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Article abstract

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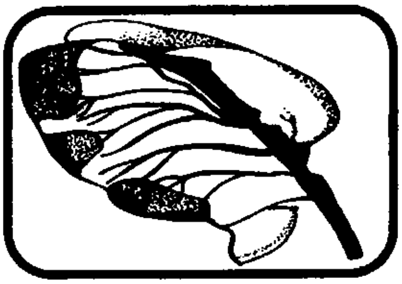
Articles



Ice-sheet Sourced Juxtaposed Turbidite Systems in Labrador Sea

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SUMMARY

Ice-sheet sourced Pleistocene turbidite systems of the Labrador Sea are different from non-glacially influenced systems in their facies distribution and depositional processes. Two large-scale sediment dispersal systems are juxtaposed, one mud-dominated and associated with the Northwest Atlantic Mid-Ocean Channel (NAMOC), the other sand-dominated and forming a huge submarine braided sandplain. Co-existence of the two systems reflects grain-size separation of the coarse and fine fractions on an enormous scale, caused by sediment winnowing at the entrance points of meltwater from the Laurentide Ice Sheet (LIS) to the sea (Hudson Strait, fiords) and involves a complex interplay of depositional and redepositional processes. The mud-rich NAMOC system is multi-sourced and represents a basinwide converging system of tributary canyons and channels. It focusses its sand load to the central trunk channel in basin centre, in the fashion of a "reverse" deep-sea fan. The sand plain received its sediment from the Hudson Strait by turbidity currents that were generated either by failure of glacial prodelta slopes at the ice margin, or by direct meltwater discharges with high bedload concentration. We speculate that the latter might have been related to subglacial-lake outburst flooding through the Hudson Strait, possibly associated with ice-rafting (Heinrich) events.

RÉSUMÉ

Les dépôts turbiditiques pleistocènes d'origine glaciaire de la mer du Labrador diffèrent d'autres dépôts turbiditiques non-glaciaires, autant par leurs faciès que par leurs processus de sédimentation. Deux grands complexes de dépôts sédimentaires se jouxtent, l'un comprenant surtout des sédiments à grains fins, relié au Chenal Médio-Océanique de l'Atlantique nord-ouest (CMNOA) et l'autre, comprenant surtout des sables et formant une gigantesque plaine à chenaux anastomosée sous-marine. La co-existence de ces deux systèmes reflète la séparation par taille des grains des fractions grossières et fines sur une échelle énorme et est le résultat de l'action d'un gigantesque mécanisme de vannage, existant aux points d'entrée des eaux de fonte de la calotte glaciaire des Laurentides (CGL) dans la mer (détroit de Hudson et fiords) et qui est à l'origine de processus complexes de sédimentation et de re-sédimentation. Le complexe riche en boues de CMNOA s'alimente à plusieurs sources et agit à l'échelle du bassin où convergent les apports sédimentaires de nombreux canyons et chenaux tributaires. Il concentre la portion sableuse de sa charge dans le chenal central, au centre du bassin, à la façon d'un éventail sédimentaire profond inversé. Les sédiments arrivent à la plaine d'épandage par le détroit de Hudson, transportés par des courants de turbidité déclenchés par des ruptures des pentes prodeltaïques glaciaires à la bordure de la marge glaciaire, ou par les eaux de fontes à fortes charges de fond ; ce dernier type d'apport aurait pu être lié à une rupture de lac sous-glaciaire par le détroit de Hudson, et possiblement associé à des événements Heinrich.

INTRODUCTION

Increasing research activity in arctic and subarctic regions has improved our knowledge and understanding of glaciomarine depositional processes and environments, including those of the deep sea. In the deep Labrador Sea, the interpretation of Late Pleistocene turbidite systems has changed fundamentally over the past 10 years and revealed significant differences to mid- to low-latitude turbidite systems lacking glacial sources. The purpose of this paper is to review the characteristics of ice-sheet sourced deep-marine depositional systems for a general readership and to identify differences between ice-sourced and non-glacial systems.

ICE SHEETS AS MAJOR DETRITAL SEDIMENT SOURCES IN THE LABRADOR SEA

At times of glacial maxima, the succes-

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sive Pleistocene Laurentide Ice Sheets (LIS) were in contact with the sea over the entire length of the Labrador continental margin (Josenhans *et al.*, 1986), partly because glacio-isostatic depression kept the Labrador Shelf submerged even at eustatic sea-level lowstands, and partly because of the extensive lateral spreading and merging of shelf glaciers from adjacent outlets. Sediment was delivered directly to the marine environment through major (Hudson Strait, Gulf of St. Lawrence) and minor outlets (fiords). Much of the material that arrived at the glacier termini was eventually dumped on the outer shelf (presently below 500-700 m water depth) and upper slope, where it was remobilized and carried to lower-slope, rise and deep-basin sites by mass-flow processes. Bedload-rich meltwater discharges from the glacier tongues could have directly formed turbidity currents. Glacially derived detrital sediment has contributed significantly to the basin fill in the Labrador Sea: 500 m of terrigenous sediment were deposited during the last 3 million years in the Late Pliocene and Pleistocene (Srivastava *et al.*, 1986), overlying 1.5 km of predominantly pelagic sediment and thus representing about 25% of the total sediment volume, supplied in less than 5% of the basin's life time.

Although the Labrador Sea was fringed by Late Pliocene–Pleistocene continental ice sheets on both the Canadian and Greenland continental margins, the asymmetric basin fill shows that the contribution from the sediment-starved Greenland side has been much less (*e.g.*, Chough *et al.*, 1987; Myers and Piper, 1988, fig.4). This is due to the much smaller drainage area of the Greenland Ice Sheet (GIS), the lack of prominent outlets comparable to the Hudson Strait or Gulf of St. Lawrence, and the persistence of the GIS, which rarely (if ever) vanished during interglacials. This paper focusses on the LIS-related sediment-dispersal systems of the Labrador Sea during the Late Wisconsinan Glaciation. Two large-scale turbidite systems occur in juxtaposition: one, a mud-dominated tributary system of slope canyons and basin channels (labelled D, E, F, G, H on Fig. 1), which has the Northwest Atlantic Mid-Ocean Channel (NAMOC; Fig. 1) as its central trunk channel; the other, sand-dominated and forming a huge submarine braided sand and gravel plain. NAMOC crosses the basin from northwest to southeast and exports sediment into the western North Atlantic. This overview is based on the results of seven cruises during the last 10 years, which used sleeve-gun and

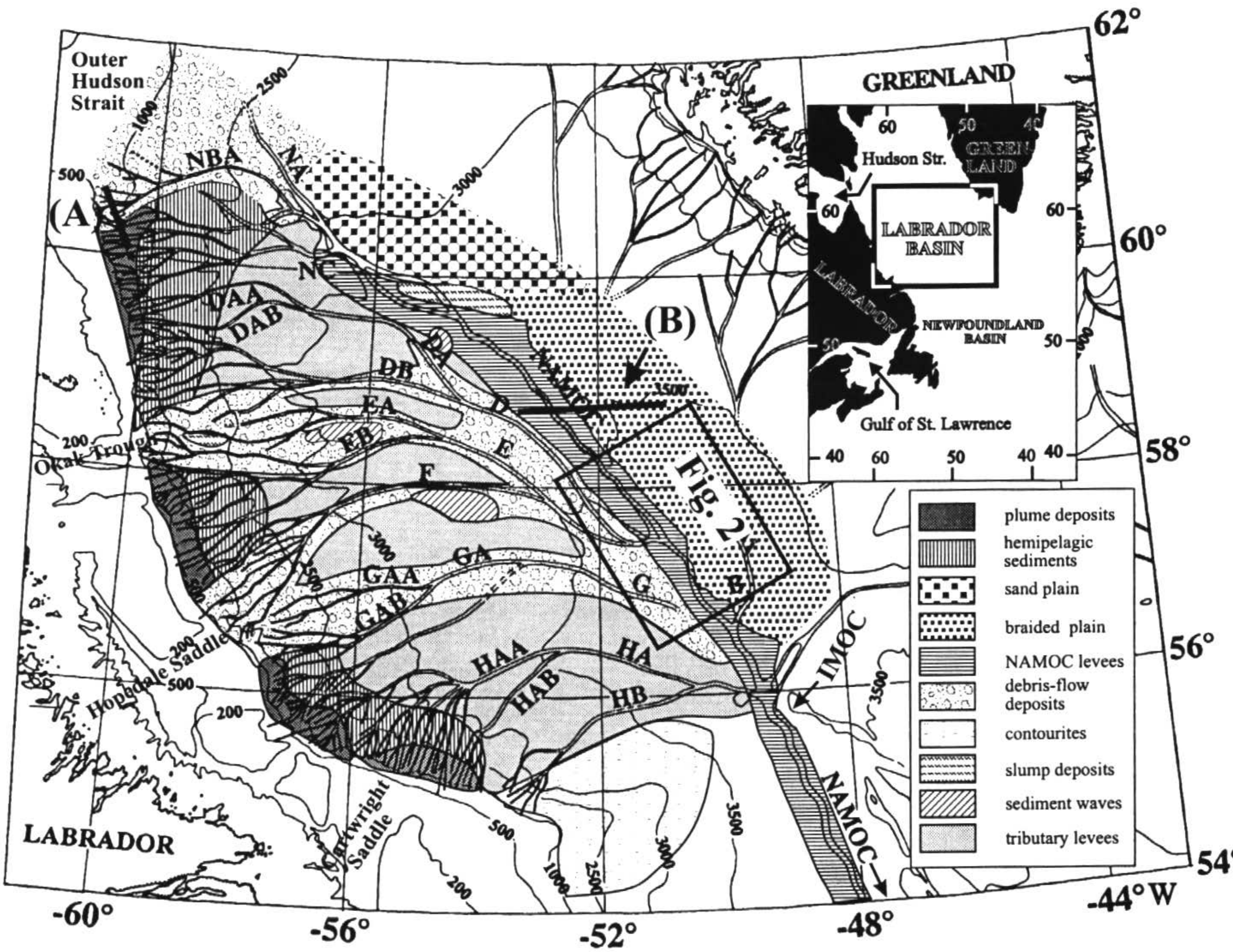


Figure 1 *Facies distribution map, Labrador Slope and Basin, based on seismic profiles, sidescan sonar imaging and ground-truthing piston cores. Bathymetric contours in meters. Letter-labelling of tributary canyons and channels (first letter) to the NAMOC is counter-clockwise around the basin slopes; letter sequence refers to progressive upslope tributary branching.*

3.5 kHz seismic profiles, 12 kHz bathymetric profiles, piston and gravity cores and culminated in the acquisition of 140,000 km² of high-quality mid-range sidescan sonar imagery in 1993, using the HAWAII MR-1 (HMR-1) system (Hesse *et al.*, 1996).

THE TWIN DEPOSITIONAL SYSTEMS OF THE NAMOC AND SUBMARINE SAND PLAIN OF THE LABRADOR SEA

Braided Sand and Gravel Plain

Discovery of a huge submarine sand and gravel plain, which is at least 600 km long and 100 km wide (Fig. 1) and is braided in its distal part (the southern 400 km; Hesse and Rakofsky 1992), was confirmed during a sidescan sonar study of a corridor 2500 km in length along the NAMOC (Hesse *et al.*, 1996). Piston cores with thick massive and graded sand layers from the region east of NAMOC provide the ground truth (Hesse *et al.*, 1990). This sand plain thus is not the lateral extension of the mud-rich eastern levee of NAMOC, as previously thought (Chough and Hesse, 1976), and contrasts with the western floodplain of NAMOC, which contains fine-grained spill-over turbidites and debris-flow deposits (Hesse *et al.*, 1987). South of 60°N, braiding is indicated by a pattern of curved ridges and furrows (erosional features) or (depositional) bars or lobes and channels (Fig. 2), which are up to 10 km long, several hundred metres wide and have a few metres of vertical relief. The apparent lack of braiding in the northern portions of the sandy plain north of about 60°N may be an imaging artifact due to a thicker Holocene mud blanket in the north, which may conceal details of the topography of the sand surface underneath. The Imarssuak Mid-Ocean Channel (IMOC, Fig. 1), which drains the East Greenland margin and West Reykjanes Basin and joins the NAMOC at about 56°N from east, delimits the braidplain in the south by trapping any sandy flows that have not run out of sediment and diverting them to the trunk channel.

The deposits of the sand and gravel partly braided floodplain onlap (and probably interfinger) with the eastern muddy NAMOC levee (Figs. 3C, 4B). Between 57°N and 56°N the levee is absent apparently as a result of local erosion by sandy flows entering the NAMOC from the plain (Figs. 3D,E). This interpretation is supported by the curvature of the braid pattern toward the NAMOC (Fig. 2B), which suggests that the flows, having generated the pattern, joined the main channel. Flows spilling over from the channel onto the levee do not have the power to erode, because they are too thick (up to 200 m, see below) to carry sand at the top. South of 56°N, seismic reflection profiles suggest that the eastern (lower) levee of NAMOC is much sandier (Figs. 4C-G), compared with the mud-rich levee north of 56°N (Klaucke *et al.*, in press (b)). Downstream from the junction with the IMOC, sand-rich flows that joined the channel may have overflowed the levees, particularly the lower eastern levee. Some of these sand-rich flows may have travelled all the way to the channel terminus on Sohm Abyssal Plain in the central West Atlantic (Fig. 4H), 3800 km from their source in Hudson Strait (Chough and Hesse, 1976).

The Mud-dominated Converging-Tributary System of NAMOC

The 100-200 m deep (Fig. 5) and (at the level of the channel floor) 2-5 km wide NAMOC is the trunk channel of a basin-wide converging system of tributary canyons and channels (Fig. 1). The system is interrupted only in the east by the braided sand plain, under which some Greenland tributaries are buried. Most tributaries from the Labrador margin join the NAMOC in the Labrador Basin, but a few have confluences farther south in the Newfoundland Basin. Some of these tributaries, like the DA, D and E channels, flow parallel to the NAMOC for several hundred kilometres (Fig. 1) in the fashion of Yazoo channels on land, because the <80 m high levees of NAMOC block their entrance to the main channel (Hesse, 1989). The NAMOC system is the *opposite of a classic deep-sea fan:* it comprises a converging system of depositional tributaries (the reverse of the diverging system of radiating distributary valleys on a fan, where the active fan valley changes position sweeping the fan surface in a windshield wiper fashion).

The NAMOC trunk channel is a low-sinuosity meandering channel with average meander radii increasing from 25 km between 59°45' and 56°N (sea-floor gradient 1:1000) to 50 km between 56° and 54°30'N (sea-floor gradient <1:1000). It becomes more or less straight further south, where basement structures such as seamounts and fracture zones control channel position and locally cause sharp deflections in channel direction. The low sinuosity of this mud-dominated deep-sea channel, where it meanders freely, unaffected by basement topography, contrasts strongly with the high-sinuosity meandering fan valleys on the Amazon Fan and other mud-dominated deep-sea fans (Clark *et al.*, 1992), which have much higher slope gradients (Klaucke and Hesse, 1996). The density and grain-size structure of the flows in NAMOC may have been quite different from those of the large low-latitude passive-margin fans, with significantly stronger vertical gradients in the case of the former (Klaucke *et al.*, in press (a)). The pronounced Coriolis-asymmetry of the channel-levee profile of NAMOC with the western (right-hand) levee rising up to 90 m above the eastern levee (Figs. 3C, 4B, 5) reflects equilibrium between channel morphology and the forces causing the flow surfaces to tilt (*i.e.*, the Coriolis force and the centrifugal force). Coherent eastward tilt of the surface of bankful flows up to 2° obtained from the channel asymmetry regardless of position (*i.e.*, for right-turning as well as for left-turning meander bends) shows that in case of the NAMOC, the Coriolis force always exceeds the centrifugal force.

Origin of the Braided Sand and Gravel Plain

Injection of large volumes of sediment-carrying glacial meltwater into the sea at major ice-sheet outlets leads to grain-size fractionation on an enormous scale. Much of the suspended load (clay-, silt- and fine sand-sized material) rises to or stays at the sea surface forming turbid-surface plumes (Hesse *et al.*, 1997; Powell, 1981; Syvitski *et al.*, 1987). The bed load (medium sand and coarser) may be deposited in proglacial deltas or forms hyperpycnal (bottom-seeking) flows that break the density barrier of sea water and directly form turbidity currents. This winnowing process is more effective in cold subpolar environments than at the mouths of large rivers in lower latitudes, where the density contrast between fresh water and sea water may be up to 20% less (Mulder and Syvitski, 1995). We attribute the origin of the submarine sand and gravel plain to this grain-size separation effect at the ice margin off the Hudson Strait. High-density, sand-rich turbidity currents that originated either from sediment failure on steep prodelta slopes in the outer Hudson Strait or during major meltwater discharges were too voluminous to be captured by the slope canyons off the strait and were thus not or only partly channelled into the NAMOC, because these tributary canyons are too small and shallow (Fig. 4A, low-relief slope sector). They are considerably smaller than adjacent canyons south of the strait (Fig. 4A, left part), because they become repeatedly buried by debris flows that are much more common on this portion of the slope than further south (Figs. 1, 4A). The turbidity currents generated one way or the other near the ice tongue of the Hudson Strait ice stream bypassed the NAMOC in the east, crossing the slope and starting to deposit their load beyond the base of slope on the sand and gravel plain.

The smaller outlets of the LIS in the fiords of the Labrador margin did not develop their own distinct sandy floodplains; therefore, where the tributaries merge on the western floodplain of NAMOC, no large-scale sand plain is observed. However, the regions of streaky backscatter reflections south of the E/F (Fig. 2A) and H tributary systems, may at least in part represent wash-over fans downstream from sharp meander bends of these tributaries where deeper sandier portions of the flows — which were much thinner than the flows in the main channel — spilled over the channel banks (Klaucke and Hesse, 1996).

The provenance of the sand from Hudson Strait is documented petrographically by a high content of detrital carbonate (Khodabakhsh, 1997), corresponding to the Canadian provenance of the sand fraction in Heinrich (iceberg rafted) layers (Andrews and Tedesco, 1992). Sediment of Greenlandian provenance has not been detected, neither on the sandy floodplain nor in NAMOC system (Chough *et al.,* 1987); however, we have not yet analysed sediment provenance south of 56°N, downstream from the confluence with the IMOC, because cores from this part of the system have become available only very recently. The IMOC may well have contributed sediment from Greenland sources to the lower reaches of NAMOC.

The sheer length of the sand and gravel plain may require flooding events of extraordinary size, particularly in view of the possibility that some of them might have continued to spread for more than 1000 or 2000 km beyond the southern end of the plain in NAMOC; however, at present we can only speculate. We also speculate that some of them may have been related to subglacial-lake outburst flooding associated with Late Pleistocene Heinrich events, short-lived periods of intensified iceberg drift in the North Atlantic that occurred every 7-10 k.y. and deposited regionally extensive layers rich in ice-rafted detritus (Broecker *et al.,* 1992; Bond *et al.,* 1993). Mass release of icebergs may have occurred when the

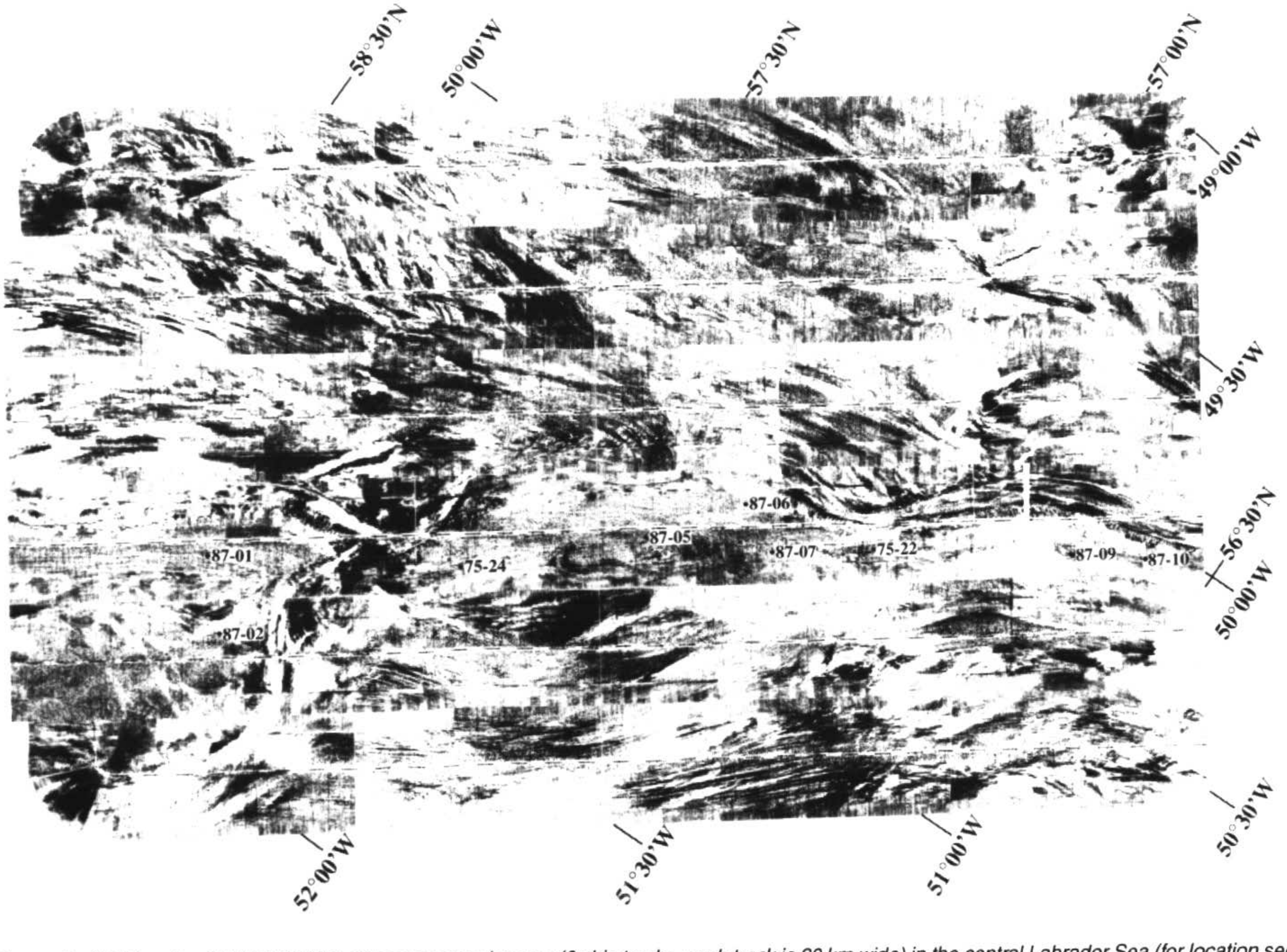


Figure 2 (**A**) *Mosaic of HAWAII MR-1 sidescan sonar images (6 ship tracks, each track is 20 km wide) in the central Labrador Sea (for location see inset in Fig. 1) showing submarine braidplain with curved ridges and sand and gravel bars (bright) immediately east of the meandering NAMOC with its muddy levees. The imagery is displayed in normal polarity,* i.e., *low backscatter reflectivity appears dark and high backscatter reflectivity bright.*

ice stream in the strait started to surge, removing an ice-barrier or end moraines that may have dammed subglacial lakes (Hesse *et al.,* 1996). Supporting evidence for catastrophic outburst flooding similar to jökulhlaups is provided by gorges cut into bedrock in the outer Hudson Strait region that may have served as spillways as suggested by Johnson and Lauritzen (1995). As these authors hypothesized, such flooding events need not have been restricted to the relatively rare Heinrich events, but could have occurred on shorter time scales (1-2 k.y.) and be related to short-term climatic fluctuations with similar frequency to those recorded in Greenland ice cores (Dansgaard *et al.,* 1993).

Origin of the NAMOC System by Remobilization of Slope Blanket of Sediments

The sediment sources of the NAMOC are numerous tributary canyons on Labrador Slope south of the Hudson Strait (Fig. 1). In water depths above 3400 m on the rise and slope, none of the canyons can be singled out as the main feeder canyon of the system, and only below this depth can the NAMOC be deciphered as its trunk channel. Few of the tributaries are directly connected with fiords that served as outlets from the LIS during glacial time. Most tributaries end blind on the relatively smooth, low-relief uppermost slope between 500 m and 700 m water depth (Fig. 1) at the limit of till deposition (Piper, 1988). The tributaries result from retrograde erosion of the mud blanket of turbid-plume deposits (plumites) and hemipelagic sediments on slope (Hesse and Klaucke, 1995) as indicated by their dendritic branching pattern of increasing upslope complexity. The NAMOC thus taps the reservoir of dominantly fine-grained sediments on the Labrador Slope delivered primarily by surface plumes and the hemipelagic rain of particles, to a lesser extent by nepheloid-layer flow, turbidity currents, and ice rafting (Wang and Hesse, 1996). The efficiency of turbid-surface plumes in distributing fine-grained sediments over the slope is a key element for the dichotomy between the juxtaposed muddy NAMOC system and the sandy braid plain (Hesse *et al.,* 1997). Their efficiency was probably enhanced by the south-flowing Labrador Current, by katabatic winds (Shipboard Scientific Party, 1987), and the nature of the suspended sediment, which contains a high proportion of fine-grained detrital carbonate (glacial flour) that is less subject to flocculation than clay-rich sediments. Ice rafting delivered both coarse and fine sediment to the slope, including Heinrich layers, which volumetrically are subordinate to other deposits. Most

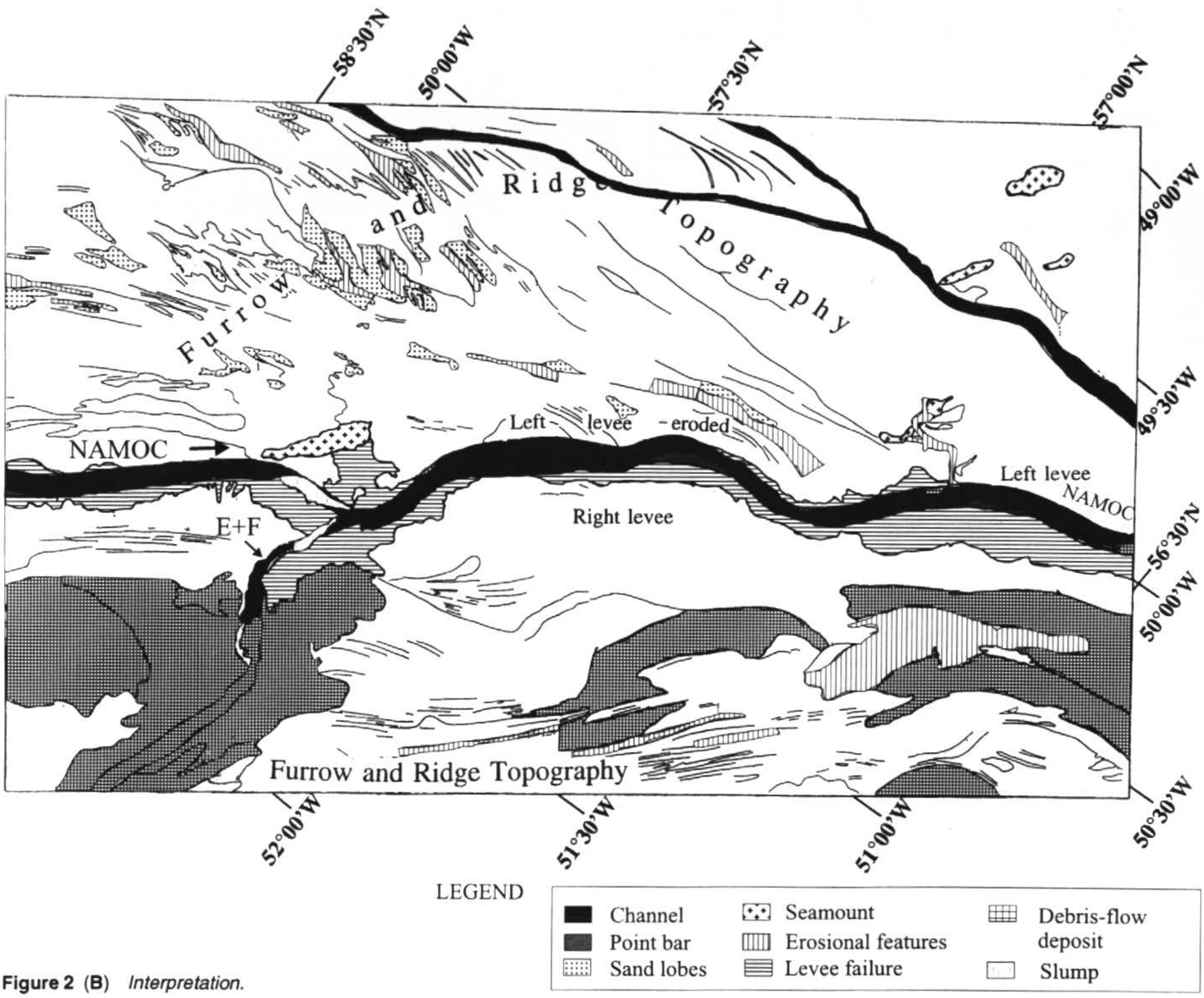


Figure 2 **(B)** *Interpretation.*

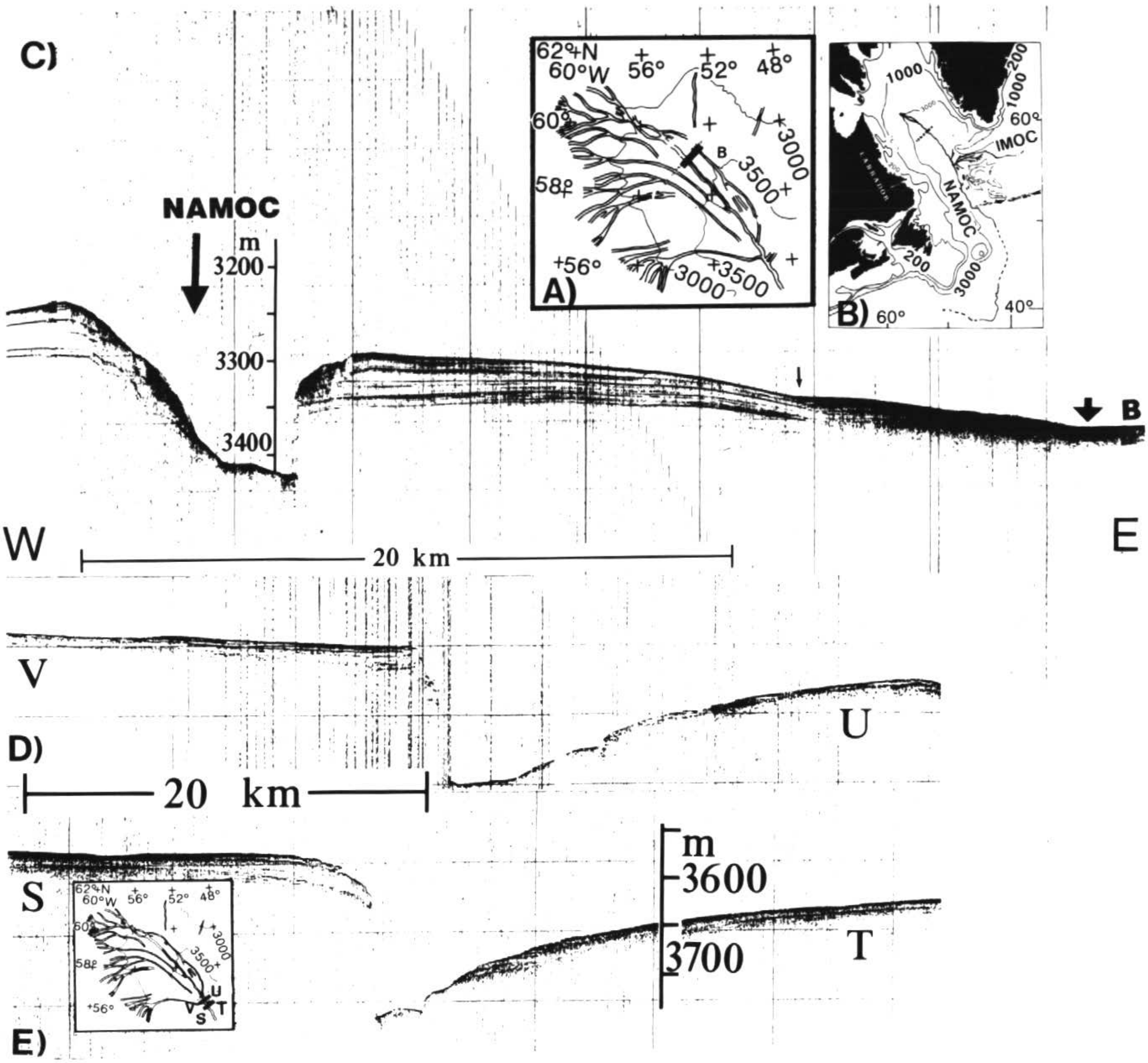
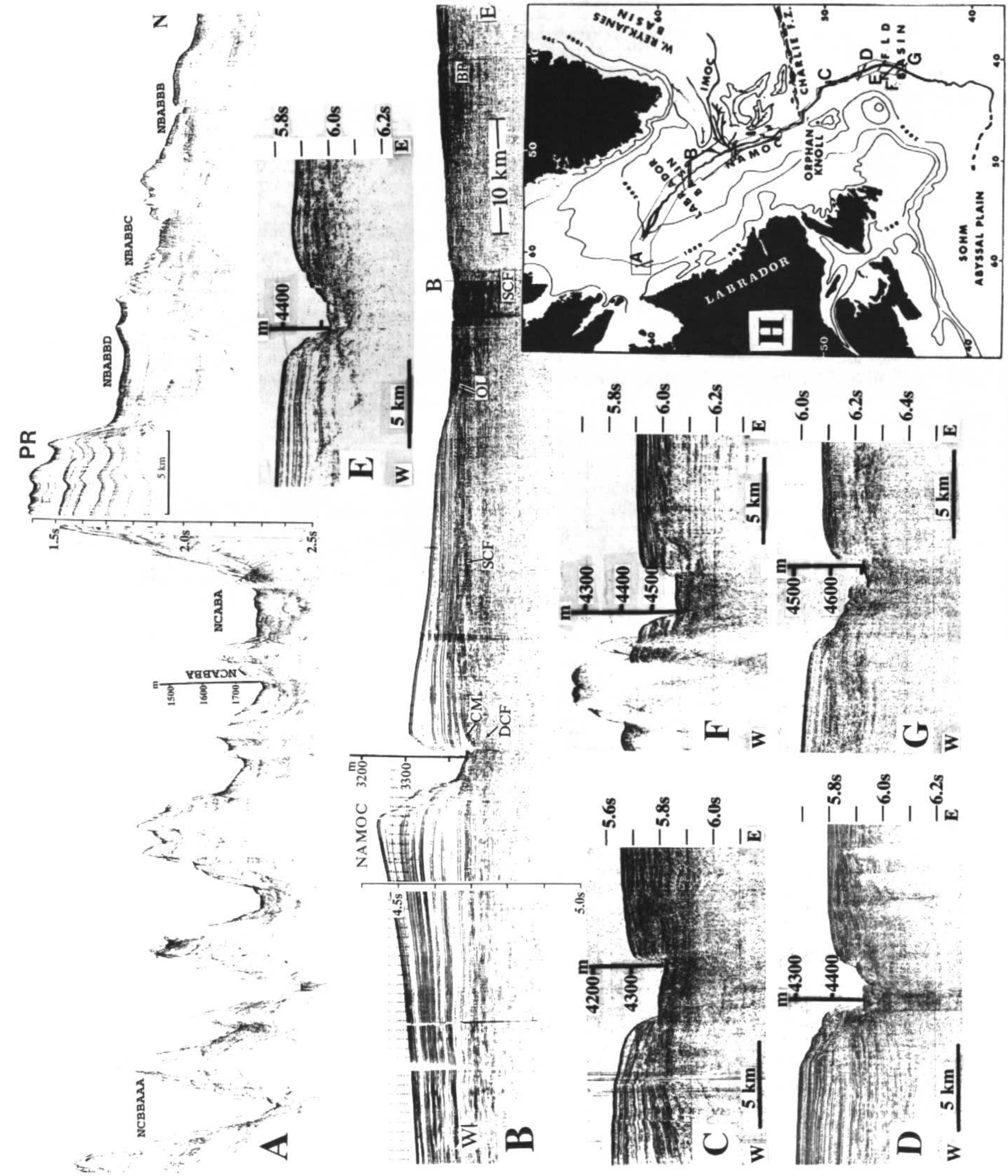


Figure 3 *3.5 kHz seismic profiles across the NAMOC between about 59° and 56°N. (**C**) Onlap on (thin arrow) and (?) interfingering of the sandy braidplain (opaque reflections under and west of channel B, marked by bold arrow) with the eastern muddy levee of NAMOC (modified from Hesse, 1989, fig. 1). The relatively transparent NAMOC levees in this profile with sharp, continuous higher-amplitude reflectors is indicative of the muddy nature of the spillover turbidites which alternate with some more reflective layers. (**D-E**) Erosion of the eastern levee and deposition of sand in profiles V-U and S-T (from Hesse and Rakofsky, 1992, fig. 6). In profiles V-U and S-T the western levee also dips towards the NAMOC providing evidence that it may have been shaped by flows from tributary channel H, rather than spillover from the main channel.*

Figure 4 (facing page) *655 cm³ (40 in³) sleeve-gun seismic profiles from Labrador Slope and Basin recorded with 25 ft NSRF hydrophone chain using 150 - 1200 Hz filter band. For location of (**A**) and (**B**) see Figure 1. (**A**) Profile along the Upper Labrador Slope at about 1,500 m water depth; vertical exaggeration: approximately 25x. The high-relief sector (left half of profile **A**, south of the Hudson Strait) shows parallel, undulating low-amplitude reflections, grouped into packages by a few higher-amplitude reflections. Deep sound penetration (up to 600 milliseconds two-way travel time or 550 m subbottom depth, assuming a sound velocity of 1.8 km·s⁻¹) is characteristic of turbid surface-plume and pelagic-dominated sedimentation. The high relief is due to retrograde canyon erosion. In low-relief sector (in front of the Hudson Strait), more highly reflective sediment under the shallow canyon floors (e.g., canyons NBABBC, NBABBB) indicates sandy canyon fill. The ridges consist of weakly stratified to transparent sediment (?) debris flow deposits cut by canyons) with sound penetration up to 400 ms (up to 350 m subbottom). The relief has been smoothed by repeated (?) debris flow deposition. (**B**) Basin section with approximately 25x vertical exaggeration at about 59°N showing the highly asymmetrical NAMOC levees and the eastern braidplain. Deep penetration and the numerous parallel, low-amplitude reflections are similar to the high-relief sector of profile A, which is the source region for the fine-grained turbidity currents that built up the levees by spilling over the NAMOC walls. The sand facies of the eastern braidplain (BP) onlaps (OL) the muddy eastern NAMOC levee truncating it. Slight lateral migration of the meandering NAMOC is indicated by a former channel margin (CM); however, the thick sand facies (**DCF**) under the NAMOC floor suggests relative stability of the channel position. (**C-G**). Profiles across the middle reaches of NAMOC between 49°35' and 44°35'N indicating a relatively high sand content of the eastern levee by high reflectivity. (**C**) Crossing at 49°N35'N. (**D**) 48°20'N. (**E**) 47° 01'N. Only this profile shows well developed levee crest on the eastern levee. (**F**) 46°10'N. Right levee onlaps seamount forming a moat. (**G**) 45°05'N. (**H**) Index map showing approximate location of profiles.*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SOHM ABYSSAL PLAIN
IMOC
CHARLIE T.Z.
W. REYKJANES BASIN

Figure 4

of the mass-flow activity (debris flows and turbidity currents) on the slope is secondary in origin, resulting from the remobilization of these sediments by slumping (Wang and Hesse, 1996).

DIFFERENCES BETWEEN ICE-SHEET SOURCED TURBIDITE SYSTEMS AND MAJOR LOWER-LATITUDE RIVER-SOURCED DEEP-SEA FANS

The differences, in order of their significance with respect to the paleoclimatic setting of the systems compared, include: 1) the multisourced *versus* single-sourced nature, 2) the efficiency of ice-margin winnowing, and 3) the vergence (convergence *versus* divergence) of the canyon/channel pattern.

Multi-sourced Nature of the NAMOC and Similar Systems

Modern large deep-sea fans typically are fed by a single major river (*e.g.*, Bouma *et al.*, 1985; Weimer and Link, 1991); line- or multisourced turbidite systems produce slope aprons and are relatively rare in non-glacial environments (Nelson *et al.*, 1991). One of the larger multisourced systems, the Maury Channel system of the Northeast Atlantic (Cherkis *et al.*, 1973), developed under similar conditions as the NAMOC system and was sourced from neighboring Pleistocene continental icecaps on Iceland and the British Isles. The smaller line-sourced system of submarine canyons on the slope off Georges Bank is also ice-margin related (Keeley, 1991), as is the Surveyor Channel system in the northeast Pacific (Ness and Kulm, 1973). The converging canyon and depositional lobe system in the southern Bering Sea is volcaniclastic, but probably also glacially influenced, although little information seems to be available on the timing of mass-flow activity with respect to glacial cycles (Kenyon and Millington, 1995).

However, there is no *a priori* reason why numerous prolific sediment sources could not also exist in the surroundings of large tropical or subtropical basins, particularly at active continental margins with proximal mountain belts. In the latter case, presence of a deep-sea trench and active subduction may, however, prevent the coalescence of smaller fans into a continuous slope apron. The western Gulf of Corinth, where fan deltas on either side of the Gulf feed into an axial channel (multisourced), which eventually debouches onto an abyssal plain (Piper *et al.*, 1990), and the multisourced Bounty Channel system off New Zealand (Carter and Carter, 1987) provide smaller-scale mid-latitude examples in non-glacial settings, but these seem to be less common than glacially influenced counterparts.

Efficiency of Ice-margin Winnowing

Separation of suspended load and bedload by large-scale winnowing at the ice margin, named ice-margin sifting by Hesse *et al.* (1996), apparently was very efficient for the Hudson Strait outlet, otherwise it could not have led to the more or less independent development of the sand-rich braid plain and the adjacent mud-rich NAMOC system. At present, no case of a similar twin system, derived from the same sediment source (*i.e.*, Hudson Strait), is known to the authors from modern or ancient deep-sea environments. However, an analog may exist in the sandy fan valleys of the Laurentian Fan and muddy levees to the west. Because of the greater incision of subglacial meltwater channels on the Scotian Shelf, which may result from the greater availability of meltwater from warm-based mid-latitude glaciers (Aksu and Piper, 1987), the upper part of Laurentian Fan is much more erosional than the slope off the Hudson Strait. Thus, abundant sands are trapped within an unusually broad (25 km wide) fan valley on the Laurentian Fan, while very muddy sediment accumulated in valley complexes with high levees parallel to this valley to the west (Piper *et al.*, 1984, 1985). Turbid surface plumes play a crucial role in this fractionation process. Although their role in glaciomarine sedimentation has been recognized for some time (Barrie and Piper, 1982; Piper and Sparkes, 1987; Pfirman and Solheim, 1989; Lemmen, 1990; Wang and Hesse, 1996; Hesse *et al.*, 1997), they have previously not attracted the attention they deserve. They may also be active contributors of fine-grained sediment to the continental slope in lower latitudes (Nemec, 1995), particularly during sea-level lowstands, but no example for fractionation of the sand and mud from a single source into separate, juxtaposed depositional systems has been found in the literature for these environments. Lateral juxtaposition of a sandy and braided floodplain and a meandering, muddy tributary-channel system is quite different from the proximal-to-distal arrangement of similar environments in river basins on land, and reflects the special conditions of ice-margin sifting.

The Converging Canyon/Channel Pattern of the NAMOC System and Absence of a Deep-sea Fan

The converging tributary pattern appears to be related more to the pond-shaped geometry of the Labrador Basin than paleoclimatic setting. This pattern has a distinct influence on the distribution of sand in the basin. Whereas deep-sea fans diffuse their sand contents in depositional lobes and interlobe depressions (Hiscott *et al.*, 1997) over the fan surface, converging mid-ocean channel systems focus sand deposition in the basin centre. This is important from an oil-

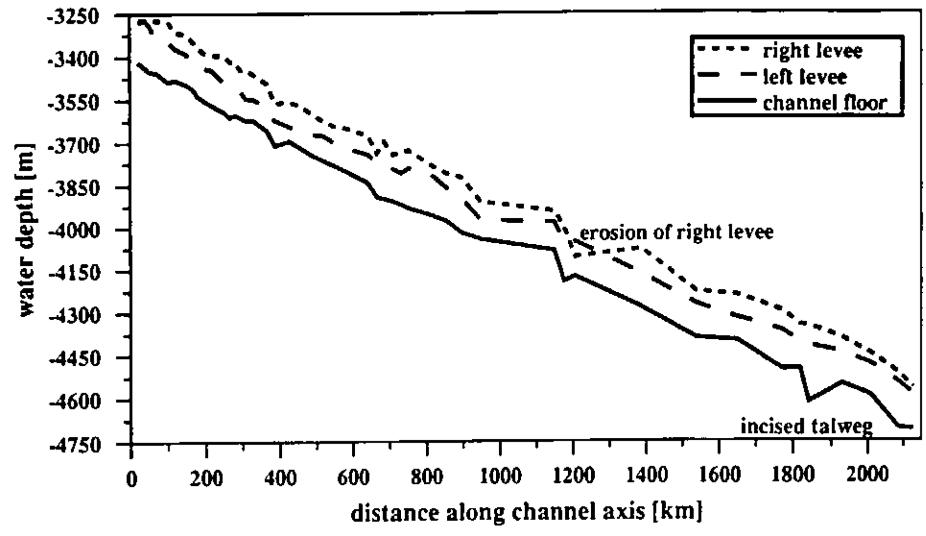

Figure 5 *Depth of the right and left levees and the channel floor of NAMOC from the confluence of the two channel branches at about 59°30'N (see Fig. 1) to about 44°30'N. Erosion of left levee by sand-rich turbidity currents from the braidplain occurred around km 400.*

explorationist's point of view for potential reservoirs in ancient high-latitude settings.

The absence of a fan off the Hudson Strait outlet may be due to the absence of a distinct change in slope gradient at the slope–rise transition, although Myers and Piper (1988) suggested that a buried fan may be present. Abrupt changes in gradient at the base of slope are thought to be responsible for the development of a hydraulic jump in mass-flows crossing the transition region, which seems to be a phenomenon conducive to fan formation. However, gradual deepening across the slope–rise boundary may have been an original feature of the northern Labrador Sea related to the possible existence of a hot spot under the Davis Strait in Early Tertiary (Hyndman, 1973; Srivastava and Arthur, 1989; Hesse and Rakofsky, 1992).

CONCLUSION

The example of the Labrador Sea reinforces the fact that continental ice sheets can be dominant sources of the basin fill in neighboring small ocean basins, generating a basin-wide drainage system. Combined with the subglacial drainage array, more than 2000 km in length, under the Hudson Bay Icedome of the LIS, the NAMOC system is one of the world's longest interconnected Pleistocene subglacial/submarine drainage systems. Hyperpycnal, bottom-seeking sedimentary gravity-flows in the system may bear an interesting relationship to surface processes of ice-rafting and turbid surface plumes, if the hypothesized association of Heinrich events and subglacial-lake outburst floods through the Hudson Strait can be substantiated by future work.

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