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Donald C. Barber
Bryn Mawr College, dbarber@brynmawr.edu

J. T. Andrews

A. E. Jennings

D. D. Erbel

B. Maclean

See next page for additional authors

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Authors
Donald C. Barber, J. T. Andrews, A. E. Jennings, D. D. Erbel, B. Maclean, M. E. Kirby, and J. S. Stoner

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Varying sediment sources (Hudson Strait, Cumberland Sound, Baffin Bay) to the NW Labrador Sea slope between and during Heinrich events 0 to 4

J. T. ANDREWS,[1]* D. C. BARBER,[2] A. E. JENNINGS,[1] D. D. EBERL,[3] B. MACLEAN,[4] M. E. KIRBY[5] and J. S. STONER[6]
[1]INSTAAR and Department of Geological Sciences, University of Colorado, Boulder, CO 80309, USA
[2]Geology Dept/Environmental Studies Program, Bryn Mawr College, PA, USA
[3]US Geological Survey, Boulder, CO, USA
[4]Geological Survey of Canada, Atlantic, Bedford Institute of Oceanography, Dartmouth, Canada
[5]Cal-State Fullerton, Department of Geological Sciences, Fullerton, CA, USA
[6]College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA

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ABSTRACT: Core HU97048-007PC was recovered from the continental Labrador Sea slope at a water depth of 945 m, 250 km seaward from the mouth of Cumberland Sound, and 400 km north of Hudson Strait. Cumberland Sound is a structural trough partly floored by Cretaceous mudstones and Paleozoic carbonates. The record extends from ∼10 to 58k cal a BP. On-board logging revealed a complex series of lithofacies, including buff-colored detrital carbonate-rich sediments [Heinrich (H)-events] frequently bracketed by black facies. We investigate the provenance of these facies using quantitative X-ray diffraction on drill-core samples from Paleozoic and Cretaceous bedrock from the SE Baffin Island Shelf, and on the < 2-mm sediment fraction in a transect of five cores from Cumberland Sound to the NW Labrador Sea. A sediment unmixing program was used to discriminate between sediment sources, which included dolomite-rich sediments from Baffin Bay, calcite-rich sediments from Hudson Strait and discrete sources from Cumberland Sound. Results indicated that the bulk of the sediment was derived from Cumberland Sound, but Baffin Bay contributed to sediments coeval with H-0 (Younger Dryas), whereas Hudson Strait was the source during H-events 1–4. Contributions from the Cretaceous outcrops within Cumberland Sound bracket H-events, thus both leading and lagging Hudson Strait-sourced H-events.

KEYWORDS: Baffin Bay; detrital carbonate (DC-) events; Heinrich events; Labrador Sea; Laurentide Ice Sheet.

Introduction

In the 1970s research on the sediments associated with the North Atlantic Mid-Ocean Channel resulted in the description of a series of facies associated with turbidites sourced from the Hudson Strait (Chough and Hesse, 1976; Chough, 1978). A major feature was the presence of facies rich in detrital carbonate (DC facies). Piper (1973), Aksu (1981) and Aksu and Mudie (1985) described cores from Baffin Bay and the NW Labrador Sea where they also noted DC facies and a variety of other facies delimited on the basis of mineralogy and color. In subsequent research the DC facies emanating from Hudson Strait were correlated with ice-rafted debris (IRD) units in the north-central North Atlantic described by Heinrich (1988) and which are now universally known as Heinrich (H-) layers or events (Andrews and Tedesco, 1992; Bond *et al.*, 1992). Subsequent research has shown that Hudson Strait is the main source of H-layer sediments (Farmer *et al.*, 2003; Hemming, 2004), although the depositional processes are far more complex than sedimentation from an 'armada of icebergs' (cf. Hesse *et al.*, 1990; Hesse, 1992).

A largely unknown issue is whether H-events are coeval with ice-margin events of the other major ice streams that drained toward the Labrador Sea and Baffin Bay (Marshall and Clarke, 1996; Dyke *et al.*, 2002; Marshall and Koutnik, 2006; De Angelis and Kleman, 2007). One such ice stream may have occupied Cumberland Sound, a 1200-m-deep trough that connected the Foxe Basin sector of the Laurentide Ice Sheet with the NW Labrador Sea (Jennings *et al.*, 1996; Kaplan *et al.*, 1999). However, there is no stream of carbonate erratics from the Paleozoic outcrop in Foxe Basin to the head of Cumberland Sound (Andrews and Miller, 1979) as there is to the north into Home Bay (Andrews *et al.*, 1970) and to the south to the head of Frobisher Bay.

The purpose of this paper is to examine evidence for the phasing of sediment delivery from ice streams in Cumberland Sound, Hudson Strait and Baffin Bay, between and during H-vents. We do this by examining the mineral composition of sediments from cores on the slope below Cumberland Sound, namely HU97-048-007, HU87-033-009 and HU75-009-IV-056, on the shelf (HU82034-41), and within Cumberland Sound (core HU85-027-029) (Figs 1 and 2, supporting information, Table S1) and comparing these data with analyses of bedrock and sediment samples from the shelf, Cumberland Sound, Resolution Basin outer Hudson Strait, and Baffin Bay (Figs 1 and 2). A particular focus is on source for a DC-0 (∼Younger Dryas) carbonate event, which Kirby (1998) detected as a rather subtle (dolomite-rich) event in cores from NW Labrador Sea below 2000 m water depth (cores HU75009-IV-055 and -056; Fig. 1, supporting Table S1). Knutz *et al.* (2011) did not detect this event in a nearby core, DA04-31P, from 2525 m (Fig. 1).

Background

To better understand the implications of our research we review the background to the study.

Bedrock geology

The predominant outcrops on the floor of Cumberland Sound and adjacent areas are Precambrian granites and gneisses (Riley, 1960; MacLean *et al.*, 2011), including the Cumberland batholith, with ages of 2.2–1.81 Ga (Jackson and Berman, 2000). The Baffin region was affected by early Tertiary volcanic

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*Correspondence: J. T. Andrews, as above.
E-mail: andrewsj@colorado.edu

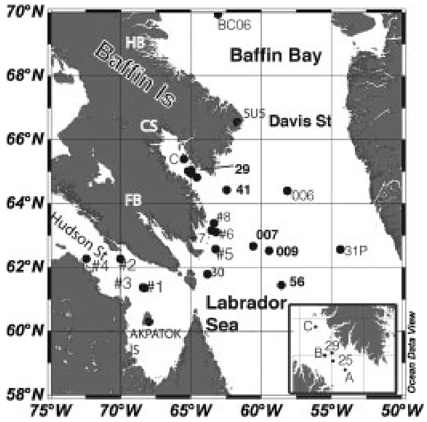

Figure 1. Map of the research area showing the location of cores mentioned in the text (see supporting Table S1) (filled circles), and the location of bedrock samples examined in this paper (open circles) (supporting Table S1). The arrows identify the following probable ice streams; HB = Home Bay; CS = Cumberland Sound; FB = Frobisher Bay; and HS = Hudson Strait. See Table 1 for identification of individual stations identified in this figure.

activity and rifting (MacLean *et al.*, 1990; Skaarup *et al.*, 2006) that resulted in the creation of a series of grabens that preserved Paleozoic carbonates on the floor of Hudson Strait, on the SE Baffin Shelf and extending into Cumberland Sound (MacLean *et al.*, 1990, 2011; MacLean, 2001) (Fig. 2). The graben on the north-eastern side of Cumberland Sound is 1200 m deep and contains Cretaceous mudstones. Borehole drilling on the shelf and within Cumberland Sound led to the extraction of Paleozoic, Cretaceous and Tertiary sedimentary rock samples (MacLean *et al.*, 2011) (Fig. 2).

Glacial geology

Studies of the Quaternary sediments within Cumberland Sound (Jennings, 1993) proved critical in the 'Big versus Little Ice' controversy of the 1980s (Denton and Hughes, 1981; Miller *et al.*, 2002) as it showed that ice filled Cumberland Sound until at least ~12k cal a BP. Cosmogenic exposure ages of bedrock and moraine boulders, especially along the northern shores of Cumberland Sound, indicated that Cumberland Sound had been filled by ice during the Late Glacial Maximum with retreat occurring relatively late in the deglacial cycle (Kaplan *et al.*, 2001; Marsella *et al.*, 2000). A large ridge occurs near the shelf break upslope from 007PC (Praeg *et al.*, 1986), which probably represents a terminal moraine.

Cumberland Sound was inferred to have contained an ice stream (Kaplan *et al.*, 1999, 2001), although the recently acquired limited multibeam surveys of the seafloor have not produced significant evidence for steamlined bedforms that characterize other regions (Dowdeswell *et al.*, 2008; MacLean *et al.*, 2010). As noted above and in Andrews and Miller (1979), there is no evidence for the dispersal of carbonate erratics from the outcrop in Foxe Basin to the head of Cumberland Sound. This indicates that an ice divide must have lain across the lowland that connects Foxe Basin and Cumberland Sound. Thus, any detrital carbonate in sediments within Cumberland Sound or on the adjacent slope must have come from either the outcrop within Cumberland Sound (Fig. 2) or externally from other source areas.

Glacial and glacial marine depositional processes

High-resolution single-channel seismic data and a substantial number of marine piston cores have been used to describe the stratigraphy and lithofacies of sediments deposited on the slope of SE Baffin Island and the Labrador Sea[Q3] (Aksu and Mudie, 1985; Hesse, 1992; Jennings *et al.*, 1996; Kirby, 1997; Andrews *et al.*, 1998; Rashid *et al.*, 2003). In the North Atlantic a great deal of attention has been focused on H- layers and IRD (i.e. the coarse sand and larger fractions) (Heinrich, 1988), but the dominant depositional processes on the slopes seaward of the NE Laurentide Ice Sheet were associated with debris flows (Stravers and Powell, 1997) and meltwater, either as suspended sediment plumes or as turbidites (Hesse *et al.*, 1990; Rashid *et al.*, 2003). Intervals of rapid sediment deposition have been interspersed with hemipelagic conditions, which fortunately allowed the accumulation of sufficient foraminifera for

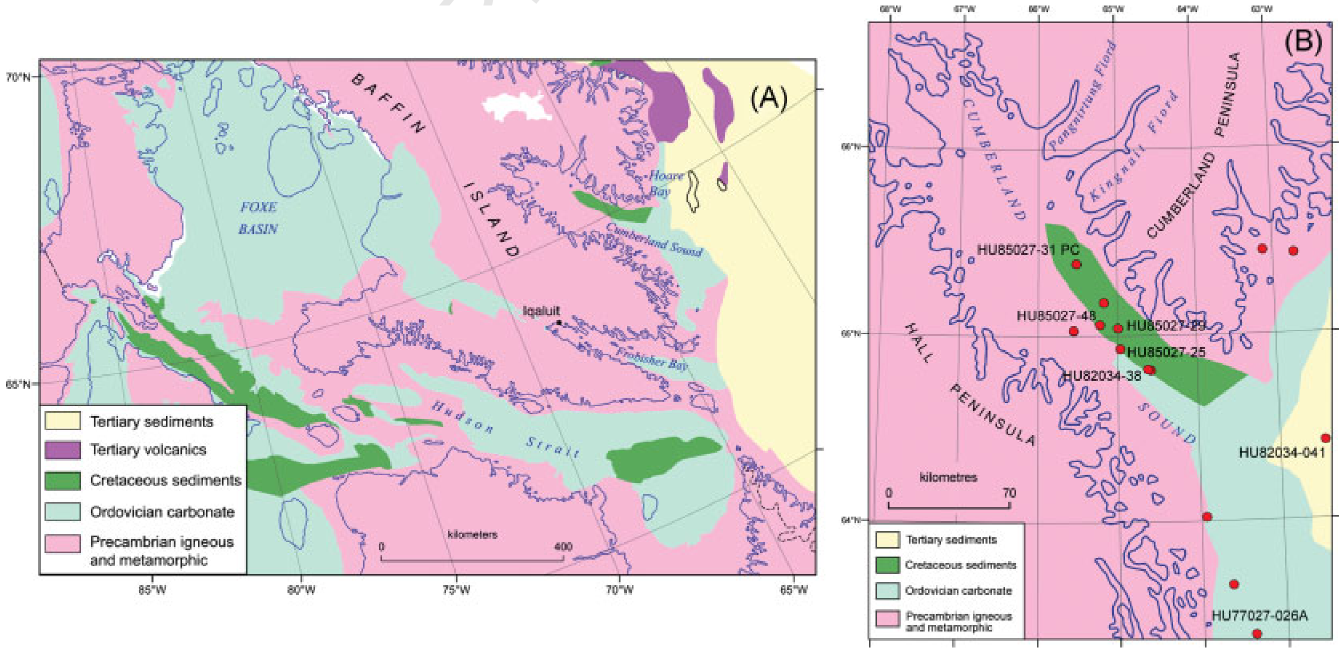

Figure 2. (A) General bedrock geology of southern Baffin Island and Hudson Strait (MacLean *et al.*, 2011). (B) Bedrock geology (after MacLean *et al.*, 1986) and[Q2] location of various drill and piston cores (supporting Table S1).

accelerator mass spectrometry (AMS) radiocarbon dating (supporting Table S2). Below about 1800 m water depth, the Western Boundary Undercurrent (McCave and Tucholke, 1986) flows counterclockwise along the lower slope, bringing with it fine-grained sediments from the Iceland/Greenland region (Fagel *et al.*, 1996; Knutz *et al.*, 2011).

Methods and data

On board measurements of the color of the wet sediment were undertaken on HU97-048-006TWC and 007PC (hereafter 0006TWC and 007PC) for measurements of L* (black to white), a* (blue to red) and b* (yellow to green) at 5-cm spacing (Piper, 1997). At INSTAAR, the CIE* color of dry sediment was measured using an X-Rite Model 530 spectrophotometer. Magnetic susceptibility was determined on the whole core prior to splitting using a Bartington MS meter with an 11-cm loop. The split cores were sampled with u-channels for paleomagnetic and sediment magnetic properties. Samples were taken every 5 cm for subsequent laboratory determination of grain-size distribution, mass magnetic susceptibility, total organic and total inorganic carbon using a UIC Coulometer. Residual splits from the sediment archives were used for qualitative X-ray diffraction (qXRD) measurements.

Our emphasis in this paper is on core 007PC, but to place this site in context we evaluate it along a transect from Cumberland Sound to the floor of the Labrador Sea (Fig. 1, supporting Table S1). We focus on the quantitative weight per cent (wt%) of minerals in the < 2-mm sediment fraction using the methodology of Eberl (2003) and principally the use of ZnO as a calibration spike, and Rockjock v6 (RJ v6) as the program for quantifying the XRD patterns (Eberl, 2004). qXRD has been reported on the clay-size mineralogy of some of the cores studied in this paper (Jennings, 1993; Kirby, 1997). The identification of specific minerals is restricted to the XRD-patterns of the 124 minerals in the RJv6 standards (see Eberl, 2003). The level of 'fit' between the predicted and observed XRD patterns was calculated as a degree-of-fit statistic (Eberl, 2003). Replicate measurements of a series of standards of known composition were used to determine instrument performance and to obtain estimates of accuracy and precision. It is important to note that because wt% data must sum to 100, large wt% changes in one species must have an inverse impact on the wt% of other species (Chayes, 1971).

To gain an understanding of the mineralogy of the regional bedrock we also ran qXRD analyses on bedrock drill-core samples from Hudson Strait, the SE Baffin shelf and Cumberland Sound (Fig. 1, supporting Table S3). Nine Paleozoic carbonate drill-core samples and three samples from the Cretaceous mudstone from Cumberland Sound were measured (Figs 1 and 2). All but one of the carbonate samples is primarily calcitic in composition, but site #5 has about 60 wt% dolomite (Fig. 1; supporting Table S3). The composition of the Cretaceous mudstones is dominated by quartz, disordered kaolinite, smectites and illite, with small amounts of chlorite and vermiculite (supporting Table S3). The Cretaceous mudstone bedrock fragments in basal diamictic sediments in HU85027-025PC have higher values of quartz and feldspars, and lower amounts of kaolinite, than the two drill-core samples. The Cretaceous mudstones have color values of L*, a* and b* of 32–40, 2.5–3.2 and 5.0–8.8, respectively, and thus are 'red' toned, dark-colored sediments. Analysis of the Tertiary mudstones that outcrop closer to the shelf break (Fig. 2) revealed large amounts of smectite in the clay-size fraction[Q4] (Jennings, 1989, 1993).

We use an unmixing algorithm, initially referred to as MinunMix v3 (Eberl, 2004), but now updated to 'SedUnMix' (Andrews and Eberl, 2012), to estimate the possible source contributions comprising the mineral composition of each sediment sample. This program has now evolved to a more sophisticated version called 'SedUnMix' (Andrews and Eberl, 2011, 2012[Q5]; ftp://brrcrftp.cr.usgsgov/pub/ddeberl/), which allows the input of five representative samples per end member/source, for up to a maximum of six six different source areas, which are randomly entered in the calculations of between one and 200 iterations per sample composition, allowing an estimate of errors to be determined.

Chronology

The chronology of 007PC is based on six AMS ^{14}C dates (supporting Table S2, Fig. 3) (Smith and Licht, 2000; Barber, 2001). The dates were obtained on tests of the polar planktonic foraminifera *N. pachydera* sinistral (Nps[Q6]) and were converted to calibrated years by the use of the Intcal94 marine calibration data set (supporting Table S2) – the youngest date constrains the base of H-1 at ~207 cm (Fig. 3) and the oldest date lies below H-4. Rashid *et al.* (2012) have obtained additional dates from 007PC that are not included in our age/depth model; the additional dates do not substantially alter the core chronology. To obtain a more complete depth/age model we established a robust correlation based on a comparison of the 1-cm Cryogenic Magnetometer measurement of the relative paleomagnetic intensity of 007PC versus MD95-2024 (50°12.26′N/45°41.14′W, 3448 m water depth) (Stoner *et al.*, 2000). This

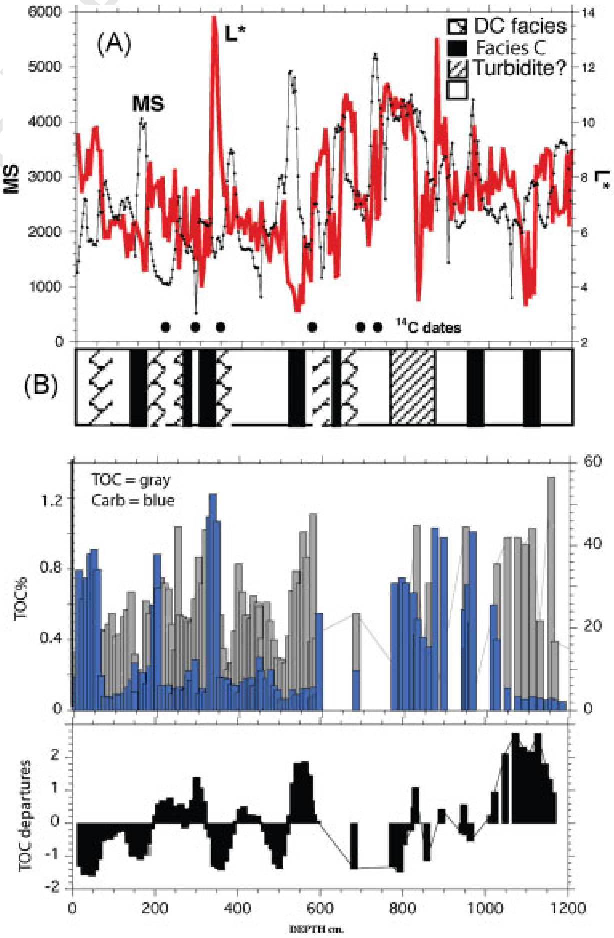

Figure 3. Initial description of the lithostratigraphy of HU97-048-007PC (B) based on the color parameter L* and whole-core magnetic mass susceptibility (MS, units x 10^{-11} SI) (A). (C) Measurements of total carbonate content, and (D) standardized departures [(observed – mean)/SD] from the five-point smoothed TOC%. This figure is available in colour online at wileyonlinelibrary.com/journal/jqs.

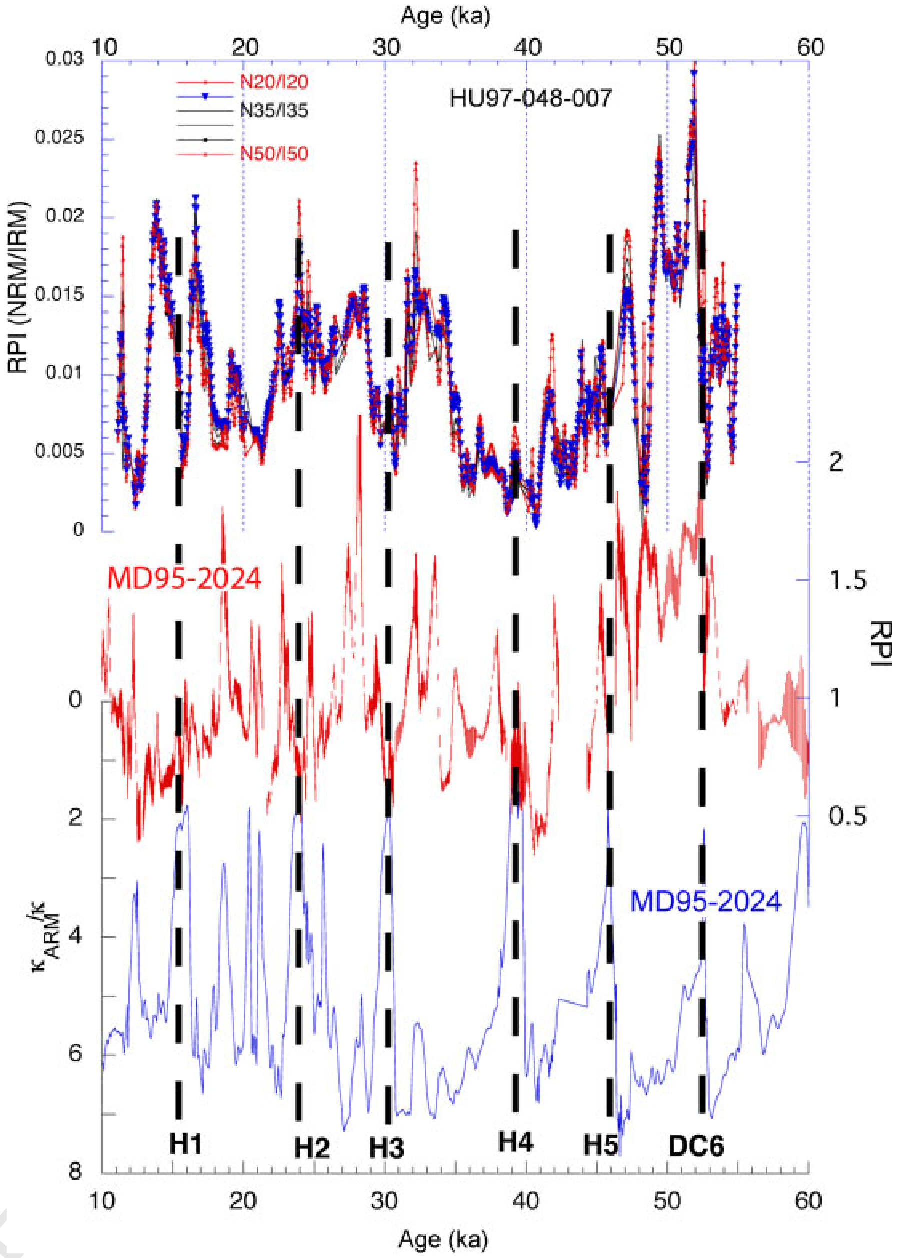

Figure 4. (top) Relative paleomagnetic intensity (NRM/IRM) from HU97048-007PC for various demagnetization steps, correlated (middle) with the relative paleointensity (RPI) record from MD95-2024 (Stoner *et al.*, 2000); (bottom) the magnetic grain-size data from MD95-2024–compare with Fig. 6D and data from 007PC. This figure is available in colour online at wileyonlinelibrary.com/journal/jqs.

comparison (Fig. 4) indicates that 007PC extends back to ca. 58 ka at[Q7] 850 cm depth (Fig. 3C) and encompasses H-5 and DC-event 6 in MD95-2024. The youngest DC-event (H-0) (Fig. 3) is dated at ~13k cal a BP. The data indicate that the average sediment accumulation rate is ~20 cm a^{-1}; sampling resolution averaged about one sample per 50 years for the IRM[Q8]/k measurements, one sample per 100 years for the IRD counts and one sample per 450 years for the qXRD determinations.

HU97048-007PC description and properties

HU97-048-006TW (1.4 m in length) and -007PC (12 m in length) were taken at the same site (Fig. 1) (Piper, 1997). Four main lithofacies were recognized[Q9] (Piper, 1997; Barber, 2001) (Fig. 3): (1) buff-colored (10YR 6/2) detrital carbonate (DC); (2) dark grey (5Y 3/1) relatively coarse-grained sediment (Facies C, Aksu and Mudie, 1985); (3) olive green (5YR 4/2) relatively fine-grained, hemipelagic sediments poor in detrital carbonate; and (4) a turbidite interval between 710 and 870 cm core depth. Six DC intervals and seven black lithofacies were initially identified (Fig. 3). The DC-facies are indentified as peaks in L* values and are associated with low magnetic susceptibility minima because of the diamagnetic properties of carbonate-rich sediments (Stoner and Andrews, 1999). Laboratory measurements of proxies for the DC- and black lithofacies included determination of total inorganic carbon (TIC%) and organic carbon (TOC%). Of significant interest is the relationship between the carbonate peaks and high TOC values (Fig. 3C). TOC% oscillates around a median value of 0.51% and often attains the highest values of ≥ 1% immediately above a carbonate peak (Fig. 3D).

To identify the variations in glacial sediment sources the data (Fig. 3) indicate the need to (i) determine the source(s) of the carbonate in the DC-facies, (ii) examine the composition of the black facies and (iii) determine the overall down-core variations in sediment mineralogy.

Mineralogy along a transect from Cumberland Sound to the Labrador Sea

We first examine the mineralogy of a core within Cumberland Sound, and then extend the analysis to cores on the shelf, slope and the NW Labrador Sea.

HU85027-029PC – Cumberland Sound

HU85027-029PC (029PC) from Cumberland Sound (Fig. 1, inset) sampled late Quaternary sediments overlying the Cretaceous mudstone (Jennings, 1993). The radiocarbon dates indicate that the base of the core is coeval with the top of 007PC (supporting Table S2); however, the core ends in the ice-proximal glacial marine sediments above the kaolinite-rich basal diamicton present in 025PC (supporting Table S3). Core 029PC thus includes deposition of sediment during deglaciation, and provides integrated source information on bedrock mineralogy within the Cumberland Sound drainage (Fig. 2).

The lowermost 2 m of this core ($\geq$ 10.9k cal a BP) is marked by an initial high wt% of kaolinite and smectite, which then fall to much lower 'background' values after 10.9k cal a BP (Fig. 5). Feldpars and quartz are initially low (data not shown) but rise rapidly in the interval 9–10 m. Little calcite is present ($\leq$ 2%) but dolomite peaks at 8% just above 9 m (Fig. 5). The precise source for the dolomite is unclear (Jennings *et al.*, 1996); it might be derived from local Paleozoic carbonate outcrops within Cumberland Sound (Fig. 2), although they tend to be calcite-rich (supporting Table S3), or it might be rafted in from northern Baffin Bay (Andrews *et al.*, 1996).

Core HU82034-41 (Cape Mercy Basin)

This 3.68-m core is from the small Cape Mercy Basin in 340 m of water and is located on Tertiary sediments, but is just east of the Paleozoic carbonate and Cretaceous bedrock limits (Praeg *et al.*, 1986) (Fig. 2, supporting Tables S1 and S4). The core consists of a basal sandy mud overlain by silty and sandy muds. Ice-rafted clasts occur from the base to about 0.5 m and coal fragments were observed at several levels. There are no reliable dates on this core but, based on cosmogenic dates (Kaplan *et al.*, 2001) WNW of the core site, and the basal dates from Cumberland Sound (e.g. Fig. 5), deglaciation of the basin is bracketed between 18 and 13k cal a BP. Four samples for qXRD were taken between 150 and 310 cm. The sediment is very dark gray to brown (5YR2.5/1) with CIE values (L^*, a^*, b^*) of 28–35, 0.5–0.8 and ~7.0, respectively. The samples between 210 and 262 cm have high clay-mineral content (> 30%) with 11–12% kaolinite but only modest amounts (< 7%) of smectite. The calcite content is low and dolomite makes up only 1–3 wt%.

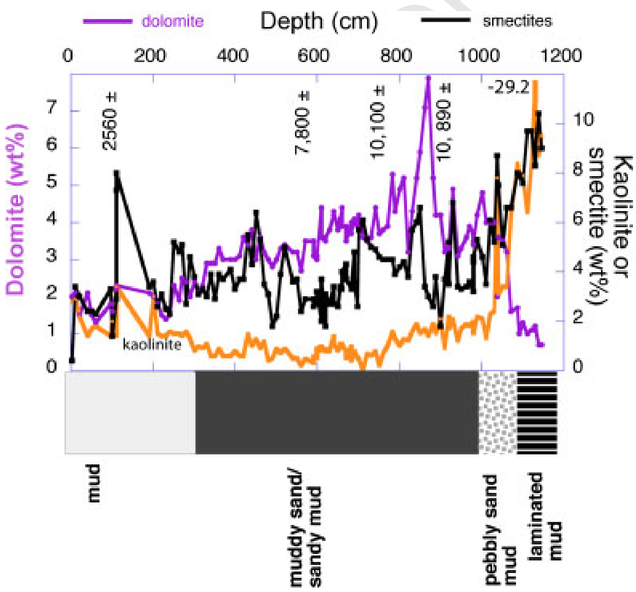

Figure 5. Lithofacies (Jennings, 1993) and selected mineralogy of HU85027-029PC from Cumberland Sound (Fig. 1). This figure is available in colour online at wileyonlinelibrary.com/journal/jqs.

Overall the sediments in core 41 between 210 and 262 cm reflect a similar mineralogy to the Cretaceous bedrock (supporting Table S3).

qXRD and grain-size record from HU97048-007PC

We have three measures of grain size in core 007PC: (i) counts from X-radiographs of clasts > 2 mm; (ii) grain size on the < 2-mm fraction using a Malvern laser-sizer for the depth interval 150–410 cm (a focus on H-2); and (iii) magnetic grain size (Stoner *et al.*, 1996) based on the ratio IRM/k, measured at 1-cm intervals.

H-events are largely defined based on their carbonate content (Fig. 3), and hence we first plot the qXRD calculated wt% of total carbonate, dolomite and quartz (Fig. 6B) and compare these data with the IRD counts and coarse sand (> 250 μm) (Fig. 6C). The results show clear leads and lags in the carbonate versus coarse IRD. This is especially noticeable during H-2 (Fig. 6B), but the quartz wt% data tend to track the coarse IRD inputs, indicating that the IRD component involves a significant bedrock felsic fraction as quartz wt% reaches up to 30% of the total sediment < 2 mm. High quartz wt% tends to bracket the DC facies, but this results in part from the closed array mathematics (Aitchison, 1986). The high carbonate values are mimicked by the wt% of clay (data not shown), indicating that the carbonate is largely being transported as very

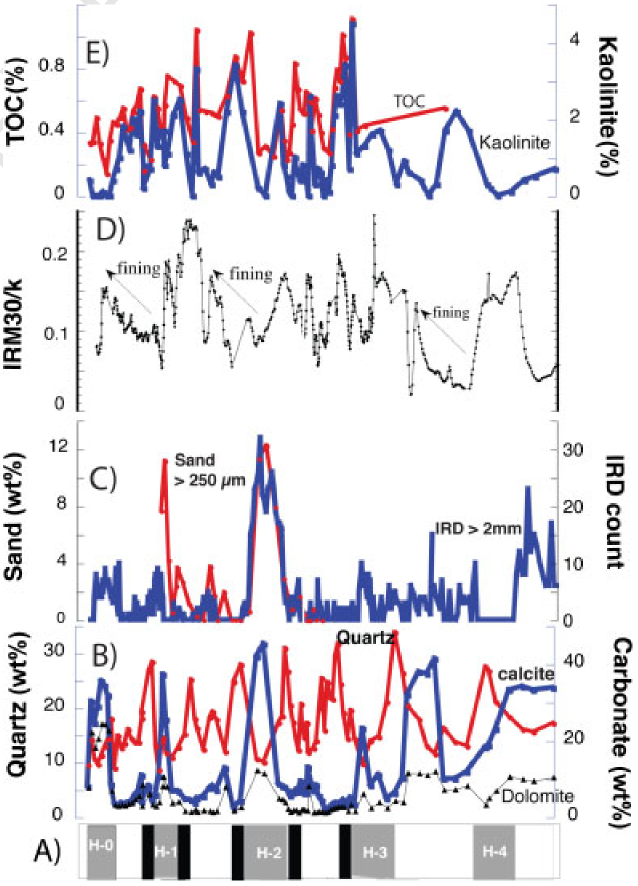

Figure 6. Grain-size variations and selected non-clay and clay mineral variations (wt%) in HU97048-007PC between 0 and 700 cm (10–45k cal a BP). (A) Location of H-events and black facies based on Fig. 3. (B) Plot of total carbonate (red), dolomite (black) and quartz (blue). (C) Plots of the IRD counts of clasts > 2 mm (blue) and the sand fraction > 250 μm (red). (D) IRM/k: magnetic grain-size. (E) Kaolinite (blue) and TOC (red). This figure is available in colour online at wileyonlinelibrary.com/journal/jqs.

fine-grained sediment. The > 2-mm IRD counts (Fig. 6C) and the wt% >250-μm sand fraction both show that H-2 had a much larger component of coarse-grained sediment than any of the other H-events. IRD counts for much of the core are < 10 clasts per sample and the rest of the H-events do not stand out in this variable. In every occurrence of the DC-rich facies, other than H-0, the calcite to dolomite ratio is between 6:1 and 4:1, but in H-0 this ratio is reduced to 1.5:1, suggesting a significantly different source (Andrews *et al.*, 1995; Kirby, 1997).

The IRM/k ratio (Fig. 6D) is a measure of magnetic grain size, with higher values representing finer grain size (King and Channell, 1991). Because there is an estimate every ~50 years, this property shows considerably more structure than the qXRD data (Fig. 6B). The IRM/k ratio tends to have an inverse relationship with the quartz, kaolinite and coarse sand abundances, thus corroborating its utility as a measure of magnetic grain size as well as bulk sediment particle size.

Figure 6E shows the very close correspondence between TOC% and kaolinite wt%, and confirms that the black facies (Fig. 3) are associated with the erosion of the Cretaceous mudstones (Fig. 2; supporting Table S3) (Jennings, 1993). There is also some association between quartz and kaolinite wt% in 007PC, which is not surprising given the large fraction of quartz in the Cretaceous mudstone (supporting Table S3).

HU87033-009PC & HU75009-IV-56

Analyses on these cores were undertaken at coarse resolution with the main goals of establishing the calcite to dolomite ratios and the presence of kaolinite and smectite. HU87033-009PC (009PC) lies at 1437 m water depth, ~500 m lower on the slope than 007PC (Fig. 1) and has well-defined H-1 and H-2 DC facies, although the nature of H-0 is complicated by probable downslope transport (Jennings *et al.*, 1996). There is a small, additional DC interval between H-1 and H-2. Total carbonate reached maximum values of 18 wt% with dolomite remaining steady in the range 1–5 wt% (Fig. 7). The calcite to dolomite ratio reached a maximum value of 2.2:1, thus differing substantially from the results in 007PC (Fig. 6). Kaolinite varied between 0.2 and 0.9 wt%, with a significant increase during and immediately after H-2. A comparison between the TOC% data from 009PC and the limited kaolinite data suggests a series of discrete black facies, which are high in TOC% and kaolinite (data not shown).

HU75009-IV-056PC is from the base of the slope in the NW Labrador Sea (Kirby, 1997) in 2434 m water depth (Fig. 1, supporting Table S1). The calcite to dolomite ratio in core 056PC averages 2.4:1 during the DC events but reaches a maximum value of 5:1 prior to H-2. Smectite wt% values are highest between H-3 and H-2 (Fig. 7B), whereas the low wt% kaolinite estimates actually peak during H-3. Kirby (1997) showed that there is a subtle dolomite-rich event (H-0) toward the top of this core and core 055 (supporting Table S1).

Composition of potential sediment sources

The qXRD data indicate significant down-core variability in mineral species and a major question is whether we can ascribe the mineralogy to specific source areas, other than the assumed association of the DC-rich intervals with transport from Hudson Strait (Alley and MacAyeal, 1994; Andrews and MacLean, 2003). In addition to sediment being transported out of Hudson Strait and Cumberland Sound, the complex of ice-margins around Baffin Bay probably provided meltwater-plumes and ice-rafted sediments via the southward-flowing Baffinland Current. Fortunately, the qXRD compositions of sediments from Baffin Bay, and from the deglacial interval in Hudson Strait, are available (Jennings *et al.*, 2007; Andrews and Eberl, 2011).

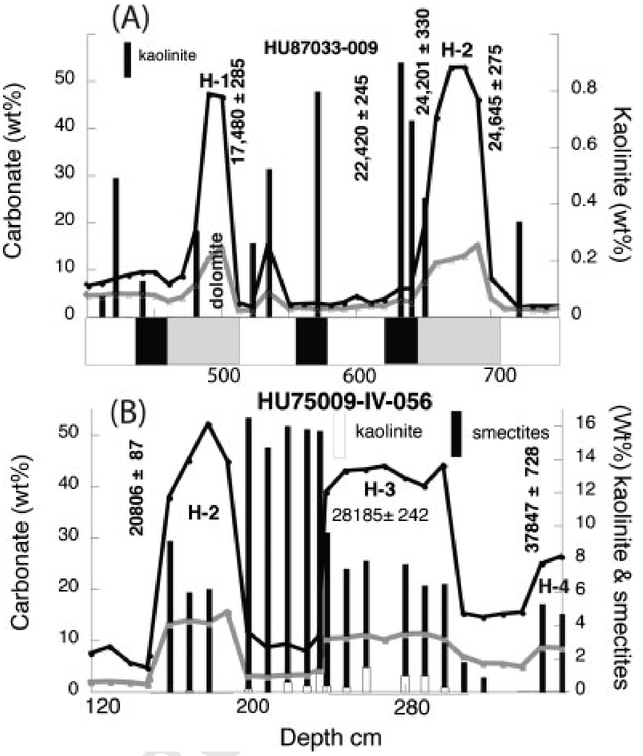

Figure 7. Composition of sediments < 2 mm in cores farther downslope from HU97048-007PC (Fig. 1). Calibrated radiocarbon dates are shown. (A) HU87033-009PC, and (B) HU75009-IV-056. Both graphs show the total carbonate (black line) and dolomite (gray line). Kaolinite and smectite contents are bars.

We use the program SedUnMix to estimate downcore changes in sediment provenance in 007PC. Andrews and Eberl (2012) recommended that sediment mixtures of potential source areas be produced, which will then allow an assessment of how successfully the program can estimate the contributions from source areas. In terms of 007PC, it is reasonable to suggest that the sediment compositions are potentially the mixing product of four source areas: (i) the hinterland of Cumberland Sound, (ii) the outer basin of Cumberland Sound (which contains the Cretaceous mudstone, (iii) Hudson Strait/shelf – as the source for the calcite-rich sediments (supporting Tables S3 and S5) and (iv) Baffin Bay – being the upstream source and a contributor of dolomite from outcrops in NW Greenland and the Canadian Arctic islands (Parnell *et al.*, 2007).

Samples from the potential source areas were selected as follows (supporting Table S5): (i) inner Cumberland Sound was represented by the uppermost five samples from HU85027-029PC (Fig. 5); (ii) outer Cumberland Sound was represented by the five basal samples from HU85027-029PC; (iii) Baffin Bay carbonate events are represented by the DC interval in JR175-006BC (Fig. 1) (Andrews and Eberl, 2011); and (iv) Hudson Strait DC events are represented by five samples from Resolution Basin, seaward of Hudson Strait, taken within H-0 in HU90023-030LCF (supporting Table S5) (Andrews *et al.*, 1995). Five prepared samples from each of the source areas were combined and then mixed in varying proportions. Twenty non-clay and clay minerals were selected after removal of species that had persistent low wt% (supporting Table S5). We found that SedUnMix predicted the compositional mixtures quiet well, although not perfectly (Fig. 8). The ratio of the observed/expected composition for all mixtures indicates that inner Cumberland Sound tends to be under-represented

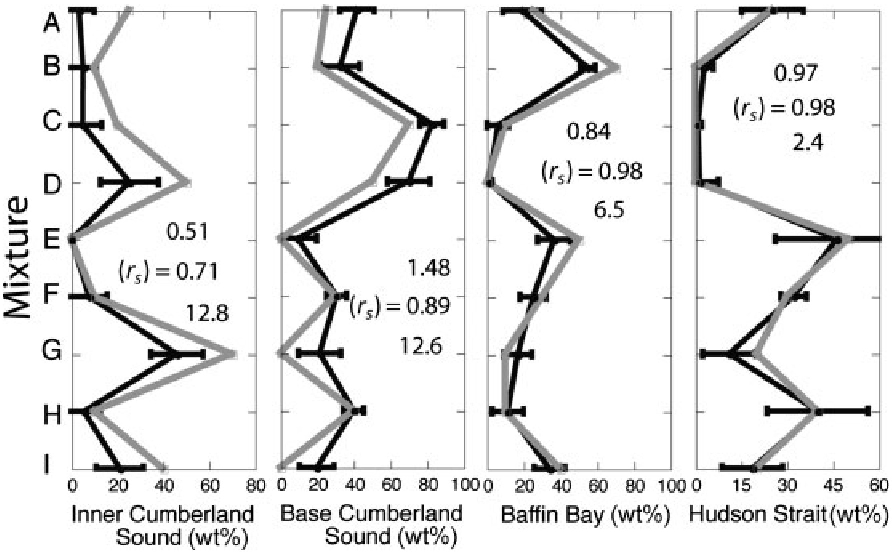

Figure 8. Results of the controlled end-member mixing experiments (supporting Table S4) showing the expected compositions (gray line) versus the observed compositions (black line) as computed in SedUnMix with four end-members and five samples per end-member. The error bars are ± 1 standard deviation after 20 iterations. The numbers within each panel represent various measures of the degrees of fit (see text). The top number refers to the observed/expected ratio (supporting Table S4); r_s is Spearman's rank correlation coefficient (all significant at $P > 0.05$); and the lowest number is the average absolute deviation (expected – observed) composition of all mixtures (supporting Table S4).

whereas the deep outer basin sediments are over-represented. Fits for changes in the proportion of Hudson Strait and Baffin Bay sediments produce nearly perfect rank correlation coefficients with relatively small average deviations (Fig. 8).

SedUnMix was then run on the down-core qXRD data from 007PC using the above noted four end-members. The average absolute differences between the expected and computed mineralogy is 1.7 ± 0.5% (Fig. 9C) (Andrews and Eberl, 2011, 2012). On Fig. 9 we summarized the major temporal changes in sediment sources in 007PC between 10 and[Q10] 45k cal a BP. Several DC-events are evident with the youngest having a large dolomite component whereas the remaining five are dominantly calcitic. The kaolinite-rich (black) sediments (Facies C), associated with the Cretaceous mudstone outcrop in Cumberland Sound (Figs 2 and 5), tend to precede or follow the DC events (Fig. 9A). Sediments dominated by felsic minerals, such as characterize the bedrock in inner Cumberland Sound, predominate for about one-half of the[Q11] 35k cal BP record, and represent a significant sediment source to the adjacent slope. Additional research is needed, however, to ascertain whether there are contributions from the upstream sources along Baffin Island and West Greenland.

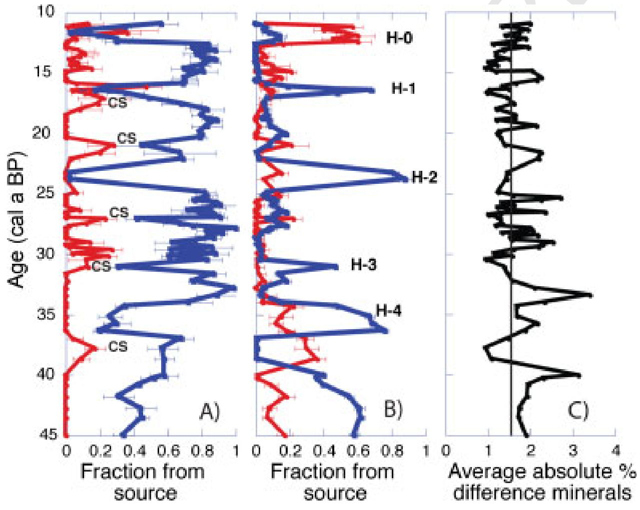

Figure 9. Estimates and standard deviations on the varying sources of sediment in HU97048-007PC – on the paleointensity time-scale (Fig. 4). (A) Estimates of contribution from inner Cumberland Sound (red) and the outer basin (blue), and (B) Baffin Bay (red) and Hudson Strait (blue). Heinrich (H-) events are labeled, as are events associated with erosion of the Cretaceous mudstones flooring part of Cumberland Sound (CS). (C) Average absolute difference between expected and observed mineral compositions – the vertical line is the average difference (1.7%). This figure is available in colour online at wileyonlinelibrary.com/journal/jqs.

Interpretation of the phasing of the different sources with wt% data is hindered by the 'closed sum' mathematics (Aitchison, 1986), and knowledge of thousand-year-scale sediment accumulation rates is lacking, and hence meaningful flux calculations are impossible. It is clear, however, that the uppermost DC event (H-0) is not sourced from Hudson Strait (Kirby, 1997). In our four-source scenario the sediment compositions align them with the dolomite-rich Younger Dryas (YD) event in Baffin Bay (Andrews *et al.*, 1996). However, in an earlier study on 009PC, Jennings *et al.* (1996) noted that the uppermost sediments in this core were disturbed (debris flow) and suggested that the high dolomite content might be associated with a more local source. However, available bedrock carbonate samples from sites on the shelf near the entrance to Cumberland Sound (#6 and #7, Fig. 1; supporting Table S3) are limestones. Although there is an interval of moderately high dolomite content (≤ 8 wt%) in 029PC (Fig. 5), the results from 041PC (Fig. 2) show only low carbonate content (supporting Table S4). To investigate a possible Cumberland Sound/Shelf dolomite source (HU85Dolo) we re-ran SedUnMix with these samples as a fifth end-member. Factor analysis of the logratio-transformed wt% data (Aitchison, 1986) of the five end-members indicated that the three Cumberland Sound sources overlapped to a degree on both the 1st and 2nd PC axes, with the kaolinite-rich sediments being the most distinctive (supporting Fig. S1).

The evidence for the DC-0 event decreases downslope and is not strongly represented, if at all, at depths below 2000 m (Kirby, 1997; Knutz *et al.*, 2011). This suggests that the dolomite-rich sediment is being transported in the surface waters of the Baffinland Current.

Discussion

On the basis of radiogenic isotopic data from the area of Cumberland Sound and Hudson Strait, Barber (2001; see also Farmer *et al.*, 2003) proposed different transport paths for the sediments in 007PC (Fig. 10). $\varepsilon Nd_{(0)}$ data from a Cumberland Peninsula till had the most depleted value of −30.5 compared with −29.2 in basal sediments from 029PC (Fig. 5). Two slightly less depleted values were measured in 007PC (Fig. 3). However, farther down the slope in 009, the $\varepsilon Nd_{(0)}$ values in hemipelagic sediments ranged between −22.3 and −25.9,

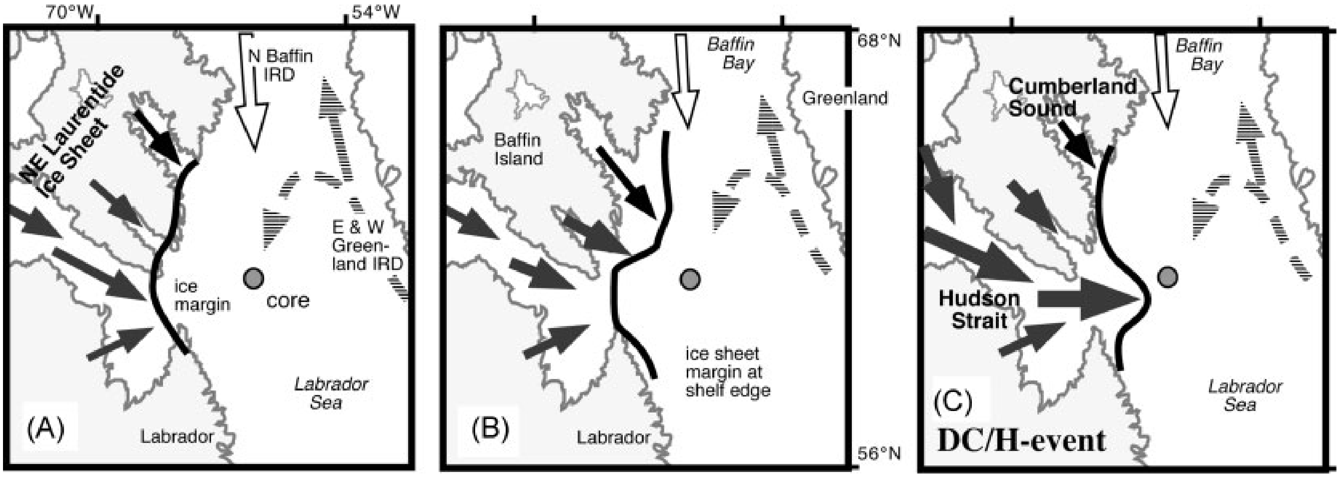

Figure 10. Suggested variations in the patterns of ice flow and ocean currents in the region (from Barber, 2001). (A) Scenario with ice margins withdrawn onto land and IRD originating from Baffin Bay (DC-0, Fig. 9B) (minimum Canadian Shield input to the Labrador Sea; maximum Irminger Basin input); (B) ice extending onto the shelf off Cumberland Sound – CS events (Fig. 9A) (SE Baffin Island/ Cumberland Sound ice margin activity, no Hudson Strait DC, and reduced relative input from Irminger Basin); (C) major DC- (Heinrich events) and collapse of the Hudson Strait ice stream (maximum Hudson Strait input = DC/H-event; minimum relative input from Irminger Basin).

suggesting the mixing with sediments from the Irminger Basin (Fig. 10A), as compared with values of ca. −27 to −28 for H-1 and H-2 (Farmer *et al.*, 2003) (Fig. 10C).

Because of the relative low cost of qXRD versus radiogenic isotope measurements, we are able to expand this initial assessment of sediment transport, and in particular, the transport of sediment from Cumberland Sound and Baffin Bay (Fig. 10). The DC/H-sediments are often bracketed by a black mud facies, Facies C of Aksu and Mudie (1985) (Fig. 3). Our analysis indicated that the DC events were, in the main, sourced from the calcite-rich Paleozoic outcrop in Hudson Strait and the SE Baffin Island shelf (Fig. 10C). However, the last major DC event in 007PC (and also present in the 006TWC; data not shown) is very different, and represents a Younger Dryas/H-0 event sourced primarily from north of Davis Strait (Andrews *et al.*, 1996; Andrews and Eberl, 2011) (Fig. 10A).

Probable scenarios for changes in ice sheet dynamics and sources, plus changes in the smectite content of the sediments associated with the Western Boundary Undercurrent, are sketched in Fig. 10. Smectite is present in the samples from the Cretaceous and Tertiary mudstone around Cumberland Sound (Fig. 2; supporting Table S3) and is a component of the Labrador Sea Tertiary marine sediments (Piper and Slatt, 1977). Kaolinite and various smectites are also a significant component of the clay mineralogy in Baffin Bay (Aksu, 1981; Andrews and Eberl, 2011). Smectite can also be advected in to the Labrador Sea in North Atlantic Deep Water from weathering of volcanic bedrock across the Iceland–Greenland Ridge (Fagel *et al.*, 1996) (Fig. 10A), although volcanic rocks occur locally and to the north in Davis Strait and Cape Dyer (MacLean *et al.*, 1982). In terms of Rjv6 standards (Eberl, 2003), the smectite group includes saponite, Fe-smectite and altered illite. In 007PC the median value for smectites is 6 wt%, compared with 13 and 8 wt% in 009PC and 056, respectively. There is, however, a considerable range of values in 007PC and 056 (up to ~15 wt%) compared with a tight grouping in 009PC.

The hypothesis that the Hudson Strait and presumably the Cumberland Sound ice streams were buttressed by an ice-shelf (Denton and Hughes, 1981) has recently been revived (Hulbe *et al.*, 2004; Marcott *et al.*, 2011; but see Alley *et al.*, 2005). Sedimentological evidence (Anderson *et al.*, 1991) for the existence of an ice-shelf at sites on an adjacent slope should include (i) a general absence of coarse IRD clasts, (ii) a restricted mineralogical variability (Anderson *et al.*, 1991) and (iii) a pervasive absence of planktonic foraminifera (Jennings *et al.*, 1996). Our grain-size and mineralogical data (Fig. 6) offer no compelling evidence for an ice-shelf between the major H-events.

Conclusions

During the last glaciation the north-western slope of the Labrador Sea received sediment from a variety of sources and processes. Core HU97048-007PC captures these shifts in sediment supply. A series of detrital-rich carbonate lithofacies are coeval with the North Atlantic Heinrich events 1–4 and can be linked to massive meltwater and iceberg discharges from Hudson Strait. However, the youngest event, H-0, has a major contribution from Baffin Bay. Facies C is black and kaolinite-rich and represents erosion of Cretaceous mudstones that floor part of Cumberland Sound. Facies C often brackets the DC facies and this suggests that the dynamics of the Cumberland Sound ice stream was triggered by the larger ice stream in Hudson Strait. Our ongoing work on cores HU2008029-0006BC and 0008PC (same site, Fig. 1) will determine the long-term sediment transport southward from Baffin Bay.

Supporting information

Additional supporting information can be found in the online version of this article:

Table S1 Latitudes and longitudes for core sites
Table S2 AMS dates
Table S3 Composition of bedrock samples
Table S4 Mineralogy of core HU-041
Table S5 Mineralogy of the four source areas
Figure S1. Plot of the logratio-transformed varimax factor scores on the first two factors for the five end-member run of SedUnMix.

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Abbreviations. AMS, accelerator mass spectrometry; DC, detrital carbonate; H-event, Heinrich event; IRD, ice-rafted debris; TIC, total inorganic carbon; TOC, total organic carbon; XRD, X-ray diffraction.

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