Sediment sources of northern Québec and Labrador glacial deposits and the northeastern sector of the Laurentide Ice Sheet during ice-rafting events of the last glacial cycle

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\textbf{ABSTRACT}

Provenance studies of anomalously high-flux layers of ice-rafted detritus (IRD) in North Atlantic sediments of the last glacial cycle show evidence for massive iceberg discharges coming from the Hudson Strait region of the Laurentide Ice Sheet (LIS). Although these so-called Heinrich events (H events) are commonly thought to be associated with abrupt drawdown of the LIS interior, uncertainties remain regarding the sector(s) of this multi-domed ice sheet that conveyed ice through Hudson Strait. In Northern Québec and Labrador (NQL), large-scale patterns of glacial lineations indicate massive ice flows towards Ungava Bay and Hudson Strait that could reflect the participation of the Labrador–Québec ice dome in H events. Here we evaluate this hypothesis by constraining the source of NQL glacial deposits, which provide an estimate of the provenance characteristics of IRD originating from this sector. Specifically, we use \textsuperscript{40}Ar/\textsuperscript{39}Ar ages of detrital hornblende grains in 25 till samples distributed along a latitudinal transect (lat. 58\textdegree\textquoteright N) extending east and west of Ungava Bay. The data show that tills located west and southwest of the Ungava Bay region are largely dominated by hornblende grains with Archean ages (>2.6 Ga), while tills located east of Ungava Bay are characterized by grains with early Paleoproterozoic ages (2.0–1.8 Ga), although most samples contain a few Archean-age grains. IRD derived from the NQL region should thus be characterized by a large proportion of Archean-age detrital grains, which contrasts significantly with the predominant Paleoproterozoic \textsuperscript{40}Ar/\textsuperscript{39}Ar ages (1.8–1.6 Ga) typically reported for the dominant age population of hornblende grains in H layers. Comparisons with IRD through the last glacial cycle from a western North Atlantic core off Newfoundland do not show evidence for any prominent ice-rafted event with the provenance characteristics of NQL glacial deposits, thereby suggesting that significant ice-calving event(s) from the Labrador–Québec sector may have been limited throughout that interval. Although these results tend to point towards a relative stability of this ice dome during H events, our study also indicates that further provenance work is required on IRD proximal to the Hudson Strait mouth in order to constrain with a greater confidence the sector(s) of the LIS that fed ice into Hudson Strait during H events. Alternatively, these results and other paleogeographic considerations tend to support models suggesting that part of the Ungava Bay glacial lineations could be associated with a Late-Glacial ice flow across Hudson Strait.

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1. Introduction

The greater Hudson Strait region was subject to important ice-dynamic events during the last glacial cycle, notably in the form of large drainage episodes of glacial ice through Hudson Strait (e.g. Andrews, 1998), with concomitant massive iceberg discharges in the North Atlantic ocean that have had a strong impact on climate (Bond et al., 1992; Broecker et al., 1992). These so-called Heinrich events (H events) are also significant in terms of ice sheet dynamics because the composition and sedimentological characteristics of the associated ice-rafted detritus (IRD) imply sudden and episodic collapses of the Laurentide Ice Sheet (LIS) (Andrews and Tedesco, 1992; Dowdeswell et al., 1995; Gwiazda et al., 1996; Hemming et al., 1998, 2000;
Other North Atlantic ice sheets appear to have released icebergs in approximate synchrony (Grousset et al., 1993, 2000, 2001; Bond and Lotti, 1995; Scourse et al., 2000; Knutz et al., 2001, 2002, 2007; 2003; Jullien et al., 2006; Peck et al., 2006, 2007), but their contribution to IRD concentrations was small with respect to the LIS. Although multiple mechanisms have been suggested to explain the cause/origin of H events (e.g., Hemming, 2004), most glaciological and paleoclimatic proxy-based models put forward to explain these large iceberg discharges involve drawdown of large amount of ice from the central part of the LIS (MacAyeal, 1993; Alley and MacAyeal, 1994; Alley et al., 2005; Marshall and Koutnik, 2006). The spatial distribution of glacial lineations and patterns of post-glacial rebound (e.g., Peltier, 2002; Tarasov and Peltier, 2004), however, indicate that Hudson Bay was not the area with the thickest ice, but was rather surrounded by three important ice domes that fed the margins as well as the interior of the LIS (Fig. 1a) (Dyke and Prest, 1987). Extensive mapping of glacial striations on multifaceted rock outcrops and boulder tracing of lithological indicators of glacial transport indicate large-scale displacements of these ice domes during the last glacial cycle (Parent et al., 1995; Veillette et al., 1999; Clark et al., 2000; Jansson et al., 2002; McMartin and Henderson, 2004; Veillette, 2004). These reorganizations of the ice divide system likely reflect important ice-surface changes of the LIS, which could be related to the postulated ice sheet collapses during Heinrich events (Clark et al., 2000; Dyke et al., 2002).

Additionally, the occurrence of major ice-flow patterns that converge towards Hudson Bay and Hudson Strait could also reflect disintegration paths associated with Heinrich-type drawdown episodes of the LIS. This is well illustrated in Northern Quebec and Labrador (NQL) where the numerous fields of glacial lineations that characterize the Ungava Bay region (Fig. 1b) were linked to a major ice-draining event (or several synchronous events) of the northeastern sector of the LIS that may have contributed to the massive iceberg discharges associated with H events (Jansson et al., 2003). The contribution of the Labrador–Quebec ice dome to H events during the Last Glacial cycle and the significance of the NQL glacial flutings in such events, however, remain largely unconstrained. Overall, little is known on the sector(s) of the LIS and associated ice-flow paths that conveyed ice to the Hudson Bay/Strait region during H events, and this represents an important limitation in our understanding of the LIS in the context of H events.

Here we document the provenance of NQL glacial sediments (tills) representing the sediment source carried by Ungava Bay ice streams and other regional ice-flow trajectories, which ultimately delivered ice and associated IRD to the ocean. For this purpose, we use the single-step laser fusion $^{40}$Ar/$^{39}$Ar method to date 241 detrital hornblende grains from 25 samples roughly located on the

![Fig. 1.](image-url)
referred to the web version of this article. Coasts and main river valleys show the approximate extent of the post-glacial marine invasion. For interpretation of the references to colour in this figure legend, the reader is postulated ice flows within and around the Hudson Strait and Ungava Bay regions based from field evidence and inferred by glaciological modeling. Light gray areas around the here used to identify the main trajectories along which detrital material can be transported to the ocean, regardless of the age of formation of these features. Black arrows show 2. What sector of the LIS contributed to the ice discharges?

The identification of the LIS as the main source for the massive iceberg discharges associated with H events comes primarily from provenance work on anomalously high-flux layers of IRD in North Atlantic deep-sea sediments of the last glacial cycle, which were first recognized by the high concentrations of lithic grains in the coarse fraction of IRD (Heinrich, 1988). The high detrital carbonate concentration that characterizes the terrigenous sediment fraction of H layers was attributed to a calving ice margin that overrode a carbonate-floored substrate, likely corresponding to the one that covers large areas of Hudson Bay and Hudson Strait (Andrews and Tedesco, 1992; Bond et al., 1992; Broecker et al., 1992). The LIS origin for H event was also reinforced by radiogenic provenance studies. Lead and neodymium isotope systematics measured on bulk sediment suggested an Archean heritage of the terrigenous fraction of H layers, while Pb isotopes of feldspar grains and 40Ar/39Ar ages of hornblende grains indicated Paleoproterozoic metamorphism (∼ 1.8 Ga) of the source-rocks of H layers (Gwiazda et al., 1996; Hemming et al., 1998, 2000; Hemming, 2004). These characteristics further confined the source region of H layers to the rocks of the Paleoproterozoic Churchill Province of the Canadian Shield, which outcrop in the Hudson Strait area (Fig. 3). These results, along with other sedimentological data, led to the interpretation that a large fraction of the LIS in Hudson Bay drained repeatedly through an ice stream flowing in Hudson Strait (e.g. Andrews, 1998).

Although the LIS was unequivocally the main contributor of detrital material to H layers, the exact sector of the LIS that conveyed ice through Hudson Strait has yet to be identified. Hudson Bay is commonly regarded as the source of the drawdown of large amount of ice, mostly because this region is underlain by Paleozoic carbonates. Unlike the coarse-grained crystalline rocks of the Shield, this substrate provides soft-bedded conditions that are necessary to generate the fast-flowing ice that has been invoked to accommodate the massive iceberg discharges, in addition to provide a source for the high detrital carbonate content of most H layers (Andrews and Tedesco, 1992; Marshall and Clarke, 1997). However, field-based paleogeographic reconstructions and patterns of post-glacial uplift indicate that Hudson Bay was a site of lower ice-surface elevation where ice flows were converging from the three nearby centers of outflow (Dyke and Prest, 1987; Dyke, 2004; Tarasov and Peltier, 2004) (Fig. 1a). The difficulty in identifying the sector of the LIS that fed the Hudson Strait ice stream on the basis of sedimentary and radiogenic data from ocean cores also comes from the occurrence at the mouth of Hudson Strait of a bedrock sill, which is composed of Paleoproterozoic crystalline rocks of the Churchill Province (Fig. 3). Because this sill rises ∼ 300–400 m above the seafloor, it likely acted as an important grounding line for this ice stream (Andrews and MacLean, 2003; Hulbe et al., 2004; Alley et al., 2005). The occurrence of a significant over-deepened zone located up-ice from the sill further suggests that it may have been an area of important subglacial erosion during the calving/streaming episodes that led to H events (Hemming, 2004). Consequently, part of the geochemical signature of H layers likely contain erosional products of this bedrock protuberance, thereby complicating the identification of ice flow coming from the LIS interior on the basis of IRD data alone. This points to the need of

Fig. 2. Location of till samples investigated in this study (red squares) with respect to the main ice-flow patterns in Northern Quebec and Labrador, shown here as flow-sets. Ice-flow sets were defined by Clark et al. (2000) on the basis of detailed mapping of glacial lineations. Ice-flow set fsJ03 comes from Jansson et al. (2003). These ice-flow patterns are here used to identify the main trajectories along which detrital material can be transported to the ocean, regardless of the age of formation of these features. Black arrows show postulated ice flows within and around the Hudson Strait and Ungava Bay regions based from field evidence and inferred by glaciological modeling. Light gray areas around the coasts and main river valleys show the approximate extent of the post-glacial marine invasion. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.
better documenting the provenance of glacial deposits that are associated with massive ice-flow paths extending from the different ice domes into the Hudson Bay and Hudson Strait region in order to further constrain the source of LIS ice for H events.

Nonetheless, in addition to large-scale patterns of glacial lineations that indicate massive ice flows towards Hudson Bay/Strait (e.g. Clark et al., 2000; Jansson et al., 2003), Heinrich-type drawdown episodes are suggested by the occurrence of sequences of shifting ice flows documented from rock outcrops all around Hudson Bay (Parent et al., 1995; Veillette et al., 1999; McMartin and Henderson, 2004; Veillette, 2004), mostly because these reorganizations of ice sheet profile require significant ice-surface lowering of certain sectors of the LIS. These erosive and geomorphic features, however, have yet to be documented within the context of H events.

3. NQL glacial lineations and the northeastern sector of the Laurentide Ice Sheet

The NQL region comprises a large fraction of the area formerly occupied by the Labrador–Québec ice dome, which was the main center of ice outflow of the northeastern sector of the LIS (Fig. 1). The landscape of this region is characterized by abundant drumlins, crag-and-tails, glacially molded bedrock outcrops, and fluted till plains with disseminated areas of crystalline rock outcrops (Fig. 4) (Hughes, 1964; Prest et al., 1968; Lauriol, 1982; Gray and Lauriol, 1985; Bouchard and Marcotte, 1986; Gray et al., 1993; Parent et al., 1995; Clark et al., 2000; Gray, 2001; Jansson et al., 2003). These glacial lineations are associated with former glacial flow-lines that were coming from this ice dome, presumably sometime after the last glacial maximum (LGM) (Fig. 1). This region encompasses Ungava Bay where the long axis of most glacial lineations shows an impressive pattern of converging ice flows towards Ungava Bay (Fig. 2) (Clark et al., 2000; Jansson et al., 2002). Detailed examination of aerial photographs and satellite images showed that the Ungava Bay glacial lineations can be grouped into discrete networks of ice-flow sets (Clark et al., 2000; Jansson et al., 2003). These swarms of glacial lineations were attributed to fast-flowing ice and interpreted to reflect imprints of former ice streams. On the basis of cross-cutting relationships, as evidenced by abrupt lateral margins of the different ice-flow fans and other geomorphological features, a relative chronology describing a sequence of ice stream development was further proposed. In this model, these landform systems would have formed over a relatively broad time-interval spanning part of the last glacial cycle (Jansson et al., 2003). There are, however, almost no chronological constraints for these events. This lack of constraints is at the origin of considerable contrasting interpretations regarding the age of these glacial lineations (e.g. Clark et al., 2000; Jansson et al., 2002), ranging from relict landforms from an older deglaciation preserved under cold-based ice during the last glacial cycle (Kleman et al., 1994), to Late-Glacial features of the last glaciation (Veillette et al., 1999; Dyke et al., 2002).

Of importance here is that the ice-dynamic conditions imposed by the large-scale ice-flow patterns formed by the Ungava Bay glacial lineations led to the suggestion that these Ungava Bay ice-flow systems were likely the results of a major ice-flow event(s) that drained the Labrador–Québec ice dome interior during H events, supposedly through glacial flow-lines feeding the Hudson Strait ice stream (Jansson et al., 2003). This link between the Labrador–Québec sector and drawdown episodes of the LIS can also be seen in various geological models and paleogeographic reconstructions on H events, mainly in the form of a branch of the Hudson Strait ice stream (Fig. 2) (Andrews, 1998; Andrews and MacLean, 2003; Hulbe et al., 2004). Although involving the Labrador–Québec ice dome in Heinrich-type events appears to be a logical mechanism to drain large amount of ice from the deep interior of the ice sheet, there is little direct evidence to support such a model. Involving the northeastern sector of the LIS in the ice discharges of H events through Ungava Bay also requires important constraints to be met, notably an ice-free Hudson Strait (i.e. an ice stream retracted west of Ungava Bay), or, alternatively, the presence of a Hudson Strait ice stream that has ice thickness/velocity characteristics that allows ice from the Ungava ice stream network to feed this main ice outlet (e.g. Kirby and Andrews, 1999; Andrews and MacLean, 2003).

4. Approach and methods

Twenty-five till samples were collected along an east–west transect roughly centered on latitude 58° North (Figs. 1 and 2). This transect is broken into three sectors due to the presence of extensive marine deposits that mask the underlying glacial deposits in low-lying areas around the coasts of Ungava Bay and eastern Hudson Bay (Figs. 1b and 2). The surficial till samples used in this study were collected above the post-glacial marine limit to avoid
any possible reworking of the glacial deposits. The samples come from glacially fluted till plain composed of a relatively thin mantle (2–3 m) of glacial deposits that is broken in places by rock outcrops (Fig. 4). Till in this area is characterized by a coarse (sandy) matrix containing abundant clasts, reflecting the erosion of local crystalline lithologies (Parent et al., 2004).

Figs. 1 and 2 show the position of the three sectors of till samples with respect to the main glacial flow-lines in this region. These flow-lines are largely based on the geomorphologic and stratigraphic records, for which chronological constraints are often lacking. Although some of these flow-lines may be asynchronous, and thus schematic, they provide important information on the possible trajectories along which ice may have flowed from the ice dome to the ocean. Within the context of the main ice-flow paths in the NQL region (Clark et al., 2000; Jansson et al., 2003), the till samples are expected to characterize the catchment areas of the glacial debris entrained by ice flowing toward north-northeast and northwest into Ungava Bay westard into northeastern Hudson Bay, and to the eastward (into the Labrador Sea (Fig. 2). Although there are no till samples located directly south of Ungava Bay in the area comprising ice-flow sets extending northward into the bay, the regional ice-flow patterns (Clark et al., 2000; Jansson et al., 2003) indicate that the till samples of the middle sector lie on the western edge of such former ice-flow paths (Fig. 2). The patterns of regional ice flows also indicate that the till of the middle sector, like the till south of Ungava Bay, originates from ice taking its source in the interior of Labrador–Quebec ice dome. Because of their nature (till genesis), the composition of these deposits should represent a mixture of the lithologies that were progressively incorporated during glacial transport, and their provenance characteristics should thus reflect the general bedrock composition of this region. The main geological divisions show that tills southwest and south of Ungava Bay derive largely from the erosion of the same source-rock, i.e. the Superior Province (Fig. 5). Consequently, whether the middle sector till samples are associated with erosion/deposition of a northeastward flowing ice (as suggested by the dominant ice-flow pattern) or by northward-flowing ice (as suggested by regional ice-flow patterns), the geological setting of this area indicates that these tills should integrate the same source-rock. Accordingly, the provenance characteristics of the middle sector till samples can be considered representative of sediments that would be carried by ice flowing northward into Ungava Bay.

Individual hornblende grains of 125–250 μm in size were extracted from the fine-grained matrix of till samples using a binocular microscope. Hornblende grains were irradiated for ten hours in the Cd-lined, in-core facility (CLICIT) of the TRIGA reactor at Oregon State University, along with hornblende-monitor standard Mmhb (age of 525 Ma; Samson and Alexander, 1987) and a sandstone standard (Cima, 18.9 Ma, relative to MMhb-1 age of 523.2 ± 2.3 Ma; Spell and McDougall, 2003). Approximately 10 detrital hornblende grains were dated in each sample using the \(^{40}\)Ar/\(^{39}\)Ar method through single-step laser fusion at Lamont–Doherty Earth Observatory (LDEO), for a total of 241 age-determinations. Ages were calculated from Ar isotope ratios corrected for mass fractionation, interfering nuclear reactions, procedural blanks, and atmospheric Ar contamination.

The \(^{40}\)Ar/\(^{39}\)Ar ages of detrital hornblende are first evaluated within the context of the numerical ages reported for the potential rock-source areas (i.e. the main geological provinces found in the region, described in the next section). The \(^{40}\)Ar/\(^{39}\)Ar ages of hornblende correspond to either an estimate of igneous crystallization, or, alternatively, the last time the source terrane was subjected to high-temperature metamorphism (i.e. >450 °C) (McDougall and Harrison, 1999). Given the numerous orogens that characterize the geological history of this part of the Canadian Shield, the \(^{40}\)Ar/\(^{39}\)Ar ages of hornblende grains from NQL tills should primarily reflect the last time the source terranes were involved in a major metamorphic event. These \(^{40}\)Ar/\(^{39}\)Ar ages provide information on the provenance of the glacial sediments entrained by ice, and thus the geochemical signature of ice-rafted material that would be associated with iceberg discharges coming from the NQL region.

The \(^{40}\)Ar/\(^{39}\)Ar ages of hornblende grains of tills are also compared to \(^{40}\)Ar/\(^{39}\)Ar ages of IRD grains from H layers and minor IRD layers of marine sediments spanning the time-interval comprised between the early Holocene and 43 ka (Hemming and Hajdas, 2003).

5. Geological setting of the Ungava Bay region

With the exception of the Paleozoic carbonate rocks covering the floor of Hudson Strait and part of Ungava Bay, the rocks underlying the study area are almost entirely composed of Precambrian basement rocks of the Canadian Shield, which in the Ungava Bay region, includes three structural provinces that were assembled during various orogens: the Superior, Churchill, and...
Nain provinces (Fig. 5) (Hoffman, 1989). The rocks forming these provinces, and thus rock-source regions for this study, can be distinguished according to their dominant radiometric imprint, which generally reflects the last major orogenic (metamorphic) event to affect the province (i.e. age of thermotectonic resetting).

Specifically, the region west of Ungava Bay is composed of Archean gneiss and other high-grade metamorphic rocks of the Superior Province (Minto sub-province). Hornblende grains derived from the glacial erosion of these rocks should thus be characterized by \(^{40}\text{Ar}/^{39}\text{Ar}\) ages of \(>2.6\) Ga (Card, 1990). The northern tip of the Ungava Peninsula consists primarily in Paleoproterozoic (2.5–1.6 Ga) volcanic-arc terranes of the Cape Smith thrust belt that were accreted during the New-Quebec orogen (St-Onge et al., 1999). This orogen is also responsible for the formation of the Labrador Trough that extends southward from Ungava Bay, along a band of a few hundred kilometers wide. The rocks east and southeast of Ungava Bay also belong to the eastern Churchill (Rae) Province (Lewry and Stauffer, 1990) and although they have an Archean heritage, they are primarily characterized by a strong Paleoproterozoic imprint inherited from major episodes of high-temperature metamorphism (Lewry and Stauffer, 1990), notably during the Tornag Orogen that produced the prominent Tornag mountain range that separates Ungava Bay from the Labrador Sea. In this area, the Nain Province shows up as a series of Mesoproterozoic (1.6–0.9 Ga) intrusions that cover a large area extending from the Labrador coast to the southernmost extent of the Labrador Trough. Consequently, \(^{40}\text{Ar}/^{39}\text{Ar}\) ages of the hornblende grains originating from the erosion of the Churchill (Rae) rocks should cluster around 1.9–1.7 Ga, while tills derived from ice advances having overidden the Nain sector should have hornblende grains yielding \(^{40}\text{Ar}/^{39}\text{Ar}\) ages of \(1.6–1.4\) Ga. Meta-sedimentary rocks of the Churchill Province also crop out at the eastern end of Hudson Strait, within the Abloviak shear zone that extends from the Tornag Mountains in a NW–SE trend, parallel to the main regional structural boundaries (MacLean, 2001).

6. Results

The results of \(^{40}\text{Ar}/^{39}\text{Ar}\) dating of individual hornblende grains from tills are shown as individual probability plots in Fig. 6 where data are grouped into 5 sectors according to the position of the major ice-flow trajectories defined by the patterns of glacial flow-lines in the region (Bouchard and Marcotte, 1986; Clark et al., 2000; Jansson et al., 2003). Tills samples from the eastern, west-central, and western sectors should represent the characteristics of sediments transported by ice converging into Ungava Bay (Fig. 2). Tills of the westernmost sector represent sediment source from ice draining into northeastern Hudson Bay, while tills from the easternmost sector characterize material draining directly into the Labrador Sea (Fig. 2).

Tills from the westernmost and western sectors show detrital hornblende grains with Archean ages, with \(^{40}\text{Ar}/^{39}\text{Ar}\) ages ranging predominantly from 2.60 to 2.75 Ga (Fig. 6), thus in agreement with age of the source-rock from this region – the Superior Province. Tills from the eastern and easternmost sectors are largely dominated by \(^{40}\text{Ar}/^{39}\text{Ar}\) ages ranging from 1.95 to 1.60 Ga (Fig. 6), reflecting the erosion of the underlying Paleoproterozoic bedrock of the Churchill and Nain provinces present in this area. A few grains with Archean ages are also found in tills adjacent to the eastern Ungava Bay coastline. This could reflect ice advance across the bay, from western Ungava Bay, as suggested by erosional marks that indicate the occurrence of such ice flow in this region (Paradis and Parent, 2002). Alternatively, the occurrence of sparse Archean-age grains may also reflect ice flow coming from the south. The ice-flow patterns in the Ungava Bay region (Clark et al., 2000; Jansson et al., 2003), show that some of the northward-flowing fans appear to take their source deep enough into the Labrador–Quebec sector to reach rocks of the Superior Province (Figs. 2 and 5). Tills from the west-central sector show a large population of hornblende grains with Archean ages, as well as abundant Paleoproterozoic-age grains (Fig. 6). This likely reflect the geographic position of these samples, which are located nearby the boundary between Archean and Paleoproterozoic

Fig. 5. Simplified bedrock geology of the Hudson Strait and Ungava Bay regions (based on the Geological Survey map 1860A by Wheeler et al., 1996).
Fig. 6. A) Normalized probability plot showing $^{40}$Ar/$^{39}$Ar ages of hornblende grains dated in till samples of the study area. Colors correspond to the different sectors discussed in text. B) Stack histograms showing the distribution of $^{40}$Ar/$^{39}$Ar ages of hornblendes for the 25 till samples of the different sectors. Note that Y axes are different in each histograms, while X axes are all identical, with 50-Myr bins. The number (n) of dated hornblende grains and associated samples in each sector are given at top of each histogram. The complete $^{40}$Ar/$^{39}$Ar data set and samples coordinates are presented in Table DR1, as supplementary material in the on-line appendix.
terranes (Fig. 5). The occurrence of Paleoproterozoic-age grains could also be attributed to ice-flow paths taking their source slightly to the east, on the Paleoproterozoic rocks of the Labrador Through, as indicated by the regional ice-flow patterns (Fig. 2).

7. Discussion – conclusions

Sedimentary and radiogenic provenance studies indicate that the detrital carbonate and crystalline rock fractions of IRD forming H layers derive from the Hudson Strait region (Hemming, 2004). Based on the age and geochemical composition of the IRD crystalline fraction, H layers show a clear link with the rocks forming the Hudson Strait sill, but the carbonate clast content of H layers implies a larger catchment area for which the extent is unconstrained. Ambient (non-Heinrich) IRD off Hudson Strait does not include abundant carbonate clasts (e.g. Andrews and Tedesco, 1992), thereby indicating that the ice discharges related to H events represent a different calving mechanism than those occurring between H events. Taken together, these results support models attributing the iceberg discharges of H events to an ice stream draining the LIS interior and calving at the mouth of Hudson Strait. How the LIS fed this ice stream is currently unknown, and an objective of this study was to examine whether the Labrador–Québec sector may have been a contributor. Large-scale patterns of glacial lineations around Hudson Bay tend to agree with the postulated disintegration models of the LIS, whereby they indicate the convergence of massive ice flows from the three major ice-dispersal centers towards Hudson Bay/Strait (Dyke et al., 2002). Problems in identifying which of these ice domes fed the ice flow along the axis of Hudson Strait come from the fact that Churchill-age rocks are found in the western and northern Hudson Bay regions, directly under or adjacent to the former position of these three major centers of ice outflow.

Another difficulty comes from uncertainty in interpreting the significance of these major ice-flow patterns converging towards Hudson Bay and Hudson Strait. This complexity is well exemplified in the NQL region where multiple sets of glacial lineations indicating convergent ice flows towards Ungava Bay were interpreted to reflect a drainage-event(s) of the Labrador-Québec ice dome interior during H events (Jansson et al., 2003). The data presented in this paper suggest that it may be possible to evaluate this hypothesis by constraining the rock-source of the glacial sediments from three sectors located west, southwest, and east from Ungava Bay, which should provide an estimate of the provenance characteristics of IRD deriving from ice exiting these sectors. Specifically, $^{40}$Ar/$^{39}$Ar ages of detrital hornblende grains from NQL glacial sediments indicate that ice flow from the northeastern sector of the LIS through northeastern Hudson Bay and Ungava Bay should have incorporated debris characterized by a significant portion of Archean-age detrital grains.

Insights on the occurrence of ice-draining event(s) from the Labrador–Québec sector can be obtained from the provenance of major (Heinrich) and minor (non-Heinrich) IRD deposits in North Atlantic sediment cores located downstream from Hudson Strait. The chronology of deep-sea record could further provide timing for this event(s). Hemming and Hajdas (2003) report an extensive record of near-continuous IRD sources in a core that spans the last 43 ka, an interval encompassing Heinrich event 0 (H0) through H4 (dated at ~11, 14.5, 20.5, 27, 34 $^{14}$C ka, respectively). Because of its location off Newfoundland, in the western part of the Ruddiman IRD belt, this core (V23–14) provides a record of LIS iceberg contributions coming from the Gulf of St-Lawrence as well as the Labrador Sea, thus including the Hudson Strait region (Fig. 1). The $^{40}$Ar/$^{39}$Ar ages of hornblende grains reported show a predominance of Paleoproterozoic-age IRD during and between H events from 43 to 30 ka, and after 17 ka. The data also document the a real evolution of the LIS through time, with IRD contribution from the Grenville and Appalachians becoming more common from H3 (~30 ka) to H1 (~17 ka), as the ice sheet gained in volume and expanded over southern latitudes (Fig. 7). Does this record contain IRD with a strong Archean-age signature such as the one that would be expected for ice draining the NQL region?

IRD layers with grains corresponding to source-rocks typical of the Superior Province are present throughout this interval, but they form at most 5–10% of the population of grains dated. No significant ice-rafting event with a predominant Archean source-rock has been identified throughout this interval. However, the overall predominance of IRD derived from a Paleoproterozoic rock-source may also be related to the bedrock sill of this age at the mouth of Hudson Strait, as discussed earlier. If this site was subject to important glacial erosion, this may have resulted in the production of a large volume of sediments, which may have diluted the signal of other rock-sources associated with ice flows coming from the ice sheet interior. On the other hand, the occurrence of a prominent dispersal train of distinctive glacial erratics (reddish rocks of the Dubawnt Group) coming from Keewatin and going across northern Hudson Bay (Shilts, 1980) suggests that important amount of detrital material can be transported into the Strait, and possibly into Labrador Sea. The presence of significant amount of carbonate grains in IRD also suggests that detrital material up stream from the sill can reach the ocean. The greater proximity of Ungava Bay to the

![Fig. 7. Scatter plot of $^{40}$Ar/$^{39}$Ar ages of detrital hornblende grains sampled from major and minor IRD in core V23–14 in the northwest Atlantic ocean (34.4°N, 45.25°W, 3177 m; data from Hemming and Hajdas, 2003). The horizontal zones labeled H1–H4 indicate the position of the Heinrich layers; the vertical lines on each side of the C and S letters delineate the age-range associated with the Churchill and Superior provinces, respectively.](image-url)
Hudson Strait outlet thus tends to suggest that a drawdown from this sector can potentially be reflected in the marine IRD record. These issues clearly indicate that quantifying the amount of detrital sediments produced at the mouth of Hudson Strait sill and differentiating these sediments from other rock-sources in North Atlantic IRD represents an important challenge that should be the focus of future studies. Although our results tend to preclude the occurrence of a major draining-event from the Labrador–Québec sector, we believe that a detailed study involving large volume of IRD in the Labrador Sea near the Hudson Strait is needed to provide a more rigorous test of the contribution of NQL in H events, even though the Archean-age fraction may end up to be diluted by erosional processes at the mouth of Hudson Strait.

These results also leave open the question of when the Ungava Bay glacial lineations were formed, and where was the outlet of the ice involved? Direct interaction between the Labrador–Québec sector and the Labrador Sea through Ungava Bay is intimately linked with the dynamics and position of the Hudson Strait ice stream. Although interpretation of airphotos and satellite images have led to the suggestion that parts of the Ungava Bay landform swarm may have been formed over different time-intervals spanning part of the last glaciation (Clark et al., 2000; Jansson et al., 2003), extensive field measurements of ice-flow erosional features in NQL suggest that a large fraction of the Ungava Bay glacial lineations were formed in Late-Glacial time, through the inland propagation of a northward ice flow that was initially confined into the Ungava Bay basin, and that eventually altered the radial outflow of the Labrador–Québec ice dome (Veillette et al., 1999). This capture event was attributed to the Cold Cove ice advance, which crossed Hudson Strait from Ungava Bay and reached the southern tip of Baffin Island at ~ 10 $^{14}$C ka BP (Miller and Kaufman, 1990; Kaufman et al., 1993). If this scenario is correct, the northward trending Ungava Bay glacial lineations could be associated with an ice advance that took place either before or after H0 (~ Younger Dryas), during a period when the Hudson Strait ice stream had retreated westward, away from the mouth of the Strait (Andrews, 1998; Kirby and Andrews, 1999; Clark et al., 2000; Dyke et al., 2002; Andrews and MacLean, 2003). Another alternative would be that the Ungava Bay glacial lineations were formed during H3, late in Middle Wisconsinan time, because the provenance characteristics of H3 layers differ significantly from the other H layers. This suggests that through flow of ice along the eastern axis of Hudson Strait was probably absent at that time, and this setting would then allow across-the-strait flow from Ungava Bay. However, the relative chronology deduced from the striation records does not appear to support this hypothesis (e.g. Veillette et al., 1999).

In summary, the comparison of provenance characteristics of glacial deposits underlying distinct flow patterns of the NQL region and IRD of the North Atlantic marine record suggests that the Labrador–Québec sector contribution to calving event(s) into the North Atlantic appears to have been limited during the last glacial cycle. Although these results suggest a relative stability of the Labrador–Québec ice dome during H events, this interpretation needs to be evaluated within the geological and geomorphological context of the Hudson Strait region. This study indicates indeed that further constraining the role of the Hudson Strait sill in the production of detrital sediments is critical to our understanding of the exact sector of the LIS (and other North Atlantic ice sheets) that contributed to the marine IRD record throughout the last glacial cycle. Similarly, the composition (radiogenic fingerprinting) of glacial deposits associated with distinct flow patterns on land should be further investigated in order to better define ice sheet–ocean interactions and the role of ice sheets in climate changes, as well as to bring additional information on the disintegration patterns of the LIS.

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**Appendix. Supplementary information**

Supplementary data associated with this article can be found in the version at doi:10.1016/j.quascirev.2009.08.008

**References**


