"Heinrich events" (& sediments): A history of terminology and recommendations for future usage

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Abstract

We document the history of terms used to describe Heinrich (H-) layers and events and which mark major glaciological iceberg discharge events in the North Atlantic. We argue that the usage “Heinrich layer,” “Heinrich zone”, or “Heinrich event” should be restricted to only those sediments that can be ascribed to an origin from the Hudson Strait Ice Stream and the Laurentide Ice Sheet. We also argue that the commonplace understanding of these events---as dominated by massive iceberg discharges ---fails to include the earlier well-documented evidence that these events were also massive meltwater events linked to deposition along the North Atlantic Mid-Ocean Channel (NAMOC) in the Labrador Sea. We make five recommendations for future usage of “Heinrich events,” which include: restricting the usage to those events that can be mineralogically/geochemically linked to Hudson Strait; abandoning the term “Heinrich stadial”; and promote local terminology for “ice rafted events” that may be correlated, or not, with Hudson Strait Heinrich events based on calibrated radiocarbon dates or other appropriate chronological markers.

Introduction

In a recent paper (Andrews et al., 2017) comparing sediment records from north (PS2644) and south of the Denmark Strait (MD99-2260) (Fig. 1A and B) we stated, in terms of discrete ice rafted debris (IRD) events “*….we suggest that this term (H-events) be restricted to sediments that have a diagnostic mineral and geochemical signature linked to that source (i.e. Hudson Strait/Hudson Bay) (Andrews and Tedesco, 1992; Farmer et. al., 2003; Hemming, 2004). Despite our* *own prior usage we now argue that the IRD events recorded in MD99-2260 and PS2644 should be given their own designation (e.g. Kangerlussuaq IRD event 1 or PS2644 IRD event 2) and that temporal correlation with H-events may or may not be required."* This paper outlines the rationale behind this quotation.

The Hudson Strait Heinrich (H)-events originated from the major ice stream draining the Laurentide Ice Sheet (Alley and MacAyeal, 1994; Andrews and MacLean, 2003; Stokes et al., 2016), but it is important to note that this ice stream differs from virtually all others, at least in the Northern Hemisphere. It is not, for example, associated with the deposition of massive trough mouth fans (TMF) at the foot of the slope (O'Cofaigh et al., 2003; Vorren and Labert, 1997), but rather with a highly gullied slope that leads to the North Atlantic Mid-Ocean Channel (NAMOC) (Chough et al., 1987; Hesse et al., 1996; Praeg et al., 1986) (Fig. 1C). This implies that the Hudson Strait Detrital Carbonate events may not have equivalent counter-parts seaward of other Northern Hemisphere ice streams, and that proximal sediment processes might be very different. We would also affirm the statement made by Marshall and Koutnik (2006, p. 10 of 13) "*The difference between Heinrich events and D-O cycles has been broadly misunderstood by the paleoclimate community"*. Our "Opinion Paper" is in no-way intended as an in depth review of all facets of H-events (Hemming, 2004), and thus, the purpose of this note is to:

1) discuss the history of the usage of the term H- layer/events,
2) emphasize the complexity of these ice stream collapse sediments,
3) compare and contrast with the terminology and usage of discrete volcanic tephra plumes, and
4) suggest the use of the term "Heinrich" be more rigorously restricted.

Definition and usage of Heinrich layers/events: history

On Figure 1A, B, and C we illustrate the location of cores that have been associated with or correlated with H-events, whereas on Figure 2 we show the large range in the number of citations linked to the key papers. In Supplemental Table 1 we document the papers that preceded and followed Heinrich's classic paper (Heinrich, 1988), the terminology and proxy/proxies employed, and the areas affected (Fig. 1A, B, C).

The role of icebergs and sea ice in contributing sediments to the ocean floor has a long history (e.g. Tarr, 1897; Trask, 1932) but the recognition of IRD in North Atlantic sediments may have been first documented by Bramlette and Bradley (1940), followed by Connolly and Ewing (1965) (see Andrews and Matsch (1983) for literature review and bibliography). Iceberg rafting gained paleoclimate prominence when Ruddiman (1977) described a series of sand-rich units in the eastern North Atlantic which defined a broad area between 46 to 50°N and 20 and 30°W (Fig. 1A, B), frequently termed the "ice-rafting belt" or the "Ruddiman IRD belt". Andrews (1998) noted that research in Baffin Bay (Aksu, 1985; Aksu and Mudie, 1985) and the Labrador Sea (Chough, 1978; Hesse et al., 1987) described relatively thick facies of both coarse iceberg rafted sand grains and clasts, and fine-grained water transported facies. These units were generally buff colored and had high % of carbonate (both calcite and dolomite). But these papers received little notice both prior to and post Heinrich's classic paper (1988) (Fig. 2), perhaps because subsequent H events related studies focused mainly on: i) the open North Atlantic latitudes within and north/south of the Ruddiman IRD belt (Fig. 1B, Suppl. Table 1), and ii) on retrieving high-resolution sequences from the sediment drifts formed by the Western Boundary Undercurrent (e.g. Orphan Knoll, Blake Bahama Outer Ridge) and from the deep overflows from the Nordic Seas (e.g. Gardar Drift, Feni Drift).

Heinrich (1988) described a series of cores from the Dreizack seamount (47°23’N, 19° 40’W) (Fig. 1A, Suppl. Table 1) and on his Figure 3 (core Me69-17) he documented a series of discrete IRD units (seven total) plus Ash Zone I (~Vedde, 12.2 cal ka BP) and what is now called North Atlantic Ash Zone (NAAZ) II (~55 cal ka BP). The grain-size used for the IRD designation was 180 to 3000 µm, and it is worth noting that there has been no consensus on what sand-size fraction constitutes “ice-rafted debris” (Andrews, 2000). Heinrich (1988) referred to the discrete sand-rich units as “IRD layers” (p. 147) or “dropstone layers (p.149)” and recognized 5 such units < 54 cal ka BP. This work was followed up by Huon et al. (1991) in a far-sighted paper dealing with the radiometric ages of the sand fractions in the Dreizack cores.

In 1992 Broecker et al. (1992) recognized the implications and importance of Heinrich’s data and in this paper referred to “Heinrich events” and called the sand-rich (> 150 µm) layers “Heinrich zones” and noted that they represent a distinct switch from foraminiferal rich deep-sea sediments to those dominated by coarse sand grains. They also noted that “*….Heinrich layers 1, 2, 4 and 5 (but not 3) contain detrital limestone and dollomite not present in sediment between layers…..”* (Fig. 1A, Suppl. Table 1).

In 1992 the link between “Heinrich zones/layers” and the Laurentide Ice Sheet, in particular the Hudson Strait ice stream, was confirmed by the work of Bond et al. (1992), and by Andrews and Tedesco (1992) who recognized (following Hesse et al., 1990), that the thick Detrital Carbonate (DC)-rich facies in the Labrador Sea were the proximal record of the distal IRD units described by Heinrich (1988) and Broecker et al. (1992). Andrews and Tedesco (1992) noted *“Our evidence indicates that Heinrich events 1 and 2 are associated with the dynamics of the Hudson Strait* *ice stream and denote considerable glaciological instability."* Bond et al. (1992) described Heinrich layers as "*….rich in ice-rafted debris and unusually poor in foraminifera."* In Bond et al. (1992, p. 248, their Table 3) the *"thickness of detrital carbonate-rich units within Heinrich deposits (H)"* are listed with a range between 61.5°N and 41.0°N and 58.65° to 16.83°W; the DC-rich zones (Fig. 1A) thin rapidly downstream (Dowdeswell et al., 1995).

This was followed in 1993 by a highly influential paper that argued that H-events could be tied into the newly documented Greenland Ice Sheet record and the link to atmospheric processes was explicit in the use of "climate" in the paper's title (Bond et al., 1993). This paper is the most cited of the Heinrich literature (Fig. 2) and represented a fundamental shift from the previous sediment/source foci to atmospheric and ocean climate links. In particular the paper placed the occurrence of H-events in the context of the rapid isotopic oscillations (Dansgaard-Oeschger (D-O) events) documented from the Greenland ice cores (Dansgaard et al., 1993). It is worth noting that D-O events are difficult to detect in H-event dominated Labrador Sea cores (Andrews and Barber, 2002), but the reverse is true off NE Greenland (core PS2644) where D-O events constitute the dominant signal (van Kreveld et al., 2000; Voelker, 1999, 2002) versus a weak possible H-like IRD event (Andrews et al., 2017).

Grousset et al. (1993) (Fig. 1A, Suppl. Table 1) defined "Heinrich layers" on the basis of volume magnetic susceptibility, color, lithic grains > 150 µm, and the presence of the polar planktonic foraminifera species *Neoglobquadrina pachyderma*. Their sites lay within the Ruddiman IRD belt and their results (their Fig. 6) mapped out an eastward thinning of the H-layers (see also Dowdeswell et al., 1995). Revel et al. (1996) then utilized Sr and Nd isotopic ratios on lithic grains to further investigate the source(s) of the North Atlantic H-layers (or events). This was a precursor to several papers dealing with the provenance of the IRD units (e.g. Farmer et al., 2003; Hemming, 2004; Hemming et al., 1998; Snoeckx et al., 1999).

The importance of meltwater in the formation and creation of the proximal H-layers (Hesse, 2016; Hesse and Khodabakhsh, 2016) has, in our opinion, not been given the attention it deserves, and the literature has rather focused on the ice-rafting component. It is also important to note the connection between Hudson Strait and the massive NAMOC, that was the conduit for extensive turbidites (Chough, 1978; Chough et al., 1987), coeval with the more cited IRD sand units.

Thus the basic literature on the recognition of what Broecker et al. (1992) and Bond et al. (1992) termed H-zones, layers and events, had been published by 1992. The descriptive terms “zone, layer, and event” had been used interchangeably and the term “Heinrich” was already linked to these sediment-based descriptive terms.

The early literature clearly focused on the North Atlantic (Fig. 1A) but the term “Heinrich” expanded in the mid- to late 1990’s to include IRD sediments originating from the eastern margin of the Greenland Ice Sheet (Andrews et al., 1998; Elliot et al., 1998; Stein et al., 1996; Voelker et al., 1998) or from the western margin of the Scandinavian Ice Sheet (Rasmussen et al., 1996; Dokken and Jansen, 1999) (Fig. 1B). This was also the general period during which the D-O events were initially recognized and eventually brought into the H-event scenario through the concept of the “Bond Cycle” (Bond et al., 1997); earlier Bond and Lotti (1995) argued that they could detect evidence (core VM28-14 south of the Denmark Strait, Fig. 1B, Suppl. Table 1) that the Iceland Ice Sheet responded as a precursor to the Laurentide H-events. Discrete DC-events have also been described from cores across the Arctic Basin (Fig. 1B) (Phillips and Grantz, 2001) and they too have been titled

"Heinrich events" (Darby and Zimmerman, 2008; Stokes et al., 2005) and linked to ice export events from the ice streams that occupied the Canadian Arctic Channels (Margold et al., 2015) (Fig. 1B).

The term "Heinrich stadial" may have been applied for the first time by Vautravers and Shackleton (2006) but was then used by Barker et al. (2009), Sanchez-Goñi and Harrison (2010) and Stanford et al (2011); this usage has increased over the last several years. It may have been introduced to simply provide a "name" to the stadial interval associated with a H- event in regions (rather than using established geologic-climate terms such as Late Wisconsinan or Late Weischelian) where the sea-surface temperature signal (cooling) exceeds the IRD signal in duration and often magnitude, such as the southern Portuguese margin (Vautravers and Shackleton, 2006; Sanchez-Goñi and Harrison, 2010). Stanford et al. (2011) on-the-other-hand used it to name the stadial interval between the LGM and the Boelling/Allerød interstadial (i.e., the interval between Greenland interstadial 2 and 1; Rasmussen et al., 2014). However, we note that the term "stadial" is a geologic-climate term that traditionally defined an interval of glacial advance (Flint, 1971, p. 372) and there has been no attempt to directly link the Greenland Ice Sheet isotopic identification of stadials and interstadials with the Greenland glacial record. For example, what is the precise link between the Greenland Flakkerhuk stadial (Funder and Hansen, 1996; Funder et al., 2004) and Greenland interstadial 2? Unfortunately, the literature now has examples of "Heinrich stadial (H-1)" being used both for the event (< 1 ky in duration) (Li et al., 2017; Butzin et al., 2017), and for the stadial period between the LGM and the Boelling/Allerød (Barker et al., 2009; Stanford et al., 2011). This interval is also being called the "mystery interval" (Denton et al., 2006) because of the contradictory paleoclimate evidence. Thus over time, the term "Heinrich event" evolved from its original definition as lithostratigraphic unit describing an ice-sheet surge/collapse event, to a chronostratigraphic term of unclear and confused duration.

Summary: After Heinrich's first description in 1988 of a series of IRD-rich sediment units and the subsequent identification of "Heinrich zones/layers" or "events," the use has spread, even escalated, to include cores and areas well removed from any influence of deposition sourced from Hudson Strait (Fig. 1B, C), which we argue is fundamental in the recognition and usage of the term. It is amazing that the mineral signature (e.g. dolomite) and radiogenic signatures of the Hudson Strait H-events is retained along a ~3500 km transect from Hudson Strait as far east as the Bara Fan on the Celtic margin (Haapaniemi et al., 2010; Fig. 1A, Suppl. Table 1). The high rates of accumulation of ice rafted sediments along the Labrador Sea indicates that significant melting occurred along the transport path. Thus given our knowledge of the processes that cause the destruction of icebergs (mainly wave erosion; Bigg, 2016; Clarke and Prairie, 2001; Venkatesh et al., 1985; Venkatesh et al., 1994) the retention of sediment over such distances implies either i) very large icebergs, and/or ii) sediment dispersed (evenly?) throughout the iceberg (Dowdeswell et al., 1995). The latter may imply the freezing in of sediment (Alley et al., 1998; Lawson et al., 1998; Andrews and MacLean, 2003).

All the major H-events can be traced back to the Laurentide Ice Sheet and Hudson Strait, including H-0 (Pearce et al., 2015; Stoner et al., 1996), although there has been considerable discussion about H-3 (Bigg et al., 2010; Kirby and Andrews, 1999; Rashid et al., 2003). Rashid et al (2003) argued that this event, not always present in the northernmost Labrador Sea records, represented an ice flow across Hudson Strait, similar to the ~10.8 cal ka BP Gold Cover event (Kaufman et al., 1993). This and subsequent events associated with the final stages in the collapse of the LIS are recorded as a complex of DC and IRD events on the Labrador Shelf (Barber et al., 1999; Jennings et al., 2015) (Fig. 3A). Also, H-1 could be seen as a special case within the H events of the last glacial period, because it represents a deglacial event during the early phase of Termination 1 (e.g. Barker et al., 2009). Within the Pleistocene, H-1 is, however, not unique because deglacial ice-rafting events with a detrital carbonate signal, i.e. a Hudson Strait event, also occurred during Termination 2 (H-11, e. g. Lototskaya and Ganssen, 1999; H-7 in van Kreveld et al., 1996; Stoner et al., 1996) and older Terminations back to Marine Isotope Stage 16 (Hodell et al., 2008; Stein et al., 2009; Channell et al., 2012).

The duration of H-events, while difficult to accurately determine, are probably < 1 ky (Veiga-Pires and Hillarie-Marcel, 1999; Hemming, 2004). We have compiled published ^{14}C dates from the base and top of H-1 and H-2 (see Andrews et al., 1999; Stolk et al., 1994) from cores near the outlet of the Hudson Strait ice stream as representing the "type area"(Andrews et al., 1994; Rashid and Piper, 2007; Rashid et al., 2011). Sedimentation rates were high and the thicknesses of these H-layers are in the range of 30-60 cm thus negating any problems with bioturbation. The dates were calibrated using a Δ R of 0 ± 100 y using the "^{14}C date combination" option in Oxcal (Bronk Ramsey, 2008); all the dates were on *Neoglobquadrina pachyderma*. On Figure 4 we show the probability density plots and the estimate "best estimates" for H-2 as 24856 ± 202 to 24127 ± 149 cal y BP, a duration of ≤ 730 y, and H-1 from 17678 ± 142 to 16744 ± 200 cal y BP, or a duration of ≤ 1085 y. These estimates are based on the assumption that ΔR does not change before and after these two H-events, and they are consistent with earlier evaluations of 800 and 600 y (Francois and Bacon, 1994) based on ^{230}Th excess.

Given the temporal errors across the North Atlantic in the ocean reservoir correction (e.g. Stern and Lisieki, 2013; Butzin et al., 2017), and in the Greenland Ice Sheet's isotopic record (Rasmussen et al., 2014), it is difficult if not impossible to argue where H-events lie exactly within the D-O framework (Fig. 3). Indeed, Rasmussen et al. (2014) did not designate the temporal positions of H-events; and (p. 26) they state "*We recommend that the term "Heinrich event" or more accurately "Heinrich layer" is used to designate only the period where IRD is found in a particular record.*" For correlations to be made it would appear important for the periodicities of the two signals to have some common value(s). Long and Stoy (2013) used the Lomb-Scargle algorithm on the GISP2 and NGRIP isotope data for the 30 to 60 cal ka BP interval and noted several significant periodicities but none easily adapted to the ~7 cal ky H- beat. In our analysis we converted the NGRIP data into an equi-spaced 250 yr series (between 10 and 60 cal ka BP) and used spectral methods from the UCLA Toolkit (Ghil et a., 2002) to detrend the series (Fig. 3B) and to examine the residuals for statistically significant periodicities and to then reconstruct the time-series (Fig. 3C & D). Note how the location of the H-events varies within the range of the D-O oscillations. We should add, however, that Ditlevsen et. Al. (2007) concluded that the D-O cycle is "…probably noise..". The "heart-beat" of H-events (Fig. 3A) has been estimated at a pacing of ~7 ky (Hemming, 2004) or 7.2± 2.4 ky (Sarnthein et al., 2001), and this was reinforced when Rashid et al. (2003b) reported a H-event between 5 and 6 (H-5a), which reduced the original timing between H-5 and H-6 to ~7 ky. This timing, however, relies heavily on the GISP2 chronology (the tuning target for many earlier studies), which in the interval > 40 ky becomes significantly younger than the GICC05 chronology of NGRIP (Svensson et al., 2008). Regardless of the specific forcing(s) the relatively steady pacing between the H-events argues for a “binge/purge” process (Alley and MacAyeal, 1994; MacAyeal, 1993). Many of the issues associated with the interpretation of H-events are linked to the efforts to partner H- and D-O events (Fig. 3A, B and C), and we re-emphasise our earlier quotation from Marshall and Koutnik (2006) suggesting that “tuning” H-events to D-O may pose problems. Indeed, as we noted earlier, the D-O signal is dominant in the western Nordic Seas (in both the near-surface isotopic record and the sediment archive; e.g. van Kreveld et al., 2000; Andrews et al., 2017), but hardly detectable in the Labrador Sea. Tuning records means that potentially critical leads and lags between the atmosphere, ocean, and cryosphere are unable to be determined (Blaauw, 2012)---for example, the Baffin Bay DC events lag the Hudson Strait DC (H-) events (Jennings et al., 2017; Simon et al., 2014), and the spatial and temporal variations in the ocean reservoir correction also make it difficult to determine if IRD- events are synchronous or not (Dowdeswell et al., 1999). Thus the use of “H-stadial” is firmly tied (incorrectly in our view) to the inclusion of the D-O atmospheric signal into the H-event glaciological signal (Fig. 3B & C)---in this interval the amplitude of D-O events is severely dampened.

In retrospect, it is now obvious that the series of papers in 1992 on “Heinrich events” marked a major change in marine paleoclimate focus away from insolation-driven time-scales (Hays et al., 1976) to millennial-scale abrupt events, as typified earlier in ice cores. This has placed an emphasis on rapid changes in the Earth’s climate system, perhaps very appropriate given current concerns and evidence for “Climate Change”.

Discussion

We argue that the confusion/misuse in usage of H layers/events/stadials arose from the following:

1) It is difficult to correctly calibrate marine ^{14}C ages of North Atlantic deep-sea sediments because of the large reservoir-age changes around these massive IRD and meltwater events (e.g., Sarnthein, 2011; Sarnthein et al., 2001; Waelbroeck et al., 2001), so many authors use(d) the approach of correlating surface-water records with one of the Greenland ice core $\delta^{18}O$ records to establish a chronology for their millennial-scale climate oscillations (e.g., Bond et al., 1999; Shackleton et al., 2000; van Kreveld et al., 2000; Voelker et al., 1998). This is problematic because "tuning" the two records (H- and D-O events, Fig.3) argues for a "cause and effect" and ignores the possibility of leads and lags between the records.

2) The Greenland ice core $\delta^{18}O$ records do not contain a signal that can be related to the ice-rafting event *per se* – the very reason why the INTIMATE event stratigraphy never refers to H events in their figures or list of events (Lowe et al., 2008; Rasmussen et al., 2014). However, new types of analyses in the ice cores, such as ^{17}O excess (Guillevic et al., 2014), might help in the future to identify the imprints of H events in the ice core records.

3) The impression of millennial-scale climate variability, in particular the amount and duration of IRD sedimentation and of meltwater presence, greatly varies between the different North Atlantic regions (e.g., sites within the IRD belt vs. north/south of the belt) and the Nordic Seas. Some paleoclimate records, especially along the eastern North Atlantic margin, show IRD precursor events (linked to the European ice sheets; e.g., Bond and Lotti, 1995; Grousset et al., 2000; Hall et al., 2006, but see Andrews, 2008; Haapaniemi et al., 2010). Other papers even recorded a three phased climate evolution during a H "stadial" interval (e.g., Naughton et al., 2009; Stanford et al., 2011). Furthermore, a climatic response to the H events can be detected in world-wide paleoclimate records (e.g., Voelker, 2002). Thus there is no consensus on the correct

terminology to be used to refer to these world-wide events. As already pointed out above, it is unfortunate that the term “Heinrich stadial” now commonly refers to a long interval correlative with the youngest interval of Greenland Stadial 2 (Rousseau et al., 2006), i.e. Greenland Stadial 2a (Lowe et al., 2008; Voelker et al., 2009) that has a much longer duration (Lowe et al. 2008 = 2200 y; Rasmussen et al., 2014 =2788 y) than estimated for H 1 in the near source sediment cores (≤ 1085 y; Fig. 4).

The issue of whether other ice sheets, or other sectors of the Laurentide Ice Sheet, were involved in a synchronous manner with the Hudson Strait H events is implicit in the usage of “Heinrich” as a precursor identifier. However, arguments for the global synchronicity of IRD events are difficult to develop, and arguments for asynchronous glaciological responses (Dowdeswell et al., 1999; Dyke et al., 2014; Jackson et al., 2017; Stokes et al., 2014) have been advanced. In the Norwegian Sea “H- events” can even be recorded as meltwater events but with no coeval IRD signal (Lekens et al., 2006).

The existence of the IRD-belt (Ruddiman, 1977) implies that debris-rich icebergs retain their sediment load over a considerable distance with little or no melting. Melting of icebergs, and release of any entrained sediment, is a function of several variables (Bigg, 2016; Daley and Veitch, 2000) although wave erosion is judged to be the most important (Venkatesh et al., 1994); this process could be reduced if the icebergs are travelling within heavy concentrations of sea ice. The notion of the dominance of melting to explain the IRD belt is contradicted by the evidence for a decrease in H-layer thickness along the transport trajectory (Bond et al., 1992; Dowdeswell et al., 1995). Modeling of iceberg discharge during an H-event also documents considerable melting near the iceberg source (Bigg et al., 2011) suggesting associated sediment release. The distributions of the flux of sand (mg/cm^2

ky), as of 1977 (Fig. 1), may have been biased by the available core distribution (note also that carbonate was removed) and the integration over a longer period of time than individual H-events. This is hinted at by the values of 800 mg/cm^2 ky just south of Denmark Strait (Ruddiman, 1977), and our own data (Andrews et al., 2017) from nearby sites in Denmark Strait with average fluxes between 30 to 40 cal ka BP of ~2000 mg/cm^2 ky (JM96-122GC) and 900 mg/cm^2 ky (PS2644). Furthermore, in a proximal H- site (HU87033-009, Fig. 5), the sediment accumulation rate (SAR) between H-/DC events is ~22 cm/ky versus ~100 cm/ky within the events. During H-2, the median sand flux (> 63 µm) was 10,000 mg/cm^3/ky, the > 250 µm flux was 1700 mg/cm^2/ky, and the deposition of detrital carbonate approached 50,000 mg/cm^2/ky. It would be useful to map not only the thicknesses of H-events but also to calculate the IRD flux along the iceberg drift trajectories (e.g. Dowdeswell et al., 1995, their Fig. 1).

The implicit notion of H events as being solely IRD events, based on the earlier papers (e.g. Heinrich, 1988) and on an “armada of ice bergs,” neglects the complexity of the depositional processes off the Hudson Strait Ice Stream where four distinct sediment facies have been identified (Hesse et al., 1997, 1999; Hesse and Khodabakhsh, 2016). In core HU87033-009 (Suppl. Table 1) (Andrews and Tedesco, 1992), north of Hudson Strait (Fig. 1A, 4A), the DC-events are much broader than the IRD events (either > 250 or > 125 µm) (Fig. 5B), which occur at the onset of the DC/H-events. They are also marked by a trough in the mass susceptibility, due to the dominance of calcite (Stoner and Andrews, 1999). Furthermore, the textural description of the sediment at this ice proximal site testifies to the dominance of silt-sized grains, although the presence of IRD is clearly evident in the grain-size “shoulder” for modes 2 and 3 and more emphatically by the counts on X-radiographs (every 2 cm) of clasts > 2mm. Thus, especially within the Labrador Sea, the sediment regimes during deposition of DC/H-layers is more complex than suggested by a simple IRD signal.

Recommendations

Rarely, if ever, has a lithostratigraphic unit been named for an individual, and despite arguments of prior recognition (Andrews, 1998) the terms “Heinrich layer, zone, or event” are so entrenched in the literature that to argue for removal would be both unlikely and disrespectful. In a stratigraphic sense Heinrich sediment events are “xenoconformities” (Carroll, 2017; Halverson, 2017) defined as “*a stratigraphic surface or gradational interval that records a fundamental, abrupt, and persistent change in sedimentary facies across basinal to global scales*” (Carroll, 2017, p. 639). However, it is clear that the “Heinrich” usage needs both clarification and restriction in usage---in particular the term “Heinrich stadial” is a radical departure from the original usage, and is clearly associated with the absence of D-O excursions onto the longer H-event recurrence interval (Fig.3). It is noteworthy that the number of citations dealing with the meltwater events and sediment facies in the Labrador Sea only number in the 10’s to 100 (Fig. 2) indicating that this facet of H-event glaciological/sedimentological processes (Alley et al., 1995; Hesse, 2016; Hesse and Khodabakhsh, 2016; MacAyeal, 1993a, b) is not being adequatly addressed nor understood by many in the paleoclimate community (see however Johnson and Lauritzen, 1995 as introducing the possibility of outburst floods being associated with the Hudson Strait H-events).

A useful analog for the recognition and naming of abrupt IRD-rich ice sheet events that terminate in the ocean is the deposition of tephras---in so-far-as that they have a specific source, have a geochemistry that is linked to that source, and have a geographic pattern of dispersal (e.g. Bursik et al., 1992; Lacasse et al., 1998; Voelker and Haflidason, 2015; Wastegard et al., 2003). The literature might document that tephras from several volcanic centers might be coeval, but these are not “lumped” into a single stratigraphic unit. Similarly in the case of Heinrich layers, there may be some provenance ambiguity at times, especially if the criterion is based on isotope geochemistry (Farmer et al., 2003; Grousset et al., 2000). We further note that biogeochemical proxies also have a role to play in provenance identification (Naafs et al., 2013; Parnell et al., 2007; Rosell-Mele et al., 1997).

Our specific recommendations are as follows:

1. IRD-rich events that can be attributed to a Hudson Strait mineral/geochemical source, or are located along the iceberg drift trajectory, be called “Hudson Strait Heinrich events” (HSH-layers/events).
2. Discrete IRD-rich sediment units that cannot be linked to Hudson Strait should have their own designation, such as for example: PS2644 IRD #2, or Scoresby Sund TMF#3. Such a process would naturally lead toward a more rigorous and independent analysis of global ice sheet instabilities on late Quaternary time-scales
3. Correlation between IRD-events should be based on radiocarbon ages and specific geochemical signature. This approach, combined with recommendation #2 above, would shed light on the important issue of whether discrete IRD events represent individual ice sheet/ice stream responses or whether there is a synchronous response.
4. The term “Heinrich stadial” should be abandoned; a more appropriate linkage would be via the Greenland stadial/interstadial nomenclature.

5. We suggest that papers “tuning” their records to the GIS D-O calendar need to explicitly state their underlying assumptions and an assessment as to whether this may ignore leads or lags in the driving processes.

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Figures

Figure 1: A: Core sites of the initial Heinrich layer/event studies (red dots; published between 1988 and 1999; see Supplementary Table 1 for details) and sites with a detrital carbonate signal during Heinrich events (polygons). B: Core sites with IRD signals during Heinrich events (published between 1978 and 2017; see Supplementary Table 1 for details). Inset on the right shows cores in the Arctic Ocean with reference to H events. In A and B, the dark gray dots mark the core sites studied by Ruddiman (1977). Petrol-blue colored lines indicate IRD concentrations reconstructed by Ruddiman (1977) for the period from 25-40 ka, i.e. late Marine Isotope Stage 3 and encompassing H 3 and H 4, with numbers 200 and 50 (thinner line) denoting the respective concentrations [milligrams per square centimetre per 1000 y]. The stippled area marks the region referred to as “Ruddiman IRD belt”. Black lines show the Last Glacial Maximum ice sheet extent according to Stokes et al. (2016) for North

America, Greenland and Iceland and to Hughes et al. (2016) for Scandinavia, Ireland, England and northern Europe. C (inset on left in B): Close-up of the Labrador Sea with the North Atlantic Mid-Ocean Channel (NAMOC) and some feeder channels on the Canadian margin indicated by black lines. All maps were generated with Ocean Data View (Schlitzer, 2016).

Figure 2: Graph of citation numbers of select references using the www.webofknowledge.com/ online service for the number of citations.

Figure 3: A) Suggested timing of the Hudson Strait Heinrich/detrital carbonate events (Hemming, 2004; Rashid et al., 2003b), including the deglacial detrital carbonate events (Jennings et al., 2015). The ages are plotted with a range of ± .2 ky with the central bar two-times the height of the range; B) The NGRIP data, integrated to a 0.25 ky time-series (10-65 ka BP), and the Singular Spectrum trend (Ghil et al., 2002); C) residuals from the trend and the 3.7 ky pacing that explains 49% of the residual variance; D) Multi-Taper Method (MTM) showing the reconstruction based on 4 significant periodicities (* = 95%, and ** = 99% confidence levels). Explained variance is the r^2 value of the residuals versus the two reconstructions (C & D). Black stippled lines in B) to D) indicate Greenland stadials during which the respective H event occurred. Note that position of line does not mark the exact timing of the H event within the Greenland stadial!

Figure 4: Probability density function plots of dates at the base and top of H-2 and H-1 from the northwestern Labrador Sea (e.g. Fig. 5A). n = number of dates per event.

Figure 5: A) The location of core HU87033-009 off Hudson Strait. B) Downcore plot of sediment data from core HU87033-009 off Hudson Strait in 1437 m water depth (Andrews et al., 1993). The core has 4 H-/DC events (a H-3 event is not evident).

The relationships between coarse IRD (number of clasts per 20 cm^2), mass magnetic susceptibility ($*10^{-7}$ kg/m^3), carbonate sources and $\partial^{18}O$ is evident, but also note that there are additional discrete IRD events (e.g. 820 and 560 cm) (see also Bond and Lotti, 1995).

Supplemental Table 1:

Compilation of data for the reported Heinrich events (see text and Figures 1A, B and C).

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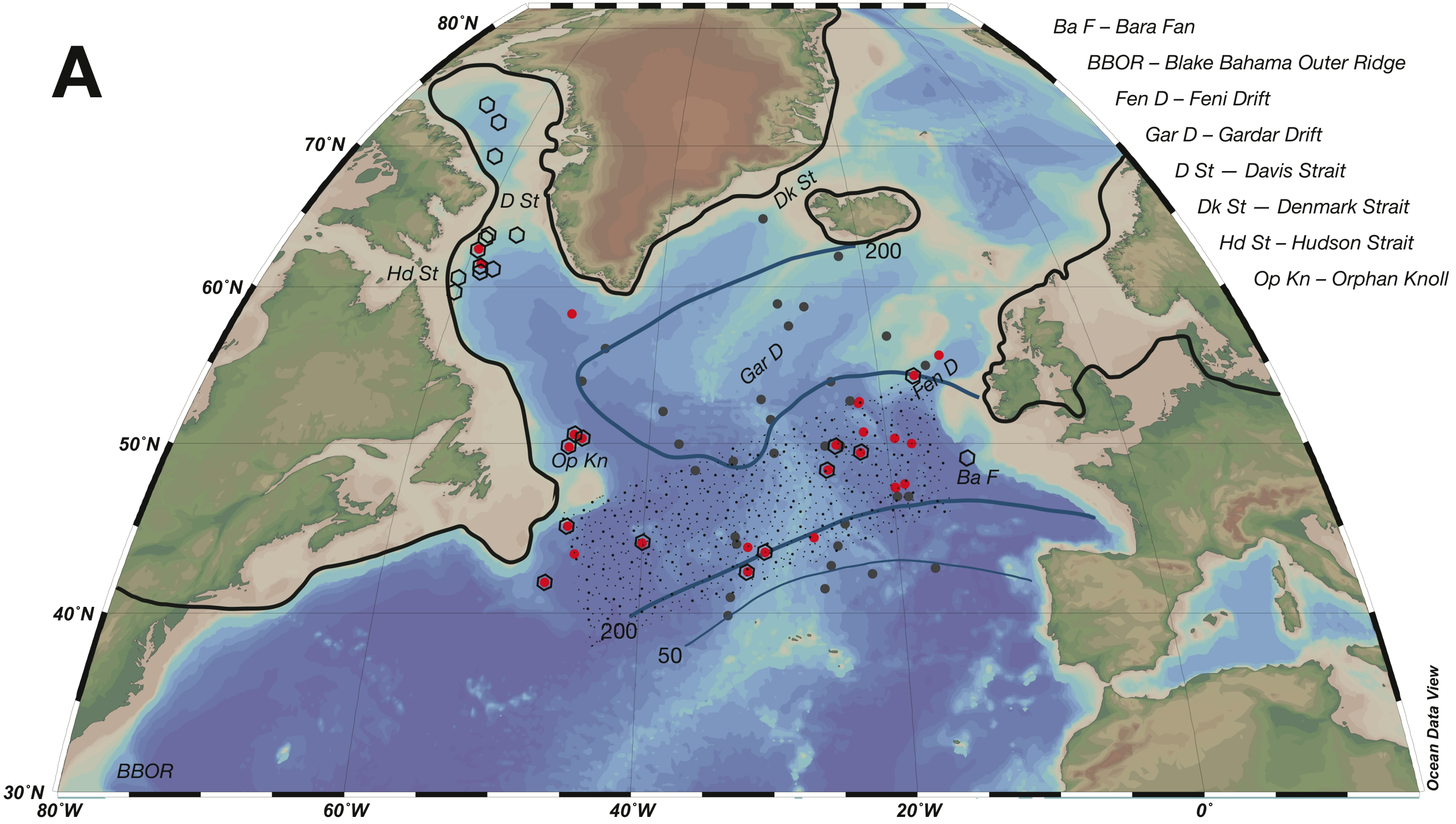
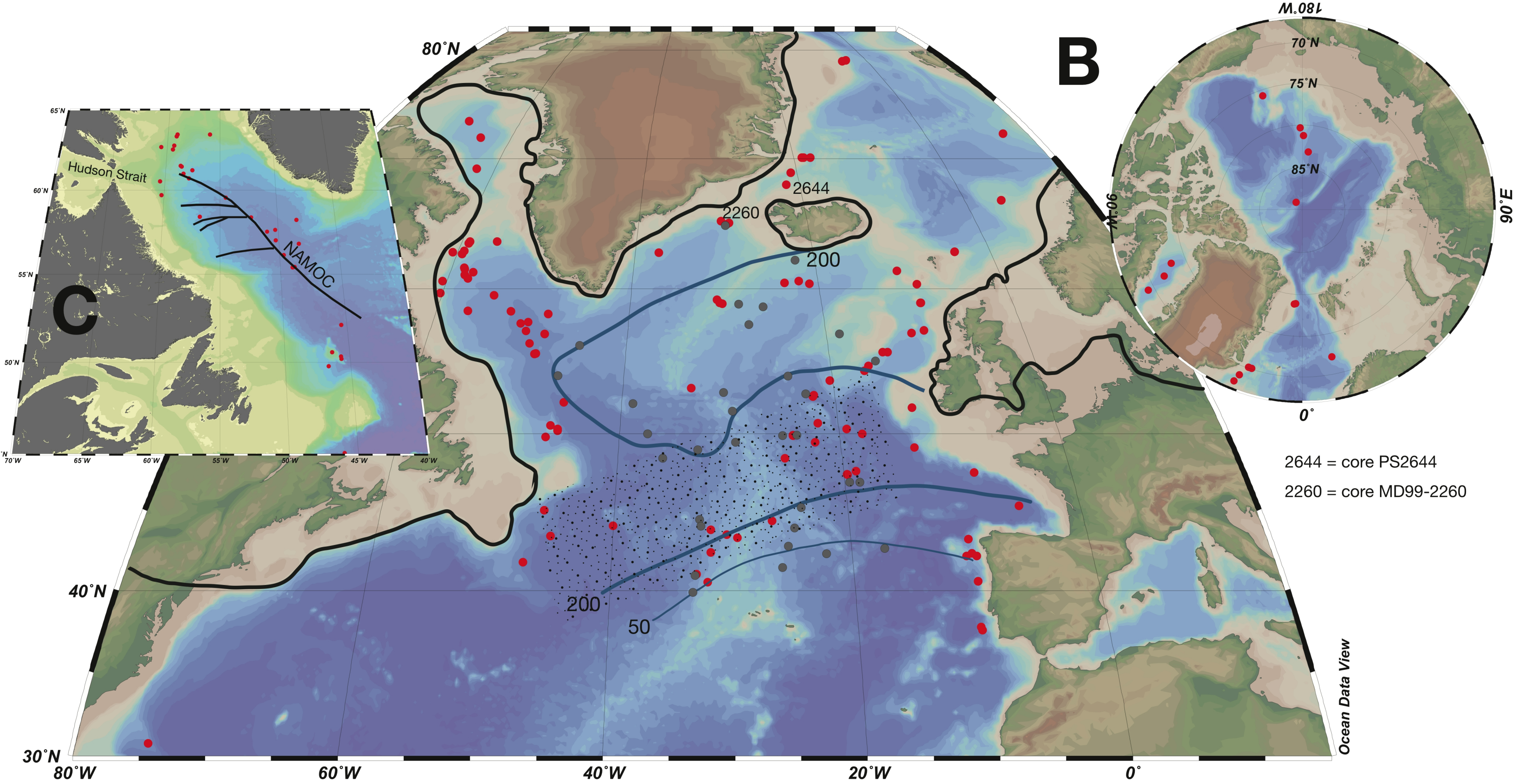
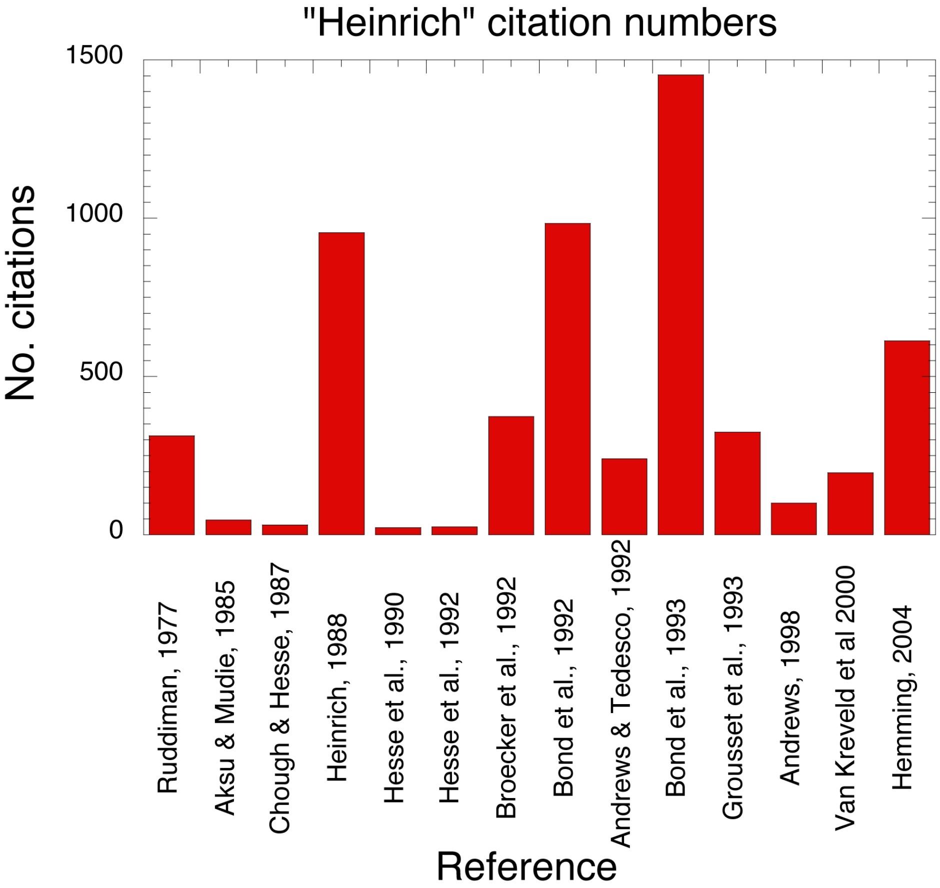


Ba F – Bara Fan
BBOR – Blake Bahama Outer Ridge
Fen D – Feni Drift
Gar D – Gardar Drift
D St — Davis Strait
Dk St — Denmark Strait
Hd St – Hudson Strait
Op Kn – Orphan Knoll



2644 = core PS2644

2260 = core MD99-2260

"Heinrich" citation numbers
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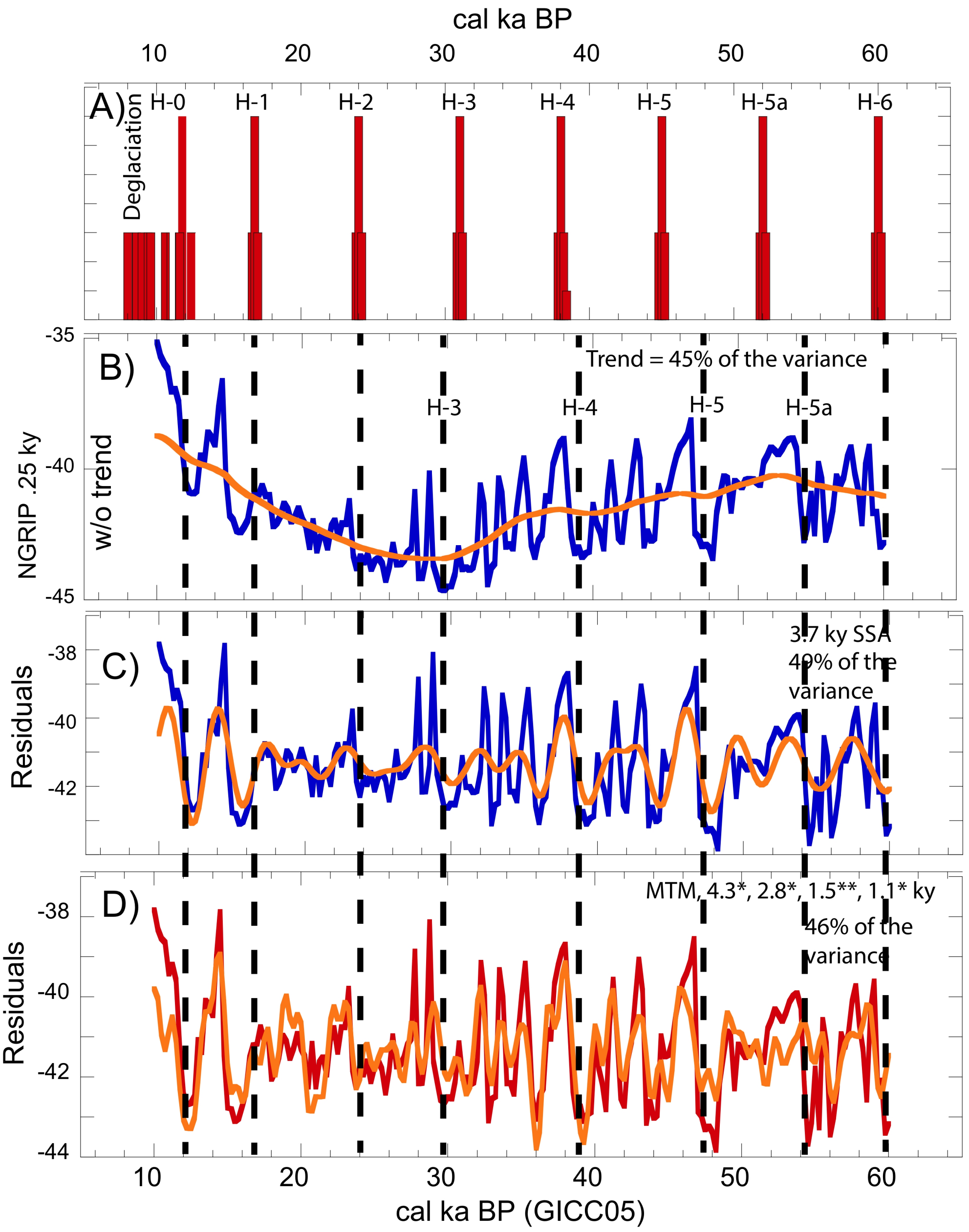
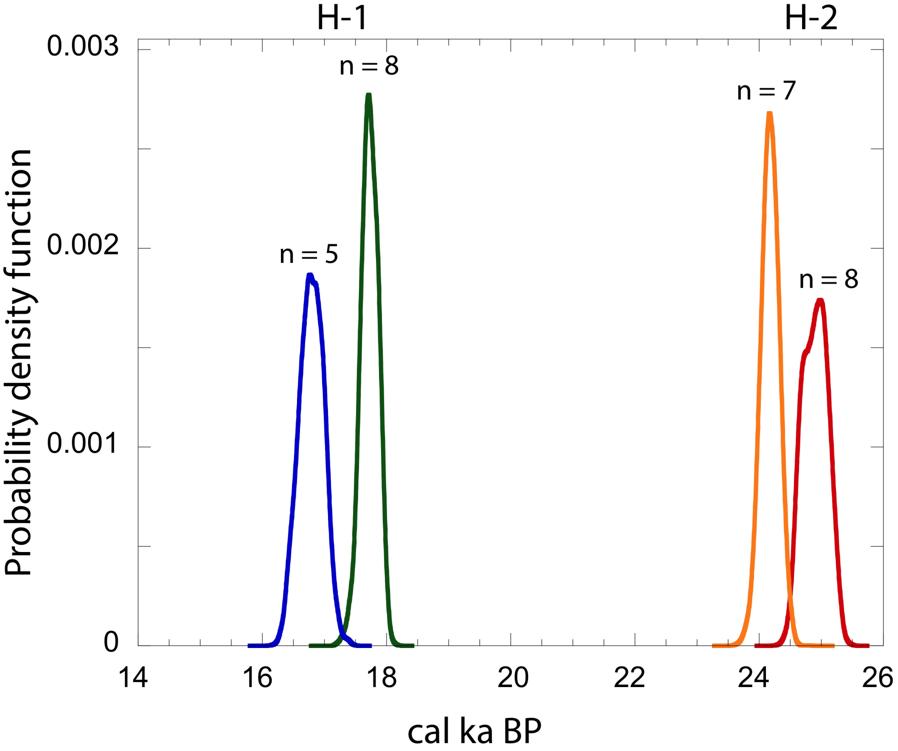
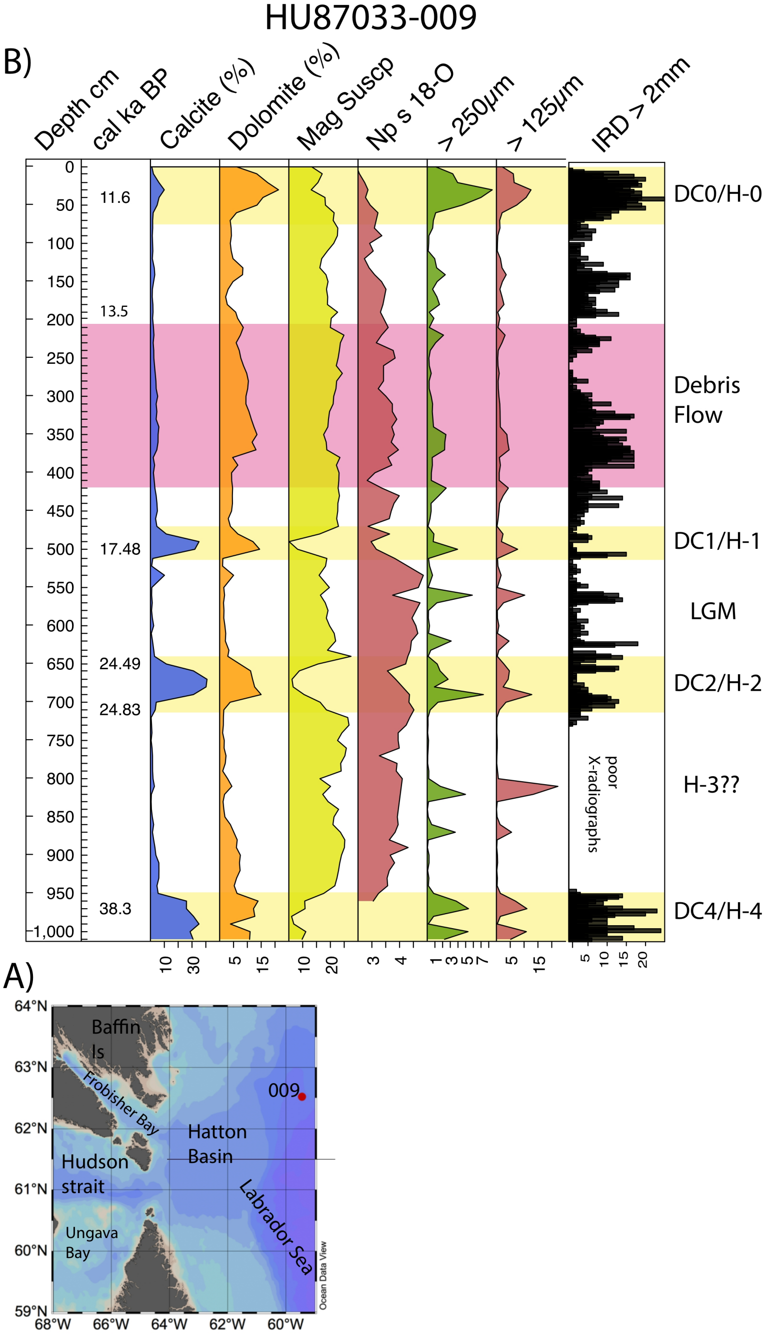

cal ka BP
10
20
30
40
50
60
A)
Deglaciation
H-0
H-1
H-2
H-3
H-4
H-5
H-5a
H-6
B)
-35
-40
-45
NGRIP .25 ky
w/o trend
Trend = 45% of the variance
H-3
H-4
H-5
H-5a
C)
-38
-40
-42
Residuals
3.7 ky SSA
49% of the
variance
D)
-38
-40
-42
-44
Residuals
MTM, 4.3*, 2.8*, 1.5**, 1.1* ky
46% of the
variance
10
20
30
40
50
60
cal ka BP (GICC05)


H-1
H-2
0.003
0.002
0.001
0
n = 8
n = 5
n = 7
n = 8
Probability density function
14
16
18
20
22
24
26
cal ka BP


HU87033-009
B)
Depth cm
cal ka BP
Calcite (%)
Dolomite (%)
Mag Suscp
Np s 18-O
> 250µm
> 125µm
IRD > 2mm
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1,000
11.6
13.5
17.48
24.49
24.83
38.3
DC0/H-0
Debris Flow
DC1/H-1
LGM
DC2/H-2
poor X-radiographs
H-3??
DC4/H-4
10 30
5 15
10 20
3 4
1 3 5 7
5 15
5 10 15 20
A)
64°N
63°N
62°N
61°N
60°N
59°N
68°W
66°W
64°W
62°W
60°W
Baffin Is
Frobisher Bay
009
Hatton Basin
Hudson strait
Labrador Sea
Ungava Bay
Ocean Data View