4, although the AMS date of 32,650 ± 330 ^{14}C years at the base is somewhat younger than the AMS age of about 34.50 ka ^{14}C obtained by *Cortijo et al.* [1997] (cf. Table 3). This identification is plausible in view of the widespread occurrence of HL-4 in the Labrador Sea reported in the literature [*Andrews et al.*, 1998; *Bond and Lotti*, 1995; *Hillaire-Marcel et al.*, 1994].

[36] The Heinrich event between 485 and 515 cm subsurface depth, by correlation of the light δ^{18}O value, the coarse-fraction peak and associated high carbonate concentration peak corresponds to H5 in core MD95-24. This is further supported by the immediately overlying ash layer AL5 recognized above H5 in core Hu90-29. H5 has an age equivalent to ~46 ka cal BP by correlation of MD-95-24 with the GISP2 chronology. Similar ages of ~45.75 ka cal BP for H5 have been reported from the Iceland and Irminger seas [*Voelker et al.*, 1998, 2000; *van Kreveld et al.*, 2000]. These ages correspond reasonably to the calibrated ages of 42.0 and 44.9 ka cal BP obtained from measured ages of 37,900 and 40,800 ^{14}C years in Hu90-29 (Table 2).

[37] The deepest Heinrich layer between 950 and 975 cm is correlated with H6 on the basis of its position just above the base of MIS 4. Furthermore, this Heinrich layer contains foraminiferal sand like H6 in cores MD99-2237 and Hu91-94 from the Orphan Knoll area of the southern Labrador Sea [*Hillaire-Marcel and Turon*, 1999; *Stoner et al.*, 1996].

[38] The Heinrich layer between 620 and 790 cm has an age of ~52.50 ka cal BP based on correlation of Hu90-29 with MD95-24. The identification of ash layer AZ2 between 820 and 830 cm supports this correlation. This Heinrich event is significantly older than H4 and H5 but younger than H6. We therefore identify this Heinrich event as an additional event between H5 and H6 and name it H5a. *van Kreveld et al.* [2000] identified a Heinrich event in cores PS2644 and SO82-5 from the Irminger and Icelandic seas from a correlative stratigraphic horizon, termed H5.2 by these authors.

[39] This Heinrich layer 5a is an additional iceberg discharge event in the Labrador Sea that originated from the Hudson Strait. It correlates with D-O event 14 of GISP2 ice core. The identification of AZ2 at the base of D-O event 14 and its presence between 820 and 830 cm in core Hu90-29 confirms this interpretation. Heinrich layer 5a is unique among the Heinrich layers described from core Hu90-29 in that it displays numerous thin, fine-grained, parallel-laminated and carbonate-rich nepheloid flow deposits interbeded with 2 to 3 cm thick layers of ice-rafted debris whereas other Heinrich layers are comprised only of nepheloid flow deposits. In addition, finely laminated, carbonate-rich, mud-turbidites devoid of IRD occur both at the top and bottom of HL-5a. In these respects, it resembles HL-3 in core MD99-33 [*Rashid et al.*, 2003b].

4.2. Is H5a Present in Other Cores From the Labrador Sea and North Atlantic?

[40] Plots of oxygen isotopes, concentration of detrital carbonate, and the coarse-fraction content in sediment cores from the Labrador Sea and North Atlantic Ocean as a function of depth (Figures 4–6) show that Heinrich layers 1 to 6 can be traced from the Labrador Sea to the North Atlantic and can be correlated with the oxygen isotope record in Greenland ice cores. Correlation of H1 to H4 in the cores shown in Figures 4–6 is straightforward as it is constrained by sufficient numbers of ^{14}C-AMS dates.

[41] Correlation of Heinrich layers older than H4 is more complex since the reliability of ^{14}C-AMS dates >40 ka is limited because of large standard deviations. Well-known markers are rare and detrital carbonate may be high in turbidites not associated with Heinrich events and thus is not a parameter that can be used by itself for correlation. This holds true for the proximal cores MD99-33 and Hu88-11 both of which do not penetrate beyond H5a, although core MD99-33 is 25 m long [*Rashid et al.*, 2003b]. However, owing to the high sedimentation rates in front of the mouth of the Hudson Strait, stratigraphically it did not penetrate deeper. In these two cores H5 and H5a were correlated with core Hu90-29 based on coarse-fraction content which reaches 30 and 15% in MD99-33 and Hu88-11, respectively, but falls to 0 or 3% between the two layers. In MD99-33 detrital carbonate concentration is high in the entire interval between H5 and H5a due to the presence of mud turbidites and cannot be used alone for Heinrich event correlation. In Hu88-11 carbonate content is high in the lower half of the interval between H5 and H5a, which again makes it not suitable for correlation. No oxygen isotopes are available from the nepheloid flow deposits of the Heinrich layers and the mud turbidites in these cores.

[42] Core Hu90-28, which includes H6, is similar in its detrital carbonate and coarse fraction profiles to nearby core Hu90-29, particular in the interval between H4 and H5a. The sedimentary structures revealed in X-radiographs can also be correlated between these two cores. H5a in this core is overlain and underlain by 70 and 20 cm thick intervals of parallel-laminated mud-turbidites, similar to Hu90-29. Nepheloid flow deposits in this core and Hu90-29 are significantly thicker than in cores MD99-33 and Hu88-11.

Table 3. Ages of Heinrich Layers in Key North Atlantic and Labrador Sea Cores[a]

Heinrich Event	*Bond et al.* [1993][b]	*Grousset et al.* [1993][b]	*Manighetti et al.* [1995][b]	*Andrews et al.* [1998]	*Cortijo et al.* [1997]	*van Kreveld et al.* [2000][c]	Revised Age of HE
Core ID	DSDP site 609	SU90-08	BOFS 5K	HU87-009	SU90-08	SO82-5	this study[d]
Location	49.53°N 24.14°W	43.30°N 30.24°W	50.41°N 21.52°W	62°30.99N 59° 26.82W	43.30°N 30.24°W	59°N 31°W	
H1	14–15	14.50	14.65	14.080 (base)	12.8–14.7		<17.60
H2	20.37–21.77	20	21.578	19.88–20.17	20.5–22.6	23.5–24.25	~24.50
H3	27	27	27.622	X	26–28	29.2–30	~31.30
H4	35.50[b]	38[b]	39.129[b]	33.110 (top)	34–35.73	38.45–39.40	39.40
H5	50[b]	52[b]	54.70[b]	X	42.8–44.6	45.45–45.75	~46
H5a	X	X	X	X	X	52–52.23	52–53
H6	66[b]	67[b]	69[b]				~59–60

[a]Radiocarbon ages are in uncalibrated ka ^{14}C years; 7th and 8th columns are calibrated radiocarbon ages in calendar years BP.
[b]Older ages were interpolated by using the curve of *Martinson et al.* [1987].
[c]Ages are calibrated to calendar years BP where present is set at 1950.
[d]Calibrated (approximate) radiocarbon ages (thousand) in calendar years BP where present is set at 1950.

[43] Since correlation of Heinrich layers older than H4 in Hu90-29 with cores in Orphan basin (cores MD95-24,-25 and Hu77-04) is well constrained due to the presence of ash zone 2 at the base of H5a, in addition to the similarities in isotopes, carbonate concentrations and coarse-fraction contents, we think that the correlation of the stratigraphic records shown in Figures 4–6 is reasonable beyond doubt. As mentioned, the presence of H6 in cores MD95-24 and 25

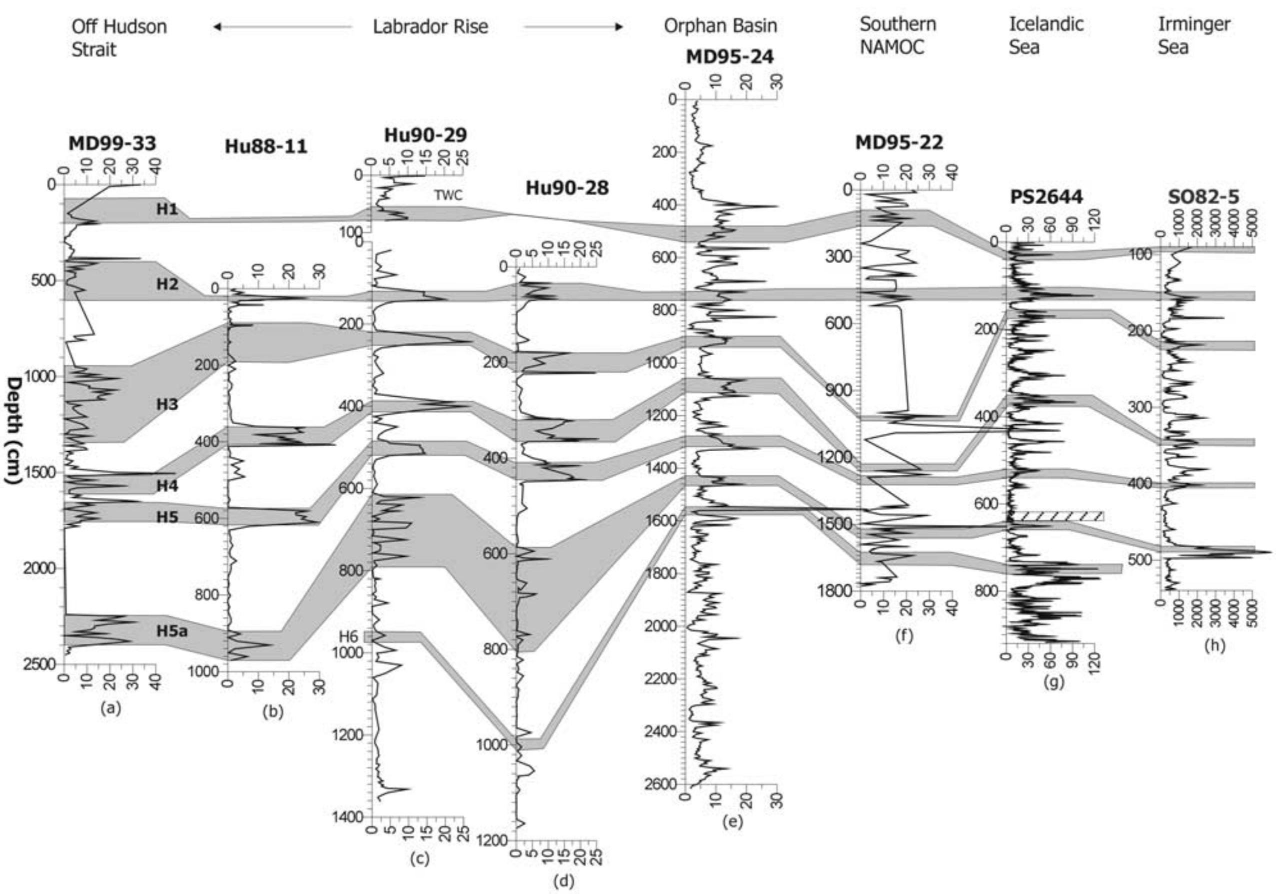


Figure 6. Ice-rafted detritus (IRD) profiles in core (a) MD99-33, (b) Hu88-11, (c) Hu90-29, (d) Hu90-28, (e) MD95-24 [*Stoner et al.*, 1994], (f) MD95-22, (g) PS2644 [*Voelker et al.*, 1998], and (h) S082-5 [*van Kreveld et al.*, 2000]. IRD concentration in all cores was plotted as the percentage of coarse fraction per one gram of dry sediment except in PS2644 and SO82-5, where it has been plotted as numbers of grains per gram. Elevated peaks of coarse particles at 400, 1500 in Figure 6a are due to the high concentration of foraminifera, whereas minor peaks within H3 are due to IRD layers. Note in Figure 4f that two prominent peaks at 1080 and 1520 cmbsf are due to high concentration of foraminifera. Stippled interval in Figure 4g indicates H5.2 according to *van Kreveld et al.* [2000].

was reported by *Rasmussen et al.* [2003], *Hiscott et al.* [2001], and *Stoner et al.* [2000].

[44] All Heinrich layers including H5a in cores MD95-25 and -24 exhibit high detrital carbonate intervals coupled with high coarse-fraction content and sharp but narrow peaks of light $\delta^{18}O$ values. The light $\delta^{18}O$ value representing H5a in core MD95-25 is preceded by a light $\delta^{18}O$ value before the onset of the event, which is not seen in MD95-24. H5a in core MD95-22 shows high detrital carbonate peak, high coarse-fraction content as well as light $\delta^{18}O$ values.

[45] In the North Atlantic Vema core V23-81 and DSDP site 609, *Bond et al.* [1992, 1993] have correlated H6 at the end of the rising limb of the *N. pachyderma* (s) concentration (%) curve at 760 and 398 cm, respectively. We have correlated H6 with the increase of detrital carbonate as well as with the high concentration (%) of *N. pachyderma* (s) (Figure 3). These authors have also reported an increase in the concentration of *N. pachyderma* (s) just above (?) the AZ2 coupled with the increase of Icelandic glass. We suspect that that spike might be the equivalent of H5a in these cores but this tentative assignment needs further investigation. In the Orphan Knoll core MD95-24, *Stoner et al.* [2000] reported the presence of an additional detrital carbonate layer coupled with an increased >125 μm fraction (%) and light $\delta^{18}O_{Npl}$ values between H5 and H6. We have tentatively correlated H5a with that additional ice-rafted detrital carbonate event. However, in their earlier studies *Stoner et al.* [1996] interpreted this event as H6.

[46] In a recent study of core SU90-24 (62°N, 37°W) from the Irminger Sea, *Elliot et al.* [1998, 2001] reported the presence of a high IRD peak between H4 and H5 equivalent to the magnitude of IRD peaks in Heinrich events, which these authors referred to as "DE (detrital event)." The basal age of this detrital event is 40.60 ka ^{14}C years [*Elliot et al.*, 1998]. In *Elliot et al.*'s [1998] age scale for SU90-24 interpolated ages for the bases of H4 and H5 are ~35.20 and ~44.80 ka ^{14}C years, respectively. According to these authors, this detrital event at 40.60 ka is the product of local instability of the ice shelf at the Irminger Sea margin.

[47] However, *van Kreveld et al.* [2000] and *Voelker et al.* [1998, 2000] reported the presence of an IRD peak "identical to the DE peak" of *Elliot et al.* [1998] from the same stratigraphic horizon in cores PS2644 (67°N, 22°W) and SO82-5 (59°N, 31°W) from the Irminger and Icelandic seas, respectively. These authors interpreted the event as an additional Heinrich event between H5 and H6 labeled H5.2. Core SU90-24 was retrieved from 5° north and 3° south of cores PS2644 and SO82-5, respectively. This suggests that the DE peak of *Elliot et al.* [1998] corresponds to H5.2. Since the newly discovered event H5a is coeval with the H5.2 event reported by *van Kreveld et al.* [2000], the event H5a is widespread in the North Atlantic rather than of local Labrador Sea origin.

4.3. Similarities and Differences of HLs in the North Atlantic Sediment Cores

[48] Heinrich layers in cores from the Irminger and Icelandic seas show characteristics different from those in the Labrador Sea. Heinrich events from the Labrador Sea cores are characterized by the high detrital carbonate concentration and coarse-fraction content as well as light $\delta^{18}O$ peaks in *N. pachyderma* (s). In contrast, none of the Heinrich events in Icelandic and Irminger seas show any trace of detrital carbonate. Another difference is that in core SO82-05 from the Irminger Sea, H2, H4 and H5a are associated with high IRD peaks but lack light $\delta^{18}O$ peaks in planktonic foraminifera [*van Kreveld et al.*, 2000] in contrast to the Labrador Sea cores. H3 and H5 exhibit light $\delta^{18}O$ peaks as well as high IRD peaks. On the other hand, core PS2644, which is from a location more proximal to the East Greenland ice sheet margin than core SO82-5, exhibits both light $\delta^{18}O$ peaks as well as high IRD peaks (Figures 4–6) [*Voelker et al.*, 2000]. We have correlated Labrador Sea Heinrich events with the Heinrich events as reported in cores PS2644 and SO82-5 by *Voelker et al.* [2000] and *van Kreveld et al.* [2000], respectively. We have correlated H5a with an IRD layer between 645 and 660 cm in core PS2644 instead of 620 and 635 cm as originally reported by *Voelker et al.* [2000] and our correlation included the IRD peak as well as the light $\delta^{18}O$ peak.

[49] *Hiscott et al.* [2001] reported a rapid increase in sea-surface temperature (SST) during Heinrich events in core MD95-25 from the Orphan Basin (Figures 4–6) in the southern Labrador Sea (Figure 1) as opposed to the hypothesis that Heinrich events occurred at the end of interstadials accompanied by a massive discharge of icebergs and meltwater in the North Atlantic [*Bond et al.*, 1993, 1999]. These reconstructed SSTs during the Heinrich events contrast with the findings of *de Vernal and Hillaire-Marcel* [2000] in core Hu91-94 from the same region. *Hiscott et al.* [2001] also reported the presence of an additional detrital carbonate interval coupled with increased SST and lighter $\delta^{18}O_{Npl}$ value centered at 35 ka BP (^{14}C years) and labeled it as "a1." We do not subscribe to their interpretation of Heinrich events being associated with an SST increase. We rather identified Heinrich layers based on the presence of high carbonate content in conjunction with the increase in coarse-fraction content as well as light $\delta^{18}O$ values in the polar *N. pachyderma* (s) in core MD95-25 [*Rashid*, 2002]. With the revised Heinrich event stratigraphy, we interpreted the "a1-detrital carbonate event" as being equivalent to H4 and their Heinrich event-4 centered at 40 ka BP (^{14}C years) being equivalent to Heinrich event 5 (Figures 4–6).

5. Conclusions

[50] Heinrich events 1 to 3 are clearly documented in core Hu90-29 and a consistent identification of deeper Heinrich layers has been achieved. Most reconstructed radiocarbon dates for Heinrich events 5 and 6 are between 50 to 52 and 66 to 67 ka, respectively, making the recurrence interval between these two events more than twice as long as the average recurrence interval of 7.4 ka [*Sarnthein et al.*, 2001, p. 377] between the Late Pleistocene Heinrich events. An additional ice-rafting event between H5 and H6, here termed H5a, has been identified in the Labrador Sea and North Atlantic. An equivalent event was identified by previous studies in two cores from the Irminger and Icelandic seas without the recognition that it is ubiquitous in the North Atlantic and Labrador Sea. The significance of this finding is that it makes the temporal spacing between successive Heinrich events more equal. This lends support to the "binge-purge" model

for the resumption and termination of Heinrich events from the Laurentide Ice Sheet of *MacAyeal* [1993]. It also explains some of the discrepancies between the published ages for H5 and H6 in the literature, because it seems H5a had previously been interpreted as H6 by some authors.

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