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Abstract

Core HU2008029-12PC from the Disko trough mouth fan on the central West Greenland continental slope is used to test whether an ice shelf covered Baffin Bay during the Last Glacial Maximum (LGM) and at the onset of the deglaciation. We use benthic and planktic foraminiferal assemblages, stable isotope analysis of planktic forams, algal biomarkers, ice-rafted detritus (IRD), lithofacies characteristics defined from CT scans, and quantitative mineralogy to reconstruct paleoceanographic conditions, sediment processes and sediment provenance. The chronology is based on radiocarbon dates on planktic foraminifers using a ΔR of 140 ± 30 14C years, supplemented by the varying reservoir estimates of Stern and Lisiecki (2013) that provide an envelope of potential ages. HU2008029-12PC is bioturbated throughout. Sediments between the core base at 11.3 m and 4.6 m (LGM through HS1) comprise thin turbidites, plumites and hemipelagic sediments with Greenlandic provenance consistent with processes active at the Greenland Ice Sheet margin grounded at or near the shelf edge. Abundance spikes of planktic forams coincide with elevated abundance of benthic forams in assemblages indicative of chilled Atlantic Water, meltwater and intermittent marine productivity. IRD and IP25 are rare in this interval, but brassicasterol, an indicator of marine productivity reaches and sustains low levels during the LGM. These biological characteristics are consistent with a sea-ice covered ocean experiencing periods of more open water such as leads or polynyas in the sea ice cover, with chilled Atlantic Water at depth, rather than full ice-shelf cover. There is no supporting data for the existence of a full Baffin Bay ice shelf cover extending from grounded ice on the Davis Strait. Initial Greenland Ice Sheet retreat from the West Greenland margin is manifested by a pronounced lithofacies shift to bioturbated, diatomaceous mud with rare IRD of Greenlandic origin at 467 cm (16.2 cal ka BP; ΔR=140 yrs) within Heinrich Stadial 1 (HS1). A spike in foraminiferal abundance and ocean warmth indicator benthic forams precedes the initial ice retreat from the shelf edge. At the end of HS1, IP25, brassicasterol and benthic forams indicative of sea-ice edge productivity increase, indicating warming interstadial conditions. Within the Bølling/Allerød interstadial a strong rise in IP25 content and IRD spikes rich in detrital carbonate from northern Baffin Bay indicate that northern Baffin Bay ice streams were retreating and provides evidence for increased open water, advection of Atlantic Water in the West Greenland Current, and formation of an IRD belt along the W. Greenland margin.

Keywords	Arctic ocean and adjacent high latitudes; micropaleontology (forams); paleooceanography; Glacial sediments
Taxonomy	Ice Sheets, Paleoceanography, Quaternary Stratigraphy

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Data for: Baffin Bay Paleoenviroments in the LGM and HS1: Resolving the ice-shelf question

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Baffin Bay Paleoenvironments in the LGM and HS1: Resolving the ice-shelf question

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Core HU2008029-12PC from the Disko trough mouth fan on the central West Greenland continental slope is used to test whether an ice shelf covered Baffin Bay during the Last Glacial Maximum (LGM) and at the onset of the deglaciation. We use benthic and planktic foraminiferal assemblages, stable isotope analysis of planktic forams, algal biomarkers, ice-rafted detritus (IRD), lithofacies characteristics defined from CT scans, and quantitative mineralogy to reconstruct paleoceanographic conditions, sediment processes and sediment provenance. The chronology is based on radiocarbon dates on planktic foraminifers using a ΔR of 140 ± 30 ^{14}C years, supplemented by the varying reservoir estimates of Stern and Lisiecki (2013) that provide an envelope of potential ages. HU2008029-12PC is bioturbated throughout. Sediments between the core base at 11.3 m and 4.6 m (LGM through HS1) comprise thin turbidites, plumites and hemipelagic sediments with Greenlandic provenance consistent with processes active at the Greenland Ice Sheet margin grounded at or near the shelf edge. Abundance spikes of planktic forams coincide with elevated abundance of benthic forams in assemblages indicative of chilled Atlantic Water, meltwater and intermittent marine productivity. IRD and IP_{25} are rare in this interval, but brassicasterol, an indicator of marine productivity reaches and sustains low levels during the LGM. These biological characteristics are consistent with a sea-ice covered ocean experiencing periods of more open water such as leads or polynyas in the sea ice cover, with chilled Atlantic Water at depth, rather than full ice-shelf cover. They do not support the existence of a full Baffin Bay ice shelf cover extending from grounded ice on the Davis Strait. Initial ice retreat from the West Greenland margin is manifested by a pronounced lithofacies shift to bioturbated, diatomaceous mud with rare IRD of Greenlandic origin at 467 cm (16.2 cal ka BP; ΔR=140 yrs) within HS1. A spike in foraminiferal abundance and ocean warmth indicator benthic forams precedes the initial ice retreat from the shelf edge. At the end of HS1, IP_{25}, brassicasterol and benthic forams indicative of sea-ice edge productivity increase, indicating warming interstadial conditions. Within the Bølling/Allerød interstadial a strong rise in IP_{25} content and IRD spikes rich in detrital carbonate from northern Baffin Bay indicate that northern Baffin Bay ice streams were retreating and provides evidence for increased open water, advection of Atlantic Water in the West Greenland Current, and formation of an IRD belt along the W. Greenland margin.

Keywords: Greenland Ice Sheet, Baffin Bay, paleoceanography, ice shelf, foraminifera, Heinrich Stadial 1

1. Introduction

Last Glacial Maximum (LGM) climatic and oceanic conditions in Baffin Bay are currently poorly known, but according to the temperature reconstructions from the Greenland Ice Sheet borehole (Dahl-Jensen and al., 1998) and ice-core data (Buizert et al., 2014), summit temperatures were ~20°C colder than present. Applying this temperature difference down to sea level using the adiabatic lapse rate, suggests that the annual temperature at the surface of Baffin Bay adjacent to Baffin Island would approach -36°C. Such cold temperatures support the argument that cold-based ice covered the forelands of eastern Baffin Island (Briner et al., 2003) with “Antarctic-like” conditions across Baffin Bay, which would also suggest that Baffin Bay was covered in perennial sea ice. At the LGM, confluent, Innuitian (IIS), Laurentide (LIS) and Greenland (GIS) ice sheets (England et al., 2006) blocked the channels that connect Baffin Bay to the Arctic Ocean (Dyke, 2002) and terminated in northern Baffin Bay as large ice streams (Li et al., 2011; Blake, 1977). The Greenland ice sheet reached the continental shelf edge via large ice streams off west Greenland (Ó Cofaigh et al., 2013a; Jennings et al., ~~in revision~~2017; Slabon et al., 2016; Sheldon et al., 2016; Dowdeswell et al., 2014), but the outer limits of the ice on the Baffin shelf are not known.

On the basis of modeling, it has been proposed that Baffin Bay was blocked at its southern end by an ice shelf extension of the Hudson Strait ice stream that grounded across Davis Strait to reach southern Greenland, thus sealing Baffin Bay from the Labrador Sea (Hulbe et al., 1997; Álvarez-Solas et al., 2010; Marcott et al., 2011). This ice shelf was the starting point for modeling the processes that produce Heinrich events (Hulbe et al., 1997; Álvarez-Solas et al., 2010; Marcott et al., 2011), but physical evidence for it has not been recovered. An ice shelf of this scale would have environmental consequences that should be recorded in Baffin Bay sediments. Firstly, grounding of a Labrador Sea ice shelf along Davis Strait would prevent seawater exchange between Baffin Bay and the Labrador Sea, excluding advection of organic matter into Baffin Bay. It also would shut down *in situ* primary marine productivity in Baffin Bay so that planktic and benthic organisms, their biomarkers, and bioturbation would be absent in the sediment. Secondly, ice shelves and even extensive sea-ice cover are known to restrict the movement and export of icebergs (Reeh et al., 2001; Domack and Harris, 1998). Thus iceberg rafting and mixing of sediments of various provenances in Baffin Bay would be reduced. Using these concepts, we test the LGM Baffin Bay ice-shelf hypothesis by studying the sedimentological and biological characteristics of sediments in HU2008029-12PC from the continental slope off western Greenland, a core that extends from the LGM into the Younger Dryas (YD) and that recorded retreat of the Greenland Ice Sheet during deglaciation (Jennings et al., ~~in revision~~2017).

2. Setting of core HU2008029-12PC

Detailed studies of LGM and deglacial environments in Baffin Bay have been hampered by relatively slow sediment accumulation rates and poor calcium carbonate preservation (cf. Aksu, 1985; de Vernal et al., 1992; Simon et al., 2012). HU2008029-12PC (hereafter called 12PC) was raised from the northern side of the Disko trough mouth fan (TMF) from acoustically stratified sediments with continuous parallel reflections on the eastern side of Baffin Bay (68°13.69' N; 57°37.08' W; 1475 m water depth; Campbell and de Vernal, 2009) (Figs. 1 and 2). This site on the trough mouth fan has higher sediment accumulation than sites in the deep basin of Baffin Bay that have variable sedimentation rates that range between 3 and 35 cm/ka (Andrews et al., 1998; Hillaire-Marcel et al., 1989, 2004; Simon et al., 2012; 2014) (Fig. 1).

The Disko TMF was built throughout the Quaternary by rapid sediment deposition in front of the fast flowing Disko ice stream (Fig. 1) when the GIS margin was extended on the shelf, and from hemipelagic sedimentation during and after ice retreat (ÓCofaigh et al., 2013a, b; Jennings et al., ~~in revision~~2017; Hofmann et al., 2016). An ice sheet grounded at or near the shelf edge delivers abundant sediments directly to the continental slope in the form of sediment gravity flows, including turbidity currents that form graded sand layers, stratified sand/silt beds, and glacigenic debris flows (ÓCofaigh et al., 2013a, b, Lucci and Rebesco, 2007). Turbid meltwater plumes released from the ice front produce plumites, which are finer grained than the turbidites as the sand is dropped near the ice front and the silt and clay continue offshore in suspension (Hesse et al., 1997; Lucchi and Rebesco, 2007). Depending on sea surface conditions such as perennial sea ice and/or ice shelves, icebergs would also deliver sediment to the slope as they melted during their transit in Baffin Bay (Andrews et al., 1998; 2014; Jennings et al., 2014; Simon et al., 2012; 2014; 2016; Sheldon et al., 2016).

~~Each year, the~~The modern sea ice edge extends southeast to northwest within Baffin Bay and sea ice cover is greater in the western than in the eastern half due to the influence of the relatively warm and saline West Greenland Current that enters Baffin Bay from the southeast (Tang et al., 2004; Münchow et al., 2015) (Fig. 1). The boundary between lower salinity, sea-ice bearing, Arctic Surface Water (ASW) that passes from the Arctic Ocean through the channels of the Canadian Arctic Archipelago into Baffin Bay and Atlantic Waters of the West Greenland Current (WGC) moving northward along West Greenland is oriented NE-SW and migrates through the year. The relatively warm, saline Atlantic Water submerges beneath the ASW (Buch, 2000a, b) and forms the West Greenland Intermediate Water (WGIW) (Fig. 1 inset) (Tang et al., 2004). During the LGM, however, the circulation regime in Baffin Bay would have been different because the southward flow of ASW into Baffin Bay was blocked by confluent ice sheets grounded in the channels of the Canadian Arctic Archipelago until the early Holocene (England, 1999; Zreda et al., 1999; Jennings et al., 2011a; Piénkowski et al., 2011). Today, warm Atlantic Water carried in the WGC accesses the GIS margins via cross shelf troughs and fjords, where the ice sheet terminates in the sea (Holland et al., 2008) and promotes basal melting (Straneo et al., 2012). WGC Atlantic Water flow was initiated as early as 14.4 cal ka BP off central West Greenland and is implicated in Greenland Ice Sheet retreat from the LGM position at the shelf edge (cf. Knutz et al., 2011; Sheldon et al., 2016; Jennings et al., ~~in revision~~2017).

3. Methods:

3.1 Age Model

The age model for 12PC is based on 7 radiocarbon dates between 201 and 860 cm on the arctic planktic foraminifer, *Neogloboquadrina pachyderma* (*sensu* Darling et al., 2006). The dates were previously published in Jennings et al., (~~in revision~~2017) (Table 1). Radiocarbon dates were calibrated using the Marine13 curve (Reimer et al., 2013). OxCal version 4.2.4 (Ramsey and Lee, 2013) was used to compute an age/depth model (Fig. 3). An age reversal in the upper 110 cm of the core limited the chronology to the interval from 200 cm to the base of the core (1130 cm). The age of the core base is assumed to be no older than 26.5 ka BP, the beginning of the LGM (Clark et al., 2009). This assumed basal age results in a large uncertainty in the modeled age of the base of the core (24 to 28 cal ka BP). Given this basal age, we might expect to record Baffin Bay Detrital Carbonate (BBDC) event BBDC3 that is found in central Baffin Bay from c. 23.5 to 25 cal ka BP (Simon et al., 2016). A single data point with 20% NBB source at 21.5 cal ka BP may represent BBDC2 (21 cal ka BP; Simon et al., 2016) although it is not associated with a coarse clast-rich interval as would be expected if it represented a BBDC event (Andrews et al., 1998; Simon et al., 2012; Jackson et al., 2017) (Fig. 3). The lack of an interval of high NBB and IRD below 467 cm (16.2 cal ka BP) in 12PC indicates that BBDC2 and BBDC3 were not recovered in 12PC. Either these two events were not deposited basin wide or the basal age of 12PC is younger than the 21 ka BP age of BBDC2. Given that the deepest radiocarbon age in 12PC is 21.8 cal ka BP (ΔR=140 years) and there are 3 meters of sediment below this depth in the core, we suggest it is more likely that BBDC2 and 3 were not deposited basin wide. Without additional information we continue with the assumption that the core base is no older than the beginning of the global LGM of 26.5 ka BP (Clark et al., 2009).

~~lack in core 12PC of Baffin Bay Detrital Carbonate (BBDC) events BBDC2 and BBDC3, deposited between 24.7 to 25 cal ka BP and 26.4 to 27.7 cal ka BP, respectively (Simon et al., 2014).~~We initially built the age model assuming a marine reservoir offset (ΔR) of 140±30 years based on recent work in Disko Bugt (Lloyd et al., 2011), for consistency with other central West Greenland sediment core records (cf Jennings et al., 2014; ~~in revision~~2017; Jackson et al., 2017; Hogan et al., 2016; Sheldon et al., 2016), and we note that prior to 2011, many publications used a ΔR=0 years (Andrews et al., 1998; Knudsen et al., 2008). However, recognizing that the marine reservoir offset could be large and variable over the time interval of 12PC and because this core extends into the LGM, defined here as beginning at 26.5 ka (Clark et al., 2009) and ending at the beginning of the Oldest Dryas period, 18 ka BP (Buizert et al., 2014), we used the variable North Atlantic R values in Stern and Lisiecki (2013) to provide an envelope of calibrated age so that we could consider the correlations of boundaries and conditions recorded in the core with established climatic intervals (Fig. 3f). To accomplish this we first calibrated each date with ΔR=0 ^{14}C years, which provides the maximum age. We then used the ΔR=0 ages to identify the appropriate 500 year bin of maximum, average and minimum R values from Table S1 of Stern and Lisiecki (2013) and calibrated each of the dates using these three R-values. The resulting envelope of ages, from ΔR=0 to the maximum Stern and Lisiecki 2013 R-value, illustrates how the choice of ΔR affects correlation of boundaries in the core with climate intervals from LGM through the YD (Fig. 3f; Table 1). Regardless, these results confirm that the core contains LGM and

Heinrich Stadial 1 (aka Oldest Dryas) sediments, a key requirement for testing the ice shelf model (Hulbe et al., 1997; Álvarez-Solas et al., 2010; Marcott et al., 2011).

3.2 Foraminiferal analyses.

One-cm wide samples were weighed wet and sieved on a 63-µm screen. Material >63 µm was kept wet in a storage solution of 70% distilled water and 30% ethanol with baking soda as a buffer. Foraminifera were counted wet to prevent destruction of fragile tests that disintegrate under the stress of drying. A wet splitter was used when necessary to achieve a count of 200-300 benthic formaminifers and as many planktic foraminifers as were in the benthic split. In most cases the full sample was counted. Equivalent dry weights of the foram samples were estimated from sedimentology samples from the same depths that had both wet and dry weights, allowing foraminifera/gram sediment to be calculated.

3.3 Stable isotope analyses

Stable oxygen and carbon isotopes were measured on the planktic foram species *Neogloboquadrina pachyderma* picked from the 150-250 µm size fraction in 41 samples; results from 3 samples were rejected because they yielded a low signal. Samples >100 µg have standard deviations of 0.01 and 0.03 ‰ for $\delta^{13}C$ and $\delta^{18}O$ respectively. Samples weighing <100 µg are reported with a standard deviation of 0.06 ‰ for $\delta^{13}C$, and an error of ±0.2 ‰ for $\delta^{18}O$. The oxygen isotope values are expressed as ‰ vs VPDB. Between 1050 and 857 cm all samples were of small weight but otherwise seemed reliable. Measurements were made on a Micromass IsoprimeTM dual inlet coupled to a

MulticarbTM system at the Light Stable Isotope Geochemistry Laboratory at the University of Montréal – UQAM.

3.4 CT scan.

CT scanning of the half round core was performed at the sediment core laboratory at the University of Quebec at Rimouski. A CT number (a measure of sediment density) was extracted from the images. The CT scan image was used to determine lithofacies and boundaries, sedimentary structures, and to identify bioturbation, a key source of evidence for the presence of benthic organisms and a source of information about sedimentation rate variations between the radiocarbon dates (Wetzel, 1991). Counts of >2 mm clasts interpreted as ice rafted detritus (IRD) were made from the CT images by counting in a 2 cm wide window across the core width continuously along the core length (Grobe, 1987).

3.5 Biomarkers: IP_{25} and Brassicasterol

Biomarker analyses (IP_{25} and brassicasterol) were performed using methods described previously (Belt et al., 2012; Belt et al., 2015). Briefly, 9-octylheptadec-8-ene (9-OHD, 10 μL; 10 μg mL^{-1}) and 5α-androstan-3β-ol (10 μL; 10 μg mL^{-1}) were added to ca. 1 – 2 g of each freeze-dried sediment sample prior to extraction to permit quantification of IP_{25} and sterols, respectively. Samples were then extracted using dichloromethane/methanol (3 x 3 mL; 2:1 v/v) and ultrasonication. Following removal of the solvent from the combined extracts using nitrogen, the resulting total organic extracts (TOE) were purified using column chromatography (silica) with IP_{25} (hexane; 6 mL) and brassicasterol (20:80 methylacetate/hexane; 6 mL) collected as two single fractions. Non-polar lipid fractions were further separated into saturated and unsaturated hydrocarbons using glass pipettes containing silver ion solid phase extraction material (Supelco Discovery® Ag-Ion). Saturated hydrocarbons were eluted with hexane (1 mL), while unsaturated hydrocarbons (including IP_{25}) were eluted with acetone (2 mL). All fractions were dried under a stream of nitrogen.

Analysis of individual fractions was carried out using gas chromatography - mass spectrometry (GC-MS) with operating conditions as described previously (e.g. Belt et al., 2012; Brown and Belt, 2012). Sterols were derivatized (BSTFA; 50 µL; 70 ºC; 1 h) prior to analysis by GC-MS. Mass spectrometric analysis was carried out in total ion current (TIC) and single-ion monitoring (SIM) modes. Individual lipids were identified on the basis of their characteristic GC retention indices and mass spectra obtained from standards. Quantification of IP_{25} was achieved by dividing its integrated GC-MS peak area by that of the internal standard (9-OHD) in SIM mode (both *m/z* 350) and normalizing this ratio using an instrumental response factor (obtained from laboratory standards of each analyte) and the mass of sediment (Belt et al., 2012). Analytical reproducibility (6 %, n = 3) was monitored using a sediment with a known concentration of IP_{25}. Brassicasterol concentrations were obtained by comparison of their respective peak areas in SIM mode (brassicasterol, *m/z* 470) with those of the internal standard (*m/z* 333) and normalized as per IP_{25}.

3.6 Quantitative X-ray diffraction Mineralogy

Quantitative x-ray diffraction (qXRD) analyses were used to identify shifts in sediment sources between ~~more~~ ‘local’ West Greenland (WG) and ‘distal’ Northern Baffin Bay

(NBB). Samples for qXRD analysis were taken at 10 to 20 cm intervals throughout the core. Sediment samples were freeze-dried and processed at INSTAAR using the method described by Eberl (2003) and Andrews and Eberl (2011). The qXRD samples were analysed on a Siemens D5000 XRD unit at a 0.02 2-θ step with a 2 second count; minerals were identified using the program RockJock v.6 (Eberl, 2003). The qXRD 2-source data to 17.5 cal ka BP is presented in Jennings et al. (~~in revision~~2017). The determination of sediment provenance is based on the quantitative X-ray diffraction (qXRD) analysis of the < 2 mm surface and core sediments using the method outlined by Eberl (2003) and described in more detail for our area by (Andrews and Eberl, 2012; Andrews et al., 2014; O'Cofaigh et al., 2013a; Simon et al., 2014). We use the Excel macro unmixing program "SedUnMix" (~~first described by~~ Eberl ~~(2004)~~, 2004; Andrews and Eberl, 2012) to ~~and developed further by Andrews and Eberl (2012) to~~ ascribe sediment mineral assemblages to probable source areas. In this present study we discriminated between two glacial derived sources; first a regional West Greenland source dominated by specific ranges in quartz, plagioclase, k-feldspars and other non-clay and clay minerals, versus a North Baffin Bay detrital carbonate source dominated by dolomite (Andrews et al., 2014; O'Cofaigh et al., 2013; Jennings et al., ~~in revision~~2017).

4. Results and Interpretation

4.1 Lithofacies Characteristics

There are two main lithofacies units defined by the sediment parameters in 12PC (Fig. 3). The boundary between the two units (Fig. 4b) is well expressed by an abrupt shift to lower CT# (Fig. 3A). This transition dates to 16.2 cal ka BP using ΔR=140 years and has been interpreted to represent the retreat of the Greenland Ice Sheet from the shelf edge (Jennings et al., ~~in revision~~2017). However, the full age-envelope ranges between 16.4 (ΔR=0) to 14.0 (Max R) ka, or, late in Heinrich Stadial 1 to the end of the Bølling (Fig. 3f). Calibrated radiocarbon dates (Fig. 3F; ΔR=140, pink) in the lower unit range from 21.8 to 16.2 cal ka BP. The lower three radiocarbon dates fall within the LGM regardless of the marine reservoir age selected (Fig. 3F). The radiocarbon date at 571.5 cm falls within Heinrich Stadial 1 regardless of the marine reservoir age (Fig. 3F).

The lower lithofacies unit, which represents the period when the ice sheet grounding line was at or near the shelf edge, has higher magnetic susceptibility (Fig. 3C), ~~higher~~ variable sand content including high weight percentage peaks (Fig. 3D) and a west Greenlandic sediment composition (Fig. 3E) but rare >2mm clasts (Fig. 3B). From the base of the core to 1022 cm, sediments are laminated mud with straight, sharp contacts defining the laminae and vertically oriented burrows (Fig. 4f). Between 1025 and 768 cm the sand content increases and stratification is disrupted by bioturbation (Fig. 3E). Stratified mud with distinct vertical burrows extends from 768 to 735 cm (Fig. 3D). From 735 cm to 688 cm sand content increases. This sandy unit is overlain by another sequence of stratified mud with distinct burrows between 688 and 630 cm. The sediment between 630 and 467 cm is bioturbated, stratified mud with layering disturbed by bioturbation (Fig. 4c). The uppermost part of this unit has high sand content and marks the transition to the upper lithofacies unit.

The upper lithofacies from 467 to 0 cm, which represents deglaciation and the Holocene (Jennings et al., ~~in revision~~2017), has overall lower CT number (lower density) (Fig. 3A), lower magnetic susceptibility (Fig. 3C) and generally lower sand content (Fig.

3D). But, it has much higher numbers of >2mm clasts (IRD) (Fig. 3B). Immediately above the boundary the sediments are low-density bioturbated mud with the sand fraction comprising *Coscinodiscus* planktic diatoms and setae of *Chaetoceras*, consistent with the low MS values (Fig. 3c). Well-defined, thin laminae and rare IRD occur at the base of the unit, but transition upward to less-well defined laminae and rare to absent IRD from 420 cm to 352 cm. This fine interval was interpreted to record a period in the initial deglaciation as the grounding line retreated off the shelf edge with retention of an ice shelf (Jennings et al., ~~in revision~~2017). At 352 cm (marked by middle horizontal blue line on Figure 3) the CT # (density), MS and sand increase ~~and a spike in Greenlandic IRD occurs at 330 cm~~ (Fig. ~~3A~~3A, B, C,~~;~~ D~~E~~). This level marks the start of renewed retreat of the GIS grounding line by calving (Jennings et al., ~~in revision~~2017).) ~~.~~The sediments are bioturbated but stratification is still evident, suggesting moderate sedimentation rates. Apart from a peak in >2mm clasts of west Greenland provenance at 330 cm~~The CT#, MS and sand values increase to moderate levels at 355 cm (Fig. 3A, B, C) but~~ the main rise in >2mm clasts coincides with the entry of the ~~and~~ Northern Baffin Bay sediment source (NBB source) ~~content do not increase until~~at 290 cm (Fig. 3B, E). ~~The relatively low MS is consistent with the high detrital carbonate content of the NBB source (Fig. 3C, E).~~ Bioturbated, pebbly mud associated with a rise in NBB provenance occurs between 280 and 175 cm with the highest IRD interval from 280-240 cm (Fig. 3B, E). This NBB DC interval has been found in several cores on the central West Greenland slope (Sheldon et al., 2016; Jennings et al., ~~in revision~~2017; Jackson et al., 2017) and has been correlated to BBDC1 (Simon et al., 2012; 2014; Jackson et al., 2017), marking the retreat of NBB ice streams. The NBB DC event is overlain by bioturbated mud with small, dispersed IRD and discontinuous silt stringers between 175 and 152 cm. Bioturbated pebbly mud between 152 and 52 cm has high NBB provenance between 160 and 90 cm, an interval that contains an age reversal and a mixture of radiocarbon ages (Fig. 3F). The age reversal suggests that the upper NBB peak is reworked. The upper 52 cm of the core is bioturbated mud with dispersed IRD likely represents the middle to late Holocene time period, although it is undated.

4.2 Biological Proxies

Biological proxy data are expressed against age using the age model based on $\Delta R=140$ yrs (Fig. 5).

4.2.1 Bioturbation

The CT scan image (Fig. 3) reveals that the entire core is bioturbated~~, except for one short interval in the LGM from 974 to 1005 cm~~, indicating that there was sufficient oxygenation and food to support the benthos in Baffin Bay throughout the time period represented by the core (Löwemark et al., 2012). Variations in burrow shape and density are indicative of the interplay between oxygenation, sedimentation rate, sedimentation processes, substrate consistency and food supply (Reineck and Singh, 1980, Wetzel, 1991; Löwenmark et al., 2012) (Fig. 4). Intensely bioturbated intervals in which sand layers are disrupted by burrowing (e.g. Fig. 4a, c, e) suggest periods of relatively slow sedimentation (Wetzel, 1991), whereas intervals of vertical burrows terminated by overlying strata (e.g. Fig. 4d, f) indicate episodic rapid sedimentation (Jennings et al., 2011a). Figure 4 shows expanded views of segments of the CT image shown in full on Figure 3 to illustrate some of the key lithofacies characteristics and trace fossil types that provide evidence for sedimentation processes. Muddy intervals typically have vertical burrows that are truncated by subsequent strata (Fig. 4d). These mud intervals likely represent plumites deposited from turbid meltwater plumes, whereas the sandy, stratified intervals with varying degrees of bioturbation likely represent distal turbidites (Ó Cofaigh and Dowdeswell, 2001) (Fig. 4c, f).

4.2.2 Foraminifera and Stable Isotopes

The Foraminiferal abundances in 12PC are spiky, with intervals of low benthic and planktic numbers per gram of dry sediment punctuated by periods of much higher numbers of foraminifers per gram (Fig. 5D). The high variability in abundance relates to variations in marine productivity, overprinted by carbonate dissolution, and dilution by high (12.8 cm/ka on average from 250-860 cm) and varying sedimentation rates. The lithofacies characteristics suggest widely varying sedimentation rates in the core that are not captured by the less frequent age control. Therefore we did not attempt to calculate foraminiferal flux, which would have been a more direct measure of productivity, but rather rely on foraminiferal numbers per gram as a measure of productivity.

N. pachyderma, the only planktic species, forms abundance spikes up to 1620 specimens/g, with intervening periods of very low abundance to absence (Fig. 5). The planktic forams were quite small from the base of the core to 860 cm (22 cal ka BP), but increased in size above that level. In general the planktic and benthic foram abundances rise and fall together, suggesting that the abundance spikes represent *in situ* productivity and a link between surface productivity and benthic food supply, although we cannot control for variations in carbonate preservation. Low numbers of *N. pachyderma* per gram are consistent with low productivity under perennial sea ice and the high numbers per gram are consistent with periods of more open water, such as leads or polynyas in summer (e.g. Nørgaard-Pedersen et al., 2003). Advection of planktic foraminifers from outside Baffin Bay is unlikely, especially given the linkage between the benthic and planktic productivity (cf Knutz et al., 2011; Nørgaard-Pedersen et al., 2003).

Oxygen isotope values on *N. pachyderma* ranged between 5.4 and 2 ‰. The interval between 22 and 18.2 cal ka BP has mostly heavy values that fall between 4 and 5 ‰ (Fig. 5), comparable to MIS 2 values in the Fram Strait (Nørgaard-Pedersen et al., 2003). A shift to lighter $\delta^{18}O$ and $\delta^{13}C$ values begins at 18 cal ka BP, suggests reduced ventilation (Sarnthein et al., 1995). This interval falls within HS1 regardless of which ΔR is applied (Fig. 2; Table 1). Above this shift the $\delta^{18}O$ values remain above 3.7 ‰. A pronounced light $\delta^{18}O$ spike at 19.4 cal ka BP corresponds to high planktic abundance and increased IP_{25} and Brassicasterol (Fig. 5). Oxygen isotopic values of this magnitude can either be related to glacial meltwater, especially if they are paired with light $\delta^{13}C$ values (Sarnthein et al., 1995) or to increased rate of sea-ice production that can produce brines with a light isotopic signature (Hillaire-Marcel et al., 2004; Hillaire-Marcel and de Vernal, 2008). The overall trend in the $\delta^{13}C$ values is toward heavier values suggesting better ventilation at the top of the record than at the bottom (Fig. 5).

The benthic foraminiferal assemblages (Fig. 6) provide insights into the productivity of surface waters, stratification of the water column, and turbid glacial meltwater influx. For example, sea-ice edge migration, either seasonal or in the form of leads or polynyas, produces pulses of phytoplankton production that sink to the seabed, providing food for benthic communities. The three most common benthic foraminiferal species in 12PC are *Stainforthia feylingi*, *Cassidulina reniforme* and *Elphidium* *excavatum* forma *clavata*. *S. feylingi* is dominant in conditions of stratified water column with a cold freshwater lid and has been associated with productivity at the seasonal sea ice edge (Seidenkrantz, 2013). It has been found in high abundances associated with biosiliceous sediments (Jennings et al., 2006). *E. excavatum* and *C. reniforme* occur together in glacial marine settings (Hald and Korsun, 1997). *C. reniforme* is also considered to represent chilled Atlantic Water (Slubowska et al., 2005) and is found in areas of relatively high, stable salinities (Polyak et al., 2002). *E. excavatum* is an opportunistic species that thrives in unstable environmental conditions influenced by rapid sedimentation and fluctuating salinities from turbid meltwater plumes (Hald and Korsun, 1997). The agglutinated species, *Spiroplectammina biformis*, which occurs mainly in the lower lithofacies unit is found in arctic fjords with strong meltwater signal (Jennings and Helgadottir, 1994; Schaffer and Cole, 1986).

Several species indicative of marine productivity associated with nutrient rich Atlantic Water occur in both the lower and upper lithofacies unit: *Melonis barleeanus, Buccella frigida, Nonionella turgida* and *Nonionellina labradorica*. *Islandiella norcrossi* and *I. helenae* both are arctic species, but *I. helenae* is associated with sea-ice edge productivity while *I. norcrossi* reflects chilled Atlantic Water of normal marine salinity (Polyak et al., 2002; Wollenburg et al., 2004; Lloyd, 2006). *I. norcrossi* is a common calcareous species on the west Greenland shelf associated with Atlantic Water in the West Greenland Current (e.g. Lloyd, 2006; Perner et al., 2012).

Near the top of the lower unit (16.5 cal ka BP), and continuing into the base of the overlying biosiliceous mud, several species associated with marine productivity and nutrient rich Atlantic Water spike to high percentages. These include *N. turgida*, *M.*

barleeanus, *B. frigida*, *I. norcrossi* and very low percentage of *Pullenia bulloides*. Current indicator species, *Cibicides lobatulus* also increases at this boundary. The central part of the diatom-rich mud is barren of calcareous foraminifers and is characterized by low faunal abundances dominated by agglutinated foraminiferal species (e.g. *Textularia earlandi*), suggesting that dissolution of carbonate likely overprinted the assemblages. The upper part of the diatom-rich mud shows a return of several of the marine productivity species along with increased percentages of *P. bulloides*, a chilled Atlantic water species, that is common on the SE Greenland and Northern Iceland shelves under conditions of strong Irminger Current Atlantic water inflow (Eiríksson et al., 2000; Jennings et al., 2011b).

Above the diatom-rich mud, the percentages of *N. labradorica* and *I. norcrossi* increase, and *S. feylingi* continues with high percentages. The chilled Atlantic Water species, *Cassidulina neoteretis*, is abundant at the top of the dated section along with *I. norcrossi*, consistent with intermediate Atlantic Water and less prominent glacial meltwater influence (Jennings and Helgadottir, 1993). The gap in foraminifers between 12 and 13.9 cal ka BP is likely a consequence of carbonate dissolution as other cores from the central West Greenland margin, but in slightly shallower water (JR175-VC29; Fig. 1) have *C. neoteretis* continuously between 14 and 11 cal ka BP (Jennings et al., ~~in revision~~2017).

4.2.3 Biomarkers

Further evidence of marine productivity and sea ice comes from the algal biomarkers brassicasterol and IP_{25} (Fig. 5). In general, the presence of IP_{25} indicates release from melting seasonal sea ice (Fahl and Stein, 2012; Belt et al., 2013), while the absence of

IP_{25} is consistent with intervals of thick perennial sea ice cover or no ice cover at all (Fahl and Stein, 2012). Brassicasterol implies productivity in open-water conditions, but it also can come from melting sea ice (Belt et al., 2013). In addition, the occurrence of polynyas has been given as a possible reason for presence of IP_{25} and brassicasterol under otherwise heavy ice conditions, even in the central Arctic Ocean (Xiao et al., 2013).

In the lower, high CT lithofacies unit of 12PC, brassicasterol and IP_{25} are present in low abundances from 26 to 22 ka (ΔR=140 yrs), coinciding with low foraminiferal abundances (Fig. 5). Between 22 and 20 ka, brassicasterol rises but IP_{25} is low to absent. Foraminiferal abundances rise in this interval and the benthic fauna is characterized by productivity species (*B. frigida*, *I. helenae*, *M. barleeanus* and *N. labradorica*). An overall rise in IP_{25} and a large peak in brassicasterol occur at 19.5 ka, and continue with moderate values until another rise in brassicasterol values within the ~~biosiliceous~~ diatom-rich mud unit (16.2 to 15.1 cal ka BP). Both IP_{25} and brassicasterol continue to rise after 15.1 cal ka BP, but IP_{25} in particular rises to values unprecedented in the core after 14.3 cal ka BP.

This pattern of presence of IP_{25} and brassicasterol in the lower lithofacies unit argues for seasonal sea ice and some open water, although the generally low concentrations suggest that these were both likely less than in the upper unit - probably due to more extensive ice cover and only periodic opening - possibly as leads or polynyas. As the final increase in IP_{25} beginning at 16.2 ka is accompanied by rising, high brassicasterol it likely points to development of a marginal ice zone where there is increased marine productivity with probably more seasonal sea ice presence than before.

5. Discussion

5.1 Did an LGM Ice Shelf cover Baffin Bay?

There has been limited research on the LGM within Baffin Bay, which explains how the Baffin Bay ice shelf concept has remained untested. Radiocarbon dates on planktic foraminifers indicate that other cores besides 12PC have planktic fauna in the LGM. Andrews et al (1998) obtained a pair of AMS ^{14}C dates from abundant planktic foraminifera in southern Baffin Bay core HU77029-017PC (17,990 ± 110, and 17,930 ± 210 ^{14}C yrs; Andrews et al., 1998) (Fig. 1). These ^{14}C ages calibrate to the LGM (~21 ka BP; ΔR=140 years). A ^{14}C date on planktic foraminifers from core HE006-4-2PC (21,440± 140 ^{14}C yrs) on the northern side of the Uummannaq TMF (Fig. 1) calibrates to ~25 ka BP (ΔR=140 years) (Ó Cofaigh et al., 2013a). In the LGM interval of 12PC (1130 cm to at least 690 cm) when the modeled Baffin Bay ice shelf would be in place, there are multiple lines of evidence for biological activity, including bioturbation, algal biomarkers and benthic and planktic foraminifers (Figs. 3 - 6). These findings are consistent with perennial sea-ice cover with some open water in the form of leads or polynyas on the eastern side of Baffin Bay. Full ice-shelf cover from an ice shelf extending from the Hudson Strait ice stream and grounding on Davis Strait all the way to Greenland (Alvarez-Solas et al., 2010; 2011; Marcott et al., 2011) would not allow the surface productivity (e.g. algal biomarkers, planktic forams) in Baffin Bay that would be needed to feed the benthic organisms that are evident (bioturbation and benthic foraminifers). On this basis we reject the modeling result of a full Baffin Bay ice shelf. While life has been observed under modern ice shelves in Antarctica, it is dependent on strong ocean inflow to the sub ice-shelf cavity from outside the ice shelf (Post et al., 2014). In the case of the Baffin Bay ice shelf cover as it is modeled, it would be sealed from the Labrador Sea marine advection and food supply.

The idea of the Davis Strait grounded ice shelf sprang in part from efforts to test a mechanism for Heinrich Event 1 (H1), in which subsurface warming reconstructed in the N. Atlantic in response to reduced Atlantic meridional overturning circulation (AMOC) during HS1 (McManus et al., 2004) weakens a buttressing ice shelf fronting the Hudson Strait ice stream and produces a Heinrich event (Álvarez-Solas et al., 2010; 2011; Marcott et al., 2011). Hulbe et al. (2004) modified their original 1997 Labrador Sea ice shelf idea to support instead fringing ice shelves along the coasts in Eastern Canada that were proposed to have met their demise through a process of meltwater infilling of surface crevasses. The existence of this type of ice shelf and H-event process has been contested (Alley et al., 2005), but it is more consistent with the 12PC data than the original idea of an ice shelf grounding on Davis Strait (Hulbe et al., 1997).

5.2 Heinrich Stadial Environments

The data in 12PC allow examination of the environmental response in Baffin Bay to the transition from LGM to HS1, and the response in Baffin Bay to the large ice discharge from Hudson Strait during H1 which occurred when subsurface ocean heat was at a maximum and AMOC at a minimum (Marcott et al., 2011). Locating the LGM/HS1 transition and H1 in 12PC is made difficult by the uncertainties in the magnitude of the local marine reservoir age through time (Fig. 3F) (Stern and Lisiecki, 2013). The accepted timing of H1 calving event is 16.8 ka BP (Hemming, 2004), although it may be closer to 16 ka BP based on the timing of the peak of IRD in the North Atlantic IRD stack during HS1 (Stern and Lisiecki, 2013). If we apply the ΔR ~~envelop~~envelope approach using data from Stern and Lisiecki (2013) to the mean value of the best 2 constraining radiocarbon ages from the base of DC1 (=H1) in cores HU75009-IV-055PC and HU87033-009 LCF (Fig. 1; Andrews et al., 1994; Jennings et al., 1996), from the Labrador Sea, we obtain a range of ages for the event that spans HS1 (Table 1). The ΔR that matches best the H1 16.8 ka age determined by Hemming (2004) is the lower ΔR from Stern and Lisiecki (2013) (Table 1). On this basis, we chose to use the Lower ΔR to determine where HS1 lies in the 12PC record. Lower ΔR places the base of HS1 (18 ka BP) at 610 cm and its end (14.7 ka BP) at 395cm, right at the end of the ~~diatomaceous~~ diatom-rich mud unit and before the initiation of calving retreat (Fig. 3F and 7). Lower ΔR also puts the calving retreat and the timing of the west Greenland DC event (=BBDC1; Jackson et al., 2017) (Fig. 3) in the Bølling/Allerød interstadial (Fig. 7). The age model calculated with an invariant ΔR=140 years places the lithofacies transition which represents the grounding line retreat from the west Greenland shelf edge at 16.2 cal ka BP, within HS1 (Jennings et al., ~~in revision~~2017), but places the end of HS1 after the initiation of GIS calving retreat.

Figure 7 illustrates how key proxy data map into the Heinrich Stadial interval defined by evidence of sluggish AMOC (McManus et al., 2004) using the lower ΔR of Stern and Lisiecki (2013). In the Labrador Sea HS1 is an interval of anomalously warm bottom waters (Marcott et al., 2011) within which H1 occurred (Fig. 7). We would expect this massive freshwater (meltwater and icebergs) outflow from collapse of the Hudson Strait ice stream (Andrews and Tedesco, 1992; Hesse and Khodabakhsh, 2016) to perturb environments in Baffin Bay or initiate a transition to different paleoceanographic conditions.

The transition to lighter $\delta^{18}O$ values and a shift to very high percentages of *S. feylingi* coincide with HS1 (Fig. 7). This signal is also seen in nearby core JR175-VC29 (Fig. 1), from 900 m water depth (Jennings et al., ~~in revision~~2017) and is associated in both 12PC and VC29 with deposition of ~~diatomaceous bioturbated~~diatom-rich mud with rare IRD; a fine-grained unit of similar age is observed in core GeoTü SL-170 (Jackson et al., 2017) slightly north of VC29. The~~is~~ diatom-rich mud interval has been interpreted by Jennings et al. (~~in revision~~2017) to ~~indicate protection of the~~indicate exclusion of coarse sediment delivery to the Disko TMF by retention of a fringing ice shelf ~~Disko Trough Mouth fan from coarse sediments released at the grounding line sediments by retreat of the grounding line but retention of a fringing ice shelf~~after initial grounding line retreat. Overall, brassicasterol abundances are low in HS1. A period of high productivity of benthic forams indicative of nutrient rich Atlantic water at the subsurface (Fig. 5) (indicated on Fig. 7 by red stars and ~~the~~ low percentages of the benthic foraminiferal species, *S. feylingi*) coincides with the initial GIS retreat from the shelf edge as indicated in the CT# profile (Jennings et al., ~~in revision~~2017). Subsequent interstadial conditions are marked by rising marine productivity, renewed subsurface Atlantic Water influence, and renewed retreat of the GIS, followed by development of consistent seasonal sea ice and release/melting of detrital carbonate bearing ice bergs from ice margins of northern Baffin Bay termed a west Greenland DC event by (Jennings et al., ~~in revision~~2017) that has been shown to be correlative to BBDC1 (Simon et al. (2016) by Jackson et al. (2017).

6. Conclusions

1. Based on the data presented we reject the hypothesis that Baffin Bay was covered by a full ice shelf during the LGM. W~~W~~e conclude instead ~~that rather than being completely covered by an ice shelf,~~ that Baffin Bay was perennially sea-ice covered ~~in the LGM~~with nutrient rich, relatively warm Atlantic water present at depth through the LGM. Evidence of marine productivity suggests that there were openings in the sea-ice cover as leads and polynyas to support marine productivity. Concurrently, sediment-laden, glacial-meltwater and turbidity currents were released from the GIS, grounded at the shelf edge, but IRD was rare suggesting the ice front was protected by a fringing ice shelf and/or the perennial sea-ice cover.

2. Reduced ventilation and productivity, coincident with a cold surface lid of meltwater was established in HS1. After Heinrich Event 1, but within the Heinrich stadial, an interval of increased productivity and Atlantic Water is associated with the retreat of the GIS grounding line from the shelf edge.

3. The implication for Heinrich Events and Ocean warming/Ice Shelf hypothesis is that perennial sea-ice cover and/or fringing ice shelves may be sufficient to explain the heat retention and back-pressure proposed to explain the dynamics that produce Heinrich Events.

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8. Figure Captions

Figure 1. Bathymetric map centered on Baffin Bay (BB) showing the location of core HU2008029-12PC (12PC) and other cores mentioned in the text, the distribution of Paleozoic carbonate bedrock, mapped ice margin positions in northern Baffin Bay (Li et al., 2011) and central west Greenland (Ó Cofaigh et al., 2013a) and major ice streams. UIS = Uummannaq ice stream; DIS = Disko ice stream; SSIS = Smith Sound ice stream; LSIS = Lancaster Sound ice stream. Northward flowing West Greenland Current (WGC) is shown as the thin red line and the southward flowing Baffin Current (BC) is shown as a thin blue line. The position of the acoustic profile in Figure 2 is shown as a black line. HU2008029-016PC=16; HE006-4-2PC=2; JR175-VC29=29; HU77029-017PC=17; HU75009-IV-055PC=55 and HU87033-009 LCF=9. Inset plot shows the salinity and temperature against water depth at from the same location as 2008029-12PC. ASW=Arctic Surface Water; WGIW=West Greenland Intermediate Water; DBBW=Deep Baffin Bay Water.

Figure 2. A. 3.5 kHz sub-bottom profile over the site of 2008029-12PC demonstrationg the acoustically-stratified character of the seabed in the area. B. A zoom in map of the 3.5 kKz sub-bottom profile and the core location shown in Figure 1. The bathymetry is from GEBCO.

Figure 3. Lithological proxies and age control for 2008029-12PC. A is the CT image against depth in the core. Black bars along depth axis show the locations of CT images shown in Figure 4. 'V' denotes locations of vertical burrows. B. IRD counts (>2mm clasts) from CT scan in 2 cm increments. C. CT number, a measure of density derived from the CT image. D. Magnetic Susceptibility measure by multi sensor track (MST). E. Weight percentage of >63 µm sand fraction from foraminiferal samples. F. Two-source provenance of minerals: Northern Baffin Bay (NBB, brown) vs. the local source, central west Greenland (green). F. Depth-Age model in pink (ΔR=140±30 yrs) showing 1σ and 2 σ uncertainties of the model. Excluded from the model are benthic foraminiferal ages (green distributions) and outliers at 1 meter. Age ~~envelop~~envelope for other potential ΔR calibrations are shown by blue (ΔR=0); Red, green, orange = lower, mean, and upper ΔR values from Stern and Lisiecki~~,~~ (2013). Climate units are along the age scale.

Figure 4. Examples of lithofacies and bioturbation types from 2008029-12PC CT scans. See Figure 3 for locations of these examples on the CT image of the core.

Figure 5. Biological proxies from 12PC compared with CT# plot to assist with comparison to depth on depth in Figure 3. A. CT#; B. sea ice biomarker, IP_{25}; C. marine productivity biomarker, brassicasterol; D. Benthic (blue) and planktic (red) forams per gram of dry sediment; E. $\delta^{18}O$ of planktic foraminifer, *N. pachyderma*, blue; F. $\delta^{13}C$ of *N. pachyderma*, green.

Figure 6. Benthic foraminiferal species in 12PC. Green represent marine productivity species; Red=Atlantic Water species; Blue = Arctic species; Light Blue; Glacial marine species; Orange=transformed (cooler and slightly lower salinity) Atlantic Water species.

Figure 7. Comparison between Pa/Th record of AMOC (McManus et al., 2004) and the timing of Heinrich Event 1 (H1) to key paleoenvironmental proxies in 12PC. The HS1 interval (yellow box) is defined in the core with use of the Lower ΔR of Stern and Lisiecki (2013) (Fig. 3f). Blue lines show where key events in the core map into the climatic intervals with use of the Lower ΔR of Stern and Lisiecki (2013). A. CT # from 12PC; B. Brassicasterol, 12PC; C. IP_{25}, 12PC; D. *Stainforthia feylingi*, 12PC; E. Oxygen isotope ratios, 12PC; F. Pa/Th ratios (McManus et al., 2004).

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- Baffin Bay was not covered by an ice shelf in the LGM.
- Baffin Bay was perennially sea-ice covered through the LGM.
- LGM marine productivity promoted by leads and polynyas in perennial sea-ice cover.
- Heinrich stadial paleoenvironments vary and are associated with GIS retreat
- H1 Ice Shelf hypothesis rejected; no evidence for Baffin Bay full ice shelf.

Baffin Bay Paleoenvironments in the LGM and HS1: Resolving the ice-shelf question

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Core HU2008029-12PC from the Disko trough mouth fan on the central West Greenland continental slope is used to test whether an ice shelf covered Baffin Bay during the Last Glacial Maximum (LGM) and at the onset of the deglaciation. We use benthic and planktic foraminiferal assemblages, stable isotope analysis of planktic forams, algal biomarkers, ice-rafted detritus (IRD), lithofacies characteristics defined from CT scans, and quantitative mineralogy to reconstruct paleoceanographic conditions, sediment processes and sediment provenance. The chronology is based on radiocarbon dates on planktic foraminifers using a ΔR of 140 ± 30 ^{14}C years, supplemented by the varying reservoir estimates of Stern and Lisiecki (2013) that provide an envelope of potential ages. HU2008029-12PC is bioturbated throughout. Sediments between the core base at 11.3 m and 4.6 m (LGM through HS1) comprise thin turbidites, plumites and hemipelagic sediments with Greenlandic provenance consistent with processes active at the Greenland Ice Sheet margin grounded at or near the shelf edge. Abundance spikes of planktic forams coincide with elevated abundance of benthic forams in assemblages indicative of chilled Atlantic Water, meltwater and intermittent marine productivity. IRD and IP_{25} are rare in this interval, but brassicasterol, an indicator of marine productivity reaches and sustains low levels during the LGM. These biological characteristics are consistent with a sea-ice covered ocean experiencing periods of more open water such as leads or polynyas in the sea ice cover, with chilled Atlantic Water at depth, rather than full ice-shelf cover. They do not support the existence of a full Baffin Bay ice shelf cover extending from grounded ice on the Davis Strait. Initial ice retreat from the West Greenland margin is manifested by a pronounced lithofacies shift to bioturbated, diatomaceous mud with rare IRD of Greenlandic origin at 467 cm (16.2 cal ka BP; ΔR=140 yrs) within HS1. A spike in foraminiferal abundance and ocean warmth indicator benthic forams precedes the initial ice retreat from the shelf edge. At the end of HS1, IP_{25}, brassicasterol and benthic

forams indicative of sea-ice edge productivity increase, indicating warming interstadial conditions. Within the Bølling/Allerød interstadial a strong rise in IP_{25} content and IRD spikes rich in detrital carbonate from northern Baffin Bay indicate that northern Baffin Bay ice streams were retreating and provides evidence for increased open water, advection of Atlantic Water in the West Greenland Current, and formation of an IRD belt along the W. Greenland margin.

Keywords: Greenland Ice Sheet, Baffin Bay, paleoceanography, ice shelf, foraminifera, Heinrich Stadial 1

1. Introduction

Last Glacial Maximum (LGM) climatic and oceanic conditions in Baffin Bay are currently poorly known, but according to the temperature reconstructions from the Greenland Ice Sheet borehole (Dahl-Jensen and al., 1998) and ice-core data (Buizert et al., 2014), summit temperatures were ~20°C colder than present. Applying this temperature difference down to sea level using the adiabatic lapse rate, suggests that the annual temperature at the surface of Baffin Bay adjacent to Baffin Island would approach -36°C. Such cold temperatures support the argument that cold-based ice covered the forelands of eastern Baffin Island (Briner et al., 2003) with “Antarctic-like” conditions across Baffin Bay, which would also suggest that Baffin Bay was covered in perennial sea ice. At the LGM, confluent, Innuitian (IIS), Laurentide (LIS) and Greenland (GIS) ice sheets (England et al., 2006) blocked the channels that connect Baffin Bay to the Arctic Ocean (Dyke, 2002) and terminated in northern Baffin Bay as large ice streams (Li et al., 2011; Blake, 1977). The Greenland ice sheet reached the continental shelf edge via large ice streams off west Greenland (Ó Cofaigh et al., 2013a; Jennings et al., 2017; Slabon et al., 2016; Sheldon et al., 2016; Dowdeswell et al., 2014), but the outer limits of the ice on the Baffin shelf are not known.

On the basis of modeling, it has been proposed that Baffin Bay was blocked at its southern end by an ice shelf extension of the Hudson Strait ice stream that grounded across Davis Strait to reach southern Greenland, thus sealing Baffin Bay from the Labrador Sea (Hulbe et al., 1997; Álvarez-Solas et al., 2010; Marcott et al., 2011). This ice shelf was the starting point for modeling the processes that produce Heinrich events (Hulbe et al., 1997; Álvarez-Solas et al., 2010; Marcott et al., 2011), but physical evidence for it has not been recovered. An ice shelf of this scale would have environmental consequences that should be recorded in Baffin Bay sediments. Firstly, grounding of a Labrador Sea ice shelf along Davis Strait would prevent seawater exchange between Baffin Bay and the Labrador Sea, excluding advection of organic matter into Baffin Bay. It also would shut down *in situ* primary marine productivity in Baffin Bay so that planktic and benthic organisms, their biomarkers, and bioturbation would be absent in the sediment. Secondly, ice shelves and even extensive sea-ice cover are known to restrict the movement and export of icebergs (Reeh et al., 2001; Domack and Harris, 1998). Thus iceberg rafting and mixing of sediments of various provenances in Baffin Bay would be reduced. Using these concepts, we test the LGM Baffin Bay ice-shelf hypothesis by studying the sedimentological and biological characteristics of sediments in HU2008029-12PC from the continental slope off western Greenland, a core that extends from the LGM into the Younger Dryas (YD) and that recorded retreat of the Greenland Ice Sheet during deglaciation (Jennings et al., 2017).

2. Setting of core HU2008029-12PC

Detailed studies of LGM and deglacial environments in Baffin Bay have been hampered by relatively slow sediment accumulation rates and poor calcium carbonate preservation (cf. Aksu, 1985; de Vernal et al., 1992; Simon et al., 2012). HU2008029-12PC (hereafter called 12PC) was raised from the northern side of the Disko trough mouth fan (TMF) from acoustically stratified sediments with continuous parallel reflections on the eastern side of Baffin Bay (68°13.69' N; 57°37.08' W; 1475 m water depth; Campbell and de Vernal, 2009) (Figs. 1 and 2). This site on the trough mouth fan has higher sediment accumulation than sites in the deep basin of Baffin Bay that have variable sedimentation rates that range between 3 and 35 cm/ka (Andrews et al., 1998; Hillaire-Marcel et al., 1989, 2004; Simon et al., 2012; 2014) (Fig. 1).

The Disko TMF was built throughout the Quaternary by rapid sediment deposition in front of the fast flowing Disko ice stream (Fig. 1) when the GIS margin was extended on the shelf, and from hemipelagic sedimentation during and after ice retreat (ÓCofaigh et al., 2013a, b; Jennings et al., 2017; Hofmann et al., 2016). An ice sheet grounded at or near the shelf edge delivers abundant sediments directly to the continental slope in the form of sediment gravity flows, including turbidity currents that form graded sand layers, stratified sand/silt beds, and glacigenic debris flows (ÓCofaigh et al., 2013a, b, Lucci and Rebesco, 2007). Turbid meltwater plumes released from the ice front produce plumites, which are finer grained than the turbidites as the sand is dropped near the ice front and the silt and clay continue offshore in suspension (Hesse et al., 1997; Lucchi and Rebesco, 2007). Depending on sea surface conditions such as perennial sea ice and/or ice shelves, icebergs would also deliver sediment to the slope as they melted during their transit in Baffin Bay (Andrews et al., 1998; 2014; Jennings et al., 2014; Simon et al., 2012; 2014; 2016; Sheldon et al., 2016).

The modern sea ice edge extends southeast to northwest within Baffin Bay and sea ice cover is greater in the western than in the eastern half due to the influence of the relatively warm and saline West Greenland Current that enters Baffin Bay from the southeast (Tang et al., 2004; Münchow et al., 2015) (Fig. 1). The boundary between lower salinity, sea-ice bearing, Arctic Surface Water (ASW) that passes from the Arctic Ocean through the channels of the Canadian Arctic Archipelago into Baffin Bay and Atlantic Waters of the West Greenland Current (WGC) moving northward along West Greenland is oriented NE-SW and migrates through the year. The relatively warm, saline Atlantic Water submerges beneath the ASW (Buch, 2000a, b) and forms the West Greenland Intermediate Water (WGIW) (Fig. 1 inset) (Tang et al., 2004). During the LGM, however, the circulation regime in Baffin Bay would have been different because the southward flow of ASW into Baffin Bay was blocked by confluent ice sheets grounded in the channels of the Canadian Arctic Archipelago until the early Holocene (England, 1999; Zreda et al., 1999; Jennings et al., 2011a; Piénkowski et al., 2011). Today, warm Atlantic Water carried in the WGC accesses the GIS margins via cross shelf troughs and fjords, where the ice sheet terminates in the sea (Holland et al., 2008) and promotes basal melting (Straneo et al., 2012). WGC Atlantic Water flow was initiated as early as 14.4 cal ka BP off central West Greenland and is implicated in Greenland Ice Sheet retreat from the LGM position at the shelf edge (cf. Knutz et al., 2011; Sheldon et al., 2016; Jennings et al., 2017).

3. Methods:

3.1 Age Model

The age model for 12PC is based on 7 radiocarbon dates between 201 and 860 cm on the arctic planktic foraminifer, *Neogloboquadrina pachyderma* (*sensu* Darling et al., 2006). The dates were previously published in Jennings et al., (2017) (Table 1). Radiocarbon dates were calibrated using the Marine13 curve (Reimer et al., 2013). OxCal version 4.2.4 (Ramsey and Lee, 2013) was used to compute an age/depth model (Fig. 3). An age reversal in the upper 110 cm of the core limited the chronology to the interval from 200 cm to the base of the core (1130 cm). The age of the core base is assumed to be no older than 26.5 ka BP, the beginning of the LGM (Clark et al., 2009). This assumed basal age results in a large uncertainty in the modeled age of the base of the core (24 to 28 cal ka BP). Given this basal age, we might expect to record Baffin Bay Detrital Carbonate (BBDC) event BBDC3 that is found in central Baffin Bay from c. 23.5 to 25 cal ka BP (Simon et al., 2016). A single data point with 20% NBB source at 21.5 cal ka BP may represent BBDC2 (21 cal ka BP; Simon et al., 2016) although it is not associated with a coarse clast-rich interval as would be expected if it represented a BBDC event (Andrews et al., 1998; Simon et al., 2012; Jackson et al., 2017) (Fig. 3). The lack of an interval of high NBB and IRD below 467 cm (16.2 cal ka BP) in 12PC indicates that BBDC2 and BBDC3 were not recovered in 12PC. Either these two events were not deposited basin wide or the basal age of 12PC is younger than the 21 ka BP age of BBDC2. Given that the deepest radiocarbon age in 12PC is 21.8 cal ka BP (ΔR=140 years) and there are 3 meters of sediment below this depth in the core, we suggest it is more likely that BBDC2 and 3 were not deposited basin wide. Without additional information we continue with the assumption that the core base is no older than the beginning of the global LGM of 26.5 ka BP (Clark et al., 2009).

We initially built the age model assuming a marine reservoir offset (ΔR) of 140±30 years based on recent work in Disko Bugt (Lloyd et al., 2011), for consistency with other central West Greenland sediment core records (cf Jennings et al., 2014; 2017; Jackson et al., 2017; Hogan et al., 2016; Sheldon et al., 2016), and we note that prior to 2011, many publications used a ΔR=0 years (Andrews et al., 1998; Knudsen et al., 2008). However, recognizing that the marine reservoir offset could be large and variable over the time interval of 12PC and because this core extends into the LGM, defined here as beginning at 26.5 ka (Clark et al., 2009) and ending at the beginning of the Oldest Dryas period, 18 ka BP (Buizert et al., 2014), we used the variable North Atlantic R values in Stern and Lisiecki (2013) to provide an envelope of calibrated age so that we could consider the correlations of boundaries and conditions recorded in the core with established climatic intervals (Fig. 3f). To accomplish this we first calibrated each date with ΔR=0 ^{14}C years, which provides the maximum age. We then used the ΔR=0 ages to identify the appropriate 500 year bin of maximum, average and minimum R values from Table S1 of Stern and Lisiecki (2013) and calibrated each of the dates using these three R-values. The resulting envelope of ages, from ΔR=0 to the maximum Stern and Lisiecki 2013 R-value, illustrates how the choice of ΔR affects correlation of boundaries in the core with climate intervals from LGM through the YD (Fig. 3f; Table 1). Regardless, these results confirm that the core contains LGM and Heinrich Stadial 1 (aka Oldest Dryas) sediments, a key requirement for testing the ice shelf model (Hulbe et al., 1997; Álvarez-Solas et al., 2010; Marcott et al., 2011).

3.2 Foraminiferal analyses.

One-cm wide samples were weighed wet and sieved on a 63-μm screen. Material >63 μm was kept wet in a storage solution of 70% distilled water and 30% ethanol with baking soda as a buffer. Foraminifera were counted wet to prevent destruction of fragile tests that disintegrate under the stress of drying. A wet splitter was used when necessary to achieve a count of 200-300 benthic formaminifers and as many planktic foraminifers as were in the benthic split. In most cases the full sample was counted. Equivalent dry weights of the foram samples were estimated from sedimentology samples from the same depths that had both wet and dry weights, allowing foraminifera/gram sediment to be calculated.

3.3 Stable isotope analyses

Stable oxygen and carbon isotopes were measured on the planktic foram species *Neogloboquadrina pachyderma* picked from the 150-250 μm size fraction in 41 samples; results from 3 samples were rejected because they yielded a low signal. Samples >100 μg have standard deviations of 0.01 and 0.03 ‰ for $\delta^{13}C$ and $\delta^{18}O$ respectively. Samples weighing <100 μg are reported with a standard deviation of 0.06 ‰ for $\delta^{13}C$, and an error of ±0.2 ‰ for $\delta^{18}O$. The oxygen isotope values are expressed as ‰ vs VPDB. Between 1050 and 857 cm all samples were of small weight but otherwise seemed reliable. Measurements were made on a Micromass IsoprimeTM dual inlet coupled to a MulticarbTM system at the Light Stable Isotope Geochemistry Laboratory at the University of Montréal – UQAM.

3.4 CT scan.

CT scanning of the half round core was performed at the sediment core laboratory at the University of Quebec at Rimouski. A CT number (a measure of sediment density) was extracted from the images. The CT scan image was used to determine lithofacies and boundaries, sedimentary structures, and to identify bioturbation, a key source of evidence for the presence of benthic organisms and a source of information about sedimentation rate variations between the radiocarbon dates (Wetzel, 1991). Counts of >2 mm clasts interpreted as ice rafted detritus (IRD) were made from the CT images by counting in a 2 cm wide window across the core width continuously along the core length (Grobe, 1987).

3.5 Biomarkers: IP_{25} and Brassicasterol

Biomarker analyses (IP_{25} and brassicasterol) were performed using methods described previously (Belt et al., 2012; Belt et al., 2015). Briefly, 9-octylheptadec-8-ene (9-OHD, 10 µL; 10 µg mL^{-1}) and 5α-androstan-3β-ol (10 µL; 10 µg mL^{-1}) were added to ca. 1 – 2 g of each freeze-dried sediment sample prior to extraction to permit quantification of IP_{25} and sterols, respectively. Samples were then extracted using dichloromethane/methanol (3 x 3 mL; 2:1 v/v) and ultrasonication. Following removal of the solvent from the combined extracts using nitrogen, the resulting total organic extracts (TOE) were purified using column chromatography (silica) with IP_{25} (hexane; 6 mL) and brassicasterol (20:80 methylacetate/hexane; 6 mL) collected as two single fractions. Non-polar lipid fractions were further separated into saturated and unsaturated hydrocarbons using glass pipettes containing silver ion solid phase extraction material (Supelco Discovery® Ag-Ion). Saturated hydrocarbons were eluted with hexane (1 mL), while unsaturated hydrocarbons (including IP_{25}) were eluted with acetone (2 mL). All fractions were dried under a stream of nitrogen.

Analysis of individual fractions was carried out using gas chromatography - mass spectrometry (GC-MS) with operating conditions as described previously (e.g. Belt et al., 2012; Brown and Belt, 2012). Sterols were derivatized (BSTFA; 50 µL; 70 ºC; 1 h) prior to analysis by GC-MS. Mass spectrometric analysis was carried out in total ion current (TIC) and single-ion monitoring (SIM) modes. Individual lipids were identified on the basis of their characteristic GC retention indices and mass spectra obtained from standards. Quantification of IP_{25} was achieved by dividing its integrated GC-MS peak area by that of the internal standard (9-OHD) in SIM mode (both *m/z* 350) and normalizing this ratio using an instrumental response factor (obtained from laboratory standards of each analyte) and the mass of sediment (Belt et al., 2012). Analytical reproducibility (6 %, n = 3) was monitored using a sediment with a known concentration of IP_{25}. Brassicasterol concentrations were obtained by comparison of their respective peak areas in SIM mode (brassicasterol, *m/z* 470) with those of the internal standard (*m/z* 333) and normalized as per IP_{25}.

3.6 Quantitative X-ray diffraction Mineralogy

Quantitative x-ray diffraction (qXRD) analyses were used to identify shifts in sediment sources between ‘local’ West Greenland (WG) and ‘distal’ Northern Baffin Bay (NBB). Samples for qXRD analysis were taken at 10 to 20 cm intervals throughout the core. Sediment samples were freeze-dried and processed at INSTAAR using the method described by Eberl (2003) and Andrews and Eberl (2011). The qXRD samples were analysed on a Siemens D5000 XRD unit at a 0.02 2-θ step with a 2 second count; minerals were identified using the program RockJock v.6 (Eberl, 2003). The qXRD 2-source data to 17.5 cal ka BP is presented in Jennings et al. (2017). The determination of sediment provenance is based on the quantitative X-ray diffraction (qXRD) analysis of the < 2 mm surface and core sediments using the method outlined by Eberl (2003) and described in more detail for our area by (Andrews and Eberl, 2012; Andrews et al., 2014; O'Cofaigh et al., 2013a; Simon et al., 2014). We use the Excel macro unmixing program “SedUnMix” (Eberl, 2004; Andrews and Eberl, 2012) to ascribe sediment mineral assemblages to probable source areas. In this present study we discriminated between two glacial derived sources; first a regional West Greenland source dominated by specific ranges in quartz, plagioclase, k-feldspars and other non-clay and clay minerals, versus a North Baffin Bay detrital carbonate source dominated by dolomite (Andrews et al., 2014; O'Cofaigh et al., 2013; Jennings et al., 2017).

4. Results and Interpretation

4.1 Lithofacies Characteristics

There are two main lithofacies units defined by the sediment parameters in 12PC (Fig. 3). The boundary between the two units (Fig. 4b) is well expressed by an abrupt shift to lower CT# (Fig. 3A). This transition dates to 16.2 cal ka BP using ΔR=140 years and has been interpreted to represent the retreat of the Greenland Ice Sheet from the shelf edge (Jennings et al., 2017). However, the full age-envelope ranges between 16.4 (ΔR=0) to 14.0 (Max R) ka, or, late in Heinrich Stadial 1 to the end of the Bølling (Fig. 3f). Calibrated radiocarbon dates (Fig. 3F; ΔR=140, pink) in the lower unit range from

21.8 to 16.2 cal ka BP. The lower three radiocarbon dates fall within the LGM regardless of the marine reservoir age selected (Fig. 3F). The radiocarbon date at 571.5 cm falls within Heinrich Stadial 1 regardless of the marine reservoir age (Fig. 3F).

The lower lithofacies unit, which represents the period when the ice sheet grounding line was at or near the shelf edge, has higher magnetic susceptibility (Fig. 3C), variable sand content including high weight percentage peaks (Fig. 3D) and a west Greenlandic sediment composition (Fig. 3E) but rare >2mm clasts (Fig. 3B). From the base of the core to 1022 cm, sediments are laminated mud with straight, sharp contacts defining the laminae and vertically oriented burrows (Fig. 4f). Between 1025 and 768 cm the sand content increases and stratification is disrupted by bioturbation (Fig. 3E). Stratified mud with distinct vertical burrows extends from 768 to 735 cm (Fig. 3D). From 735 cm to 688 cm sand content increases. This sandy unit is overlain by another sequence of stratified mud with distinct burrows between 688 and 630 cm. The sediment between 630 and 467 cm is bioturbated, stratified mud with layering disturbed by bioturbation (Fig. 4c). The uppermost part of this unit has high sand content and marks the transition to the upper lithofacies unit.

The upper lithofacies from 467 to 0 cm, which represents deglaciation and the Holocene (Jennings et al., 2017), has overall lower CT number (lower density) (Fig. 3A), lower magnetic susceptibility (Fig. 3C) and generally lower sand content (Fig. 3D). But, it has much higher numbers of >2mm clasts (IRD) (Fig. 3B). Immediately above the boundary the sediments are low-density bioturbated mud with the sand fraction comprising *Coscinodiscus* planktic diatoms and setae of *Chaetoceras*, consistent with the low MS values (Fig. 3c). Well-defined, thin laminae and rare IRD occur at the base of the unit, but transition upward to less-well defined laminae and rare to absent IRD from 420 cm to 352 cm. This fine interval was interpreted to record a period in the initial deglaciation as the grounding line retreated off the shelf edge with retention of an ice shelf (Jennings et al., 2017). At 352 cm (marked by middle horizontal blue line on Figure 3) the CT # (density), MS and sand increase (Fig. 3A, B, C, D). This level marks the start of renewed retreat of the GIS grounding line by calving (Jennings et al., 2017). The sediments are bioturbated but stratification is still evident, suggesting moderate sedimentation rates. Apart from a peak in >2mm clasts of west Greenland provenance at 330 cm the main rise in >2mm clasts coincides with the entry of the Northern Baffin Bay sediment source (NBB source) at 290 cm (Fig. 3B, E). Bioturbated, pebbly mud associated with a rise in NBB provenance occurs between 280 and 175 cm with the highest IRD interval from 280-240 cm (Fig. 3B, E). This NBB DC interval has been found in several cores on the central West Greenland slope (Sheldon et al., 2016; Jennings et al., 2017; Jackson et al., 2017) and has been correlated to BBDC1 (Simon et al., 2012; 2014; Jackson et al., 2017), marking the retreat of NBB ice streams. The NBB DC event is overlain by bioturbated mud with small, dispersed IRD and discontinuous silt stringers between 175 and 152 cm. Bioturbated pebbly mud between 152 and 52 cm has high NBB provenance between 160 and 90 cm, an interval that contains an age reversal and a mixture of radiocarbon ages (Fig. 3F). The age reversal suggests that the upper NBB peak is reworked. The upper 52 cm of the core is bioturbated mud with dispersed IRD likely represents the middle to late Holocene time period, although it is undated.

4.2 Biological Proxies

Biological proxy data are expressed against age using the age model based on ΔR=140 yrs (Fig. 5).

4.2.1 Bioturbation

The CT scan image (Fig. 3) reveals that the entire core is bioturbated, indicating that there was sufficient oxygenation and food to support the benthos in Baffin Bay throughout the time period represented by the core (Löwemark et al., 2012). Variations in burrow shape and density are indicative of the interplay between oxygenation, sedimentation rate, sedimentation processes, substrate consistency and food supply (Reineck and Singh, 1980, Wetzel, 1991; Löwenmark et al., 2012) (Fig. 4). Intensely bioturbated intervals in which sand layers are disrupted by burrowing (e.g. Fig. 4a, c, e) suggest periods of relatively slow sedimentation (Wetzel, 1991), whereas intervals of vertical burrows terminated by overlying strata (e.g. Fig. 4d, f) indicate episodic rapid sedimentation (Jennings et al., 2011a). Figure 4 shows expanded views of segments of the CT image shown in full on Figure 3 to illustrate some of the key lithofacies characteristics and trace fossil types that provide evidence for sedimentation processes. Muddy intervals typically have vertical burrows that are truncated by subsequent strata (Fig. 4d). These mud intervals likely represent plumites deposited from turbid meltwater plumes, whereas the sandy, stratified intervals with varying degrees of bioturbation likely represent distal turbidites (Ó Cofaigh and Dowdeswell, 2001) (Fig. 4c, f).

4.2.2 Foraminifera and Stable Isotopes

The Foraminiferal abundances in 12PC are spiky, with intervals of low benthic and planktic numbers per gram of dry sediment punctuated by periods of much higher numbers of foraminifers per gram (Fig. 5D). The high variability in abundance relates to variations in marine productivity, overprinted by carbonate dissolution, and dilution by high (12.8 cm/ka on average from 250-860 cm) and varying sedimentation rates. The lithofacies characteristics suggest widely varying sedimentation rates in the core that are not captured by the less frequent age control. Therefore we did not attempt to calculate foraminiferal flux, which would have been a more direct measure of productivity, but rather rely on foraminiferal numbers per gram as a measure of productivity.

N. pachyderma, the only planktic species, forms abundance spikes up to 1620 specimens/g, with intervening periods of very low abundance to absence (Fig. 5). The planktic forams were quite small from the base of the core to 860 cm (22 cal ka BP), but increased in size above that level. In general the planktic and benthic foram abundances rise and fall together, suggesting that the abundance spikes represent *in situ* productivity and a link between surface productivity and benthic food supply, although we cannot control for variations in carbonate preservation. Low numbers of *N. pachyderma* per gram are consistent with low productivity under perennial sea ice and the high numbers per gram are consistent with periods of more open water, such as leads or polynyas in summer (e.g. Nørgaard-Pedersen et al., 2003). Advection of planktic foraminifers from outside Baffin Bay is unlikely, especially given the linkage between the benthic and planktic productivity (cf Knutz et al., 2011; Nørgaard-Pedersen et al., 2003).

Oxygen isotope values on *N. pachyderma* ranged between 5.4 and 2 ‰. The interval between 22 and 18.2 cal ka BP has mostly heavy values that fall between 4 and 5 ‰ (Fig. 5), comparable to MIS 2 values in the Fram Strait (Nørgaard-Pedersen et al., 2003). A shift to lighter $\delta^{18}O$ and $\delta^{13}C$ values begins at 18 cal ka BP, suggests reduced ventilation (Sarnthein et al., 1995). This interval falls within HS1 regardless of which ΔR

is applied (Fig. 2; Table 1). Above this shift the $\delta^{18}O$ values remain above 3.7 ‰. A pronounced light $\delta^{18}O$ spike at 19.4 cal ka BP corresponds to high planktic abundance and increased IP_{25} and Brassicasterol (Fig. 5). Oxygen isotopic values of this magnitude can either be related to glacial meltwater, especially if they are paired with light $\delta^{13}C$ values (Sarnthein et al., 1995) or to increased rate of sea-ice production that can produce brines with a light isotopic signature (Hillaire-Marcel et al., 2004; Hillaire-Marcel and de Vernal, 2008). The overall trend in the $\delta^{13}C$ values is toward heavier values suggesting better ventilation at the top of the record than at the bottom (Fig. 5).

The benthic foraminiferal assemblages (Fig. 6) provide insights into the productivity of surface waters, stratification of the water column, and turbid glacial meltwater influx. For example, sea-ice edge migration, either seasonal or in the form of leads or polynyas, produces pulses of phytoplankton production that sink to the seabed, providing food for benthic communities. The three most common benthic foraminiferal species in 12PC are *Stainforthia feylingi*, *Cassidulina reniforme* and *Elphidium excavatum* forma *clavata*. *S. feylingi* is dominant in conditions of stratified water column with a cold freshwater lid and has been associated with productivity at the seasonal sea ice edge (Seidenkrantz, 2013). It has been found in high abundances associated with biosiliceous sediments (Jennings et al., 2006). *E. excavatum* and *C. reniforme* occur together in glacial marine settings (Hald and Korsun, 1997). *C. reniforme* is also considered to represent chilled Atlantic Water (Slubowska et al., 2005) and is found in areas of relatively high, stable salinities (Polyak et al., 2002). *E. excavatum* is an opportunistic species that thrives in unstable environmental conditions influenced by rapid sedimentation and fluctuating salinities from turbid meltwater plumes (Hald and

Korsun, 1997). The agglutinated species, *Spiroplectammina biformis*, which occurs mainly in the lower lithofacies unit is found in arctic fjords with strong meltwater signal (Jennings and Helgadottir, 1994; Schaffer and Cole, 1986).

Several species indicative of marine productivity associated with nutrient rich Atlantic Water occur in both the lower and upper lithofacies unit: *Melonis barleeanus, Buccella frigida, Nonionella turgida* and *Nonionellina labradorica*. *Islandiella norcrossi* and *I. helenae* both are arctic species, but *I. helenae* is associated with sea-ice edge productivity while *I. norcrossi* reflects chilled Atlantic Water of normal marine salinity (Polyak et al., 2002; Wollenburg et al., 2004; Lloyd, 2006). *I. norcrossi* is a common calcareous species on the west Greenland shelf associated with Atlantic Water in the West Greenland Current (e.g. Lloyd, 2006; Perner et al., 2012).

Near the top of the lower unit (16.5 cal ka BP), and continuing into the base of the overlying biosiliceous mud, several species associated with marine productivity and nutrient rich Atlantic Water spike to high percentages. These include *N. turgida*, *M. barleeanus*, *B. frigida*, *I. norcrossi* and very low percentage of *Pullenia bulloides*. Current indicator species, *Cibicides lobatulus* also increases at this boundary. The central part of the diatom-rich mud is barren of calcareous foraminifers and is characterized by low faunal abundances dominated by agglutinated foraminiferal species (e.g. *Textularia earlandi*), suggesting that dissolution of carbonate likely overprinted the assemblages. The upper part of the diatom-rich mud shows a return of several of the marine productivity species along with increased percentages of *P. bulloides*, a chilled Atlantic water species, that is common on the SE Greenland and Northern Iceland shelves under conditions of strong Irminger Current Atlantic water inflow (Eiríksson et al., 2000; Jennings et al., 2011b).

Above the diatom-rich mud, the percentages of *N. labradorica* and *I. norcrossi* increase, and *S. feylingi* continues with high percentages. The chilled Atlantic Water species, *Cassidulina neoteretis*, is abundant at the top of the dated section along with *I. norcrossi*, consistent with intermediate Atlantic Water and less prominent glacial meltwater influence (Jennings and Helgadottir, 1993). The gap in foraminifers between 12 and 13.9 cal ka BP is likely a consequence of carbonate dissolution as other cores from the central West Greenland margin, but in slightly shallower water (JR175-VC29; Fig. 1) have *C. neoteretis* continuously between 14 and 11 cal ka BP (Jennings et al., 2017).

4.2.3 Biomarkers

Further evidence of marine productivity and sea ice comes from the algal biomarkers brassicasterol and IP_{25} (Fig. 5). In general, the presence of IP_{25} indicates release from melting seasonal sea ice (Fahl and Stein, 2012; Belt et al., 2013), while the absence of IP_{25} is consistent with intervals of thick perennial sea ice cover or no ice cover at all (Fahl and Stein, 2012). Brassicasterol implies productivity in open-water conditions, but it also can come from melting sea ice (Belt et al., 2013). In addition, the occurrence of polynyas has been given as a possible reason for presence of IP_{25} and brassicasterol under otherwise heavy ice conditions, even in the central Arctic Ocean (Xiao et al., 2013).

In the lower, high CT lithofacies unit of 12PC, brassicasterol and IP_{25} are present in low abundances from 26 to 22 ka (ΔR=140 yrs), coinciding with low foraminiferal abundances (Fig. 5). Between 22 and 20 ka, brassicasterol rises but IP_{25} is low to absent.

Foraminiferal abundances rise in this interval and the benthic fauna is characterized by productivity species (*B. frigida*, *I. helenae*, *M. barleeanus* and *N. labradorica*). An overall rise in IP_{25} and a large peak in brassicasterol occur at 19.5 ka, and continue with moderate values until another rise in brassicasterol values within the diatom-rich mud unit (16.2 to 15.1 cal ka BP). Both IP_{25} and brassicasterol continue to rise after 15.1 cal ka BP, but IP_{25} in particular rises to values unprecedented in the core after 14.3 cal ka BP.

This pattern of presence of IP_{25} and brassicasterol in the lower lithofacies unit argues for seasonal sea ice and some open water, although the generally low concentrations suggest that these were both likely less than in the upper unit - probably due to more extensive ice cover and only periodic opening - possibly as leads or polynyas. As the final increase in IP_{25} beginning at 16.2 ka is accompanied by rising, high brassicasterol it likely points to development of a marginal ice zone where there is increased marine productivity with probably more seasonal sea ice presence than before.

5. Discussion

5.1 Did an LGM Ice Shelf cover Baffin Bay?

There has been limited research on the LGM within Baffin Bay, which explains how the Baffin Bay ice shelf concept has remained untested. Radiocarbon dates on planktic foraminifers indicate that other cores besides 12PC have planktic fauna in the LGM. Andrews et al (1998) obtained a pair of AMS ^{14}C dates from abundant planktic foraminifera in southern Baffin Bay core HU77029-017PC (17,990 ± 110, and 17,930 ± 210 ^{14}C yrs; Andrews et al., 1998) (Fig. 1). These ^{14}C ages calibrate to the LGM (~21 ka BP; ΔR=140 years). A ^{14}C date on planktic foraminifers from core HE006-4-2PC

(21,440± 140 ^{14}C yrs) on the northern side of the Uummannaq TMF (Fig. 1) calibrates to ~25 ka BP (ΔR=140 years) (Ó Cofaigh et al., 2013a). In the LGM interval of 12PC (1130 cm to at least 690 cm) when the modeled Baffin Bay ice shelf would be in place, there are multiple lines of evidence for biological activity, including bioturbation, algal biomarkers and benthic and planktic foraminifers (Figs. 3 - 6). These findings are consistent with perennial sea-ice cover with some open water in the form of leads or polynyas on the eastern side of Baffin Bay. Full ice-shelf cover from an ice shelf extending from the Hudson Strait ice stream and grounding on Davis Strait all the way to Greenland (Alvarez-Solas et al., 2010; 2011; Marcott et al., 2011) would not allow the surface productivity (e.g. algal biomarkers, planktic forams) in Baffin Bay that would be needed to feed the benthic organisms that are evident (bioturbation and benthic foraminifers). On this basis we reject the modeling result of a full Baffin Bay ice shelf. While life has been observed under modern ice shelves in Antarctica, it is dependent on strong ocean inflow to the sub ice-shelf cavity from outside the ice shelf (Post et al., 2014). In the case of the Baffin Bay ice shelf cover as it is modeled, it would be sealed from the Labrador Sea marine advection and food supply.

The idea of the Davis Strait grounded ice shelf sprang in part from efforts to test a mechanism for Heinrich Event 1 (H1), in which subsurface warming reconstructed in the N. Atlantic in response to reduced Atlantic meridional overturning circulation (AMOC) during HS1 (McManus et al., 2004) weakens a buttressing ice shelf fronting the Hudson Strait ice stream and produces a Heinrich event (Álvarez-Solas et al., 2010; 2011; Marcott et al., 2011). Hulbe et al. (2004) modified their original 1997 Labrador Sea ice shelf idea to support instead fringing ice shelves along the coasts in Eastern Canada that were proposed to have met their demise through a process of meltwater infilling of surface crevasses. The existence of this type of ice shelf and H-event process has been contested (Alley et al., 2005), but it is more consistent with the 12PC data than the original idea of an ice shelf grounding on Davis Strait (Hulbe et al., 1997).

5.2 Heinrich Stadial Environments

The data in 12PC allow examination of the environmental response in Baffin Bay to the transition from LGM to HS1, and the response in Baffin Bay to the large ice discharge from Hudson Strait during H1 which occurred when subsurface ocean heat was at a maximum and AMOC at a minimum (Marcott et al., 2011). Locating the LGM/HS1 transition and H1 in 12PC is made difficult by the uncertainties in the magnitude of the local marine reservoir age through time (Fig. 3F) (Stern and Lisiecki, 2013). The accepted timing of H1 calving event is 16.8 ka BP (Hemming, 2004), although it may be closer to 16 ka BP based on the timing of the peak of IRD in the North Atlantic IRD stack during HS1 (Stern and Lisiecki, 2013). If we apply the ΔR envelope approach using data from Stern and Lisiecki (2013) to the mean value of the best 2 constraining radiocarbon ages from the base of DC1 (=H1) in cores HU75009-IV-055PC and HU87033-009 LCF (Fig. 1; Andrews et al., 1994; Jennings et al., 1996), from the Labrador Sea, we obtain a range of ages for the event that spans HS1 (Table 1). The ΔR that matches best the H1 16.8 ka age determined by Hemming (2004) is the lower ΔR from Stern and Lisiecki (2013) (Table 1). On this basis, we chose to use the Lower ΔR to determine where HS1 lies in the 12PC record. Lower ΔR places the base of HS1 (18 ka BP) at 610 cm and its end (14.7 ka BP) at 395cm, right at the end of the diatom-rich mud unit and before the initiation of calving retreat (Fig. 3F and 7). Lower ΔR also puts the calving retreat and the timing of the west Greenland DC event (=BBDC1; Jackson et al., 2017) (Fig. 3) in the Bølling/Allerød interstadial (Fig. 7). The age model calculated with an invariant ΔR=140 years places the lithofacies transition which represents the grounding line retreat from the west Greenland shelf edge at 16.2 cal ka BP, within HS1 (Jennings et al., 2017), but places the end of HS1 after the initiation of GIS calving retreat.

Figure 7 illustrates how key proxy data map into the Heinrich Stadial interval defined by evidence of sluggish AMOC (McManus et al., 2004) using the lower ΔR of Stern and Lisiecki (2013). In the Labrador Sea HS1 is an interval of anomalously warm bottom waters (Marcott et al., 2011) within which H1 occurred (Fig. 7). We would expect this massive freshwater (meltwater and icebergs) outflow from collapse of the Hudson Strait ice stream (Andrews and Tedesco, 1992; Hesse and Khodabakhsh, 2016) to perturb environments in Baffin Bay or initiate a transition to different paleoceanographic conditions.

The transition to lighter $\delta^{18}O$ values and a shift to very high percentages of *S. feylingi* coincide with HS1 (Fig. 7). This signal is also seen in nearby core JR175-VC29 (Fig. 1), from 900 m water depth (Jennings et al., 2017) and is associated in both 12PC and VC29 with deposition of diatom-rich mud with rare IRD; a fine-grained unit of similar age is observed in core GeoTü SL-170 (Jackson et al., 2017) slightly north of VC29. The diatom-rich mud interval has been interpreted by Jennings et al. (2017) to indicate exclusion of coarse sediment delivery to the Disko TMF by retention of a fringing ice shelf after initial grounding line retreat. Overall, brassicasterol abundances are low in HS1. A period of high productivity of benthic forams indicative of nutrient rich Atlantic water at the subsurface (Fig. 5) (indicated on Fig. 7 by red stars and low percentages of the benthic foraminiferal species, *S. feylingi*) coincides with the initial GIS retreat from the shelf edge as indicated in the CT# profile (Jennings et al., 2017). Subsequent interstadial conditions are marked by rising marine productivity, renewed subsurface Atlantic Water influence, and renewed retreat of the GIS, followed by development of consistent seasonal sea ice and release/melting of detrital carbonate bearing ice bergs from ice margins of northern Baffin Bay termed a west Greenland DC event by (Jennings et al., 2017) that has been shown to be correlative to BBDC1 (Simon et al. (2016) by Jackson et al. (2017).

6. Conclusions

1. Based on the data presented we reject the hypothesis that Baffin Bay was covered by a full ice shelf during the LGM. We conclude instead that Baffin Bay was perennially sea-ice covered with nutrient rich, relatively warm Atlantic water present at depth through the LGM. Evidence of marine productivity suggests that there were openings in the sea-ice cover as leads and polynyas to support marine productivity. Concurrently, sediment-laden, glacial-meltwater and turbidity currents were released from the GIS, grounded at the shelf edge, but IRD was rare suggesting the ice front was protected by a fringing ice shelf and/or the perennial sea-ice cover.

2. Reduced ventilation and productivity, coincident with a cold surface lid of meltwater was established in HS1. After Heinrich Event 1, but within the Heinrich stadial, an interval of increased productivity and Atlantic Water is associated with the retreat of the GIS grounding line from the shelf edge.

3. The implication for Heinrich Events and Ocean warming/Ice Shelf hypothesis is that perennial sea-ice cover and/or fringing ice shelves may be sufficient to explain the heat retention and back-pressure proposed to explain the dynamics that produce Heinrich Events.

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8. Figure Captions

Figure 1. Bathymetric map centered on Baffin Bay (BB) showing the location of core HU2008029-12PC (12PC) and other cores mentioned in the text, the distribution of Paleozoic carbonate bedrock, mapped ice margin positions in northern Baffin Bay (Li et al., 2011) and central west Greenland (Ó Cofaigh et al., 2013a) and major ice streams. UIS = Uummannaq ice stream; DIS = Disko ice stream; SSIS = Smith Sound ice stream; LSIS = Lancaster Sound ice stream. Northward flowing West Greenland Current (WGC) is shown as the thin red line and the southward flowing Baffin Current (BC) is shown as a thin blue line. The position of the acoustic profile in Figure 2 is shown as a black line.

HU2008029-016PC=16; HE006-4-2PC=2; JR175-VC29=29; HU77029-017PC=17; HU75009-IV-055PC=55 and HU87033-009 LCF=9. Inset plot shows the salinity and temperature against water depth at from the same location as 2008029-12PC. ASW=Arctic Surface Water; WGIW=West Greenland Intermediate Water; DBBW=Deep Baffin Bay Water.

Figure 2. A. 3.5 kHz sub-bottom profile over the site of 2008029-12PC demonstrationg the acoustically-stratified character of the seabed in the area. B. A zoom in map of the 3.5 kKz sub-bottom profile and the core location shown in Figure 1. The bathymetry is from GEBCO.

Figure 3. Lithological proxies and age control for 2008029-12PC. A is the CT image against depth in the core. Black bars along depth axis show the locations of CT images shown in Figure 4. 'V' denotes locations of vertical burrows. B. IRD counts (>2mm clasts) from CT scan in 2 cm increments. C. CT number, a measure of density derived from the CT image. D. Magnetic Susceptibility measure by multi sensor track (MST). E. Weight percentage of >63 μm sand fraction from foraminiferal samples. F. Two-source provenance of minerals: Northern Baffin Bay (NBB, brown) vs. the local source, central west Greenland (green). F. Depth-Age model in pink ($\Delta R=140\pm30$ yrs) showing 1σ and $2\ \sigma$ uncertainties of the model. Excluded from the model are benthic foraminiferal ages (green distributions) and outliers at 1 meter. Age envelope for other potential ΔR calibrations are shown by blue ($\Delta R=0$); Red, green, orange = lower, mean, and upper ΔR values from Stern and Lisiecki (2013). Climate units are along the age scale.

Figure 4. Examples of lithofacies and bioturbation types from 2008029-12PC CT scans. See Figure 3 for locations of these examples on the CT image of the core.

Figure 5. Biological proxies from 12PC compared with CT# plot to assist with comparison to depth on depth in Figure 3. A. CT#; B. sea ice biomarker, IP_{25}; C. marine productivity biomarker, brassicasterol; D. Benthic (blue) and planktic (red) forams per gram of dry sediment; E. $\delta^{18}O$ of planktic foraminifer, *N. pachyderma*, blue; F. $\delta^{13}C$ of *N. pachyderma*, green.

Figure 6. Benthic foraminiferal species in 12PC. Green represent marine productivity species; Red=Atlantic Water species; Blue = Arctic species; Light Blue; Glacial marine species; Orange=transformed (cooler and slightly lower salinity) Atlantic Water species.

Figure 7. Comparison between Pa/Th record of AMOC (McManus et al., 2004) and the timing of Heinrich Event 1 (H1) to key paleoenvironmental proxies in 12PC. The HS1 interval (yellow box) is defined in the core with use of the Lower ΔR of Stern and Lisiecki (2013) (Fig. 3f). Blue lines show where key events in the core map into the climatic intervals with use of the Lower ΔR of Stern and Lisiecki (2013). A. CT # from 12PC; B. Brassicasterol, 12PC; C. IP_{25}, 12PC; D. *Stainforthia feylingi*, 12PC; E. Oxygen isotope ratios, 12PC; F. Pa/Th ratios (McManus et al., 2004).

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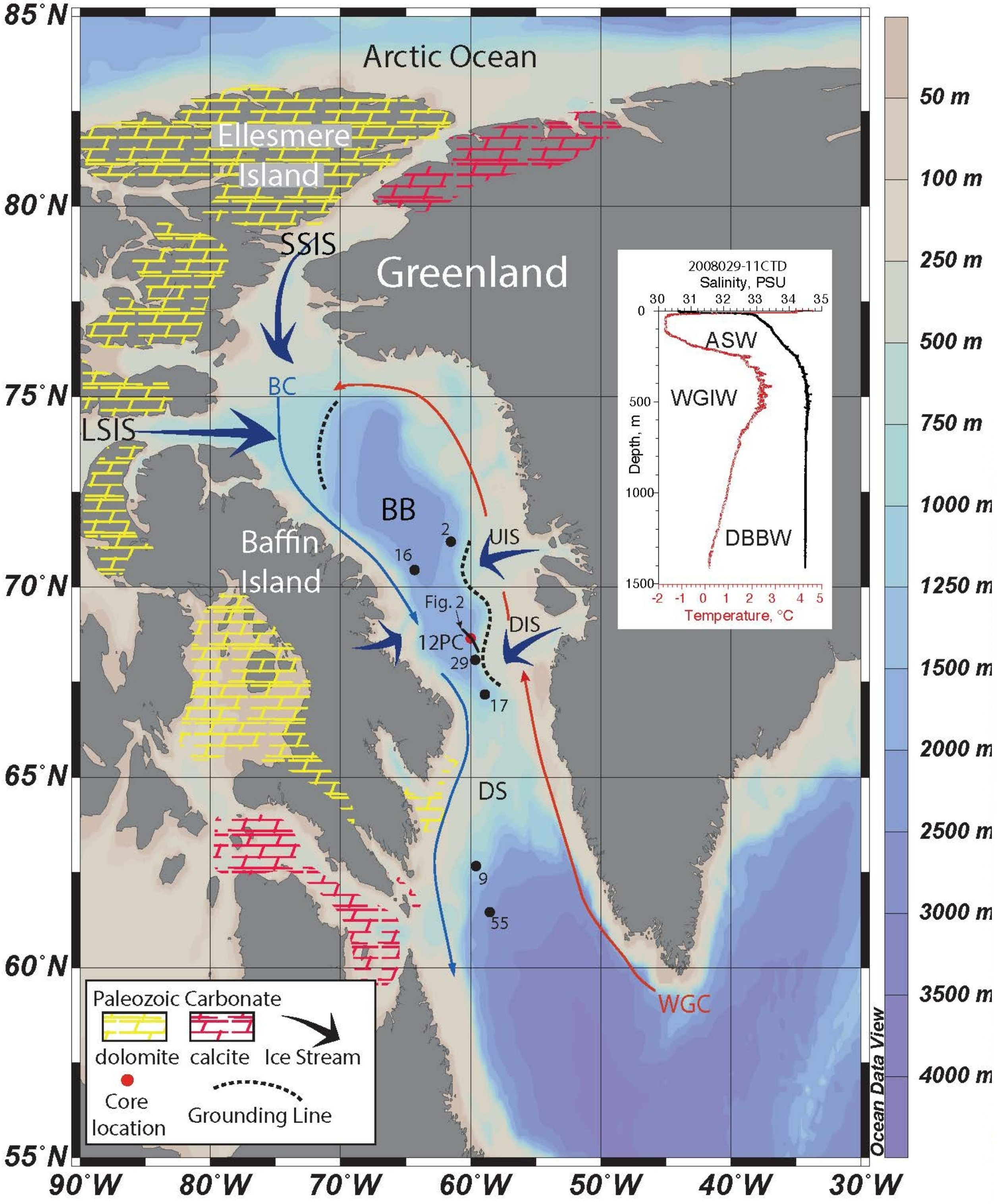
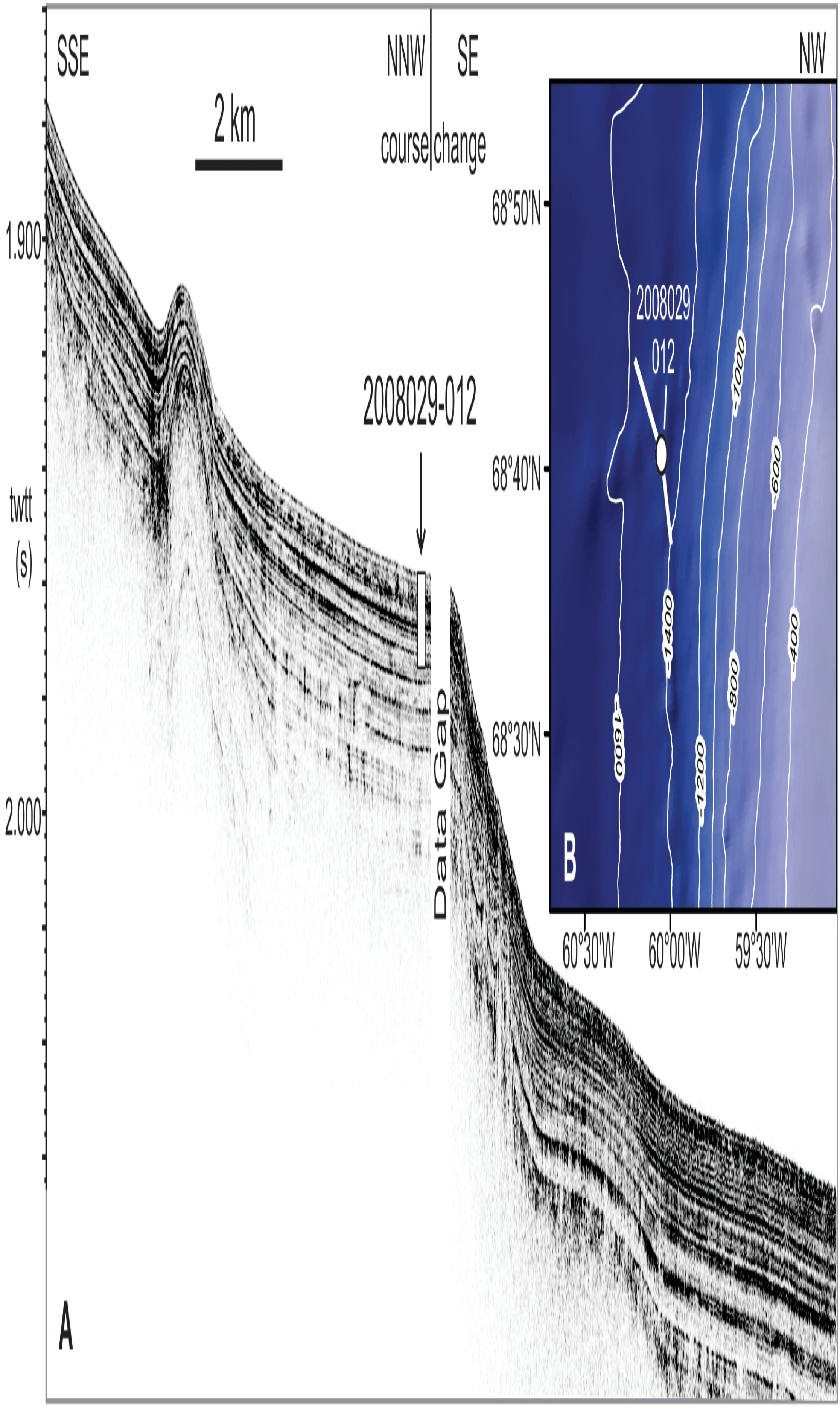
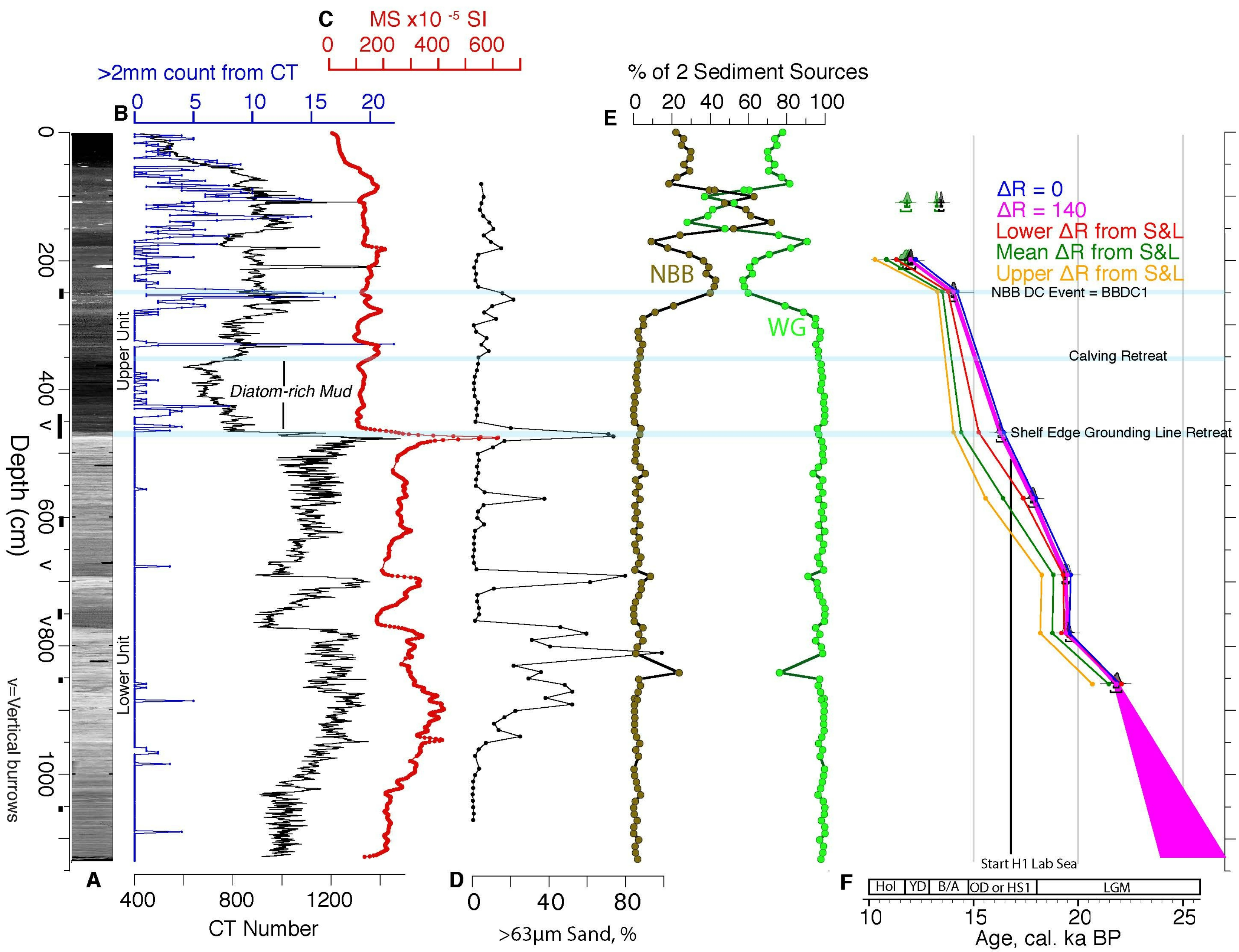


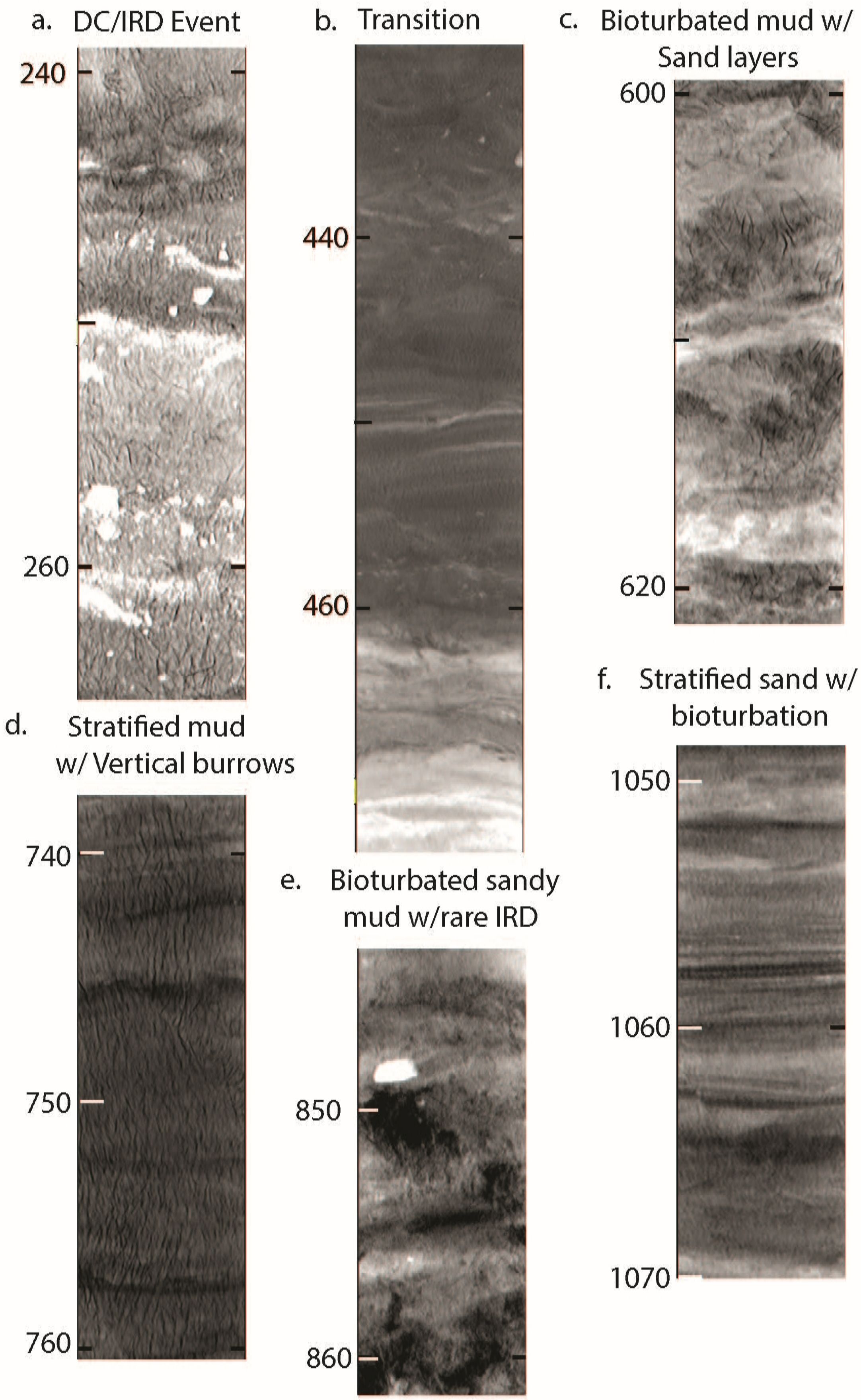
85°N
80°N
75°N
70°N
65°N
60°N
55°N
90°W
80°W
70°W
60°W
50°W
40°W
30°W
Arctic Ocean
Ellesmere Island
Greenland
SSIS
BC
LSIS
BB
Baffin Island
UIS
DIS
Fig. 2
12PC
2
16
29
17
DS
9
55
WGC
2008029-11CTD
Salinity, PSU
30 31 32 33 34 35
0
500
1000
1500
Depth, m
ASW
WGIW
DBBW
-2 -1 0 1 2 3 4 5
Temperature, °C
Paleozoic Carbonate
dolomite
calcite
Ice Stream
Core location
Grounding Line
50 m
100 m
250 m
500 m
750 m
1000 m
1250 m
1500 m
2000 m
2500 m
3000 m
3500 m
4000 m
Ocean Data View

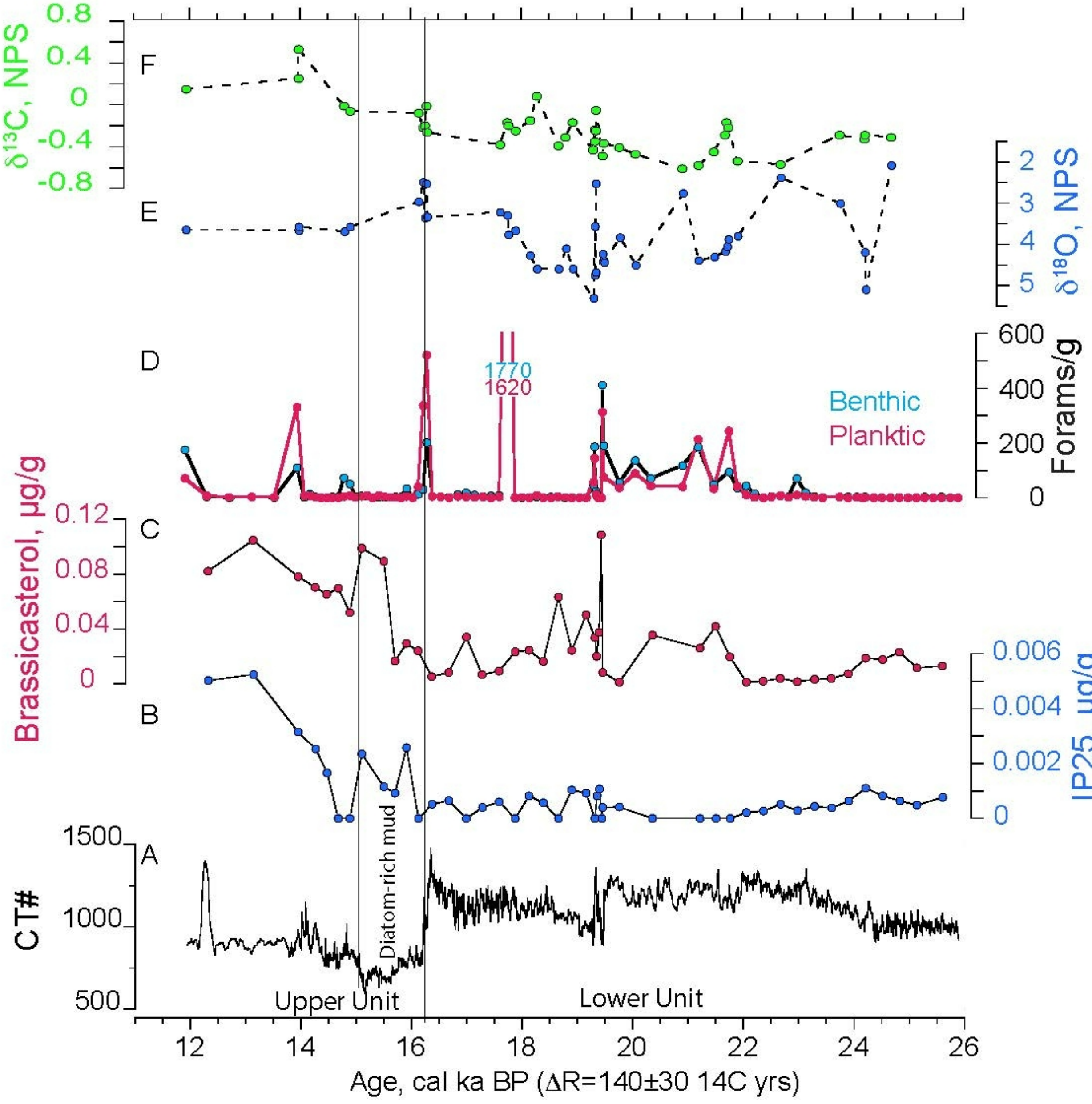


SSE
NNW
SE
NW
2 km
course
change
1.900
2.000
twtt
(s)
2008029-012
Data Gap
A
68°50'N
68°40'N
68°30'N
2008029
012
-1000
-600
-1400
-400
-800
-1600
-1200
B
60°30'W
60°00'W
59°30'W



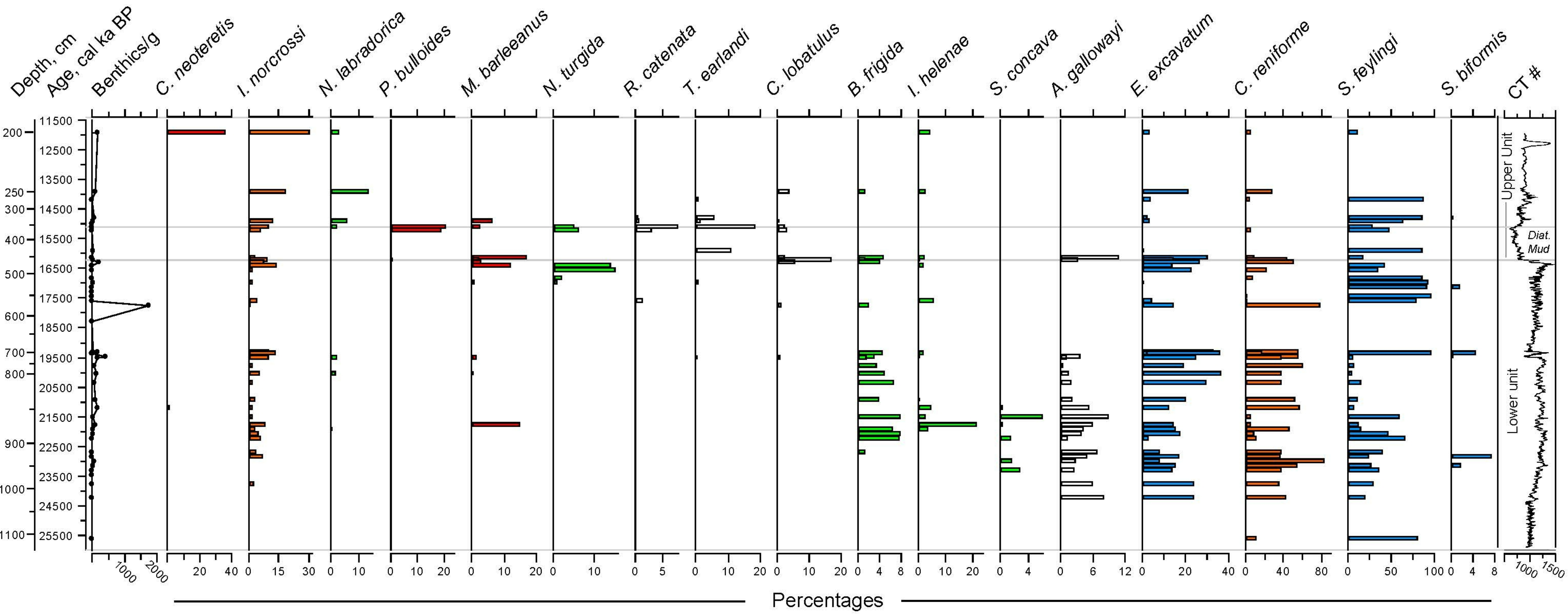
C
MS x10 -5 SI
0 200 400 600
>2mm count from CT
B
0 5 10 15 20
% of 2 Sediment Sources
0 20 40 60 80 100
E
ΔR = 0
ΔR = 140
Lower ΔR from S&L
Mean ΔR from S&L
Upper ΔR from S&L
NBB
WG
NBB DC Event = BBDC1
Calving Retreat
Diatom-rich Mud
Shelf Edge Grounding Line Retreat
Upper Unit
Lower Unit
Depth (cm)
0
200
400
600
800
1000
v=Vertical burrows
Start H1 Lab Sea
A
400 800 1200
CT Number
D
0 40 80
>63μm Sand, %
F
Hol YD B/A OD or HS1 LGM
10 15 20 25
Age, cal. ka BP

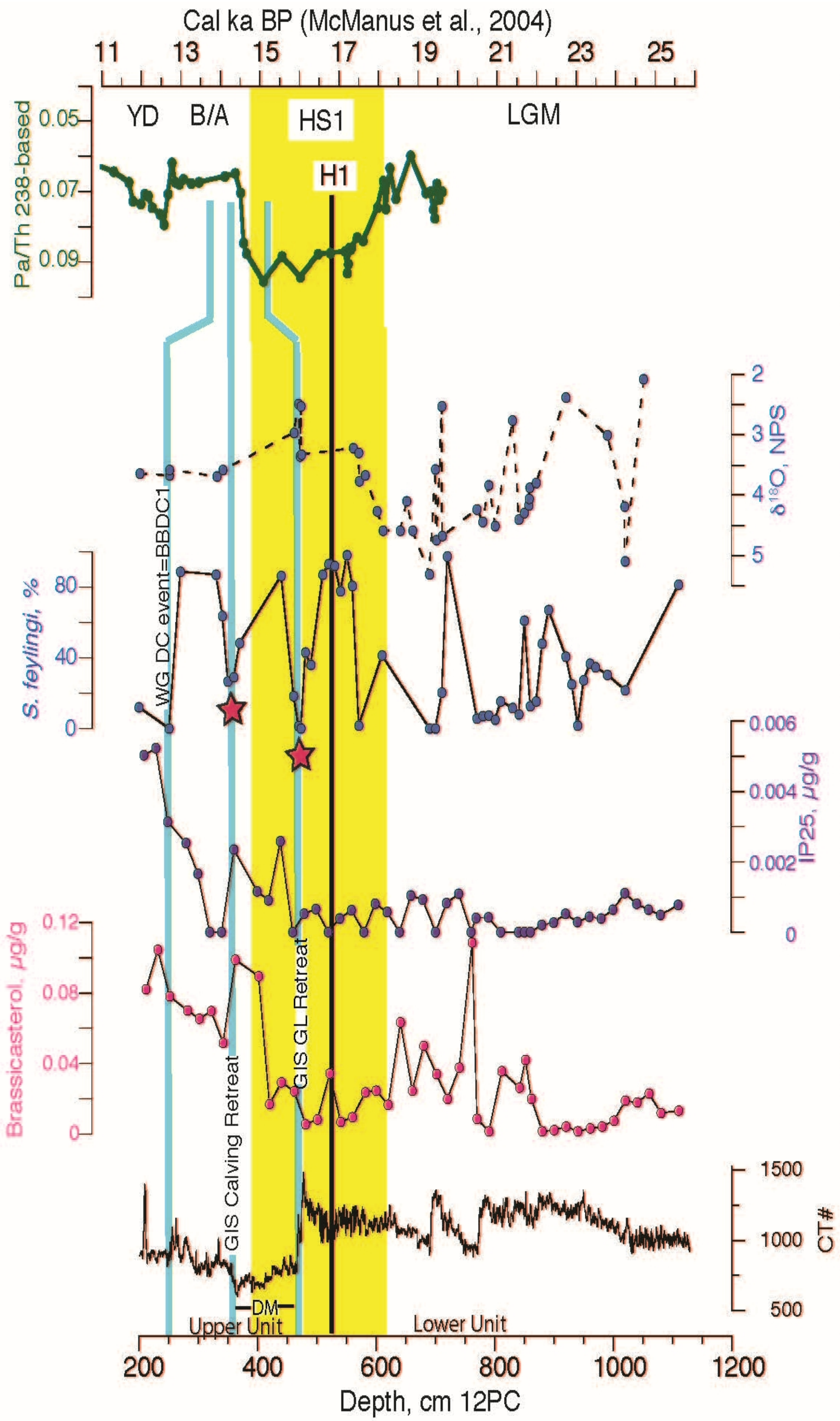

a. DC/IRD Event
240
260
b. Transition
440
460
c. Bioturbated mud w/ Sand layers
600
620
d. Stratified mud w/ Vertical burrows
740
750
760
e. Bioturbated sandy mud w/rare IRD
850
860
f. Stratified sand w/ bioturbation
1050
1060
1070



δ13C, NPS
0.8
0.4
0
-0.4
-0.8
F
E
δ18O, NPS
2
3
4
5
D
1770
1620
600
400
200
0
Forams/g
Benthic
Planktic
Brassicasterol, μg/g
0.12
0.08
0.04
0
C
B
0.006
0.004
0.002
0
IP25, μg/g
CT#
1500
1000
500
A
Diatom-rich mud
Upper Unit
Lower Unit
12
14
16
18
20
22
24
26
Age, cal ka BP (ΔR=140±30 14C yrs)

HU2008029-12PC Benthic Foraminifera





Cal ka BP (McManus et al., 2004)
11
13
15
17
19
21
23
25
YD
B/A
HS1
H1
LGM
Pa/Th 238-based
0.05
0.07
0.09
2
3
4
5
δ18O, NPS
WG DC event=BBDC1
S. feylingi, %
80
40
0
0.006
0.004
0.002
0
IP25, µg/g
Brassicasterol, µg/g
0.12
0.08
0.04
0
GIS Calving Retreat
GIS GL Retreat
1500
1000
500
CT#
DM
Upper Unit
Lower Unit
200
400
600
800
1000
1200
Depth, cm 12PC

Table 1. Radiocarbon ages and their calibrations with varying ΔR.

HU2008029-12PC

Date	Depth	14C	error	ΔR	Date (14C age
CURL14065	201.5	10760	35	0	CURL14065 wi
CURL14065	201.5	10760	35	140	CURL14065 wi
CURL14065	201.5	10760	35	470	CURL14065 wi
CURL14065	201.5	10760	35	900	CURL14065 wi
CURL14065	201.5	10760	35	1340	CURL14065 wi
AA90386	251.5	12666	61	0	AA90386 with
AA90386	251.5	12666	61	140	AA90386 with
AA90386	251.5	12666	61	380	AA90386 with
AA90386	251.5	12666	61	630	AA90386 with
AA90386	251.5	12666	61	900	AA90386 with
CURL16671	469.5	14030	40	0	CURL16671 wi
CURL16671	469.5	14030	40	140	CURL16671 wi
CURL16671	469.5	14030	40	850	CURL16671 wi
CURL16671	469.5	14030	40	1260	CURL16671 wi
CURL16671	469.5	14030	40	1500	CURL16671 wi
CURL18165	571.5	15150	60	0	CURL18165 wi
CURL18165	571.5	15150	60	140	CURL18165 wi
CURL18165	571.5	15150	60	500	CURL18165 wi
CURL18165	571.5	15150	60	1150	CURL18165 wi
CURL18165	571.5	15150	60	1750	CURL18165 wi
CURL14067	690.5	16660	45	0	CURL14067 wi
CURL14067	690.5	16660	45	140	CURL14067 wi
CURL14067	690.5	16660	45	290	CURL14067 wi
CURL14067	690.5	16660	45	720	CURL14067 wi
CURL14067	690.5	16660	45	1250	CURL14067 wi
CURL16663	780.5	16600	50	0	CURL16663 wi
CURL16663	780.5	16600	50	140	CURL16663 wi
CURL16663	780.5	16600	50	290	CURL16663 wi
CURL16663	780.5	16600	50	720	CURL16663 wi
CURL16663	780.5	16600	50	1250	CURL16663 wi
CURL18628	859.5	18540	80	0	CURL18628 wi
CURL18628	859.5	18540	80	140	CURL18628 wi
CURL18628	859.5	18540	80	-50	CURL18628 wi
CURL18628	859.5	18540	80	420	CURL18628 wi
CURL18628	859.5	18540	80	1010	CURL18628 wi

Base of H1 ages from the Labrador Sea

HU87033-009 LCF, 500-501 cm; Jennings et al., 1996

AA-9364		14980	90	0	AA-9364 with
AA-9364		14980	90	140	AA-9364 with
AA-9364		14980	90	500	AA-9364 with

AA-9364	14980	90	1150	AA-9364 with
AA-9364	14980	90	1750	AA-9364 with
HU75009-IV-055PC, 115-117 cm; Kaufman and Williams, 1992				
AA-5999	15010	105	0	AA-5999 with
AA-5999	15010	105	140	AA-5999 with
AA-5999	15010	105	500	AA-5999 with
AA-5999	15010	105	1150	AA-5999 with
AA-5999	15010	105	1750	AA-5999 with

				Calibrated	
1sigma from	1sigma to	2sigma from	2sigma to	mean	error
12306	12075	12430	12028	12215	109
12026	11865	12100	11755	11937	86
11317	11210	11432	11161	11282	70
10868	10706	10972	10667	10805	79
10291	10196	10373	10176	10260	51
14279	14051	14542	13964	14208	142
14095	13926	14165	13840	14007	83
13845	13665	13930	13555	13748	91
13552	13392	13657	13332	13484	81
13312	13180	13375	13114	13246	66
16511	16309	16632	16233	16423	102
16311	16144	16424	16045	16232	90
15282	15148	15375	15076	15221	73
14507	14193	14701	14136	14398	155
14086	13947	14143	13873	14011	68
18035	17854	18130	17740	17941	94
17887	17687	17973	17598	17785	97
17465	17236	17549	17125	17345	110
16491	16261	16631	16174	16390	117
15680	15408	15776	15297	15541	128
19698	19528	19832	19467	19631	91
19550	19372	19609	19260	19449	88
19368	19168	19466	19070	19268	99
18850	18739	18905	18674	18791	57
18328	18149	18395	18039	18226	90
19634	19467	19749	19360	19553	91
19480	19283	19560	19203	19380	93
19257	19061	19385	18986	19177	99
18802	18680	18856	18605	18735	62
18267	18071	18337	17973	18160	94
22113	21850	22271	21751	21993	131
21916	21670	22057	21537	21795	127
22175	21905	22301	21820	22051	128
21594	21299	21746	21137	21442	149
20772	20537	20913	20434	20662	119

17878	17633	17984	17515	17752	120
17725	17460	17883	17333	17599	136
17281	16963	17437	16789	17115	161

16288	16021	16449	15861	16155	140
15443	15143	15656	15041	15318	155
17916	17650	18037	17513	17780	133
17785	17490	17925	17345	17634	147
17345	17000	17495	16800	17156	174
16345	16032	16538	15875	16200	163
15528	15180	15733	15060	15367	174

median
12207
11943
11270
10796
10250
14180
14009
13751
13478
13246
16416
16230
15218
14378
14014
17943
17786
17349
16381
15544
19621
19455
19264
18793
18234
19551
19382
19173
18738
18163
21985
21798
22048
21444
20657
17753
17597
17115

16154
15302
17781
17633
17159
16195
15356