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Rare-earth elements and Nd and Pb isotopes as source indicators for Labrador Sea clay-size sediments during Heinrich event 2

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Abstract

Elemental abundances and Nd and Pb isotope ratios were determined on samples from the carbonate-free, clay-size fractions of sediments from intervals above, within, and below Heinrich event 2 (H-2) in core HU87-9 from the Northwest Labrador Sea slope. In HU87-9, rare-earth element (REE) distributions and elemental concentrations within the H-2 event are distinct from those outside this event. $\varepsilon_{Nd}(0)$ and $^{206}Pb/^{204}Pb$ data also indicate different values for sediments deposited within and outside the H-2 event. Comparisons of REE patterns from the H-2 interval with those from bedrock units in Baffin Island, northern Quebec, and Labrador indicate that the Lake Harbour Group (LHG), which crops out on the north side of the Hudson Strait, is the most probable bedrock source of the clay-size fraction found within the H-2 interval in HU87-9. The Tasiuyak Gneiss (TG) and Lac Lomier Complex (LLC) have REE patterns (including a negative Eu anomaly) similar to those found in H-2 sediments; however, the La/Yb ratios of these units are smaller than those associated with H-2 sediments. The Nd and Pb isotope data support and complement REE-based interpretations of provenance; i.e., the Nd–Pb signatures of sediments deposited at the HU87-9 site during the H-2 event are similar to Nd–Pb signatures obtained on diamicts from the western end of Hudson Strait.
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1. Introduction

The description of abrupt changes in lithic content, mineralogy, and planktic foraminifera in North Atlantic marine cores has led to the identification of Heinrich events (Heinrich, 1988; Andrews and Tedesco, 1992; Bond et al., 1992; Broecker et al., 1992; Andrews, 1998). H-events are attributed primarily to sudden collapses of the Laurentide Ice Sheet, with a main focus on Hudson Strait as the channel through which the ice flowed (Fig. 1) (Alley and MacAyeal, 1994; Broecker, 1994; Dowdeswell et al., 1995; Marshall and Clarke, 1997; Hesse and Khodabakhsh, 1998). Other data suggest coeval or asynchronous responses of portions of the North American ice sheet (Andrews et al., 1998). Landscape-scale studies of the imprint of glacial activity around Hudson Strait indicate that a belt of intense glacial scouring occurs along the north shore of the strait, whereas there is little evidence of glacial scouring on the southwestern flank from the Ungava Peninsula (Fig. 1) (Sugden, 1977; Andrews et al., 1985). Scouring is most intense from the mid-point of the strait westward to Foxe Peninsula (Fig. 1). Most of the Meta Incognita Peninsula (Fig. 1) at the eastern end of the strait was not scoured (Stravers, 1986). The distribution of erratics and striations on the islands at the western end of Hudson Strait (Fig. 1) (Shilts, 1980; Laymon, 1992) indicates that ice from[2] Keewatin and Ungava was confined to the southern part of the strait (Andrews et al., 1985).

A key issue has been the search for specific provenance indicators which would allow a more rigorous delineation of the source area(s) of ice-rafted detritus that accompanied massive decreases in the sizes of Northern Hemisphere glaciers. Various approaches have been adopted, most which have utilized the age and

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[2] Keewatin is not shown in Fig. 1. It is located in the Northwest Territories of Canada west of Hudson Bay ~600 km west of the western end of Hudson Strait.

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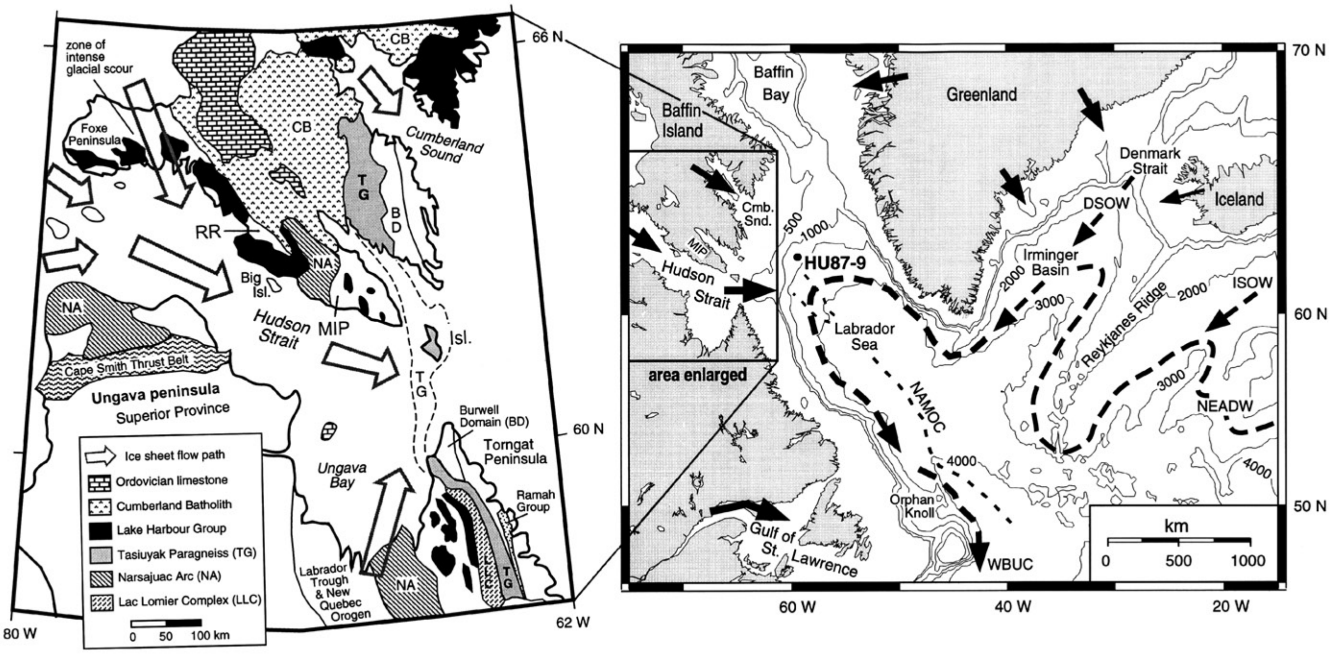

Fig. 1. Location of HU87-9 and simplified geologic map of bedrock groups on Labrador and Baffin Island (adapted from Fig. 1, Thériault, 1998). REE distributions from the Narsajuaq Arc (NA), the Cumberland Batholith (CB) the Burwell Domain (BD) and the Superior Province lack the distinctive negative Eu anomaly seen in HU87-9. Arrows indicate possible ice flow directions. REE data indicate that most of the fine-grained sediment deposited at the HU87-9 site during Heinrich event 2 (H-2) came from ice streams that crossed the Foxe peninsula and then followed Hudson Strait. RR indicates the location of the Ramsay River orthogneiss, MIP indicates the Meta Incognita Peninsula, and Isl. indicates the locations of islands.

isotopic values of individual sand-size grains, the $<63\,\mu m$ fraction, or bulk sediments (Grousset et al., 1993; Gwiazda et al., 1996; Revel et al., 1996; Barber et al., 1997; Hemming et al., 1998).

In this paper, we show that rare-earth element (REE) distributions combined with Nd and Pb isotope values can be used to characterize the bedrock source of carbonate-free, $<2\,\mu m$ sediments deposited in north-eastern Labrador Sea sediments during H-2. Normal weathering of most igneous and metamorphic rocks produces a grain-size distribution similar to the mineral-size distribution of the original rock with clay minerals comprising most of the clay-size fraction. Glacial abrasion of igneous and metamorphic rocks produces a grain-size distribution containing a higher percentage of non-clay but clay-size mineral fragments (Bischoff et al., 1997). The clay-size fraction of the "rock flour" thus has a chemical composition that approximates that of the parent rock. Thus the bulk chemical composition of the clay-size fraction can be used to determine the type of bedrock that was eroded during glacial advances (Bischoff et al., 1997; Benson et al., 1998). In cores that contain primary carbonate (e.g., coccoliths, foraminifera), it is often difficult to identify Heinrich events solely on the basis of carbonate concentrations. Using the carbonate-free clay-size fraction has the potential to resolve this difficulty as well as aid in tracing current-borne material produced during a Heinrich event. We also show that the results from elemental analyses complement and are consistent with provenance results obtained by analyzing Nd and Pb isotopic signatures of the fine sediment fraction ($<63\,\mu m$) from the same samples (Barber, 2001).

Material from eastern Canada may have been transported to the Labrador Sea by glaciers that scoured Cumberland Sound (Baffin Island), Hudson Strait, and the Torngat Peninsula (Fig. 1). Potential transport mechanisms for non-carbonate clay-size particles found within the H-2 interval in HU87-9 include glacial erosion and subglacial meltwater outflows from Hudson Strait and Cumberland Sound. Previous work (Jennings et al., 1996) showed that HU87-9 received kaolinite and dolomite eroded from Cumberland Sound sediments before and after H-2, but that deposition of limestone-rich sediments, possibly derived from Hudson Strait, dominated during H-2.

We have excluded eastern source regions (Iceland, the Reykjanes Ridge, and Greenland) of glacial clay-size materials from our consideration (Fig. 1). These regions contribute materials to deep areas in the Labrador Sea via the Western Boundary Undercurrent (WBUC) (Rabinowitz and Eittreim, 1974; Fagel et al., 1996). However, core HU87-9 was recovered in 1447 m of water, ~ 500 m above the present upper boundary of the WBUC; therefore, it is probable that sediment transported via the WBUC would have been deposited at depths greater than that of HU87-9. In addition, Fagel et al. (1997) have shown, using smecite/illite ratios in core HU90-13 from the Labrador Basin, that the WBUC was weaker and probably deeper during H-2.

2. Sampling and methods

Our samples come from the northeastern Labrador Sea (core HU87033-009, 62.5°N, 59.4°W; 1447 m water depth) (Fig. 1). HU87-9 contains a series of distinct detrital carbonate (DC) events which can be correlated on the basis of AMS ^{14}C dates to H-events in the North Atlantic (Bond et al., 1992; Jennings et al., 1996; Kirby and Andrews, 1999). DC-2 is 60-cm thick and is bracketed by reservoir-corrected (−450 yr) ^{14}C dates of 20.66±0.22 and 20.33±0.26 kyr obtained on planktic foraminifera (Kirby and Andrews, 1999). In HU87-9, seven samples were taken from within H-2 and four samples were taken from hemipelagic sediments on either side of this distinct carbonate-rich event. A core log for HU87-9 is illustrated in Jennings et al. (1996).

For the elemental analyses, the cation exchange sites of samples were saturated prior to digestion with Cs to provide an approximate indicator of the amount of expandable clay in each sample. Separation of the clay-size fraction, removal of carbonate minerals, sample digestion, Cs exchange, and ICP-AES and ICP-MS analyses are discussed in Garbarino and Taylor (1993), Briggs (1996) and Benson et al. (1998).

Nd and Pb isotopic data were obtained by Barber (2001). For the isotopic analyses, samples were obtained from ice-proximal glacial-marine diamicts located in the western part of the Hudson Strait and in Cumberland

Table 1
Elements whose concentrations increase during Heinrich event 2. Concentrations of Al, K are in wt%; all other concentrations in μg/g; H-2 indicates samples deposited during Heinrich event 2

Depth (cm)		Al	Be	Ce	Eu	Ho
535–536		8.9±0.5	2.0±0.2	100±9	0.99±0.09	0.48±0.02
550–552		8.5±0.3	1.8±0.1	94±2	0.89±0.06	0.42±0.00
654–656	H-2	9.2±0.2	2.2±0.1	113±8	1.00±0.07	0.45±0.01
657–659	H-2	9.6±0.5	2.5±0.1	121±7	1.12±0.09	0.55±0.03
659–661	H-2	8.9±0.3	2.4±0.2	114±4	1.11±0.05	0.55±0.03
661–663	H-2	8.9±0.2	2.4±0.0	116±0	1.04±0.00	0.54±0.00
668–670	H-2	9.4±0.7	2.3±0.1	116±4	1.09±0.08	0.54±0.03
680–682	H-2	9.5±0.3	2.1±0.0	88±7	0.81±0.07	0.35±0.02
695–696	H-2	8.9±0.2	2.2±0.1	124±2	1.07±0.07	0.54±0.01
750–752		7.6±0.2	1.5±0.1	64±3	0.68±0.02	0.30±0.01
920–922		8.2±0.2	1.8±0.1	62±4	0.72±0.06	0.35±0.02
		K	La	Li	Nd	Rb
535–536		2.57±0.04	44±3	77±7	31±3	148±2
550–552		2.28±0.05	42±1	76±4	27±1	153±2
654–656	H-2	2.86±0.12	54±0	81±4	33±2	172±5
657–659	H-2	3.34±0.05	56±3	97±6	38±1	173±7
659–661	H-2	3.25±0.08	54±2	82±3	36±1	171±4
661–663	H-2	3.19±0.11	53±0	83±2	37±2	169±7
668–670	H-2	3.17±0.04	53±1	85±9	36±1	174±5
680–682	H-2	3.34±0.03	44±0	84±5	27±2	171±2
695–696	H-2	2.77±0.10	55±0	80±2	37±0	168±3
750–752		2.33±0.05	29±1	62±2	19±1	149±8
920–922		2.39±0.08	29±2	62±1	19±2	164±4
		Sm	Th	U	Y	Zr
535–536		4.6±0.3	9.0±0.3	1.4±0.0	12.3±0.4	116±3
550–552		4.1±0.2	8.8±0.4	1.0±0.1	10.9±0.2	116±3
654–656	H-2	5.1±0.3	11.7±0.3	1.7±0.0	13.0±0.6	141±8
657–659	H-2	5.6±0.3	10.8±0.7	2.3±0.1	14.7±0.5	149±8
659–661	H-2	5.5±0.3	10.0±0.6	2.1±0.1	15.5±0.6	144±6
661–663	H-2	5.6±0.3	11.4±0.3	2.3±0.1	15.1±0.1	148±0
668–670	H-2	5.4±0.3	10.7±0.2	2.1±0.0	14.7±0.7	152±3
680–682	H-2	3.8±0.2	8.6±0.3	1.8±0.1	9.5±0.1	133±5
695–696	H-2	5.3±0.3	11.4±0.4	1.6±0.1	14.7±0.3	136±4
750–752		3.0±0.2	6.7±0.3	0.6±0.0	7.6±0.4	96±6
920–922		3.0±0.2	6.7±0.5	1.0±0.1	9.6±0.3	119±0

Table 2
Elements whose concentrations decrease during Heinrich event 2 Concentrations of Ca, Cs, Mg, Na, Ti are in wt%; all other concentrations in μg/g; H-2 indicates samples deposited during Heinrich event 2

Depth (cm)		Ba	Ca	Co	Cs	Mg
535–536		673±11	1.19±0.01	25.5±0.1	4.21±0.13	2.70±0.11
550–552		681±17	1.33±0.00	29.5±0.7	4.42±0.22	2.88±0.06
654–656	H-2	645±1	0.92±0.01	22.4±0.8	3.37±0.04	2.41±0.05
657–659	H-2	648±14	0.86±0.03	19.8±0.9	3.20±0.11	2.67±0.08
659–661	H-2	679±34	0.86±0.00	20.4±0.7	3.29±0.14	2.43±0.05
661–663	H-2	595±13	0.86±0.04	20.5±0.3	3.00±0.08	2.44±0.03
668–670	H-2	624±7	0.99±0.06	22.0±0.5	2.61±0.08	2.69±0.00
680–682	H-2	627±0	0.77±0.00	19.1±0.2	3.08±0.12	2.57±0.02
695–696	H-2	616±38	1.08±0.00	26.3±0.2	3.33±0.04	2.69±0.04
750–752		674±26	1.29±0.02	28.1±1.8	5.58±0.23	2.93±0.01
920–922		700±15	1.39±0.02	26.8±0.4	4.53±0.15	2.67±0.15
		Mn	Na	Ni	Ti	
535–536		580±26	1.31±0.04	76±1	0.59±0.03	
550–552		621±15	1.29±0.02	86±2	0.60±0.02	
654–656	H-2	454±11	1.10±0.01	67±2	0.53±0.01	
657–659	H-2	452±16	1.12±0.01	62±3	0.48±0.02	
659–661	H-2	437±11	1.10±0.01	63±2	0.47±0.02	
661–663	H-2	425±4	1.13±0.02	60±3	0.46±0.01	
668–670	H-2	478±36	1.17±0.06	63±5	0.50±0.01	
680–682	H-2	455±4	1.17±0.02	59±1	0.49±0.01	
695–696	H-2	545±8	1.16±0.03	78±1	0.53±0.01	
750–752		617±21	1.29±0.05	82±6	0.56±0.02	
920–922		606±29	1.38±0.07	73±2	0.58±0.03	

Sound. Prior to Nd- and Pb-isotope analyses, samples were rinsed with deionized water and disaggregated by freeze drying, and then dry sieved to obtain the <63 μm fraction. Samples were leached in dilute HCl to remove carbonates and ashed to remove organic material. The siliciclastic residues were acid-digested in HF, $HClO_4$ and HNO_3. Elemental separations and isotope analyses followed techniques given in Farmer et al. (1991).

3. Results

Assuming that Cs is associated with cation exchange sites in an end-member montmorillonite; i.e., $Cs_{0.33}(Al_{1.67}Mg_{0.33})Si_4O_{10}(OH)_2$, the clay-size fraction within the H-2 event contains, on average, 25.6±2.2% smectite. Outside H-2, the clay-size fraction averages 38.4±5.0% smectite. Assuming that the non-smectite fraction was glacially derived, these data indicate that glacially derived sediments comprise most of the clay-size fraction in HU87-9 before, during, and after H-2, and that the non-smectite glacial component increases from 62% to 74% during H-2.

Elemental data from HU87-9 indicate that in the clay-size fraction concentrations of REE, Al, Be, K, Li, Rb, Th, U, Y, and Zr are elevated during H-2 and that concentrations of Ba, Ca, Co, Cs (exchange-site proxy), Mg, Mn, Na, Ni, and Ti are elevated before and after H-2. (Tables 1 and 2).

The REE distributions plotted relative to C1 non-volatile chondritic abundances (Anders and Ebihara, 1982) for HU87-9 indicate a tight distribution of samples and a pronounced negative Eu anomaly (Fig. 2A). Normalizing the REE distributions relative to the 750-cm pre-H-2 REE distribution indicates that sediments deposited during H-2 have higher REE concentrations and possess more pronounced negative Eu anomalies (Fig. 2B). One sample (680 cm) deposited within the H-2 interval has a relatively low concentration of REE and lacks the enhanced negative Eu anomaly. The Cs concentration in this sample is similar to all those within the H-2 interval, indicating no reduction in the supply of glacially derived material to the core site. This suggests that this sample was derived from a different bedrock source area. Plotting the REE distributions relative to the North American shale composite (Haskin et al., 1968) removes the negative Eu anomaly and indicates a modest negative Dy anomaly (Fig. 2C). The 680-cm sample continues to indicate a source region that differs from other samples deposited during H-2.

4. Discussion

REE data from Baffin Island and northern Labrador are available for a variety of igneous and metamorphic rocks, including alkali granites, granodiorites,

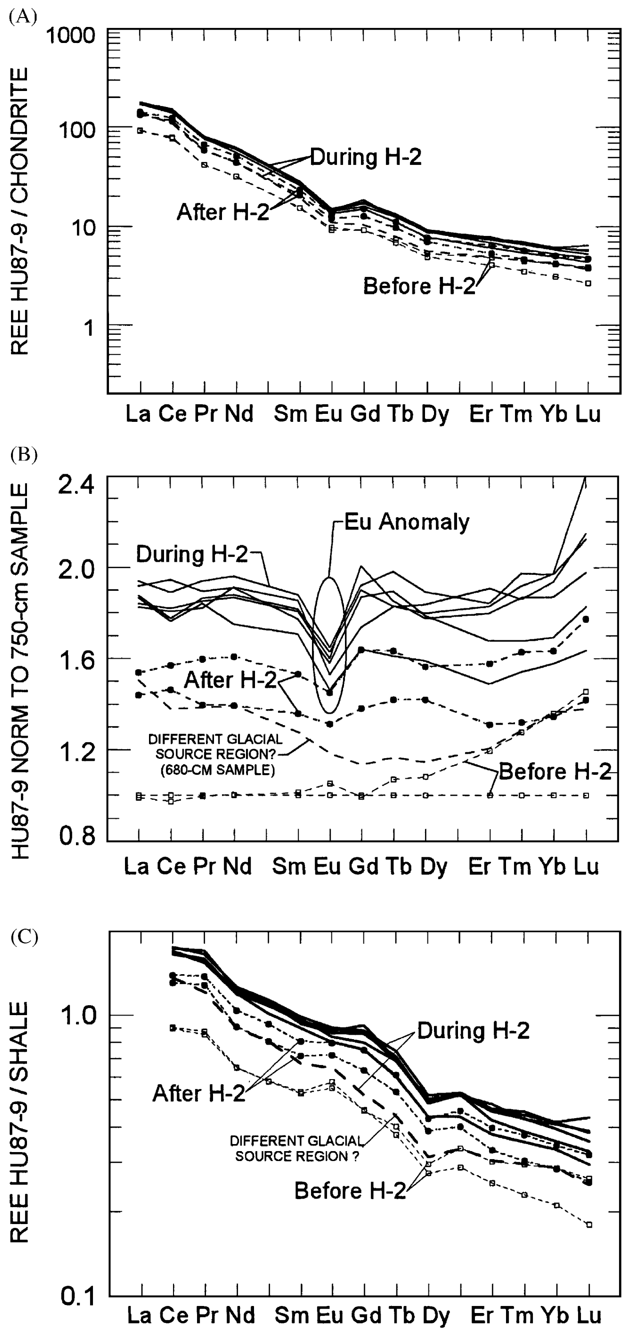

Fig. 2. (A) REE distributions of samples from HU87-9 plotted relative to C1 chondritic REE abundances; note the negative Eu anomaly. (B) Normalization of the REE distributions relative to the 750-cm pre-H-2 distribution. Eu anomaly was pronounced during H-2 (ellipse). (C) REE distributions of samples from HU87-9 plotted relative to the North American shale composite.

monzogranites, syenogranites, tonalites, gneisses, tholeiites, metasediments, metaplutonics, and metaigneous rocks (Campbell, 1997; Thériault and Ermanovics, 1997; Thériault, 1998). Rocks from the Superior Province, Cumberland Batholith, Narsajuaq Arc, and most of the Burwell Domain (Fig. 1) generally exhibit zero or positive Eu anomalies (Fig. 3A–D), excluding the regions in which they crop out as major contributors of clay-size material to HU87-9.

Six lithologic groups exhibit negative Eu anomalies, including: (1) Ramsay River orthogneisses that crop out in a small area on the north central part of the Hudson Strait, (2) Rae Province granites that crop out on the west central edge of the Torngat Peninsula, (3) Ramah Group metasediments that crop out near the eastern border of the Tasiuyak gneiss between 57.5°N and 58.5°N, (4) Lac Lomier metasediments that crop out along a north–south transect immediately west of the Tasiuyak gneiss, (5) Tasiuyak gneisses that lie along a north–south band that begins in the southern end of the Torngat Peninsula, and (6) metasediments of the Lake Harbour Group that crop out west of the Lac Lomier complex, along the northern side of the Hudson Strait, and along the northeast side of Cumberland Sound (Fig. 1). REE distributions of Ramsay River orthogneisses can be found in Thériault (1998) and Thériault and Ermanovics (1997). Outcrops of Ramsay River orthogneisses and Rae granites are too small to have contributed much glacial sediment to the Labrador Sea.

REE distributions for the Ramah, Lac Lomier, Tasiuyak and Lake Harbour rocks are depicted in Fig. 4A–D. The shapes of the negative Eu anomalies are not sufficiently distinctive to demonstrate that only one of these lithologic units was the sole source of clay-size sediments deposited during H-2. La/Yb ratios (Table 3) indicate nearly identical values for Lake Harbour Group metasediments and HU87-9 sediments, suggesting that the Lake Harbour Group was the principal source of fine-grained sediments transported to HU87-9. However, combinations of other sources (e.g. 50% Tasiuyak gneiss or 50% Lac Lomier metasediments combined with 50% Ramah) would also yield a La/Yb ratio similar to the La/Yb ratio of H-2 sediments (Table 3). We attribute the high U values of the clay-size fraction of H-2 to the presence of shales within the Lake Harbour Group; i.e., organic-rich shales often provide a reducing environment that removes U from ground water.

Nd and Pb isotopic ratios (Table 4) support a Hudson Strait source for sediments deposited in HU87-9 during H-2 (Fig. 5); i.e., sediment within H-2 overlaps in isotopic composition with the isotopic composition of diamict from the western Hudson Strait. The diamict was deposited immediately south of intensely scoured Lake Harbour Group bedrock (Figs. 1 and 5). Most Nd sotope values of sediments deposited before and after H-2 in HU87-9 are less radiogenic than Cumberland Sound values, ruling out the Sound as a source of these sediments. However, one of the HU87-9 samples has a relatively unradiogenic Nd value, similar to Cumberland Sound diamict, and supports Jennings et al. (1996) contention that kaolinite-rich, sediment deposited in

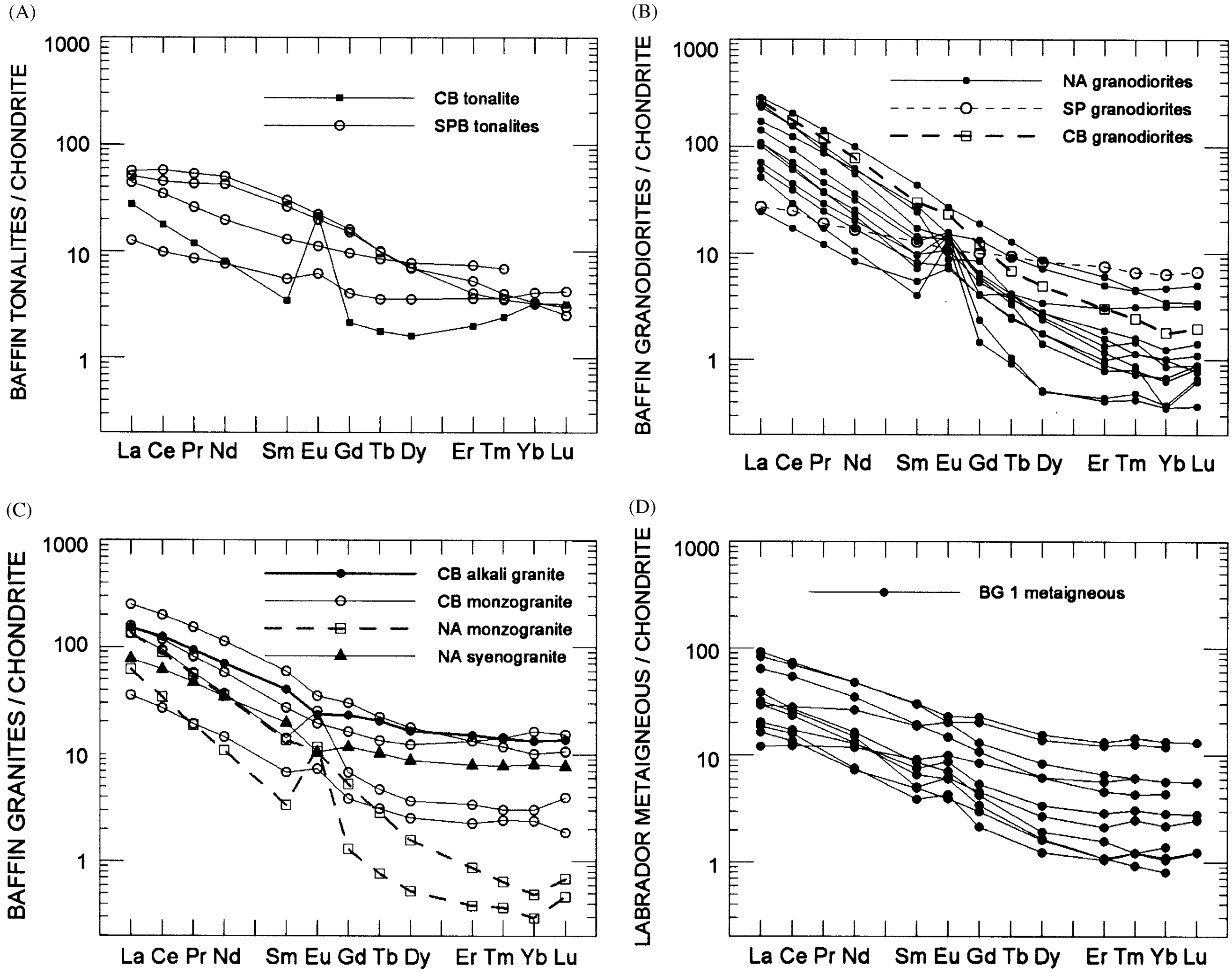

Fig. 3. REE distributions in (A) Cumberland Batholith (CB) and Superior Province (SPB) tonalites, (B) Narsajuaq Arc (NA), Superior Province (SP), and Cumberland Batholith (CB) granodiorites, (C) Cumberland Batholith (CB) and Narsajuaq Arc (NA) granites, and (D) Burwell Group (BG) metaigneous rocks (Campbell, 1997; Thériault, 1998).

HU87-9 may have derived from Cumberland Sound. Although we cannot rule out a contribution from the Tasiuyak Gneiss, Nd and Pb isotopic data, in combination with REE distributions and La/Yb values, point to the importance of the Lake Harbour Group metasediments, located on the northwestern border of Hudson Strait, as the principal source of H-2 sediment in HU87-9.

Although this study does not completely rule out a Baffin Bay or west Greenland source of sediment in HU87-9 for H-2, Andrews et al. (1998) demonstrated that DC layers, including H-2, thinned southward along the length of Baffin Bay. They concluded that the possibility of input of sediment to the North Atlantic from Baffin Bay or Greenland was slight. In addition, Farmer et al. (2003) have recently compared the isotopic compositions of ice-proximal siliciclastic glacimarine sediments from a variety of sites in the North Atlantic with values for IRD in the North Atlantic and have confirmed that Hudson Strait is the likely source of low $\varepsilon_{Nd}(0)(<-15)$ detritus in H-2.

5. Summary and conclusions

In this study, we have shown that the percentage of non-carbonate clay-size sediments increased from 62% to 74% during H-2, signaling an increase in the discharge of ice to the Labrador Sea. REE distributions and other elemental concentrations (e.g. Al, Ba, Be, Ca, Cd, K, Li, Rb, Th, U, and Zr) are useful in distinguishing clay-size sediments deposited during H-2.

Comparison of REE distributions of lithologic units that constitute the bedrock of Baffin Island and north-eastern Labrador with REE distributions in sediments deposited during H-2 in HU87-9 enables us to eliminate the Superior Province, Cumberland Batholith, Narsajuaq Arc, and most of the Burwell Domain as major

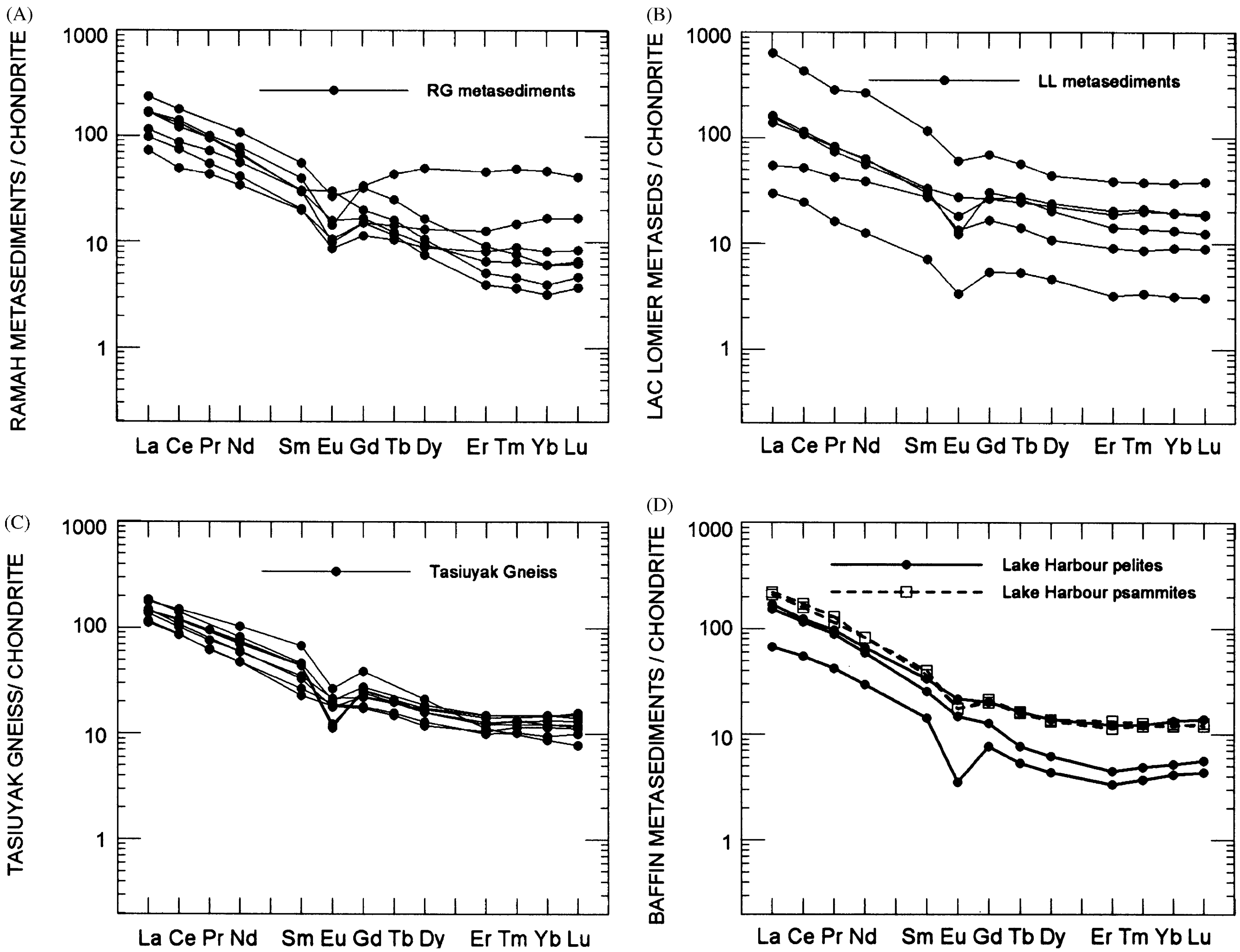

Fig. 4. REE distributions in (A) Ramah Group (RG) metasediments, (B) Lac Lomier (LL) metasediments, (C) Tasiuyak gneisses, and (D) Lake Harbour metasediments (Thériault and Ermanovics, 1997; Thériault, 1998).

Table 3
La/Yb ratios for Baffin Island/Labrador rocks and HU87-9 sediments

SITE	La/Yb
Lake Harbour Group	28±09
Ramsay River	(15–500)
Lac Lomier	16±08
Ramah	43±27
Tasiuyak Gneiss	18±05
HU87-9 (H-2)	31±03
HU87-9 (outside H-2)	28±04

contributors of clay-size material to HU87-9. This allows us to exclude much of the southern half of Baffin Island and northern Quebec as sources of fine-grained sediment reaching HU87-9. Comparison of Nd and Pb isotopic ratios from Cumberland Sound and Hudson Strait diamicts with isotopic ratios from HU87-9 sediments also allows us to rule out Cumberland Sound as a source area for most sediments found in HU87-9 (Fig. 5).

There are several lithologic units that crop out along the Hudson Strait and on the Torngat Peninsula of Labrador that possess a distinctive Eu anomaly similar to the anomaly that characterizes clay-size sediments deposited during the H-2 event in HU87-9. However, only Lake Harbour metasediments possess La/Yb ratios that are nearly identical to those found in sediments from the H-2 interval. This conclusion is supported by Nd and Pb isotope analyses of the $<63\,\mu m$ fraction (Barber, 2001). These findings also corroborate previous modeling studies suggesting that a Hudson Strait ice stream emanating from near Hudson Bay is the only source capable of supplying sufficient iceberg volume to create the observed Heinrich layer thicknesses and sea-surface freshening (Alley and MacAyeal, 1994; Dowdeswell et al., 1995; Cortijo et al., 1997; Marshall and Clarke, 1997). The importance of the Lake Harbour Group as a source of sediments deposited during the H-2 event in HU87-9 is, thus, in good agreement with

Table 4
$^{206}Pb/^{204}Pb$ and $\varepsilon_{Nd}(0)$ reported in Barber (2001) and shown in Fig. 5

Location/Core No./Sample No.	Depth (cm)	Sample source	$^{206}Pb/^{204}Pb$	$\varepsilon_{Nd}(0)$
W Hudson Strait				
HU90023-101				
GRL-8040	398–400	W. Hudson St. diamict	17.95	−28.17
GRL-8048	657–661	W. Hudson St. diamict	18.09	−28.89
GRL-8050	727–729	W. Hudson St. diamict	18.75	−28.11
Cumberland SND				
HU85027-029 PC				
GRL-4777	1027–1078	Cumberland Sound diamict	16.04	−29.20
HU85027-031 PC				
GRL-4896	778–782	Cumberland Sound diamict	17.22	−29.22
NW Labrador Sea Slope				
HU87-033-009				
GRL-6440	30–32	Outside H-2	16.47	−26.47
GRL-6453	170–172	Outside H-2	17.22	−29.79
GRL-6633	430–432	Outside H-2	15.83	−23.14
GRL-6881	550–552	Outside H-2	16.76	−25.89
GRL-6892	659–661	Within H-2	17.42	−28.03
GRL-6893	670–672	Within H-2	17.52	−27.99
GRL-6894	680–682	Within H-2	18.49	−28.66
GRL-6901	760–762	Outside H-2	16.00	−25.38
GRL-6918	890–892	Outside H-2	15.75	−22.26

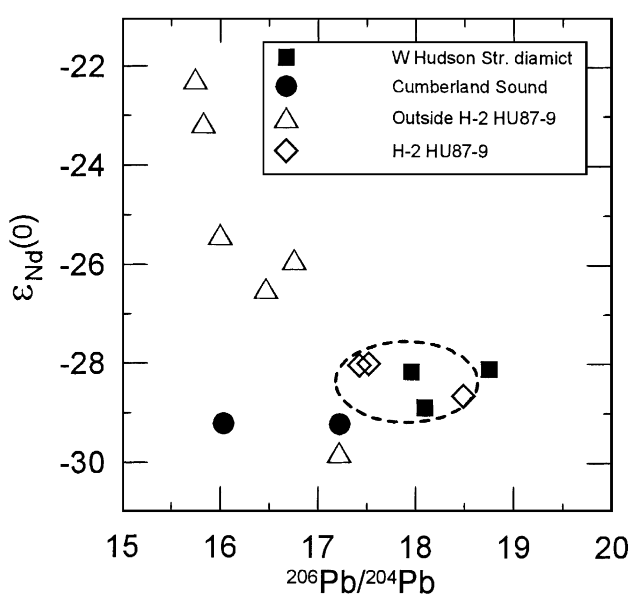

Fig. 5. $\varepsilon_{Nd}(0)$ and $^{206}Pb/^{204}Pb$ isotopic data fields from Barber (2001). Open triangles indicate samples from above and below H-2 in core HU87-9. Open diamonds surrounded by dashed ellipse indicates samples deposited during H-2 in HU87-9. Filled squares are samples of ice-proximal diamict in the western Hudson Strait, and filled circles are samples of ice-proximal subglacial diamict from Cumberland Sound. Note that $\varepsilon_{Nd}(0)$ expresses the deviation of measured $^{143}Nd/^{144}Nd$ isotopic compositions from a present-day $^{143}Nd/^{144}Nd_{CHUR}$ composition of 0.512638; i.e., $\varepsilon_{Nd}(0) = [(\text{measured } ^{143}Nd/^{144}Nd/0.512638) - 1] \times 10^4$.

the pattern of glacial erosion in Hudson Strait as determined by Andrews et al. (1985) and Laymon (1992).

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References

Alley, R.B., MacAyeal, D.R., 1994. Ice-rafted debris associated with binge-purge oscillations of the Laurentide ice sheet. Paleoceanography 9, 503–511.

Anders, E., Ebihara, M., 1982. Solar-system abundances of the elements. Geochimica et Cosmochimica Acta 46, 2363–2382.

Andrews, J.T., 1998. Abrupt changes (Heinrich events) in late Quaternary North Atlantic marine environments: a history and review of data and concepts. Journal of Quaternary Science 13, 3–16.

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

Andrews, J.T., Stravers, J.A., Miller, G.H., 1985. Patterns of glacial erosion and deposition around Cumberland Sound, Frobisher Bay and Hudson Strait and the location of ice streams in the Eastern Canadian Arctic. In: Andrews, J.T. (Ed.), Models in Geomorphology. Allen and Unwin, Boston, pp. 93–117.

Andrews, J.T., Kirby, M., Aksu, A., Barber, D.C., Meese, D., 1998. Late Quaternary detrital carbonate (DC-) layers in Baffin

Bay marine sediments (67°–74°N): correlation with Heinrich events in the North Atlantic. Quaternary Science Reviews 17, 1125–1137.

Barber, D.C., 2001. Laurentide ice sheet dynamics from 35 to 7 ka: Sr–Nd–Pb isotopic provenance of NW North Atlantic margin sediments. Ph.D. Thesis, University of Colorado, Boulder, 160pp, unpublished.

Barber, D.C., Farmer, G.L., Andrews, J.T., 1997. Ice-flow paths during Heinrich events in the Hudson Strait region: provenance data from Nd and Pb isotopes. Eos Transactions, American Geophysical Union 78, 311.

Benson, L.V., May, H.M., Antweiler, R.C., Brinton, T.I., Kashgarian, M., Smoot, J.P., Lund, S.P., 1998. Continuous lake-sediment records of glaciation in the Sierra Nevada between 52,000 and 12,500 ^{14}C yr B.P. Quaternary Research 50, 113–127.

Bischoff, J.L., Menking, K.M., Fitts, J.P., Fitzpatrick, J.A., 1997. Climatic oscillations 10,000–155,000 yr B.P. at Owens Lake, California, reflected in glacial rock flour abundance and lake salinity in core OL-92. Quaternary Research 48, 251–260.

Bond, G., Heinrich, H., Broecker, W.S., Labeyrie, L., McManus, J., Andrews, J.T., Huon, S., Jantschik, R., Clasen, S., Simet, C., Tedesco, K., Klas, M., Bonani, G., Ivy, S., 1992. Evidence for massive discharges of icebergs into the glacial Northern Atlantic. Nature 360, 245–249.

Briggs, P.H., 1996. Analytical Methods Manual for the Mineral Resource Surveys Program. U.S. Geological Survey Open-File Report 96–525, pp. 77–94.

Broecker, W.S., 1994. Massive iceberg discharges as triggers for global climate change. Nature 372, 421–424.

Broecker, W.S., Bond, G., McManus, J., Klas, M., Clark, E., 1992. Origin of the Northern Atlantic's Heinrich events. Climatic Dynamics 6, 265–273.

Campbell, L.M., 1997. Isotopic and geochemical investigations of Precambrian continental crust in the Torngat Orogen, Northeastern Canada: constraints on the mechanisms of Precambrian crust formation and on the early Proterozoic assembly of Northeastern Laurentia. Ph.D. Thesis, University of Colorado, Boulder, 193p, unpublished.

Cortijo, E., Labeyrie, L., Auffret, G., 1997. Changes in sea surface hydrology associated with Heinrich event 4 in the North Atlantic ocean between 40 and 60 degrees N. Earth and Planetary Sciences Letters 146, 29–42.

Dowdeswell, J.A., Maslin, M.A., Andrews, J.T., McCave, I.N., 1995. Iceberg production, debris rafting, and the extent and thickness of Heinrich layers (H-1,H-2) in North Atlantic sediments. Geology 23, 301–304.

Fagel, N., Robert, C., Hillaire-Marcel, C., 1996. Clay mineral signature of the NW Atlantic boundary undercurrent. Marine Geology 130, 19–28.

Fagel, N., Hillaire-Marcel, C., Robert, C., 1997. Changes in the western boundary undercurrent outflow since the last glacial maximum from smectite/illite ratios in deep Labrador Sea sediments. Paleoceanography 12, 79–96.

Farmer, G.L., Broxton, D.E., Warren, R.G., Pickthorn, W., 1991. Nd, Sr and O isotopic variations in metaluminous ash-flow tuffs and related volcanic rocks at the Timber Mountain/Oasis Valley Caldera complex, SW Nevada: implications for the origin and evolution of large-volume silicic magma bodies. Contributions to Mineralogy and Petrology 109, 53–68.

Farmer, G.L., Barber, D., Andrews, J., 2003. Provenance of Late Quaternary ice proximal sediments in the North Atlantic; Nd, Sr and Pb isotopic evidence. Earth and Planetary Science Letters, in review.

Garbarino, J.R., Taylor, H.E., 1993. Inductively coupled plasma-mass spectrometric method for the determination of dissolved trace elements in water. U.S. Geological Survey Open-File Report 94–358, 92pp.

Grousset, F.E., Labeyrie, L., Sinko, J.A., Cremer, M., Bond, G., Duprat, J., Cortijo, E., Huon, S., 1993. Patterns of ice-rafted detritus in the glacial North Atlantic (40–55°N). Paleoceanography 8, 175–192.

Gwiazda, R.H., Hemming, S.R., Broecker, W.S., Onsttot, T., Mueller, C., 1996. Evidence from Ar/Ar ages for a Churchill province source of ice-rafted amphiboles in Heinrich layer 2. Journal of Glaciology 42, 440–446.

Haskin, L.A., Haskin, M.A., Frey, F.A., Wildman, T.R., 1968. Relative and absolute terrestrial abundance of the rare earths. In: Ahrens, L.H. (Ed.), Origin and Distribution of Elements. Pergamon, Oxford, pp. 880–912.

Heinrich, H., 1988. Origin and consequences of cyclic ice rafting in the Northeast Atlantic Ocean during the past 130,000 years. Quaternary Research 29, 143–152.

Hemming, S.R., Broecker, W.S., Sharp, W.D., Bond, G.C., Gwiazda, R.H., McManus, J.F., Klas, M., Hajdas, I., 1998. Provenance of Heinrich layers in core V28-82, Northeastern Atlantic: ^{40}Ar/^{39}Ar ages of ice-rafted hornblende, Pb isotopes in feldspar grains, and Nd–Sr–Pb isotopes in the fine sediment fraction. Earth and Planetary Science Letters 164, 317–333.

Hesse, R., Khodabakhsh, S., 1998. Depositional facies of late Pleistocene Heinrich events in the Labrador Sea. Geology 26, 103–106.

Jennings, A.E., Tedesco, K.A., Andrews, J.T., Kirby, M.E., 1996. Shelf erosion and glacial ice proximity in the Labrador Sea during and after Heinrich events (H-3 or 4 to H-0) as shown by foraminifera. In: Andrews, J.T., Austin, W.E.N., Bergsten, H., Jennings, A.E. (Eds.), Late Quaternary Palaeoceanography of the North Atlantic Margins. Geological Society Special Publications, pp. 29–49.

Kirby, M.E., Andrews, J.T., 1999. Mid-Wisconsin Laurentide ice sheet growth and decay: implications for Heinrich events 3 and 4. Paleoceanography 14, 211–223.

Laymon, C.A., 1992. Glacial geology of Western Hudson Strait, Canada with reference to Laurentide ice sheet dynamics. Geological Society of America Bulletin 104, 1169–1177.

Marshall, S.J., Clarke, G.K.C., 1997. A continuum mixture model of ice stream thermomechanics in the Laurentide ice sheet, I. Theory. Journal of Geophysical Research 102, 20599–20613.

Rabinowitz, P.D., Eittreim, S.L., 1974. Bottom current measurements in the Labrador Sea. Journal of Geophysical Research 79, 4085–4090.

Revel, M., Sinko, J.A., Grousset, F.E., Biscaye, P.E., 1996. Sr and Nd isotopes as tracers of North Atlantic lithic particles: Paleoclimatic implications. Paleoceanography 11, 95–113.

Shilts, W.W., 1980. Flow patterns in the central North American ice sheet. Nature 286, 213–218.

Stravers, J.A., 1986. Glacial Geology of the outer Meta Incognita Peninsula, Southern Baffin, Island, Arctic Canada. Ph.D. Thesis, University of Colorado, 231pp, unpublished.

Sugden, D.E., 1977. Reconstruction of the morphology, dynamics and thermal characteristics of the Laurentide ice sheet at its maximum. Arctic and Alpine Research 9, 21–47.

Thériault, R.J., 1998. Nd and Pb isotopic and geochemical framework of Paleoproterozoic Southern Baffin Island, and comparisons with other segments of the Eastern Trans-Hudson Orogen, in Eastern Canadian shield Onshore–Offshore transect (ECSOOT) Report of 1998 transect meeting, Merrickville, Ontario. Lithoprobe Report 68, 170–187.

Thériault, R.J., Ermanovics, I., 1997. Sm–Nd isotopic and geochemical characterization of the Paleoproterozoic Torngat Orogen, Labrador, Canada. Precambrian Research 81, 15–35.