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Millennial-scale depositional cycles related to British Ice Sheet variability and North Atlantic paleocirculation since 45 kyr B.P., Barra Fan, U.K. margin

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Abstract. Lithology, lithic petrology, planktonic foraminiferal abundances, and clastic grain sizes have been determined in a 30 m-long core recovered from the Barra Fan off northwest Scotland. The record extends back to around 45 kyr B.P., with sedimentation rates ranging between 50 and 200 cm/kyr. The abundance of ice-rafted debris indicates 16 glacimarine events, including temporal equivalents to Heinrich events 1-4. Enhanced concentrations of basaltic material derived from the British Tertiary Province suggest that the glacimarine sediments record variations in a glacial source on the Hebrides shelf margin. Glacimarine zones are separated by silty intervals with high planktonic foraminifera concentrations that reflect an interstadial circulation regime in the Rockall Trough. The results suggest that the last British Ice Sheet fluctuated with a periodicity of 2000-3000 years, in common with the Dansgaard-Oeschger climate cycle.

1. Introduction

Ice-rafted debris (IRD) deposited in the North Atlantic during the last glaciation provides evidence of sub-Milankovitch climate changes involving abrupt decay of marine ice margins. Major episodes of IRD deposition in the central North Atlantic, also known as Heinrich events, are related to instability of the Laurentide Ice Sheet (LIS) which occur at 5-10 kyr intervals [*Heinrich*, 1988; *Bond et al.*, 1992; *Broecker et al.*, 1992]. More recently, ice sheet variability operating at 2000-3000 year intervals has been demonstrated in northeast Atlantic cores [*Bond and Lotti*, 1995; *Fronval et al.*, 1995; *Elliot et al.*, 1998]. These rapid glacimarine fluctuations appear to be linked to the Dansgaard-Oeschger climate cycle of the Greenland ice cores, but further understanding of paleoclimatic teleconnections is presently limited by inadequate definition of IRD sources and local ice stream dynamics [*Dowdeswell et al.*, 1999]. Such information can be obtained from continental margin records, which may also provide the necessary resolution for defining phase relationships between ice sheet variability and other paleoclimatic proxies.

In the North Atlantic region the British Ice Sheet (BIS) was probably the most sensitive and earliest amplifier of climatic change because of its extreme maritime position at the southern limit of the last glaciation in NW Europe [*Eyles and McCabe*, 1989; *Boulton*, 1990]. To investigate depositional variations related to ice sheet fluctuations and paleo-oceanography, a 30-m long piston core (MD95-2006) was recovered by RV *Marion Dufresne* in the Rockall Trough during IMAGES cruise 101. The coring operation formed part of the United Kingdoms's North East Atlantic Palaeoceanography and Climate Change program (NEAPACC). In this paper we present Accelerator Mass Spectrometry (AMS) ^{14}C chronology, analyses of lithofacies, IRD petrology, grain sizes, and planktonic foraminiferal abundance. The results reveal a sediment record influenced by frequent changes in bottom current flow and glacimarine discharges from the Hebrides shelf dating back to 45 kyr B.P.

2. Background

By correlation with the Greenland ice $\delta^{18}O$ record it appears that Heinrich events correspond to the major cooling events of the Dansgaard-Oeschger (D-O) cycle, while the millennial-scale IRD pattern is tuned to intervening stadial periods [*Bond et al.*, 1992; *Bond and Lotti*, 1995]. Deciphering the cause of these millennial-scale climate cycles and responding feedback mechanisms presents a major challenge in climate research. It is an open question whether abrupt changes were forced by an external mechanism or generated by internal oscillations operating within the ocean, atmosphere, and cryosphere.

MacAyeal [1993] proposed a model whereby Heinrich events could be produced by internal dynamics of the LIS. This oscillator is maintained by periodic thawing of the glacial base by excess heat, which leads to fast ice flow, and

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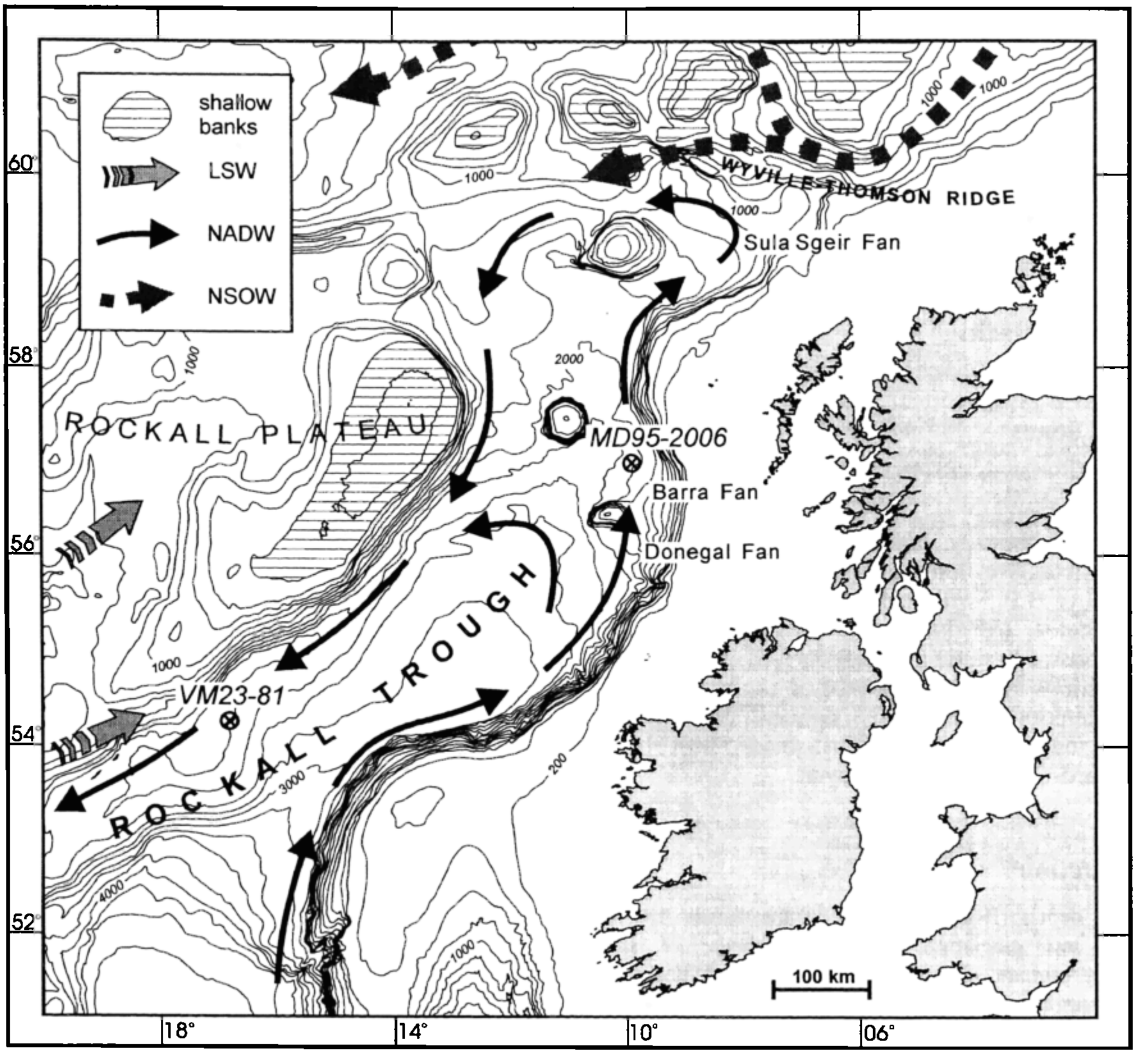

Figure 1. Topographic features, bottom water circulation pattern, and principal water masses on the British Atlantic margin. LSW, Labrador Sea Water; NADW, North Atlantic Deep Water; NSOW, Norwegian Sea Overflow Water. Bathymetric contour interval is 200 m. Positions of cores MD95-2006 and VM23-81 are shown.

subsequent release of meltwater and icebergs along glacial margins. In order to explain the existence of Heinrich-like events sourced from other ice sheets it has been suggested that a major collapse of the LIS could propagate to other glacial margins by inducing a rapid sea level rise of several meters [*MacAyeal*, 1993; *Andrews*, 1998]. However, the synchroneity of IRD deposition during Heinrich events has recently been questioned because intercorrelation between cores from the Nordic Seas is lacking [*Dowdeswell et al.*, 1999]. The more complex pattern of glacimarine sediment delivery in the Nordic Seas suggests that ice streams there behaved differently from the immense Hudson Bay ice stream.

External forcing of millennial-scale oscillations has been proposed on the basis of the global distribution of glacial records linked to the D-O frequency [*Lowell et al.*, 1995; *Behl and Kennett*, 1996] and the evidence of similar rapid climate shifts in Holocene sediments from the North Atlantic [*Bond et al.*, 1997]. External forcing may be related to solar variability or harmonics of orbital frequencies [*Stuiver et al.*, 1995; *McIntyre and Molfino*, 1996], but no such mechanisms have yet been proven. Increasing evidence of climatic feedbacks revolving around the North Atlantic thermohaline conveyor, which appear to operate across the Pleistocene-Holocene boundary, may provide new clues to the origin of the D-O cycle [*Alley et al.*, 1999; *Bianchi and McCave*, 1999; *Dokken and Jansen*, 1999].

3. Geological and Oceanographic Setting

The Barra-Donegal fan complex extends from the Hebridean continental slope into the central part of the Rockall Trough and forms the most southern glacigenic fan system on the European continental margin (Figure 1). The bulk of the Barra Fan is constructed from debris flow lobes and glacimarine sediments fed by ice streams established during Pleistocene glaciations [*Stoker*, 1995]. The former presence of glacial outlets is evidenced by iceberg plough marks, subglacial erosional features, and morainal banks on the adjacent shelf margin [*Davies et al.*, 1984; *Stoker et al.*; 1993]. Core MD95-2006 (57°01.82 N; 10°03.48 W) was retrieved from a water depth of 2120 m on the northern edge of the Barra Fan. The corer penetrated a well-layered and laterally continuous acoustic sequence interpreted as contourites and distal glacimarine sediments [*Howe*, 1996; *Knutz et al.*, 2001].

The Rockall Trough constitutes a narrow SW-NE trending basin confined by the Rockall Plateau to the west, the continental shelf of Britain and Ireland to the east, and the Wyville-Thomson Ridge to the north (Figure 1). The bottom flow regime in the Rockall Trough involves several water masses: (1) North Atlantic Deep Water (NADW), which follows the European continental slope northward at depths of 2-3 km; (2) Labrador Sea Water (LSW), which enters the basin from the southwest at 1-2 km depth; and (3) Norwegian Sea Overflow Water (NSOW), which is supplied intermittently across the Wyville–Thomson Ridge (Figure 1) [*Lee and Ellet*, 1965; *Jones et al.*, 1970; *Swallow et al.*, 1977]. The water masses combine to form a cyclonic loop with outflow along the western flank of the basin and possibly a recirculating gyre in the north.

4. Methods

Volume magnetic susceptibility was measured on split core sections in increments of 2 cm using the point sensor and automated computer tracking facilities of a GEOTEK core logger. Fine muddy material was initially sampled at 10-30 cm intervals with careful discrimination of sandy structures representing downslope sediment transport. Closer sampling down to a centimeter scale was subsequently carried out within intervals showing elevated IRD concentrations. The concentration and composition of lithic grains were examined using a conventional light microscope. In the >500 μm fraction, all lithic grains were counted. In the 250-500 μm fraction, four grain components were recorded: (1) total lithics, (2) quartz showing fresh conchoidal fractures, (3) basalt grains separated using a hand held magnet, and (4) unbroken tests of unspecified planktonic foraminifera. Benthic foraminifera were generally rare and therefore not recorded. In samples representing lithic abundance peaks, detrital grains in the 250-500 μm fraction were classified as quartz, hemi-crystalline basalt, acidic igneous fragments, discrete feldspar grains, and detrital carbonate. Grain size spectra of the fine-clastic fraction were measured on a Micromeritics Sedigraph 5100 after leaching the sediment with dilute acetic acid.

The chronology of core MD95-2006 is based on seven monospecific foraminiferal AMS ^{14}C ages previously reported by *Kroon et al.* [2000]. In addition, the presence of ash 1 Thol. 2 at a core depth of 260 cm was used as a chronostratigraphic marker. This ash horizon is a component of the Icelandic-sourced North Atlantic Ash Zone 1 [*Kvamme et al.*, 1989] and has been dated in a core from the nearby St. Kilda Basin [*Austin and Kroon*, 1996]. Radiocarbon ages have been corrected for a marine reservoir effect of 400 years and transformed into calendar years using the second-order polynomial relationship between radiocarbon and ^{230}Th-^{234}U dates of corals determined by *Bard et al.* [1998]. Ages are quoted in calendar years unless these are specifically stated as ^{14}C years B.P.

5. Results

5.1. Chronology

The analytical errors of age determinations lie between ±1% to ±2% (Table 1), although the "true" error, reflecting analytical precision, ocean reservoir changes and "geological" effects such as bioturbation, is likely to be at least ± 3% in the range 10-40 ^{14}C kyr B.P. [*Andrews et al.*, 1999]. The age/depth model for MD95-2006 is based on the assumption of linear sedimentation rates between the upper four dating points, while a second-order polynomial fit is used to estimate sample ages between 19.90 and 25.20 m core depth (Figure

Table 1. Chronostratigraphic Data from MD95-2006

Laboratory Number	Material	Depth, cm	^{14}C Age,[a] years B.P. ±1σ	Calendar Age,[b] years B.P.
-	1 Thol. 2 Ash	260	10,893	12,685
AA-22347	*N. pachyderma* (s)	760	14,860 ±140	17,493
AA-22348	*N. pachyderma* (s)	1320	17,660 ±130	20,830
AA-22349	*N. pachyderma* (s)	1990	24,310 ±280	28,565
AA-32312	*N. pachyderma* (s)	2140	25,810 ±270	30,273
AA-32313	*G. bulloides*	2260	29,000 ±370	33,860
AA-32314	*G. bulloides*	2390	29,330 ±470	34,227
AA-22350	*G. bulloides*	2520	33,480 ±610	38,794

[a] Including marine reservoir correction of 400 years.
[b] Calendar years based on *Bard et al.* [1998].

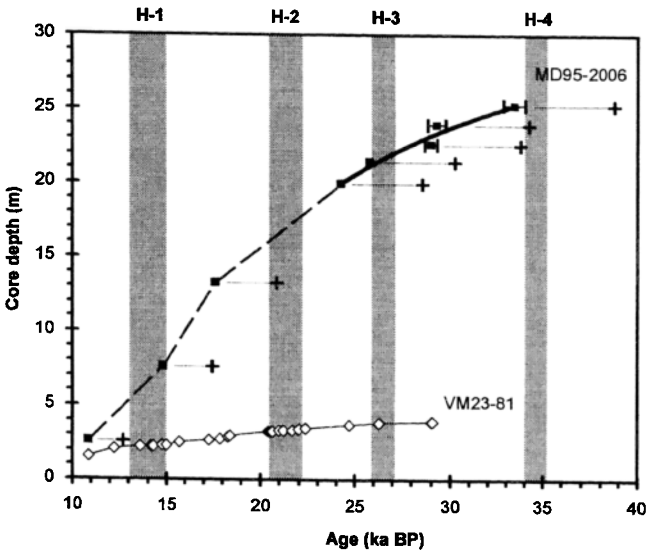

Figure 2. Age/depth relation for core MD95-2006 in comparison with VM23-81. Solid squares indicate ^{14}C dating points from MD95-2006, while crosses indicate the corresponding calendar ages according to *Bard et al.* [1998]. Radiocarbon dates of VM23-81 (open diamonds) are obtained from *Elliot et al.* [1998]. A marine reservoir correction of 400 years has been applied to both data sets. Average duration of North Atlantic Heinrich events 1-4 is indicated by gray bands. Sample ages between 19.9- and 25.2-m core depth are based on a second-order polynomial fit between five dates (core depth = -2 65×10^{-6} [age]^2 + 0.2096 [age] - 1527).

2). This approach was preferred because the two dates at 22.60 m and 23.90 m depth indicate a tenfold increase in sedimentation rate, which was found suspicious. The core base is estimated to be older than 45 kyr B.P. by comparison with the Greenland Ice Sheet Project 2 (GISP2) record (Figure 5). Age/depth relations in MD95-2006 indicate sedimentation rates ranging from around 40 cm/kyr in the lower part, corresponding to marine isotope stage (MIS) 3, to 200 cm/kyr across the Last Glacial Maximum.

5.2. Lithology and Magnetic Susceptibility

Six lithofacies in a succession of five lithological units (LU) were identified in core MD95-2006 based on texture, sediment structures, colour, and carbonate content. Lithofacies and inferred depositional environments are summarised in Figure 3. Details of the lithofacies description and interpretation are presented by *Knutz et al.* [2001].

Volume magnetic susceptibility (MS) is frequently used as an indicator of relative changes in siliclastic versus biogenic calcareous deposition [*Bloemendal et al.*, 1992]. In core MD95-2006 magnetic susceptibility corresponds mainly to shifts in fine-clastic background composition and discrete layers of sandy turbidites (Figure 3b). These provide a strong MS signal due to a high content of magnetite-bearing basalt. Four bundles of thin-bedded turbidites are observed within LU 4, and one is observed in the top of LU 2. The high background in magnetic susceptibility observed in LU 1, LU 3 (middle part), and LU 5 (below 25.5 m core depth) may be caused by the concentration of silt-size heavy minerals from current winnowing or an increased concentration of Fe oxides in the clay fraction. Abrupt decreases in MS at 12.0- and 25.5-m core depth could be related to condensed intervals formed by bottom currents or a sudden change in fine-clastic sediment source. Horizons with elevated IRD concentrations are difficult to discern from the MS signal because of the presence of sandy turbidites. In the lower part of the core, thin, sharp peaks in MS appear to coincide with minor ice-rafting events (BF 10, BF 13, and BF 14 in Figure 4).

5.3. Grain Sizes and Biogenic Components

The lithology of core MD95-2006 mainly consists of clay except in LU 1, where the silt fraction (2-63 μm) is more abundant (Figure 3c). The clay content displays a general increase from <40 wt % at the lithofacies boundary around 24-m core depth to a maximum concentration of >75 wt % in LU 2. The coarse silt content shows a distinct variability through the core, which is unrelated to changes in IRD abundance but tend to follow the concentration of biogenic constituents (Figures 3 and 5). The percentage of <63 μm non-detrital matter, determined from the amount of material dissolvable in weak acetic acid, reflects the content of fine calcium carbonate and covaries with planktonic foraminifera abundance (Figure 3d).

5.4. Lithic Components

The abundance of lithic grains derived from muddy intervals in MD95-2006 was determined to indicate variations in the supply of ice-carried sediments to the Barra Fan (Figure 4). The lower limit for IRD was defined at 250 μm to avoid a down-slope or along-slope transported sediment component, which on the continental slope, could influence the finer part of the sand-size spectrum. Also, by using a 250-μm sieve it was possible in the majority of samples to count the total number of grains and hence avoid the counting error that result from using sample splits. In order to observe any grain size effects, IRD in size fractions 250-500 μm (IRD_{250}) and >500 μm (IRD_{500}) were determined separately and recorded as lithic grains per gram bulk sediment (Figures 4a and 4b). Lithic components display a broadly corresponding pattern with 16 horizons of raised IRD abundances. These are shown as grey bands denoted as BF 1-16 in Figure 4. Exceptions to this similarity in variation of lithic abundances is the enhanced amplitude of BF 1 in IRD_{250} and the low amounts of magnetic basalt characterizing BF 11-16. The strong BF 8 peak corresponds to a horizon of gravel-size clasts at 18 m core depth, presumed to be dropstones.

Although quartz dominates the lithic petrology of the 250-500 μm fraction, significant changes in IRD composition are observed through the sequence (Figure 4e). Basalt concentrations range from 2 to 17%, igneous rock fragments range from 3 to 22%, and discrete feldspar grains range from 5 to 10%. Detrital carbonate is generally rare except in BF 13, which contains >15% of pale pink to yellowish carbonate grains. Petrographic thin-section analysis of IRD_{500} from BF 13 reveals a dolomite-rich composition, suggesting a source rock of Paleozoic age or older. The highest concentrations of basalt and igneous rock fragments (>30%) occur at the base of LU 4, but from this level both components decrease up through LU 4-2 with a concomitant increase in quartz. IRD

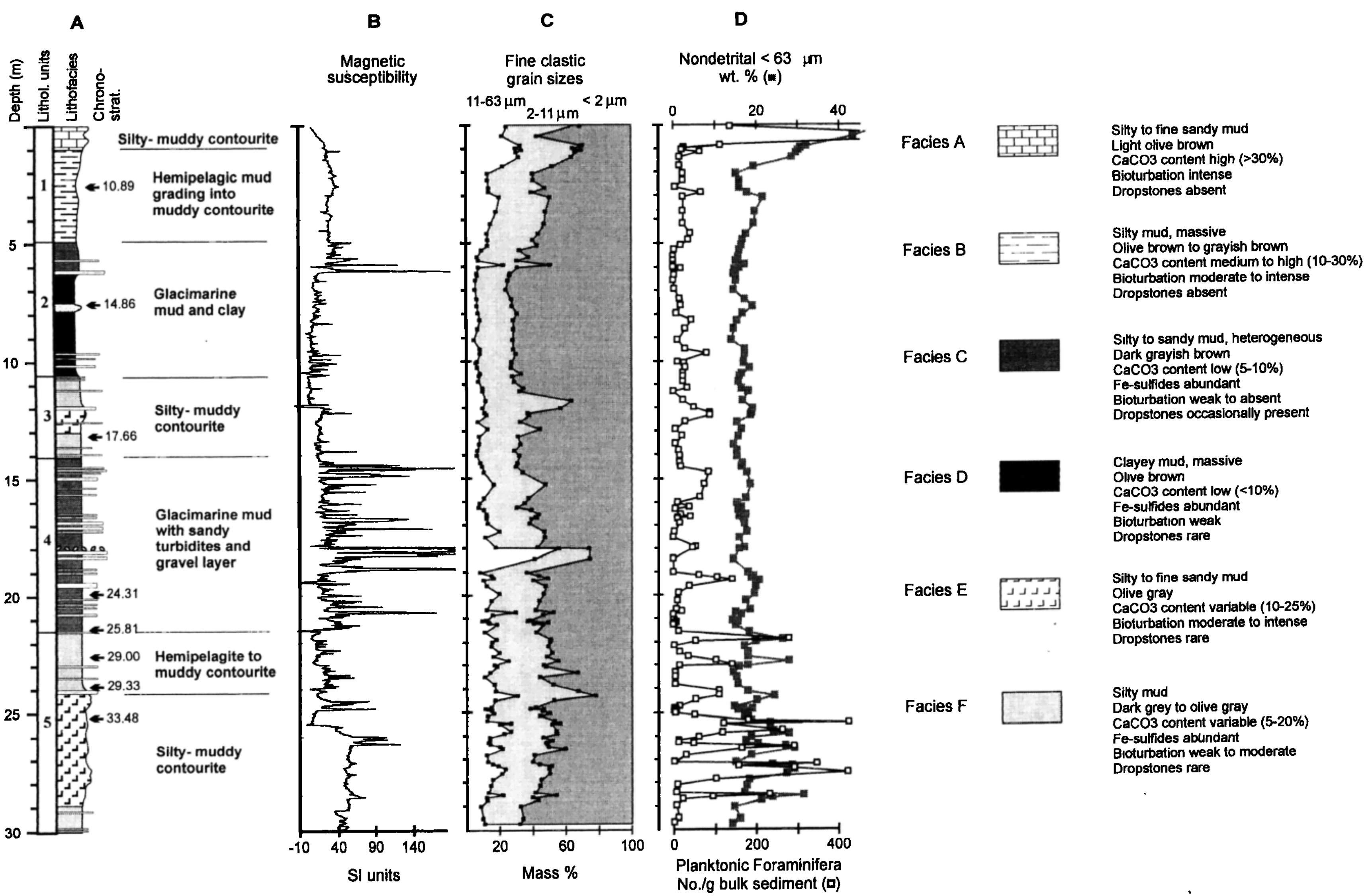

Figure 3. Lithological interpretation, geochronology, magnetic susceptibility, and sedimentological results from core MD95-2006. Non-detrital matter represents carbonate and amorphous compounds dissolvable in 25% vol/vol acetic acid, while abundance of planktonic foraminifera represents the number of unbroken specimens in the 250-500 µm fraction per gram bulk sediment (Figure 3d).

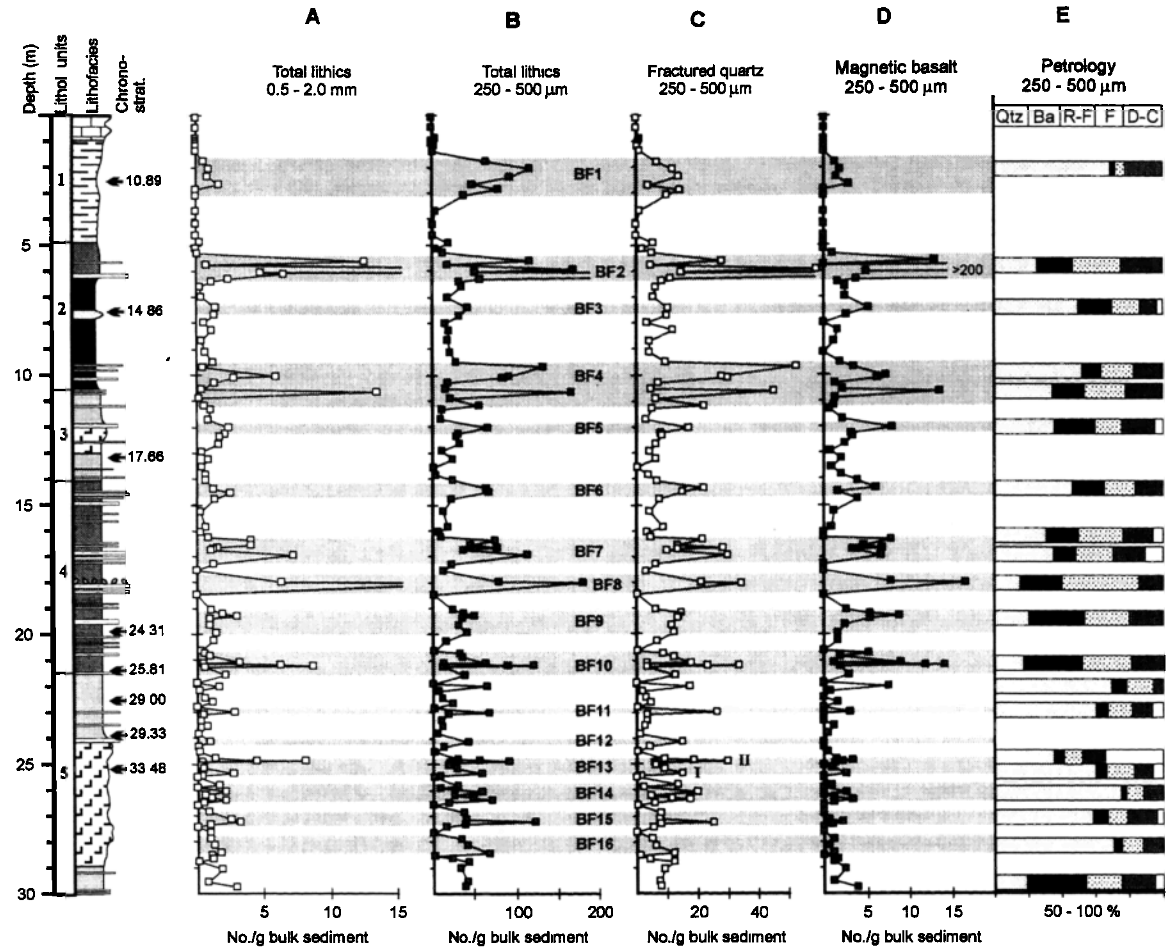

Figure 4. Lithic abundances and petrology of ice-rafted debris (IRD) in core MD95-2006 from the Barra Fan. Lithology and ^{14}C dating levels are also shown. Results are presented as the number of grains per bulk sediment weight in grams. Raised levels of IRD are marked with gray bands numbered 1-16. Petrology (Figure 4e) indicates the percentage of the following grain types determined by conventional microscopy: Qtz, quartz; Ba, basalt; R-F, igneous rock fragments; F, feldspar; D-C, detrital carbonate. Note the scale in Figure 4e runs from 50 to 100% with quartz always > 50%.

petrology in LU 5 is dominated by quartz except at the base where basalt and igneous rock fragments are abundant.

Basaltic particles appear mainly as dark, dense microcrystalline fragments, but vesicular basalt is also present. Petrographic thin-section and scanning electron microscope analyses of the dense basalt type reveal an ophitic texture with plagioclase laths enclosed in anhedral clinopyroxene. Olivine phenocrysts are relatively rare, while Ti-Fe oxides (titanomagnetite, ilmenite) occur as abundant accessory phases.

5.5. Timescale Correlation with North Atlantic Climate Records

The paleoclimatic relation between the Barra Fan and the North Atlantic was examined by comparing the concentration of fractured quartz, clastic silt, and planktonic foraminifera from MD95-2006 with the IRD record from core VM23-81 (position shown in Figure 1) and the $\delta^{18}O$ signal derived from the GISP2 ice core (Figure 5). For the two marine records, uncertainties in the calendar age time-scale increase significantly beyond 24 kyr B.P. because only two coral ages exist for the 40-24 cal kyr interval, while ^{14}C measurements become subject to large errors (±1500-2000 years at 40 kyr B.P.). The time-scale correlation is also limited by the accuracy of the GISP2 age model which is estimated to be within ±5% back to about 40-50 kyr B.P. [*Meese et al.*, 1997].

Sixteen intervals of raised IRD concentrations can be identified during the period 10-45 kyr B.P. in core MD95-2006 (Figure 5b). This pattern is remarkably similar to the lithic cycles in VM23-81 (Figure 5a). Although the limited number of dating points in MD95-2006 does not warrant a detailed correlation or interpretation of lead/lag between the two records, the similarity in frequency of IRD peaks suggests that the British Ice Sheet contributed to the millennial-scale pattern of iceberg discharges in the NE Atlantic. The high-frequency IRD signals observed in both cores cannot be regarded as local noise (e.g., deposition from single icebergs) between Heinrich events but seem to reflect regular events with a periodicity of 2000-3000 years, similar to the Dansgaard-Oeschger cycle.

Peaks in planktonic foraminifera percentages, which reflect high foram:lithic ratios, occur with an average spacing of 2.5 kyr. This parameter records clearly the last deglaciation

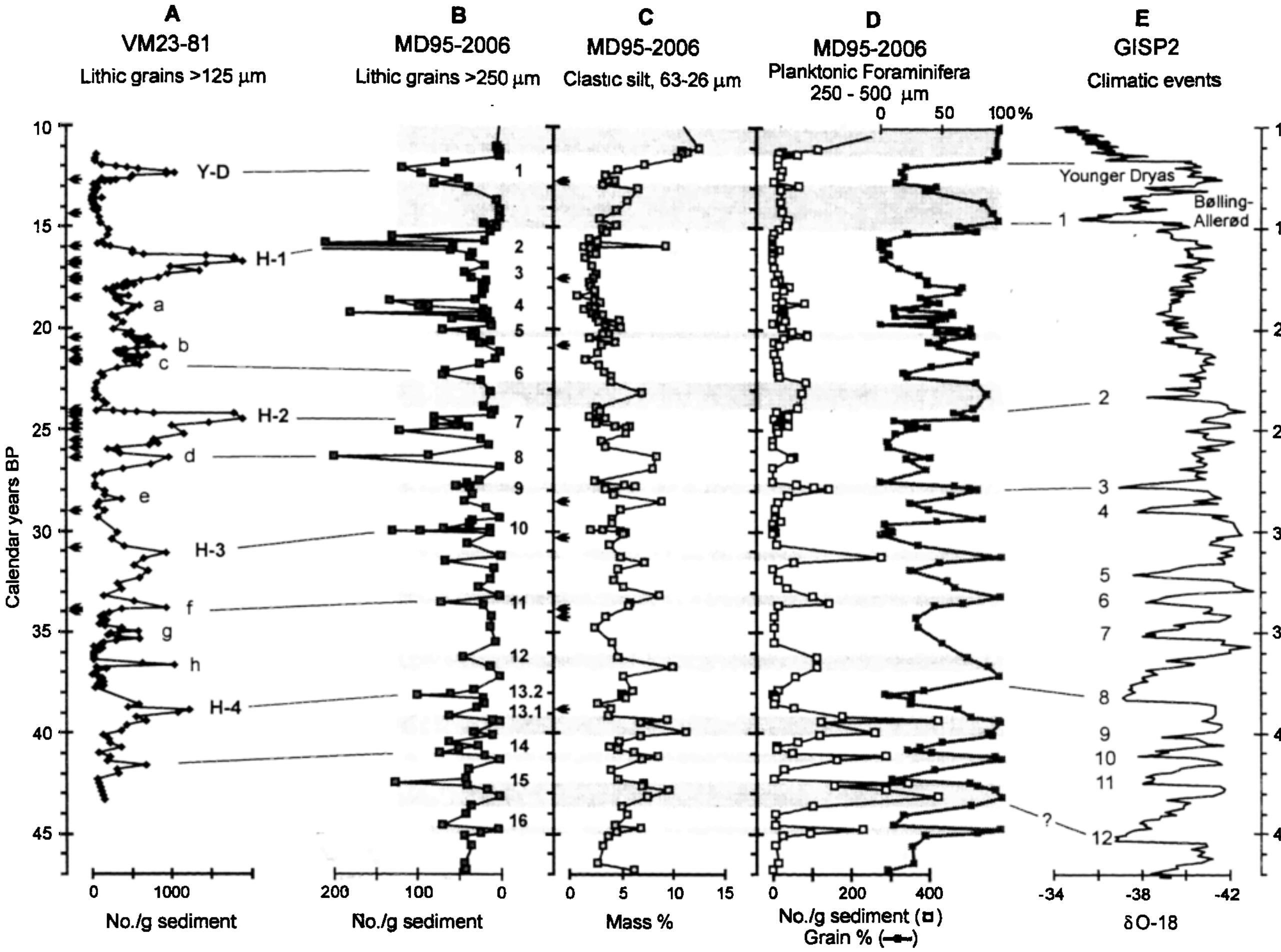

Figure 5. Correlation of palaeoclimatic variables from MD95-2006 (Barra Fan) with VM23-81 (southern Rockall Trough) and Greenland Ice Sheet Project 2 (GISP2). (a) Abundance of lithic grains in VM23-81 were obtained from G. Bond, Lamont-Doherty Earth Observatory, Columbia University. Heinrich events and minor IRD events are shown according to *Bond and Lotti* [1995]. (b) Abundance of lithic grains in MD95-2006 with numbers denoting peaks BF 1-16. (c) Coarse clastic silt concentrations in MD95-2006. (d) Planktonic foraminifera (250-500 μm) abundances and concentrations in MD95-2006. Gray bands indicate high foraminiferal abundances. (e) The $\delta^{18}O$ curve from GISP2 [*Grootes and Stuiver*, 1997; *Meese et al.*, 1997] with numbers denoting Dansgaard-Oeschger interstadial events. The data were obtained from the Greenland Summit Ice Cores CD-ROM, National Geophysical Data Center, United States. Small arrows indicate dating points in the marine cores. The ^{14}C ages from both cores have been converted to a calendar time-scale according to *Bard et al.* [1998].

encompassing Allerød-Bølling, Younger Dryas, and the Holocene transition, previously documented on the Barra Fan [*Kroon et al.*, 1997]. Foraminifera abundance peaks are poorly resolved in the upper part of the Barra Fan record, probably due to high fine-clastic sedimentation rates. The phase relationship between peaks in planktonic foraminifera concentrations in MD95-2006 and $\delta^{18}O$ in GISP2 is not precisely defined at the present level of resolution. It appears, however, that high concentrations of planktonic foraminifera and coarse clastic silt in MD95-2006 are linked to interstadial events in the Greenland Summit record (Figures 5c, 5d, and 5e).

6. Discussion

6.1. IRD Provenance

The abundance of basaltic grains in the lithic sand fraction of MD95-2006 indicates glacigenic sediment transport from the Tertiary volcanic provinces of the NW British Isles to the edge of the continental shelf. Tertiary igneous centers in western Scotland and Northern Ireland formed regions of high relief that were subjected to intense glacial erosion [*McCabe*, 1985]. Morphological and stratigraphic evidence suggests that glacial outlets draining western Scotland, the Outer Hebrides, and Northern Ireland converged in the Minch and on the Hebrides shelf and expanded onto the continental shelf margin (Figure 6) [*Davies et al.*, 1984; *Peacock et al.*, 1992; *Ballantyne et al.*, 1998]. The positions of the Barra-Donegal and Sula Sgeir Fan systems indicate focused deposition of glacigenic sediments and, by implication, the termination of confluent ice streams on the shelf margin. Because the Tertiary formations on the Hebrides shelf, proximal to the Barra Fan, are covered by several hundred meters of pre-Devensian sediments [*Stoker et al.*, 1993], the most likely sources of ice-rafted basalt are the mainland igneous centers.

The volcanic rocks of Northern Ireland and the Inner

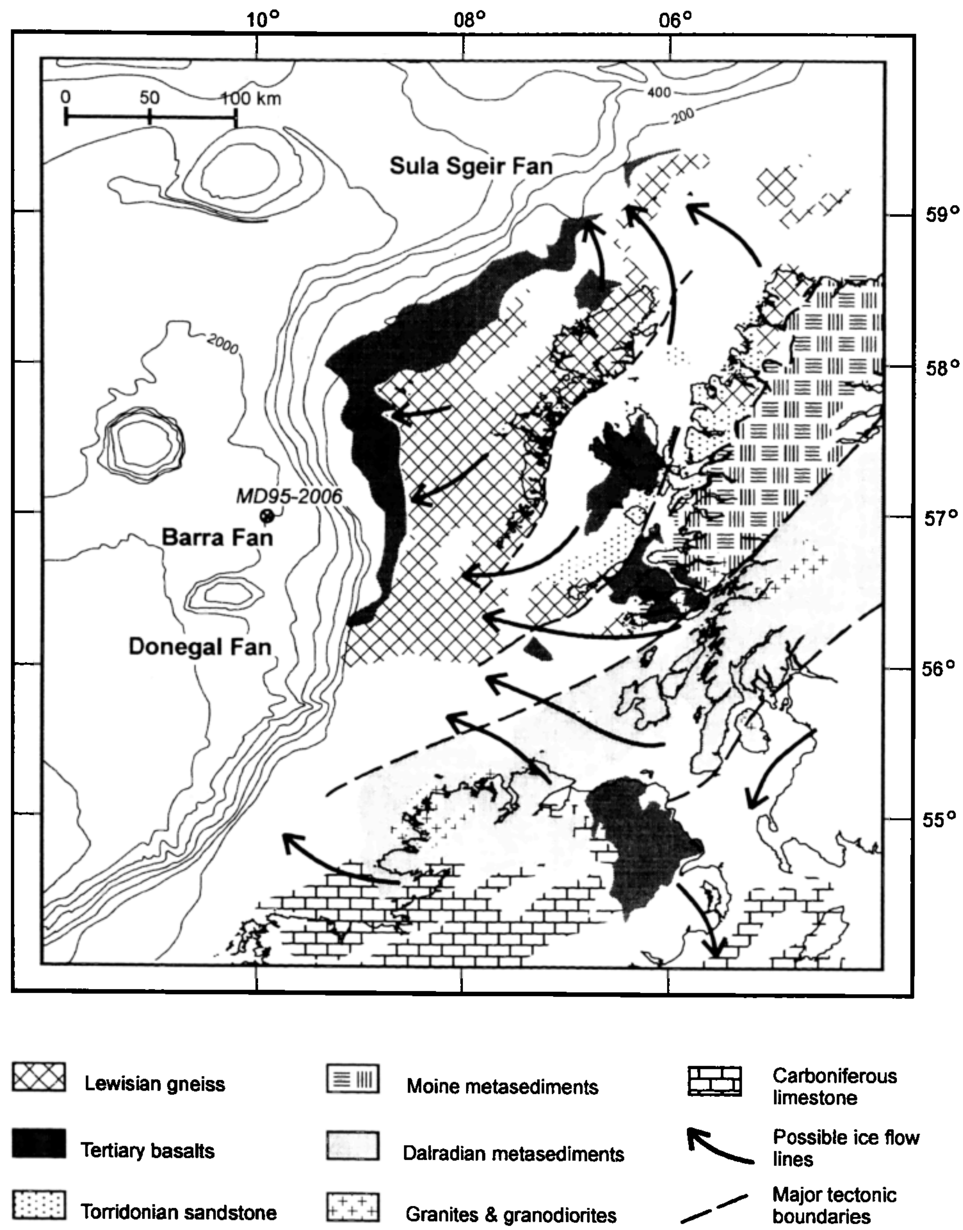

Figure 6. Geology and inferred ice flow directions on the northwestern margin of the British Isles White areas on the Hebrides shelf and in the Irish Sea are largely occupied by Mesozoic-Tertiary sedimentary basins.

Hebrides are predominantly basaltic and include a range of textural and compositional varieties derived from tholeiitic and olivine-basalt magma types [*Preston*, 1982]. The numerous dyke swarms that cut across the British Tertiary Province provide another source for volcanoclastic material. The possibility of ice-rafted basalt from Iceland, the Faeroe Islands, and east Greenland reaching the Rockall Trough cannot be excluded, but basaltic glass of presumed Icelandic origin [*Ruddiman and Glover*, 1972; *Lackschewitz and Wallrabe-Adams*, 1997; *Elliot et al.*, 1998] is rare in the Barra Fan record (except for the ash horizon at around 2.6 m core depth). IRD peaks characterized by abundant basalt in MD95-2006 are also enriched in quartz-rich igneous rock fragments that may have been derived from the Lewisian gneiss of the Outer Hebrides (Figure 6).

Detrital carbonate is not a significant constituent of the IRD record of MD95-2006, indicating a minimal input from the Carboniferous limestone formations of Ireland. This may possibly be due to a southward drift of icebergs released from the western Irish margin (Figure 6). One horizon at 25 m depth (BF 13.2), corresponding to H-4, contains a relatively high concentration of distinct pale yellowish dolomitic carbonate (Figure 4e). This component may represent either glacially weathered material of Irish origin or "Heinrich layer" carbonate released by far-travelled icebergs calved from the LIS [*Andrews and Tedesco*, 1992]. The difference in composition between BF 13.1 and BF 13.2 (Figure 4) supports the hypothesis proposed by *Snoeckx et al.*, [1999] that an early European ice-rafting event occurred prior to the main H-4 event. Sr-Nd isotope measurements across Heinrich layers 1 and 2 are also indicative of IRD input from western Europe prior to massive iceberg calving from the Laurentide Ice Sheet [*Grousset et al.*, 2000].

Fractured quartz in the 250-500 μm lithic fraction (Figure 4c) is related to basal debris released from melting icebergs [*Heinrich*, 1988] whereas the total IRD_{250} fraction (Figure 4b) may represent a mixed sea ice/iceberg signal [*Nurnberg et al.*, 1994]. The match between the IRD_{250} and abundance of fractured quartz suggests that IRD_{250} mainly reflects sediment carried by icebergs. The anomalous prominent BF 1 peak represented by IRD_{250} (Figure 4b) could reflect a dominant sea ice transport mode during the Younger Dryas.

6.2. Ice Margin Fluctuations on the Hebrides Shelf

The character of coarse-grained turbidites in MD95-2006 suggests that these derived from an ice-proximal glacimarine environment and are possibly associated with high discharges of subglacial meltwater [*Knutz et al.*, 2001]. Their presence may thus indicate periods when glacial ice was grounded on the Hebrides shelf margin. The pattern of IRD fluctuations, with an average periodicity of ~2500 years, is superimposed on the general lithofacies variations and may correspond to rapid changes in glacial dynamics of the BIS.

6.2.1. Before 30 kyr B.P. Low concentrations of basaltic IRD in LU 5 point to a lack of glacigenic supply from the Tertiary volcanic provinces of the Inner Hebrides and Northern Ireland before 30 kyr B.P. (~MIS 3) (Figure 4e). Glaciers may have existed in western Scotland and Northern Ireland [*Bowen*, 1999] but were probably grounded above the marine limit. However, variable deposition of quartz-rich IRD between 45 and 30 kyr B.P. suggests that glacimarine conditions were intermittently established along the NW British margin. Radiocarbon dates from terrestrial sequences suggest that ice-free conditions prevailed in the majority of the Scottish lowlands from ~40 to 27 ^{14}C kyr B.P., but glaciers appear to have been present in the Firth of Clyde before 33 ^{14}C kyr B.P. [*Hall*, 1997].

6.2.2. 30-22 kyr B.P. An abrupt increase in basaltic IRD at 30 kyr B.P. (BF 10) suggests that glaciers carrying eroded material from the Tertiary formations of NW Britain had reached the shelf edge. BF 10 coincides with a change from a hemipelagic setting to a glacimarine environment with abundant gravity flow deposition and a substantial increase in sediment supply from the shelf (Figures 3a and 3b). Hence both IRD and lithological data indicate that glaciers had reached the western margin of the Hebrides shelf at a time that correlates with H-3 in the central North Atlantic. Judging from the abrupt cessation of gravity flow events at 14-m core depth it is inferred that ice withdrew from the outer shelf subsequent to deposition of BF 6 (Figure 5b). This lithological transition has not been dated but is likely to have occurred between 21 and 23 kyr B.P. Previous land-based studies suggest the last glacial maximum in the Irish Sea Basin was reached between 20 and 25 kyr B.P. but considerable uncertainty surrounds the timing and extent of the western margin of the BIS during MIS 2 and 3 [*Bowen and Sykes*, 1988; *Eyles and McCabe*, 1989]. The lithological evidence from MD95-2006 is largely consistent with the timing of maximum glacial advance in the northern North Sea [*Sejrup et al.*, 1994]. A recent study from the Celtic Sea margin show that glaciers in the Irish Sea produced two ice-rafting events between 22.2 and 20.0 ^{14}C ka B.P. [*Scourse et al.*, 2000]. The younger peak coincides with the Laurentide H-2 event, whereas the older peak is related to a European precusor event [*Bond and Lotti*, 1995; *Grousset et al.*, 2000]. These iceberg discharges may correspond to BF 7 (~H-2) and BF 8 on the Barra Fan.

6.2.3. After 22 kyr B.P. High rates of fine-clastic sedimentation between 21 and 12 kyr B.P. suggest that meltwater plumes dominated the depositional environment on the Barra Fan. This glacimarine regime is probably associated with the deglaciation of the Hebrides shelf margin with the main phase placed between 18 and 16 kyr B.P. [*Austin and Kroon*, 1996]. Renewed gravity flow sedimentation and a clearly defined IRD horizon (BF 2) at 5-6 m depth in MD95-2006 suggests that glacial ice extended to the outer shelf around 16-17 kyr B.P. (Figure 5b). This event corresponds to a readvance of the western sector of the BIS, which was recently demonstrated in the terrestrial record of northeast Ireland [*McCabe and Clark*, 1998]. The BIS readvance was correlated with North Atlantic H-1 but occurs with a delay of up to 1 kyr compared with the retreat of the Laurentide and the Barents Sea/Fennoscandian Ice Sheets [*Elverhoi et al.*, 1995]. *McCabe and Clark* [1998] therefore argued that the BIS readvance occurred as a response to the collapse of the LIS. The timing of the BIS "H-1" event cannot be precisely defined in core MD95-2006, but the rapid millennial-scale iceberg discharges from the British margin are inconsistent with the view that the BIS was entirely forced by instabilities of the LIS.

6.3. Millennial-scale Depositional Cycles on the Barra Fan

Feedback processes within the ocean-atmosphere-cryosphere appear to play a crucial role in the generation of millennial-scale climate cycles. In particular, the effect of meltwater discharge on the stability of the North Atlantic conveyor has been invoked as a cause for abrupt climate change [e.g., *Broecker et al.*, 1990; *Lehman and Keigwin*, 1992; *Cortijo et al.*, 1997]. During the last glacial the production of North Atlantic Deep Water appears to have fluctuated with a frequency similar to the Dansgaard-Oeschger cycle [*Keigwin and Jones*, 1994; *Oppo and Lehman*, 1995]. During interstadials a southward flow of NADW was associated with strong thermohaline convection in the Norwegian Sea, while during stadials and Heinrich events the outflow of deep water was reduced, allowing Atlantic Intermediate Water to enter the Faeroe-Shetland Channel [*Rasmussen et al.*, 1996]. This reversed and shallower current regime was probably related to shifts in convection sites from the Nordic Seas to south of the Greenland-Scotland ridge [*Labeyrie and Duplessy*, 1985; *Duplessy et al.*, 1988; *Sarnthein et al.*, 1994]. The presence of millennial-scale sediment cycles in MD95-2006 suggests that abrupt shifts in North Atlantic paleocirculation also influenced the British Atlantic margin. In particular, we relate the coeval peak response of coarse clastic silt percentages and planktonic foraminifera abundance to interstadial periods of the D-O cycle (Figures 5c and 5d). Peak concentrations in coarse silt may correspond with fast bottom currents of NADW circulating the Rockall Trough [*McCave et al.*, 1995]. The rapid fluctuations in flow of NSOW through the Faeroe-Shetland Channel documented by *Rasmussen et al.* [1996] imply that depositional systems on the British margin were affected by similar flow variations in NADW (Figure 1). Deep water may also have formed locally from downwelling of dense brines generated by freezing of sea ice in the shelf seas [*Veum et al.*, 1992]. Increases in bottom current activity during the Bølling-Allerød interstadial and across the Younger Dryas to Holocene boundary is evident from the coarse silt record (Figure 5c) and confirms the flickering onswitch of thermohaline convection during the last deglaciation [*Lehman and Keigwin*, 1992; *Haflidason et al.*, 1995].

A lack of a clear inverse relationship between the abundance of IRD and planktonic foraminifera in MD95-2006 suggests that ice-rafting peaks may not exclusively correspond to maximum stadial conditions with low surface water productivity. In the lower part of the core (LU 5), which corresponds to MIS 3, the abundance of lithic grains increases abruptly at the end of interstadial events (Figure 5b). This pattern could suggest an early response of the BIS to atmospheric cooling, perhaps facilitated by high precipitation and increased mass balance during interstadial/stadial transitions [*Sissons*, 1979]. Shifting precipitation patterns related to movements of the polar front and the intensity of thermohaline convection in the Nordic Seas would have an instant effect on the mass balance of glaciers in NW Europe. The dependence of moisture supply on ice sheet growth is demonstrated in Greenland Summit ice cores, where snow accumulation rates more than doubled across the cold-warm transitions of the last deglaciation [*Alley et al.*, 1993]. Reconstructions of Holocene glacial fluctuations in southern Norway show that high winter precipitation led to growth of the Hardangerjøkulen ice cap despite warmer summer temperatures [*Dahl and Nesje*, 1996]. If moisture was a limiting factor for ice sheet growth in NW Europe, then maximum ice growth should be expected during the interstadial part of the D-O cycle when thermohaline convection was operating effectively. The inferred relationship between ice sheet growth on the British Isles and thermohaline circulation is illustrated in Figure 7.

Ocean circulation models shows that thermohaline convection is highly sensitive to even minor changes in freshwater input if these occur at high latitudes [*Paillard and Labeyrie*, 1994; *Manabe and Stouffer*, 1995; *Rahmstorf*, 1995]. Hence, is it possible that rapid expansion of mountain ice caps on the NE Atlantic margins could have produced a positive feedback on the thermohaline conveyor by limiting the return flow of freshwater? If ice growth occurred over centuries, it may have led to a relative increase in the surface density of the Norwegian Sea. Even a modest glacial expansion covering the highland regions in Scandinavia, Britain, and Iceland (assuming 30-40 % land coverage and accumulation rates of 0.4-0.6 m/yr) would prevent a freshwater return flow of 6000-10,000 m^3/s. This flux is ~ 10% of that required to shut down the thermohaline convection in the present-day Nordic Seas (S. Rahmstorf, personal communication, 1999).

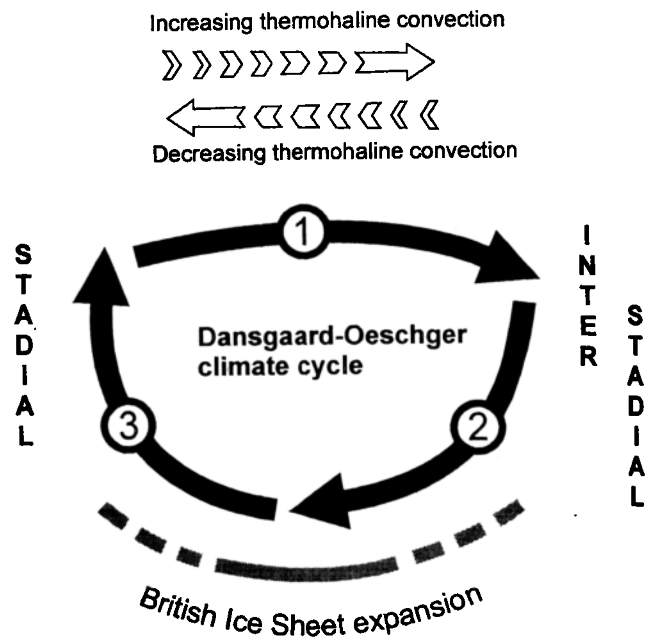

Figure 7. Timing of maximum growth phase of the British Ice Sheet in relation to the Dansgaard-Oeschger climate cycle and intensity of North Atlantic thermohaline convection. Phase 1 is associated with a rapid onset of thermohaline convection and influx of temperate surface waters in the Nordic Seas. Phase 2 is characterized by cooling of the North Atlantic and a decrease in flow of NADW. Phase 3 corresponds to full stadial conditions marked by discharges of icebergs and meltwater into the North Atlantic and strongly reduced deep convection in the Nordic Seas. This stage is also associated with the development of high-pressure circulation cells over Northern Hemisphere ice sheets [*Mayewski et al*, 1997].

7. Conclusions

A rapidly fluctuating behavior of the last British Ice Sheet is demonstrated in the paleoclimatic record of the Barra Fan. With a periodicity of 2000-3000 years, glacimarine depositional events on the Barra Fan match the millennial-scale ice-rafting cycle identified in the NE Atlantic by *Bond and Lotti* [1995]. Iceberg discharges from the British Ice Sheet may have contributed to the IRD precursors to Heinrich events observed in the central North Atlantic [*Snoeckx et al.*, 1999; *Grousset et al.*, 2000].

Maximum ice sheet advances on the Hebrides shelf margin occurred between 30 and 22 kyr B.P. and around 17-16 kyr B.P. The latter period is equivalent to the North Atlantic Heinrich event 1 and corresponds to the last major readvance on the Irish Sea margin [*McCabe and Clark*, 1998]. A distinct ice-rafting event on the Barra Fan around 30 kyr B.P., characterized by a high content of Tertiary basalt in the lithic sand fraction, corresponds with Heinrich event 3. Excursions in glacimarine sediment input from the Hebrides margin are interweaved with contourite depositional cycles, reflecting periods of enhanced bottom current activity and high surface water productivity in the Rockall Trough. These appear to be linked to interstadial Dansgaard-Oeschger events and formation of deep water in the Nordic Seas.

The results lend support to the central role of a thermohaline oscillator in the generation of the Dansgaard-Oeschger climate cycle. It is uncertain whether these oscillations evolved within the climate system, constrained by internal feedback mechanisms, or if they were forced by external factors such as solar variability or orbitally driven insolation cycles. If millennial-scale glacial fluctuations on the NE Atlantic margin were principally controlled by the flux of moisture and heat linked to thermohaline circulation, some degree of regional variability and time-transgressive behavior of iceberg discharges would be expected. Future research needs to address whether climatic oscillations revolving around the North Atlantic hydrological cycle can explain the evidence of millennial-scale climate variability in the Southern Hemisphere [*Lowell et al.*, 1995].

The use of Heinrich event stratigraphy to correlate IRD peaks outside the central North Atlantic is open to question as it presumes synchronity between circum-Atlantic ice sheets. In view of the strong coupling between ocean circulation and the dynamic behavior of regional ice caps, it is unlikely that all North Atlantic margins responded in phase on time-scales <1000 years.

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References

Alley, R. B. et al., Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event, *Nature, 362*, 527-529, 1993.

Alley, R. B, P U Clarke, and R. S. Webb, Making sense of Millennial-scale climate change, in *Mechanisms of Global Climate Change at Millennial Time Scales, Geophys. Monogr. Ser.*, vol. 112, edited by P U. Clarke, R.S. Webb, and L.D Keigwin, pp 385-394, AGU, Washington DC, 1999.

Andrews, J. T., Abrupt changes (Heinrich events) in late Quaternary North Atlantic marine environments: A history and review of data and concepts, *J. Quat. Sci., 13*, 3-16, 1998.

Andrews, J. T., and K. Tedesco, Detrital carbonate-rich sediments, northwestern Labrador Sea. Implications for ice-sheet dynamics and iceberg rafting (Heinrich) events in the North Atlantic, *Geology, 20*, 1087-1090, 1992.

Andrews, J T., D. C Barber, and A. E Jennings, Errors in generating time series and in dating events at late Quaternary millennial (radiocarbon) time series: examples from Baffin Bay, NW Labrador Sea, and East Greenland, in *Mechanisms of Global Climate Change at Millennial Time Scales, Geophys. Monogr. Ser.*, vol. 112, edited by P U. Clarke, R S. Webb, and L.D. Keigwin, pp. 23-33, AGU, Washington DC, 1999.

Austin, W E. N., and D. Kroon, Late glacial sedimentology, foraminifera and stable isotope stratigraphy of the Hebridean continental shelf, northwest Scotland, in *Late Quaternary Palaeoceanography of the North Atlantic Margins*, edited by J T. Andrews et al, *Geol. Soc. Spec. Publ.*, 187-213, 1996.

Ballantyne, C. K., D. McCarroll, A Nesje, S O Dahl, J O. Stone, and L. K. Fifield, High-resolution reconstruction of the last ice sheet in NW Scotland, *Terra Nova, 10*, 63-67, 1998

Bard, E, M Arnold, B Hamelin, N. Tisnerat-Laborde, and G. Cabioch, Radiocarbon calibration by means of mass spectrometric Th-230/U-234 and C-14 ages of corals. An updated database including samples from Barbados, Mururoa and Tahiti, *Radiocarbon, 40*(3), 1085-1092, 1998

Behl, R. J, and J P Kennett, Brief interstadial events in the Santa Barbara basin, NE Pacific, during the past 60 kyr, *Nature, 379*, 243-246, 1996.

Bianchi, G G., and I. N. McCave, Holocene periodicity in North Atlantic climate and deep-ocean flow south of Iceland, *Nature, 397*, 515-517, 1999.

Bloemendal, J, J. W. King, F. R. Hall, and S. J. Doh, Rockmagnetism of late Neogene and Pleistocene deep-sea sediments: Relationship to sediment source, diagenetic processes and sediment lithology, *J. Geophys. Res., 97*, 4361-4375, 1992.

Bond, G. C., and R. Lotti, Iceberg discharges into the North Atlantic on millennial time scales during the last Glaciation, *Science, 267*, 1005-1010, 1995.

Bond, G. et al., Evidence for massive discharges of icebergs into the North Atlantic Ocean during the last glacial period, *Nature, 360*, 245-249, 1992.

Bond, G. et al., A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial climates, *Science, 278*, 1257-1266, 1997.

Boulton, G. S., Sedimentary and sea level changes during glacial cycles and their control on glacimarine facies architecture, in *Glacimarine Environments: Processes and Sediments*, edited by J.A. Dowdeswell, and J.D. Scourse, *Geol. Soc. Spec. Publ.*, 15-52, 1990

Bowen, D. Q., Only four major 100-ka glaciations during the Brunhes Chron?, *Int. J. Earth Sci., 88*, 276-284, 1999.

Bowen, D. Q, and G A Sykes, Correlation of marine events and glaciations in the northeast Atlantic margin, *Philos. Trans. R. Soc. London, Ser. B, 318*, 619-635, 1988.

Broecker, W S., G. Bond, M. Klas, G. Bonani, and W. Wolfi, A salt oscillator in the Glacial Atlantic? 1. The concept, *Paleoceanography, 5*, 469-477, 1990.

Broecker, W. S., G. Bond, M. Klas, E. Clark, and J. McManus, Origin of the northern Atlantic's Heinrich events, *Clim. Dyn. 6*, 265-273, 1992.

Cortijo, E et al, Changes in sea surface hydrology associated with Heinrich event 4 in the North Atlantic Ocean between 40° and 60° N, *Earth Planet. Sci. Lett., 146*, 29-45, 1997.

Dahl, S. O., and A. Nesje, A new approach to calculating Holocene winter precipitation by combining glacier equilibrium line altitudes and pine-tree limits. A case study from Hardangerjokulen, central south Norway, *Holocene, 6*, 381-398, 1996

Davies, H. C., M. R. Dobson, and R. J Whittington, A revised seismic stratigraphy for Quaternary deposits on the inner continental shelf west of Scotland between 55° 30' N and 57° 30' N, *Boreas, 13*, 49-66, 1984

Dokken, T. M., and E Jansen, Rapid changes in the mechanism of ocean convection during the last glacial period, *Nature, 401*, 458-461, 1999.

Dowdeswell, J. A., A. Elverhoj, J. T. Andrews, and D. Hebbeln, Asynchronous deposition of ice-rafted layers in the Nordic Seas and North Atlantic Ocean, *Nature, 400*, 348-351, 1999

Duplessy, J.C., N J. Shackleton, R. G. Fairbanks, L. Labeyrie, D. Oppo, and N Kallel, Deepwater source variations during the last climatic cycle and their impact on the global deepwater circulation, *Paleoceanography, 3*, 343-360, 1988.

Elliot, M., L. Labeyrie, G. Bond, E Cortijo, J. L. Turon, N. Tisnerat, and J. C. Duplessy, Millennial-scale iceberg discharges in the Irminger Basin during the last glacial period: Relationship with the Heinrich events and environmental settings, *Paleoceanography, 13*, 433-446, 1998.

Elverhoi, A. et al., The growth and decay of the late Weichselian ice sheet in western Svalbard and adjacent areas based on provenance studies of marine sediments, *Quat. Res., 44*, 303-316, 1995.

Eyles, N., and A. M. McCabe, The Late Devensian (<22,000 BP) Irish Sea Basin: the sedimentary record of a collapsed ice sheet margin, *Quat. Sci. Rev., 8*, 307-351, 1989.

Fronval, T., E. Jansen, J. Bloemendal, and S Johnsen, Oceanic evidence for coherent fluctations in Fennoscandian and Laurentide ice sheets on millenium timescales, *Nature, 374*, 443-446, 1995.

Grootes, P. M., and M. Stuiver, Oxygen 18/16 variability in Greenland snow and ice with 10^3 to 10^5- year time resolution, *J. Geophys. Res., 102*(C12), 26,455-26,470, 1997.

Grousset, F. E., C. Pujol, L Labeyrie, G. Auffret, and A. Boelaert, Were the North Atlantic Heinrich events triggered by the behavior of the European ice sheets?, *Geology, 28*, 123-126, 2000.

Haflidason, H., H. P. Sejrup, D. K. Kristensen, and S. Johnsen, Coupled response of the late Glacial climatic shifts of northwest Europe reflected in Greenland ice cores. Evidence from the northern North Sea, *Geology, 23*(12), 1059-1062, 1995.

Hall, A M., Quaternary stratigraphy: The

terrestrial record, in *Reflections on the Ice Age in Scotland*, edited by J E Gordon, pp. 59-71, Scott Assoc. of Geogr Teachers/Scot Nat Heritage, Glasgow, 1997.
Heinrich, H., Origin and consequences of cyclic ice-rafting in the northeast Atlantic Ocean during the past 130 ka, *Quat. Res.*, *29*, 142-152, 1988.
Howe, J. A., Turbidite and contourite sediment waves in the northern Rockall trough, North Atlantic Ocean, *Sedimentology*, *43*, 219-234, 1996.
Jones, E. J. W., M. Ewing, J. I Ewing, and S L. Eittreim, Influence of Norwegian Sea Overflow Water on sedimentation on the northern North Atlantic and Labrador Sea, *J. Geophys. Res.*, *75*, 1655-1680, 1970.
Keigwin, L. D, and G A. Jones, Western North Atlantic evidence for millennial scale changes in ocean circulation and climate, *J. Geophys. Res.*, *99*(C6) 12,397-12,410, 1994
Knutz, P. C, E. J. W. Jones, W. E N. Austin, and T. J C van Weering, Glacimarine slope sedimentation and formation of contourite drifts on the Barra Fan, UK margin, *Mar. Geol.*, 2001.
Kroon, D, W E. N. Austin, M. R Chapman, and G. M. Ganssen, Deglacial surface circulation changes in the northeastern Atlantic: Temperature and salinity records off NW Scotland on a century scale, *Paleoceanography*, *12*, 755-763, 1997.
Kroon, D., G. Shimmield, W. E. N Austin, S. Derrick, P. Knutz, and T. Shimmield, Century-to millennial-scale sedimentological-geochemical records of glacial-Holocene sediment variations from the Barra Fan (NE Atlantic), *J. Geol. Soc. London*, *157*, 643-653, 2000.
Kvamme, T., J. Mangerud, H. Furnes, and W F. Ruddiman, Geochemistry of Pleistocene ash zones in cores from the North Atlantic, *Nor. Geol. Tiddskr.*, *69*, 251-272, 1989
Labeyrie, L. D., and J. C. Duplessy, Changes in the oceanic C13-C12 ratio during the last 140,000 years: High-latitude surface-water records, *Palaeogeogr. Palaeoclimatol Palaeoecology*, *50*, 217-240, 1985.
Lackschewitz, K. S., and H. J. Wallrabe-Adams, Composition and origin of volcanic ash zones in Late Quaternary sediments from the Reykjanes Ridge: Evidence for ash fallout and ice-rafting, *Mar. Geol.*, *136*, 209-224, 1997.
Lee, A. J., and D. J. Ellet, On the contribution of overflow water from the Norwegian Sea to the hydrographic structure of the North Atlantic, *Deep Sea Res.*, *14*, 183-190, 1965
Lehman, S J., and L. D. Keigwin, Sudden changes in North Atlantic circulation during the last deglaciation, *Nature*, *356*, 757-762, 1992.
Lowell, T. V., C. J. Heusser, B. G Andersen, P. I. Moreno, A. Hauser, L. E. Heusser, C Schluchter, D. R. Marchant, and G H Denton, Interhemispheric correlation of late Pleistocene glacial events, *Science*, *269*, 1541-1549, 1995.
MacAyeal, D. R., Binge/purge oscillations of the Laurentide ice sheet as a cause of the North Atlantic's Heinrich events, *Paleoceanography*, *8*, 775-784, 1993
Manabe, S., and R. J. Stouffer, Simulation of abrupt climate change induced by freshwater input to the North Atlantic Ocean, *Nature*, *378*, 165-167, 1995.
Mayewski, P. A, L D. Meeker, M. S. Twickler, S. Whitlow, Q. Z. Yang, W B Lyons, and M Prentice, Major features and forcing of high-latitude Northern Hemisphere atmospheric circulation using a 110,000-year-long glaciochemical series, *J. Geophys. Res.*, *102*(C12), 26,345-26,366, 1997
McCabe, A. M, Glacial morphology, in *The Quaternary history of Ireland*, edited by K. J. Edwards, and W. P. Warren, pp 67-93, Academic, San Diego, 1985.
McCabe, A. M., and P. U Clark, Ice sheet variability around the North Atlantic Ocean during the last deglaciation, *Nature*, *392*, 373-377, 1998.
McCave, I. N., B. Manighetti, and S. G. Robinson, Sortable silt and fine sediment size composition slicing: parameters for palaeocurrent speed and palaeoceanography, *Paleoceanography*, *10*, 593-610, 1995.
McIntyre, A., and B. Molfino, Forcing of Atlantic equatorial and subpolar millennial cycles by precession, *Science*, *274*, 1867-1870, 1996.
Meese, D. A., A. J. Gow, R. B. Alley, G. A. Zielinski, P. M. Grootes, M Ram, K. C. Taylor, P. A. Mayewski, and J. F. Bolzan, The Greenland Ice Sheet Project 2 depth-age scale: Methods and results, *J. Geophys. Res.*, *102*(C12), 26,411-26,423, 1997.
Nurnberg, D., I. Wollenburg, D Dethleff, H. Eicken, H. Kassens, T. Letzig, E. Reimnitz, and J. Thiede, Sediments in Arctic sea-ice: implications for entrainment, transport and release, *Mar. Geol.*, *119*, 185-214, 1994.
Oppo, D. W., and S. J Lehman, Suborbital timescale variability of North Atlantic Deep Water during the past 200,000 years, *Paleoceanography*, *10*, 901-910, 1995.
Paillard, D., and L. Labeyrie, Role of the thermohaline circulation in the abrupt warming after Heinrich events, *Nature*, *372*, 162-164, 1994.
Peacock, J D, W. E N Austin, I. Selby, D. K Graham, R. Harland, and I P. Wilkinson, Late Devension and Flandrian paleoenvironmental changes on the Scottish continental shelf of the Outer Hebrides, *J. Quat. Sci.*, *7*, 145-161, 1992.
Preston, J., Eruptive vulcanism, in *Igneous rocks of the British Isles*, edited by D S. Sutherland, pp. 351-368, John Wiley, New York, 1982.
Rahmstorf, S., Bifurcations of the North Atlantic thermohaline circulation in response to changes in the hydrological cycle, *Nature*, *378*, 145-149, 1995.
Rasmussen, T. L., E. Thomsen, T. C. E. Van Weering, and L. Labeyrie, Rapid changes in surface and deep water conditions at the Faroe Margin during the last 58,000 years, *Paleoceanography*, *11*, 757-771, 1996.
Ruddiman, W. F., and L. K. Glover, Vertical mixing of ice rafted volcanic ash in North Atlantic sediments, *Geol. Soc. Am. Bull.*, *83*, 2817-2836, 1972.
Sarnthein, M., K. Winn, S. J. A. Jung, J-C. Duplessy, L Labeyrie, H Erlenkeuser, and G. Ganssen, Changes in east Atlantic deep water circulation over the last 30,000 years: Eight time slice reconstructions, *Paleoceanography*, *9*, 209-267, 1994.
Scourse, J. D., I. R Hall, I. N McCave, J R. Young, and C. Sugdon, The origin of Heinrich layers: Evidence from H2 for European precursor events, *Earth Planet. Sci. Lett.*, *182*, 187-195, 2000.
Sejrup, H P, H. Haflidason, I Aarseth, E. King, C. F Forsberg, D. Long, and K. Rokoengen, Late Weichselian glaciation history of the northern North Sea, *Boreas*, *23*, 1-13, 1994
Sissons, J. B., Paleoclimatic inferences from former glaciers in Scotland and the Lake District, *Nature*, *278*, 518-521, 1979.
Snoeckx, H., F. Grousset, M. Revel, and A. Boelaert, European contribution of ice-rafted sand to Heinrich layers H3 and H4, *Mar. Geol.*, *158*, 197-208, 1999.
Stoker, M. S., The influence of glacigenic sedimentation on slope-apron development on the continental margin off Northwest Britain, in *The Tectonics, Sedimentation and Paleoceanography of the North Atlantic region*, edited by R.A Scrutton et al., *Geol. Soc. Spec. Publ.*, 159-177, 1995.
Stoker, M. S., K. Hitchen, and C C. Graham, United Kingdom Offshore Regional Report The geology of the Hebrides and west Shetland shelves, and the adjacent deep water areas, Br Geol. Surv, London, 1993.
Stuiver, M., P. M. Grootes, and T. F Braziunas, The GISP2 delta O-18 climate record of the past 16,500 years and the role of the sun, ocean, and volcanoes, *Quat. Res.*, *44*, 341-354, 1995.
Swallow, J. C., W. J. Gould, and P. M. Saunders, Evidence for a poleward eastern boundary current in the North Atlantic ocean, *International Council for the Exploration of the Sea, Committee Paper No. CM 1977/C* 32, Copenhagen, 1977.
Veum, T, E. Jansen, M. Arnold, I. Beyer, and J. C. Duplessy, Water mass exchanges between the North Atlantic and the Norwegian Sea during the past 28,000 years, *Nature*, *356*, 783-785, 1992.

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