Imaging Laurentide Ice Sheet Drainage into the Deep Sea: Impact on Sediments and Bottom Water

Reinhard Hesse*, Ingo Klaucke, *Department of Earth and Planetary Sciences, McGill University, Montreal, Quebec H3A 2A7, Canada*
William B. F. Ryan, *Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964-8000*
Margo B. Edwards, *Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, HI 96822*
David J. W. Piper, *Geological Survey of Canada—Atlantic, Bedford Institute of Oceanography, Dartmouth, Nova Scotia B2Y 4A2, Canada*
NAMOC Study Group†

ABSTRACT

State-of-the-art sidescan-sonar imagery provides a bird's-eye view of the giant submarine drainage system of the Northwest Atlantic Mid-Ocean Channel (NAMOC) in the Labrador Sea and reveals the far-reaching effects of drainage of the Pleistocene Laurentide Ice Sheet into the deep sea. Two large-scale depositional systems resulting from this drainage, one mud dominated and the other sand dominated, are juxtaposed. The mud-dominated system is associated with the meandering NAMOC, whereas the sand-dominated one forms a giant submarine braid plain, which onlaps the eastern NAMOC levee. This dichotomy is the result of grain-size separation on an enormous scale, induced by ice-margin sifting off the Hudson Strait outlet. At the upslope end of the mud system, fine, suspended sediment was dispersed by buoyantly rising meltwater plumes and entrained by the south-flowing Labrador Current. Deposition from the turbid surface plumes blanketed the continental slope south of the strait, whose high relief was subsequently created by retrograde canyon erosion. Remobilization of this fine-grained slope sediment created the mud-rich NAMOC. In contrast, bedload-rich meltwater discharges generated sandy turbidity currents on the low-relief slope off the Hudson Strait, which basinward formed the braid plain. Periodic surging of the Hudson Strait ice stream, possibly related to subglacial-lake outburst flooding that triggered extraordinary large, bedload-rich meltwater discharges, released unusual quantities of icebergs that left their trace in Heinrich layers rich in ice-rafted debris and marked times of short-term climate cooling. The injection of large volumes of fresh or brackish water into the ocean bottom circulation may be a side effect of Heinrich events in the deep sea.

INTRODUCTION

Pleistocene continental ice caps shaped the surface of Earth more profoundly than any other geologic phenomenon of comparable duration. Their geomorphic effects on land are best known from their smaller cousins, the Alpine mountain glaciers, but these give no idea of the extent to which large, land-based ice sheets have shaped the ocean floors adjacent to ice margins. The far-reaching marine influence of ice sheets, which we have documented in sidescan sonar imagery, is little known. Our understanding of the role of continental ice sheets in Pleistocene paleoclimate change has recently changed dramatically with recognition that ice sheets may control short-term climate variations through direct ocean-atmosphere feedback (Broecker, 1994), rather than merely record orbitally forced climate change. The role of ice sheets in short-term climate change through the thermohaline circulation may be coupled with a similarly pronounced impact on deep-sea sedimentation for the Pleistocene Laurentide Ice Sheet and neighboring Labrador Sea.

HUDSON STRAIT AND THE NAMOC SUBMARINE DRAINAGE SYSTEM

The Hudson Strait played a unique role during the late Pleistocene as a single major ice-sheet outlet. Through this outlet, the subglacial drainage system of the Hudson Bay area, a 3–4 x 10^6 km^2 area (Fisher et al., 1985; Hughes, 1987) composing the northeastern sector of the Laurentide Ice Sheet, was connected with the basin-wide submarine drainage system of the Northwest Atlantic Mid-Ocean Channel (NAMOC) on the Labrador Slope and basin floor (Hesse et al., 1987; Hesse and Rakofsky, 1992). The NAMOC extends nearly 4000 km from 61°N off the Hudson Strait to 37°N in the North American Basin (Chough and Hesse, 1976). Combined with the >2000-km-long subglacial part on land, this is one of the world's longest interconnected Pleistocene land-sea drainage systems. Through its channels, glacially derived sediments were transported as far as the Sohm Abyssal Plain in the western Atlantic, some 5000 to 6000 km from their source.

Drainage of the ice sheet involved repeated collapse of the ice dome over Hudson Bay, releasing vast numbers of icebergs from the Hudson Strait ice stream in short time spans. The repeat interval was on the order of 10^4 yr. These dramatic ice-rafting events, named Heinrich events (Broecker et al., 1992), occurred throughout the North Atlantic and flooded the ocean north of 40°N with icebergs. Heinrich events were associated with short-term climate change (Bond et al., 1993) because they caused suppression of the conveyor-belt circulation. The freshwater lid from the melting icebergs prevented deep-water formation in the Norwegian Sea, which stopped the Gulf Stream from penetrating northward, thus triggering short-term Northern Hemisphere cooling (Broecker, 1994; Paillard and Labeyrie, 1994).

SEA-FLOOR MORPHOLOGY AND CHANNEL GEOMETRY

Establishing seascape morphology with high precision by sonar imaging is a fundamental first step in interpreting sea-floor evolutionary processes (e.g., Macdonald et al., 1993). To do this, state-of-the-art sidescan-sonar imagery and swath bathymetry were acquired using the HAWAII MR-1 (Hawaii Institute of Geophysics Acoustic Wide-Angle Imaging Instrument Mapping Researcher 1) system, the successor of SeaMARC II (Rognstad, 1992), on *Hudson* cruise 93-025. The system is towed 70-80 m below the water surface at 8-9 kn with the sidescan sonar operating at frequencies of 11 and 12 kHz, respectively on the port and starboard sides. Simultaneous deployment of 3.5 kHz and airgun vertical seismic systems makes this the most efficient remote-sensing package for deep-sea floor surveys. Approximately 7000 km of real-time data covering 140 000 km^2 of seafloor were obtained and used to construct up to six-track-wide mosaics of parts of the NAMOC (each track being 20 km wide).

The resulting 2500-km-long and up to 120-km-wide corridor of sidescan imagery along the course of NAMOC (Figs. 1 and 2) provides a bird's-eye view of the ocean floor diagonally across the Labrador Sea.

Ice Sheet Drainage *continued on p. 4*

*Also at: Institut für Allgemeine und Angewandte Geologie, Ludwig Maximilians Universität, Munich, Germany.

†Saeed Khodabakhsh, Larry A. Mayer, and shipboard participants J.-F. Boily, B. Chapman, R. B. Davis, J. R. Erickson, D. J. Johnson, C. Keeley, B. Konyukhov, C. Olson Major, K. Parlee, A. Peslier, S. Renaud, S. Ryan, K. L. Sender, R. Sparkes, K. Wagner, and J. S. Won.

Ice Sheet Drainage *continued from p. 3*

Four distinct morphologic regions can be recognized.

Region 1: Continental slope in <3000 m water depth (west of 57°N, sea-floor gradient >1:500). A dendritic pattern of closely spaced tributary canyons with increasingly complex upslope branching (Fig. 2) shows steep canyon walls with spectacular relief of up to 700 m (Fig. 3A) alternating with low-relief sectors. Canyons in the low-relief regions are <120 m deep and have broad floors flanked by broad ridges or levees. Low-relief sectors occur in front of glacial outlets, seaward of the shelf break (Hesse and Klaucke, 1995), whereas high-relief sectors typically lie south of these outlets.

Region 2: Continental rise between 3000 and 3400 m water depth. Canyons (called channels on the rise and basinward) are dramatically fewer in number and have less relief than on the slope (Fig. 3B), and the NAMOC appears as a discernible trunk channel of the drainage system. No upslope canyon can be singled out as the main NAMOC feeder. On the sidescan mosaic in Figure 2, the most prominent aspect between about 57° and 54°30'W is the dichotomy between the high-backscatter-energy (light areas) muddy levees of the NAMOC, and the low-backscatter (dark areas) sand and gravel-rich plains to the northeast. Lithologies were established by piston coring (Fig. 4).

Region 3: Labrador Basin floor south of 59°45'N and below 3400 m water depth to confluence with H tributary and Imarssuak Mid-Ocean Channel at 56°N (average sea-floor gradient 1:1000 or less). The channel floor appears as a meandering 2- to 3-km-wide band of low-backscatter energy with low sinuosity (meander radius ranges from 17 to 55 km, averages 25 km). Tributaries run parallel to the NAMOC for several hundred kilometers (Hesse, 1989) but eventually join the main channel (confluence with tributary E/F at about 57°40'N; Fig. 1). Bright areas in the channel are interpreted as slumps or point bars. The point bars are concentrated on, but not restricted to, inner meander bends on the right channel wall. We imaged washover fans, hanging submarine valleys, and chute pools in this region for the first time in the deep sea (Klaucke and Hesse, 1996).

The most surprising morphologic feature of the entire mosaic is the curved alternating high- and low-backscatter-energy streaks on the sand and gravel

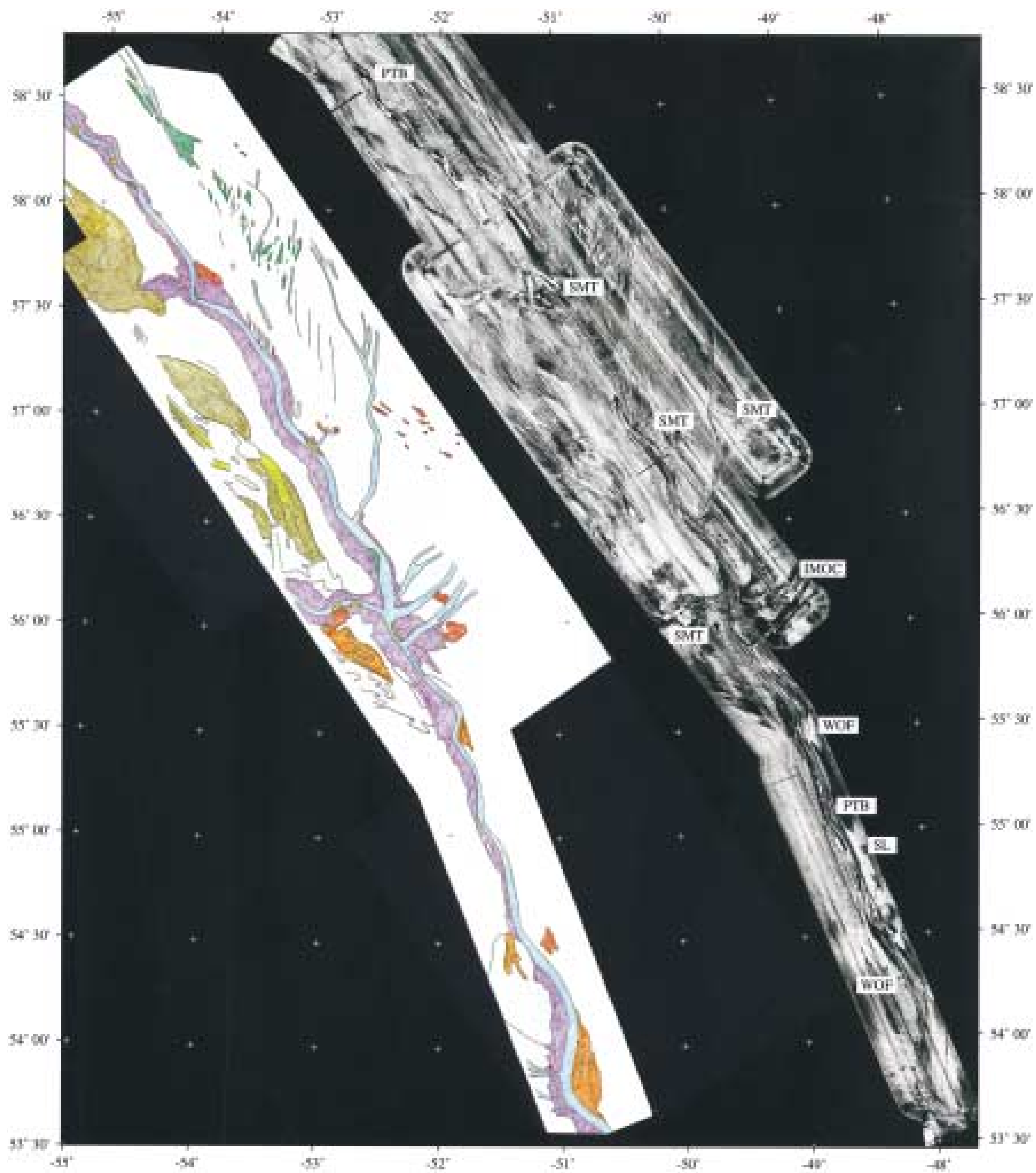

Figure 1. Mosaic of HAWAII MR-1 sidescan sonar images (6 ship tracks, each 20 km wide) in the central Labrador Sea (for location see inset in Fig. 2, southern part of red corridor) showing submarine braid plain with curved ridges and sand and gravel bars (bright) immediately east of the meandering NAMOC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

plain beyond the distal edge of the eastern NAMOC levee. This pattern corresponds to the depositional low-amplitude channel-and-bar or lobe, or the erosional ridge-and-furrow topography, of a submarine braid plain. The braid plain forms the southern, distal continuation of the nonbraided sand-gravel plain in region 2. The ridges or bars (bright streaks) are up to 10 km long, several hundred meters wide, and a few meters high. Evidence of erosion can be seen where the furrows start abruptly upstream. The prevalent curva-

Ice Sheet Drainage *continued on p. 6*

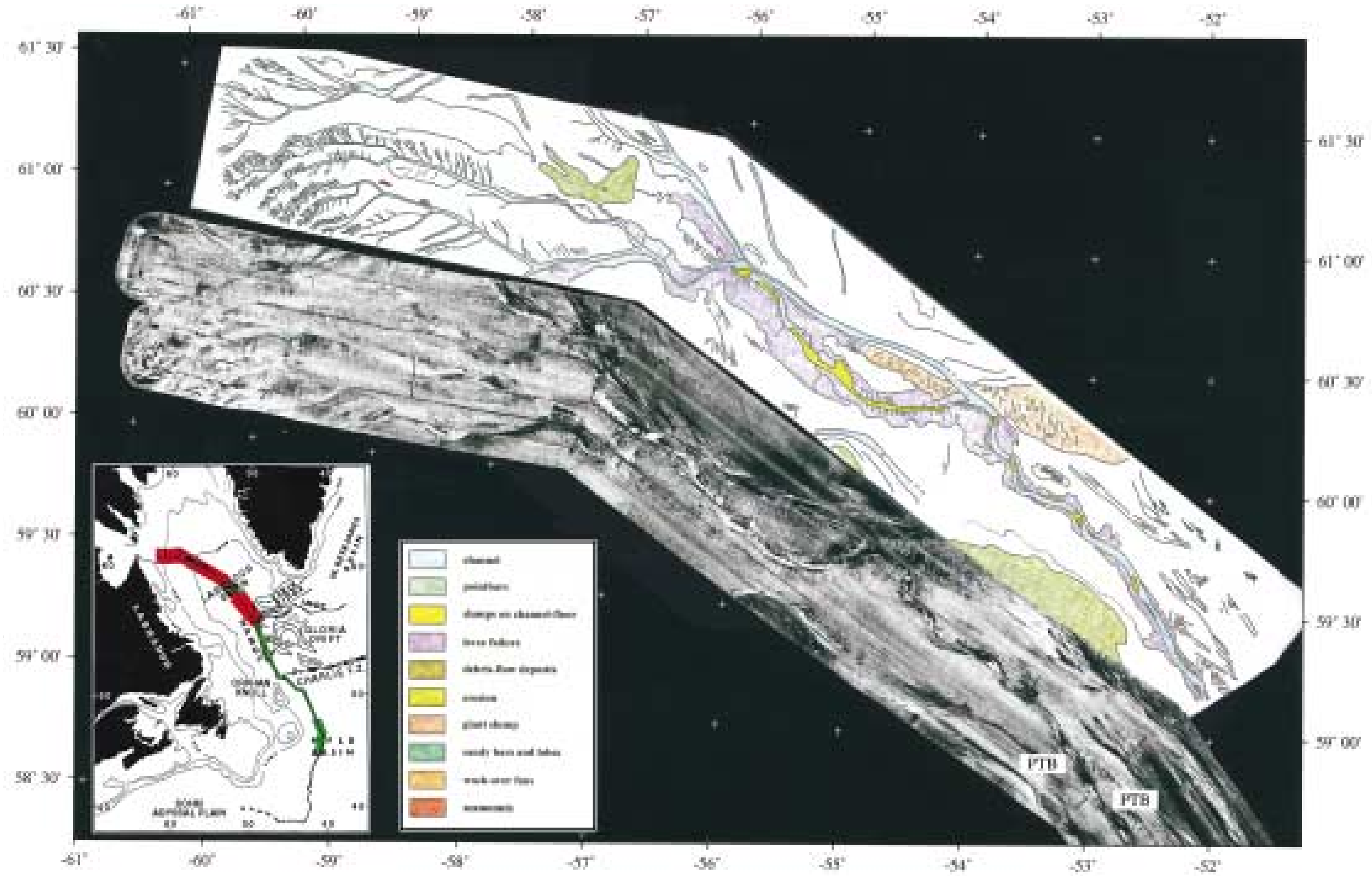

Figure 2. Mosaic of HAWAII MR-1 sidescan sonar images (4 ship tracks wide) starting at 61°W on the upper Labrador slope off the Hudson Strait. IMOC is Imarssuak Mid-Ocean Channel; PTB is submarine point bar, SL is slump; SMT is seamount.

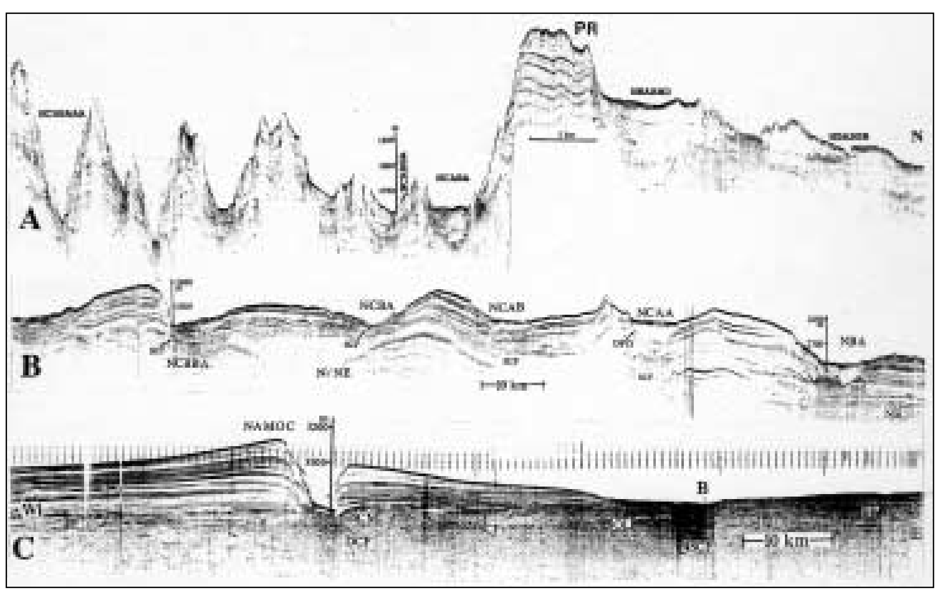

Figure 3. Sleeve-gun (655 cm^3 = 40 $in.^3$) seismic profiles from Labrador slope and basin. Locations shown in Figure 5. A. Profile along the upper Labrador slope in about 1500 m water depth (segment 1). On the high-relief sector (southern half of profile), parallel undulating low-amplitude reflections, which are grouped into packages by a few higher-amplitude reflections, and deep sound penetration (up to 800 ms two-way traveltime or 720 m subbottom depth, assuming a sound velocity of 1.8 km/s), are characteristic of turbid surface-plume and pelagic-dominated sedimentation (southern two to three tracks on upper slope, Fig. 2). In the low-relief sector to the north, more highly reflective sediment beneath the canyon floors indicates sand as canyon fill. The ridges and levees consist of large pockets of weakly stratified to transparent sediment with a few distinct reflections and deep sound penetration up to 900 ms. B: Mid-slope section (segment 2) showing reduced number and relief of tributary canyons compared with profile A. Canyon fill (SCF) is sand-rich, with the exception of canyons NBA and NCAA, which contain debris-flow deposits (DFD). Seismic reflection character and penetration beneath the ridges are very similar to those of profile A (from Hesse, 1992, Fig. 3). C: Basin section (segment 3) showing the highly asymmetrical NAMOC levees, which return numerous parallel, low-amplitude reflections and reveal deep penetration, as in the high-relief sector of segment 1 in profile A, although the levee facies results from spillover by fine-grained turbidity currents. The sand facies of the eastern braid plain (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.

Ice Sheet Drainage *continued from p. 5*

ture of the streaky pattern toward the main channel where the east NAMOC levee is absent (between 57° and 56°30'N) shows that the levee was eroded by currents flowing from the braid plain into the channel, not vice versa.

The occurrence of the submarine braid plain distal to the upslope non-braided sand-and-gravel plain (region 2) is contrary to expectation and could be an artifact of sidescan penetration through mud cover. Piston cores from the braid plain show a 1–1.5-m-thick Holocene mud blanket above massive sand layers up to several meters thick. The sidescan signal could have penetrated the thinner "mud screen" in region 3, but not the thicker mud cover near the ice outlet in region 2.

Region 4: NAMOC segment between 56°N and 44°30'N below 3800 m water depth (average sea-floor gradient: 1:2000). In this region (not shown in Fig. 1), NAMOC meander radii increase from 50 km north of 54°S, to >50 km farther south. Some channel reaches are straight (in the sense of Clark et al., 1992), whereas in others, seamounts and basement structures cause sharp, generally north-northwest–south-southeast to west-east deflections as the channel enters and leaves fracture zones.

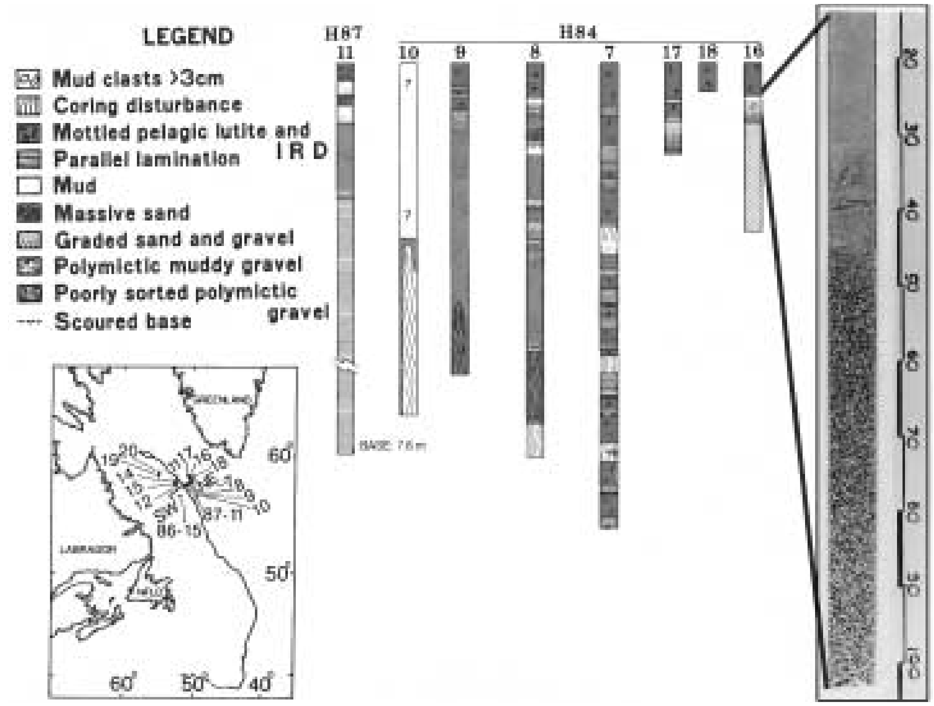

Figure 4. Piston cores from the submarine braid plain showing massive or graded sand and gravel layers up to several meters thick overlain by a 1-m-thick Holocene pelagic lutite layer. IRD is ice-rafted debris.

INTERPRETATION: EFFECTS OF SEDIMENT INPUT AND TRANSPORT MECHANISMS ON SEA-FLOOR MORPHOLOGY

The profound changes and juxtaposition of sea-floor morphologies described above can be attributed to sediment delivery and transport mechanisms during glacial episodes. The transfer of the glacially derived sediment to the marine environment requires two major steps: (1) delivery to the ice margin and upper slope by primary transport mechanisms, and (2) slope erosion and redeposition by secondary transport mechanisms. The upper-slope dichotomy of low- vs. high-relief sectors (Fig. 3A), which is projected basinward by the submarine braid-plain vs. leveed-channel dichotomy (Figs. 3B, 5) is the result of a giant grain-size fractionation process at the ice margin. When detritus carried by the glacier and its rivers reaches the sea, the suspended load is separated from the bedload by processes appropriately named ice-margin sifting.

Low-Relief Morphology: Transport by Debris Flows and "Primary" Turbidity Currents

The vast volumes of coarse material melted from the huge Hudson Strait glacier tongue led to the production of giant debris flows that had a smoothing effect on the relief. Periodic meltwater discharge peaks caused heavy sand-laden freshwater flows to break the seawater density barrier and form density underflows (Mulder and Syvitski, 1995). These turbidity currents carried sandy sediment well beyond the upper or mid-slope (as far as region 3 and probably beyond) and fed the sand and gravel plains east of the NAMOC. The plains adjacent to the NAMOC are best explained as forming by deposition of sand-rich sheet flows originating in Hudson Strait and circumventing the NAMOC and its tributaries, rather than by flooding from the trunk channel. Some of the flows were apparently of unusually large volume (see below). These currents overflowed the low-relief slope in front of the strait and cut shallow channels into the substrate of the debris-flow deposits on the upper slope (Fig. 3A).

High-Relief Morphology: Turbid-Plume Deposition, Slope Erosion and Redeposition

The normal mode of turbidity-current generation in an ice-marginal environment is secondary transport due to remobilization of glacial-front upper-slope sediment, not meltwater flooding. To a large extent, the upper-slope region south of the Hudson Strait outlet received sediment as a mud blanket deposited by particle-by-particle settling. Meltwater entering the sea, even when heavily loaded with suspended sediment, rose buoyantly to the surface, forming turbid surface plumes—a well-known phenomenon in modern tidewater glaciers (Syvitski et al., 1987; Pfirman and Solheim, 1989; Lemmen, 1990). Meltwater plumes jetting out from under or above the Labrador Sea ice were entrained by the south-flowing Labrador Current. Typical turbid-plume deposits (Fig. 6) have been identified in piston cores from within 20 km of the assumed ice-margin position. The remainder of the slope is predominantly underlain by fine-grained sediments with equal parts of hemipelagic sediments and muddy spillover turbidites. Subordinate constituents are from ice rafting (Fig. 6, B, and D), including distinct Heinrich layers (Wang and Hesse, 1996), and moving bottom layers of suspended sediment called nepheloid-layer deposits (Fig. 6).

The modern high relief of the slope has been generated by retrograde syn- or postdepositional erosion involving headward and sideward gullying in the canyons producing the present-day dendritic, high-relief canyon pattern. Remobilization of sediment by slumping, debris flow, and turbidity current formation has been the main sediment source for the NAMOC, whose muddy levees in regions 2 and 3 formed by spillover from the fine-grained tops of turbidity currents (same spillover turbidites as in Fig. 6D, but without ice-rafted debris).

Channelized Turbidity Currents

The change from the depositional-erosional topography of the slope to a mostly depositional topography on the rise is marked by the appearance of channels with true depositional levees built by overbank deposition from turbidity currents. Levee development peaked along the upper NAMOC in regions 2 and 3 (upstream from the entrance of sandy flows from the braid plain) where levees reach a maximum height of 80 m above the adjacent basin plains, and widths up to 40 km to the west and 20 km to the east of the NAMOC (Fig. 3C). Down-channel decreases of levee relief from 80 to 30–10 m and channel depth from 200 to 140–75 m imply that flow parameters decreased down-flow. The difference in levee height between the west and east levees also decreases from a maximum of 90 m to 30 m in the proximal to the distal channel reaches, signaling the decreasing effect of Coriolis force with latitude together with decreasing flow velocities and densities in the distal channel.

Quantification of flow parameters by using imaged channel geometry (width, meander radii) and a digital terrain model generated from the bathymetric data (channel depth, levee asymmetry) provide information on flow-velocity variation, both longitudinally along the flow path and vertically within the flows (Klaucke, 1995). Equilibrium-flow conditions have been established only for the first 350 km of region 3. Low flow velocities of 0.8 m/s that decrease to 0.05 m/s, calculated for region 3 bankfull flows, are flow-top velocities (Klaucke, 1995). Gravel-sized channel-fill sediments in the NAMOC along regions 2 and 3 (Chough et al., 1987) give maximum calculated bottom velocities of 6.5 to 8 m/s (for the lower 50 to 80 m of up to 200-m-thick flows). These higher bottom velocities apparently shaped the overall channel geometry, including the low-sinuosity meander pattern.

RELATION BETWEEN BRAIDPLAIN DEVELOPMENT, HEINRICH EVENTS, AND SHORT-TERM CLIMATE CHANGE

The development of the submarine braid plain in the Labrador Basin adjacent to the NAMOC (Fig. 5) sheds light on a possible relation between the injection of sand-laden meltwater by turbidity currents and Heinrich ice-rafting events. Some of the turbidity currents that deposited sand on the braid plain must have been unusually large. After having traveled more than 1000 km from the Hudson Strait outlet, some of them were still powerful enough to erode the east NAMOC levee between 57° and 56°30'N. There, they entered the main channel and traveled down channel an unknown distance, probably to the channel terminus on the Sohm Abyssal Plain. These flows deposited sandy overbank sediment all along the east levee of the distal channel (Klaucke, 1995). The only suitable reservoirs of appropriate size that could have released such very large volumes of sediment and water are subglacial lakes in Hudson Strait and its drainage area. The former existence of these lakes is indicated by large depressions (e.g., in the floor of the strait). If the lakes were dammed by end moraines, or by the ice itself, surging of the Hudson Strait ice stream during Heinrich events could have cut the barriers, causing the catastrophic emptying of the lakes. Alternatively, rising lake levels may have lifted the ice dams and been the cause that triggered ice surging and Heinrich events. The ensuing subglacial lake outburst flooding events would have cut the gorges and canyons now subaerially exposed as spillways on Meta Incognita Peninsula on the north coast of the strait (Johnson and Lauritzen, 1995). Large volumes of fresh or brackish water entrained in the resulting turbidity currents could have been injected into the deep-ocean circulation. This may have affected deep-water density and, accordingly, the deep conveyor-belt circulation in the Atlantic, at least temporarily. This possibility has not been considered previously in the climate-feedback scenarios, which have recently incorporated Heinrich events as short-term climate pacemakers.

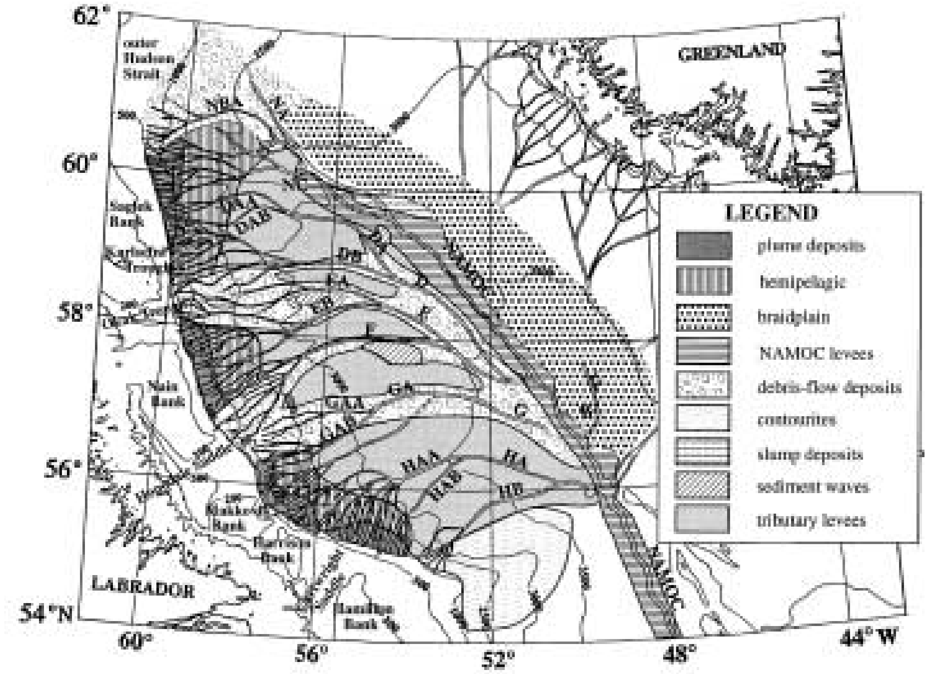

Figure 5. Facies distribution map, Labrador slope and basin, based on seismic profiles and ground-truthing piston cores.

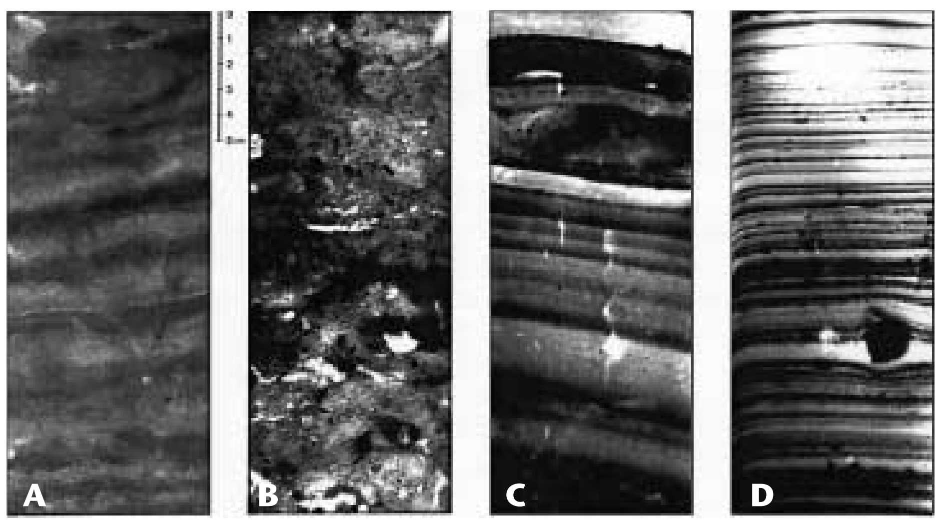

Figure 6. X-radiographs of glaciomarine depositional facies from the Labrador slope and basin. A: Turbid surface-plume deposits; B: hemipelagic sediment with ice-rafted debris; C: nepheloid-layer deposits; D: overbank levee spillover turbidites alternating with laminae of ice-rafted debris.

ACKNOWLEDGMENTS

We are grateful for a careful, in-depth review of this paper by John E. Damuth, critical comments by Andrew Hynes and

Ice Sheet Drainage *continued on p. 8*

WASHINGTON REPORT

Bruce F. Molnia

Washington Report provides the GSA membership with a window on the activities of the federal agencies, Congress and the legislative process, and international interactions that could impact the geoscience community. In future issues, Washington Report will present summaries of agency and interagency programs, track legislation, and present insights into Washington, D.C., geopolitics as they pertain to the geosciences.

Pristine No More

Several recent reports have provided a variety of information indicating that human and natural changes are having a significant impact on many of the northern and Arctic marginal seas. These areas include the Bering Sea, Kara Sea, Barents Sea, Laptev Sea, Sea of Okhotsk, and Sea of Japan. The human activities include dumping radioactive waste, overfishing, release of metals and other contaminants to the environment, and a variety of other actions. Radioactive waste has also been dumped in the northernmost northwest Pacific Ocean.

Three reports—two released in the past few months and one released last year—clearly document what is known about the extent of change to these northern areas. Two reports were released by the U.S. Interagency Arctic Research Policy Committee (IARPC). They are "Workshop on Arctic Contamination" and "Proceedings of the Japan—Russia—United States Study Group on Dumped Nuclear Waste in the Sea of Japan, Sea of Okhotsk, and the North Pacific Ocean." The third report, "The Bering Sea Ecosystem," released in May 1996, was prepared by the Polar Research Board (PRB) of the National Research Council and published by the National Academy Press.

The IARPC, a federal committee with a membership composed of the 14 agencies active in the Arctic, coordinates Federal Arctic basic and applied research, monitoring efforts, and other information-gathering activities. In 1992, after learning that several million curies of radioactive waste had been dumped by the former Soviet Union into the Arctic's marginal seas, the IARPC convened an international workshop to identify the breadth and sources of existing data and information about Arctic contamination, to identify major data gaps, and to determine whether specific Arctic contaminants present a risk to the environment, ecosystems, or human health in Alaska, the Arctic, and the global environment. The focus of the workshop was not only radioactive contamination, but also other contaminants that exist in and affect the Arctic.

The result is a 311-page proceedings volume, which contains about 60 presentations, including 12 papers and 10 abstracts by Russian experts. The workshop identified that a broad variety of contaminants are found in the Arctic, even though they are not used in that area. For instance, natural transportation processes concentrate compounds like DDT in the coastal Arctic even though they are not being used within a several thousand mile radius. The proceedings volume, was released in May 1995, as the volume 8, spring issue of *Arctic Research of the United States*.

The second report, "Proceedings of the Japan—Russia—United States Study Group on Dumped Nuclear Waste in the Sea of Japan, Sea of Okhotsk, and the North Pacific Ocean," expanded the geographic area of concern to the marginal seas of the Russian Far East. As the title implies, only nuclear contamination was considered. This workshop documented that much less radioactive waste had been dumped into the far eastern marginal seas than into the Arctic marginal seas. One reason for this was that most of the high-level solid waste in the Russian Far East, generally reactors and spent fuel rods of mothballed nuclear submarines, were still in temporary storage at naval sites along the coastline. Even more problematic was the fact that a suitable reprocessing capability and the means to transport these highly radioactive materials do not exist. The proceedings of this workshop were released in May 1996, as the volume 9, fall/winter issue of *Arctic Research of the United States*.

In June 1996, a follow-on workshop, cosponsored by the U.S. Geological Survey, was held in Niigata, Japan. Its purpose was to continue the multinational international dialogue on how to reduce the volume of radioactive waste stored in the Russian Far East. The proceedings of this workshop will be published early in 1997 in *Arctic Research of the United States*.

The third report, "The Bering Sea Ecosystem," 309 pages long, concluded that during the past 50 years, natural changes in the ocean environment have combined with the effects of human harvesting of whales, the taking of other marine mammals, such as seals, and overfishing "to cause a cascading and possibly irreversible sequence of changes in the Bering Sea ecosystem." These activities appear to have reduced the amount of high-quality food available to young marine mammals and birds. Nine recommendations are presented, including some possible changes to the management of the Bering Sea fishery.

Both IARPC proceedings are available at no cost from the Office of Polar Programs at the National Science Foundation; the PRB report may be purchased from the National Academy Press. For additional information, contact your Washington Report editor (bmolnia@usgs.gov). ■

Ice Sheet Drainage *continued from p. 7*

Kirk Maasch, substantial editorial assistance by Suzanne Kay, the cooperation of Captain Lewis, and the officers and crew of CSS *Hudson,* and major funding from the Canadian Natural Science and Engineering Research Council and the U.S. National Science Foundation.

REFERENCES CITED

Bond, G., Broecker, W., Johnson, S., McManus, J., Labeyrie, L., Jouzel, J., and Bonani, G., 1993, Correlation between climate records from North Atlantic sediments and Greenland ice: Nature, v. 365, p. 143–147.

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

Broecker, W. S., Bond, G., Klas, M., Clark, E., and McManus, J., 1992, Origin of northern Atlantic's Heinrich events: Climate Dynamics, v. 6, p. 265–273.

Chough, S. K., and Hesse, R., 1976, Submarine meandering talweg and turbidity currents flowing for 4000 km in the Northwest Atlantic Mid-Ocean Channel: Geology, v. 4, p. 529–533.

Chough, S. K., Hesse, R., and Müller, J., 1987, The Northwest Atlantic Mid-Ocean Channel of the Labrador Sea. IV. Petrography and provenance of the sediments: Canadian Journal of Earth Sciences, v. 24, p. 731–740.

Clark, J. D., Kenyon, N. H., and Pickering, K. T., 1992, Quantitative analysis of the geometry of submarine channels: Geology, v. 20, p. 633–636.

Fisher, D. A., Reeh, N., and Langley, K., 1985, Objective reconstruction of the Late Wisconsinan Laurentide Ice Sheet and the significance of deformable beds: Géographie physique et Quaternaire, v. 39, p. 229–238.

Hesse, R., 1989, "Drainage system" associated with mid-ocean channels and submarine yazoos: Alternative to submarine fan depositional systems: Geology, v. 17, p. 1148–1151.

Hesse, R., 1992, Continental-slope sedimentation adjacent to an ice margin. I. Seismic facies of Labrador Slope: Geo-Marine Letters, v. 12, p. 189–199.

Hesse, R., and Klaucke, I., 1995, A continuous along-slope seismic profile from the Upper Labrador Slope, *in* Pickering, K. T., et al., eds., Atlas of deep-water environments: Architectural style in turbidite systems: Chapman & Hall, p. 18–22.

Hesse, R., and Rakofsky, A., 1992, Deep-sea channel/submarine yazoo system of the Labrador Sea: A new deep-water facies model: American Association of Petroleum Geologists Bulletin, v. 104, p. 680–707.

Ice Sheet Drainage *continued on p. 9*

Penrose Conference Scheduled

Faults and Subsurface Fluid Flow: Fundamentals and Applications to Hydrogeology and Petroleum Geology

September 10–15, 1997

A Geological Society of America Penrose Conference, "Faults and Subsurface Fluid Flow: Fundamentals and Applications to Hydrogeology and Petroleum Geology," will be held September 10–15, 1997, in Albuquerque and Taos, New Mexico. The conference will be a synopsis of state-of-the-art field, laboratory, and computer modeling studies of the role of faults as barriers to and conduits for single- and multiphase fluid flow. Topics to be addressed will include deformation of rocks and sediments in fault zones; the influence of deformation on fluid flow and transport phenomena; diagenetic alterations and their feedback into hydrologic and structural processes; and geological and geophysical imaging of fault properties. We will emphasize both fundamental research and application to problems such as ground-water supply, ground-water contamination, petroleum migration, and petroleum production.

Participants will be picked up at the Albuquerque airport and spend the evening of September 10 in Albuquerque, and assemble the next morning for a field trip to examine the relation between faults and ground-water flow in the Albuquerque basin. Planned stops will highlight the structure and stratigraphy of the Cenozoic basin-fill aquifer system; deformational features, paleoflow indicators, and zones of cementation along faults cutting unconsolidated basin-fill sediments; and the hydrogeology of basin-bounding faults. We will then travel to Taos, for three days of oral presentations, poster sessions, and discussions concerning current and future research on the interrelation of faults and subsurface fluid flow. Participants will be returned to the Albuquerque airport before noon on September 15.

The conference will be limited to 70 participants, who will be selected to represent a broad range of disciplines and geographic areas of expertise. We encourage interested graduate students to apply, and we will be able to offer some partial student subsidies. The registration fee, which will cover lodging, meals (except for first night's dinner), ground transportation during the conference, field trip, and all other costs except personal incidental expenses, is expected to be approximately $600 to $700. Participants will be responsible for transportation to and from the conference.

Co-conveners are: ***William C. Haneberg,*** New Mexico Bureau of Mines & Mineral Resources, 2808 Central Avenue SE, Albuquerque, NM 87106, (505) 262-2774, fax 505-255-5253, E-mail: haneberg@nmt.edu; ***J. Casey Moore,*** Earth Sciences Board, University of California, Santa Cruz, CA 95064, (408) 459-2574, E-mail: casey@rupture.ucsc.edu; ***Laurel B. Goodwin,*** Department of Earth and Environmental Science, New Mexico Tech, Socorro, NM 87801, (505) 835-5178, E-mail: lgoodwin@nmt.edu; ***Peter S. Mozley,*** Department of Earth and Environmental Science, New Mexico Tech, Socorro, NM 87801, (505) 835-5311, E-mail: mozley@nmt.edu.

Application deadline is March 1, 1997. Invitations will be mailed to participants by April 1, 1997. We will have a limited number of invited oral presentations, so that a significant part of the meeting can be devoted to poster presentations and informal discussions.

Potential participants should send a letter of application to William Haneberg (address above), including a brief statement of interest, the relevance of the applicant's recent work to the themes of the meeting, and the subject of any proposed poster presentation. Although E-mail inquiries to any or all of the conveners are welcome, potential participants should submit two paper copies of their application. E-mail letters of application will not be considered. ■

About People

GSA Fellow **Wallace S. Broecker,** Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York, has been awarded the National Medal of Science for his pioneering contributions in understanding chemical changes in the ocean and atmosphere.

Fellow **Farouk El-Baz,** Boston University, Boston, Massachusetts, is the 1996 recipient of the AAPG Michel T. Halbouty Human Needs Award, for his contributions in remote sensing to the search for natural resources in arid lands.

Joining the Colorado School of Mines (Golden, Colorado) faculty are GSA Members **Murray W. Hitzman** (Charles Franklin Fogarty Distinguished Chair in Economic Geology) and **Neil F. Hurley** (Charles Boettcher Distinguished Chair in Petroleum Geology).

Fellow **John G. Vedder,** Portola Valley, California, is the fourth recipient of the Dibblee Medal, presented by the Thomas Wilson Dibblee, Jr., Geological Foundation, in recognition of extraordinary accomplishment in geologic mapping.

Ice Sheet Drainage *continued from p. 8*

Hesse, R., Chough, S. K., and Rakofsky, A., 1987, The Northwest Mid-Ocean Channel of the Labrador Sea. V. Sedimentology of a giant deep-sea channel: Canadian Journal of Earth Sciences, v. 24, p. 1595–1624.

Hughes, T., 1987, Ice dynamics and deglaciation models when ice sheets collapsed, *in* Ruddiman, W. F., and Wright, H. E. J., eds., North America and adjacent oceans during the last deglaciation: Boulder, Colorado, Geological Society of America, Geology of North America, v. K-3, p. 183–220.

Johnson, R. G., and Lauritzen, S.-E., 1995, Hudson Bay-Hudson Strait jökulhlaups and Heinrich events: A hypothesis: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 117, p. 123–137.

Klaucke, I., 1995, The submarine drainage system of the Labrador Sea: Result of glacial input from the Laurentide Icesheet [Ph.D. thesis]: Montreal, Quebec, Canada, McGill University, 248 p.

Klaucke, I., and Hesse, R., 1996, Fluvial features in the deep sea: New insights from the glacigenic submarine drainage system of the Northwest Atlantic Mid-Ocean Channel in the Labrador Sea: Sedimentary Geology (in press).

Lemmen, D. S., 1990, Glaciomarine sedimentation in Disraeli Fjord, high Arctic Canada: Marine Geology, v. 94, p. 9–22.

Macdonald, K. C., Scheirer, D. S., Carbotte, S., and Fox, P. J., 1993, It's only topography: GSA Today, v. 3, no. 1, p. 1, p. 24-25, no. 2, p. 29-31, p. 34–35.

Mulder, T., and Syvitski, J.P.M., 1995, Turbidity currents generated at river mouths during exceptional discharges to the world ocean: Journal of Geology, v. 103, p. 285–299.

Paillard, D., and Labeyrie, L., 1994, Role of the thermohaline circulation in the abrupt warming after Heinrich events: Nature, v. 372, p. 162–164.

Pfirman, S., and Solheim, A., 1989, Subglacial meltwater discharge in the open-marine tidewater glacier environment: Observations from Nordaustlandet, Svalbard Archipelago: Marine Geology, v. 86, p. 265–281.

Rognstad, M., 1992, HAWAII MR1: A new underwater mapping tool: International Conference on Signal Processing Technology '92, p. 900–905.

Syvitski, J. P. M., Burrell, D. C., and Skei, J. M., 1987, Fjords: Processes and products: New York, Springer - Verlag, 375 p.

Wang, D., and Hesse, R., 1996, Continental slope sedimentation adjacent to an ice-margin. II. Glaciomarine depositional facies on Labrador Slope and glacial cycles: Marine Geology (in press).

Manuscript received August 1, 1995; revisions received October 31, 1995, January 18, 1996, June 11, 1996; accepted June 18, 1996. ■