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**PLEISTOCENE LAURENTIDE ICE SHEET DRAINAGE INTO THE
LABRADOR SEA: SEDIMENTARY FACIES, DEPOSITIONAL
MECHANISMS, STRATIGRAPHY AND SIGNIFICANCE OF
HEINRICH EVENTS**

BY

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfilment of the requirements for
the degree of Doctor of Philosophy

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سورة التاجية

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ
الْحَمْدُ لِلَّهِ رَبِّ الْعَالَمِينَ
الرَّحْمَنِ الرَّحِيمِ
الَّذِي إِذَا نَادَيْتُكَ تَجِبْتَ
أَهْدِنَا صِرَاطَ الْمُسْتَقِيمِ
الَّذِي أَمَمْتَ عَلَيْهِمْ قَوْمَ الْقَوْمِ
عَلَيْهِمْ وَلَا الْمَسْأَلِينَ

وَالْحَمْدُ لِلَّهِ

Abstract

On the basis of sedimentary structures and textures, six depositional facies have been identified in Labrador Slope, Rise and Basin cores. They include: (1) turbid-surface plume sediments (facies P; plumites) comprising 4% of the total length of the slope cores; (2) hemipelagic sediments (facies HI and H) with and without ice-rafted debris (IRD) (48% and 20% on the slope/rise and basin centre, respectively); (3) nepheloid-layer deposits (facies N; 9% on the slope); (4) contourites (facies C; 4% on the slope), (5) turbidite facies (30% on the slope and >90% on the levees of the Northwest Atlantic Mid-Ocean Channel, NAMOC) with three subfacies: thin-bedded silt and mud turbidites (T); turbidites with laminae of IRD (TI), and sand turbidites (MS); and (6) debris-flow facies (10% on the slope) with four subfacies: gravelly (D1), sandy silt (D2), thin bedded (D3) and sandy gravelly debris-flow deposits (D4).

Facies P occurs on high-relief slope sections, deposited by buoyantly rising meltwater plumes entrained by the south-flowing Labrador Current. The high relief was caused by retrograde canyon erosion after deposition. Facies N is best developed and thickest on the slope and upper rise. It was deposited when sediment-laden meltwater from the Laurentide Ice Sheet with high concentrations of suspended sediment spread out in mid-water or along the bottom. Facies T occurs on the levees of the NAMOC and its tributaries. It originated from the remobilization of detrital carbonate-rich sediments on the slope south of the Hudson Strait. Extensive sand turbidites occur on a braided floodplain east of NAMOC. Deposition of sand turbidites by high-density turbidity currents, probably of sheet-flow type, resulted from bedload-rich meltwater discharges on the low-relief slope sector off the Hudson Strait. They may have been caused by subglacial-lake outburst flooding, which might be linked to Heinrich events. Facies C occurs on the lower slope to upper rise. Facies H is present in all parts of the basin but most abundant on the slope; together with facies T, it is the major facies in the intercanyon regions. Facies D is found mainly on low-relief slope sectors, in front and north of major glacier outlets. Debris-flow tongues in the slope canyons merge downslope forming an extensive stacked megadebris-flow deposit on the floodplain west of NAMOC. Facies D makes up >75% of the sediment thickness in the western floodplain

cores.

Four types of Heinrich layers (HL) were identified. Type I: graded muds with floating coarse IRD throughout (nepheloid-layer deposits); type II: mm- to cm-thick mud turbidites alternating with thin laminae of IRD; type III: cm-thick crudely laminated layers of IRD interbedded with mud turbidites; and type IV: bioturbated hemipelagic sediments with IRD. Type I predominates in the slope and upper rise. Type II and III HL occur where the flow paths of spill-over turbidity currents lie under the iceberg drift route (slope canyons and NAMOC levees, respectively). Type IV occurs in distal regions not influenced by nepheloid layers and turbidity currents.

On the basis of sedimentary facies, radiocarbon ages and correlation of Heinrich layers, seven lithostratigraphic units were identified spanning the last 60 ka. Unit 0 represents Holocene sediments, comprising oxygen isotope stage 1. Units 1-6 were deposited during isotope stages 2 and 3 and indicate cold conditions in the Labrador Sea. The maximum oxygen isotope values occur at the Last Glacial Maximum; large amplitude shifts to lighter values coincide with HL-1 and 2. Each lithostratigraphic unit consists of an upper (a) and a lower (b) subunit. Subunits (b) consist mainly of Heinrich layers (facies N and TI); subunits (a) are hemipelagic sediments deposited between Heinrich events. Most units contain IRD indicating that open sea conditions prevailed in this region during the last 60 ka. Contourites predominate in isotopic stages 2 and 3, implying the presence of active contour currents during glacial times.

Résumé

En se basant sur des structures et textures sédimentaires, six faciès de déposition ont été identifiés. À partir de carottes de forage provenant de la Pente, du Glacis et du Bassin du Labrador. Ces faciès incluent: (1) des sédiments dérivés de panache turbide en surface (faciès P; plumites) comprenant 4% de la longueur totale des carottes de forage de la pente; (2) des sédiments hémipélagiques (faciès HI et H) avec ou sans débris glaciaires (IRD) (48% et 20% sur la pente/du glacis et centre du bassin, respectivement); (3) des dépôts en couches néphéloïdes (faciès N; 9% sur la pente); (4) des contourites (faciès C; 4% sur la pente); (5) des turbidites (30% sur la pente et >90% sur les levées du Chenal Médio-Océanique de l'Atlantique Nord-Ouest, NAMOC) avec trois sous-faciès: silt lité en couches minces et turbidites boueuses (T); turbidites avec laminations de IRD (TI), et turbidites sablonneuses (MS); et (6) faciès de coulées de débris (10% sur la pente) avec quatre sous-faciès: dépôts de coulées de débris gravelleux (D1), silt sablonneux (D2), silt lité mince (D3) et gravelleux-sablonneux (D4).

Le faciès P est présent sur les sections à fort relief de pente, déposé par des panaches ascendants d'eau de fonte, entraîné par le Courant de Labrador qui circule vers le sud. Le fort relief a été causé par l'érosion rétrograde du canyon après le dépôt. Le faciès N est mieux développé et plus épais sur la pente et le glacis supérieur. Ce faciès a été déposé lorsque l'eau de fonte provenant de la Calotte Glaciaire Laurentienne et chargée de fortes concentrations de sédiments suspendus s'est dispersée dans l'eau ou sur le fond. Le faciès T est présent sur les levées du NAMOC et ses tributaires. Il s'est formé à partir de la remobilisation de sédiments détritiques riches en carbonates sur la pente située au sud du détroit de l'Hudson. De vastes turbidites sablonneuses sont présentes sur une plaine d'inondation en chenaux tressées située à l'est du NAMOC. Le dépôt de turbidites sablonneuses par des courants de turbidites de haute densité, probablement de type à écoulement couche, provient de décharges d'eau de fonte riches en matériaux de fond sur le secteur de pente à faible relief du détroit de l'Hudson. Ces dépôts peuvent avoir été causés par des inondations dues à la vidange catastrophique de lacs sous-glaciaires, qui pourraient être liés aux événements Heinrich. Le faciès C se présente sur la pente inférieure du glacis. Le faciès H est présent dans toutes les parties du bassin

mais il est plus abondant sur la pente: le faciès T et H sont les principaux faciès des régions inter-canyons. Le faciès D se trouve principalement dans les secteurs à faible relief, au front et au nord des exutoires glaciaires majeurs. Des langues de coulées de débris sur la pente des canyons se fusionnent au bas de la pente formant un vaste dépôt de coulée de mégadébris empilés sur la plaine d'inondation ouest du NAMOC. Le faciès D constitue plus de 75% de l'épaisseur des débris dans les carottes de forage prises de la plaine d'inondation occidentale.

Quatre types de niveaux Heinrich (HL) ont été identifiés. Type I: boues grano-classées avec des intercalations de IRD grossiers (dépôts népheloïdes laminés); type II: boues de turbidites d'épaisseurs millimétriques à centimétriques alternants avec de minces laminations de IRD; type III: niveaux de IRD grossièrement laminés, d'épaisseurs centimétriques, interlités avec des turbidites boueuses; et type IV: sédiments hémipélagiques bioturbés avec IRD. Le type I prédomine sur la pente et le glacis. Les types II et III HL sont présent là où les chemins de coulées de déversements de courants de turbidité s'épanchent sous la route des icebergs (la pente de canyons et les levées NAMOC respectivement). Le type IV se trouve dans les régions distales non influencées par les couches népheloïdes et les courants de turbidité.

A partir des faciès sédimentaires, des âges obtenus par le radiocarbone, et de la corrélation des niveaux de Heinrich, sept unités lithostratigraphiques ont été identifiées, s'étendant sur une période de 60 ka. L'unité 0 représente des sédiments Holocène, comprenant le stade isotopique d'oxygène 1. Les unités 1 à 6 ont été déposées durant les stades isotopiques 2 et 3 et indiquent des conditions froides dans la mer du Labrador. Les valeurs maximales de l'isotope de l'oxygène sont présentes au Dernier Maximum Glaciaire; un grand changement d'amplitude jusqu' à des valeurs plus faibles coïncide avec HL-1 et 2. Chaque unité lithostratigraphique consiste en une sous-unité supérieure (a) et inférieure (b). Les sous-unités (b) consistent principalement en niveaux de Heinrich (faciès N et TI); les sous-unités (a) sont des sédiments hémipélagiques déposés entre les événements de Heinrich. La plupart des unités contiennent IRD, indiquant que des conditions de mer ouverte ont prévalu dans cette région durant les derniers 60 ka. Les contourites prédominent aux stades isotopiques 2 et 3, impliquant la présence de courants

de contours actifs durant l'époque glaciaire.

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CHAPTER 1: Introduction

1.1. Geologic setting

The Labrador Sea is a small ocean basin located in the northwest part of the North Atlantic Ocean, between Labrador and Greenland (Fig. 1.1). It is connected with the Arctic region through the Davis and Hudson straits. This basin was formed by sea-floor spreading between the Late Cretaceous (magnetic anomaly 33 time, 80 Ma) and the Early Oligocene (magnetic anomaly 13 time, 36 Ma; Srivastava 1978). A distinct increase in sediment thickness towards the Labrador margin and petrographic indicators trace the source of the main portion of the sediments to the Canadian landmass (Chough et al., 1987; Myers and Piper, 1988; Hesse, 1992; Fig. 1.2). Since the Middle Pliocene, sedimentation rates in the Labrador Sea have increased by a factor of five compared to the pre-Pliocene (Late Cretaceous to Miocene) sediments (Srivastava et al., 1986). The upper 500 m of the 2 km thick central Labrador Sea sediments are terrigenous material; the underlying sediments are mainly of pelagic or hemipelagic origin (Srivastava et al., 1986) comprising >90% of this basin's life time (Hesse et al., 1990). Prior to the Pleistocene glaciations, the Labrador Sea was subjected to strong bottom water activity (Myers and Piper, 1988). Presently, bottom currents are still important in the deep Labrador margin, which is one of the areas of deep water production in the North Atlantic (besides the Norwegian-Greenland Sea; Clark and Gaskard, 1983, Mudie, 1990).

Most of the terrigenous sediments have been supplied to the basin by glaciers (Hesse et al., 1990). The Laurentide Ice Sheet (LIS) was the major source for the Plio-Pleistocene Labrador Sea sediments. The surface condition of the Labrador Sea, whether

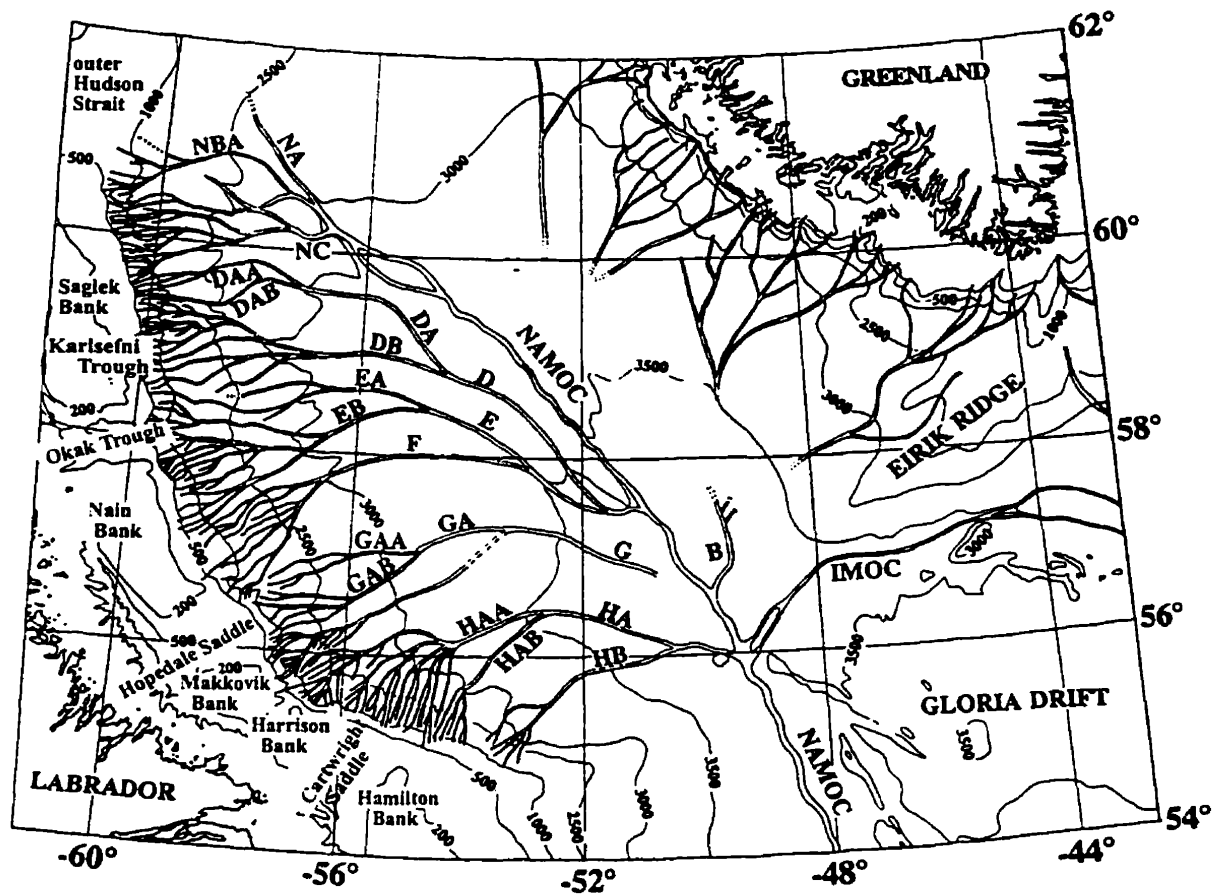


Fig. 1.1. Map of the Labrador sea showing converging channel pattern (from Klaucke, 1995). Letter labelling of the tributary canyon systems is counter-clockwise around the slope. Letter sequence is based on progressive canyon branching upslope (Hesse and rakofsky, 1992).

ice free or frozen, may have been a key factor affecting growth and decay of the LIS during the Pleistocene glaciations (Ruddiman and MacIntyre, 1981; Aksu et al., 1988). During the Wisconsinan glaciation (75 to 10 ka, Fulton and Prest, 1987) major parts of North America were covered by the Laurentide Ice Sheet (LIS) which comprised about 45% of the northern hemisphere (Piper et al., 1990) and 35% of the world ice volume (Fulton and Prest, 1987). Periodic catastrophic iceberg discharge (Heinrich events) from the LIS significantly affected paleoclimate and paleoceanography of the Labrador Sea and North Atlantic (Broecker et al., 1992). These fluctuations were linked to the Late Quaternary climatic cooling cycles revealed from Greenland ice cores (Dansgaard et al., 1993). Most models relate Heinrich events to ice surges (MacAyeal, 1993); however, they may have been triggered by catastrophic sub-glacial outburst floods (Hesse et al., 1994; Johnson and Lauritzen, 1995). After the final disappearance of the LIS around 8 ka (Josenhans and Zevenhuizen, 1990) the volume of detrital sediment reaching the Labrador Sea was dramatically reduced.

1.2. Previous work

The Northwest Atlantic Mid-Ocean Channel (NAMOC) of the central Labrador Sea was discovered by Ewing et al. (1953). The early studies delineated the NAMOC and sea floor morphology, and revealed the physiographic provinces and the general sediment distribution in the Labrador Sea (Heezen et al., 1969; Egloff and Johnson, 1975). Since then, considerable research efforts have focused on Late Cenozoic sedimentation in the Labrador Sea (Chough et al., 1985, 1987; Jacobs et al., 1985; Josenhans et al., 1986;

Hesse et al., 1987, 1990; Myers and Piper, 1988; Cremer, 1989; Hiscott et al., 1989). Since 1973 the sedimentology of the late Quaternary sediments in the Labrador Basin has been studied by Hesse and coworkers, based on sediment cores and seismic profiles. The first studies were concentrated on turbidite sedimentation associated with the NAMOC.

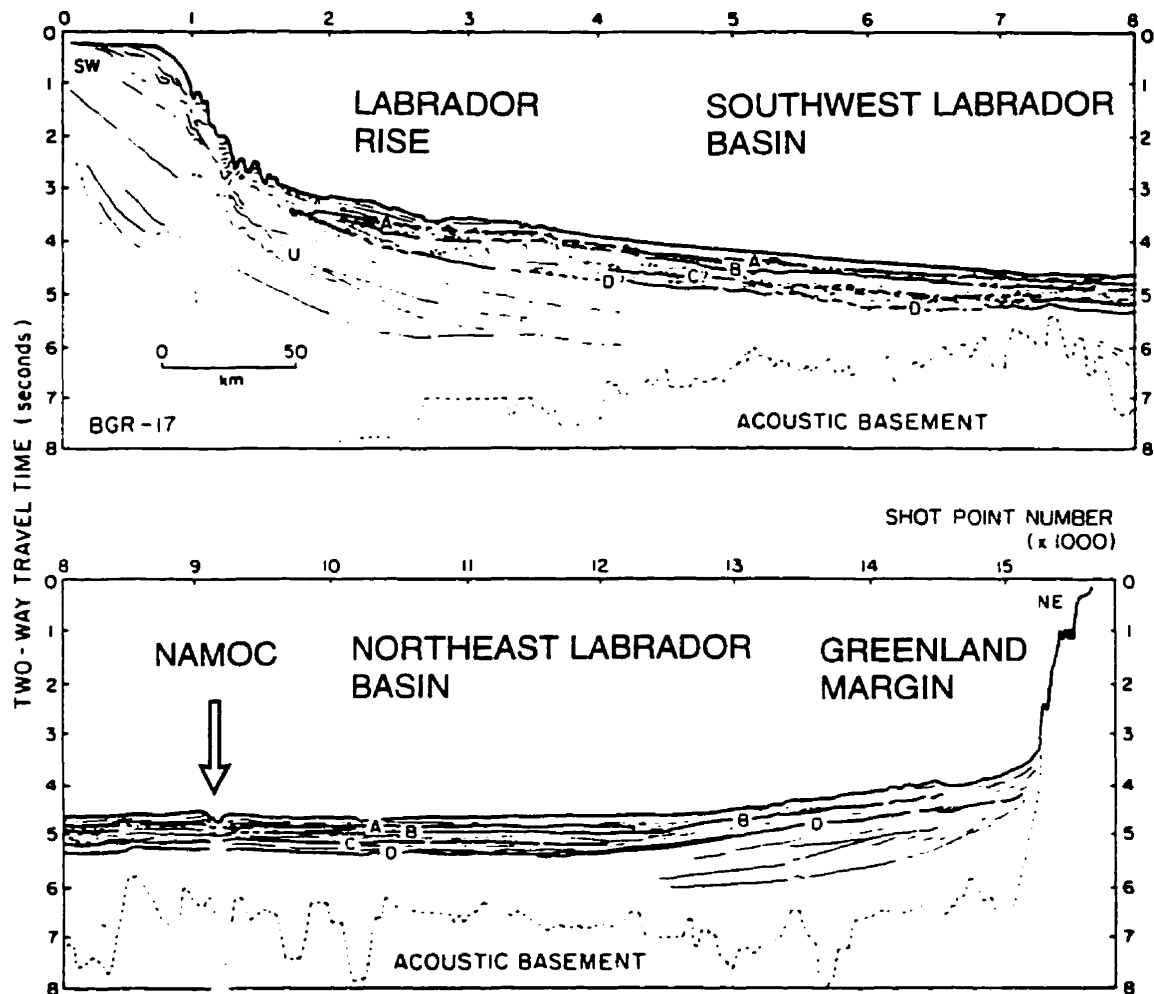


Fig. 1.2. Line drawing of east-west seismic profile BGR-17 across the central Labrador Sea (Hinz et al., 1979); reflector U=Mid-Late Miocene, reflectors A and B are Pleistocene turbidites; the reflectors C and D are Late and Middle Pliocene, respectively (from Myers and Piper, 1988).

Until 1984, the sedimentary facies in the central Labrador Sea were thought to consist of the coarse-grained channel fill deposits of the NAMOC and fine-grained spill-over deposits with hemipelagic interbeds on its levees. This interpretation was substantially changed when, during the Hudson cruise 84-030, sand and gravel deposits were retrieved in piston cores from the floodplains adjacent to the NAMOC levees (Hesse et al., 1987, 1990). Later studies showed the presence of a sandy floodplain up to 120 km wide adjacent to the eastern NAMOC levee, which is braided in its distal parts (Hesse and Rakofsky, 1992; Klaucke, 1995; Hesse et al., 1996). Another important discovery was an interconnected submarine drainage system of converging slope and rise canyons, which join the NAMOC in the basin centre. It formed the basis for a new deep-sea turbidite facies model (Hesse, 1989; Hesse et al., 1990; Hesse and Rakofsky, 1992) as alternative to conventional deep-sea fan models (Mutti and Ricci Lucchi, 1975; Shanmugam and Moiola, 1988). Tributary canyons in the Labrador Sea run parallel to the main trunk channel in the fashion of yazoo channels (Fig. 1.1; Hesse, 1989).

With interest shifting to continental slopes, sedimentological studies since 1992 have focused on the Labrador Slope. Because of its significance for sediment transfer from the glaciated shelf to the deep sea, the slope has become a key area for understanding ice-sheet drainage into the deep sea. Recent sedimentological studies revealed a large variety of depositional mechanisms such as deposition from meltwater plumes, hemipelagic settling, ice-rafting, nepheloid layers, turbidity currents and debris flows on the Labrador margin (Wang, 1992; Wang and Hesse, 1996; Hesse and Khodabakhsh, 1995; Khodabakhsh et al., 1995, Khodabakhsh and Hesse, 1996a, b;

Klaucke, 1995).

Most recently, research has concentrated on the link between rapid Quaternary climatic changes and episodic ice-rafting (Heinrich) events in the Labrador Sea and in the North Atlantic (Andrews and Tedesco, 1992; Bond et al., 1992, 1993; Broecker et al., 1992; Andrews et al., 1993, 1994a; Dansgaard et al., 1993; Broecker, 1994; Hillaire-Marcel et al., 1994). Although ice-rafted sediments are subordinate by volume in these regions, they are significant because of their paleoclimatic and paleoceanographic implications.

Recent studies have suggested that Heinrich events may have had important feedback on Pleistocene climatic oscillations by modifying the oceanic conveyor-belt circulation (Broecker, 1994). Therefore, sedimentological research on Heinrich events in the Labrador Sea ties in closely with current paleoceanographic and paleoclimatic studies (Bilodeau et al., 1994; Rahman and de Vernal, 1994) and work on Late Quaternary stratigraphy (Hillaire-Marcel et al., 1994). Even in the absence of an ice sheet on North America at present, information obtained from Heinrich events may be valuable to predict the future behaviour of the metastable West Antarctic Ice Sheet (Whillans and van der Veen, 1993) and its reaction to possible climatic change.

1.3. Objectives

The Labrador Sea is an ideal site to study the relationship between ice sheet fluctuations and sediment transfer mechanisms to the deep sea, because of its proximity to the Pleistocene LIS. A large number of cores from the Labrador Slope, Rise and Basin

(Fig. 1.3) stored in the McGill core collection provided a unique opportunity to further document the extraordinary influence of a continental ice sheet on marine sedimentation.

The specific objectives of the present thesis include:

1.3.1. Depositional regimes on the Labrador Slope. Previous studies based on seismic profiles seemed to indicate that during the Wisconsinan glaciation sedimentation on the Labrador Slope was dominated by mass flow processes (Hesse, 1992). These studies revealed high- to moderate-relief sectors alternating with low-relief sectors on the upper slope (Hesse and Klaucke, 1995) reflecting different depositional regimes which coexisted. Low-relief sectors occur in front of and north of the major outlets of the LIS and are dominated by mass flow deposition. Preferential occurrence of the high-relief sectors on the south side of the outlets is evidence for a different sediment-delivery mechanism, i.e. meltwater-plume transportation modified by the Labrador Current (Hesse et al., 1997). Using existing cores from this region, the first objective of the thesis is to verify the proposed depositional processes and characterize the resulting depositional facies.

1.3.2. Stratigraphy of the Labrador Slope. Previously, it was thought that attempts to establish a general stratigraphic correlation for different regions of the Labrador Slope would meet with little success, due to the high rates of terrigenous input triggering mass flows which may erode older sedimentary sequences and generate a discontinuous stratigraphic record (e.g. Mudie and Hardy, 1990). Surprisingly, recent sedimentological studies revealed that the Labrador-Slope sediments are relatively well preserved in a number of regions. Wang (1992) and Wang and Hesse (1996) presented a preliminary

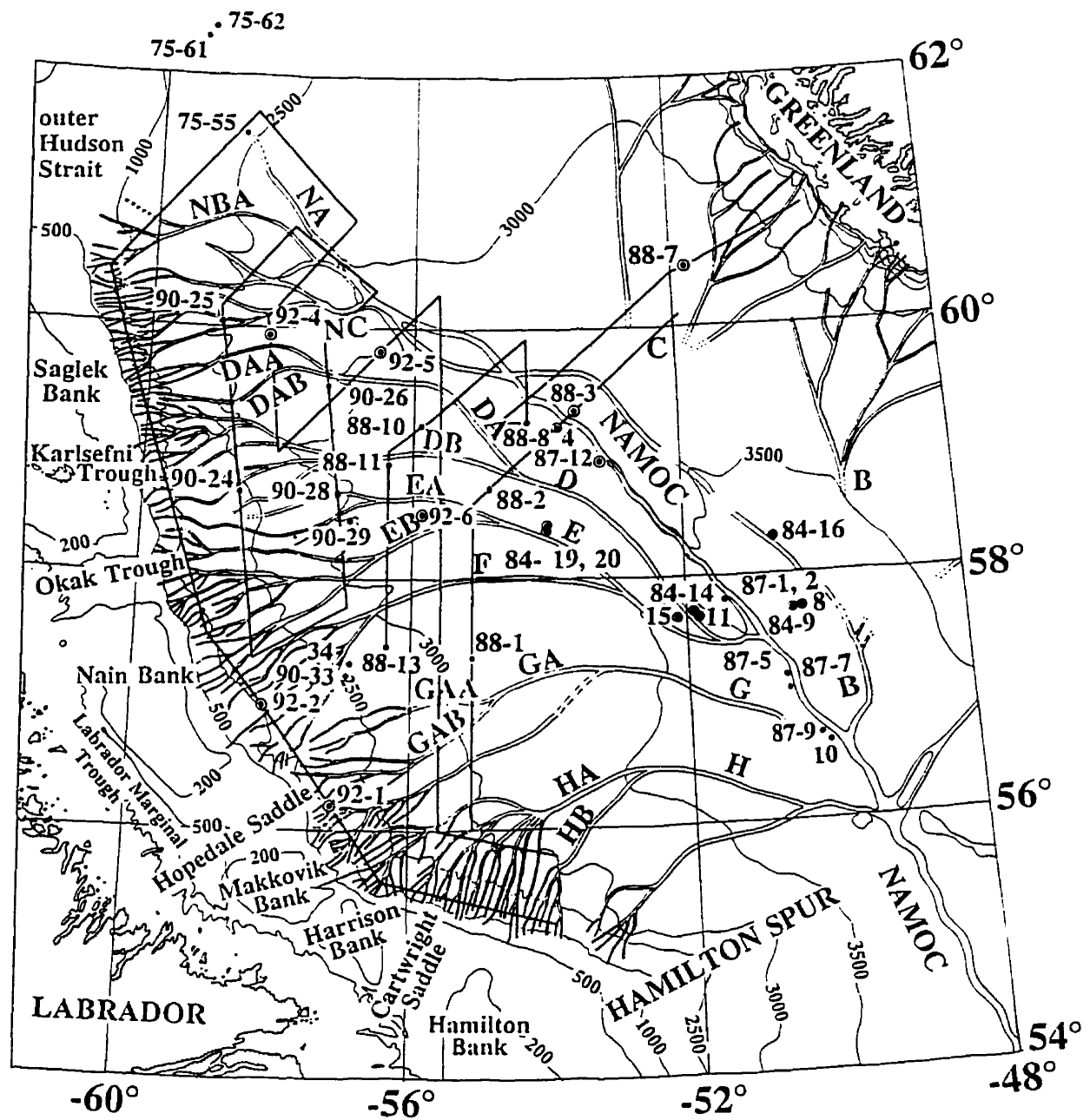


Fig. 1.3. Map of the Labrador Sea showing channel and canyon pattern (from Klaucke, 1995) and location of core stations. The solid lines are the ship tracks of Hudson cruises H-88-024, H-90-013 and H-92-045. The open circles are cores studied for the first time in the present thesis. X-radiographs of the 84 cores, courtesy A. Rakofsky).

lithostratigraphy for the slope and attempted to correlate it with glacial cycles. Since 1992, our knowledge about depositional processes, their relation with glacial cycles and sediment ages has been significantly improved by additional radiocarbon ages, isotopic data, new piston cores (this study), and seismic profiles (Klaucke, 1995). The second objective of the present study is to improve the existing lithostratigraphy by extending it laterally to the slope and to other regions of the Labrador Sea. An important stratigraphic tool are Heinrich layers, which are strictly synchronous event markers in the Labrador Sea and North Atlantic and serve to establish relationships between sediment delivery and glacial history of the study area.

1.1.3. Depositional mechanisms of Heinrich layers. Repeated collapse of the LIS is marked by deposition of horizons, named Heinrich layers by Broecker et al. (1992) after their discoverer Hartmut Heinrich (1988). Heinrich layers are rich in ice-rafted debris (IRD), distributed over thousands of square kilometres in the Labrador Sea and North Atlantic. They are recognized by abundant coarse-grained material ($>125\mu\text{m}$) in the sediment. Current research suggests that other depositional mechanisms (i.e. turbidity currents, meltwater plumes and nepheloid layers) coexisted with ice rafting during Heinrich events (Hesse and Khodabakhsh, 1995; Khodabakhsh and Hesse, 1996a; Wang and Hesse, 1996). The third objective of the present thesis is to document these processes and their relationship with ice-rafting in the Labrador Sea.

1.1.4. Possible linkage between subglacial outburst flooding events and Heinrich events.

Recent work has raised speculations that subglacial lake outburst flooding events through the Hudson Strait may have been associated with Heinrich events in the Labrador Sea (Hesse et al., 1994; Hesse, 1995; Johnson and Lauritzen, 1995). These events apparently were powerful enough to transport sand and gravel to the basin centre, more than a 1000 km from their presumed source in the Hudson Strait region. If the submarine sand- and gravel-plain in the central Labrador Sea basin received its coarse-grained sediment from subglacial flooding events through the Hudson Strait outlet of the LIS, as suggested by Hesse et al. (1996), then they would indicate a provenance from this region rather than from Greenland. The fourth objective of the thesis therefore is to test this hypothesis using petrographic evidence as well as oxygen-isotope stratigraphy and radiocarbon dating to constrain the age of these events.

CHAPTER 2: Quaternary glacial environments

2.1. Glaciomarine depositional environments

Continental ice sheets had significant influence on sedimentation processes of their neighbouring oceans. During the Wisconsinan glaciation, the Labrador Sea was the main receptor basin for glacially-derived sediment from the LIS and Greenland Ice Sheet (GIS, see section 2.2). Repeated advances and retreats of the ice sheets were the main controlling factor for sediment dispersal in the basin. Understanding of the depositional systems in the region requires knowledge about the mechanisms of sediment delivery in glaciomarine environments.

Glaciomarine environments include seas bordered by tidewater glaciers or ice shelves (Edwards, 1978). Glaciomarine environments face a variety of glacier types: (1) tidewater valley glaciers and marine ice sheets that are grounded below sea level, and (2) floating ice tongues or ice shelves which occur in front of the grounding line (Edwards, 1986; Fig. 2.1). Based on the proximity to the glacier, glaciomarine depositional systems are divided into ice-proximal and ice-distal regions (Eyles and Eyles, 1992). Ice-proximal areas are dominated by glacial processes related to sediment supply by grounded glaciers, icebergs, subglacial meltwater streams and turbid surface plumes (Andrews and Matsch, 1983; Eyles, 1987). On the basis of morphology, proximal regions can be further subdivided into low-relief (continental shelves) or high-relief glaciomarine (fjords) settings (Eyles and Eyles, 1992). In distal regions, the direct glacial influence is restricted to sedimentation from icebergs. However, resedimentation processes, triggered in regions with high accumulation rates may also influence distal glaciomarine environments. The

maximum marine influence of an ice sheet is variable. Sediments may be transported by icebergs thousands of kilometres from glacial terrains to deep marine environments (Andrews and Matsch, 1983; Gilbert and Barrie, 1985). The boundary between the proximal and distal settings is not sharp; intermediate depositional settings exist.

Another important factor in glaciomarine depositional systems is regional climate, which controls the volume of meltwater supplied from glaciers to the marine environment (Eyles and Eyles, 1992). While temperate oceanic environments generally receive large volumes of meltwater from adjacent land glaciers, polar oceans receive considerably less meltwater input. The thermal state of glaciers is the basic criterion to differentiate wet- and dry-based glaciers. Dry-based glaciers are frozen to the base and ablate mainly by calving (Edwards, 1986); wet-based glaciers are associated with substantial subglacial melting (Edwards, 1978). In polar environments, ice sheets may temporarily switch from a dry-based mode to a wet-based mode (MacAyeal, 1993).

2.2. Sediment transport and deposition

In a glacier, sediments are dispersed in three zones: (1) the basal or subglacial zone which is in contact with the bed, (2) the supraglacial zone which is the upper surface of the glacier influenced by seasonal melting, and (3) the interior or englacial zone which does not play a significant role in sediment transport (Edwards, 1978). The basal zone, containing >80% (by volume) of the glacier-transported sediment (Eyles et al., 1983), plays the most important role in glaciomarine sedimentation. Most of the debris is incorporated into the glacier base by freezing of water along the glacier bed

(Knight, 1994).

A typical ice-proximal sediment is till, consisting of a mixture of gravel, sand and mud-sized particles, deposited by grounded glaciers. Processes in the basal zone of a glacier are controlled by the thermal state of the glacier. An increase in the ice thickness and in the dip of the bed in an upglacier direction increases friction with the bed, resulting in deposition of basal till (Edwards, 1978; Fig. 2.1). During glacial expansion (sea level lowstand), large volumes of sediment are supplied to ice margins. As the glacier retreats, subsequent sediments will become ice-distal or post-glacial, reflecting sea-level highstands (Syvitski, 1991). However, sea-level fluctuations are also influenced by ice-isostasy. During the initial phase of glacial advance sea level falls eustatically. This is followed by a relative sea level rise as the land is depressed under the ice load. Since glacier retreat can be rapid (10 km/y), and isostatic response to glacial retreat is

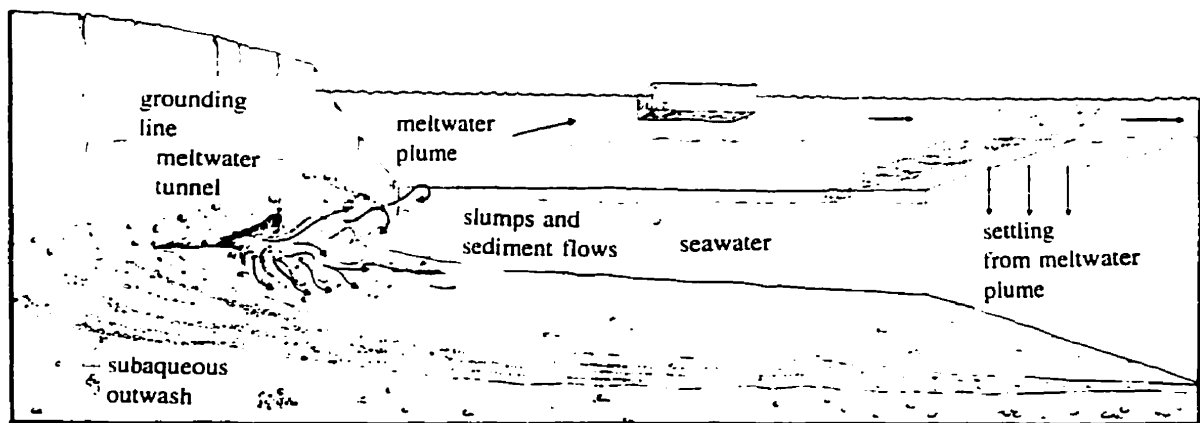


Fig. 2.1. Schematic reconstruction of sediment delivery mechanisms in a proximal glaciomarine environment (modified from Edwards, 1986).

slow (10 cm/y), relative sea-level rise precedes a later fall in relative sea level (see fig.3.12 of Syvitski et al., 1987).

During sea level lowstand the ice front progrades across the continental shelf or even further seaward to the upper slope (Josenhans, 1983; Josenhans et al., 1986; Fillon and Harms, 1982). Materials eroded from the exposed shelf and land areas are carried by various processes to the ice-marginal environments. Ice-rafting releases a wide range of grain sizes (i.e. boulder- to clay-sized material) to the ice margin (Gilbert, 1990). This process occurs in both ice proximal and distal settings. Sediment-laden meltwater is significant in supplying fine materials by vertically rising buoyant plumes in ice-proximal settings (Syvitski et al., 1987; Syvitski, 1989; Fig. 2.1). This process may be more significant in enclosed or semi-enclosed glaciomarine environments, e.g. fjords. Glaciomarine sedimentation is also affected by marine currents which control iceberg tracks (Andrews et al., 1995) and transport of fine suspended sediments by overflows (Khodabakhsh and Hesse, R. 1996b). In addition to overflows, during high sediment discharges underflows and interflows may form (Syvitski et al., 1987). Underflows may construct extensive outwash sediments adjacent to the grounding line (Edwards, 1986; Fig. 2.1). Outwash sediments are deposited by high-energy meltwater streams near the glacier tongues. Sediments consist of sand and gravel, deposited by bedload transport or mass flows (Rust, 1977). Outwash sediments also occur where the glacier front is grounded on land and does not contribute icebergs (Powell, 1981).

Glacially scoured troughs on glaciated shelves are the main pathway of ice streams (Edwards, 1986). In the Labrador Sea, the LIS margin was associated with

substantial basal flow (Dyke and Prest, 1987). Subglacial channels eroded into bedrock were formed by high-energy and confined flows at the base of glaciers. A complex system of depressions on the glaciated shelf is the continuation of subglacial channels (Josenhans and Zevenhuizen, 1990). The Labrador fjords on the coast and their seaward continuations on the ice-covered shelf acted as major outlets for supplying glacially-derived sediments to the basin through the slope canyon system (Hesse, 1992). High sediment supply during sea-level lowstand increases the slope instability which ultimately triggers mass wasting processes (i.e. creep, slides and slumps). Downslope, incorporation of water into the slide mass generates debris flows and turbidity currents, which carry sediments to the deep sea (e.g. Hesse, 1992; Hiscott and Aksu, 1994; see Ch. 5).

2.3. The Laurentide Ice Sheet

The LIS was first recognized as a complex of essentially independent glaciers (Tyrrell, 1914, cited in Fulton and Prest, 1987); later it was considered as a single ice sheet centred on Hudson Bay (Flint, 1943, cited in Fulton and Prest, 1987). More recently, it is assumed to have been formed by three major coalescent ice masses (Fulton and Prest, 1987). The three sectors include the Keewatin (west), Baffin (north) and Quebec-Labrador (east) sectors, joined at intersector saddles (Dyke and Prest, 1987). The major convergence of the ice flow was towards the Hudson Strait, which drained into the Labrador Sea (Dyke and Prest, 1987; Andrews et al., 1990; Vilks et al., 1989). The LIS showed two major glacial progressions during the Early Wisconsinan (75 to 65 ka) and Late Wisconsinan (23-12 ka). During the Middle Wisconsinan, the LIS showed a number

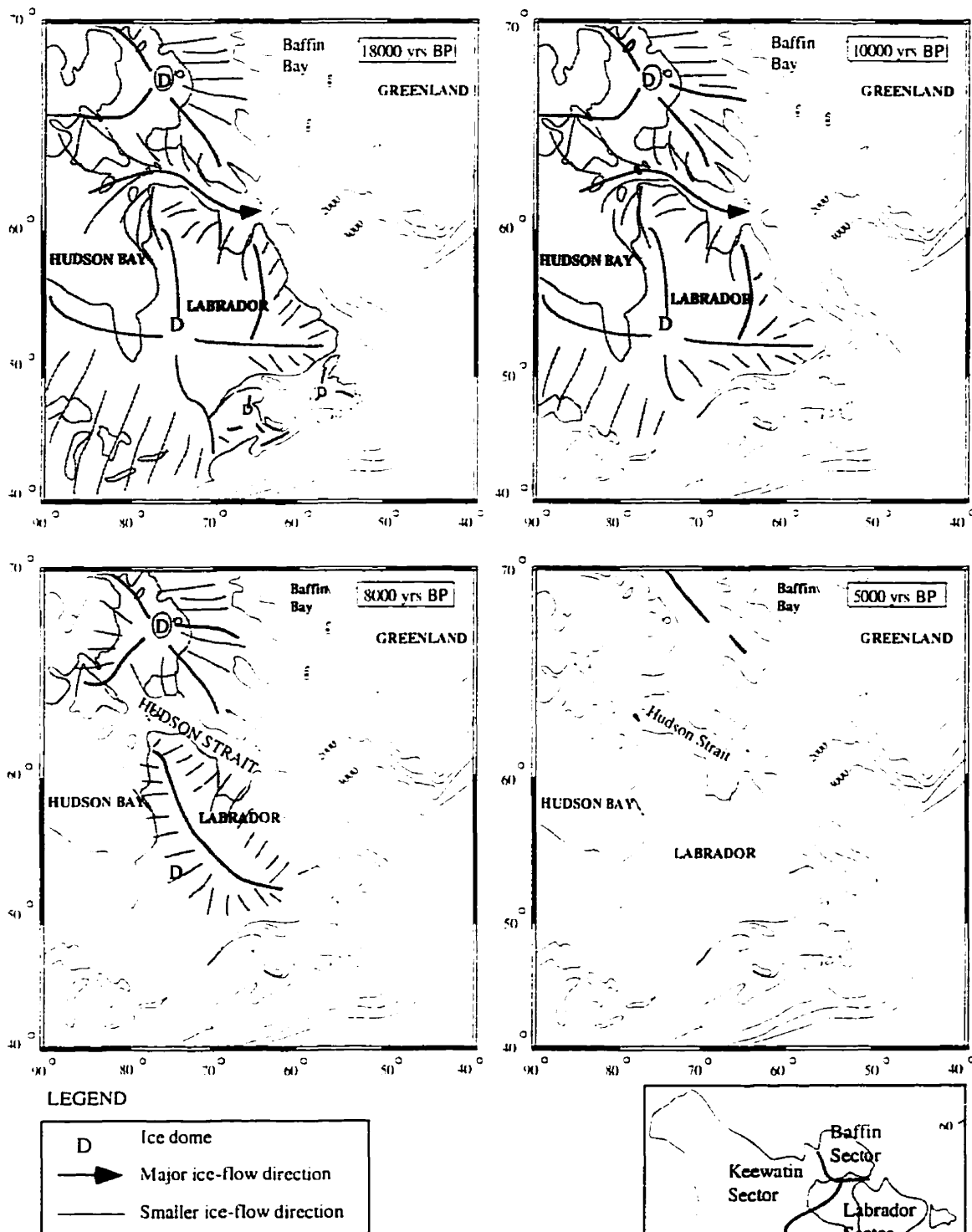


Fig. 2.2. Limits of the Laurentide Ice Sheet from 18 to 5 ka (from Dyke and Prest, 1987). The inset map shows the major ice sectors (from Fulton and Prest, 1987).

of oscillations producing a trend of gradually increasing ice volume towards the Late Wisconsinan. The maximum advance of the LIS occurred in Late Wisconsinan time (23-10 ka). It reached its maximum extension at 18 ka (Andrews et al., 1990; Dyke and Prest, 1987; Fig. 2.2). The LIS retreated slowly along the western and southern margins from 18-13 ka, while the eastern segment did not change significantly. Retreat between 13 and 8 ka was also faster in the west than the east (Dyke and Prest, 1987). The LIS has experienced several short readvances between 11-8 ka (Miller and Kaufman, 1991). By 8 ka most of the LIS had disappeared (Josenhans and Zevenhuizen, 1990; Fig. 2.2).

2.4. Relationship between climatic oscillations and ice-rafting events

Deep sea records (Bond et al., 1992) and isotopic measurements in Greenland (Dansgaard et al., 1993) and Antarctic ice cores (Barnola, 1987) document a series of rapid warm-cold climatic fluctuations during the last glaciation known as Dansgaard-Oeschger cycles (Broecker, 1994). These climatic oscillations are best documented in the ice records (Fig. 2.3), although great efforts are currently being made to identify them from high-sedimentation rate deep-sea cores (Bassinot and Labeyrie, 1996). Each cycle is characterized by a gradual decrease in temperature, followed by abrupt warming. Each long cycle (now called Bond cycle) consists of several shorter cycles (i.e. Dansgaard-Oeschger cycles) which even existed during the last interglacial (Dansgaard et al., 1993).

Ice sheets were previously considered to play a passive role as climatic recorders (through their advances and retreats) of externally (i.e. orbitally) forced climatic variations (Hays et al., 1976). However, recent studies suggest that continental ice sheets may have

had an active feedback on the short-term climatic oscillations during the last glaciation (Broecker, 1994). Bond et al. (1993) found that climatic cycles are linked to times of massive iceberg drift in the North Atlantic, the Heinrich events mentioned in Ch. 1. Most Heinrich events occurred at the end of the Dansgaard-Oeschger cycles and were related to LIS surges across the Hudson Strait and adjacent regions (i.e. Baffin Bay; see Hiscott et al., 1989). This requires wet-based glaciers (Oerlemans, 1991; MacAyeal, 1993; see Ch. 6) and open-sea conditions in adjacent oceans (Ruddiman and McIntyre, 1981, Aksu et al., 1988). The phenomenon occurred at least six times during the last glaciation (Broecker, 1994).

2.5. Relationship between climatic oscillations and thermohaline circulation

In light of new findings since 1992, abrupt climatic oscillations during the last glaciation might be related to a change in ocean circulation, triggered by fresh water input to the North Atlantic in form of meltwater and icebergs (Broecker, 1994). Iceberg melting during Heinrich events could significantly reduce sea-surface salinity as far south as 40°N (Chapman and Shackleton, 1995). This process dampens the conveyor belt that advects heat poleward (Broecker and Denton, 1989). The most significant change in the deep-water production may have occurred during Heinrich events. During these times supply of huge amounts of fresh water due to iceberg melting in the North Atlantic temporarily suppressed northward advection of the Gulf Stream which transports warm and saline water from low to high latitudes; this results in damping the deep-water formation in Norwegian-Greenland Sea (Paillard and Labeyrie, 1994). Recent

paleoceanographic studies show that deep-water generation in the North Atlantic periodically ceased prior to 26, 22.5-20.5 and 14.9-13 ka, coinciding with Heinrich events 3, 2 and 1, respectively (Rasmussen et al., 1996). When the massive iceberg flux ceased, the thermohaline circulation restarted (Paillard and Laberie, 1994). It is notable that open sea conditions prevailed during parts of the glacial cycles and at least seasonal deep-water production may have been active during these periods of time (Corliss et al., 1986; Stoker et al., 1991).

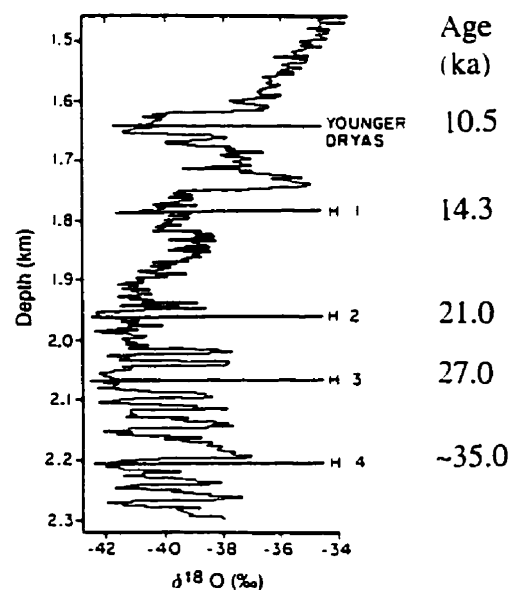


Fig. 2.3. Correlation of Heinrich events (modified from Broecker, 1994) with Quaternary climatic cycles revealed by the $\delta^{18}\text{O}$ record from the Summit Greenland (GRIP) ice-core (from Dansgaard et al., 1993). Note that Heinrich events occur at the end of a series of cooling cycles which precede warm interstadial periods.

CHAPTER 3: Sedimentary facies

3.1. Materials and methods

The sample material for this study was obtained from piston and trigger-weight cores taken during Hudson cruises H-75-009, H-84-030, H-87-025, H-88-024, H-90-013 and H-92-045 from the Labrador Sea at water depths between 1600 to 3400m (Figs. 1.3, 3.1). The maximum penetration by piston coring was 14.2 m. The uppermost 1 m of sediments are better preserved in trigger-weight cores because most piston cores lost some parts of their tops (up to 1.1 m) during core retrieval.

Five types of analyses were carried out:

(1) *Structural analysis* - X-ray radiography was used to document internal sedimentary structures, bed contacts, stratification and burrow types. The sediment slabs (1x10x27.5 cm) were X-rayed using a Picker Industrial X-ray machine and ready-packed II Kodak Industrex AA film. The voltage of the X-ray machine was set at 55 kV. Depending on the compaction-related bulk-sediment density, the exposure time varied between 12 to 24 seconds (0-15 m subsurface depth), requiring an increase of ~1 sec/m. Turbidites and debris flows, which have higher densities, require exposure times 2-3 sec greater than those of hemipelagic sediments.

(2) *Textural analyses* - Sediment-grain size was measured by the pipette method for the silt-clay fractions based on Stokes' law (Folk, 1980), and sieve analysis for sand- and gravel-sized material. For fine-grained facies (turbid-surface plume sediments and nepheloid-layer deposits) samples were analyzed in a laser microgranulometer by Dr. M. Cremer at Bordeaux University, Talence, France (Appendix 2). The abundance of IRD

was determined by counting of the numbers of grains >1 mm in the surface of X-radiographs.

(3) *Isotopic analyses* - Both radiocarbon and oxygen-isotope analyses were performed on the planktonic foraminifera *Neogloboquadrina pachyderma* (left coiling; Appendix 4). Radiocarbon ages of hand-picked foraminifera (15-20 µg of foraminifera shells from the >125µm size fraction, i.e. about 2000 specimens per sample) from hemipelagic sediments were measured by an accelerator mass spectrometer (AMS) at the Isotrace Lab of the University of Toronto. The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ analyses (performed on 50 foram shells) were done at Woods Hole Oceanographic Institution, Woods Hole, MA, USA and provided by Dr. W. Ryan at Lamont-Doherty Earth Observatory, Palisades, N.Y., USA.

(4) *Geochemical analyses* - The carbonate (=inorganic carbon) content was measured in a CO_2 Coulometer (Appendix 5a). Between 0.04-0.1 g of sample material was reacted at 100°C with 3 ml 2N HCl for 10 min. The released CO_2 was back titrated coulometrically. The organic-carbon content was determined in a Leco induction furnace by the difference between total and inorganic carbon (Appendix 6). To measure total carbon, 0.05 to 0.2 g of pulverized (<63µm) sample material was ignited; the released CO_2 was determined by the weight gain of an absorption bulb. Inorganic carbon was also determined following the same procedure, but the sample was first heated at 550°C for 2 hours (Appendix 5b). The type of organic matter was characterized by Rock-Eval pyrolysis at the Geological Survey of Canada, Energy and Environmental Subdivision, Calgary. Using a standard program, geochemical parameters of organic matter were measured at 300°C, 390°C and 600°C (see Appendix 7). The chemical composition of

feldspars and ash fragments was determined by a scanning electron microscope (SEM) combined with an energy-dispersive system (EDS) at the Université du Québec à Montréal (Appendices 8 and 9), set at an accelerating voltage of 25 kV and a beam current of 0.5 A.

(5) *Microscopic investigation* - A representative split of samples in the >125 µm fraction was used for determination of foram abundance and percentages of *N. pachyderma* (sinistral) (Appendix 3). Concentrations of detrital carbonates and ash fragments were determined microscopically in the >63 µm fraction (Appendix 3). For thin section studies, thin sections of epoxy-embedded grain-mounts of the sand fraction (>125 µm) were prepared. Mineral and rock fragment abundance were determined by point counting (Appendix 9).

3.2. Facies classification

Facies are identified on the basis of sediment colour, bioturbation, bed contacts, texture and internal structure. In this study, each facies is attributed to specific depositional processes (e.g., turbidity currents for turbidite facies, contour currents for contourite facies, etc.). The facies types that have been differentiated were modified from Wang and Hesse (1996). The seismic characteristics of the facies types have been described by Hesse and Rakofsky (1992), Wang (1992) and Klaucke (1995). My contributions for the facies classifications are: (1) documentation of two new facies (facies P and MS; see below), and (2) classification of facies D and T into 4 and 3 subdivisions, respectively. Genetic names are applied right away in the discription without

justifying these names by interpretations, which are defined in Ch. 5. This approach is legitimate, because the interpretation have already been published by Wang and Hesse (1996), with the exception of the plumite facies (see below). For abbreviation in the text, each facies is given a letter symbol. Sedimentary facies with a single-mechanism origin include: hemipelagic sediment (H), plumite (P), contourite (C), turbidite (T) and debris-flow deposits (D). Facies with a composite origin include: nepheloid-layer deposits (N), ice-rafted hemipelagic sediments (HI) and turbidites alternating with laminae of ice-rafted debris (TI). Facies HI and TI are subfacies of facies H and T, respectively. Graphic core logs associated with facies distribution profiles are shown in Figures 3.1 and 3.2. On the basis of grain-size distributions and sediment textures, facies are classified in Figures 3.5 to 3.7.

3.2.1. FACIES H: Hemipelagic sediment. This facies consists of grey (2.5Y 5/1 and 5Y 5/1), olive grey (5Y 4/1), and dark grey (5Y 5/2 and 5Y 6/2) mud to silty/sandy mud (Fig. 3.3A). The facies is rich in silt and clay, comprising >95% of the sediment (Table 3.1). Grain-size distributions reveal a mean grain size in the medium silt fraction (7.2 ϕ), a prominent mode in the clay fraction (10 ϕ) and a subordinate mode in the coarse to medium silt fraction (5-7 ϕ ; Fig.3.5f; Table 3.1). Sorting of the sediments is poor ($\sigma=2.0$ ϕ). The bed contacts with overlying and underlying sediments are transitional, but sharp contacts with mass flow deposits (facies T and D) have also been observed (Table 3.2). Bioturbation is intense. Burrow types include: dwelling structures (*Skolithos*, *Planolites*), deposit feeding (stoping) structure (*Zoophycos*), and simple feeding structures the sand

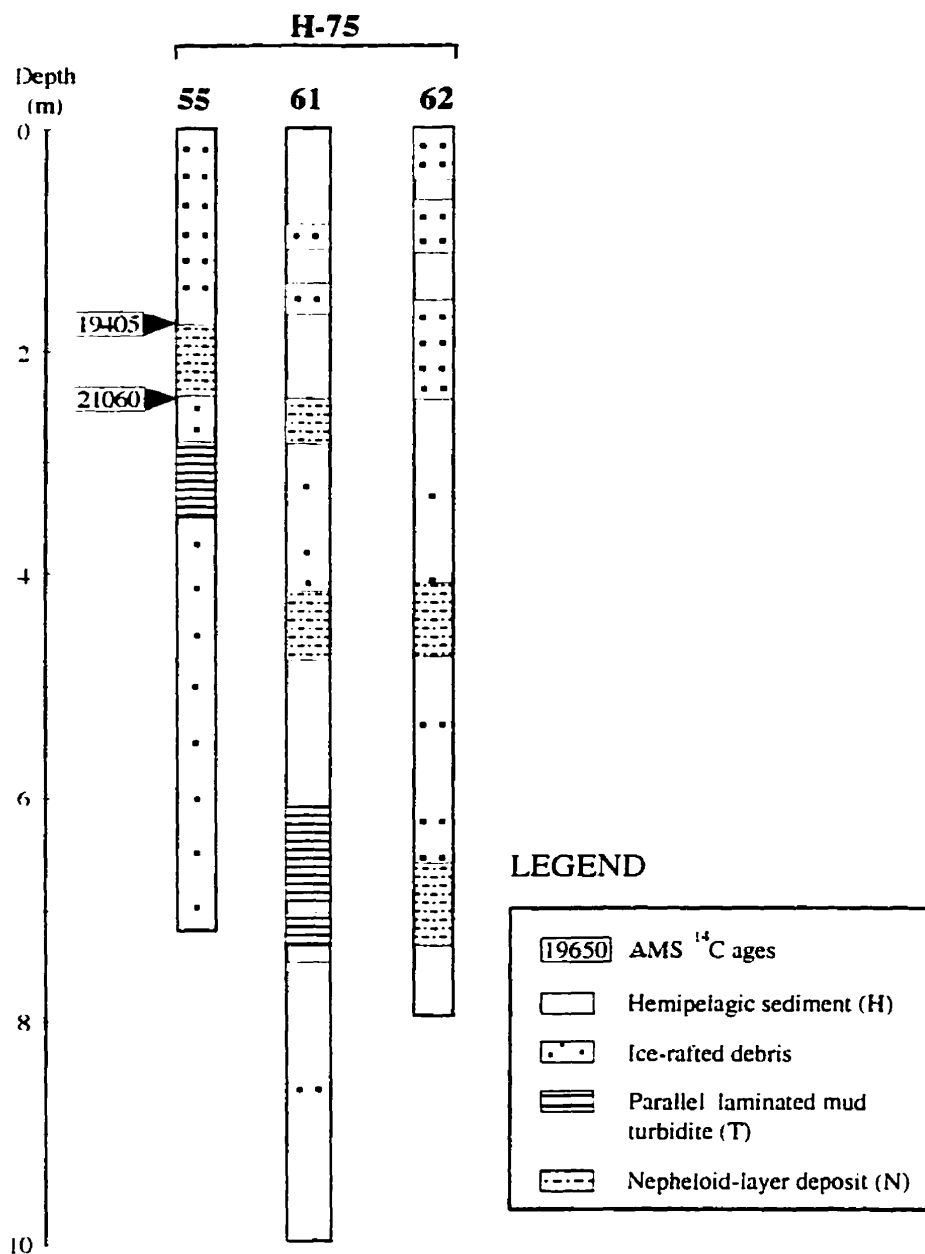


Fig. 3.1. Core logs and radiocarbon dates for 35 piston cores along the Labrador Slope, Rise and Basin (water depths between 1600-3400 m). The cores were retrieved during Hudson Cruises H-75-009, H-84-030, H-87-025, H-88-024, H-90-013 and H-92-045 (for core location see Fig. 3.1). Radiocarbon ages for core 75-55 from Andrews et al. (1994). Abbreviations of facies names in brackets.

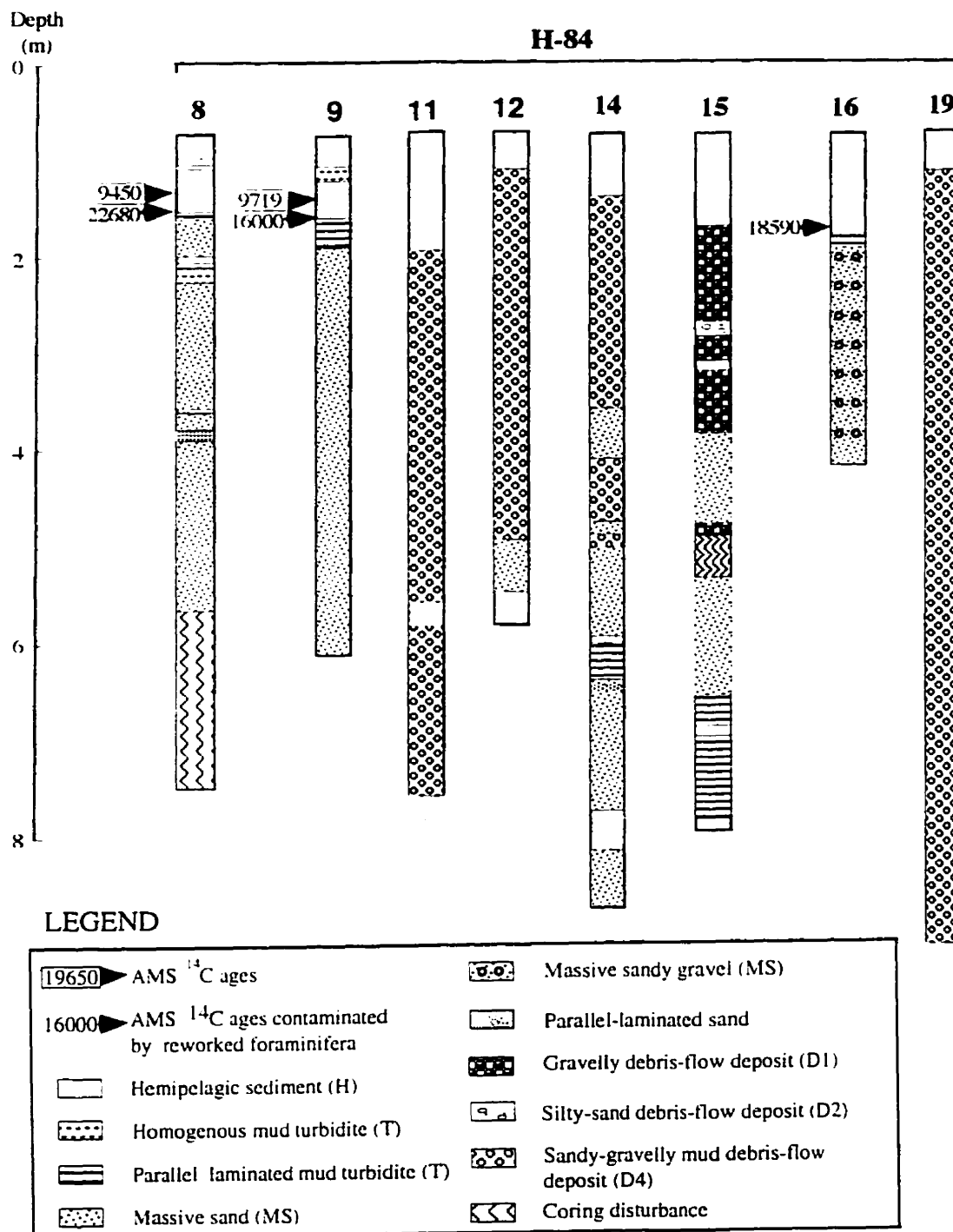


Fig. 3.1. Continued. Radiocarbon ages at the boundary between massive sands and hemipelagic muds in cores 84-8 and 84-9 are overestimated due to contamination by reworked foraminifera. Abbreviations of facies names in brackets.

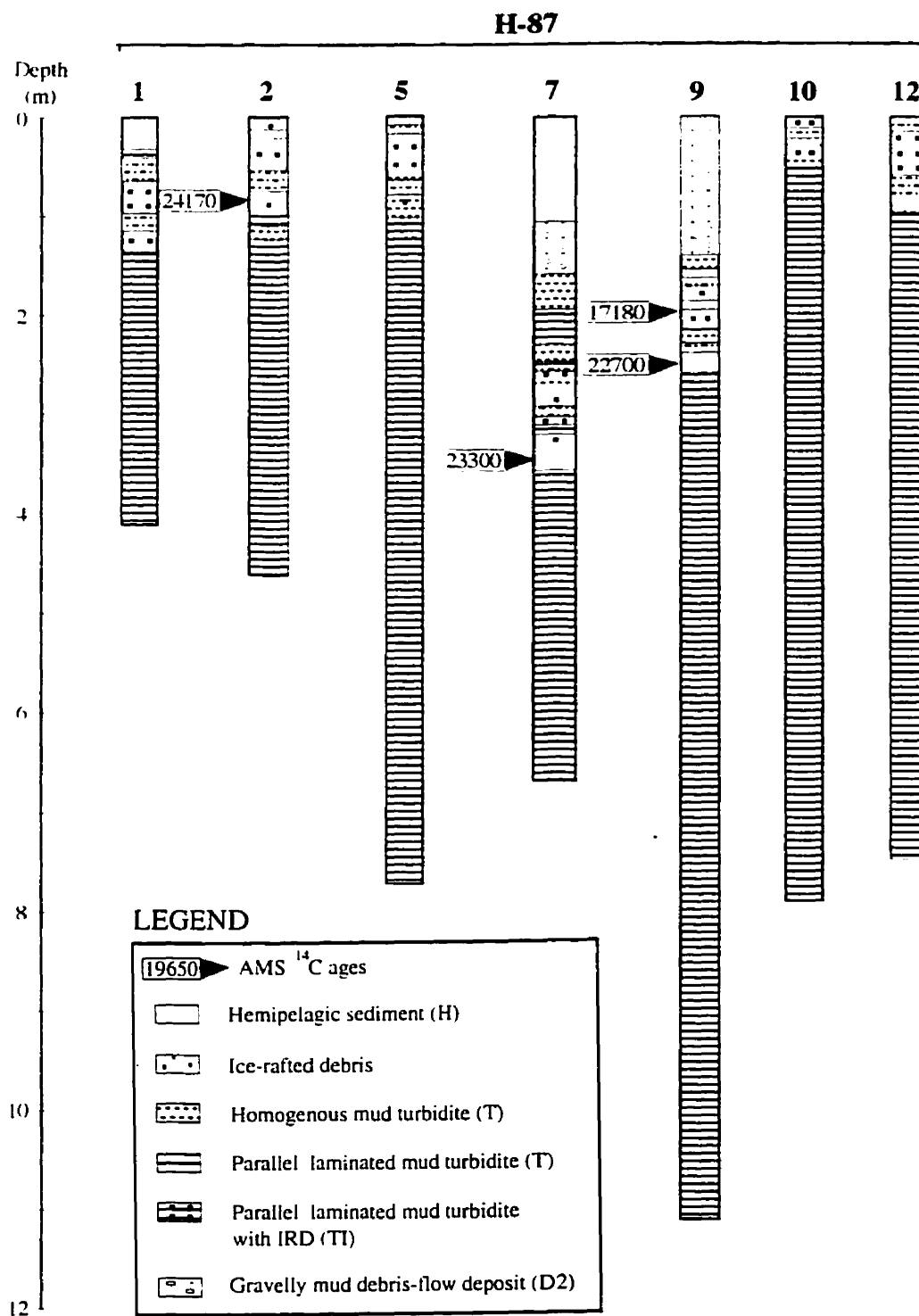


Fig. 3.1. Continued. Radiocarbon ages for cores 87-2, 7 and 9 from Hesse (1995a; see Appendix 3). Abbreviations of facies names in brackets.

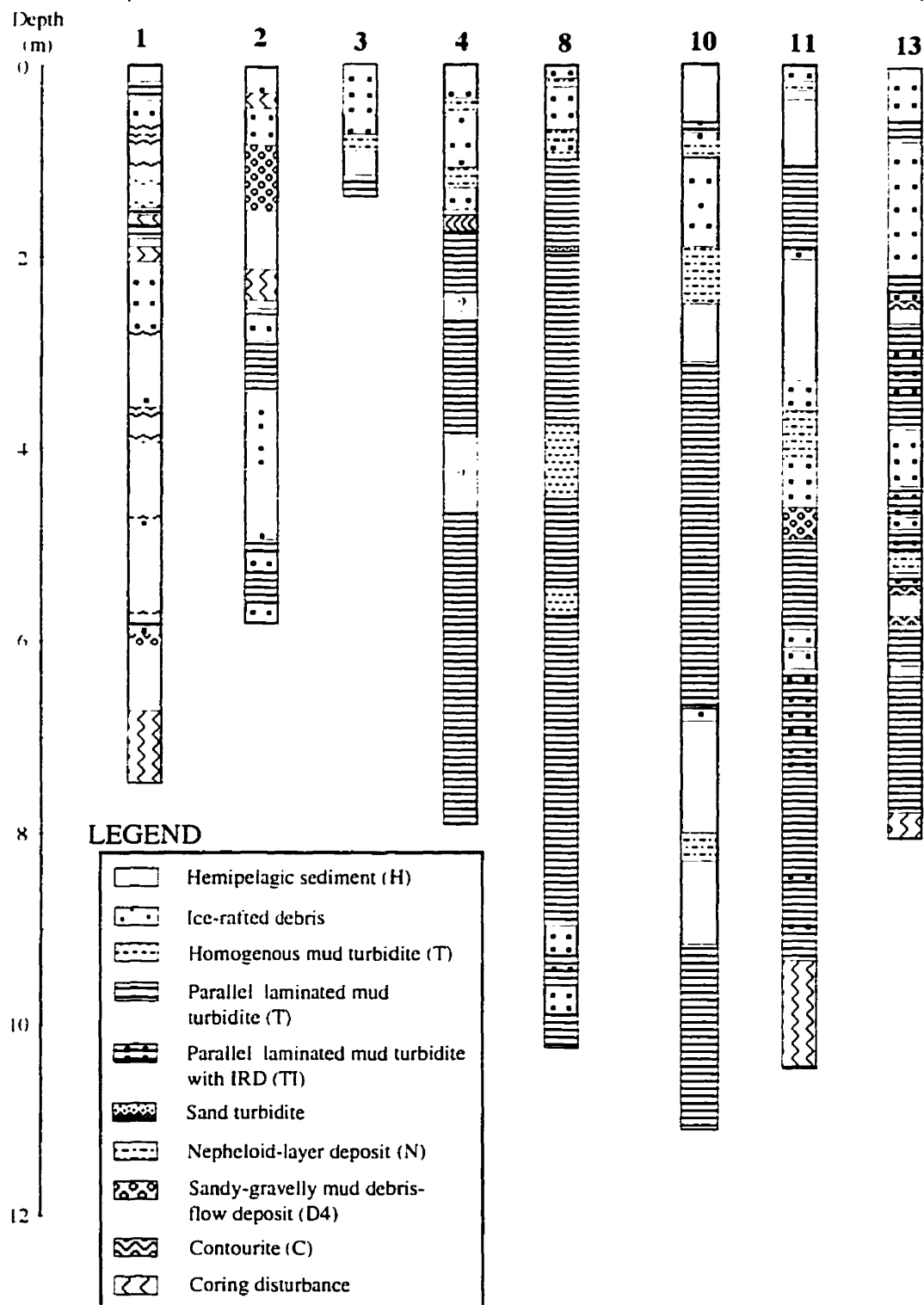


Fig. 3.1. continued. Abbreviations of facies names in brackets.

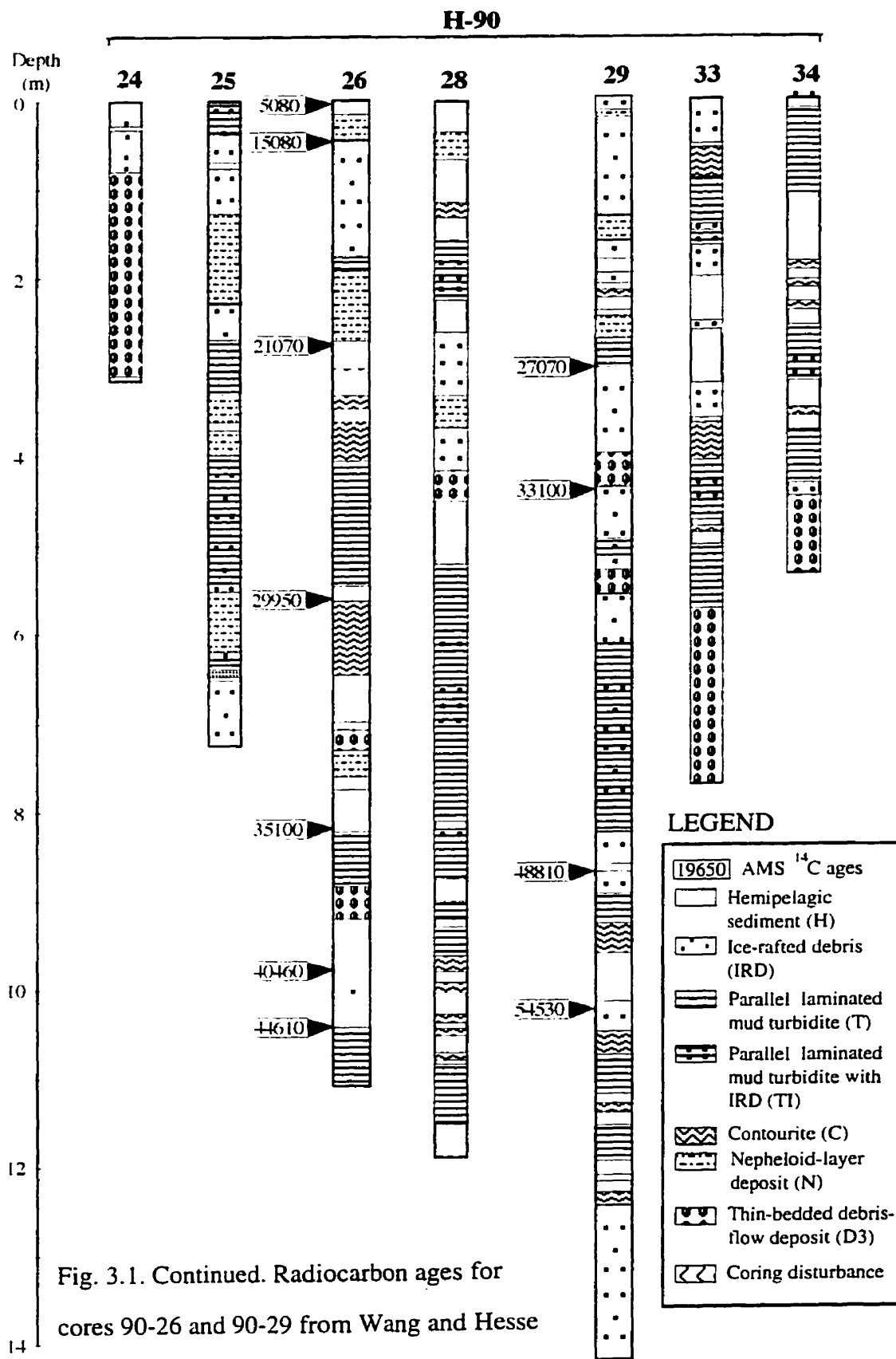


Fig. 3.1. Continued. Radiocarbon ages for cores 90-26 and 90-29 from Wang and Hesse (1996). Abbreviations of facies names in brackets.

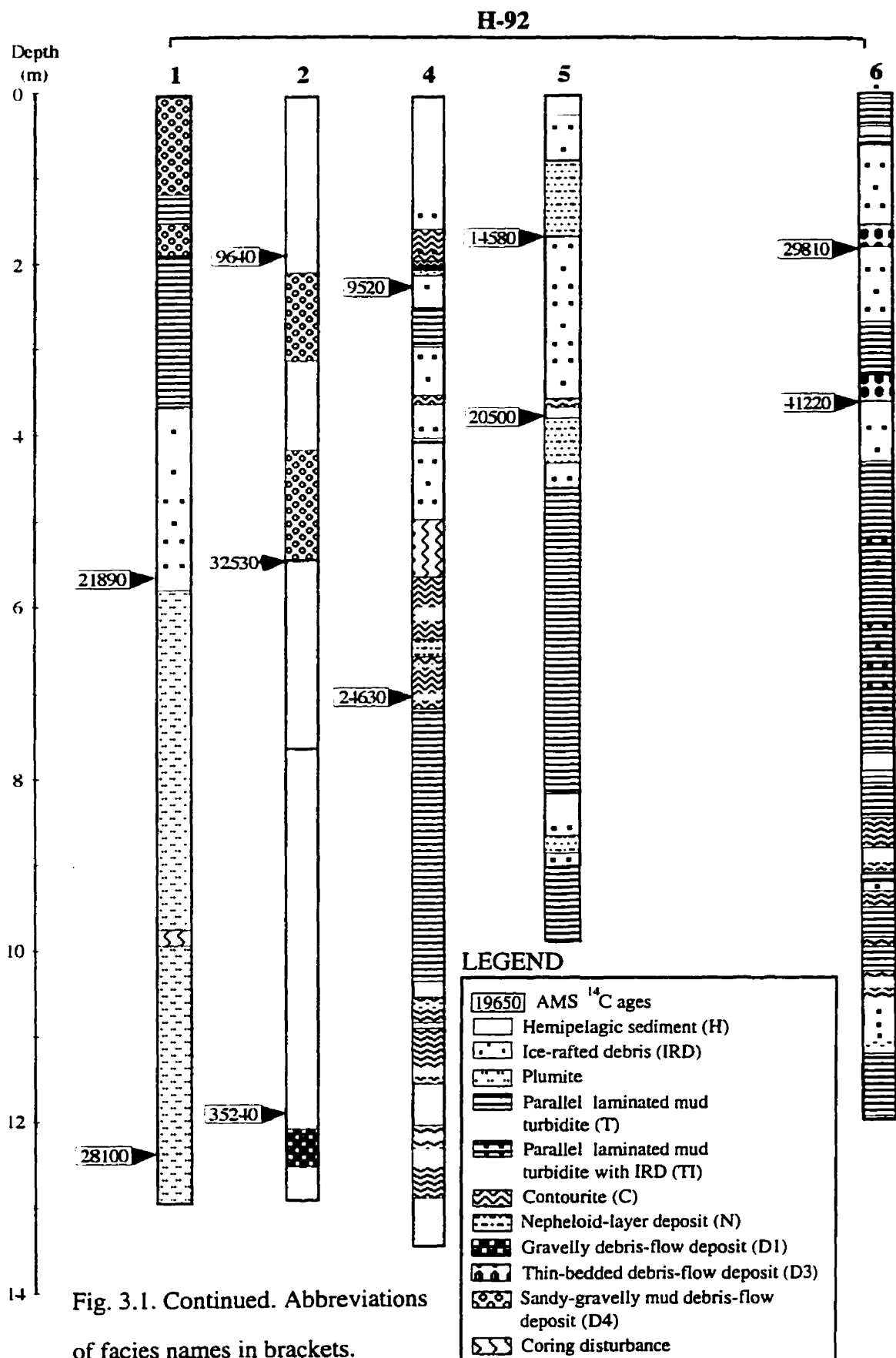
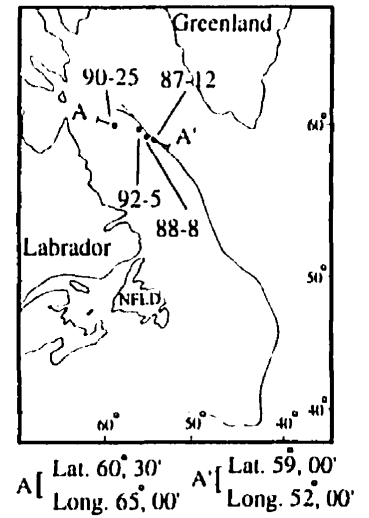
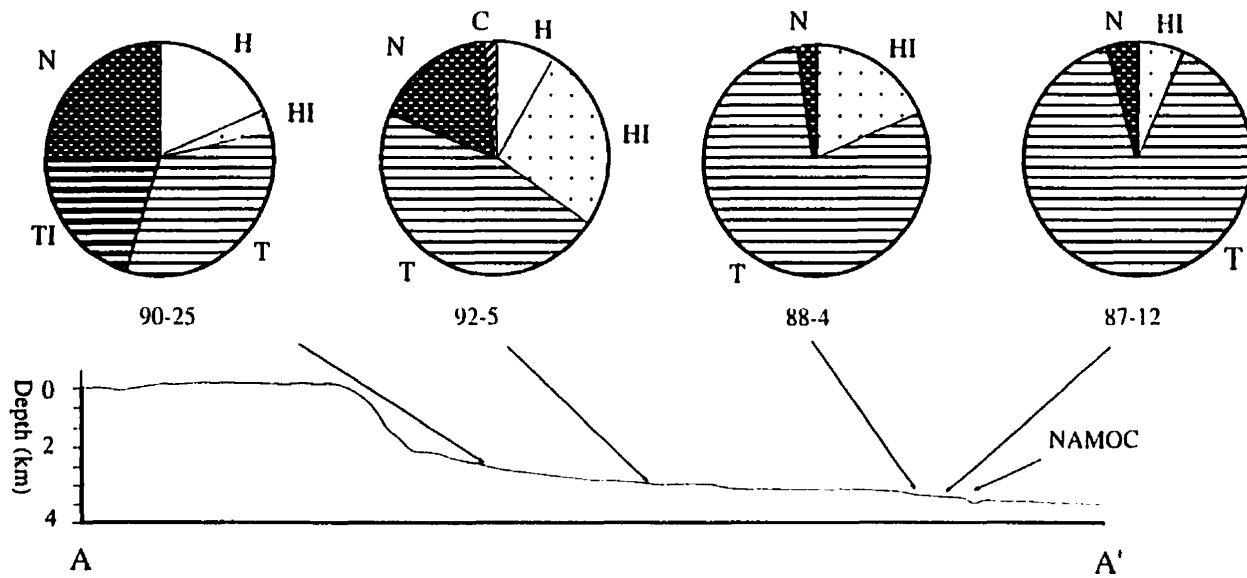


Fig. 3.1. Continued. Abbreviations of facies names in brackets.

Fig. 3.2. Downslope variation in proportion of sedimentary facies along two NW-SE profiles. Note: (i) downslope decrease in the percentage of the sum of facies H and HI; (ii) local occurrence of facies C (lower slope-upper rise) and TI (middle-lower slope); (iii) downslope increase in the percentage of facies T; and (iv) basinward decrease in percentage of facies N.



31

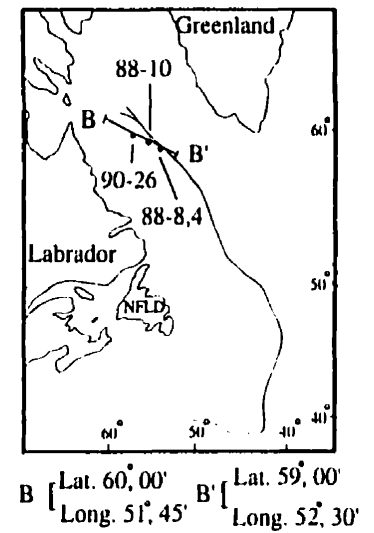
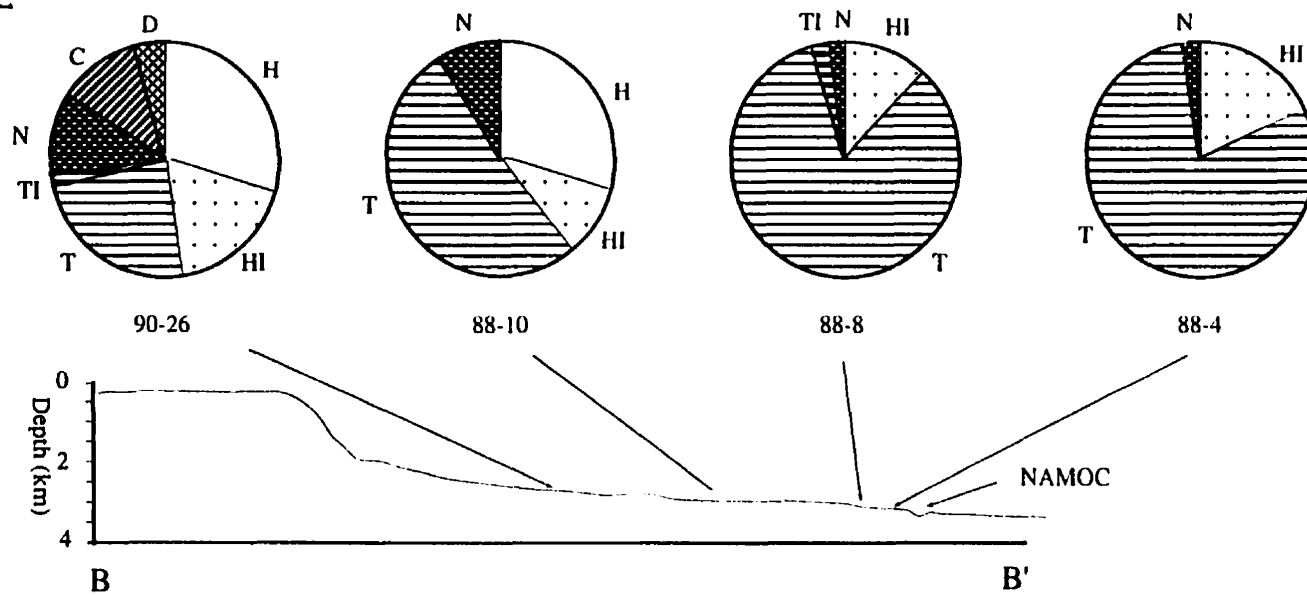
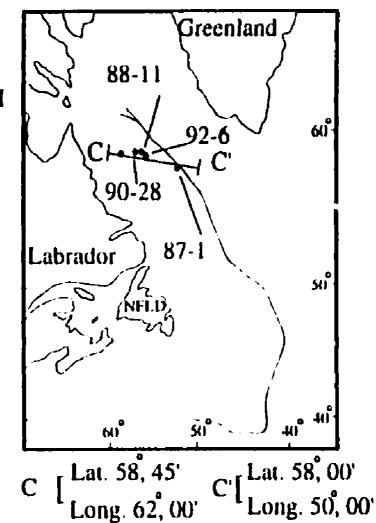
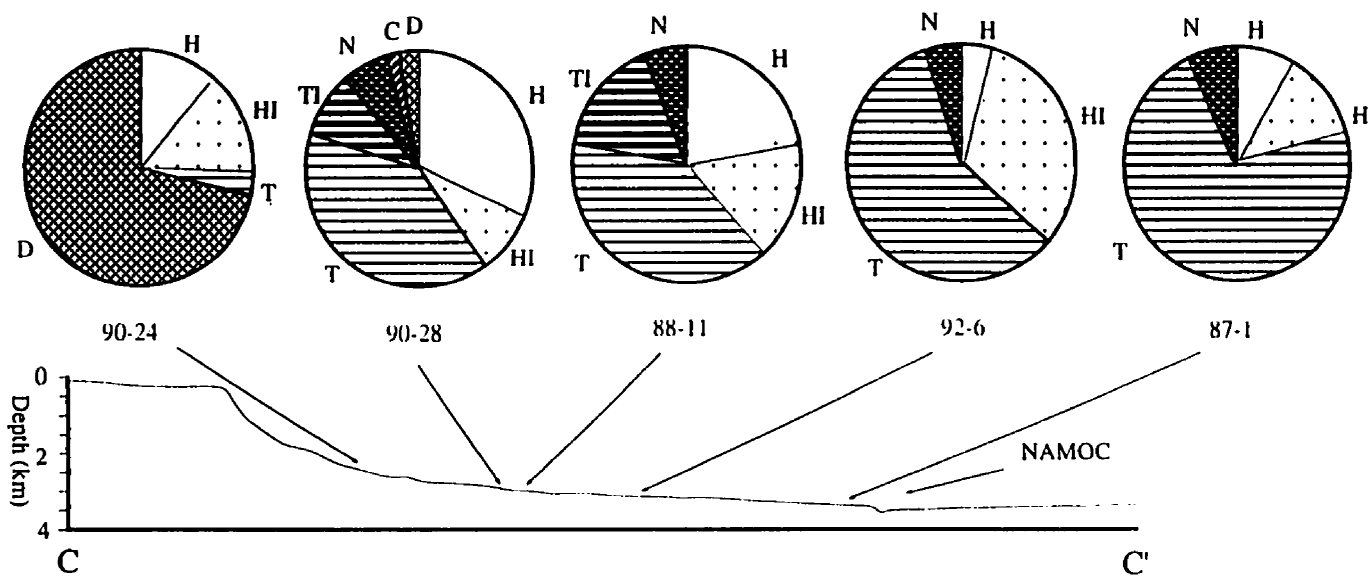


Fig. 3.2 (continued). Downslope variation in proportion of sedimentary facies along two profiles, one NW-SE and the other SW-NE. Note: (i) downslope decrease in the percentage of the sum of facies H and HI; (ii) local occurrence of facies C (lower slope-upper rise) and TI (middle-lower slope); (iii) downslope increase in the percentage of facies T; and (iv) basinward decrease in percentage of facies N. The sum of facies H and HI is lower in core 90-24 (profile CC') than that of cores 90-28 and 88-10 because of higher proportion of debris-flow deposits.



33

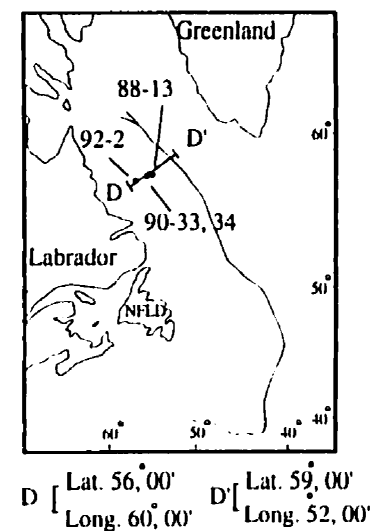
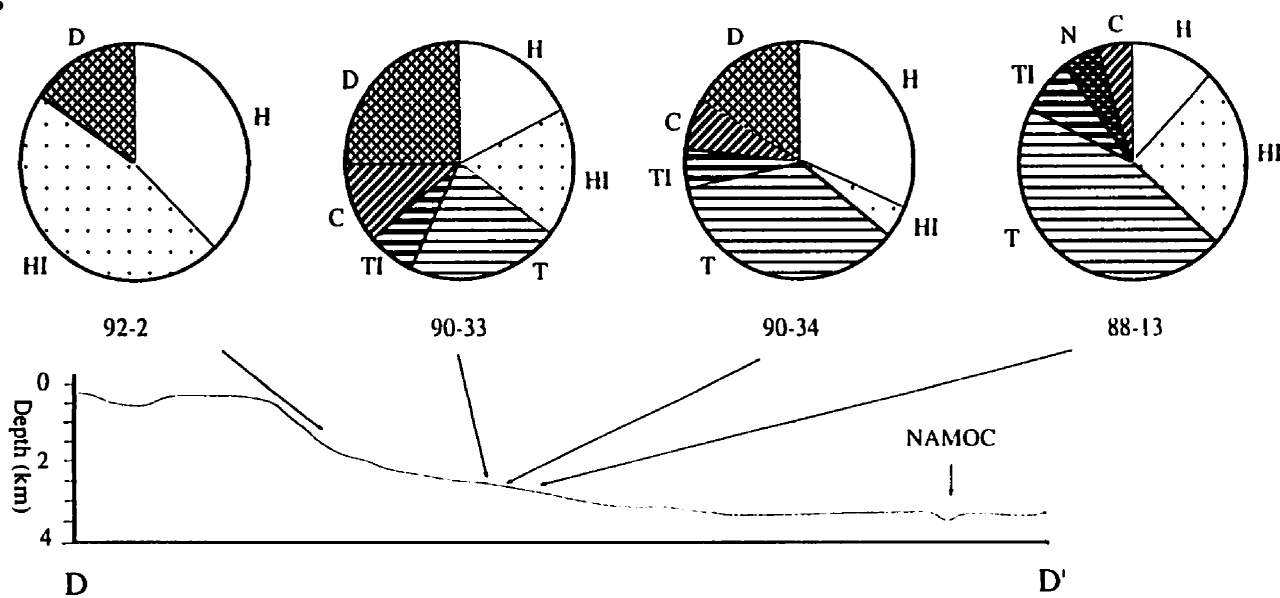


Fig. 3.3. X-radiographs of sedimentary facies: (A) hemipelagic sediment without ice-rafted debris (IRD; facies H), the upper half is mottled due to intense bioturbation; other bioturbation features include iron-sulfide filled filaments and vertical tubes (core 88-10, 771-791 cm); (B) hemipelagic sediment with IRD (facies HI). Note the scarcity of burrows and abundant IRD in the sand and pebble size fraction (core 90-33, 0-10 cm); (C) contourite (facies C) with type-1 wavy lamination (core 92-4, 171-191 cm); (D) contourite with type-2 wavy lamination (core 92-4, 1053-1073 cm); (E) a silt lens (sample no. 1) in a silty mud with discontinuous lamination (sample no.2); the lower half consists of mud turbidites; textural characteristics of two representative samples are shown between radiographs (core 90-26, 1038-1058cm); (F) foram-enriched pocket (sample no. 3) in contourites (sample no. 4); note the high proportion of biogenic constituents (foraminifera) in the sand fraction of foram-rich bed (core 92-4, 688-708 cm). The middle part of radiograph consists of facies H.



A

cm
0
5



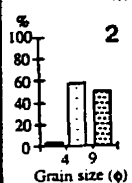
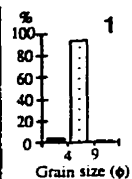
B



C



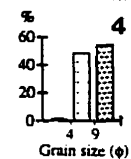
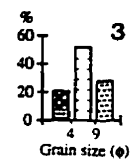
D



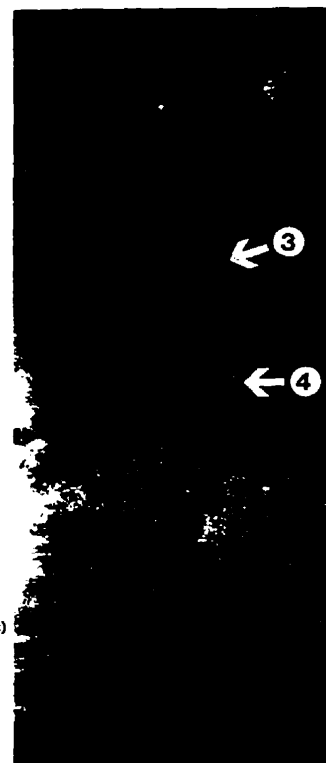
clay
silt
sand



E



clay
silt
sand (biogenic)
sand (non biogenic)



F

Fig. 3.3. continued. X-radiographs of sedimentary facies: (G) plumite (facies P); note few iron-sulfide filled filaments (arrows; core 92-1, 1041-1061 cm); (H) sand turbidite (T_b -division)(core 90-26, 901-921 cm); (I) silt and mud turbidites (facies T; core 90-29, 607-627 cm); parallel laminated darker layers are division T_d ; ripple-cross laminated layers are T_c -division; the structureless muds are division T_e ; (J) alternating thin bedded turbidites and laminae of IRD (facies TI); note alternation of millimetre-thick IR layers with parallel laminated muds and typical dropstone structure in lower third of the radiograph (see text for detail; core 90-34, 254-274 cm); (K) graded muds (nepheloid-layer deposits) with IRD; arrows show fining-upward trends (core 92-5, 115-135 cm); (L) alternation of IRD-rich layers and structureless mud turbidites on western NAMOC levee in basin centre; the upper part of the radiograph consists of parallel-laminated mud turbidites (core 87-2, 57-77 cm).



G



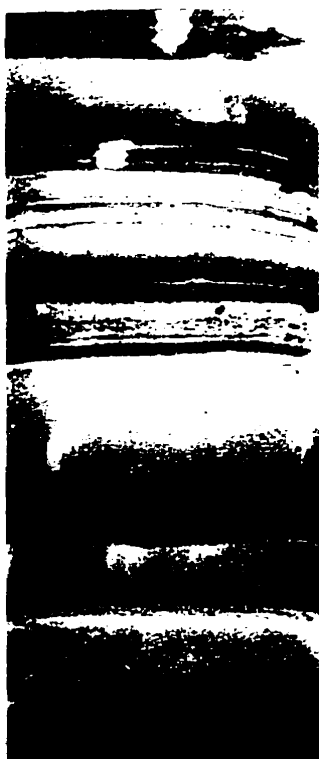
H



I



J



K



L

T_b

T_e
T_d
T_c

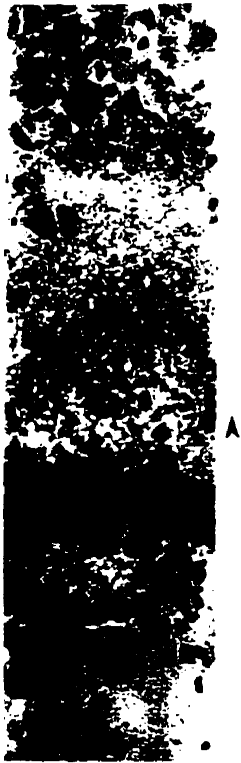
cm
0
5

A

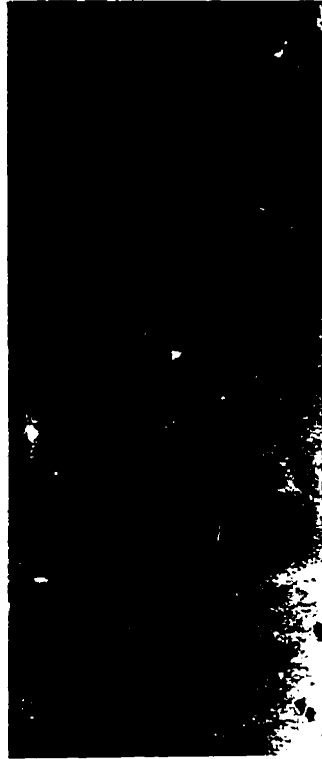
A

A

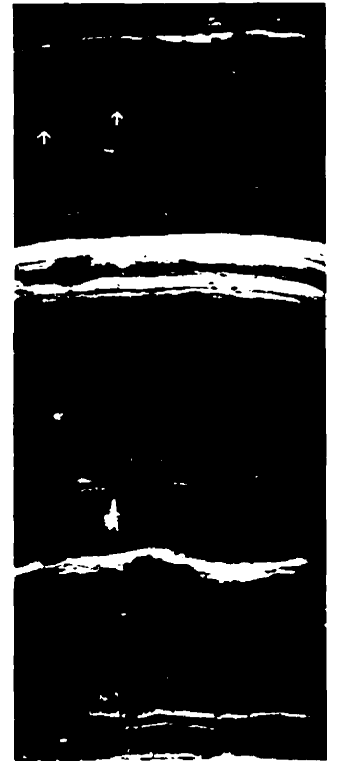
Fig. 3.3. continued. (M) gravelly debris-flow deposit (facies D1); arrow: fining-upward trend (core 84-15, 298-318 cm); (N) sandy/gravelly mud debris-flow deposit (Facies D2) with flowage bands (core 92-2, 516-536 cm); (O) thin bedded debris-flow deposit (facies D3); note the mud clasts (arrows). The lower poorly sorted basal units are draped by <1 cm-thick mud caps (core 90-34, 497-517 cm); (P) sandy/silt debris flow deposit (facies D2) with floating deformed mud clasts (core 87-9, 113-133 cm); (Q) massive gravel (bottom) overlain by parallel laminated silt turbidite; sand layer in the upper third of the radiograph is probably a coring artifact (flow-in of sand into the silt turbidites; braided floodplain east of NAMOC; core 84-16, 91-111 cm); (R) massive sand turbidite (facies MS; core 84-8, 398-418 cm); and (S) parallel laminated sand (core 84-8, 303-323 cm).



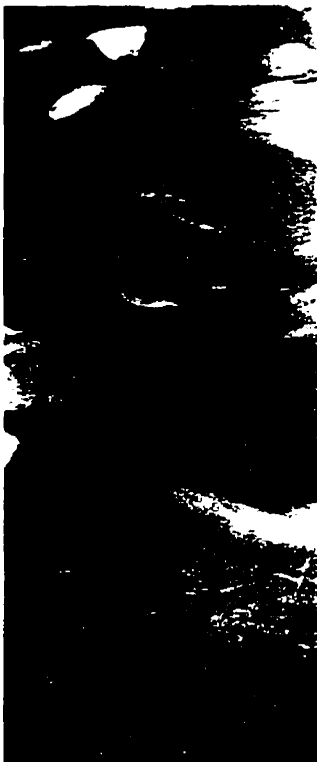
M



N



O



P



Q



R

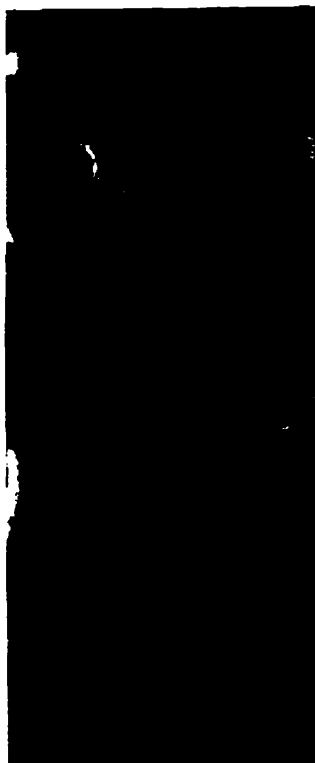


S

Fig. 3.4. Burrow types (see Table 3.2 for details): (A) dwelling structure: *Planolites* (core 92-2, 21-41 cm); (B) grazing structure: *Zoophycos* (core 92-2, 275-295 cm); (C) vertical tubes: core 75-61, 139-159 cm); (D) feeding structure: *Chondrites* (core 84-14, 52-72 cm); (E) dwelling structure (made by arthropods?; core 92-2, 1024-1044 cm); (F) feeding structure(?): iron-sulfide-filled filaments and *Trichichnus*? (arrow) (core 90-26, 956-976 cm); (G) feeding structure: polychaete burrows? (arrows; core 90-26, 199-209 cm).



A



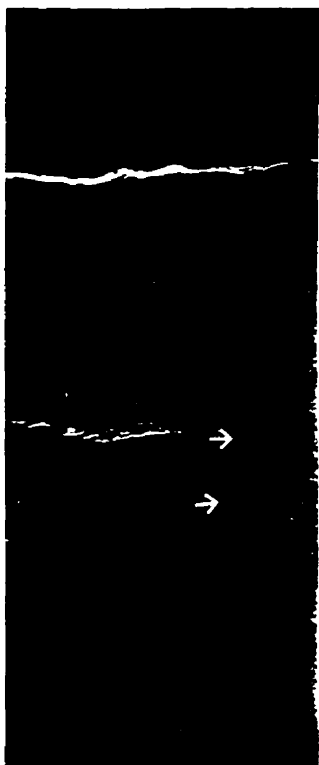
B



C



D



E

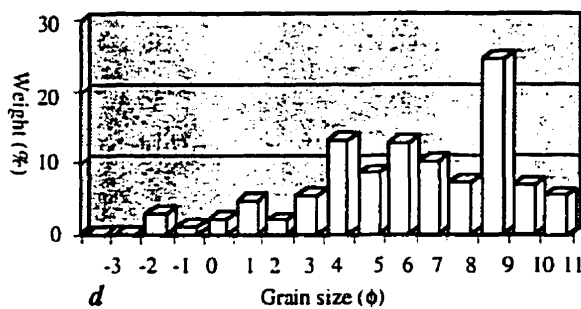


F

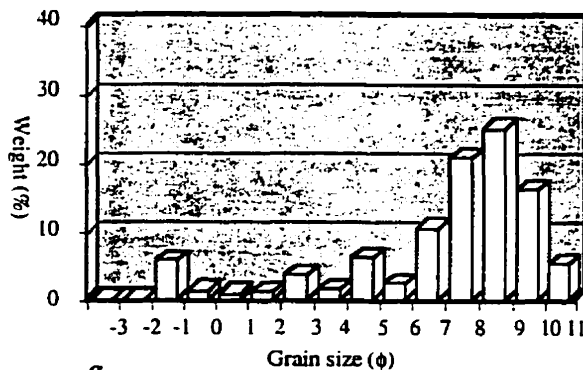


G

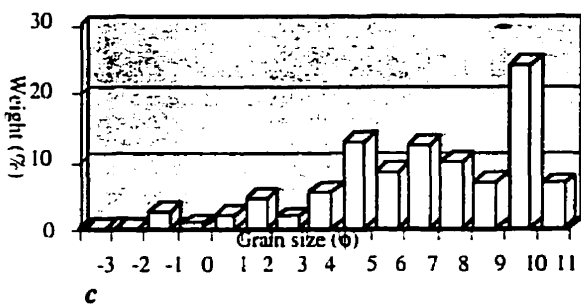
D4: Sandy/gravelly mud debris flow: core 90-34, 506 cm



HI: Ice-rafted hemipelagic sediment: core 87-9, 197 cm

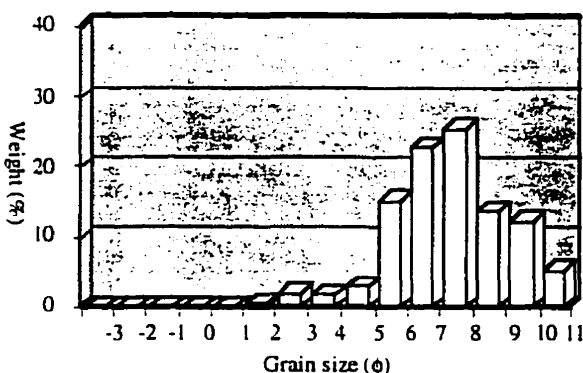


D3: Thin-bedded debris flow deposit: core 90-34, 505 cm



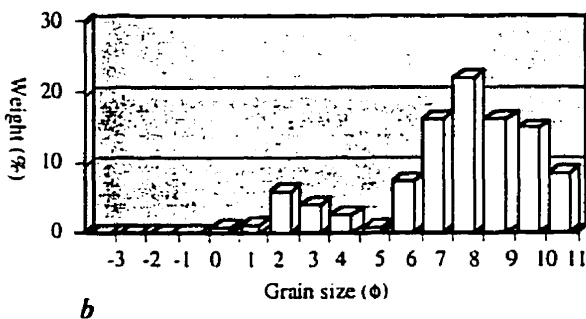
g

H: Hemipelagic sediment: core 84-8, 36 cm



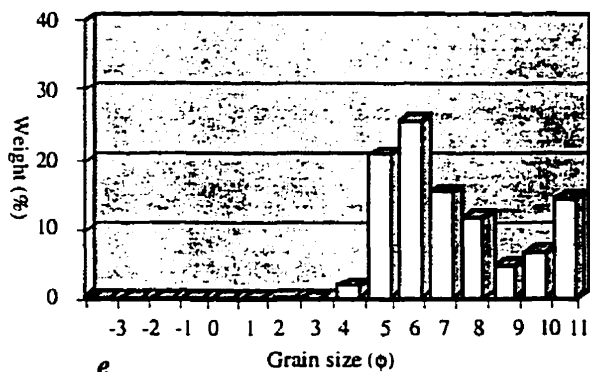
f

D2: Sandy-silt debris flow deposit: core 87-9, 115 cm



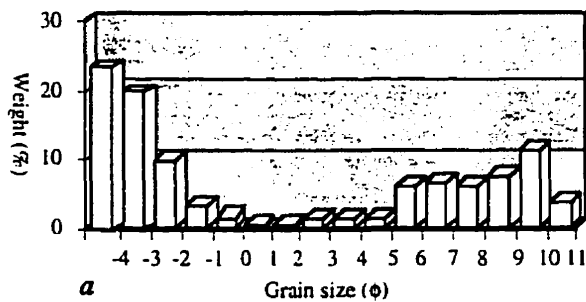
b

C: Contourite: core 92-4, 180 cm



e

D1: Gravelly debris flow: 84-15-251



a

Fig. 3.5. Grain-size distribution of representative samples for various sedimentary facies.

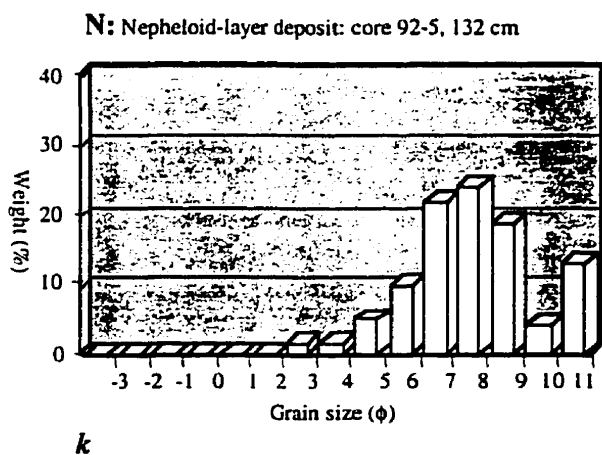
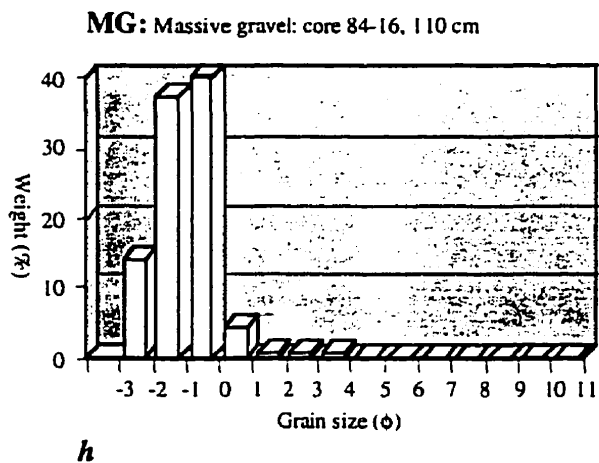
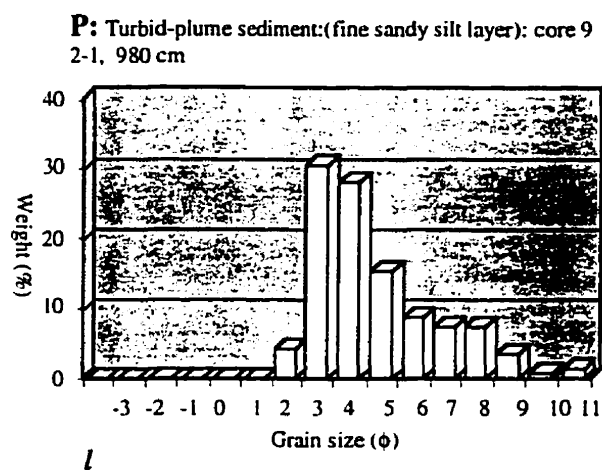
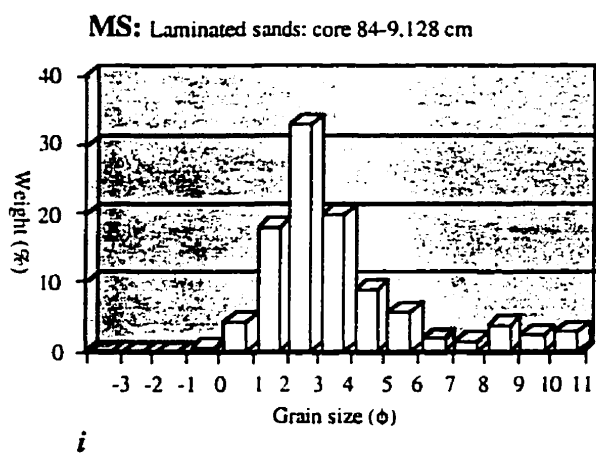
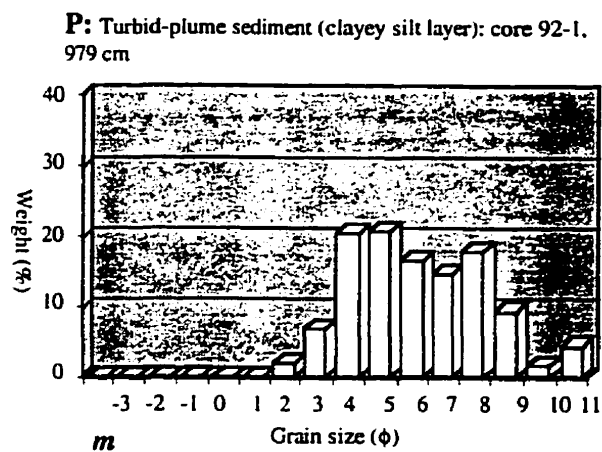
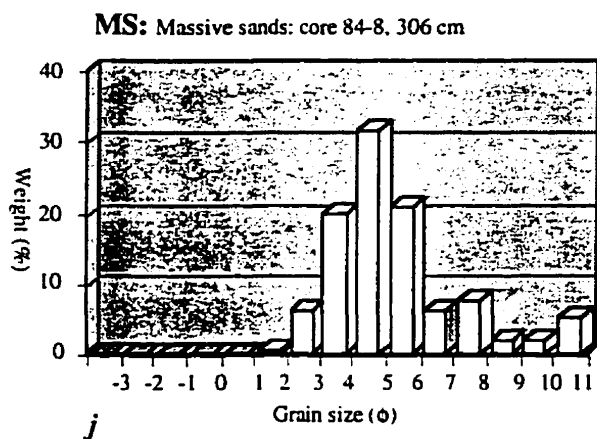


Fig. 3.5. Continued.

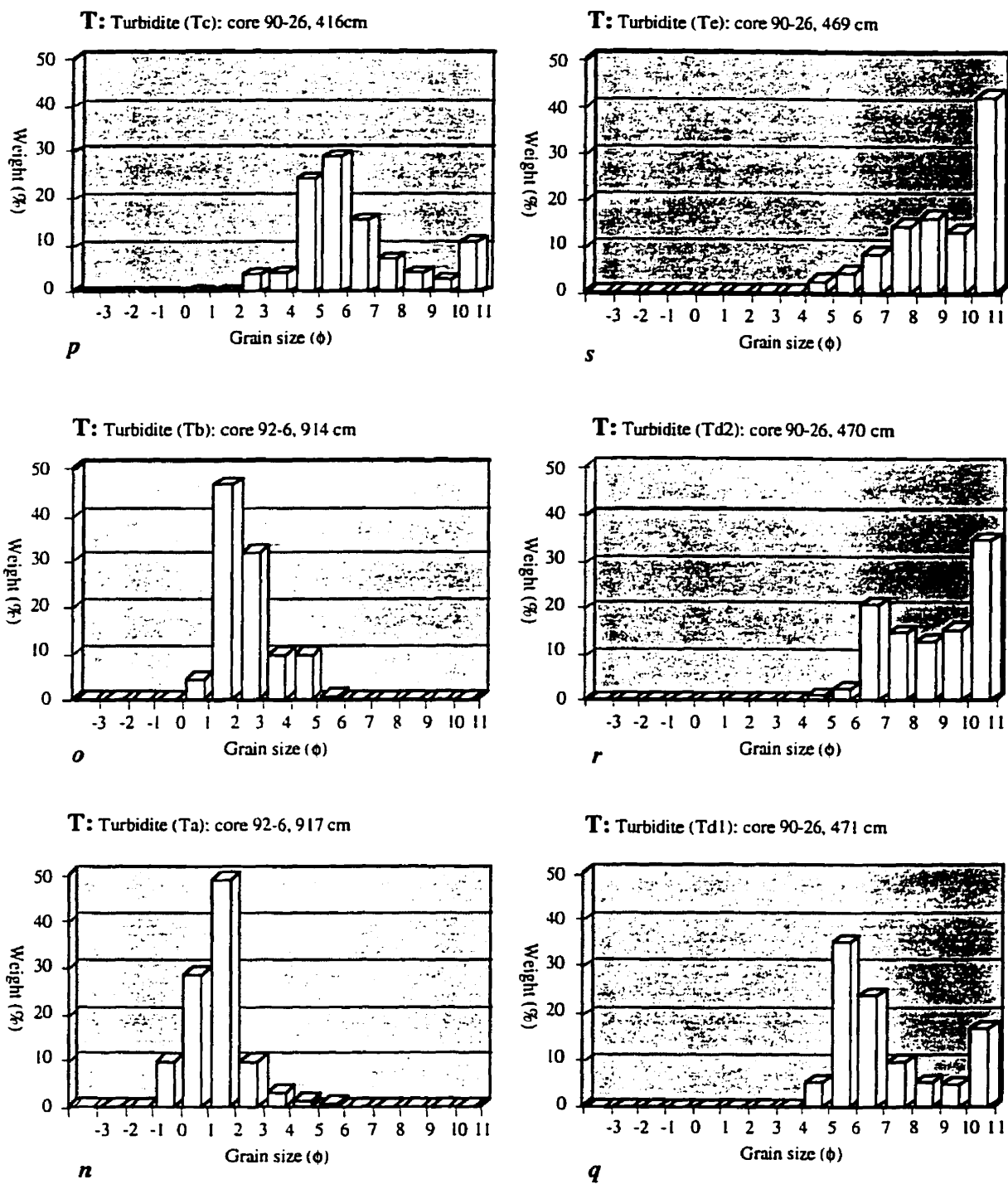


Fig. 3.5. Continued. Td1 and Td2 in samples q and r are the lower and upper parts of turbidite d-division (see Fig. 3.12).

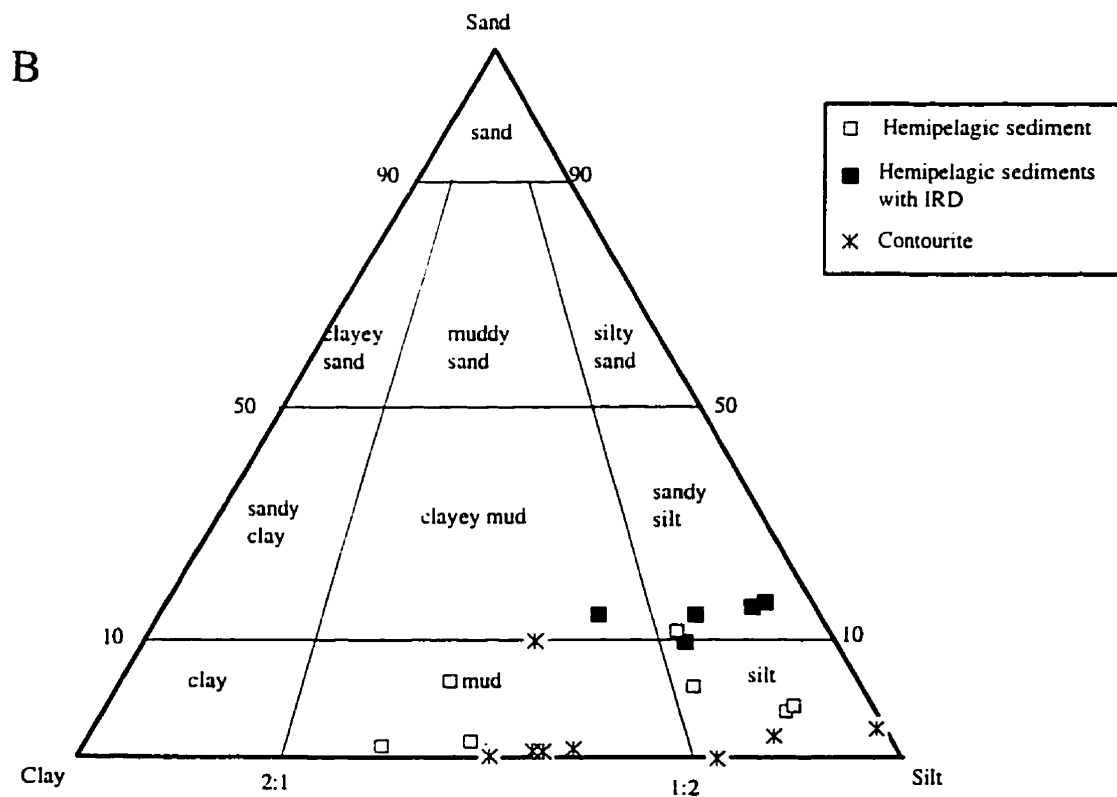
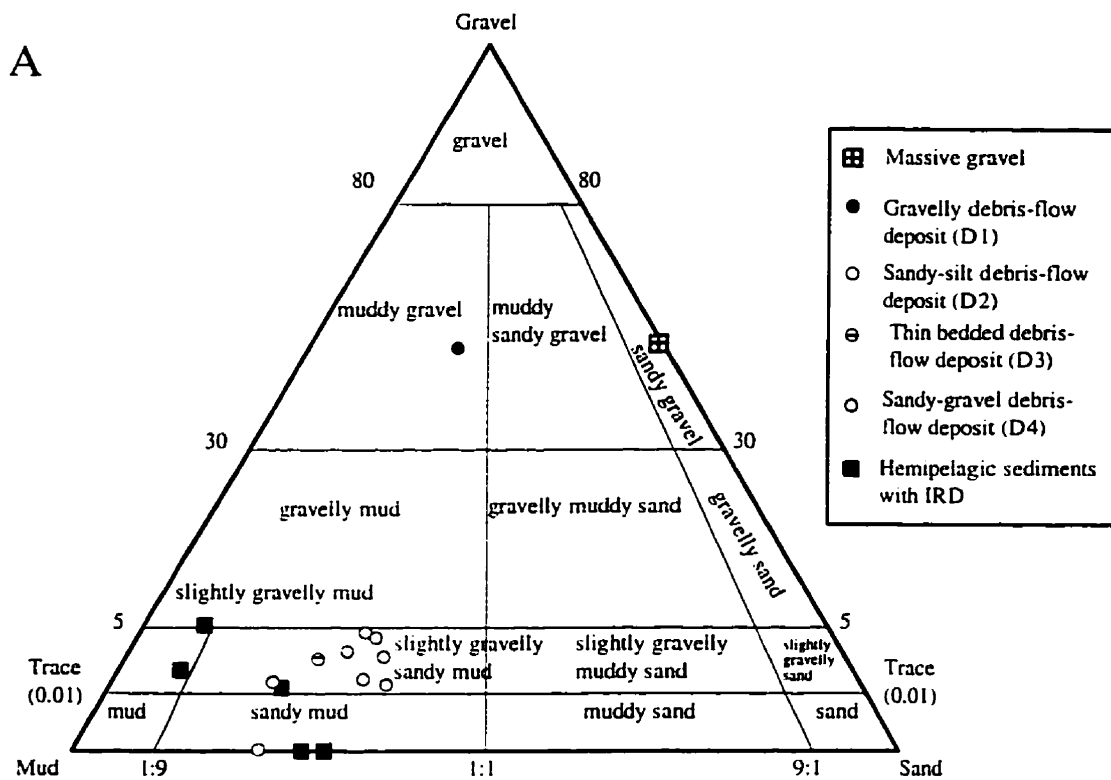


Fig. 3.6. Classification of sedimentary facies according to grain size (nomenclature after Folk, 1980).

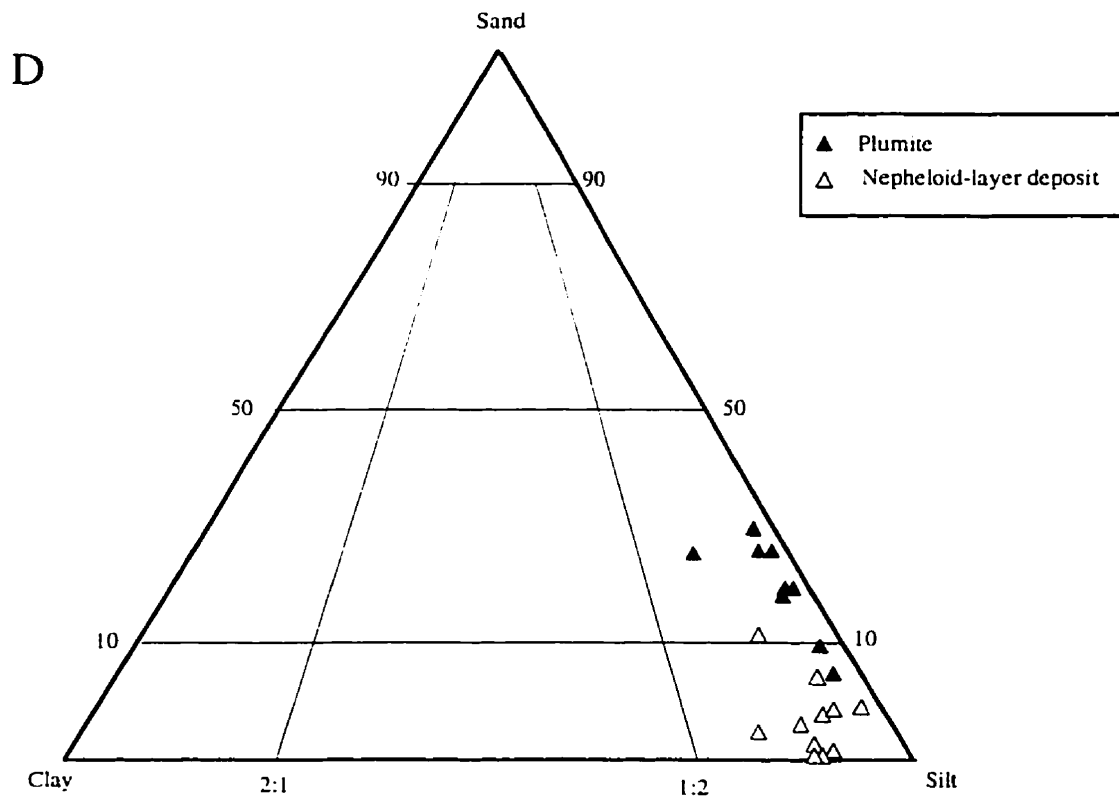
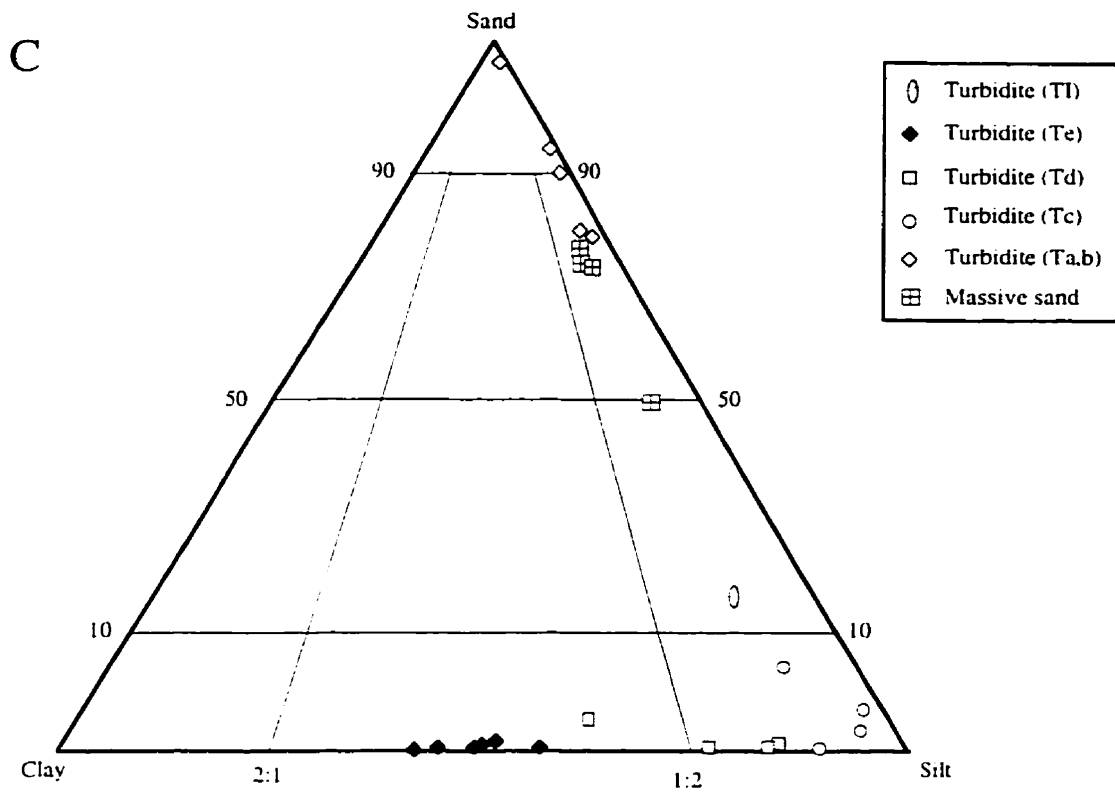
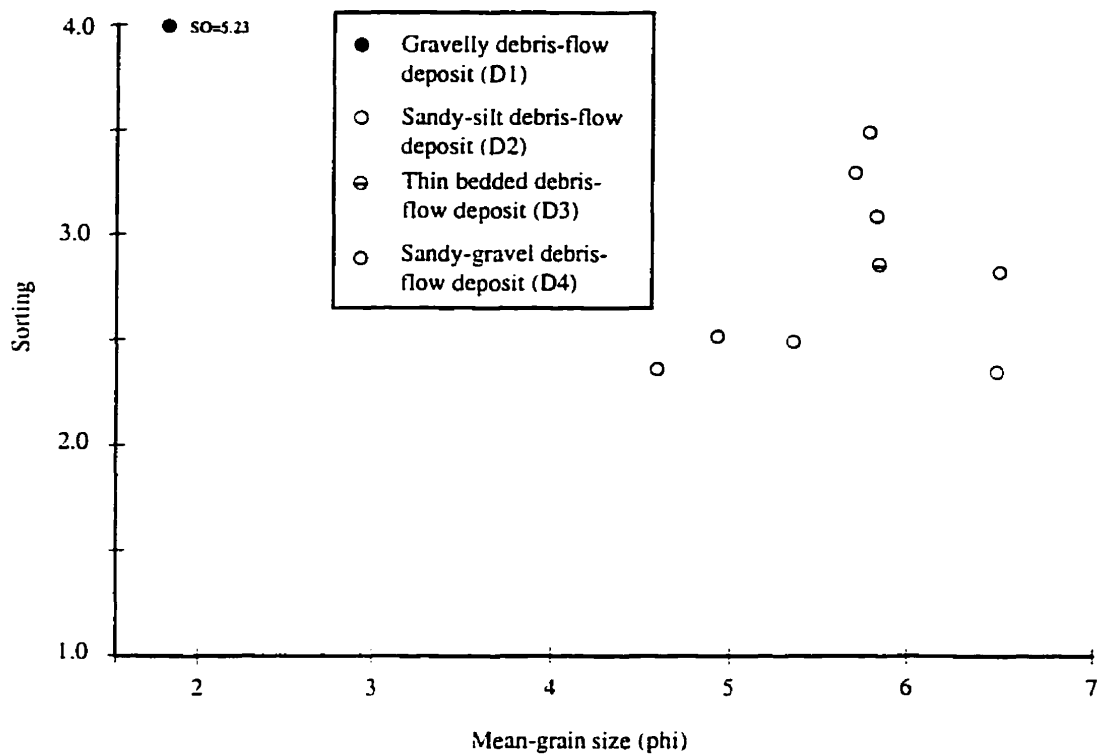
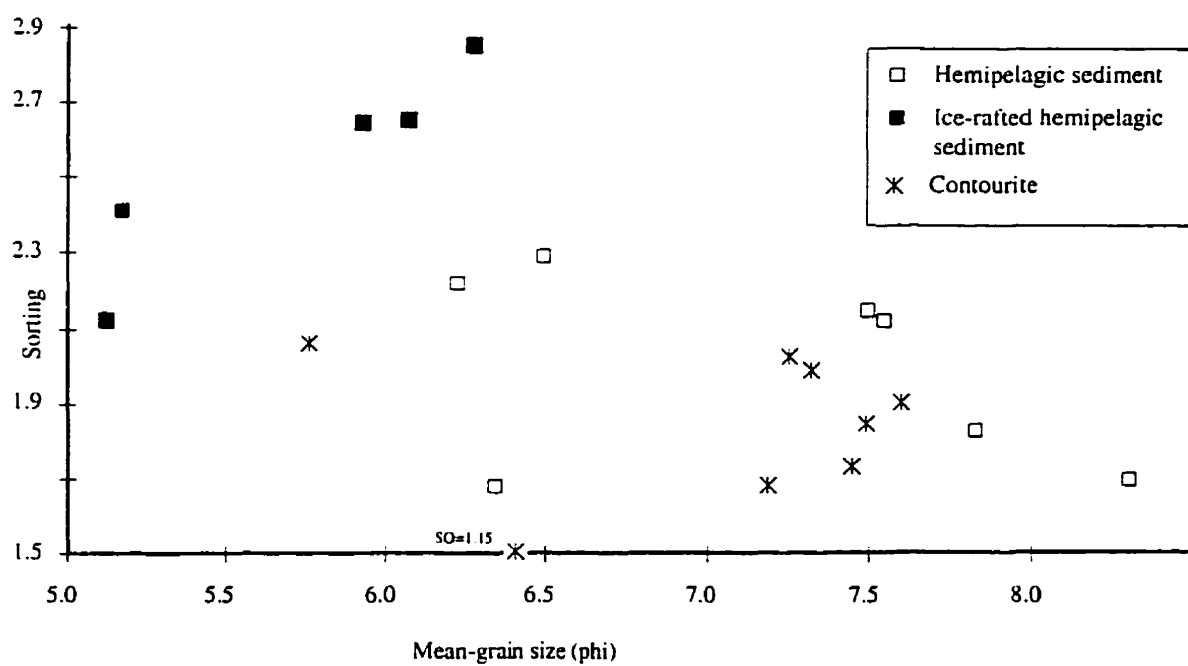


Fig. 3.6. Continued. Textural fields same as in Fig. 3.6B.



A



B

Fig. 3.7. Mean-grain size (phi units) vs. sorting (phi units) for representative samples of various sedimentary facies types.

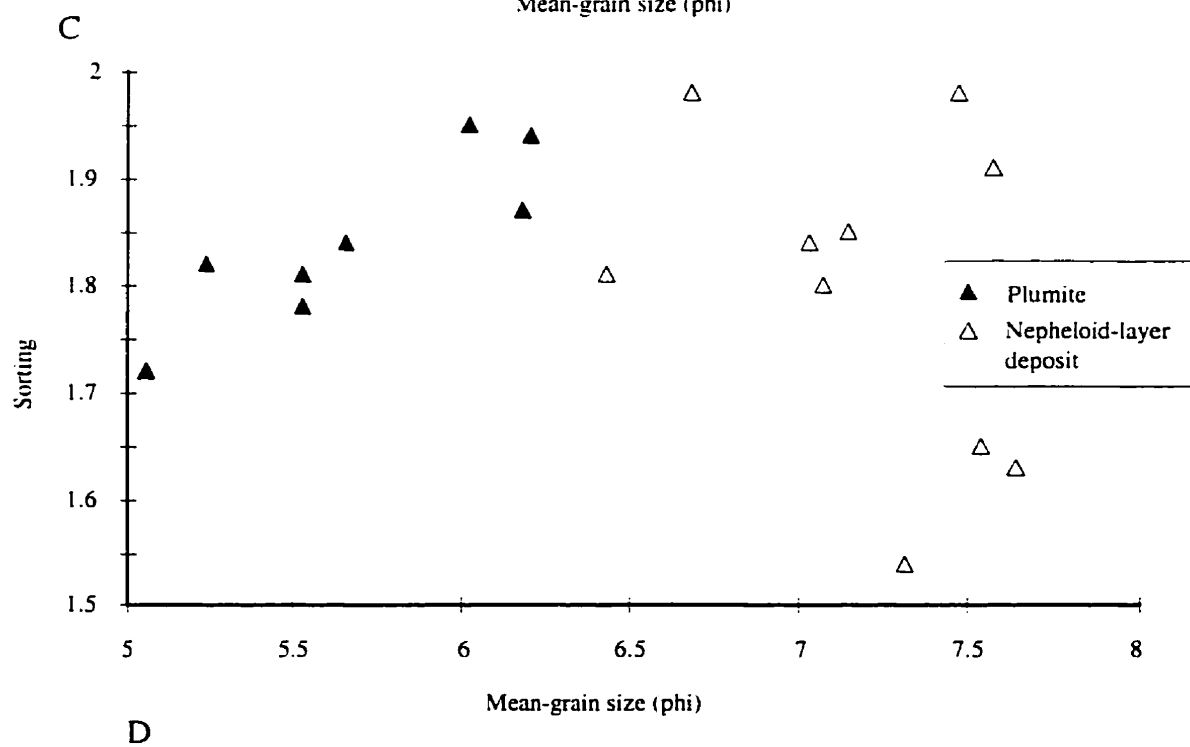
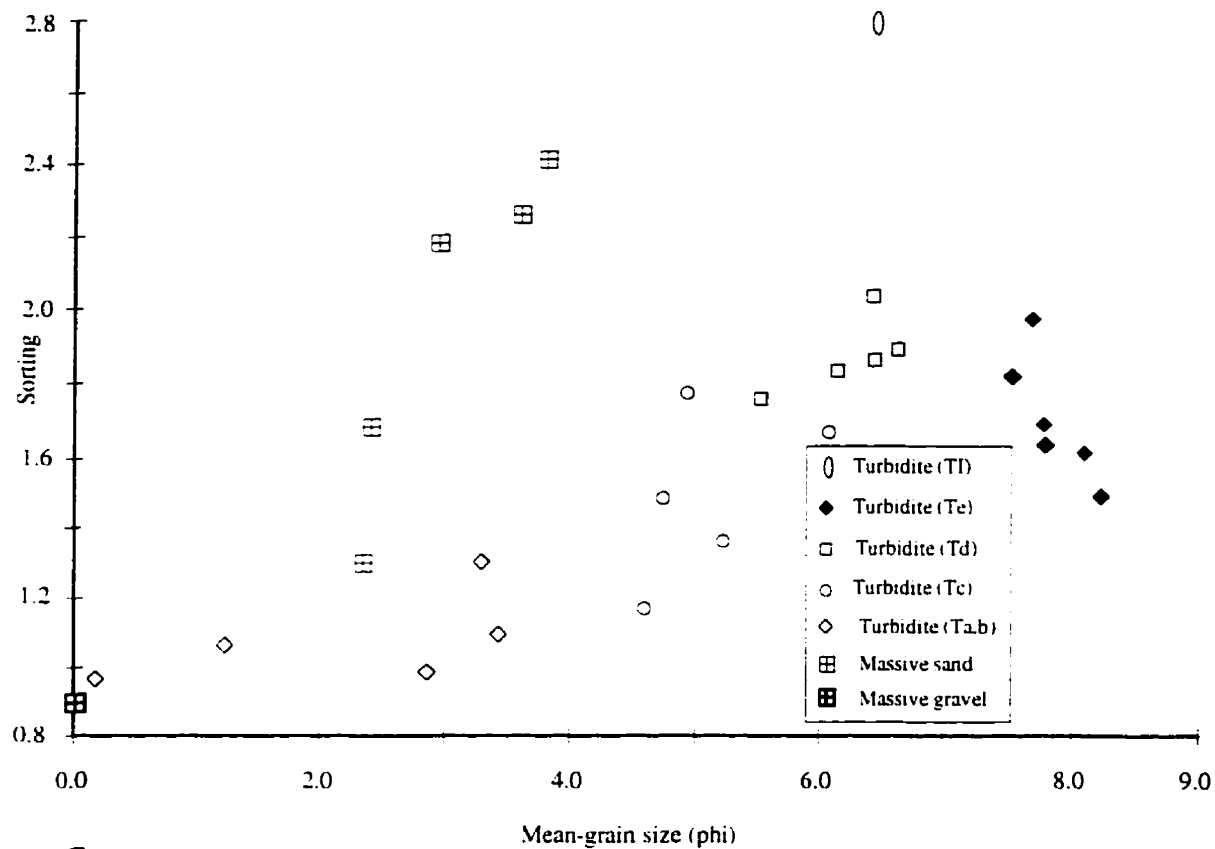


Fig. 3.7. Continued

Table 3.1. Grain-size statistics of sedimentary facies

Facies		n	Gravel%	Sand%	Silt%	Clay%	Md	MZ	MO	SD
P	Plumite (clayey silt layer)	2		5.14	58.24	35.77	6.07	6.11	4-5	1.95
"	Plumite (fine sandy silt layer)	6		15.56	59.89	24.55	5.67	5.61	3-4	1.81
C	Contourite	8	0.02	0.95	64.82	35.07	7.04	7.09	5-7	1.84
H	Hemipelagic sediment	7	0.02	4.96	57.01	37.68	7.27	7.18	5-7,10	1.99
HI	Hemipelagic sediment with ice-rafted debris	5	1.48	12.59	66.65	19.67	5.62	5.72	5-7,10	2.53
Te	Mud turbidite	4		0.32	45.75	53.76	8.30	7.93	10	1.70
Td	Silt turbidite	6		0.63	72.42	27.98	6.62	6.81	5-6, 10	1.81
Tc	"	5		2.61	88.20	9.45	4.82	5.30	4-6	1.60
Tb	Sand turbidite	3		85.76	14.64	1.50	2.35	2.60	2	1.16
Ta	"	2		95.96	4.04		1.53	1.52	1,3	0.51
MS	Massive sands	7		53.47	40.64	5.95	3.24	3.42	2-4	2.06
TI	thin-bedded turbidite with ice rafted laminae	1	7.63	16.73	11.62	3.39	6.65	6.40	10	2.82
N	Nepheloid-layer deposit	10	0.06	5.08	81.50	13.49	6.86	7.01	10	1.86
D1	Gravelly debris-flow deposit	1	52.06	5.56	27.47	14.80	-2.10	+0.43	-4	5.23
D2	Sandy-silt debris-flow deposit	1		14.49	62.67	23.54	6.55	6.50	7	2.35
D3	Thin bedded debris-flow deposit	1	2.74	14.87	51.40	31.01	5.95	5.86	9	2.85
D4	Gravelly-sand debris-flow deposit	7	2.61	19.03	59.01	19.97	5.94	5.56	6-10	2.82

Md= Median (phi)
 Mz= Mean (phi)
 Mo= Mode (phi)
 SD= Standard deviation
 n= Number of analysis

Table 3.2. Characteristics of sedimentary facies

Facies		subdivision	colour	contact with adjacent facies	bed thickness	sedimentary structure	texture	occurrence	deposition mechanism
H	Hemipelagic sediment		gray, olive gray and dark gray	top and base: transitional/sharp	8-60 cm to 0.7-2.3 m	intense bioturbation	silt to mud	all over the basin	hemipelagic settling
HI	Hemipelagic sediment	ice rafted	gray, olive gray and dark gray	top and base: transitional/sharp	0.1-2 m	slight bioturbation and dropstone structure	slightly gravelly mud to sandy mud	all over the basin, abundant on slope	mixture of hemipelagic settling and ice rafting
C	Contourite		gray, olive gray	top: transitional/sharp; base: transitional	5 to 50 cm	wavy lamination, silt lens, foram- and silt-enriched beds	mud	lower slope-upper rise	winnowing by bottom current
P	Plumite		olive gray to grayish brown	top and base: transitional/sharp	6.5 m, consisting of 0.8-3 cm thick couplets	rare parallel lamination and bioturbation	sandy silt to silt	upper slope	fallout from turbid surface plume
N	Nepheloid-layer deposit	mud-rich layer	yellowish and grayish brown to	top: sharp; base: sharp/trans.	1-4 cm	normal grading	silt	middle-lower slope, rise and	combination of nepheloid flow and ice rafting
		ice-rafted layer	brownish gray	top: sharp/trans. base: sharp	1-2 cm	dropstone structure	slightly grav. mud	basin centre	

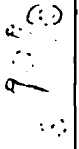
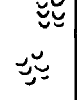
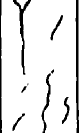
Table 3.2. Continued

Facies		subdivision	colour	contact with adjacent facies	bed thickness	sedimentary structure	texture	occurrence	deposition mechanism
T	Turbidite	Te	brownish gray to grayish brown	top: sharp/trans. base: sharp	0.7-3.5 cm	bioturbation, parallel lamination	mud	slope, rise and basin	turbidity current
		Td		top and base: sharp	0.5-2 cm	parallel lamination	silt to mud		
		Tc		top and base: sharp	0.7-1.5 cm	cross lamination	silt		
T	Turbidite	Tb	olive/ brownish gray to grayish	top: sharp/trans. base: transitional	3-4 cm	parallel lamination	silty sand	lower slope and basin centre	turbidity current
		Ta	brown	top: transitional base: sharp	2-3 cm	grading	sand		
TI	Turbidite with IR interlayers	ice rafted	brownish gray to grayish brown	top and base: transitional		dropstone structure parallel lamination	sandy/grav. silt	mid.-lower slope	turbidity current and ice rafting
MS	Massive sand		olive gray-gray	top: transitional/ sharp base: sharp	0.15-0.9 m	rare parallel lamination	silty sand to sandy silt	braidplain and western levee of NAMOC	high-concentration turbidity current
"	Massive gravel		olive gray-gray	top and bottom: sharp	1.9 m		sandy gravel	braidplain and western levee of NAMOC	

Table 3.2. Continued

Facies		subdivision	colour	contact with adjacent facies	bed thickness	sedimentary structure	texture	occurrence	deposition mechanism
D	Debris-flow deposit	D1	brownish gray, grayish brown and gray	top and base: transitional	0.1-1 m	normal and inverse grading	muddy gravel	slope and western levee of NAMOC	debris flow
		D2		top and base: sharp	0.2-1.3 m	flowage bands, floating deformed mudclasts	sandy mud	NAMOC levees	
		D3		top and base: sharp	0.9-2.5 m	parallel lamination	slightly gravelly sandy mud	slope	
		D4		top: sharp/ transitional; base: sharp	0.25-2 m	flowage bands, floating mudclasts, thin mud cap	slightly gravelly sandy mud	western flood-plain and slope	

Table 3.3. Ichnofacies types.

Ichnofacies	Major categories*	Shape	Size**	Characteristics	Occurrence in facies
Zoophycos	grazing trace stoping		L: 7->10 cm D: 1-1.5 cm	horizontal-subhorizontal single stoping burrows formed by deposit feeder organisms, in cross section appears as thin meniscal bands crossing the tube	hemipelagic sediment, debris-flow deposit
Planolites	dwelling structure		L: 2->10 cm D: 0.8-1	horizontal-subhorizontal unbranched burrows with no internal structure, in cross section appears as oval-circular shaped burrows, similar to oval-circular shaped burrows of Chough (1978) and Wang (1992)	hemipelagic sediment, upper part of mud turbidite and contourite
Skolithos	dwelling structure		L: 5-10 cm D: 2-4 mm	thin straight vertical burrows with no internal structure	hemipelagic sediment
?	dwelling structure		L: 2-7 cm D: 2-4 cm	a system of meniscal bands parallel to a central axis, probably burrowed by arthropods, similar to the trail of Tadpole shrimp of Chamberlain (1978)	hemipelagic sediment (upper slope)
Chondrites	feeding structure		L: 2-3 cm D: 1-2 mm	dendritic branching system of straight tubes with equal width, in cross section appears as a group of open or infilled tubes with random orientation	hemipelagic sediment, upper part of mud turbidite, contourite and nepheloid-layer deposit
?	feeding structure		L: 1-3 cm D: 1-3 mm	a system of small sinuous burrows made probably by foraging polychaetes, similar to polychate structure of Scott and Birdsall (1978)	hemipelagic sediment
Trichichnus			L: 0.5-4 cm D: < 1 mm	very thin tubes, usually straight, some curved to slightly sinuous, commonly iron filled, similar to Trichichnus burrows of Wetzel (1984) and pyritized filaments of Chough (1978) and Wang (1992)	hemipelagic sediment and contourite

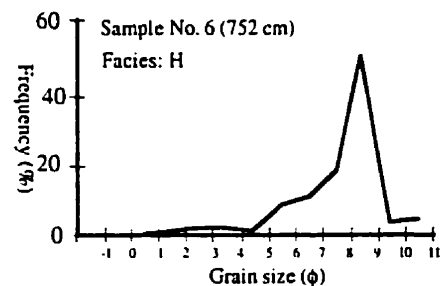
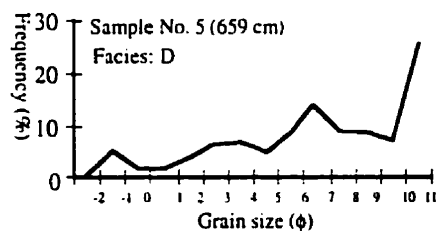
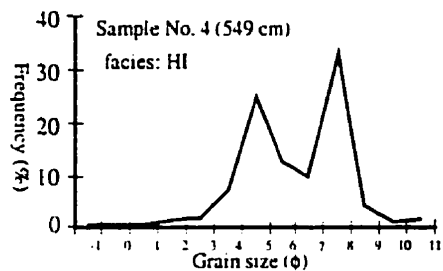
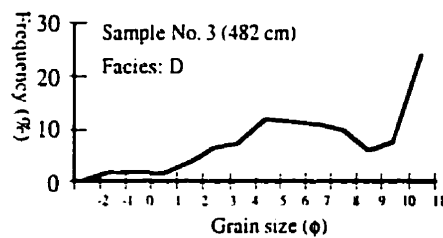
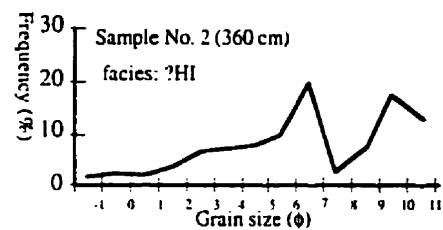
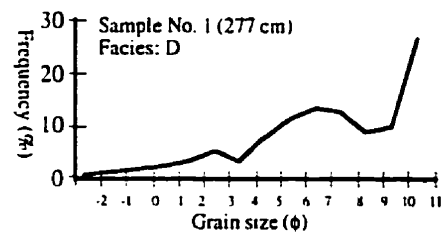
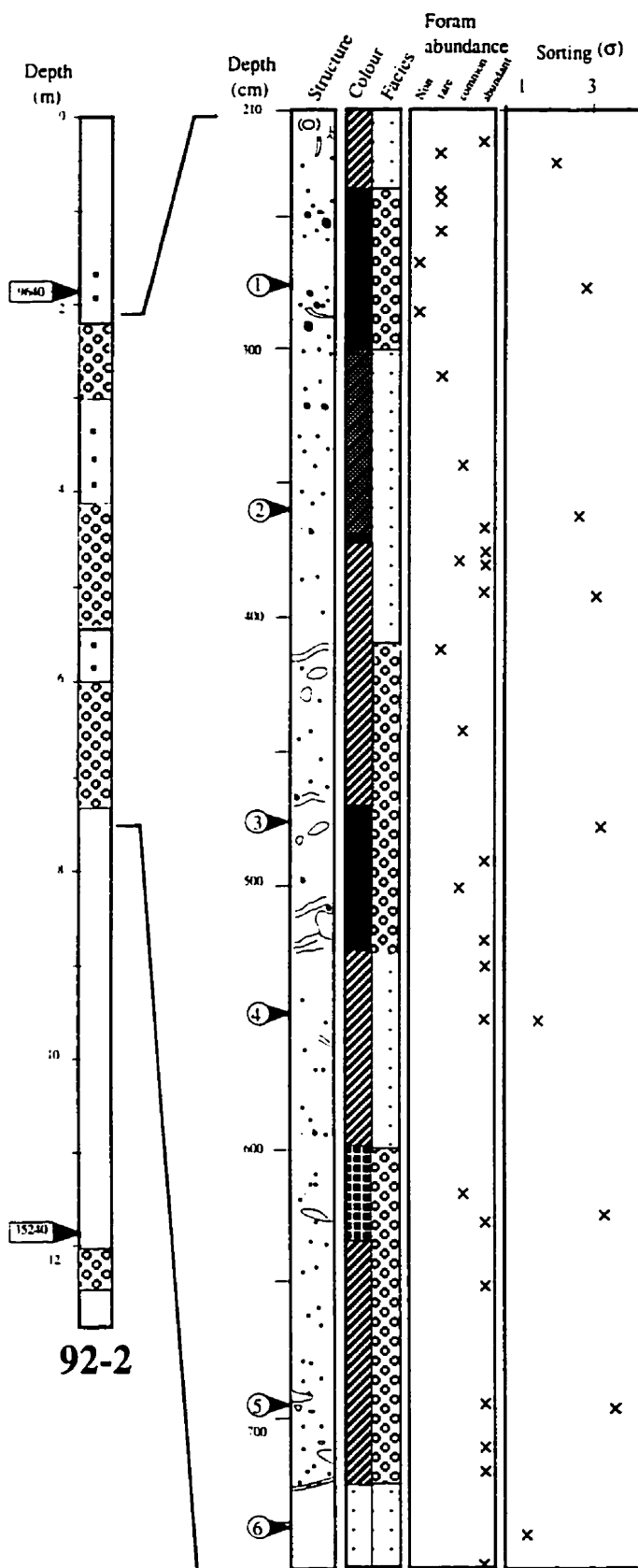
* Major categories from Frey and Pemberton (1984)

** L=length; D=diameter

(*Chondrites*, polychaete worm burrows, and *Trichichnus*) (Fig. 3.4 and Table 3.3). The sediment consists of a mixture of detrital (non-biogenic) and biogenic material. The latter includes microfossils (mainly planktonic foraminifera, radiolaria, diatoms and sponge spicules). Planktonic foraminifera are the most abundant biogenic constituents (>90% of fraction). Compared to the slope sediments, foram abundance is generally greater in the basin-centre (i.e. >1000 forams/g). The non-biogenic portion includes mainly quartz and rock fragments. Carbonate and organic-carbon values are low (0.7% and 0.8%, respectively; see Chapter 4).

Subfacies HI: Hemipelagic sediment with ice-rafted debris. This facies consists mainly of grey (5Y 4/1), olive grey (5Y 5/2) and dark grey (5Y 6/2) sandy-gravelly muds. A minor proportion (<5%) is brownish grey (2.5Y 6/2 and 10YR 6/2) and olive mud (5Y 4/3, 5Y 5/3 and 5Y 5/4). This facies is coarser (mean grain size=5.7 ϕ) and less well sorted (σ =2.5 ϕ) than the pure hemipelagic facies (Tables 3.1 and 3.2). Sand and gravel make up to 20% of the sediment. Grain-size distribution curves display a polymodal pattern with a prominent mode in the silt and clay fractions and subordinate modes in the sand and gravel fractions (Fig. 3.5g). Compared with the pure hemipelagic sediments, bioturbation is less intense (Fig. 3.3B) and in some cases absent. The microfossil content is variable but generally less than that of hemipelagic sediments (<1000 forams/g). Foram abundance is significantly reduced in layers with high concentrations of IRD (Heinrich layers, i.e. to near zero level). The non-biogenic (lithic) content is significantly higher than that of facies H, comprising >49% of the sand fraction. The detrital grains consist

Fig. 3.8. Comparison between sediment-structure, foram content and grain-size of ice-rafted hemipelagic sediments and debris-flow deposits in an upper-slope core (see Fig. 1.3 for core location). The numbers on the left side of the structure column denote sample position.



LEGEND

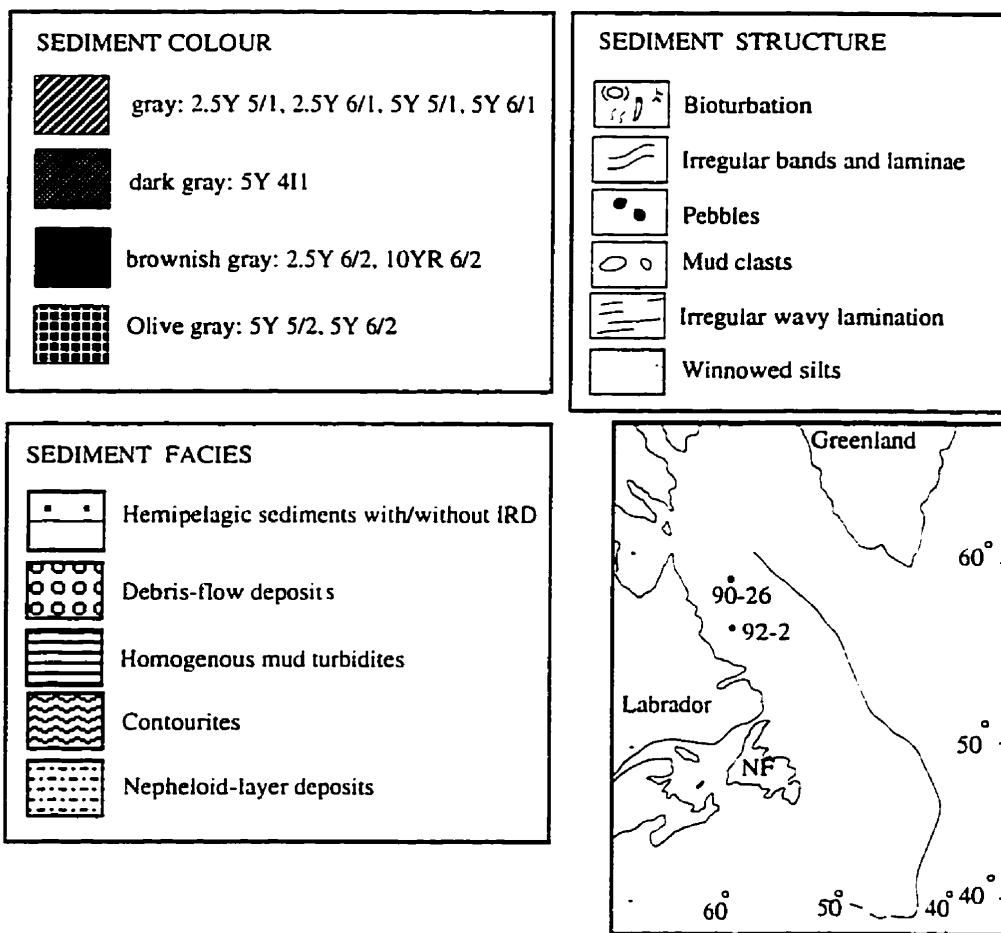


Fig. 3.8. Continued.

Table 3.4. Sedimentation rates of different sedimentary facies

Core No.	Depth (cm)	Facies	Age (ka)	Sed. rate (cm/ka)	Locality	Reference for radiocarbon dating
92-1	550-1233	P	21.9-28.0	112 ± 2.4	upper Labrador Slope	This study
75-55	81-116	N	13.2-14.6	25 ± 1.9	upper Labrador Slope	Andrews et al (1994)
75-55	181-250	N	19.4-21.1	40.6 ± 0.8	upper Labrador Slope	Andrews et al (1994)
92-5	75-161	N	13.2-14.6	61.43 ± 4.8	lower Labrador slope	This study
92-5	161-373	HI	14.6-20.5	35.9 ± 4.3	lower Labrador slope	This study
92-5	373-421	N	20.5-21.1	80 ± 3.8	lower Labrador Slope	Wang and Hesse (1996)
92-4	657-696	C	21.1-24.6	11.1 ± 0.3	lower Labrador Slope	This study
90-26	15-46	N	15.1-13.2	16.4 ± 0.8	lower Labrador slope	Wang and Hesse (1996)
90-26	46-210	HI	15.1-20.5	30.4 ± 0.5	lower Labrador slope	Wang and Hesse (1996)
90-26	210-274	N	21.1-20.5	106.7 ± 3.5	lower Labrador slope	Wang and Hesse (1996)
90-26	981-1041	H	40.5-44.6	14.6 ± 1.2	lower Labrador slope	Wang and Hesse (1996)
74-68	129-157	HI	14.6-17.2	10.8 ± 1.7	NAMOC levee	Hesse et al (1987)
75-11	249-270	HI	21.1-25.1	5.3 ± 0.2	NAMOC levee	Hesse et al (1987)
75-22	158-175	HI	21.1-23.0	8.9 ± 1.0	NAMOC levee	Hesse et al (1987)
75-24	128-140	HI	21.1-22.7	7.5 ± 1.3	NAMOC levee	Hesse et al (1987)
87-2	72-86	HI	21.1-24.2	4.5 ± 0.0	NAMOC levee	Hesse (1995)
87-7	338-356	HI	21.1-23.3	8.2 ± 0.0	NAMOC levee	Hesse (1995)
87-9	194-214	HI	17.2-20.5	6.1 ± 0.1	NAMOC levee	This study
87-9	235-245	HI	21.1-22.8	5.9 ± 0.2	NAMOC levee	Hesse (1995)

of quartz, feldspar and various rock fragments (see Chapter 4). Bed contacts with overlying and underlying facies are transitional but sharp upper contacts with mass-flow deposits (facies T and D) have also been observed (Table 3.2). Both carbonate and organic carbon content values are higher than those of facies H (3.7% and 1.2%, respectively). Facies HI has sedimentation rates up to 30 cm/ka (Table 3.4).

In a mass-flow dominated region, ice-rafted hemipelagic sediments may occur together with debris-flow deposits (see also Hill, 1984; Mosher et al., 1994). If debris-flow deposit intervals do not show any internal structure and ice-rafted sediments are free of bioturbational features, the differentiation between the two facies is difficult (see also

Hein et al., 1990; Hiscott et al., 1989). Both facies may be massive containing coarse-grained clasts (i.e. sand- and gravel-sized) that are randomly distributed in a finer grained matrix. Generally, debris-flow deposits are more poorly sorted and show a polymodal grain-size distribution while hemipelagic sediments are bimodal (or rarely unimodal; Fig. 3.8). The foram content is not an absolutely reliable criterion to differentiate the two facies (see also Hill, 1984; Fig. 3.8), because the foram content of a debris flow deposit depends on that of the original sediments. Ice-rafted layers of Heinrich events, on the other hand, may be free of forams.

Occurrence- Facies H is present in all parts of the basin varying in thickness from 0.5-1.8 m for thick beds and a few centimeters for thinner beds. The thinner beds are intercalated with mud turbidites and contourites. Facies HI can reach up to 3 m in thickness but can be as thin as a few millimeters in beds or laminae alternating with mud turbidites. Facies H comprises 48% of the slope and 20% of the rise and basin-centre sediments. The sum of facies H and HI decreases basinward proportionally to other facies (Fig. 3.2).

3.2.2. FACIES P: Turbid-surface plume sediment (plumite). The term plumite, introduced by Hesse et al. (1997) in analogy to turbidites (the deposits of turbidity currents) is used here for the deposits of turbid-surface plumes. This facies consists of olive grey (5Y 4/2) to greyish brown (2.5Y 5/2) thin-bedded to laminated (rhythmic) sediments. It comprises alternating layers of fine sandy silt and silty clay to clayey silt (Fig. 3.3G). Each fine sandy silt and clayey silt layer forms a couplet. The fine sandy silt layer has a strong mode in fine sand to coarse silt (3-5 ϕ) whereas the clayey-silt layer

Table 3.5. Characteristics of plumite couplets (data from core 92-1).

	n	fine sandy-silt layer	clayey silt layer
Layer thickness (cm)	60	0.90	1.11
Mean grain size in phi; in (micron)	10	7.52; (6.74)	8.20; (3.45)
Sorting (standard graphic deviation)	10	1.81	1.91
No. of forams/g	12	14.78	23.55
No. lithic/foram ratio	12	120.94	69.49
$\delta^{18}O_{cc}$ (N. pachyderma, left coiling)	6	3.88	3.84
$\delta^{13}C_{cc}$ (N. pachyderma, left coiling)	6	0.23	0.21
%organic carbon	18	0.65	0.83
%inorganic carbon	18	0.16	0.21
%CaCO ₃	18	1.33	1.75

exhibits less pronounced modes in the coarse and fine silt fractions (4-5 and 8 ϕ ; Figs. 3.5L and Fig. 3.9A). The fine sandy silt layers are thinner (average 0.9 cm), better sorted ($\sigma=1.8 \phi$), have lower organic carbon (0.7%) and lower foraminifera content (15 forams/g) than the clayey-silt layers (1.1 cm; $\sigma=1.9 \phi$; $C_{org}=0.8$; Tables 3.1 and 3.5). The contact between the layers is generally blurred by weak to moderate bioturbation. The only primary structure is diffuse parallel lamination. Bioturbation structures mainly consist of circular to oval-shaped burrows and small iron-sulfide filled filaments (Fig. 3.3J). Microfossil content of this facies is significantly less than that of hemipelagic sediments (<50 forams/g). The deposits from core 92-1 are low in carbonate content (1.6%; see Chapter 4). Mineralogically, this facies consists mainly of quartz (57%), feldspar (26%) and mica flakes (5%; see Appendix 9). This facies has a sedimentation

rate of 110 cm/ka (Table 3.4).

Occurrence- This facies only occurs in the upper slope and has only been recovered in one core (core 92-1, adjacent to Hopedale Saddle; see Fig. 1.3 for location). The lateral and basinward extent of the facies is not yet well known due to the limited number of cores available. In seismic profiles, Facies P appears as relatively transparent horizons with continuous, parallel low-amplitude reflections grouped into packages by a few higher-amplitude reflections (see section 5.1.1, Fig. 5.2). Seismic profiles along the upper slope show that a considerable part of the upper slope area adjacent to the Hudson Strait is covered by this facies (and/or hemipelagic facies). Basinward, this facies presumably changes gradually into facies H.

3.2.3. FACIES N: Nepheloid-layer deposits with ice-rafted debris. This facies consists of yellowish to greyish brown (2.5Y 5/2; 10YR 5/2) and brownish grey (2.5Y 6/2 and 10YR 6/2) sandy-gravelly mud. It forms 10-100 cm thick units comprising alternating 0.2-3 cm thick beds. Generally, this facies consists of a basal ice-rafted bed followed by an upper mud to silty mud (Fig. 3.3K). In some cases no rhythm is observed and facies consists of a muddy matrix with IRD randomly dispersed throughout. Some coarse ice-rafted pebbles show typical dropstone structure described by Harrison (1975). This is the term used for sediments in which an outsized ice-rafted pebble deforms underlying laminae while the overlying laminae drape the clast (Fig. 3.3j). The upper mud-rich beds are structureless but may show parallel lamination and/or grading (fining-upward; Figs. 3.3K and 3.9 b). Bioturbation is rare and occurs only on top of muddy units. This facies

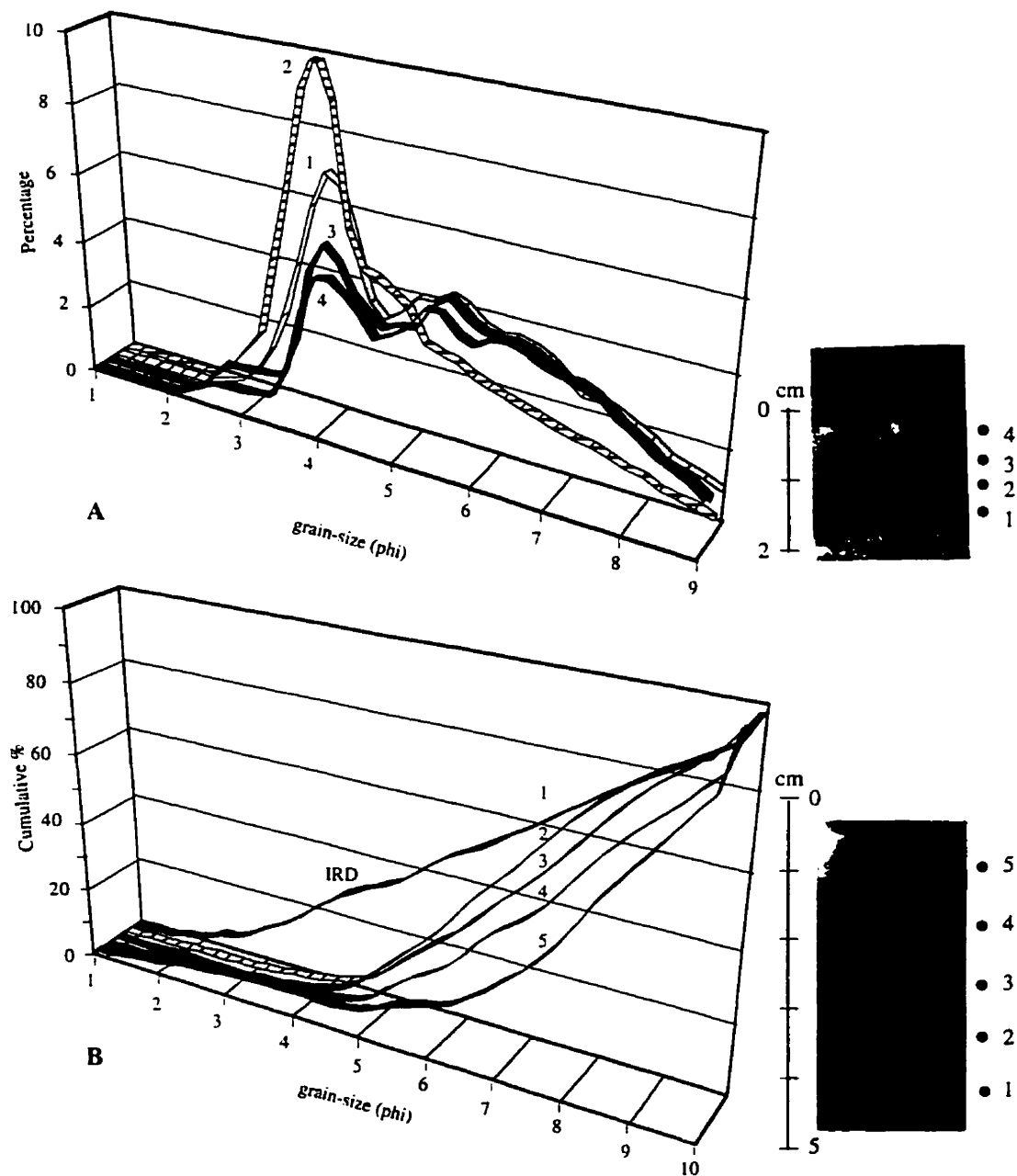


Fig. 3.9. (A) Grain-size distribution curves from a plumite couplet (core 92-1, 979-981 cm); the first two samples are rich in fine sand and silt and are overlain by a layer which is significantly finer-grained (samples 3 and 4); (B) Cumulative grain-size curves across a 4 cm thick graded mud (nepheloid-layer deposit; core 92-5, 125-129 cm); note poorly sorted basal ice-rafted layer (sample 1) overlain by silty mud with a distinct fining-upward trend (samples 2 to 5).

has the highest carbonate content (39.7% and 33.5% in slope and basin centre, respectively) among all facies (see Table 4.2). Detrital carbonates make up >20% of the sand fraction in the basal ice-rafted rich intervals. The facies has a very low content of foraminifera (<10 forams/g). The organic carbon content is 1.3%. The bed contact is sharp and erosional at the base and transitional at the top. The mineralogic composition of the sand fraction is dominated by quartz (52%), feldspar (10%) and detrital carbonate rock fragments (22%; see Table 4.4). This facies has sedimentation rates up to 100 cm/ka (Table 3.4).

Occurrence- Like facies TI, this facies forms distinct, well correlated stratigraphic horizons identified as a particular type of Heinrich layers in Chapter 6. It was found in regions below the uppermost slope (>1500 m water depth). The graded muds (nepheloid-layer deposits) occur in the upper 3m of middle and lower-slope cores. Basinward, the facies gradually decreases in thickness (Fig. 3.2), and laterally appears to change into facies HI (Ch. 6). Nepheloid-layers are maintained by contour currents, and their deposits are one particular type of contourites. In this study, it has been possible to differentiate them as a separate facies because of their IRD (see section 5.1.4).

3.2.4. FACIES C: Contourite. This facies consists of grey (2.5Y 5/1 and 5Y 5/1), and olive grey (5Y 4/1) silty muds. On a fresh-cut surface they look similar to hemipelagic sediments, but in X-radiographs they are clearly distinctive. Facies C is less bioturbated, has lower foram and higher silt content and displays wavy lamination (Tables 3.1 and

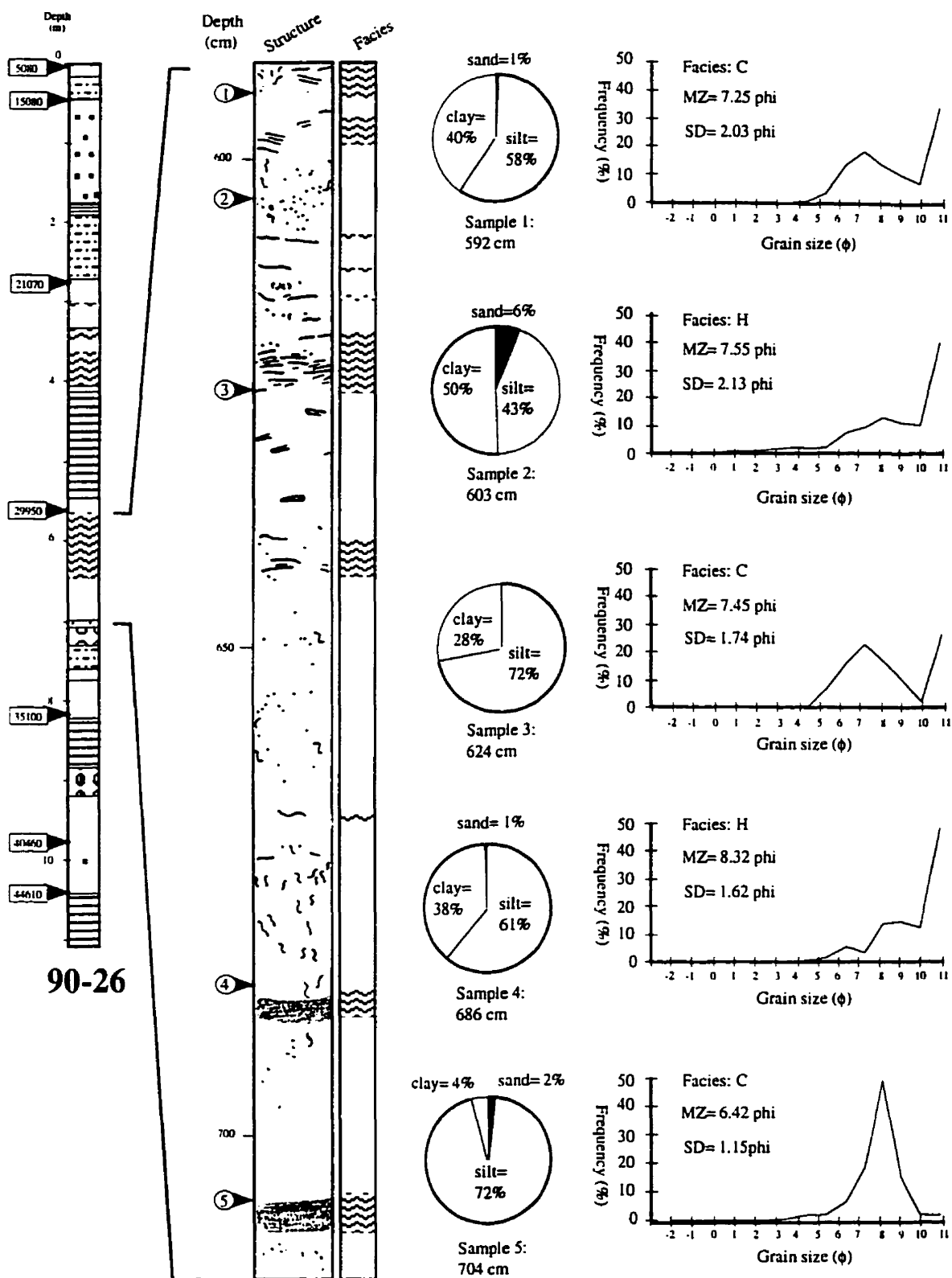
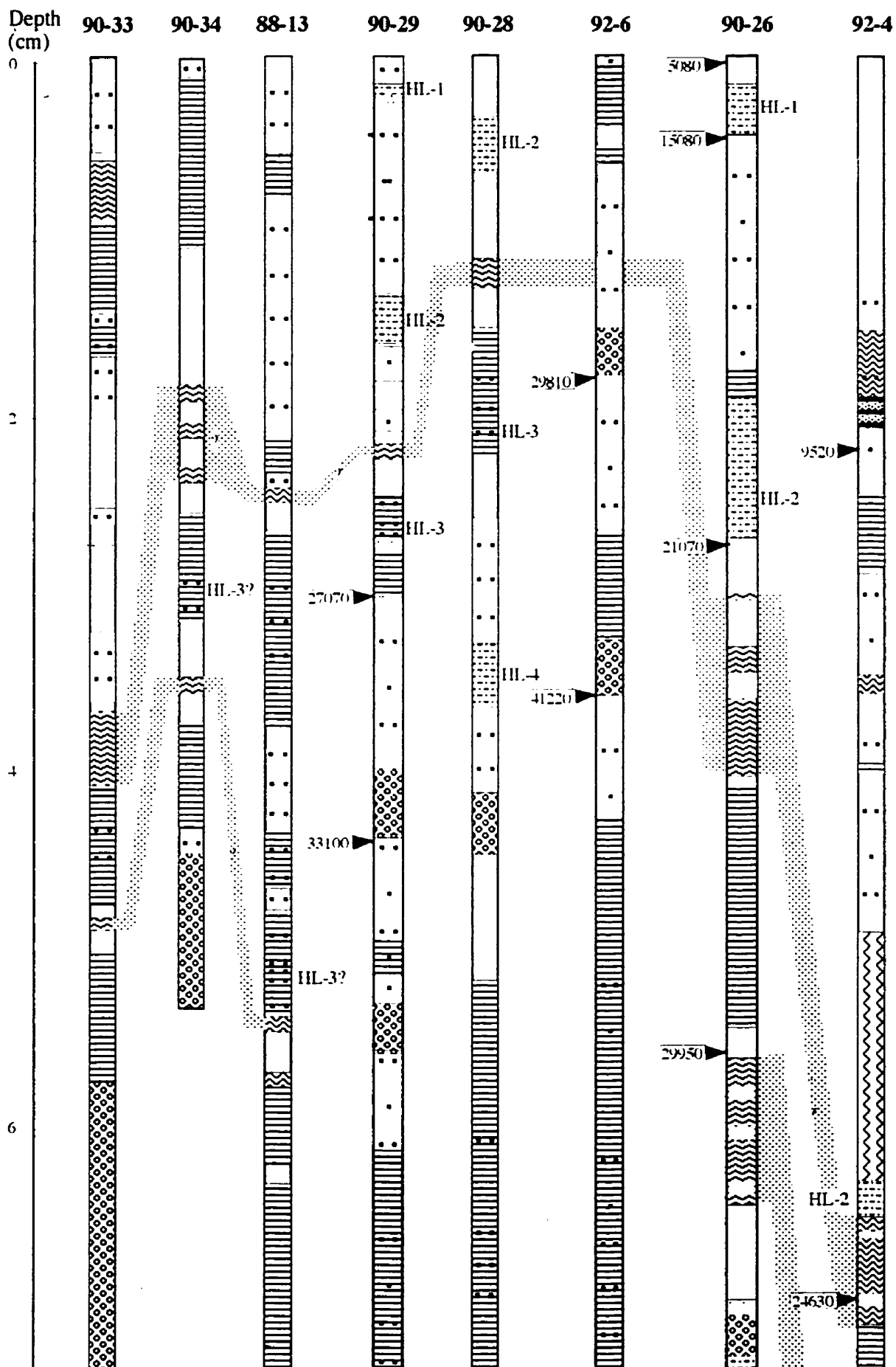
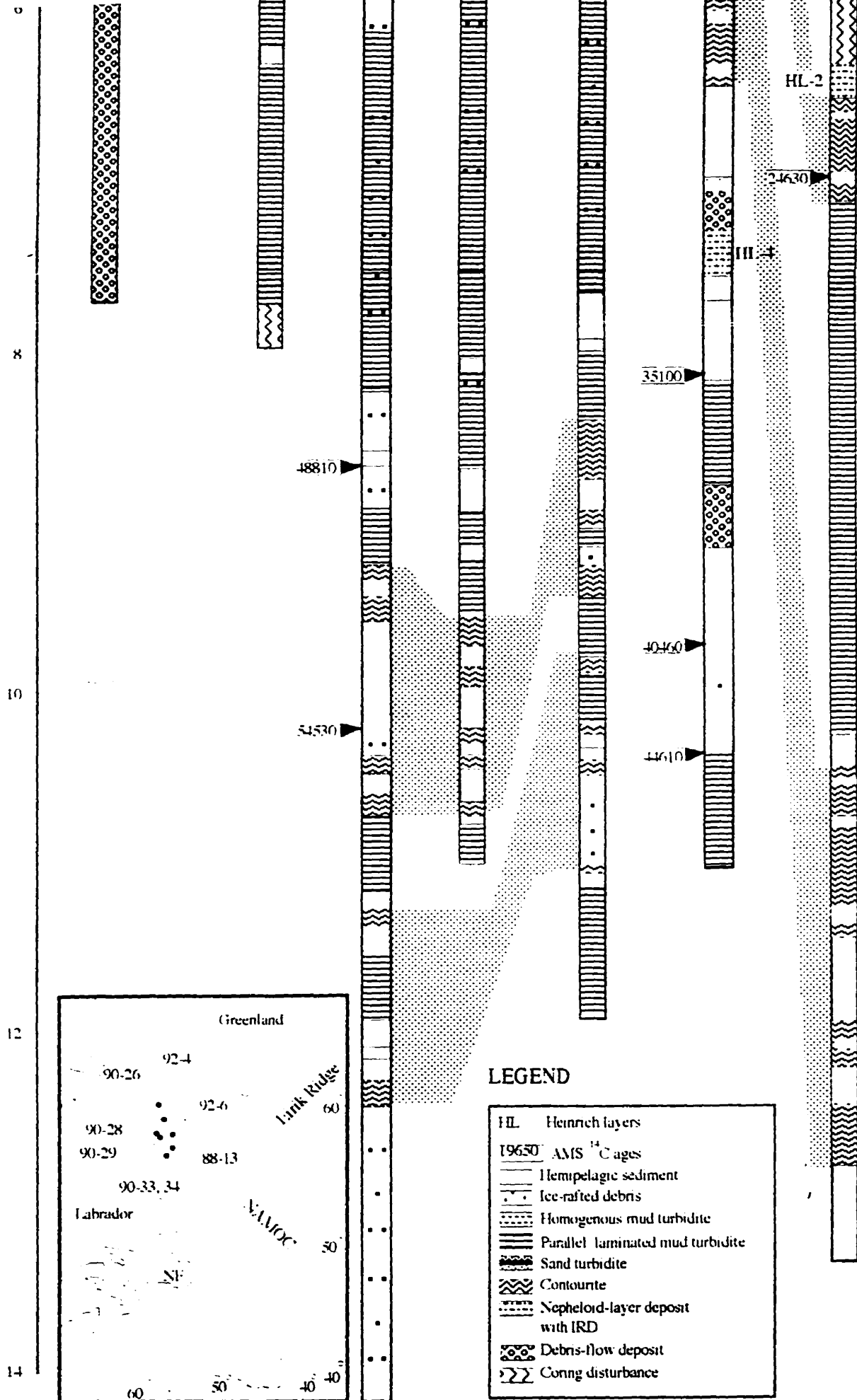


Fig. 3.10. Facies association of contourites and hemipelagic sediments in lower-slope core 90-26; for core location and facies symbols see Fig. 3.8).





3.2). It displays two types of laminae differentiated according to their continuity: (1) >5cm long wavy laminae, and (2) assemblages of <5 cm-long wavy laminae (Figs. 3.3C, D). This facies also comprises silt pockets and foram-enriched horizons (Figs. 3.3E, F). The contact with adjacent facies is mainly transitional. The mean grain-size is in fine silt (7.1 ϕ) and the mode is in the clay fraction (5-7 ϕ ; Table 3.1, Fig. 3.5e). Sediments of this facies are slightly better sorted ($\sigma=1.8 \phi$) than facies H (Fig. 3.10). The carbonate values are low (1.0%; see Chapter 4). This facies has a sedimentation rate of 10 cm/ka (Table 3.4).

Occurrence- Facies C forms thin (5-10 cm) beds intercalated with facies H and T or individual beds up to 0.5 m thick (Fig. 3.11). They occur in middle-slope to upper-rise locations. They form distinct horizons in sediments older than 20 ka (Fig. 3.11). Typical Labrador Sea contourites also occur in the Eirik Ridge, southwest of the southern tip of Greenland (Chough and Hesse, 1985).

3.2.5. FACIES T: Turbidite. Compared to other facies of the Labrador basin, turbidites are the best sorted facies. They form up to 8m thick sequences of brownish grey (2.5Y 6/2 and 10YR 6/2) to greyish brown (2.5Y 5/2; 10YR 5/2) detrital-carbonate rich sediments ($\text{CaCO}_3=34-38\%$). They contain turbidite structures of the classical Bouma (1962) sequence. On the basis of sediment texture and structure, this facies comprises three classes (modified after Piper, 1978): (i) sand turbidites consisting of divisions T_a and T_b , (ii) silt turbidites which comprise divisions T_c and T_d , and (iii) mud turbidites consisting of division T_e (Fig. 3.12). A complete sequence of the above divisions is rare.

On the Labrador Slope and Rise and on the NAMOC levees most sequences are base-cut off (sand divisions are absent). The most common sequences are T_{c-d-e} (15%) and T_{d-e} (81%).

Sand turbidite. These beds represent the basal parts of the turbidite structure sequence, and most commonly occur as individual layers (the top-cut off sequence; Fig. 3.3H). Sand turbidites are not common; they are mainly found as channel-fill sediments in NAMOC (Hesse and Rakofsky, 1992) and on the braidplain (Hesse et al., 1996). In the slope region, they form 2-6 cm thick beds, but they are up to 4 m thick on the braidplain. The basal part of the sand turbidite (division T_a) is graded or massive, comprising >95% sand (Fig. 3.6c). The basal contact with the underlying sediment is a sharp erosive boundary and the top contact with the overlying b-division may be transitional. Division a is well sorted ($\sigma=0.5 \phi$) and has a mean size of 1.5ϕ . The overlying b-division is laminated, less well sorted ($\sigma=1.2 \phi$) and finer grained (mean size= 2.6ϕ ; Fig. 3.7c).

The sand turbidites on the braidplain east of NAMOC have a similar origin as the slope sand turbidites (above). The thickness of a single turbidite is up to 1.8 m. The braidplain sand turbidites consist of olive (5Y 4/3, 5Y 5/3 and 5Y 5/4) massive silty sand to sandy silt. In one locality, sand turbidites consist of sandy gravel (core 84-16; Fig. 3.1). Sand makes up >50% of the sediment (Table 3.1). Generally, this facies is structureless, but in some localities the sediments display laminated and graded intervals (Figs. 3.3R and S). The facies is less well sorted ($\sigma=2.1 \phi$) and finer-grained (mean size= 3.4ϕ) than sand turbidites on the slope (Figs. 3.6 a and c, 3.7 a and c). The bed contact with adjacent facies is sharp. Mineralogically, this facies consists of quartz (40%),

feldspar (23%), pyroxene and amphiboles (5%) and various rock fragments (3-67%). Detrital carbonates make up to 33% of the facies. Some horizons are rich in volcaniclastic material (25% ash fragments; see section 4.3.3 and Appendix 9).

Silt turbidite. This class corresponds to turbidite divisions T_c and T_d . They are associated with mud turbidites (T_e -division) and usually consist of <0.5-2 cm thick, sandy silt to silty mud layers. Ripple cross-lamination is characteristic of division T_c (Fig. 3.3I). In inter-canyon regions on the slope and on channel-levees, the T_c -division forms the base of silt/mud turbidites and commonly overlies the T_e -division of an earlier layer. Basal and top contacts are sharp. The sediment is well sorted ($\sigma=1.6 \phi$) and has a strong mode in the coarse silt fraction (4-6 ϕ ; Table 3.1). Division T_d is parallel laminated muddy silt having a mean grain size of 6.8 ϕ . It directly overlies the T_c -division or earlier T_{d-e} sequences. In 36% of thin-bedded turbidites the T_d -division forms the base. Individual silt laminae are 0.2-0.3 mm thick and consist of alternating silt and muddy silt (Fig. 3.3I). Division T_d has a strong mode in the silt fraction (5-6 ϕ). It has a sharp contact with underlying c-division and sometimes a gradual contact with the overlying e-division. This transition is associated with a gradual decrease in the silt content from 81 to 53% (Fig. 3.12).

Mud turbidite. This class corresponds to the T_e -division. Division T_e is overlain by the next silt/mud turbidite sequence or by hemipelagic sediments (Fig. 3.12). In the latter case the top contact may be bioturbated. Division T_e is up to 3.5 cm thick, has a strong mode in the clay fraction (10 ϕ) and a mean grain size in very fine silt (7.9 ϕ ; Table 3.1).

Subfacies TI: Alternating thin bedded turbidite and ice-rafted laminae. This subfacies consists of two types: (i) millimeter- to centimeter-thick mud turbidites alternating with thin laminae of IRD; and (ii) cm-thick crudely laminated layers of IRD interbedded with mud turbidites. The number of IRD laminae and turbidite intervals are greater in the former. In general, the subfacies is between 0.2 and 1 m thick. The layers of ice-rafted material are generally <1 cm thick, but outsized ice-rafted clasts (>1 cm) forming typical "dropstone structures" are common (Fig. 3.3J). Compared to the mud turbidites, the ice-rafted layers of this facies are less well sorted ($\sigma=2.0$ and 3.3ϕ , respectively) and have a higher mean grain size (7.3 and 5.4ϕ , respectively).

Occurrence- Silt/mud turbidites locally occur in the upper slope but they become a predominant facies at depths below the middle slope. The proportion of this facies increases progressively in the basinward direction (Fig. 3.2). The thickest mud turbidites

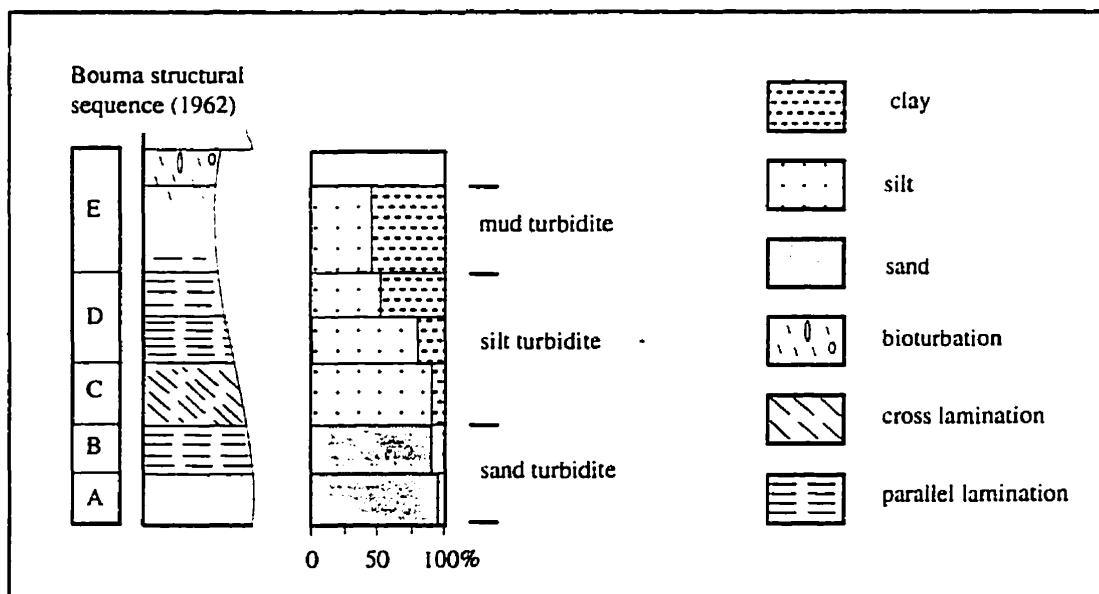


Fig. 3.12. Sediment structures and texture in turbidites.

are found on the NAMOC levee, where they comprise >90% of sediment. Massive sand turbidites are restricted to the braidplain east of NAMOC and the floodplain west of NAMOC. The massive sand turbidites of the eastern braidplain are thicker and less interrupted by other facies (especially debris-flow deposits) than those of the western floodplain (Fig. 3.1). Turbidites with the complete structure sequence T_{a-c} have been found in NAMOC (Hesse et al., 1987).

Subfacies TI, HI and facies N comprise distinct stratigraphic horizons indicative of prominent ice-rafting events (see Chapter 6). The two types of subfacies TI occur on the slope (thinly laminated) and on the NAMOC levees (crudely laminated), respectively; facies N and HI occur on the slope and in more distal basinal regions, respectively (see Fig. 6.5). The main ice-rafting events appear to be strictly synchronous (Chapter 6); however, additional occurrences of facies HI between the prominent Heinrich layers are not uncommon.

3.2.6. Facies D: Debris-flow deposit. On the basis of sediment texture this facies is classified into four subfacies (modified after Wang and Hesse, 1996). They include: (i) D1: gravelly, (ii) D2: sandy-silt, (iii) D3: thin bedded, and (iv) D4: sandy/gravelly-mud debris flow deposits (Table 3.2).

Subfacies D1: Gravelly debris-flow deposit. This facies consists of brownish grey (2.5Y 6/2 and 10YR 6/2) to greyish brown (2.5Y 5/2) and grey (2.5Y 5/1) muddy gravels. 52% of the sediment is gravel, 6% is sand, 28% silt and 19% clay (Table 3.1, Fig. 3.5a). The sediment is extremely poorly sorted ($\sigma=5.2 \phi$) having a strong mode in the gravel sizes

(-4 ϕ). Sedimentary structures include normal (arrow, Fig. 3.3M) and inverse grading. The bed contacts with adjacent facies are mainly sharp but the upper contact may be transitional. This facies varies in thickness from 0.1 to 1 m.

Subfacies D2: Sandy silt debris-flow deposit. This facies comprises brownish grey (2.5Y 6/2 and 10YR 6/2) to greyish brown (2.5Y 5/2; 10YR 5/2) sandy silts up to 1 m thick. Sand and silt comprise >75% of the constituents. Grain-size curves reveal a strong mode in the silt fraction (7-8 ϕ ; Fig. 3.5b). The facies is better sorted (σ =2.4) than subfacies D1, D3 and D4 (Table 3.1). The sediment contains abundant deformed mud clasts and discontinuous flowage bands (Fig. 3.3 P).

Subfacies D3: Thin-bedded debris-flow deposit. This facies consists of gray (5Y 5/1), dark gray (5Y 3/1 and 4/1), and olive gray (5Y 3/2, 5Y 4/2 and 5Y 4/1) thin bedded sandy-gravelly mud. Sharp upper and lower contacts of this unit are common. The sediment consists of a 5-30 cm thick coarse-grained lower unit overlain by a <1 cm thick clayey silt. 18% of the lower unit occur in the gravel and sand ranges, 51% in the silt fraction and 31% in the clay fraction. This unit is poorly sorted (σ =2.85 ϕ) having a mean grain size in the coarse silt fraction (6 ϕ). No sedimentary structures are observed in the lower unit. The upper unit is comparatively well-sorted (mean=6.6 ϕ , σ =1.9 ϕ) and consists of >91% silt. The sediment is mainly structureless, but may show parallel lamination.

Subfacies D4: Sandy gravelly-mud debris flow deposit. This facies is the most abundant type of facies D and consists of brownish grey (2.5Y 6/2 and 10YR 6/2) to greyish brown (2.5Y 5/2; 10YR 5/2) sandy-gravelly muds. They are poorly sorted (σ =2.8

φ) with a wide range of grain sizes. Sand and gravel comprise >20% of the sediment. Grain-size modes are mainly in the silt and clay fractions (6-10φ; Table 3.1). The carbonate content is high (28%). X-radiographs display subhorizontal flowage bands and floating mudclasts (Fig. 3.3N). Generally, microfossils are very rare to absent in all D subfacies. Contacts with overlying and underlying strata are mainly sharp, but transitional contacts with facies HI or D1 have been observed. The bed thickness ranges from 0.2 to 1.2 m.

Occurrence- Debris-flow deposits were interpreted from seismic profiles (see Hesse and Rakofsky, 1992). The characteristics of sediments retrieved from cores in debris-flow dominated regions confirmed this interpretation. Two main regions covered by debris-flow deposits have been recognized in the Labrador margin (Hesse and Rakofsky, 1992 ; Klaucke, 1995). They are located adjacent to the Okak Trough and Hopedale Saddle where they form the fill of major canyons (Fig. 5.3). On the western floodplain adjacent to the NAMOC, the debris-flow tongues issued from the slope canyons off Okak Trough and Hopedale Saddle join to form a stacked composite megadebris-flow, 20-40 km wide and 20 m thick that can be traced for at least 350 km (Hesse et al., 1990). Seismic profiles across the slope show extensive stacks of facies D deposits, characterized by elongated lenses of transparent horizons (Hesse, 1992). These regions are dominated by facies D4. Facies D3 occurs on the upper-slope region. Facies D1 and D2 are rare and mainly occur on the western floodplain and NAMOC levee. Sediments of this facies show a variety of facies associations. The most common facies associations are D1-D4, and D4-MS (cores 84-14, -15; Fig. 3.1).

CHAPTER 4: Isotopic, micropaleontological, geochemical and mineralogical analyses

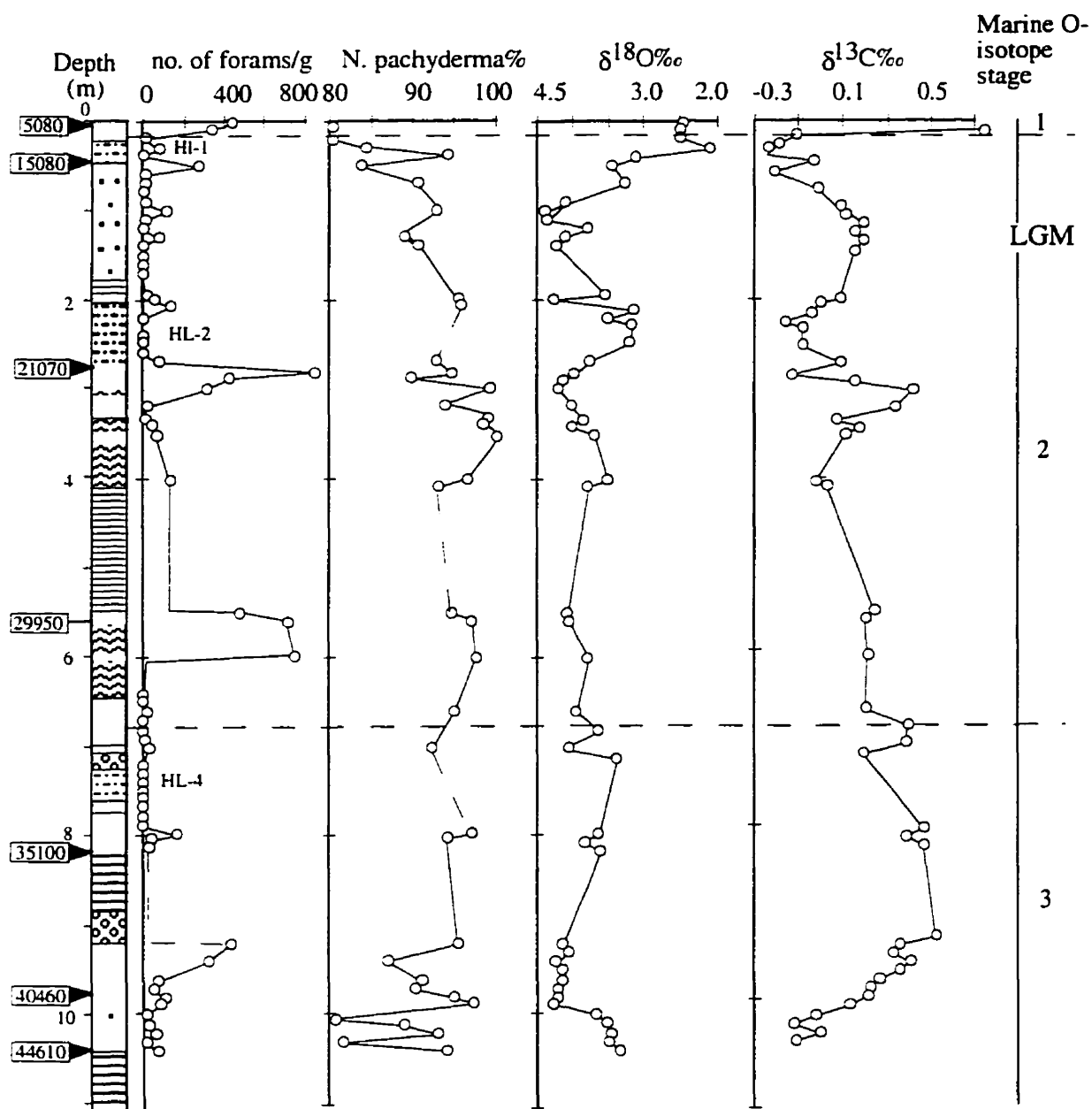
4.1. Isotope stratigraphy

4.1.1. Slope sediments

Core 90-26 has the best age control in terms of AMS radiocarbon dates among the slope and rise cores of this study and is used to establish an ^{18}O isotope stratigraphy. Although the possibility exists that parts of the stratigraphic column may have been removed by mass flows or contour currents, the marine oxygen-isotopic stages are well characterized. All isotopic analyses and radiocarbon ages (reservoir corrected) are based on *N.pachyderma* (left coiling). For the original radiocarbon dates and the isotopic analyses see Appendix 4.

Isotopic stage 1 (Holocene) is <50 cm thick in this core. Its small thickness is due to core-top loss during core retrieval. The top of core 90-26 has an AMS age of 5080 ± 70 years BP (Isotrace lab # TO-3145). A distinct feature of this stage are the low $\delta^{18}\text{O}$ values (<2.5‰ relative to SMOW). The high $\delta^{13}\text{C}$ values (>0.5‰), typical of stage 1 (e.g., Hillaire Marcel et al., 1994), are found in the uppermost 10 cm of the core. Compared to isotopic stage 2, stage 1 has higher foram contents and lower proportions of *N.pachyderma* (Fig. 4.1). The stage 1/2 boundary occurs above Heinrich Layer-1 (HL-1), and is associated with abrupt changes in foram content (from >400 above to ~10 forams/g below the boundary) and $\delta^{13}\text{C}$ values (from 0.72‰ to -0.2‰).

Stage 2 spans the depth from 0.5 to 6.8 m. It includes Heinrich-layers 1 and 2 (with ages of 15080 ± 120 and 21070 ± 190 years BP, respectively, for the immediately



90-26

LEGEND

LGM	Last Glacial Maximum
HL-4	Heinrich layer
19650	AMS ¹⁴ C ages
[Pattern]	Hemipelagic sediment
[Pattern]	Ice-rafted debris (IRD)
[Pattern]	Parallel laminated mud turbidite
[Pattern]	Contourite
[Pattern]	Nepheloid-Layer deposit with IRD
[Pattern]	Parallel laminated mud turbidite with IR laminae
[Pattern]	Debris-flow deposit

Fig. 4.1. AMS ¹⁴C age, foram content, *N. pachyderma*% and isotope stratigraphy (based on *N. pachyderma*, left coiling) in core 90-26 (for core location, see inset map in Fig. 4.4).

underlying sediments; Isotracer lab # TO-3146 and 2366)(Fig. 4.1). The high $\delta^{18}\text{O}$ values (ranging from 3.1 to 4.4‰) are characteristic of this stage. The maximum $\delta^{18}\text{O}$ value of 4.4‰ in the upper half of this stage represents the Last Glacial Maximum (LGM) at 18 ka (Dyke and Prest, 1987). It was also reported by Andrews et al. (1994) for a nearby location (core 75-55) on the northern Labrador Slope. The $\delta^{13}\text{C}$ values vary between -0.2 and 0.4‰ during this stage. The large amplitude change in $\delta^{18}\text{O}$ (-2.4‰) occurs between the LGM and the top of stage 2 (from 4.4 to 2‰) was also reported by de Vernal and Hillaire Marcel (1987) and Hillaire-Marcel et al. (1994) in the southern Labrador Sea (cores 84-3 and 91-94). The low $\delta^{18}\text{O}$ values of 2‰ are associated with HL-1. An excursion to lighter $\delta^{18}\text{O}$ values is observed in the middle of stage 2 within HL-2. In this interval, the $\delta^{18}\text{O}$ values decrease from 4.0–4.2 to 3.2‰, but above HL-2 they return to high value (4.2‰). Below HL-2 an increase in foram content and a decrease in proportion of *N. pachyderma* occur (Figs. 4.1, 4.4). The stage 2/3 boundary (at 32 ka; Fulton and Prest, 1987) occurs above HL-4 around 6.8 m subbottom, with a shift in $\delta^{18}\text{O}$ to slightly lighter values, from 3.9 to 3.6 in the samples chosen. The $\delta^{13}\text{C}$ values shift to slightly higher values in this interval (from 0.2 to 0.4; Fig. 4.1). The stage 2/3 boundary was also reported around 32 ka in nearby cores (75-41 and 90-13) by Fillon and Duplessy (1980) and Hillaire-Marcel et al. (1994).

The lower half of the core (below 6.8 m subbottom) comprises the isotopic stage 3, including Heinrich Layer 4, which is younger than 35100 ± 360 years BP (Isotracer lab # 2437; Fig. 4.1). Relatively high $\delta^{18}\text{O}$ values (ranging from 3.3 to 4.2‰) characterize isotopic stage 3 throughout with peak values of 4.3‰ occurring at 10 m subbottom below

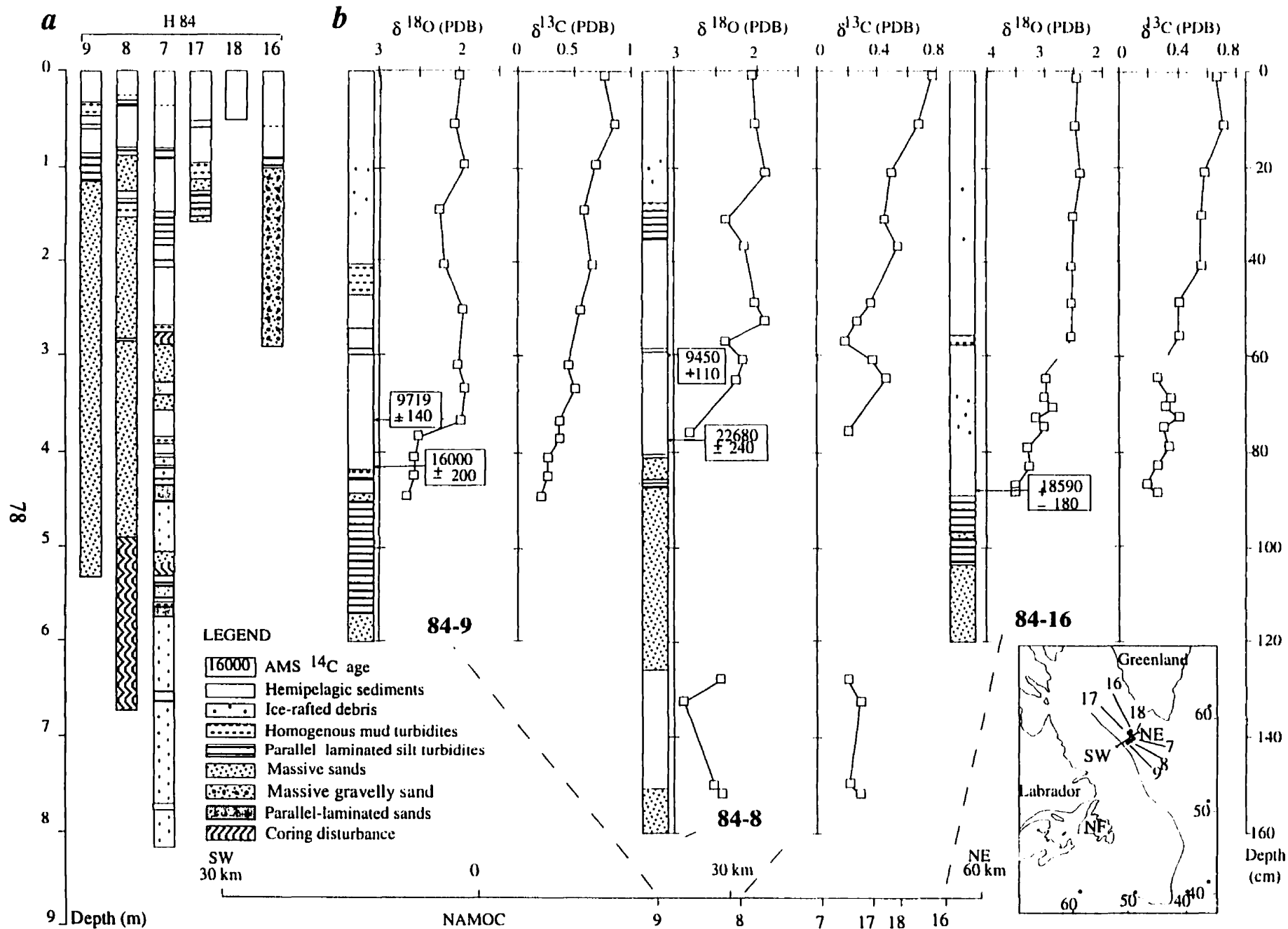
which depth they are lower ($<3.6\text{‰}$). The $\delta^{13}\text{C}$ values show the same range as those of stage 2 (-0.1 to 0.5‰). The base of stage 3 (65 ka, Fulton and Prest, 1987) was probably not penetrated in this core. The strong depletion both in ^{13}C and ^{18}O in the lower part of stage 3 was also reported by Hillaire-Marcel et al. (1994) for the southern Labrador Sea (cores 84-3 and 91-94). The $\delta^{13}\text{C}$ shift towards lower values starts at about 9 m subbottom and continues to the bottom of the core (about 10.5 m, not including turbidites penetrated below that depth), whereas the $\delta^{18}\text{O}$ shift to lower values starts at 10 m (Fig. 4.1). The lower part of stage 3 contains varying, but generally low proportions of *N.pachyderma* (95-80%; Fig. 4.1). The AMS ^{14}C age obtained for the lowest hemipelagic sediments in this interval is 44610 ± 920 (Isotrace lab # TO-2439).

4.1.2. Hemipelagic sediments overlying massive sands of the braidplain

Hemipelagic sediments interbedded between mass-flow deposits provide a mean to date sedimentary processes. Massive sands of the braidplain east of NAMOC, which might be related to submarine-flooding events linked to Heinrich events (see Ch. 6 for discussion) are overlain by 1.0-1.5 m thick hemipelagic muds. Three piston cores (84-8, 9 and 16) were used for ^{18}O isotope stratigraphy and AMS radiocarbon dating.

Radiocarbon ages obtained for layers immediately on top of the sands (Isotrace lab # TO-4661, 4662 and 4663: Appendix 4) range from 16000 ± 200 to 22680 ± 240 years BP (Fig. 4.2). An interval 0.1-1.0 m thick above the sands is associated with a shift in $\delta^{18}\text{O}$ values from 2.47 to 3.01 and in $\delta^{13}\text{C}$ values from 0.37 to 0.21. The small shift in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values, which is considerably less and opposite to known shifts for the stage

Fig. 4.2. a) Lithological columns of six piston cores retrieved from massive sand deposits in the braidplain east of NAMOC; b) AMS ^{14}C ages, ^{18}O and ^{13}C isotope stratigraphy of piston cores 84-8, 9 and 16 (see text for details). The Isotracer lab numbers are: core 84-8: TO-5212 and 4661; core 84-9: TO-5213 and 4662; core 84-16: TO-4663.



1/2 boundary in the region (Hillaire-Marcel et al., 1994), prompted resampling at a greater distance from the mud/sand boundary. Two additional radiocarbon ages (Isotrace lab # TO-5212 and 5213; Appendix 4) 8-16 cm above the previous samples gave ages of 9450 ± 110 and 9720 ± 140 years BP. These ages are confirmed by correlation with Ash zone I (9300 years BP, Ruddiman and Glover, 1975; see Fig. 4.14). The most likely interpretation of the higher ages for the hemipelagic sediments immediately overlying the sands is that they are contaminated by turbiditic material containing older foraminifera (see Ch. 5 for discussion). The boundary between the sands and overlying muds is marked by a high sand content (up to 56%), which gradually decreases to 3-4% at 10-15 cm above the boundary. The two additional ages are significant in that they make it possible that the braidplain sands could have been deposited by transport processes (subglacial-lake outburst flooding) related to Heinrich events 1 or 0 around 14.3 and 10.5 ka, respectively (Ch. 5; Broecker, 1994; Andrews et al., 1995).

4.1.3. Upper-slope plumites

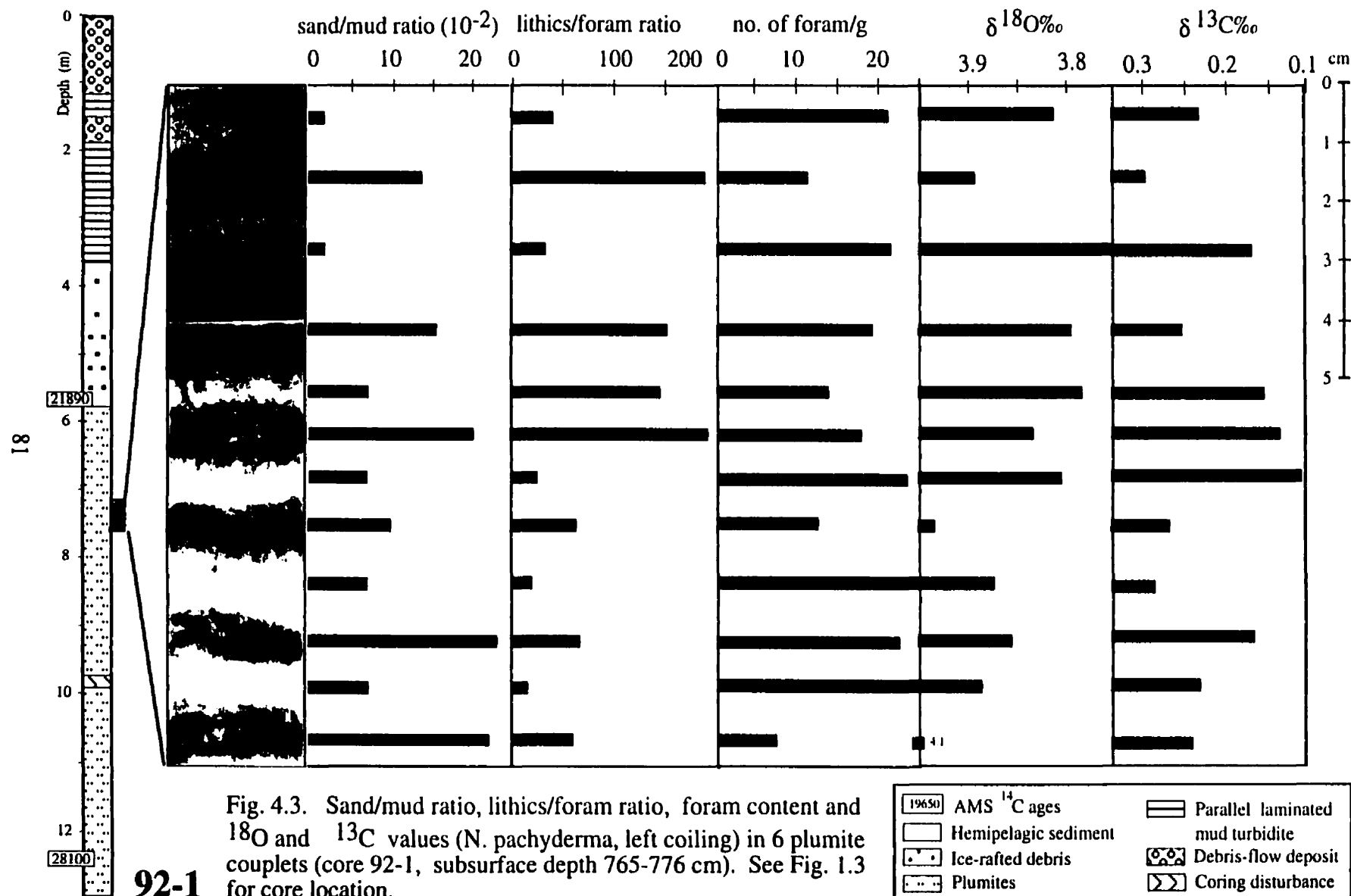
In an attempt to relate plumite deposition and glacial cycles, six successive plumite couplets were analyzed isotopically. According to AMS ^{14}C ages, the plumites were deposited during the isotopic stage 2 between 21890 ± 160 and 28100 ± 290 years BP (Isotrace lab # TO-4930 and -4931; Fig. 3.1). The O- and C-isotopic variation of *N. pachyderma* (left coiling) between the plumite couplets is small (less than 0.2‰). In general, fine sandy silt layers have slightly higher $\delta^{18}\text{O}$ values (mean=3.9‰) than those of clayey silt layers (mean=3.8‰; Fig. 4.3). The ^{18}O enrichment in the fine sandy silt

layer is visible in 5 out of 6 couplets; the remaining couplet shows more or less constant $\delta^{18}\text{O}$ values for the fine sandy silt and clayey silt layers. The maximum $\delta^{18}\text{O}$ difference is 0.16‰ (lowermost couplet in Fig. 4.3). The significance of the differences between $\delta^{18}\text{O}$ of the fine sandy silt and clayey silt layers was evaluated using a student t-test. This yielded a confidence level of 95% for the statement that compared to clayey silt layers, the enrichment in $\delta^{18}\text{O}$ of the fine sandy silt layers is significant (Dr. R. Doig, personal communication, 1996).

The $\delta^{13}\text{C}$ values are variable. Three fine sandy silt layers show a ^{13}C enrichment compared to the overlying clayey silt layer; one couplet shows the reverse trend, the remaining couplets show constant $\delta^{13}\text{C}$ values. The maximum $\delta^{13}\text{C}$ shift between the fine sandy silt and clayey silt layers is 0.17‰. The student t-test yielded a confidence level of 60% for the statement that compared to clayey silt layers, the fine sandy silt layers are enriched in $\delta^{13}\text{C}$.

4.2. Micropaleontological analysis

The total abundance of foraminifers and the proportion of the planktonic foraminifera *N. pachyderma* (sinistral) was determined in two slope cores (90-26 and 29) and a basin-centre core (87-9; Fig. 4.4). The latter species is characteristic of polar surface waters (McManus et al., 1994), and its relative abundance is indicative of the prevalence of polar conditions at any given time interval. This species is most abundant in the intervals characterized by the highest $\delta^{18}\text{O}$ values (see Fig. 4.1). Compared to the basin core, the foraminifera concentration is lower in the slope cores which is probably



due to dilution by rapidly accumulated IRD.

The uppermost 30 cm of the slope cores are characterized by high foram (up to 3400 forams/g) and nannofossil contents, a relatively low proportion of *N. pachyderma* (<87%) and relatively high diversity of planktonic foraminifera (>5 species; Figs. 4.4 and 4.5). This interval corresponds to the isotopic stage 1 (Holocene). The planktonic foraminifer assemblages of this interval include *N. pachyderma*, *Globigerina bulloides*, *Turborotalita quinqueloba*, *G. inflata* and *G. umbilicata* (Fig. 4.5). Benthic foraminifers are minor constituents (1-2.5%) and include *Hoeglundina elegans*, *Melonis pompiloides*, *Cibicides wuellerstorfi* and *Epistominella exigua*. The nannofossil assemblages of this interval are dominated by *Emiliania huxleyi*, *Coccolithus pelagicus*, *Calcidiscus leptoporus* and *Gephyrocapsa mullerae* (J. Jiraudeau, 1996, personal communication; Table 4.1).

Due to erosion by mass flows, the Holocene muds and most hemipelagic sediments below HL-2 are absent in core 87-9 (see Fig. 3.1). Compared to the slope cores, forams are more abundant in this core (up to 6000 forams/g; Fig. 4.4). In the slope cores, the highest foram contents (3400 forams/g) and lowest proportion of *N. pachyderma* (up to 77%) occur in stage 1. The highest proportion of *N. pachyderma* (up to 100%; Fig. 4.1) is found in stage 2. The value stays relatively high (>82%) during stage 3. In core 87-9, the highest proportion of *N. pachyderma* (>97%) is observed below HL-1. In the slope cores, the sediments between HL-1 to HL-4 are generally characterized by low concentrations of planktonic foraminifers (<100 forams/g), among which *N. pachyderma* is dominant. In some horizons forams are absent. In 20-50 cm

Fig. 4.4. AMS ^{14}C ages, foram content and *N. pachyderma*% in two slope cores (90-26, 29) and a basin-centre core (87-9; see the inset map for core locations).

Fig. 4.5. A) Sand fraction of Holocene sediment in slope core 92-5 (subsurface depth 15 cm). Note abundant fragments of agglutinated foram tests (arrows) characteristic of the Holocene sediments. The benthic forams include *C. lobatulus* (C), *H. elegans* (H), and *P. bulloides* (P) whereas planktonics are dominated by *N. pachyderma* (N).
B) Sand fraction of hemipelagic sediment deposited during glacial time (i.e. below HL-2; core 92-5, subsurface depth 169 cm), dominated by *N. pachyderma*.

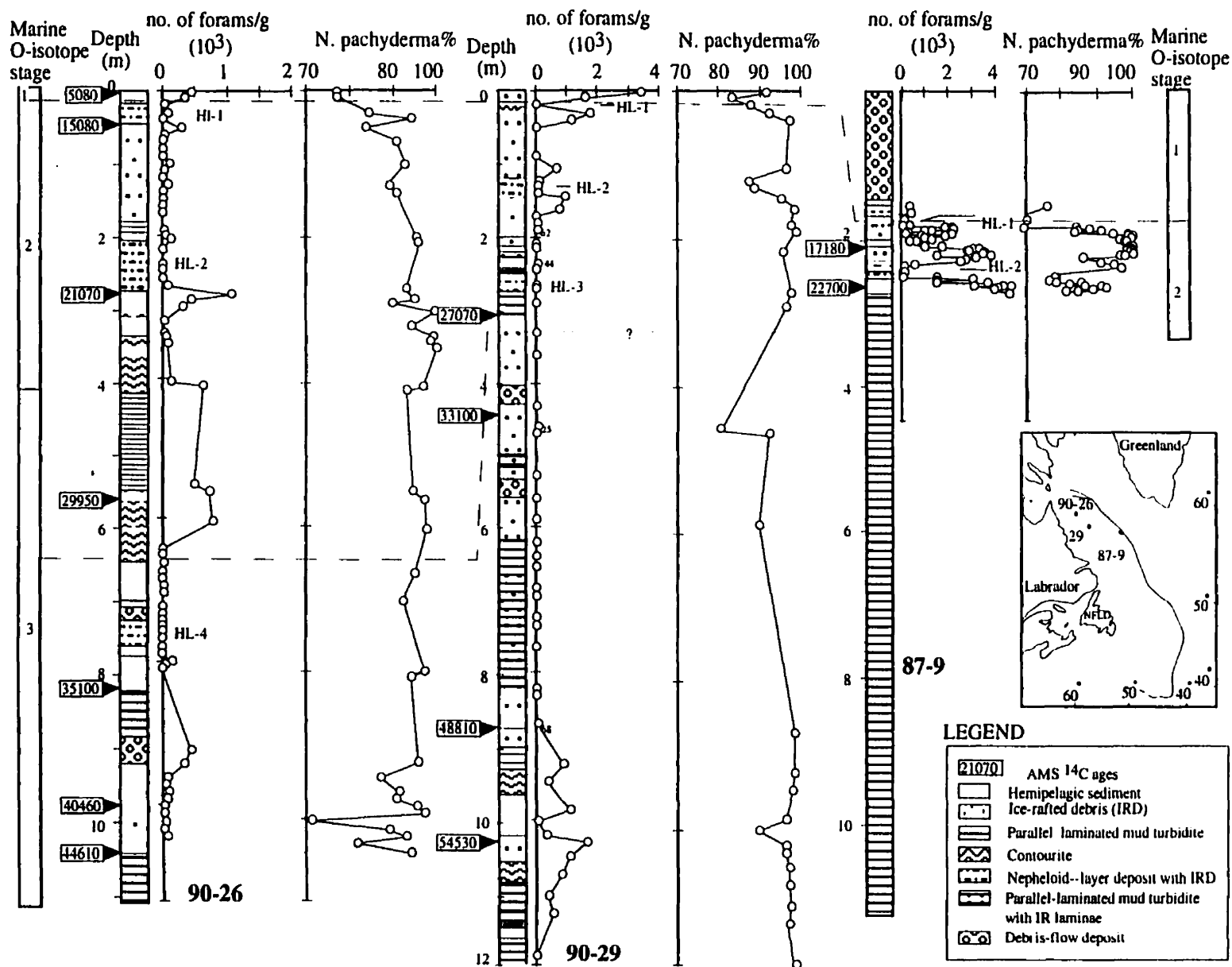


Fig. 4.5. A) Sand fraction of Holocene sediment in slope core 92-5 (subsurface depth 15 cm). Note abundant fragments of agglutinated foram tests (arrows) characteristic of the Holocene sediments. The benthic forams include *C. lobatulus* (C), *H. elegans* (H), and *P. bulloides* (P) whereas planktonics are dominated by *N. pachyderma* (N).
B) Sand fraction of hemipelagic sediment deposited during glacial time (i.e. below HL-2; core 92-5, subsurface depth 169 cm), dominated by *N. pachyderma*.

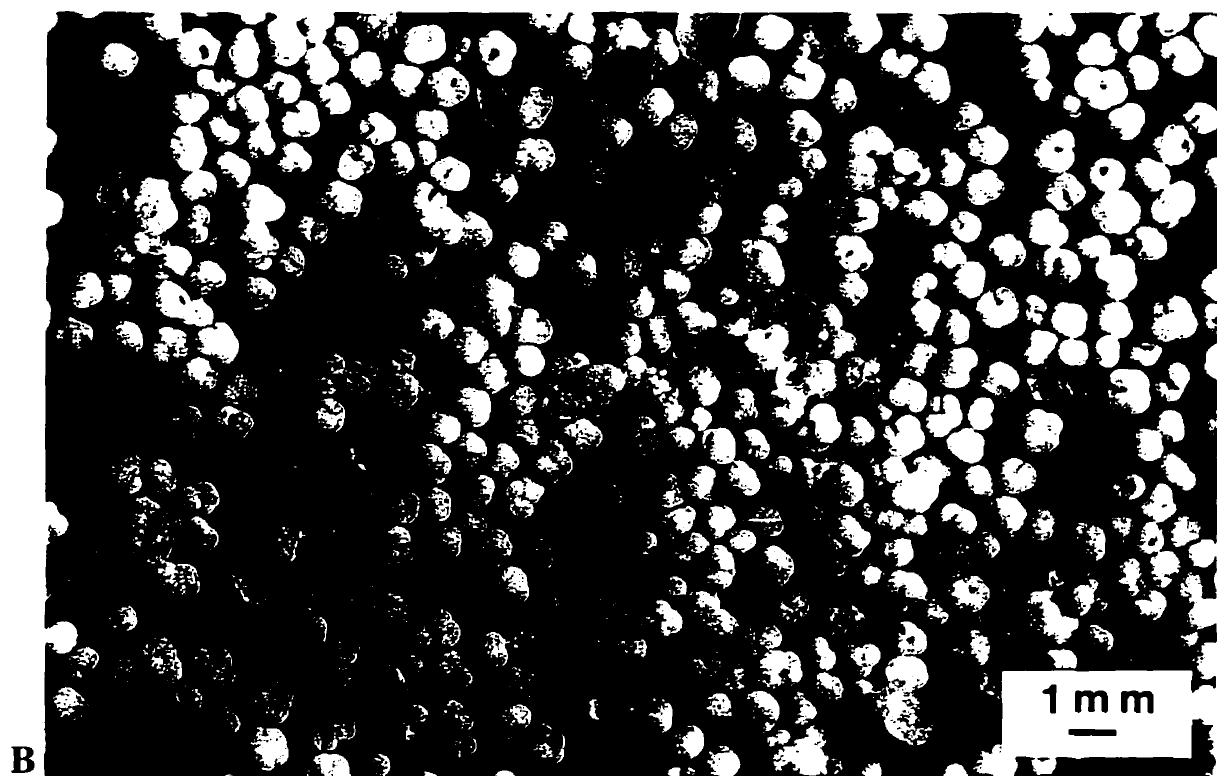
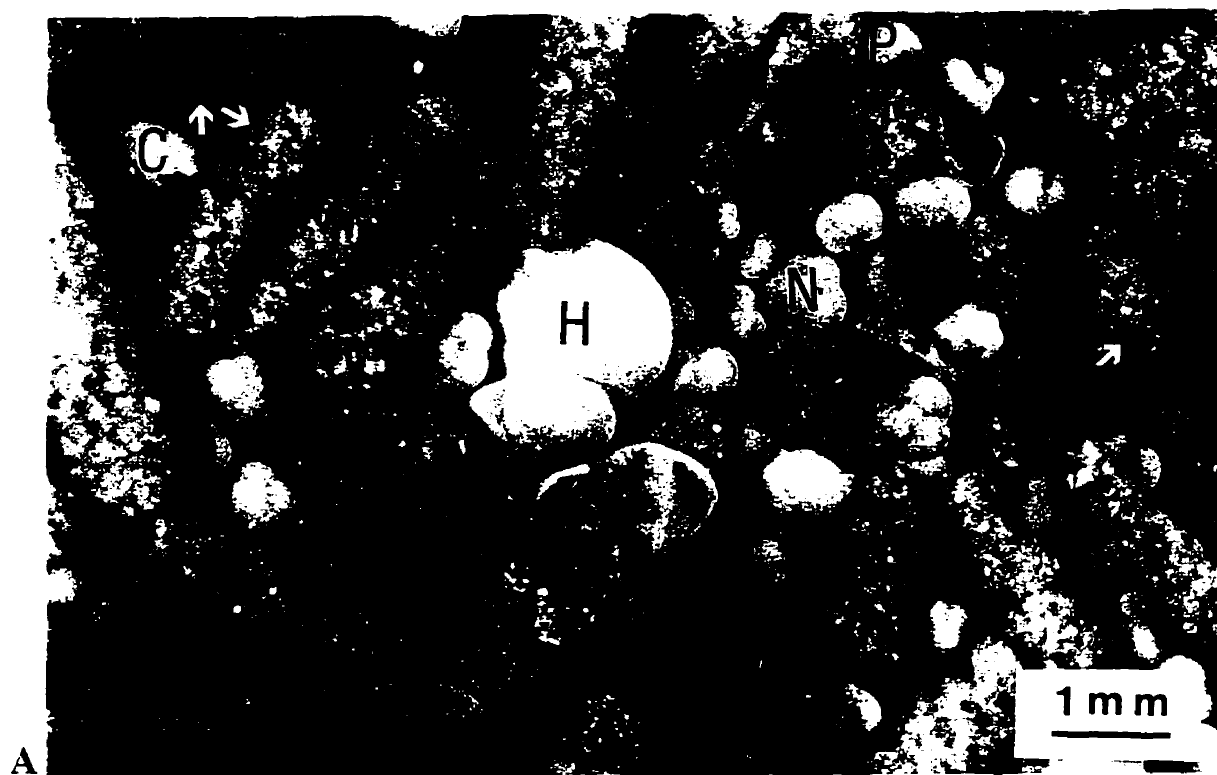


Table 4.1. Relative abundance of coccoliths species in core 90-29 (from J. Jiraudeau, 1996; personal communication)

AMS 14C ages	Depth (cm)	Coccoliths total abundance	<i>Emiliania huxleyi</i>	<i>Coccolithos pelagicus</i>	<i>Calcidiscus leptoporus</i>	<i>Helicosphaera carteri</i>	<i>Gephyrocapsa mullerae</i>	<i>Gephyrocapsa ericsonii</i>	<i>Gephyrocapsa caribbeanica</i>	<i>Umbilicosphaera sibogae</i>	Marine oxygen isotope stage
	1 (twc)	abundant									1
	12	abundant									
	50	trace (reworked species)									
	100	trace									
	150	trace									
	200	none									2
	258	trace									
27070	300	trace									
	350	none									
33100	400	none									
	450	none									
	500	none									
	550	trace									
	590	trace									3
	812	trace									
48810	857	trace									
	924	rare									
	958	common									
54530	1001	common									
	1045	abundant									
	1074	rare									
	1137	rare									
	1187	trace									
	1243	none									
	1302	none									
	1352	none									

twc: trigger-weight core

Coccolith abundance:

- dominant
- abundant
- subordinate
- rare
- very rare

thick intervals below HL-1 and 2, foram content increases up to ~1600 forams/g, but it rapidly returns to low levels (Fig. 4.4). Nannofossils are very rare or absent. The foram contents, dominated by *N. pachyderma*, increase up to 1600 forams/g at depths between ~800 to 1200 cm in core 90-29. In general, benthic foraminifers are subordinate (<3%) and include *Melonis barleeanus*, *Pullenia bulloides* and *M. pompiloides*. However, in certain layers they may make up to 41% of the total foram content (i.e. core 90-26, 1002 cm). In core 90-29, sediments between 800 to 1200 cm subbottom depths are characterized by abundant nannofossils, dominated by *E. huxleyi*, *G. mullerae* and *Gephyrocapsa caribbeanica* (J. Jiraudeau, personal communication, 1996; Table 4.1). The lowermost 2m of core 90-29 contain small amounts of forams (<10 forams/g) and no nannofossils.

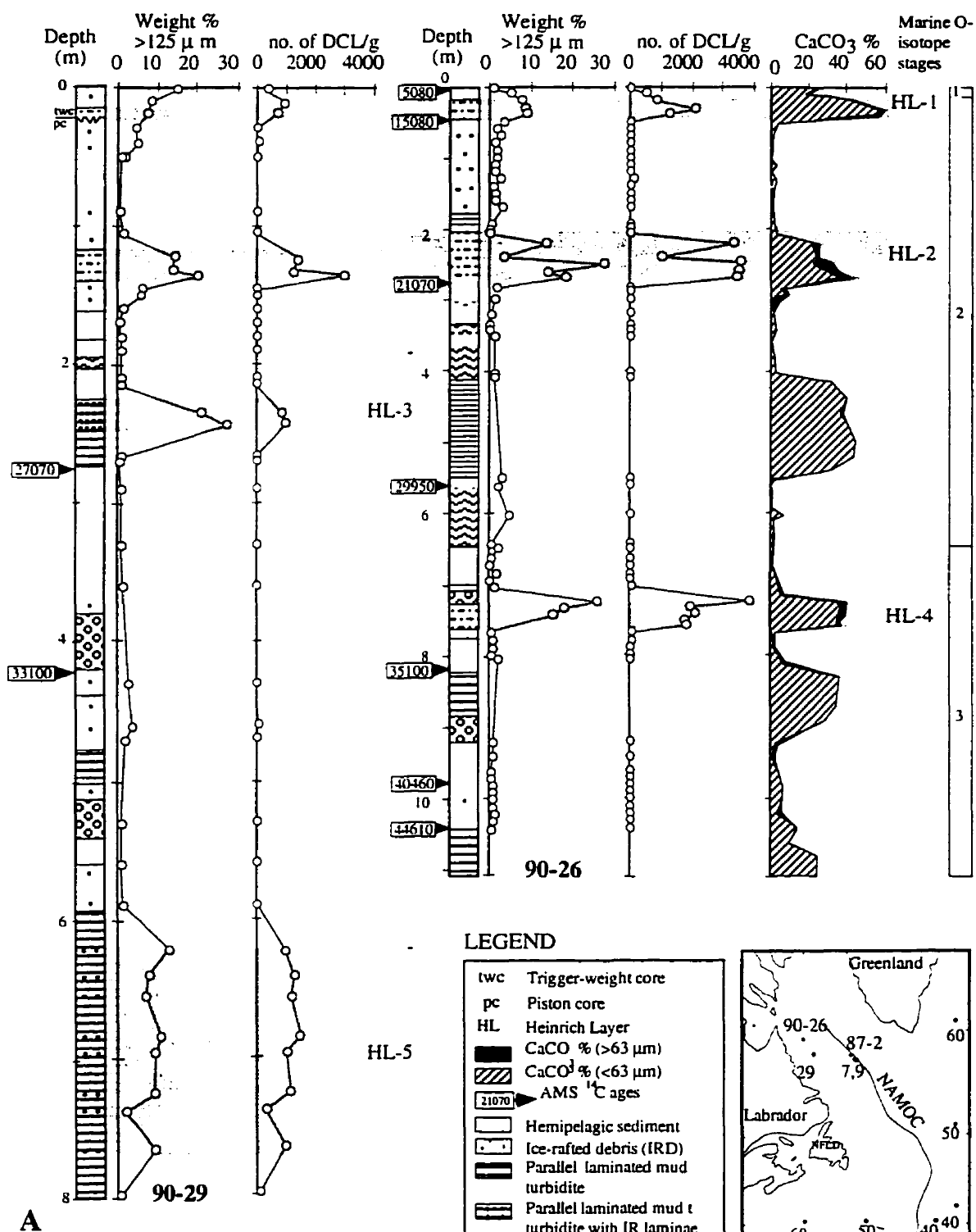
4.3. Geochemical analyses

4.3.1. Carbonate content

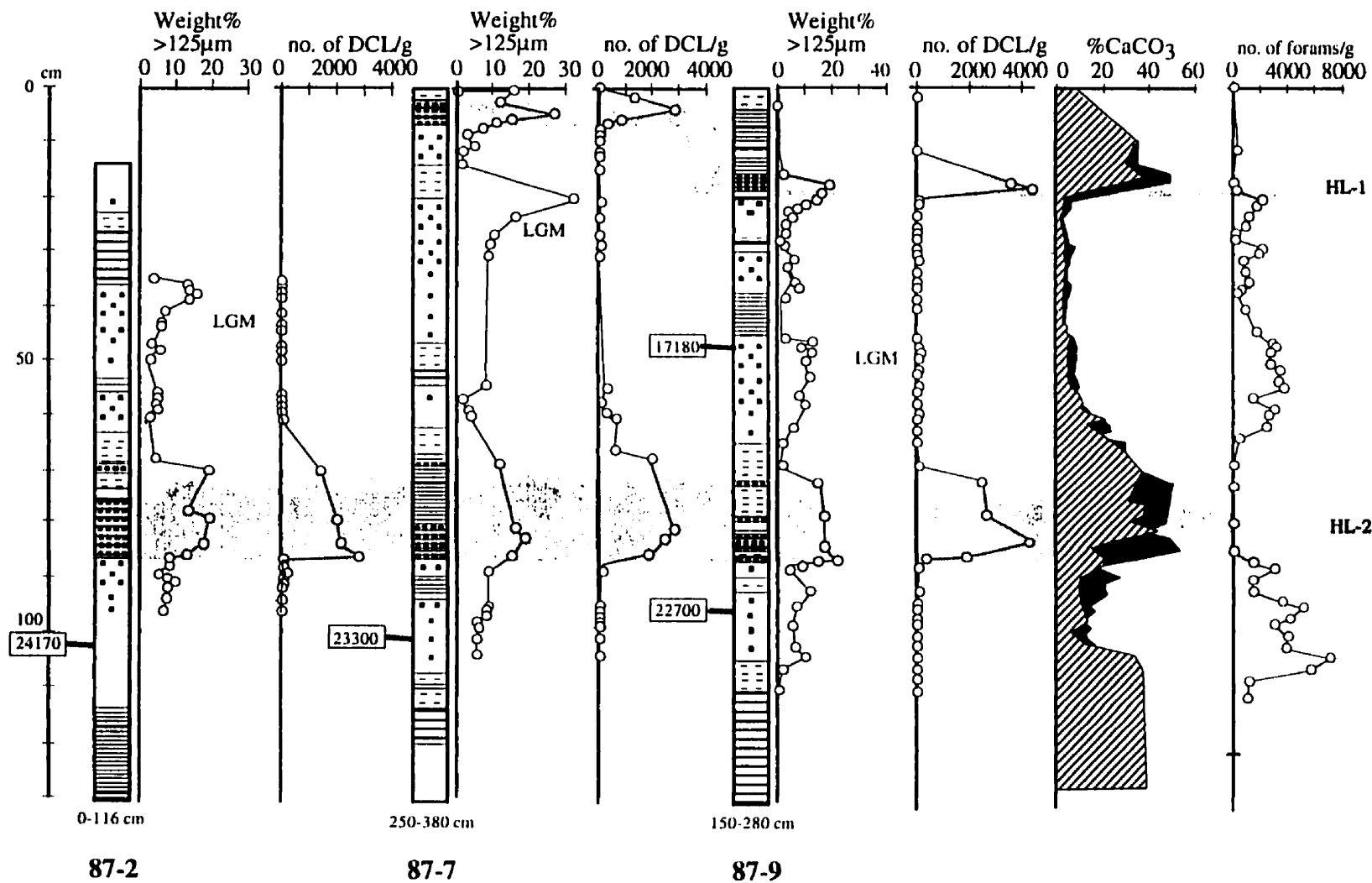
Detrital carbonates are an important petrographic tracer for Quaternary sediments in the Labrador Sea (see discussion in Ch. 5). Variation in detrital carbonate content is also considered a paleoclimatic/paleoceanographic indicator (Andrews et al, 1990). In this section, the distribution of detrital carbonates within the coarse and fine fractions in the various sedimentary facies is described, particularly in Heinrich layers. Two slope cores (90-26, 29) and three basin-centre cores (87-2, 7 and 9) were analyzed. Carbonate content was measured both in the coarse (>63 μ m) and fine fractions (<63 μ m). The concentration of detrital carbonate lithics was also point-counted in the coarse (>63 μ m) fraction (see

Figure 4.6. Coarse fraction, detrital carbonate content, $\text{CaCO}_3\%$ in fine and coarse fractions in (a) two slope cores and (b) three NAMOC levee cores (including foram content).

Note: (i) carbonate peaks are found in mud turbidites and nepheloid-layer deposits, (ii) they are associated with an increase in the coarse fraction and a decrease in foram content; (iii) 55-90% of CaCO_3 in the bulk sediment is in the fine fraction. DCL= detrital-carbonate lithic grains.



16



B

Appendix 3).

Carbonate maxima occur in two sedimentary facies: (1) mud turbidites, and (2) nepheloid-layer deposits (facies N). Facies N is associated with prominent ice-rafting events (Heinrich events) in the North Atlantic. Microscopic observation indicates that more than 95% of the carbonate in this facies (N) is of detrital (non-biogenic) origin. The average carbonate content of nepheloid-layer deposits ranges between 40% on the slope and 33.5% in the basin centre (Table 4.2). Detrital carbonate is abundant both in the coarse and fine fractions (10-45% and 30-50%, respectively). More than 82% of the total detrital carbonate is in the fine fraction (Fig. 4.6; see Appendix 5 for details). The average carbonate content of mud turbidites ranges from 34% on the slope to 38% in the basin centre (Table 4.2). More than 95% of turbidite carbonate is in the fine fraction.

The lowest carbonate values were found in distal plumites (with respect to the Hudson Strait), contourites and hemipelagic sediments, which, on the other hand, have a high proportion of biogenic carbonate (foraminifera tests). The carbonate content of hemipelagic sediments ranges from 3 to 14% (slope and basin centre, respectively). The higher carbonate content in the basin centre is due to a higher foram count (>1400 forams/g) compared to slope sediments (<800 forams/g). The Hudson-Strait plumites are carbonate-rich. This is inferred from high carbonate contents in mud turbidites in cores 90-25 and 26 (average CaCO_3 , 34.5 and 33%, respectively) measured on the middle and lower slope beneath the upper-slope plumites. The mud turbidites are derived from remobilization of the Hudson-Strait plumites higher up on the slope.

Table 4.2. Comparison of %CaCO₃ of sedimentary facies between a slope and a basin core (see Appendix 5 for details).

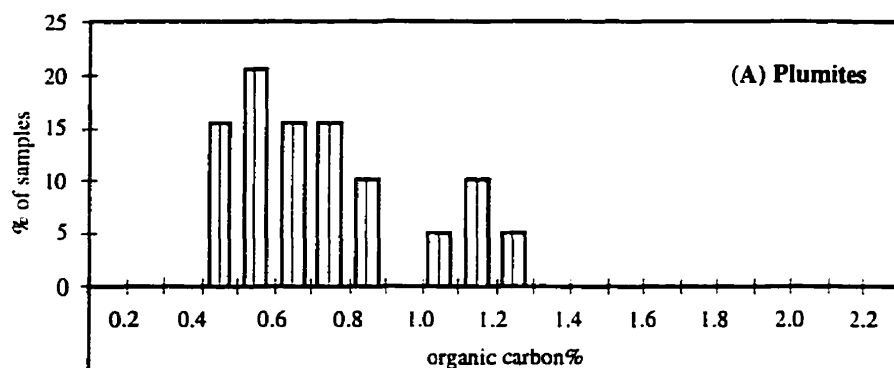
Facies	n	Slope (core 90-26)	n	Basin centre (core 87-9)
		Av. %CaCO ₃		Av. %CaCO ₃
Plumite (core 92-1)	20	1.6		
Hemipelagic sediment	17	3.0	7	14.0
Hemipelagic sediment with ice-rafted debris	20	4.8	31	10.4
Contourite	7	2.2		
Nepheloid-layer deposit	12	39.7	5	33.5
Debris-flow deposit	4	30.8		
Thin-bedded mud turbidite	15	33.7	8	38.3

The carbonate and the coarse fraction peaks are coupled (Fig. 4.6). The detrital-carbonate peaks in the sand fraction show an increase in detrital carbonate of up to three orders of magnitude (from 0-130 to >4000 grains/g) compared to the fine fraction (Fig. 4.6; see Appendix 3 for the raw data). The weight of the coarse fraction in ice-rafted sediments increases by more than an order of magnitude compared to the remainder of the cores (e.g. core 87-9, 196 cm).

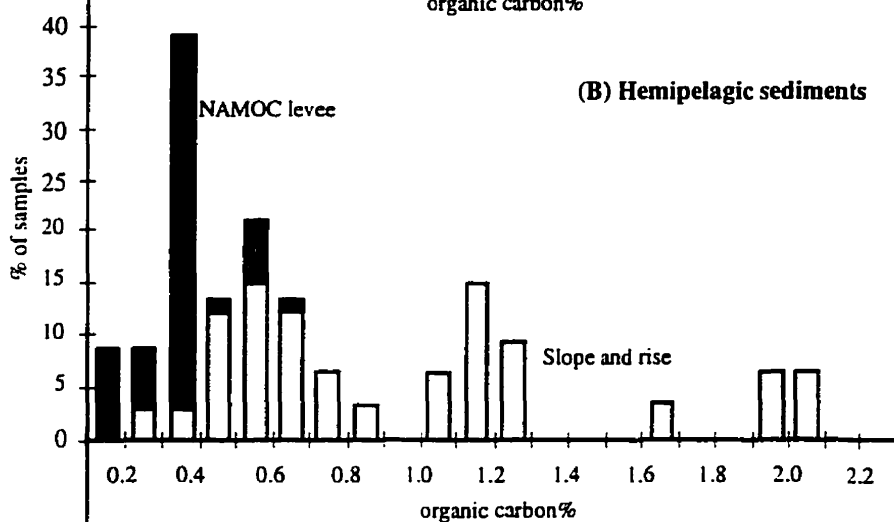
4.3.2. Organic-carbon content.

A significant difference between the various sedimentary facies is their organic-carbon content. In the following, (1) the type of organic matter in different sedimentary facies is identified, and (2) the relationship between ice-rafting events and organic-carbon content of the sediments is documented. Five cores were analyzed. Slope core 90-26 was analyzed by means of a Leco furnace for organic-carbon content and by rock-eval

Fig. 4.7. Comparison between organic carbon content of various sedimentary facies in slope/rise cores (92-1, 90-25, 26 and 88-10) and NAMOC cores (from Hesse and Rakofsky, 1992). Note: (1) plumites (A) and hemipelagic sediments (B) show the lowest organic carbon values while nepheloid-layer deposits (C) and turbidites (D) show higher values. (2) Proximal slope and rise cores (with respect to the shelf break) show higher organic carbon values in distal (NAMOC levee) cores (see Appendix 6 for details).

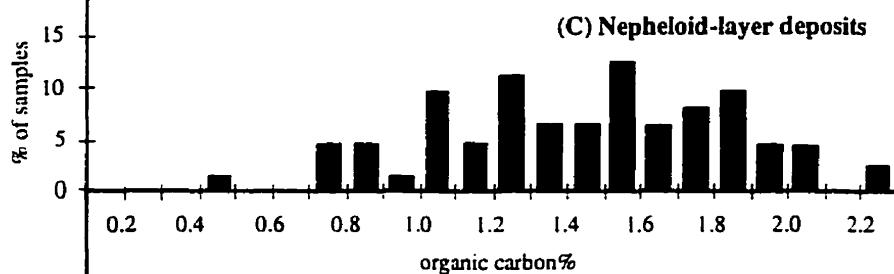


Locality: upper slope
 No. samples = 20
 Mean O.C.% = 0.75
 Mode = 0.5-0.6%
 Standard deviation: 0.25

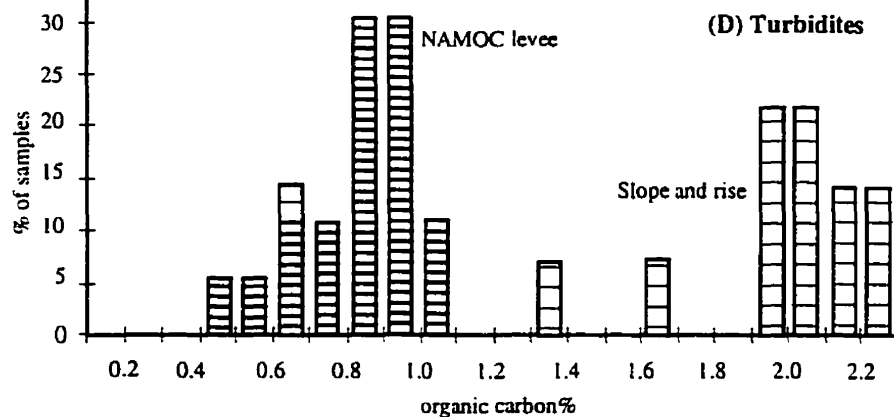


Locality: Slope and rise
 No. samples = 33
 Mean O.C.% = 0.86
 Mode = 0.5-0.6 and 1.1-1.2%
 Standard deviation: 0.53

Locality: NAMOC levee
 No. samples = 24
 Mean O.C.% = 0.4
 Mode = 0.3-0.4%
 Standard deviation: 0.13



Locality: slope and rise
 No. samples = 63
 Mean O.C.% = 1.36
 Mode = 1.5-1.6%
 Standard deviation: 0.40



Locality: slope and rise
 No. samples = 14
 Mean O.C.% = 1.80
 Mode = 1.9-2.1%
 Standard deviation: 0.54

Locality: NAMOC levee
 No. samples = 18
 Mean O.C.% = 0.8
 Mode = 0.8-1%
 Standard deviation: 0.17

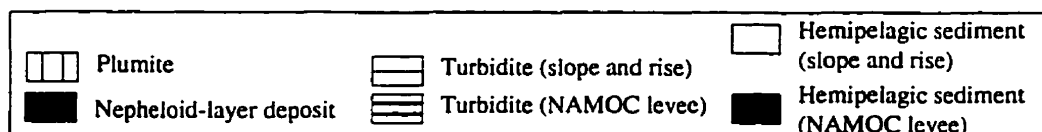
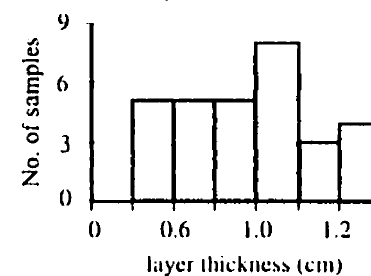
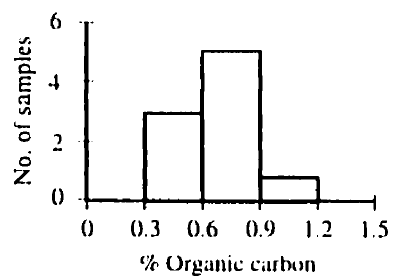
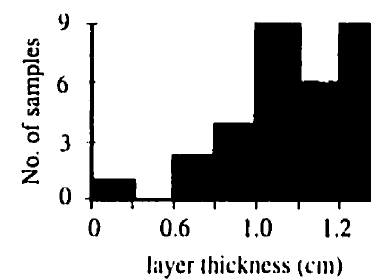
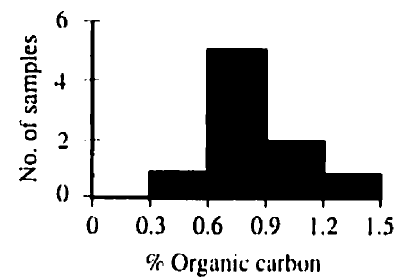
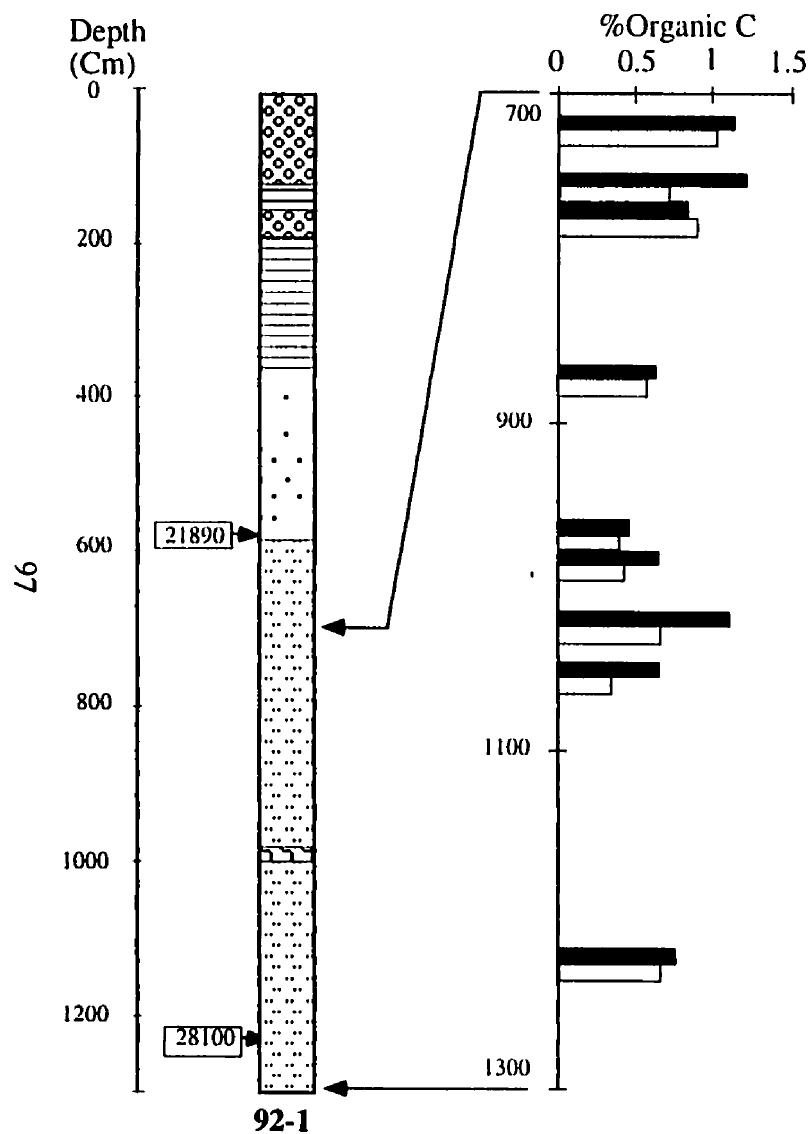


Fig. 4.8. Lithology, ^{14}C ages, organic carbon content and layer thickness of individual plumite couplets in core 92-1.

Eighteen samples from 9 individual couplets show silty clay layers having higher organic carbon content and slightly greater layer thickness ($\text{Av.}=1.1\text{ cm}$) than fine sandy silt layers ($\text{Av.}=0.9\text{ cm}$). Mean organic carbon content of fine sandy silt layers: 0.65% (range: 0.3-1.2%), and silty-clay layers: 0.83% (range 0.3-1.5%). AMS ^{14}C ages give plumite sedimentation rates of 110 cm/ka. For core location see Fig. 1.3.



LEGEND

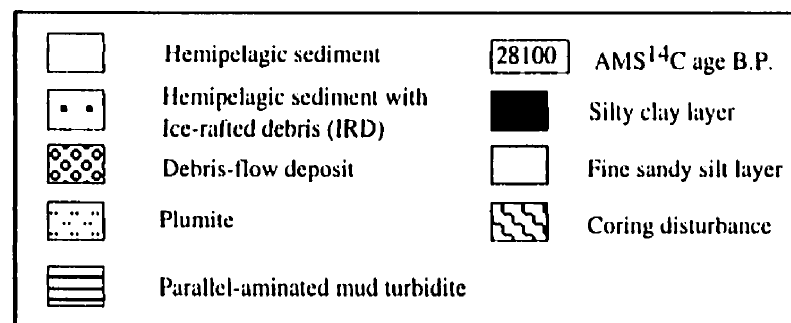
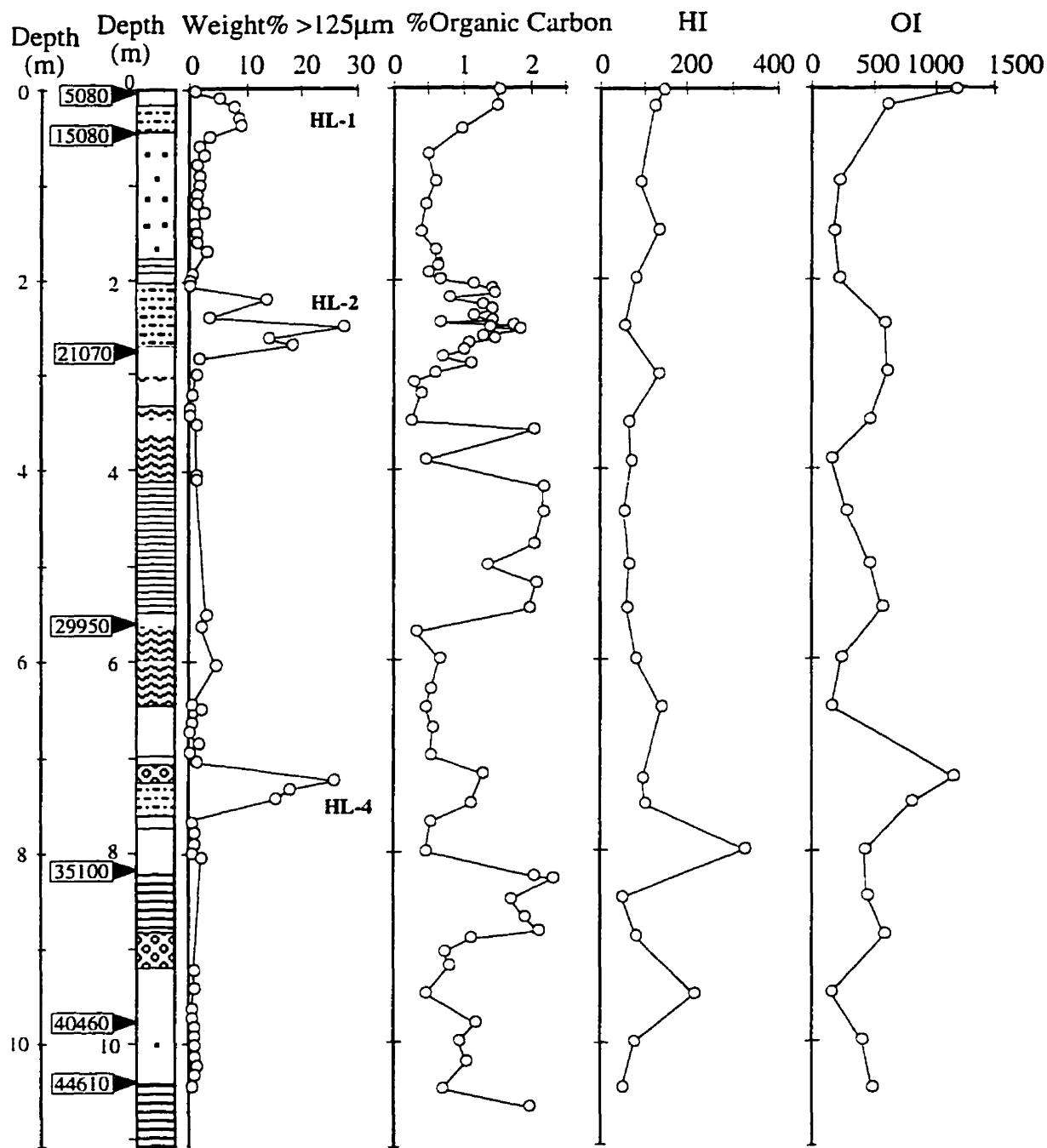


Fig. 4.9. Organic carbon percentage, hydrogen index (HI) and oxygen index (OI) for core 90-26. HI and OI values are from Rock-Eval pyrolysis and organic carbon data from Leco furnace (see Ch. 1 for details). High organic carbon values are found in turbidites and ice-rafted layers. High oxygen indices and low hydrogen indices during these intervals indicate a high contribution of land-derived organic matter (see Fig. 4.4 and text for details).



90-26

LEGEND

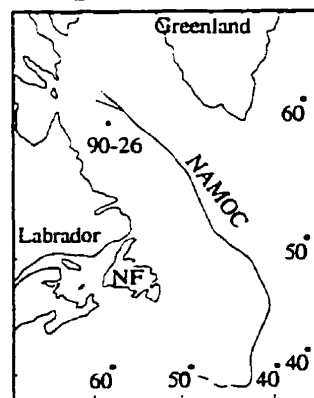
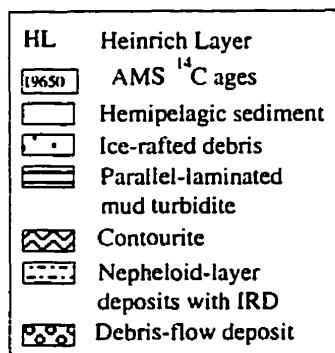


Fig. 4.10. Variation in organic- and inorganic-carbon content in Heinrich-Layer 2 in (a) two slope cores (90-25, 26) and (b) a rise (88-10) and a basin-centre core (87-12, trigger-weight core). See Fig. 1.3 for core location.

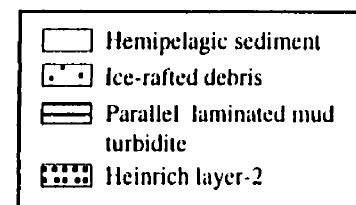
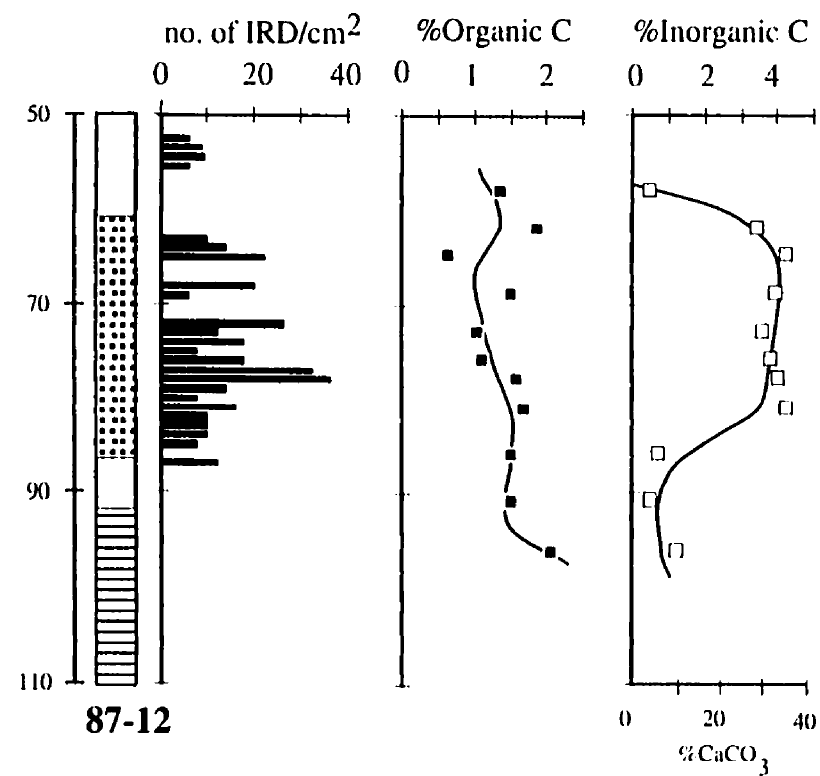
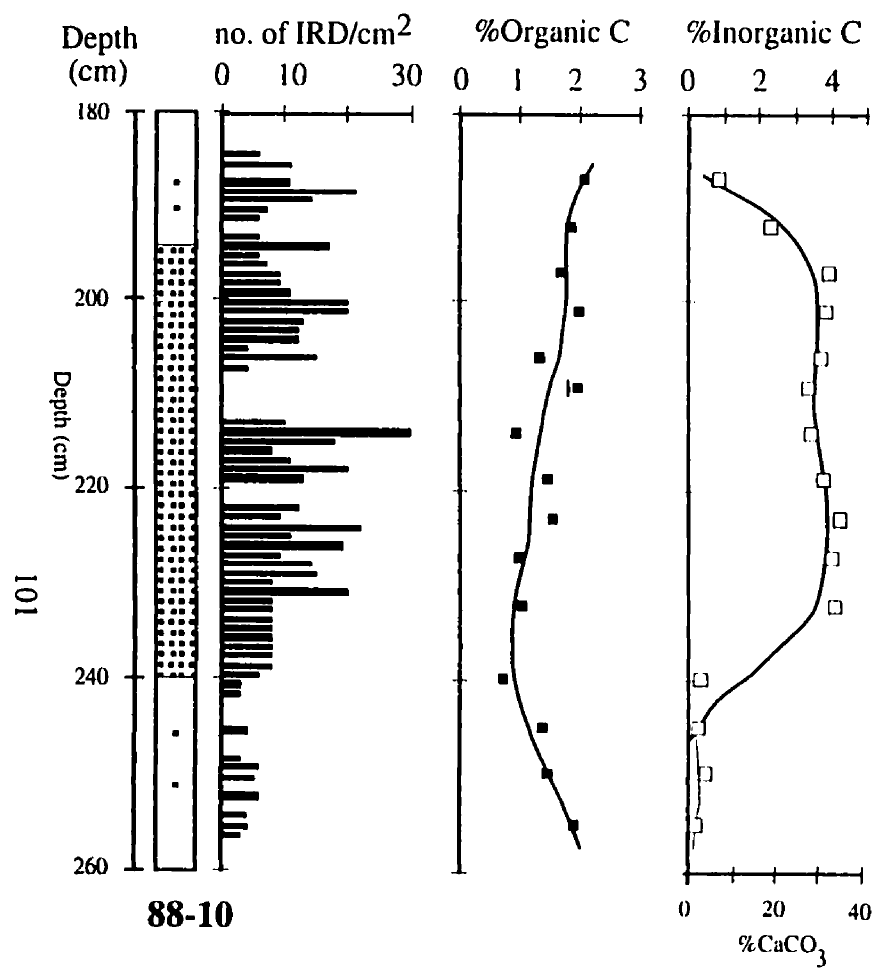
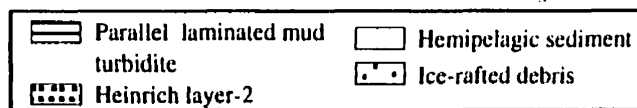
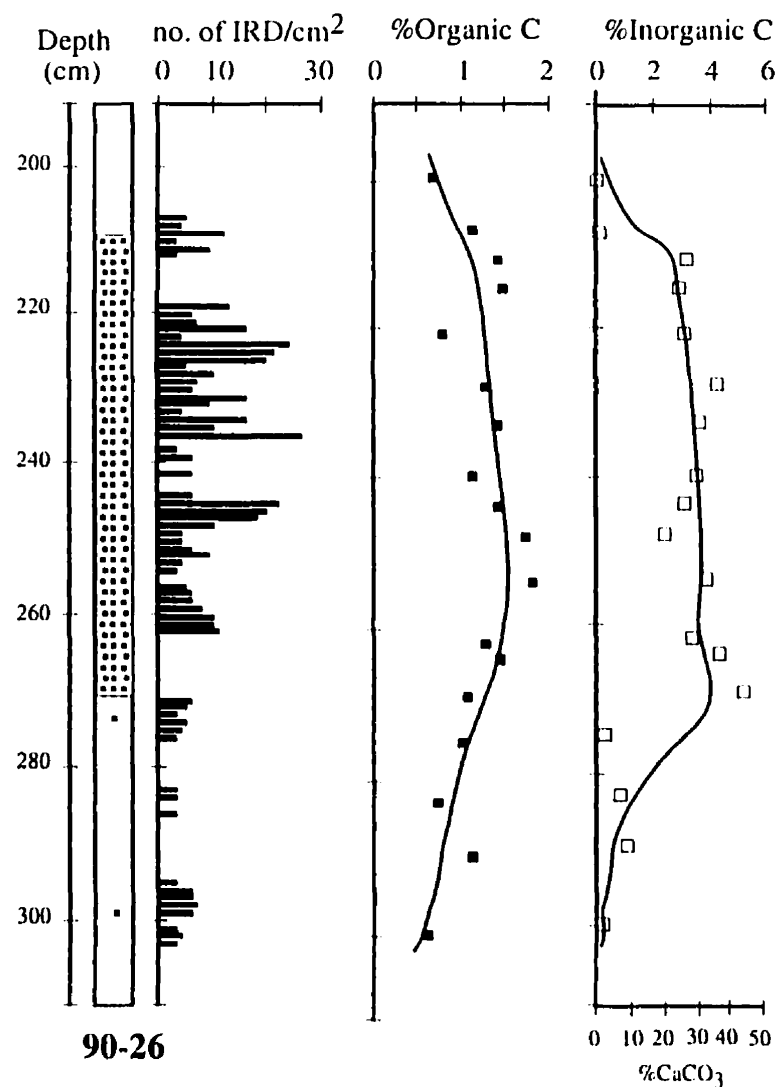
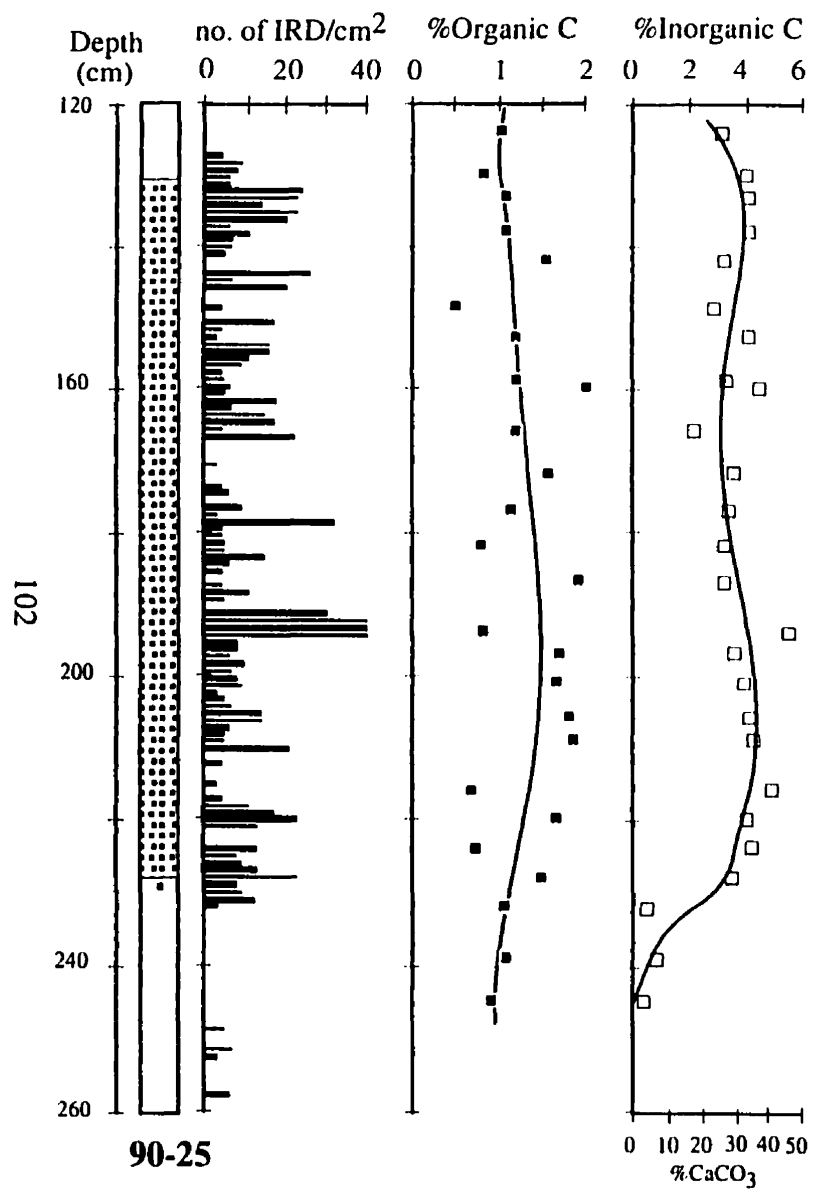


Fig. 4.10. continued



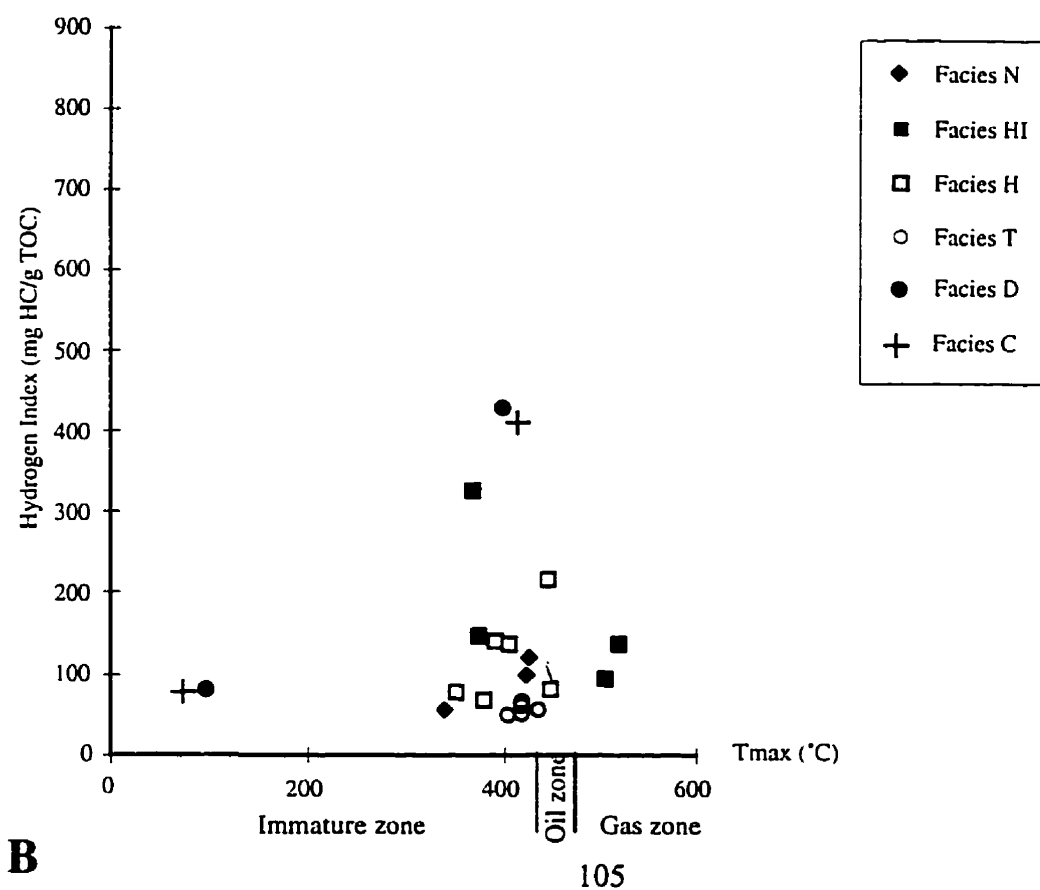
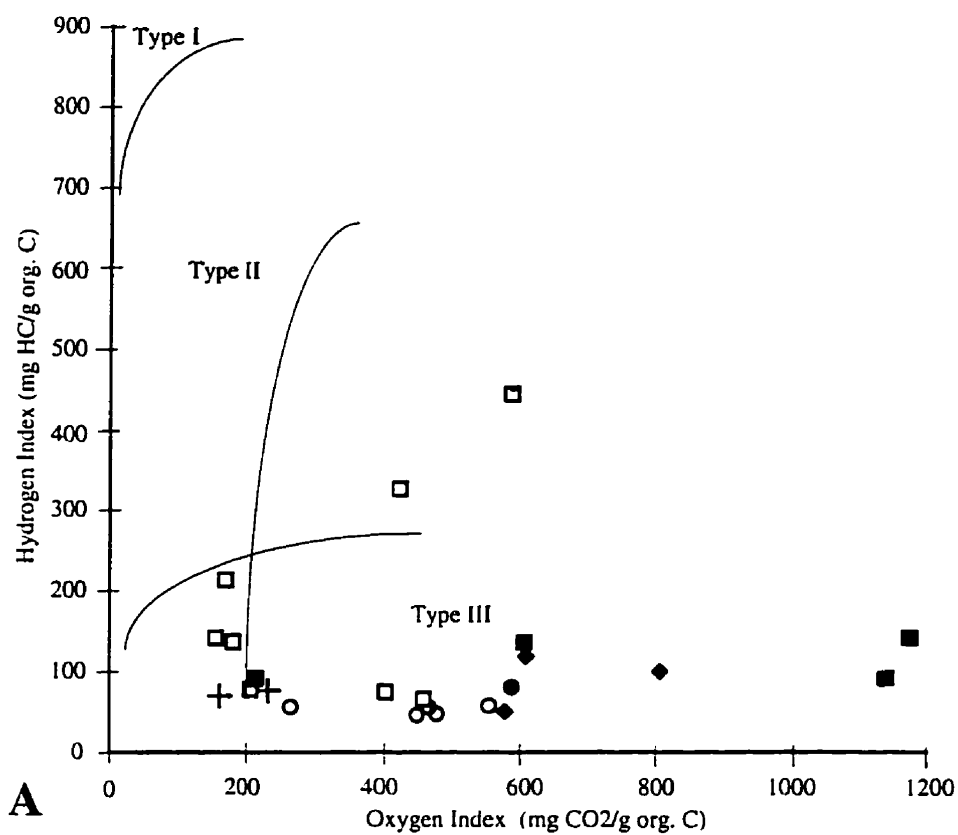
pyrolysis for organic-carbon type (for analytical results and explanation of parameters see Appendices 6 and 7). Ice-rafted layers in four cores (90-25, -26, 88-10, 87-12) were also analyzed for their organic-carbon content (see Appendix 6). Plumites and hemipelagic sediments contain the lowest concentrations of organic carbon (average of 0.75% and 0.86%, respectively; Fig. 4.7). Compared to clayey silt layers of plumites, the sandy silt layers have lower organic carbon contents (0.83 and 0.65%, respectively; Fig. 4.8). The organic carbon of hemipelagic sediments in the basin centre is lower than that of the slope facies (0.4 and 0.86%, respectively; Fig. 4.7). The same trend is observed in mud turbidites. Slope turbidites contain 1.8% organic carbon on average whereas those of the NAMOC levees (Hesse and Rakofsky, 1992) contain 0.8%.

Heinrich layers and turbidites have higher organic-carbon values compared to interbedded hemipelagic sediments (Figs. 4.7, 4.9). The organic-carbon content of HL shows the same proximal to distal trend (with respect to the Hudson Strait) as for the other facies. In the slope region, the organic-carbon content of HL-2, for example, is higher than on the rise and the basin centre (Fig. 4.10; see discussion in Ch. 5). The high inorganic carbon (i.e. carbonate-carbon) content is observed in HL-2 in all cores (Fig. 4.10).

According to "rock-eval" analyses more than 2/3 of the samples contain immature organic matter (Fig. 4.11B). More than 90% of the samples from core 90-26 have high oxygen indices (average OI of 470.3), low hydrogen indices (average HI of 103.4) and low S₂/S₃ ratios (average of 0.33), characteristic of type III kerogen, i.e. kerogen formed from land-derived organic matter (cf. fig. 3 of Tissot et al. 1982; see Appendix 7 for

Fig. 4.11. A) Classification of organic matter based on the hydrogen index (HI) versus oxygen index (OI) for core 90-26. Most samples are type III-kerogen. Note higher oxygen indices and lower hydrogen indices for the ice-rafted sediments (facies HI and N) indicating a higher proportion of land-derived organic matter (boundaries from Tissot et al., 1980). B) HI versus $T_{\max}$ diagram. Most samples are in the immature zone (see Kalkreuth and Macauley, 1989).

Facies symbols: N, nepheloid-layer deposit; HI and H, hemipelagic sediment with and without IRD; T, muddy spill-over turbidite; D, debris-flow deposit; C, contourite.



details). The oil potential of this type of material, if buried deep enough, is low (i.e. $S1+S2=0.24$; see also Peters, 1986). The $S2/S3$ parameter gives an overall estimate for the oil-generating potential of a source rock (see Appendix 7). Sediments with little IRD (i.e. hemipelagic sediment of facies H) have lower oxygen indices (average of 316.8) compared to facies with abundant IRD (i.e. facies HI and N: average of 521.2 and 666.3, respectively; Fig. 4.11A), indicating a higher proportion of land-derived (i.e. oxidized) organic matter in ice-rafted layers. This may be plant material, from interglacial times picked up by the ice and transported by icebergs to the sea.

4.3.3. Chemical and mineralogical composition of ice-rafted ash

Ash horizons are important stratigraphic markers in marine Quaternary sediments. Two major ash horizons (i.e. ash zones I and II, abbreviated as AZ-I, II), dated 9.8-11.1 ka and 55-65 ka, respectively, were recognized in Quaternary pelagic sediments of the North Atlantic (Ruddiman and Glover, 1972, 1975; Lacasse et al., 1996). Goals of this part of the study were: (1) to recognize and correlate the two major ash horizons, and (2) to identify possible additional ash horizons not recognized before in the study area. The investigation is based on geochemical, mineralogical and morphological characteristics of ash fragments. Geochemical analyses were performed with an energy dispersing system (EDS) combined with an SEM (for analytical results see Appendix 8).

The ash fragments occur mainly in hemipelagic sediments (facies H and HI). They are dispersed throughout the sediment (<1000 ash grains/g or $<5\%$ of the sand fraction) or form discrete ash layers (up to 10000 ash grains/g or 50% of the sand fraction; Fig.

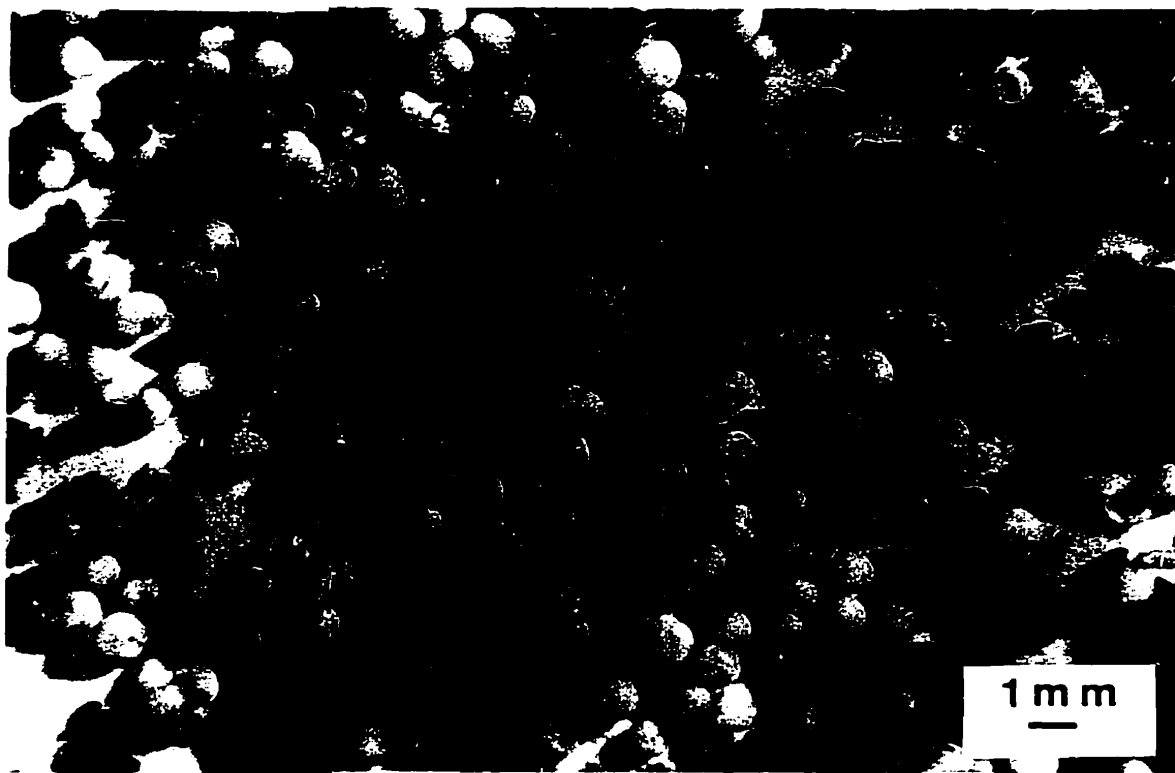
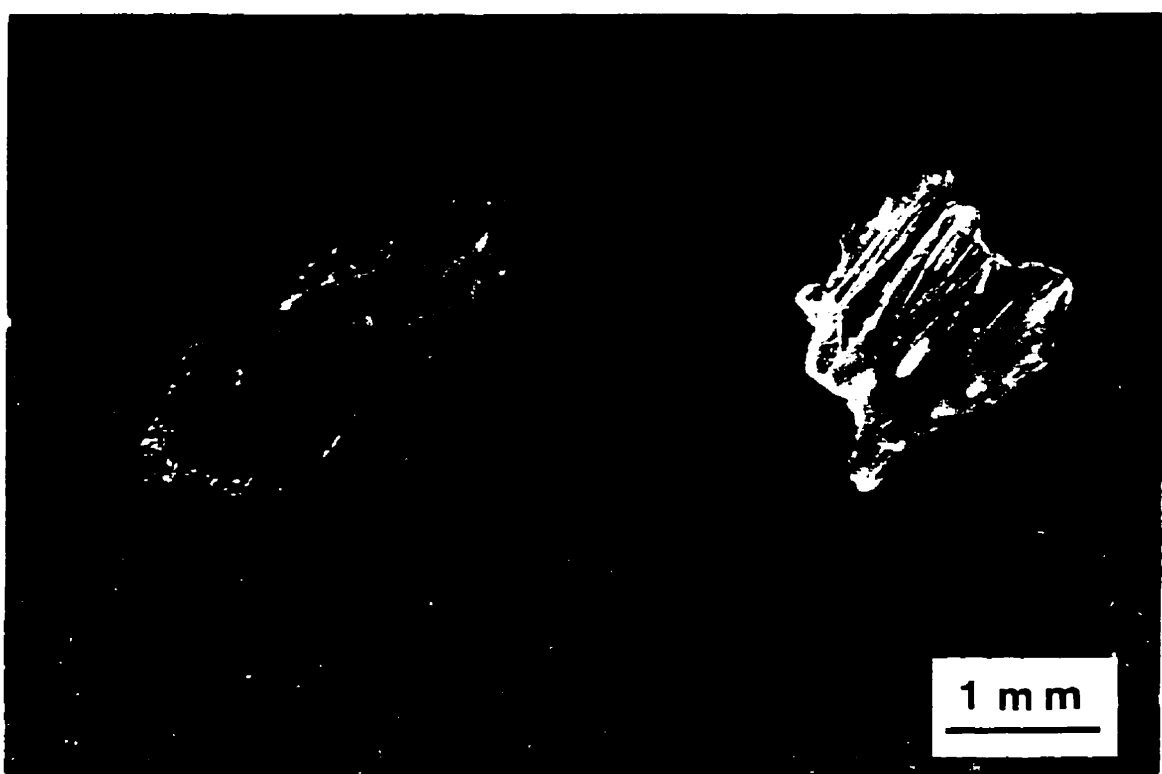


Fig. 4.12. Photomicrograph of the coarse fraction ($>125\ \mu\text{m}$) of an ash layer with abundant black to dark brown vesicular basaltic ash fragments. White: tests of planktonic foraminifera *N. pachyderma* (core 90-26, 404 cm).

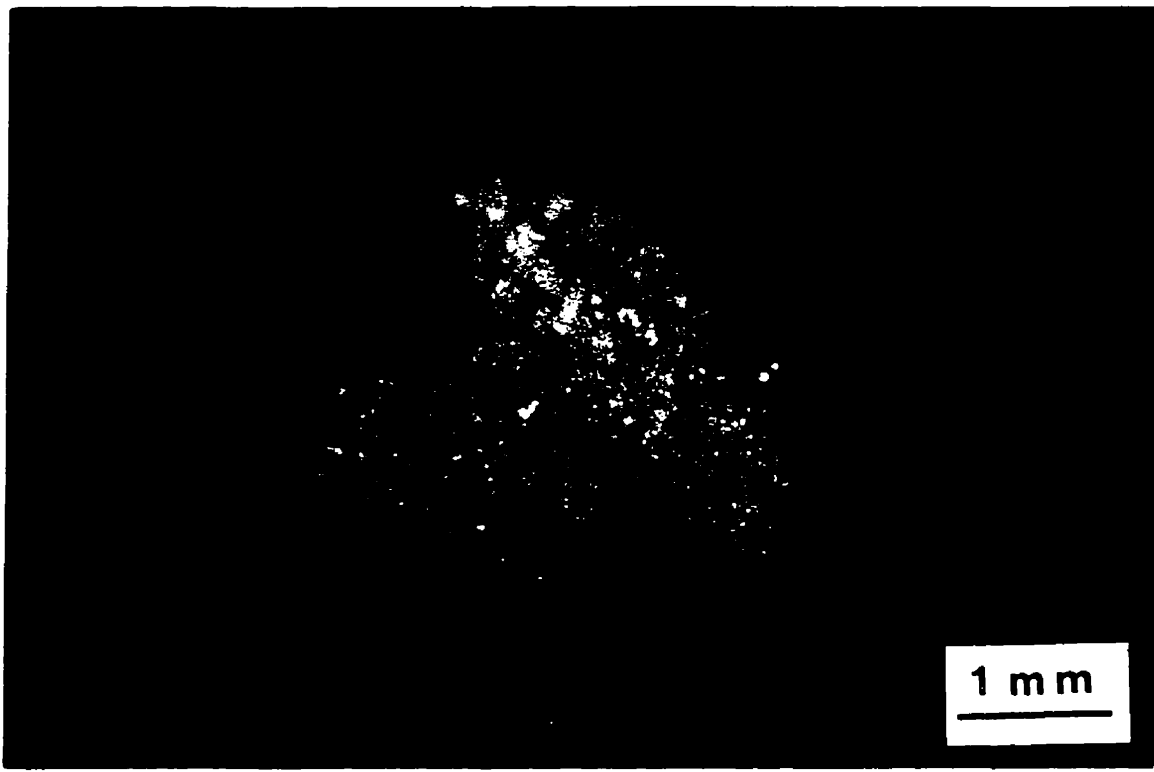
Fig. 4.13. Photomicrograph of volcanic ash types:

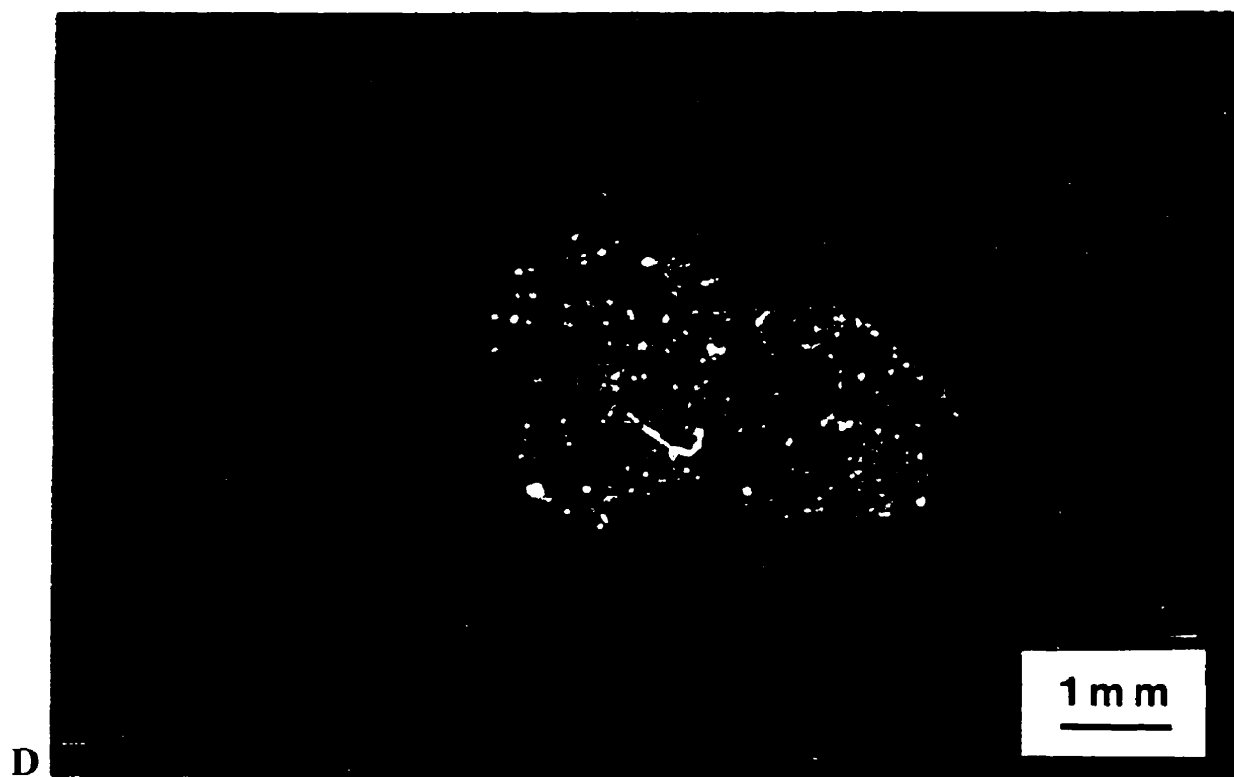
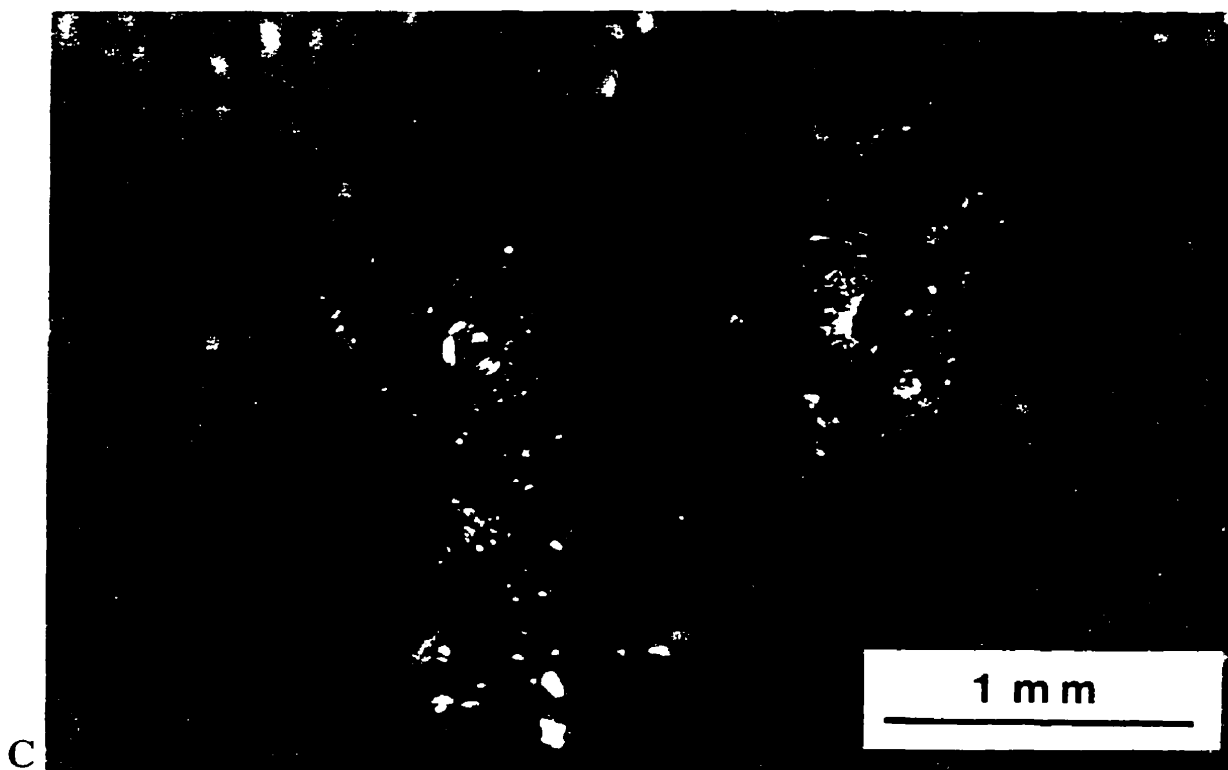
A) platy rhyolitic shards (core 84-8, 62 cm); B) vesicular rhyolitic shard (core 87-7, 260 cm); C) blocky basaltic shards (core 87-7, 261 cm); and D) vesicular basaltic shards (core 87-7, 261 cm).

A



B





4.12). Some grains are as large as 3 mm in diameter. On the basis of chemical composition, two groups of ashes have been recognized: 1- basaltic-ultrabasic group consisting of light brown to black grains; 2- rhyolitic group consisting of clear and colourless shards (Fig. 4.13).

The major-element composition of the two groups is shown in Table 4.3. The rhyolitic ash grains are rich in SiO_2 and K_2O (64.3 and 6.2%, respectively); the basaltic-ultrabasic ash shards have high FeO and CaO (24.1 and 13.1%, respectively) and low SiO_2 (38.9%) contents. The basaltic shards are blocky in shape and have a vesicular fabric (Figs. 4.13c, d). The colourless grains form platy and bubble-wall shards (Fig. 4.13a and b).

4.3.3.1. Distribution of ash layers

Six ash horizons (including AZ-I) were recognized (Fig. 4.14). Excluding AZ-I, the other 5 ash layers (Ash Layers 1 to 5) are correlated for the first time in the northwestern Labrador Sea. For brevity they are called AL-1 to -5. Their possible equivalents in the North Atlantic and Labrador Sea are shown in Table 4.5.

AZ-I occurs in the uppermost 60 cm of some cores. It is recognized in most North Atlantic and Labrador-Sea cores (Table 4.5). Two AMS dates near the bottom of AZ-I gave ages of 9719 and 9450 years BP, respectively (cores 84-8, 9, Fig. 4.14). AZ-I is about 30 cm thick and consists of both rhyolitic (up to 75%) and basaltic shards.

AL-1 to 4 consist mainly of basaltic shards. AL-1 varies in thickness between 7 to 47 cm and occurs below HL-1. Two radiocarbon ages on top of AL-1 are 14580 and

Table 4.3. Chemical composition of ash fragments.

Ash type	Chemical composition								n
	%Na ₂ O	%MgO	%Al ₂ O ₃	%SiO ₂	%K ₂ O	%CaO	%TiO ₂	%FeO	
rhyolitic	1.11	0.02	8.73	64.34	6.15	2.70	0.46	8.52	35
basaltic	0.92	1.65	7.87	38.87	1.09	13.12	4.52	24.10	51

Table 4.4. A) Mineralogical composition of major (>95%) constituents of massive sands and ice-rafted debris of facies H1 and N.

Facies	Locality	Quartz	Microcline	Orthoclase	Plagioclase	Hornblende	Pyroxene	Ash	Epidt	Rock fragments					n
										Carbonate	Granite	Anorthosite	Gabbro	Basalt	
MS	braidplain	40.3	4.0	13.4	5.9	3.0	1.7	2.4	0.3	4.2	12.8	1.0	1.1	3.3	11
MS	W. floodplain	38.8	0.5	12.3	8.7	3.7	1.2	0.0	0.0	13.6	12.2	0.5	2.6	1.7	2
H1	NAMOC levee	24.6	1.2	7.3	7.7	2.2	0.6	3.2	0.6	4.0	15.1	2.1	2.5	26.0	4
H1	Greenland Slope	53.8	6.0	5.2	4.6	1.1	2.9	2.4	1.7	2.6	7.3	0.3	0.4	8.7	3
N	slope	51.9	1.6	4.0	4.2	3.0	4.4	0.0	3.2	22.0	3.5	0.0	0.1	0.0	4

B) Chemical composition of feldspars in the braidplain massive sands.

Mineral	%SiO ₂	%Al ₂ O ₃	%FeO	%MgO	%CaO	%Na ₂ O	%K ₂ O	%BaO	%Orthoclase	%Albite	%Anorthite	n
Sanidine	65.2	15.8	0.3	0.0	0.8	1.1	16.2	0.4	87.4	8.9	3.8	22
Plagioclase	65.9	20.2	0.9	0.2	4.9	7.4	0.2	0.1	11.3	66.0	20.7	19

C) Chemical composition of feldspars in Greenlandian-Slope sediments.

Mineral	%SiO ₂	%Al ₂ O ₃	%CaO	%Na ₂ O	%K ₂ O	%Orthoclase	%Albite	%Anorthite	n
Sanidine	62.3	13.0	0.1	0.4	24.1	98.4	1.3	0.3	15
Plagioclase	65.1	18.9	13.3	2.3	0.3	4.1	34.4	61.5	11

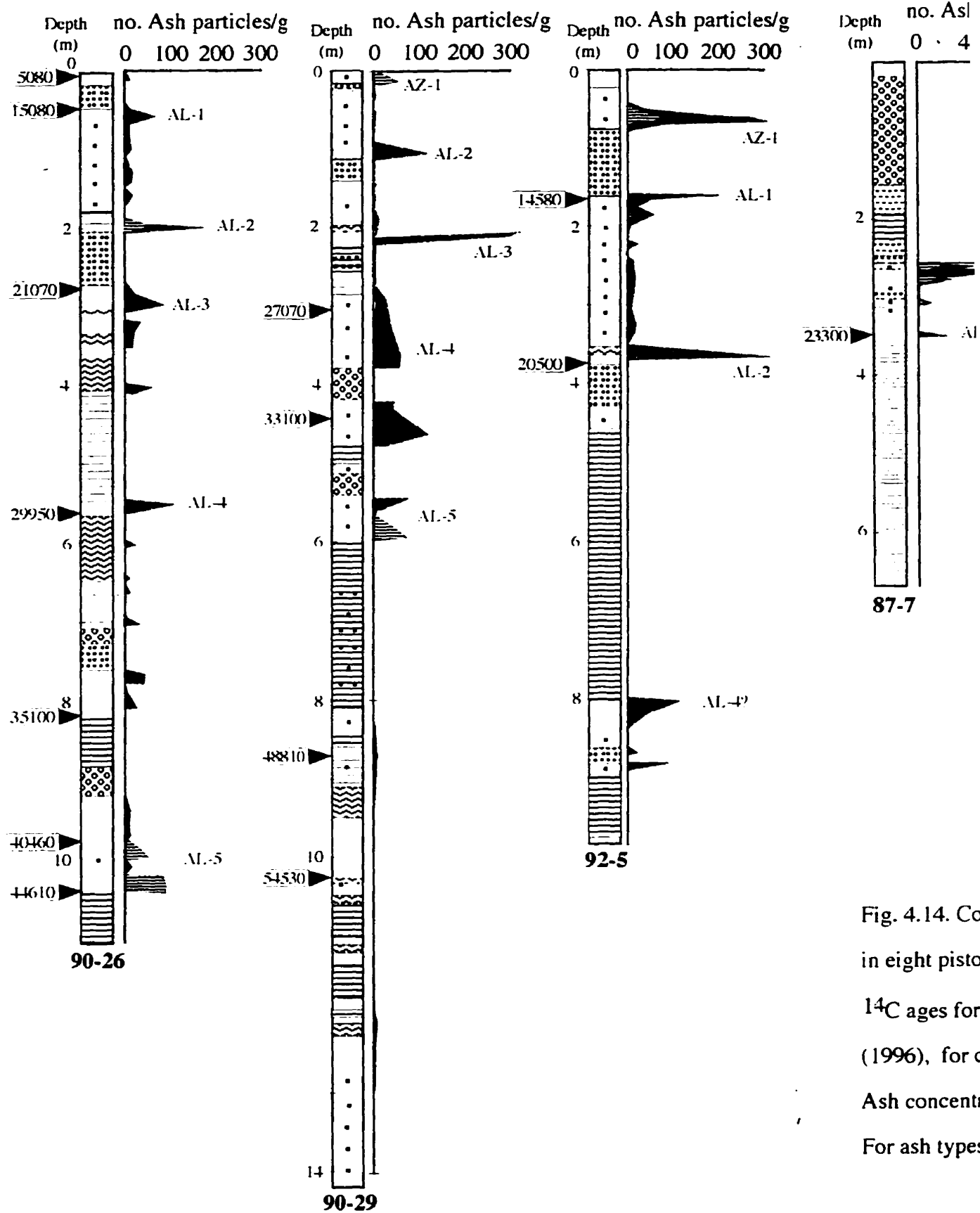


Fig. 4.14. Correlation of eight piston cores based on ^{14}C ages for core 90-26 (1996), for core 90-29 (1996), for core 92-5 (1996), for core 87-7 (1996). Ash concentrations are given in g/g. For ash types: AL-1, AL-2, AL-3, AL-4, AL-5.

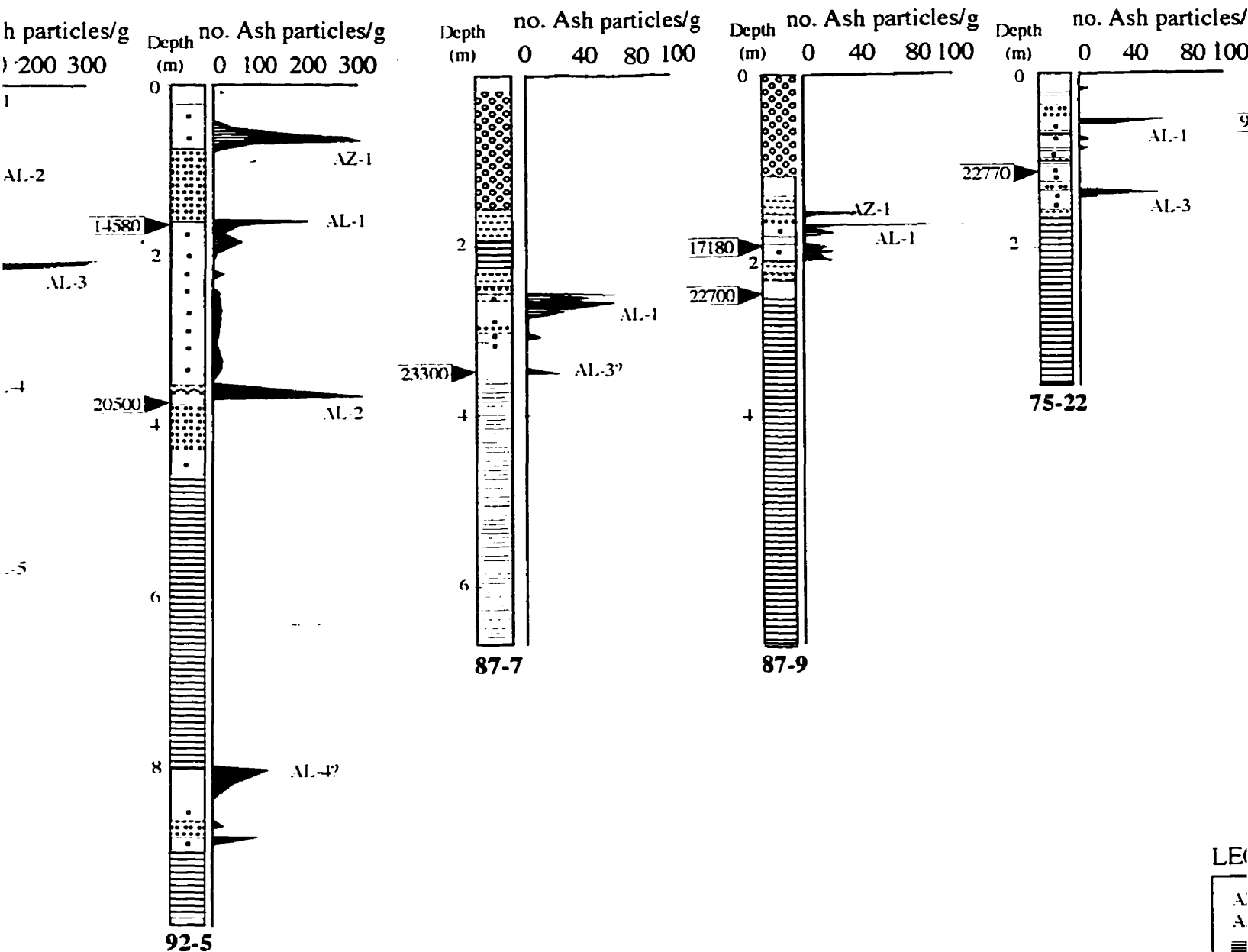
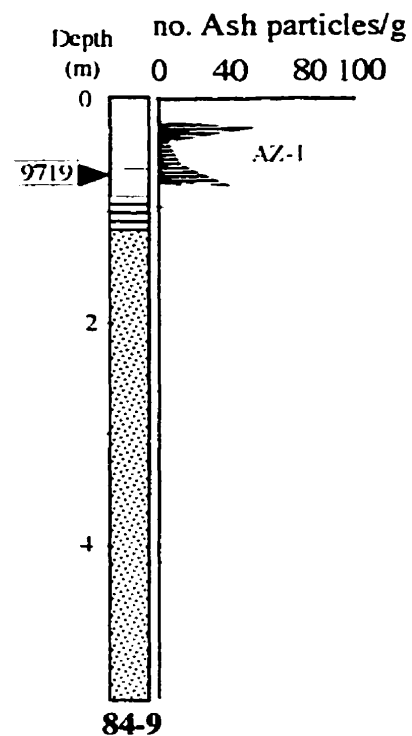
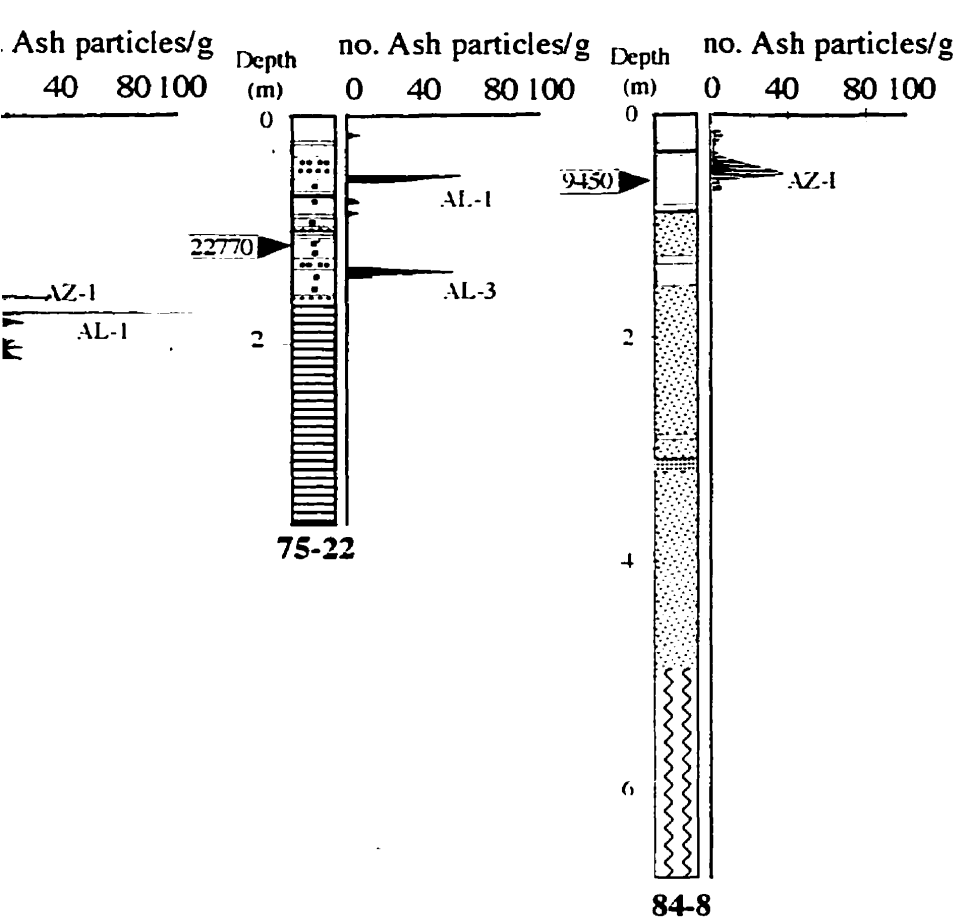


Fig. 4.14. Correlation of Ash zone I and ash layers 1 to 5 in eight piston cores from the Labrador Sea.

^{14}C ages for cores 90-26, 90-29 from Wang and Hesse (1996), for cores 87-7, 9 partly from Hesse (1995a).

Ash concentration for core 75-22 from Chough (1978).

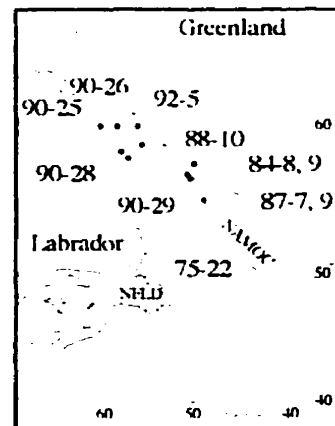
For ash types see section 4.3.3.



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AZ-I, II The North Atlantic Ash zone I, II
AL-1, 2... Ash layers 1 to 5

- Ash types (rhyolitic basaltic)
- AMS ¹⁴C ages
- Hemipelagic sediment
- Ice-rafted debris
- Homogenous mud turbidite
- Parallel-laminated mud turbidite
- Massive sand
- Parallel-laminated sand
- Contourite
- Heinrich layer
- Debris-flow deposit
- Coring disturbance



15080 years BP, respectively (cores 90-26 and 92-5, Fig. 4.14).

AL-2 is about 20 cm thick and occurs on top of HL-2. It contains the highest ash contents (>300 ash/g) of all layers. A radiocarbon date at the bottom of this layer gave an age of 20500 years BP (core 92-5, Fig. 4.14).

AL-3 is between 7 to 30 cm thick and occurs below HL-3. AL-4 is observed in a single core (90-26). It is 20 cm thick with a bottom age of 29950 years BP (core 90-26,

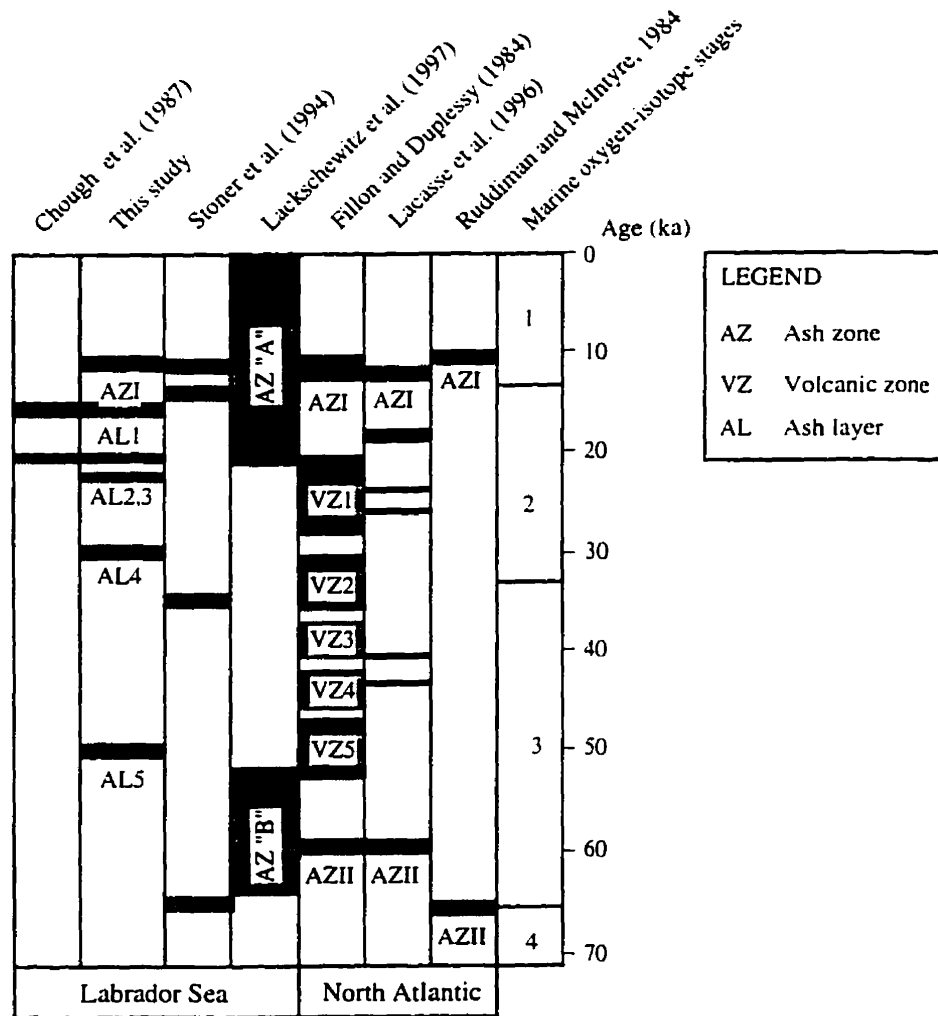


Table. 4.5. Correlation of ash horizons (gray horizontal lines) in the North Atlantic region and the Labrador Sea. Isotopic stages and radiocarbon ages are from Fulton (1987). The dark horizontal line in Lacasse et al. (1996) data are basaltic turbidites.

Fig. 4.14). AL-5 is 50-60 cm thick and consists of rhyolitic (up to 95%) and basaltic shards. Two radiocarbon dates at the top and bottom of AL-5 gave ages of 40460 and 44610 years BP, respectively. AL-4 and AL-5 were not recovered in the NAMOC levee and braidplain cores probably because they were buried under a thick turbidite sequence and massive sand.

4.4. Mineralogical analysis

4.4.1. Massive sands (MS)

Mineralogy and chemistry of sand grains are used as petrographic tracers to document the provenance of specific sedimentary facies (see also discussion in Ch. 6). Six cores from the braidplain (84-8, 9, 16 and 17) and the floodplain west of NAMOC (84-11 and 14) were analyzed for mineralogical composition and found to be very similar. Generally, they are rich in quartz (40.3 and 38.8%, respectively) and feldspar (23.3 and 24.5%, respectively) and contain about 5% of mafic minerals. Among the feldspars, orthoclase is dominant (13.4 and 12.3%, respectively; Table 4.4). Among the rock fragments, granitic fragments make up more than 12%. Detrital carbonates average 9.3% in the eastern braidplain and 12.8% in the western floodplain, respectively (Table 4.6); basaltic rock fragments comprise 1.7 to 3.3%; anorthosite rock fragments 0.5-1%. Basaltic ash fragments are minor constituents of the braidplain massive sands (average 2.3%). A single sample (core 84-8, 311 cm) contained 25% ash fragments.

Anorthositic plagioclase grains are important petrographic tracers in Labrador Sea sediments (Windley, 1969; Chough et al., 1987). The major-element composition of

Table 4.6. Concentration of detrital carbonates in the braidplain and the western floodplain massive sands.

A: braidplain

Core	Depth (cm)	%Detrital carbonate	n
84-7	333	1.7	176
"	545	7.8	141
"	730	17.4	138
84-8	100	1.2	84
"	162	1.9	108
"	350	0.7	149
"	450	1.1	92
"	490	10.6	104
84-9	128	2.1	94
"	180	3.5	141
"	370	1.8	167
84-16	110	25.0	78
"	163	23.8	122
"	280	31.2	125
Average		9.3	

B: the western floodplain

Core	Depth (cm)	%Detrital carbonate	n
84-11	438	4.9	227
84-14	105	19.4	124
"	205	13.7	124
"	295	12.7	134
"	322	21.4	103
"	405	15.0	138
"	570	13.7	131
"	650	14.63	123
"	690	16.43	140
"	750	3.1	129
"	780	5.8	68
Average		12.8	

feldspars in the eastern braidplain and the western floodplain massive sands is shown in Table 4.4. The plagioclase of the braidplain has low to moderate anorthite contents (An_{1-69}), characteristic of a Canadian source. Plagioclase grains with high anorthite values (An_{80-90}), characteristic of Greenlandian anorthosites (Windley, 1969), were not found (Fig. 4.15). The mineralogic composition of plagioclase in the cores studied ranges from albite to labradorite. Their average orthoclase, albite and anorthite content are 1.1% Or, 72.7% Ab and 26.2% An, respectively. The average orthoclase, albite and anorthite contents of the K-spars are 87.4% Or, 8.9% Ab and 3.8% An, respectively. Compared to the braidplain sands, sediments from the Greenland Slope (core 88-7) have higher anorthite contents (An_{15-100})(Fig. 4.15). Their average orthoclase, albite and anorthite contents are 4.1% Or, 34.4% Ab and 61.5% An, respectively. K-spars from the

Greenland-Slope have orthoclase, albite and anorthite contents of 98.4% Or, 1.3% Ab and 0.3% An, respectively.

4.4.2. Ice-rafted debris

Ice-rafted debris (IRD) are found in distinct stratigraphic horizons (Heinrich layers) or dispersed through up to 3m thick sediment layers (see Ch.6 for details). They are characterized by abundant coarse-grained ($>125\mu\text{m}$) components. The mineralogical composition of IRD was examined in nepheloid-layer deposits (facies N) and ice-rafted hemipelagic sediments (facies HI).

IRD in facies N are characterized by abundant detrital carbonate (average of 22%; Fig. 4.16). They are also rich in quartz (average of 52%). The total feldspar content is 9.8% and dominated by orthoclase and plagioclase (average of 4.0 and 4.2%, respectively). Pyroxene and hornblende make up 4.4 and 3.0%, respectively. Granitic rock fragments comprise 3.5% of the coarse fraction. No basaltic ash or rock fragments were observed.

IRD in facies HI are characterized by abundant granitic and basaltic rock fragments (average of 15.1 and 26%, respectively), and an average 24.6% quartz. The total feldspar content of facies HI is higher (average of 16.2%) compared to facies N (average of 9.8%), but the detrital carbonate content is lower (average of 4% compared to 22%, respectively). Among the feldspars, orthoclase and plagioclase are dominant (average of 7.3 and 7.7%, respectively). Basaltic ash fragments comprise 3.2%.

IRD in the Greenlandian-Slope sediments are rich in quartz (average of 53.8%);

basaltic and granitic rock fragments are dominant (average of 8.7% and 7.3%, respectively); detrital carbonates are low (2.6%, Table 4.4). They have almost equal amounts of different types of feldspars (4.6-6%, Table 4.4).

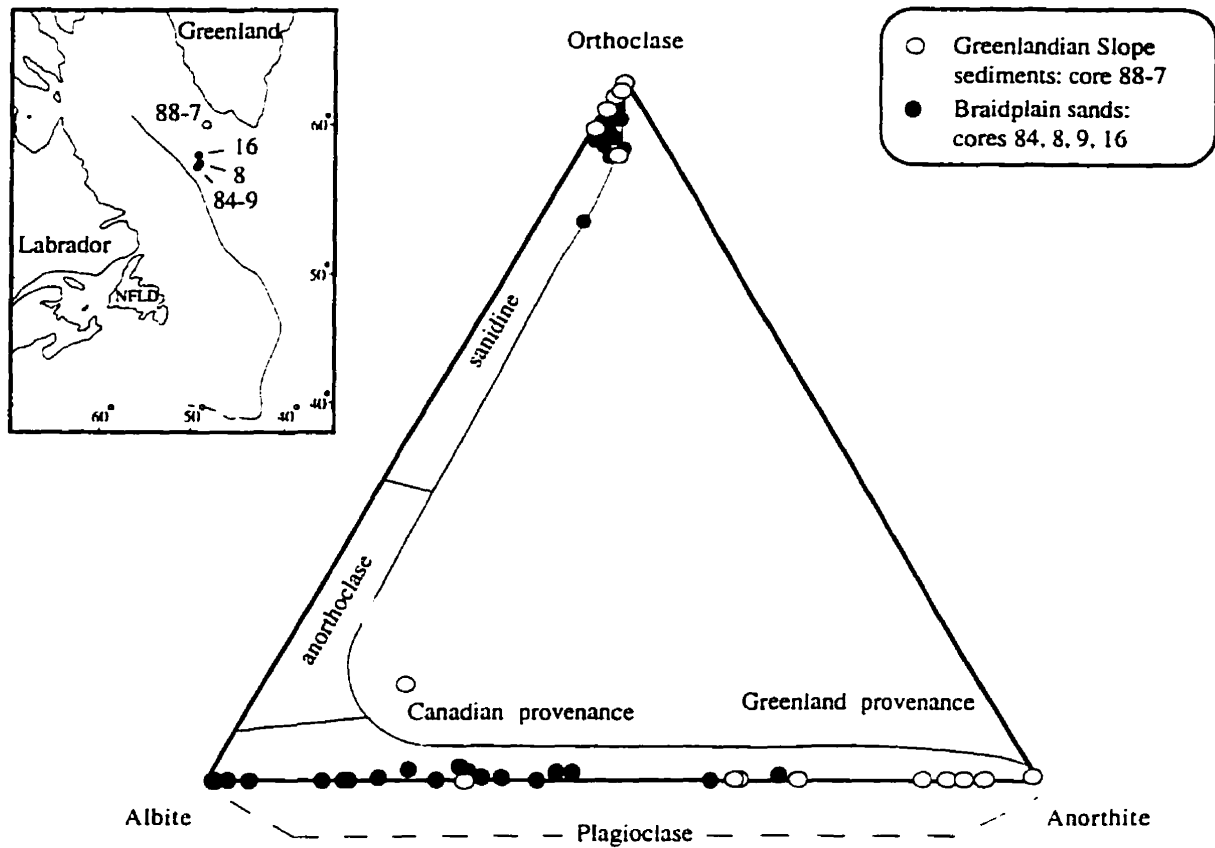
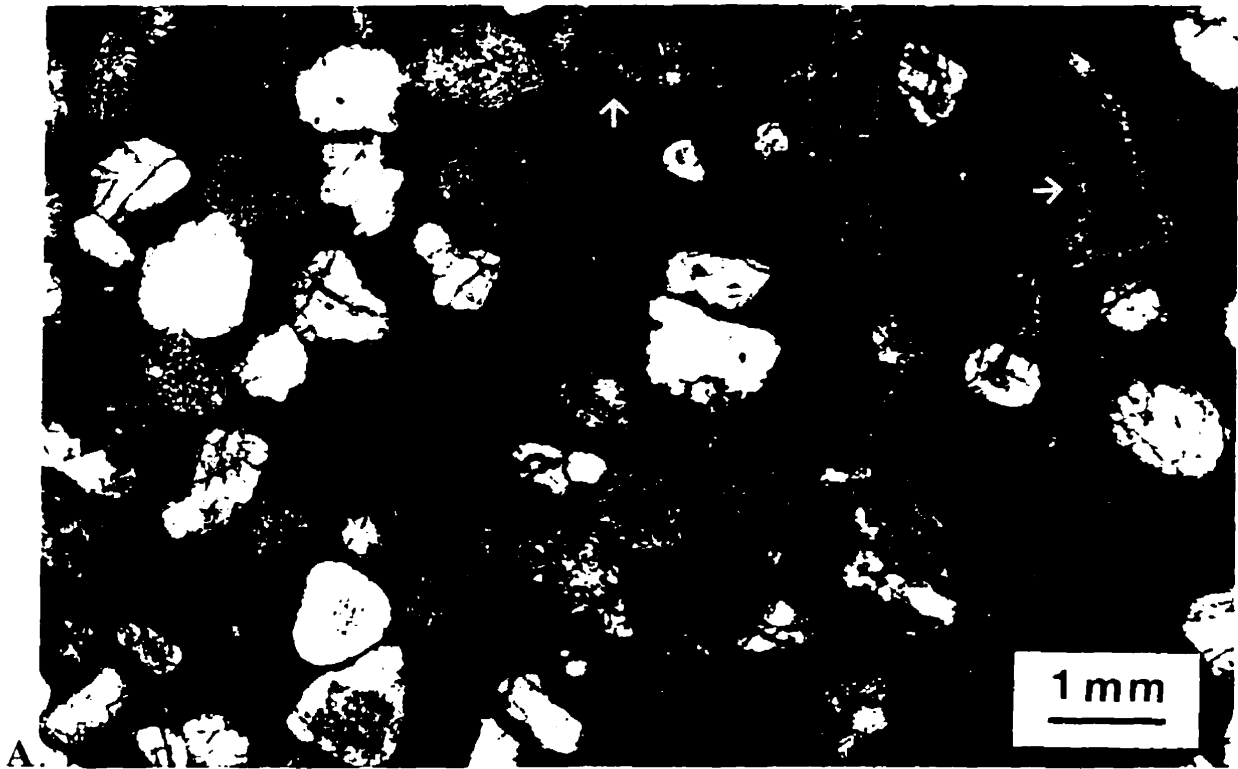


Fig. 4.15. Ternary diagram showing mineralogical composition of feldspars in braidplain massive sands and Greenland Slope sediments. Note: more than 90% of plagioclase in the braidplain massive sands have low to intermediate anorthite contents (average An=20.7%, ranging from 1-42%), implying a Canadian source. Plagioclase of the Greenland Slope have intermediate to high anorthite contents (average An=61.5%, ranging from 16-100%).

Fig. 4.16. A) Photomicrograph of the coarse fraction ($>125\ \mu\text{m}$) of Heinrich Layer-2 (core 87-9, subsurface depth 232 cm). Note abundant brownish detrital carbonate (arrows) with micritic texture and better roundness than the siliciclastic grains. B) Photomicrograph of the coarse fraction ($>125\ \mu\text{m}$) of massive sands (core 84-16, subsurface depth 100 cm). Detrital carbonates (arrows), similar to those of Heinrich layers, are abundant. A) and B) crossed nicols.



CHAPTER 5: Sedimentary processes

In high latitudes, deep-sea sedimentation may be controlled by the influence of neighboring continental ice sheets. Large volumes of terrigenous materials are supplied by glaciers to continental margin and ultimately end up in the deep sea. Two main types of sediment-delivery mechanisms operated in the ice-marginal environment on the Pleistocene Labrador Shelf, Slope and Rise (see Fig. 5.1 and Table 5.1): (1) *Primary delivery mechanisms*, whose deposits are not modified by other processes, including turbid-surface plumes, nepheloid flows, hemipelagic sedimentation, ice rafting and primary turbidity currents. (2) *Secondary delivery mechanisms*, which involve the remobilization and resedimentation of previously deposited materials, including slumps, debris flows, turbidity currents and contour currents.

5.1. Primary delivery mechanisms

5.1.1. Turbid-surface plumes (TSP)

Previous studies of plumites were focused on modern fjords and glacial lakes, until Hesse and Klaucke (1995) called attention to their significance in glaciomarine continental slope environments. Little is known about the characteristics of the deposits of turbid-surface plumes and their distribution in open marine environments. Typical plumites have been observed in a 12 m piston core (92-1) south of the Hopedale Saddle (about 700 km south of Hudson Strait). The AMS ^{14}C ages discussed in Ch. 4 indicate that the TSP layers were deposited during glacial times (marine oxygen-isotope stage 2). Similar to other occurrences of modern plumites that have been described in the literature

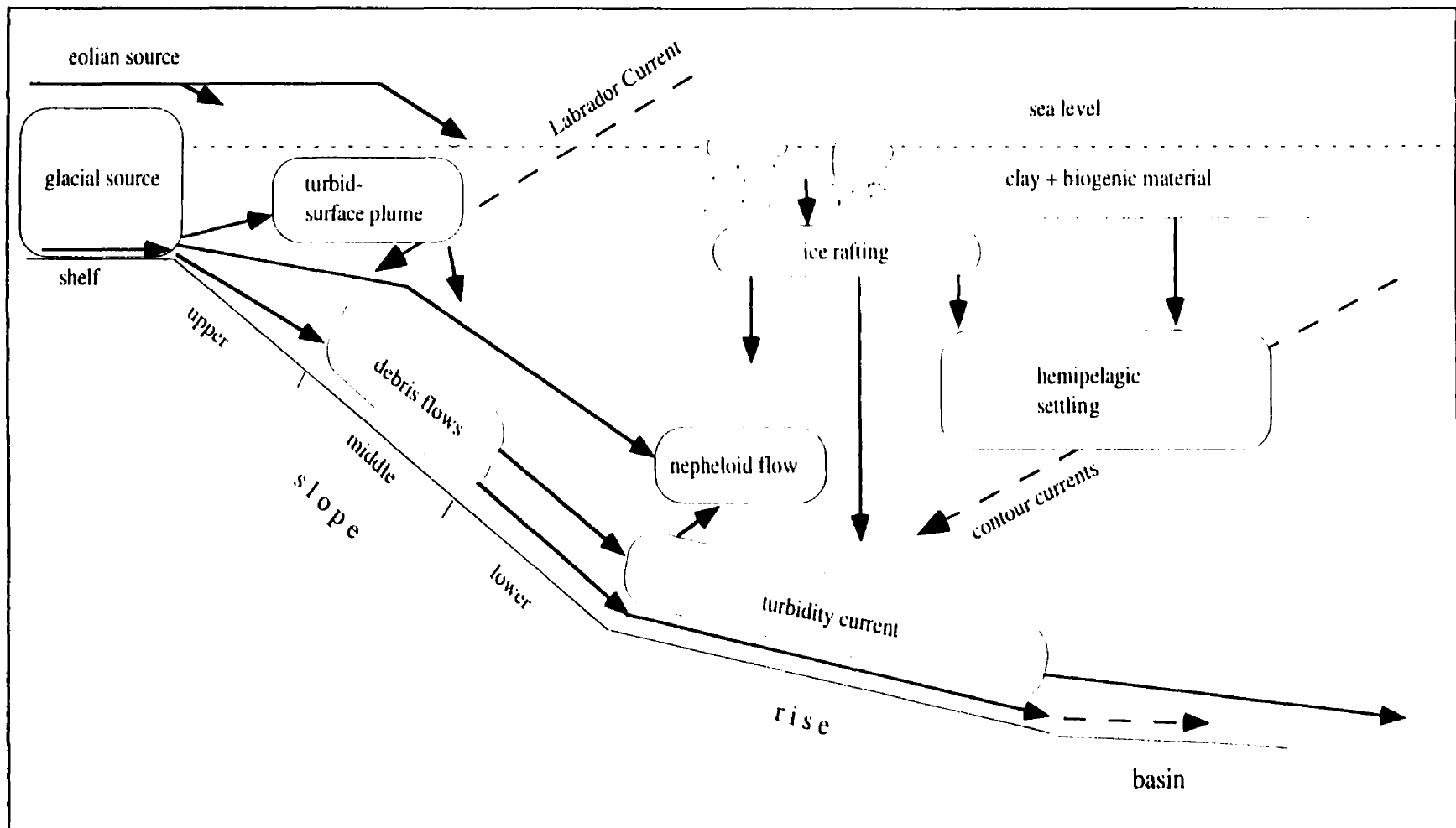


Fig 5.1. Schematic diagram of depositional processes on the Labrador Slope, Rise and in the basin centre.

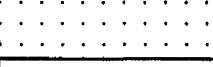
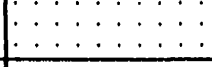
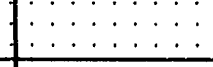
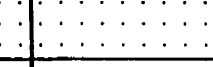
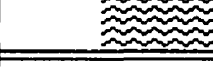
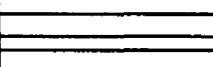
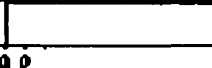
Facies	Depositional mechanism	Slope	Rise	Western floodplain	NAMOC	Braidplain
P	Turbid-surface plume					
H	Hemipelagic sedimentation					
HI, NI, TI	Ice rafting					
N	Nepheloid layer					
C	Contour current					
T	Muddy -turbidity current					
MS	Sandy -turbidity current		? ? ?			
D1						
D3	Thin-bedded debris-flow					
D4	Sandy-gravelly debris flow					

Table 5.1. Distribution of depositional facies in physiographic provinces of the Labrador Sea.

(e.g., Hein and Syvitski, 1992; Stewart, 1991), the Labrador Sea plumites are characterized by couplets of alternating centimeter-thick fine sandy silt and clayey silt layers (Table 5.3). As described in Chapters 3 and 4, the fine sandy silt layers have lower foram and organic carbon contents, compared to the clayey silt layers (Table 3.4, Fig. 4.7). The variation in organic carbon appears to be controlled by sediment texture. The finer the sediment, the higher the organic carbon content. The lower foram content of the fine sandy silt layers is probably due to dilution by detrital material. High sedimentation rates (approximately 100 cm/ka) prevented intense bioturbation. The absence of current-induced structures implies passive settling with subordinate influence of bottom currents in the final depositional stage.

Unlike glacial-lake varves, the plumite couplets do not appear to reflect annual rhythms. On average, 34 couplets (total thickness of approximately 100 cm) were counted per 10^3 years. The plumite grain-size variation is associated with a small O-isotopic change ($<0.2\text{‰}$, corresponding to a standard deviation of 0.08; Ch. 4). Both meltwater influx and temperature variations are controlling factors of O-isotope composition of seawater (e.g. Andrews et al., 1991; Bond et al., 1992). If the isotopic composition of the plumite couplets reflects variation in meltwater discharge, the fine sandy silt layers, which may be deposited during higher meltwater discharges (Khodabakhsh and Hesse, 1996b), should show lighter O-isotope composition. However, most fine sandy silt layers have heavier O-isotope ratios, compared to clayey silt layers (see Fig. 4.3).

The plumite oxygen-isotope variation might reflect variations in seawater temperature which may be associated with short-term glacial advance and retreat phases.

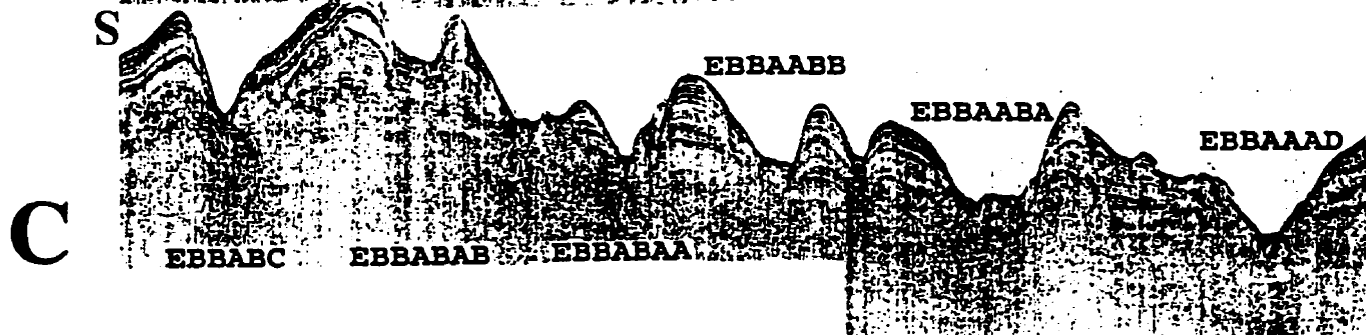
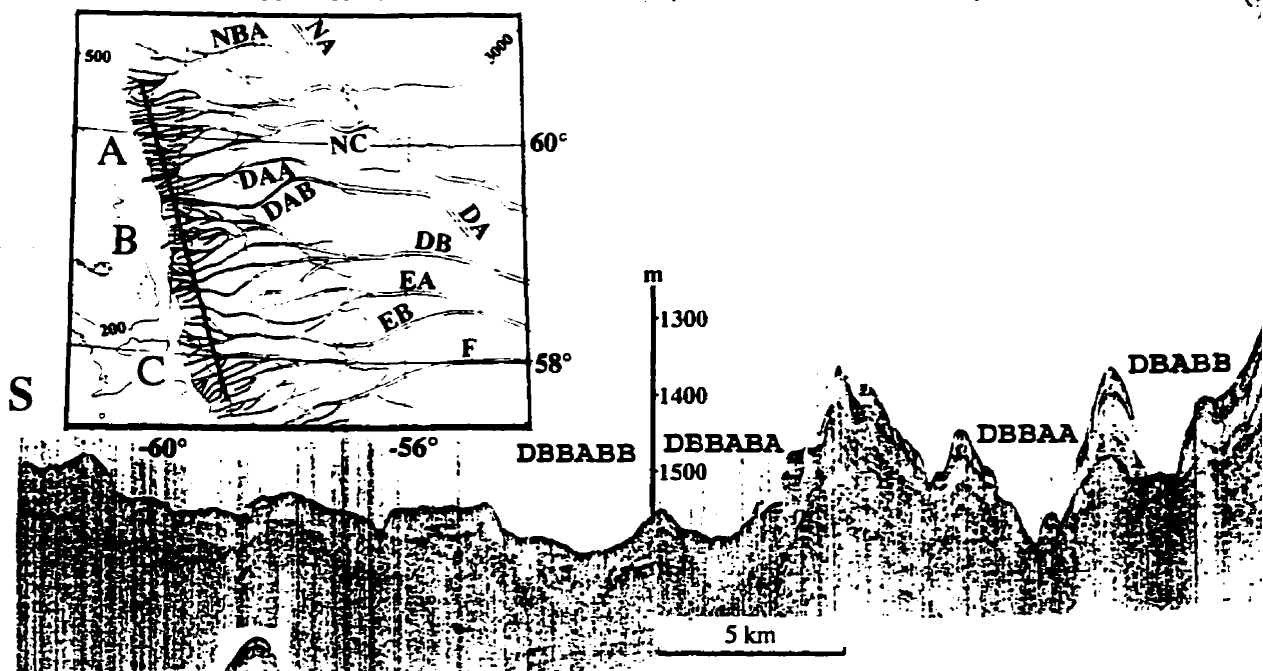
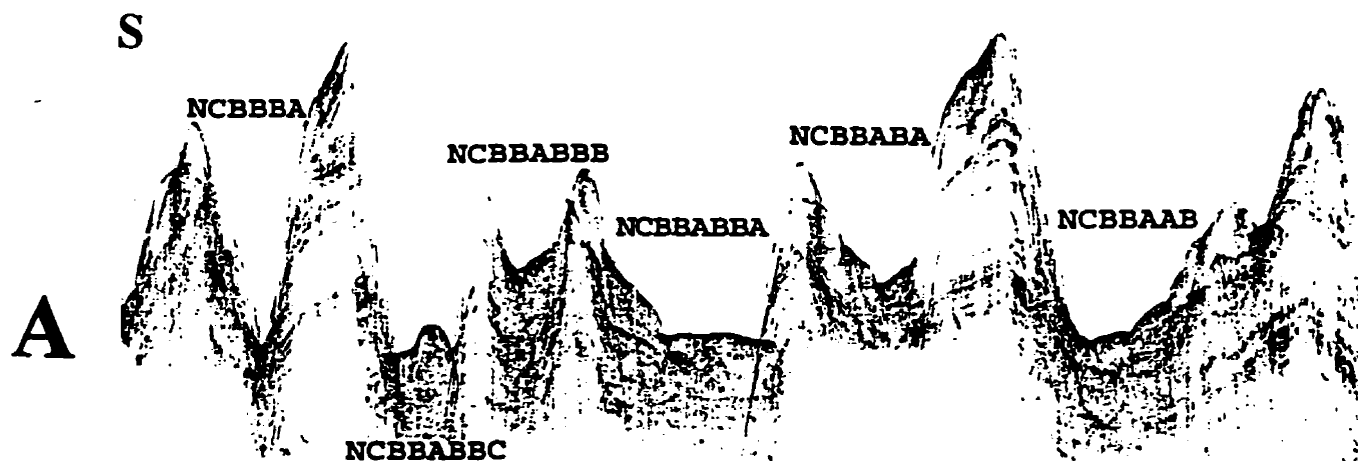
Table 5.2. Concentrations of suspended sediment of density 2.70 g/ml necessary to overcome the density difference between meltwater and seawater (from Syvitski et al. 1987; Mulder and Syvitski, 1995).

Salinity	Density of seawater (g/ml)	Seawater temperature	Sediment concentration (g/l)
10	1.008	3° C	12.7
15	1.012	3° C	19.1
20	1.016	3° C	25.4
25	1.02	3° C	31.8
30	1.024	3° C	38.1
35	1.026	3° C	41.6
35	1.027	13° C	42.74
34	1.027	1° C	43.49

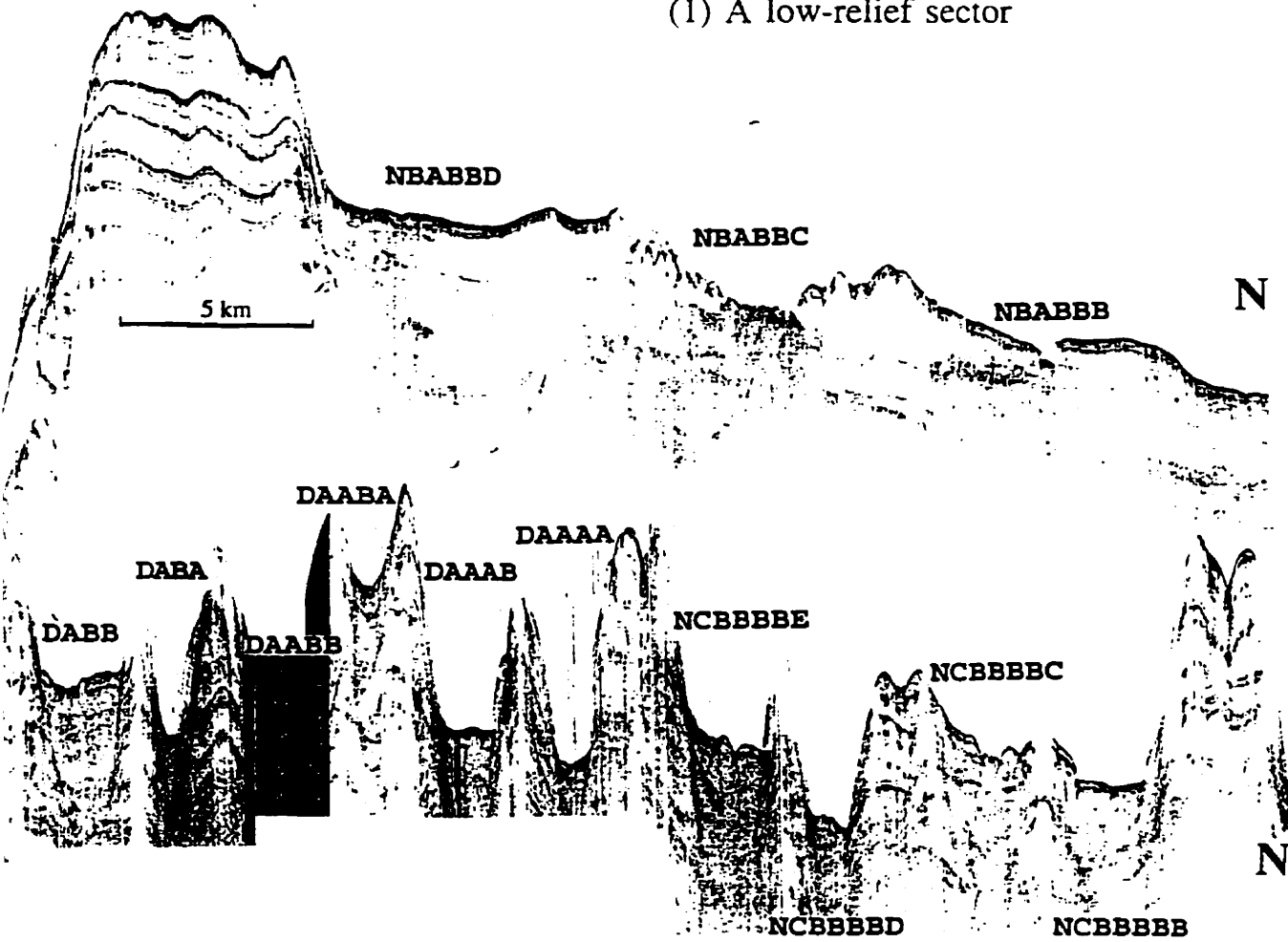
Table 5.3. Comparison between plumites.

Sediment texture	Sedimentary structure	Locality	Reference
couplets of sandy silt and silty clay	diffuse parallel lamination, fining upward (graded bedding)	upper Labrador Slope	this study
couplets of coarse and fine silty mud		a Gilbert-type delta, western Norway	Nemec (1995)
couplets of sand and mud	parallel lamination	Itirbilung Fjord, Baffin Island	Hein and Syvitski, 1992 (Facies D)
couplets of sand and silty clay	parallel lamination	tidewater glaciers, Canadian High Arctic	Stewart (1991)
silty mud	parallel lamination, silt interbeds	Axel Heiberg Shelf, Canadian polar continental margin	Hein et al. (1990) (Facies H)
couplets of fine sand to silt and mud	parallel lamination	McBride Glacier, Alaska, USA; Hector Lake, Alberta	Cowan and Powell, 1990
sandy mud	parallel lamination, fining-upward	Labrador Shelf	Josenhans et al. (1986) (Qeovik Silt Unit)
couplets of sand-silt and silt-clay	fining-upward	glacial lakes	Smith and Ashley, 1985
couplets of silt and mud	parallel lamination and fining-upward	Makkovik Bay, Labrador	Barrie and Piper (1982) (Facies D2)

Fig. 5.2. N-S seismic profile along the upper Labrador Slope (see insert map for location). A high-relief sector (with >500 m deep canyons), on the south side of outer Hudson Strait, occurs adjacent to a low-relief sector. The high-relief sector, starting south of the seismically well stratified plateau-like ridge (PR), comprises the NC- and D-canyons with seismically transparent ridges that consist predominantly of plumites, hemipelagic sediments and ice-rafted debris (IRD). The higher amplitude reflections might represent IRD horizons. The high-relief sector has been produced by retrograde, headward canyon-erosion by mass-wasting processes (from Hesse and Klaucke, 1995). Note southward decrease in the thickness of the presumed plumite facies. The low-relief sector (south of canyon DBBABA) is a debris-flow slope off Okak Trough (c.f. Fig. 5.3).



(1) A low-relief sector



low-relief debris-flow sector



Therefore, during times of colder temperatures, which may correspond to glacial advance or ice-proximal conditions, the coarser layers (fine sandy silt layers) with heavier O-isotope ratios may have been deposited. During the following relatively warmer period (glacial-retreat phase or ice-distal condition), the overlying silty clay with slightly lighter O-isotope ratios might be deposited. On the basis of the number of plumite couplets/ka (see p. 121), it appears that the duration of these glacial-advance phases may only have been a few tens of years; however, this estimate remains speculative as it is beyond the resolution of AMS ^{14}C -dating.

5.1.2. Occurrence of Labrador Sea plumites

Plumites are present in the Labrador Sea and adjacent basins such as Baffin Bay and Davis Strait (Praeg et al., 1986; Andrews et al., 1990; 1994b). Along the Labrador Slope, plumites are found as seismically relatively transparent horizons with continuous, parallel low-amplitude reflections that are grouped into packages by a few higher-amplitude reflections (Fig. 5.2). They form high- to moderate-relief sectors on the slope, which are located preferentially south of the major outlets or off the southern half of outlets (Fig. 5.3). This asymmetry is due to the south-flowing Labrador Current which entrained the surface plumes at the glacier front. At the time of deposition, plumites initially formed a mud-blanket surface. Later retrograde, headward canyon-erosion by mass-wasting processes produced the present high-relief topography (Hesse and Klaucke, 1995; Khodabakhsh et al., 1995).

There is a pronounced lithologic difference between the Hudson Strait plumites

and those of smaller outlets to the south. While the Hudson Strait plumites are rich in detrital carbonates (page 84), plumites that originated from the smaller southern outlets are rich in silicate material derived from local igneous and metamorphic rocks. The plumites found adjacent to the Hopedale Saddle consist mainly of quartz (90%), feldspar and mica flakes (core 92-1, Appendix 9) indicating a local source in the Canadian Shield. The asymmetric distribution (with respect to ice outlets) of plumites on the upper Labrador Slope, which was caused by surface currents, indicates that during major parts of Late Pleistocene the sea-surface was not frozen in summer (Khodabakhsh et al., 1995).

A special feature of the Labrador-Sea plumites is their apparent large size inferred from seismic profiles. The maximum extent of known modern turbid surface plumes in glacial environments is about 10 km seaward from the ice-margin and up to 60-80 km downcurrent along the coast (Elverhoi, 1984; Pfirman and Solheim, 1989). On the Baffin Shelf, plumites (Unit 2a of Praeg et al., 1986) were found up to 80 km from the coast adjacent to the former ice outlets in relatively protected environments such as Frobisher Bay and Cumberland Sound. They are up to 70 m thick. In the Labrador margin, plumites extend from the outer shelf (the Qeovik Silt of Josenhans et al., 1986) to the upper slope. Plumites adjacent to the Hudson Strait have been tentatively traced on seismic profiles up to 200 km from their source off the Hudson Strait along the coast and 130 km perpendicular to the coast (Fig. 5.3). A southward decrease in the thickness of the seismically transparent horizon interpreted as plumites implies a gradual southward decrease in the sediment concentration of plumes (see Fig. 5.2). If plumites on the Labrador Slope south of the Hudson Strait are in fact as extensive as suggested by

seismic profiles, then three factors might have enhanced their greater seaward extent: (i) their mineralogical composition, (ii) the effects of surface currents and katabatic winds and (iii) the magnitude of the glacial-discharge system in the Hudson Strait.

As to the first point, detrital-carbonate (glacial-flour) rich suspended sediments, discharged to the sea by meltwater from the LIS through the Hudson Strait, could stay longer in suspension due to their lower surface electrical charges, compared to clays which flocculate upon contact with sea water. Therefore this material could be entrained by the south-flowing Labrador Current farther than clay-rich sediments (Khodabakhsh et al., 1995).

Concerning the second factor, during glacial times the Labrador Current was displaced seaward to the upper slope by the ice front compared to its present position. In this situation, fine detrital carbonates supplied as "glacial flour" from the northern source area (the Hudson Strait) to the Labrador margin would be supplied to the upper slope. This might explain the occurrence of plumites 130 km (including the Qeovik silt on the shelf) from the former ice-margin (Fig. 5.3), if the interpretation of plumite distribution on seismic profiles is correct. In addition to surface currents, katabatic winds may also have aided a wider offshore distribution of plumites by generation of offshore-directed surface currents. The katabatic winds result from the steep thermal gradient between the ice-covered land and warmer ocean surface (Aksu and Mudie, 1985).

However, the seismic signature of the plumite facies may not be different from that of hemipelagic sediments interbedded with nepheloid-layer deposits. While the latter two facies occur on the slope and rise, plumites may be restricted to regions not more

than 20 km seaward from the former ice margin, where typical plumites were found in piston cores (see Ch. 3). Therefore, the seismic profiles may overestimate plumite occurrence and the area between 20 and 50 km from the shelf break, which is not yet covered by cores, may not contain plumite facies.

The references used here (Elverhoi, 1984; Pfirman and Solheim, 1989) concerning the magnitude of sediment discharge by surface-plumes are from fjord-connected glaciers in the Barents Sea and Svalbard Archipelago, respectively. Compared to these regions, the magnitude of sediment discharges through the Hudson Strait, which is >90 km wide, was likely much more intense. In the Hudson Strait region, some unusual subglacial meltwater discharges may have occurred during presumed lake-outburst floods (Hesse et al., 1994; Hesse, 1995b; Johnson and Lauritzen, 1995). Glacial outburst floods may yield discharge rates as large as $10 \text{ to } 60 \times 10^6 \text{ m}^3/\text{s}$ (Shaw et al., 1989; Kor et al., 1991; Rudoy and Baker, 1993), which is 2-3 orders of magnitude greater than the discharge to the ocean of a large river like the Mississippi during flood stage (see table IV of The Unesco Press, 1976). It is entirely feasible, therefore, that the plumite facies on the Labrador Slope south of the Hudson Strait may be much more widespread than those of the modern examples (e.g. Elverhoi, 1984; Pfirman and Solheim, 1989).

It is notable that turbidites are not absent on the upper slope, where the plumites and hemipelagic sediments predominate (e.g. in core 90-24 in Fig. 3.1). With our present knowledge, a plumite/hemipelagic dominated region on the upper to middle slope and a mass-flow dominated region below the middle-slope can be differentiated. The boundary between these regions is not sharp. A gradual increase in the abundance of turbidites

• 75-55

90-25 • 88-7 •
• 92-4 • 92-5
90-26 • 4 •
88-10 • 88-8 • 87-12
90-28 • 11 • 88-2
90-29 • 92-6 • 84-16
87-1, 2 •
14 • 84-8, 9
88-13 • 84, 15 • 11 •
92-2 • 90-33, 34 • 88-1 • 5, 7
87-9, 10 •
92-1 •

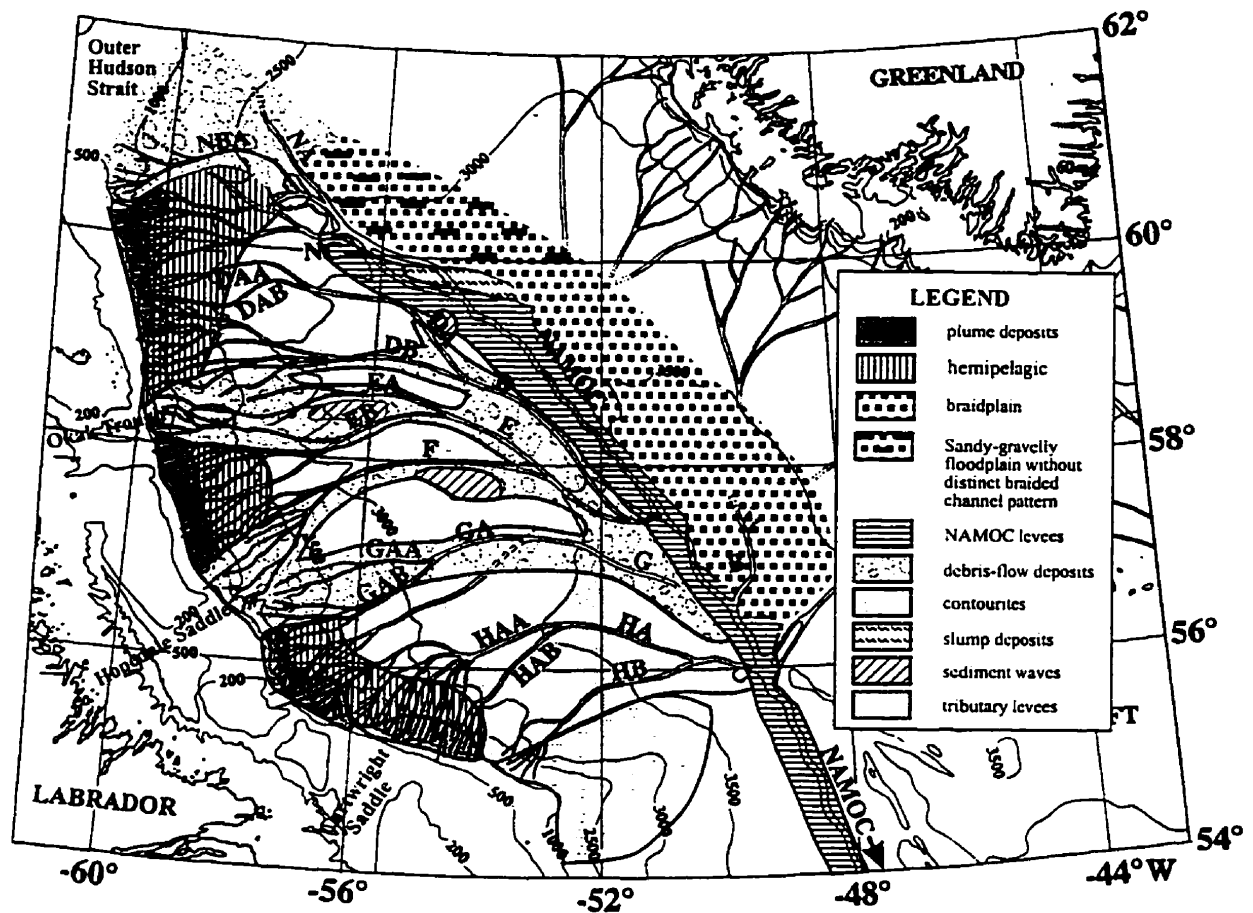


Fig. 5.3. Facies map of Labrador-Sea sediments based on 3.5 kHz and sleeve-gun seismic profiles and piston cores (from Klaucke, 1995). A different pattern for the massive sands north of 60° latitude indicates that the presence of a braided channel pattern is uncertain.

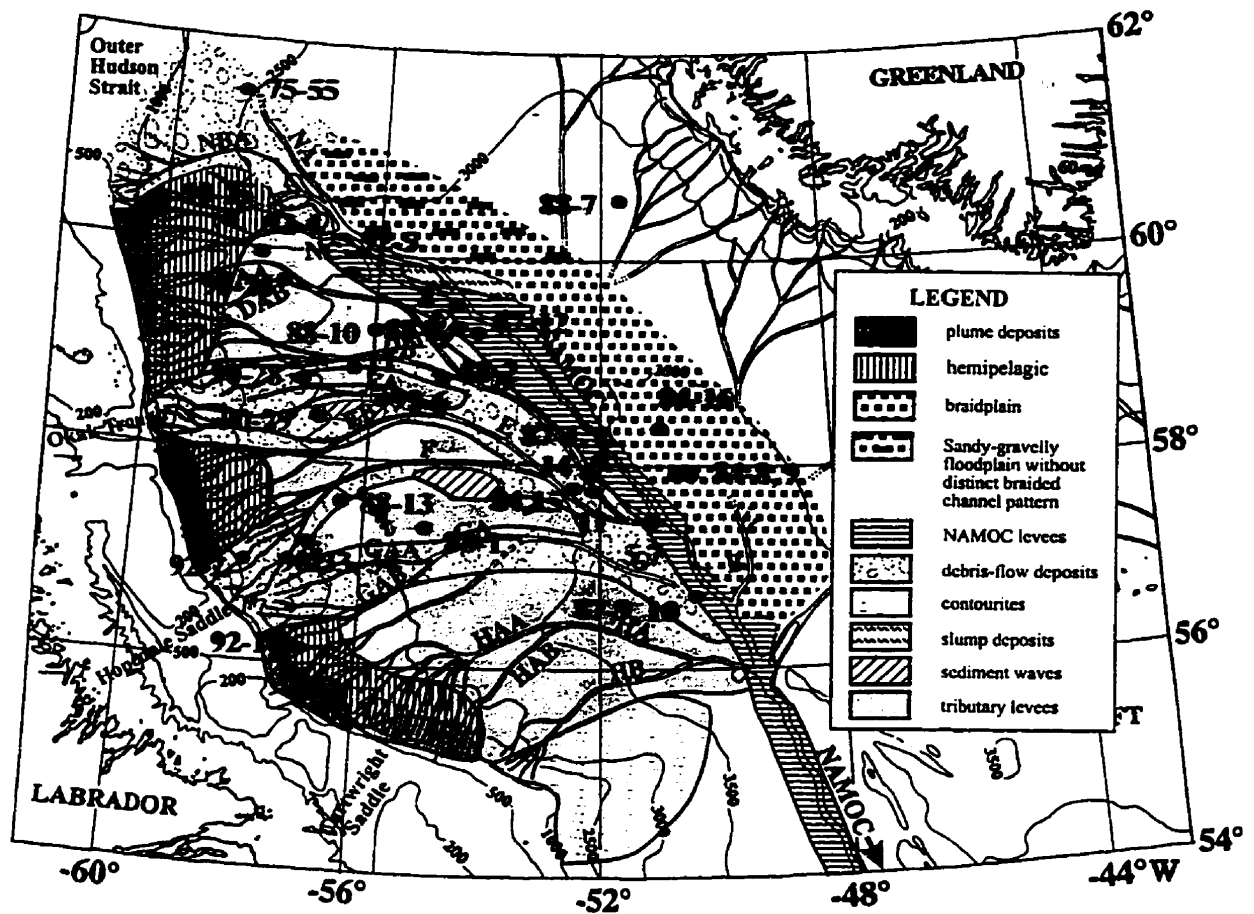


Fig. 5.3. Facies map of Labrador-Sea sediments based on 3.5 kHz and sleeve-gun seismic profiles and piston cores (from Klaucke, 1995). A different pattern for the massive sands north of 60° latitude indicates that the presence of a braided channel pattern is uncertain.

downslope suggests that a transition zone exists (see Fig. 3.2). More cores will in the future establish the details of the transition zone.

5.1.3. Hemipelagic sedimentation

The two facies of concern for hemipelagic sedimentation in the Labrador Sea are facies H and HI (see Ch. 3). In the various cores, they comprise between 21 and 84% of the slope and 7-33% of the basin-centre sediments, respectively. The lower proportion of the biogenic component in facies HI (25-75% of the sand fraction) compared to facies H (>75%) is a dilution effect due to ice-rafting. In high latitudes, ice rafting is a major contributor of the terrigenous component to hemipelagic sediment (Stow and Piper, 1984). The IRD occur mainly in the sand- and pebble-sized fractions (up to 22%; see Gilbert, 1990).

More than 85% of facies H and HI are in the clay- and silt- size fractions (Table 3.1). In these size fractions, the terrigenous constituents are supplied through various airborne and seaborne processes (i.e. wind and surface currents) to the deep sea.

A high intensity of bioturbation in these deposits indicates low sedimentation rates. The deposits are thicker in regions proximal to the sediment source where sedimentation rates are higher (Table 3.4). To give just one example, the hemipelagic sediments observed between HL-1 and HL-2 have a sedimentation rate of 35.9 cm/ka in core 92-5 on the slope-rise boundary (see Fig. 1.3 for location), whereas two rise and basin cores 88-10 and 87-9 yield values of 16.5 and 6.1 cm/ka, respectively.

5.1.4. Nepheloid layer deposits

Typical nepheloid-layer deposits that are characterized by graded muds with dispersed IRD and occasionally bioturbated layer tops (Fig. 3.3K) were found on the Labrador Slope adjacent to the Hudson Strait (cores 90-26, 28, 29 and 92-5; see Fig. 1.3 for core location). In the Labrador Sea, nepheloid-layer deposits are widespread. They can be traced for more than 300 km from the shelf break. A combination of sedimentary processes that were active at the same time were responsible for the deposition of facies N. Ice-rafting is the main transport mechanism for the randomly dispersed sand- and gravel-sized particles in the deposits, because these particles cannot have been transported by the same mechanism that transported the graded mud. The facies was deposited by gradual settling of suspended material from the nepheloid layers and icebergs. Deposition of the nepheloid layers was slow enough for incorporation of IRD, a phenomenon not observed in turbidites. The presence of some parallel laminated mud in these deposits indicates that turbidity currents also reached the sea floor at the time of deposition of this facies, suggesting that a continuum between nepheloid layers and low-density turbidity currents may exist. The nepheloid-layer deposits off the Hudson Strait are also distinct from other contourites because of the very strong input of fine suspended, detrital-carbonate-rich sediments through the Hudson Strait Ice Stream (see also section 3.2.3).

The activity of burrowing organisms shows that there was enough time between successive events for organisms to colonize the sea floor. A high detrital-carbonate content of these sediments indicates a Hudson Strait source (see Ch. 4). Deposition occurred during prominent ice-rafting events (Heinrich events). During Wisconsinan

glacial episodes, the Labrador Sea nepheloid layers probably attained much higher suspended-matter concentrations than average modern deep-sea nepheloid layers (0.01-0.3 mg/l; McCave and Swift, 1976). The residence time for fine material of modern nepheloid layers is up to a few years (McCave, 1986), and flow velocities are between 1 and 10 cm/sec (Hunkins et al., 1969; Hollister and Nowell, 1991). The presumed high concentrations during Heinrich events may have been obtained by (i) transfer of material from low density turbidity currents to nepheloid layers (Wang and Hesse, 1996) or (ii) meltwater surges associated with subglacial-lake outburst events (see Section 5.1.6). Sedimentation rates of the Labrador Sea nepheloid layers up to >100 cm/ka have been determined (Table 3.4), which is an order of magnitude higher than maximum rates of known modern counterparts (5-10 cm/ka, Stow and Holbrook, 1984). To give an idea of the upper limit of the duration of individual nepheloid flows in the Labrador Sea, during Heinrich events, this sedimentation rate would yield a value of up to 30 years for a 3 cm-thick layer. However, this value is certainly overestimated because of the times of non-deposition between successive layers inferred from bioturbation. A reasonable estimate might therefore be a few years, more in line with the residence-time for suspended sediment in modern nepheloid layers quoted above.

5.1.5. Ice rafting

Petrographic tracers imply the Canadian margin of the Labrador Sea as main source for ice-rafted sediments (Ch. 4). According to the mineralogical composition, two main sediment sources were identified: (i) a siliciclastic source in the crystalline Canadian

Shield, and (ii) a carbonate-rich source in the Hudson Strait, Hudson Bay, Baffin Island and northern Greenland regions. A minor proportion of the sediments are rich in basaltic and rhyolitic ash fragments that originated from Iceland (Ch. 4). The braidplain sands, deposited by large-scale gravity flows (see following section), have a mineralogical composition similar to the first two groups. Compared to the Canadian margin, ice-rafted sediments on the Greenland margin have a different mineralogical composition (i.e. plagioclase and hornblende, Ch. 4; see also Chough et al., 1987; Wang, 1992; Windley, 1969).

The modern iceberg flow pattern in the Labrador Sea is substantially different from that of glacial times. Today, icebergs originating from Greenland enter the Labrador Sea by the West Greenland Current (Smyth et al., 1985). At glacial times, icebergs mainly originated from the glaciated Canadian Shield throughout the Hudson Strait outlet and smaller fjords (Andrews et al., 1993). The most intense ice-rafting deposition occurred during times of maximum ice advance, when continental glaciers extended to the shelf, and during the beginning of deglaciation (Henrich et al., 1989). Ice-rafted ash particles were supplied by Greenlandian and Icelandic icebergs (or floating sea ice) entrained by the West Greenland Current to the Labrador Sea. They are present as a minor constituents in Labrador Sea sediments, but are absent in Heinrich layers (see Ch. 4, 6). This may indicate that the iceberg output through the Hudson Strait was so intense that the contribution by Greenlandian and Icelandic icebergs in Heinrich layers was diluted beyond recognition. Distribution and depositional facies of the four most recent Heinrich Layers in the Labrador Sea will be discussed in Chapter 6.

5.1.6. Sandy turbidity currents

Although most turbidity currents are triggered by remobilization of previously deposited sediment (e.g. Walker, 1992), they may originate from primary processes such as high river discharges during floods. Transport and deposition mechanisms of high-density turbidity currents, which carry gravel and coarse sand, are different from low- or medium- density currents (Lowe, 1982). In the Labrador Sea, thick sequences of sand turbidites occur in the braidplain east of NAMOC, and partly in the western floodplain, as interbeds between debris-flow deposits. Sand makes up to 77% of their constituents (see Ch. 3 for grain-size analyses). They are mainly structureless, but include some laminated and graded beds (Ch. 3). The structureless sands may be the equivalent of the T_1 -division of Bouma (1962) ($=S_1$ -division of Low, 1982). Locally, they are overlain by parallel-laminated mud turbidites (division T_2 ; see cores 84-8, 9, Fig. 4.2a).

The mineralogical composition of the massive sands indicates Canadian, rather than Greenland sources (Fig. 4.15). Most samples are rich in quartz and feldspars; some intervals are enriched in detrital carbonates and volcanic ash (Icelandic-Greenlandian origin); a single core has up to 31% detrital carbonates in this facies (Tables 4.4 and 4.6). This may imply a mixing from different sediment sources for the sands (i.e. Canadian Shield, Hudson Strait). An extensive sediment-discharge is required to transport sandy material to the braidplain in the central Labrador Sea, more than 600 km from their postulated source in the Hudson-Strait region. This condition may have occurred during subglacial outburst floods (cf. Boyd et al., 1988). Hesse et al. (1994) and Johnson and Lauritzen (1995) suggested that subglacial floods associated with iceberg discharges from

a Hudson Bay subglacial lake, dammed by ice at the mouth of the Hudson Strait, may have also occurred during Heinrich events. Catastrophic release of large volumes of subglacial meltwater or dammed glacial-lake water may produce bedload-rich flows dense enough to overcome the seawater density and sink to the seafloor as hyperpycnal flows (Normark and Piper, 1991; Mulder and Syvitski, 1995). Large depressions on the floor of the Hudson Strait could also have served as reservoirs, required to generate such flows. These high-density turbidity currents were too large and fast to be confined by the drainage system of the NAMOC, and therefore bypassed the slope canyons and formed the extensive sand-rich sediments in the floodplain east of NAMOC (Hesse, 1996; Hesse et al., 1996). Analogs of the outburst floods have also been observed in subaerial environments (e.g. Beecroft, 1983; Lord and Kehew, 1987; Shaw et al., 1989; Kor et al., 1991; Rudoy and Baker, 1993) and restricted shallow marine environments (e.g. Prior and Bornhold, 1989).

Although this study and Klaucke (1995) give ground-truth evidence for the sediment provenance and depositional mechanism of massive sands, the magnitude and characteristics of the flows responsible for their deposition remain insufficiently known. The depositional mechanism of the braidplain sands with low detrital-carbonate contents is still uncertain. With our present tools, the time of deposition of the massive-sand facies cannot be precisely bracketed to establish a relationship with Heinrich events beyond doubt (Ch. 4). Radiocarbon dates 8-16 cm above the sands give ages around 10 ka (Ch. 4). Therefore, the sands could have been deposited during Heinrich events 0, 1, 2 or earlier.

5.2. Secondary delivery mechanisms

5.2.1. Debris-flows

Extensive debris-flow deposits were observed in the Labrador Sea (Hesse, 1992; Hesse and Rakofsky, 1992) and adjacent basins such as the Newfoundland and Nova Scotia slopes and Baffin Bay (Hill, 1984; Aksu and Hiscott, 1992; Hiscott and Aksu, 1994). They were triggered by sediment failure as a result of high sediment accumulation on the slope. On the upper Labrador Slope, debris-flow deposits are observed in the low-relief slope sectors in front of former major glacier outlets (Fig. 5.4). Extensive sediment dumping at the ice margin in this region led to slope oversteepening. The slope subsequently collapsed due to successive sediment failure. Debris-flow deposition smoothed the topography of these sectors. The coarse-grained nature of the debris-flow deposits, which are less susceptible to erosion, compared to fine-grained sediments of adjacent high-relief sectors, aided in the preservation of low relief.

Debris flows on the slope tend to move from intercanions regions toward the canyon axes (see Hesse and Rakofsky, 1992; Wang and Hesse, 1996). In the debris-flow dominated-region (Fig. 5.3), most of the slope canions are filled with debris-flow deposits (e.g. Fig. 5.5). On seismic profiles, they form up to 60 m thick transparent lenses with their long axes oriented downslope. They have abrupt lateral contacts with well-stratified adjacent sediments, which indicates that they were deposited by "freezing" of the debris flows in the canions or channels (Hesse and Rakofsky, 1992). Two major debris-flow tongues extend from lower slope canions onto the rise and basin centre where they merge and produced a more than 20 m thick stacked sequence of debris-flow

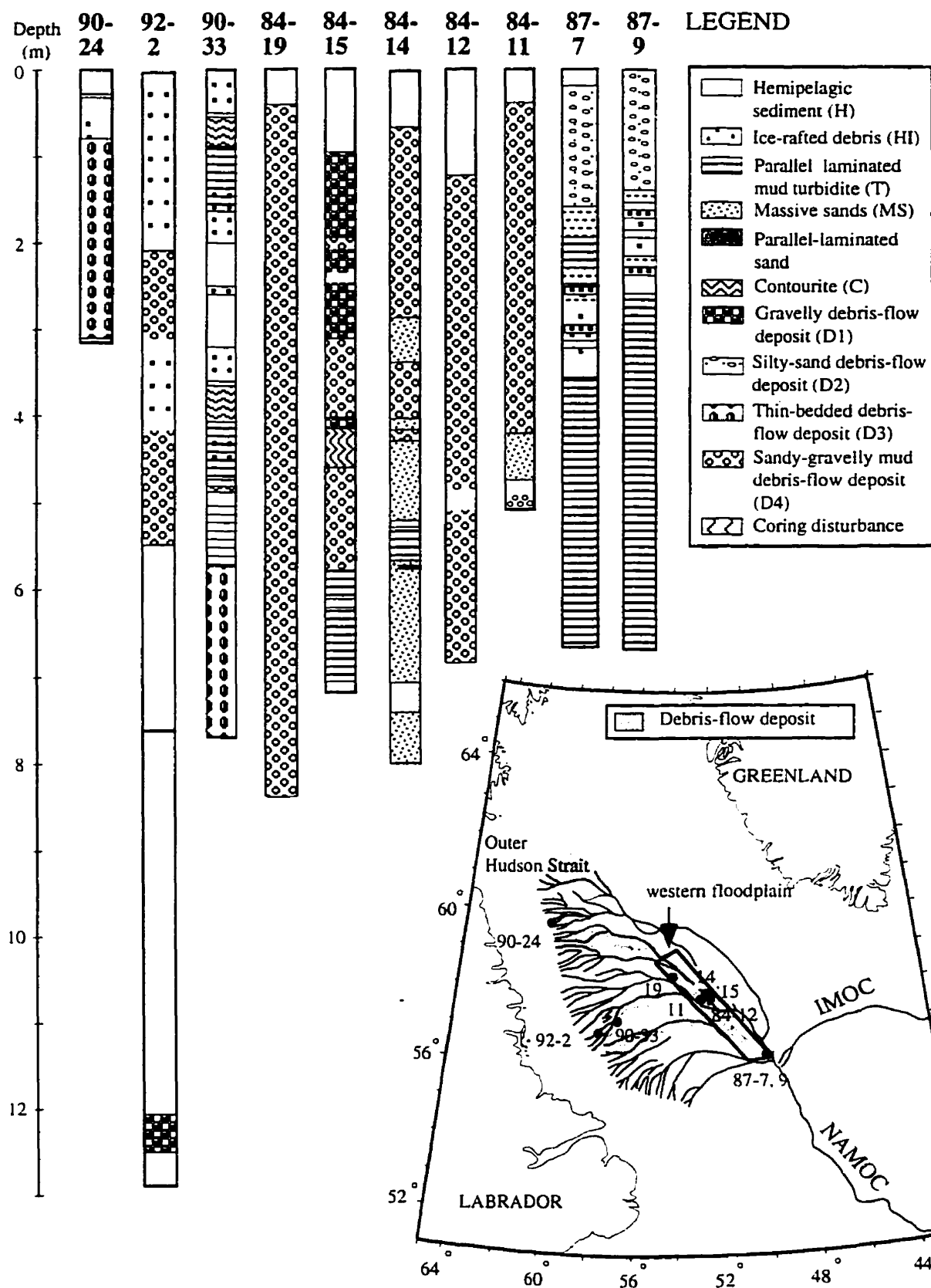
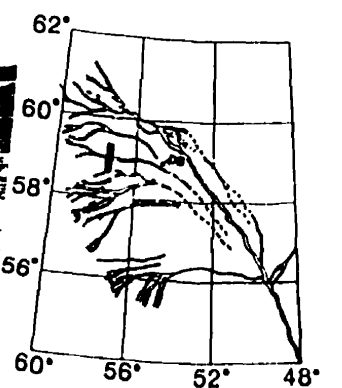
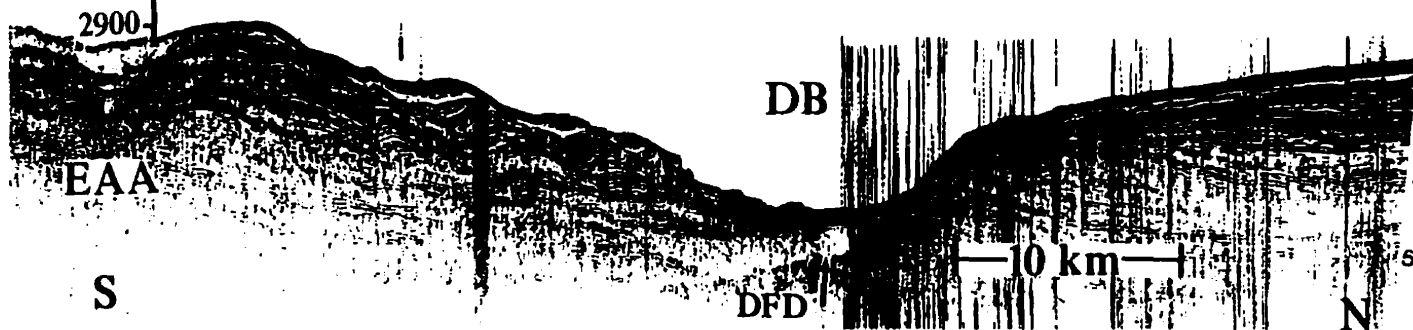
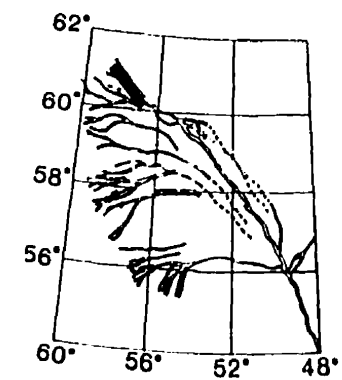
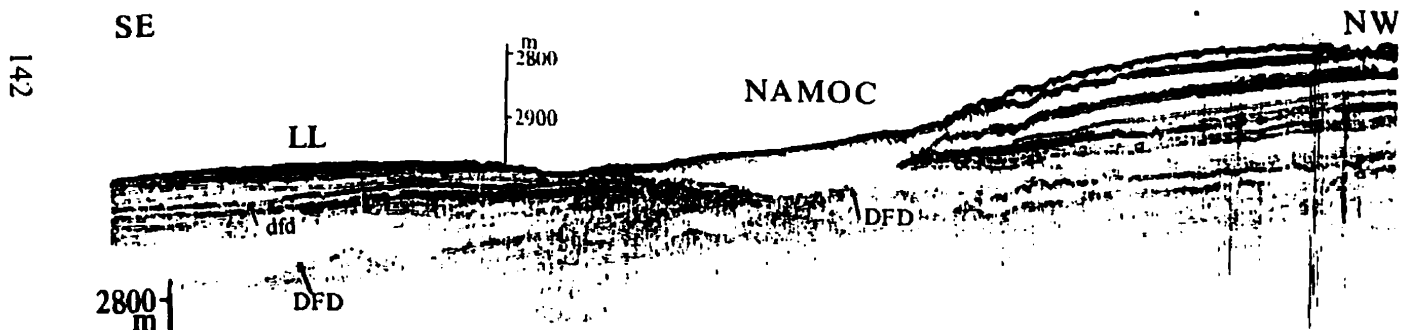
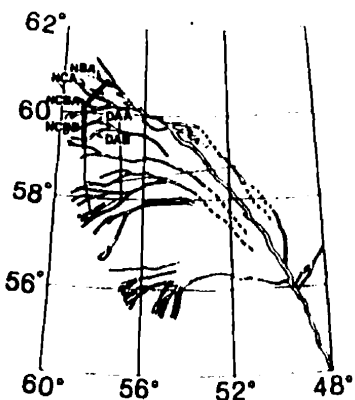
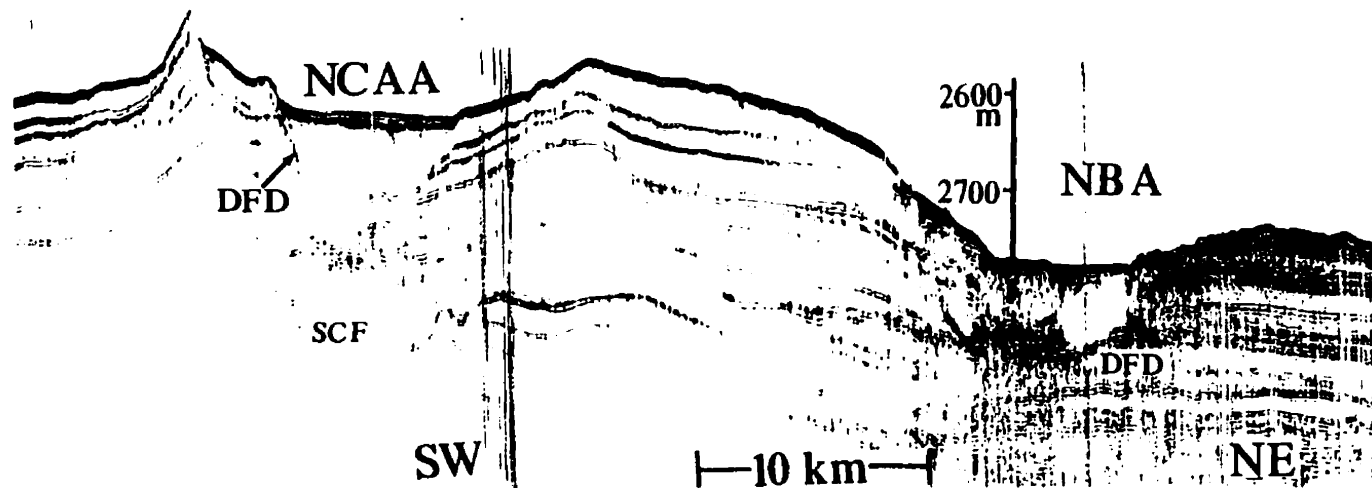


Fig. 5.4. Types and distribution of debris-flow deposits. Box: western floodplain.

Fig. 5.5. Sleeve-gun profile (40 in³) of the D- and N-canyon systems on the middle slope and NAMOC levee. Note: most canyons are filled with debris-flow deposits (DFD) or sand and gravel (SCF=second-order canyon fill; from Hesse, 1992; Hesse and Rakofsky, 1992).



deposits on the western floodplain (Fig. 5.4). Studied cores in debris-flow dominated regions include seven cores from the western floodplain (84-11, 12, 14, 15 and 19 also 87-7.9) and three upper-slope cores (90-24, 34 and 92-2; Fig. 5.4). Coring of debris-flow deposits in canyon axes, where they were expected to be encountered, has not been attempted during previous cruises to the Labrador Slope, because the paleoenvironmental and paleoceanographic information that can be obtained from debris-flow deposits is generally minor.

Most debris flow deposits in the slope canyons and the western floodplain are sandy gravelly muds (subfacies D4). In the western floodplain, subfacies D4 is associated with massive sands. It has a high detrital-carbonate content (up to 38 and 28% in slope and western floodplain, respectively). Extensive distribution, poor sorting and coarse-grained texture of subfacies D4 indicates that it may have originated by remobilization of glacial till at the grounded ice front or coarse-grained ice-rafted detrital-carbonate rich sediments higher up on the slope. Gravelly debris-flow deposits (subfacies D1) are <1m thick and grade mainly into subfacies D4. Subfacies D2 contains ripped-up mud clasts and is observed mainly in the western NAMOC levee. It probably originated locally from predominantly fine-grained sediments, such as on the NAMOC levee.

The thin bedded debris-flow deposits (subfacies D3) occur mainly in upper-slope cores (90-24, 33 and 34, Fig. 5.4). They may have an appearance similar to ice-rafted sediments in Heinrich layers, which are also poor in foraminifera. The presence of mudclasts and irregular laminae is more common in debris-flow deposits (Fig. 3.3O), but cannot be ruled out for ice-rafted sediment either. The distribution of subfacies D3

suggests a local origin. Thin-bedded debris-flow deposits in adjacent basins lack any sedimentary structures and have a massive appearance (Hill et al., 1982; Hill, 1984; Syvitski and Farrow, 1989). On the Labrador Slope, they typically consist of a lower unit of poorly sorted sandy gravel, overlain by a well sorted mud unit (Wang and Hesse, 1996; see also Ch.3). On the lower slope, the upper mud unit of this couplet is thinner (<1mm; cores 92-6 and 90-29, Fig. 3.2).

Based on the sediment thickness and maximum grain size, Hill et al. (1982) suggested that a thin-bedded debris-flow deposit (<20 cm) could be formed on a slope with an angle as low as 4° by sheet-like flows. These flows may be formed by spill-over of channelized debris flows (Hill et al., 1982). As a thin debris flow moves downslope, progressive incorporation of water at the nose of the flow may generate a turbulent cloud. Consequently, a fine-grained turbulent cloud (i.e. a turbidity current) may be formed at the top of the main body of the debris flow. When the main body "freezes", sedimentation may be followed by a thin mud turbidite (Hampton, 1972; Wright and Anderson, 1982). Each couplet of subfacies D3 may represent one depositional event. Similar to subfacies D4, the detrital-carbonate of subfacies D3 is relatively high (18%), indicating that it may have originated by remobilization of previously deposited detrital-carbonate rich ice-rafted sediments. AMS ¹⁴C dating in lower-slope cores gave ages between 33-41 ka from the base of the debris-flow deposits (see cores 90-26, 29 and 92-6 in Fig. 3.1), including the time of deposition of HL-4 (35 ka; Bond et al., 1993; Broecker et al., 1992).

5.2.2. Muddy turbidity currents

The Labrador-Sea spillover turbidites consist of silt and mud turbidites. Silt turbidites are more abundant on the slope than on the NAMOC levee (see Ch. 3). Compared to silt turbidites, mud turbidites contain relatively abundant foraminifera (up to 500 forams/g) and show a higher degree of bioturbation, implying slower sedimentation rates. On the lower slope/upper rise region, where contour currents are active, a dilute muddy turbidity current may be captured by the Western Boundary Undercurrent. Some of the mud turbidites in this region do not show typical turbidite structural sequences, but show discontinuous and irregular laminations which may be due to the winnowing action of contour currents.

The Labrador-Sea spillover turbidites are rich in detrital carbonate (>33%; cores 90-25 and 26; see Ch. 4). Turbidity currents in the slope canyons are generated by remobilization of detrital-carbonate rich plumites adjacent to the Hudson Strait. This is inferred from the high detrital carbonate contents of the turbidites occurring in greater water depth on the slope beneath the plumite facies. The high organic-carbon content of the spillover turbidites, (up to 2.3% or more than twice that of interbedded hemipelagic sediments; Ch. 4) is a preservation effect. Better preservation of organic carbon in turbidites is due to their higher sedimentation rates (Piper, 1978). Compared to the NAMOC levee sediments, the slope spillover turbidites have higher organic carbon contents, which again may be due to a higher accumulation rate on slope.

5.2.3. Contour currents

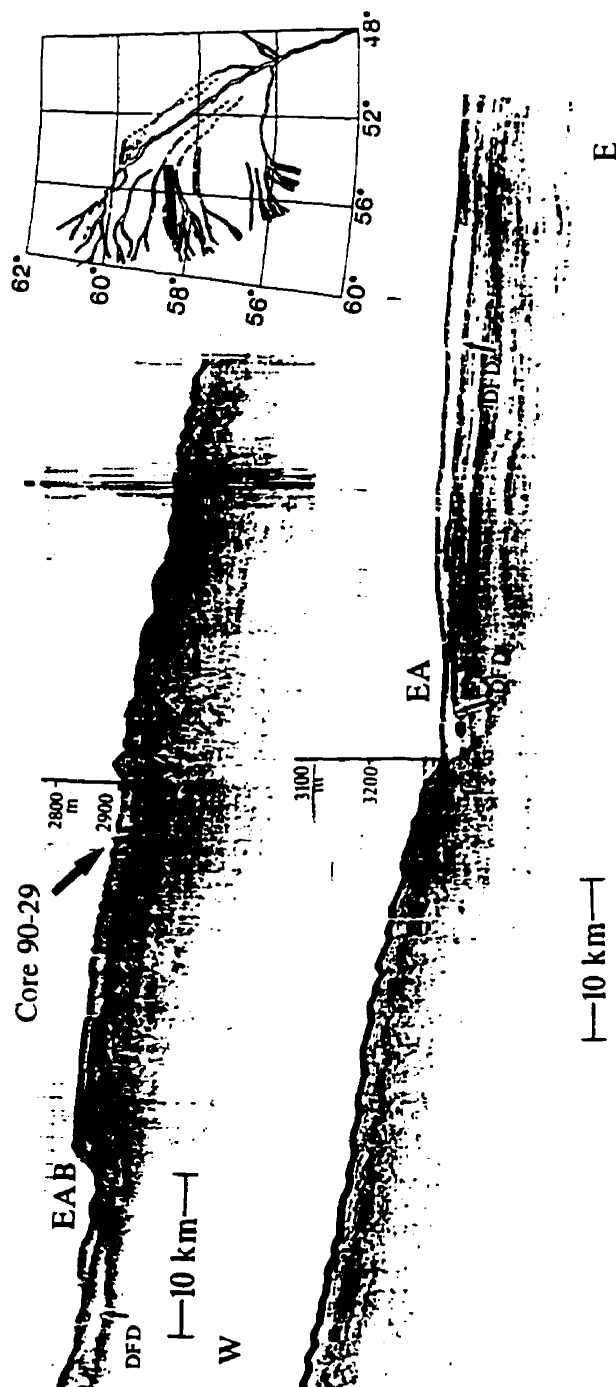
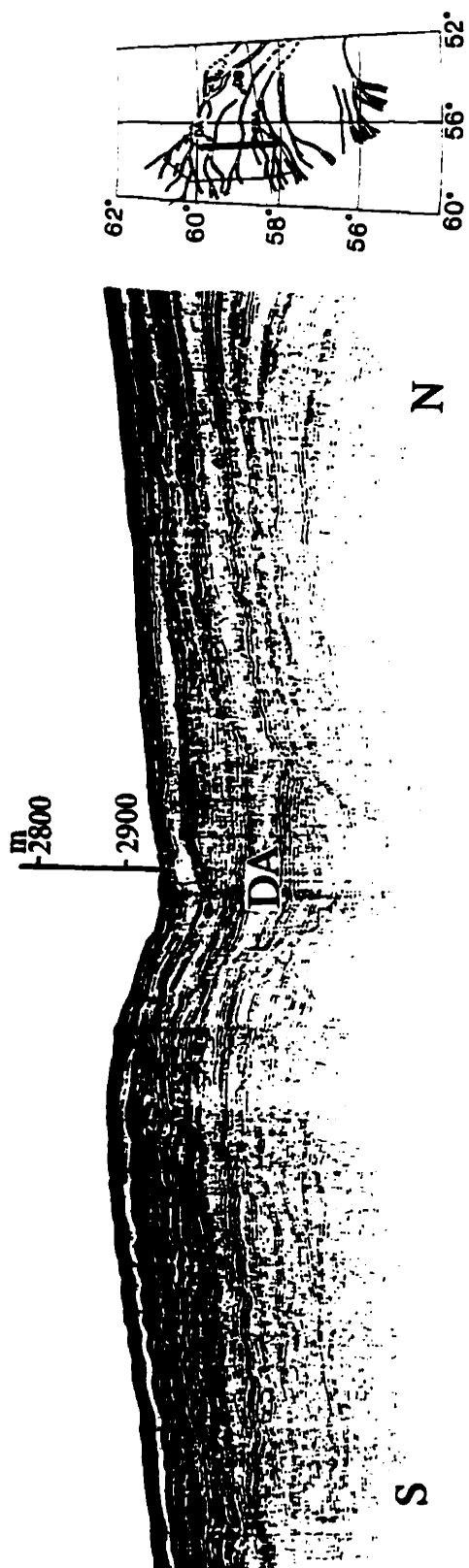
In the Labrador Sea, contourites were recognized on the Eirik Ridge south of Greenland (Chough and Hesse, 1985). Contourites occur locally under the axis of the Western Boundary Undercurrent (see below) on the Labrador Slope between 57 to 60°N around 2600-3100 m water depths (Wang and Hesse, 1996). According to the present study, they comprise up to 25% of the slope sediments and are interbedded with hemipelagic sediments and mud turbidites (Ch. 4). Interbeds of hemipelagic sediments and contourites (see Fig. 3.10) perhaps indicate fluctuating strength of bottom currents: weaker when bioturbated hemipelagic sediments with no lamination were deposited, and stronger when laminated muds (contourites) were formed. Compared to the interbedded turbidites, they have a lower organic carbon content (average of 1.8 and 0.5%, respectively) indicative of low sedimentation rates (10 cm/ka; Fig. 4.7 and Table 3.4).

In the North Atlantic Deep Water, the overflow waters from the Norwegian and Greenland Seas flow counterclockwise around the Labrador Sea as the Western Boundary Undercurrent (WBUC, Cremer et al., 1989; Carter and Schafer, 1983). It flows around 2500-3000 m water depth (Carter and Schafer, 1983). Two general processes are associated with the WBUC: (1) winnowing around the fast flowing axis, and (2) deposition under slower moving lateral parts of the current (Carter, 1979). The WBUC flows over the middle to lower slope and upper rise with a mean velocity of 8-9 cm/s in the southern Labrador Sea (Carter and Schafer, 1983).

Large sediment waves were recognized in the NAMOC levee and Labrador Slope (Fig. 5.6). Similar deep-sea features were previously attributed to contour currents (e.g.

Lonsdale and Spiess, 1977). Sediment waves on the NAMOC levee near 59°40' are more likely related to turbidity currents overflowing from the main channel, rather than bottom currents (Hesse et al., 1990). While turbidites may make up to 90% of the NAMOC levee sediments, they comprise up to 45% of the sediment-wave fields on the slope. Contourites are minor constituents (<25%) of sediments in this region. It is possible that a combination of processes (i.e. turbidity currents and bottom currents) are responsible for shaping the slope sediment waves (see Stanley and Taylor, 1977). Fine-grained sediments injected to the slope region by turbidity currents were probably deflected by the southward flowing contour currents. The contribution of the former process is likely more significant.

Fig. 5.6. Sleeve-gun profiles (40 in³) of the D- and E-canyon systems on the lower-slope to rise transition. Note a better development of sediment waves on the right-hand (southern) canyon levees, reflecting the asymmetric emplacement of spillover turbidites affected by the Coriolis force (from Hesse, 1992; Hesse and Rakofsky, 1992).



CHAPTER 6: Heinrich events

6.1. General characteristics, ages and duration

Heinrich events are episodes of intensified ice-rafting deposition in the North Atlantic during the last glaciation which left distinct, decimeter to centimeter thick layers of ice-rafted debris in Late Pleistocene sediments (Bond et al., 1992; Broecker et al., 1992). Heinrich layers are characterized by: (1) high concentration of lithic fragments, (2) low foraminifera content; (3) abundant detrital carbonate fragments; (4) high magnetic susceptibility; and (5) distinct coloration characterized by higher gray levels (ranging from 100 for light to 260 for dark colour sediments; Andrews et al., 1993; Grousset et al., 1993; Broecker, 1994). Their low foram content (<100 forams/g, compared to >2000 forams/g in normal pelagic sediments) may be due to: (i) dilution by rapidly accumulated debris from the icebergs and/or (ii) reduction in phytoplankton productivity due to blockage of light by floating ice. A low standing crop of phytoplankton reduces the number of planktonic foraminifers who feed on them. High percentages of *N.pachyderma* (left coiling) in these layers and low $\delta^{18}\text{O}$ values suggest Heinrich events occurred during times of low temperature and high meltwater discharges (Andrews et al., 1994a). The high magnetic susceptibility and grey level values of Heinrich layers (up to 1.5×10^{-4} e.m.u. and 260, respectively) reflect their high terrigenous content (Grousset et al., 1993). However, HLs of the northwestern Labrador Sea are anomalous in this respect because of their high detrital carbonate contents, which cause low magnetic susceptibility values (7.7×10^{-3} e.m.u), compared to the background level (Andrews and Tedesco, 1992).

The ^{14}C ages obtained for HL-1 to 4 in this study (14.5, 20, 27 and 35 ka,

respectively) correspond to those reported in the literature for the Labrador Sea and North Atlantic (Andrews et al., 1994a,b; Bond et al., 1993; Fig. 6.2). Heinrich layers were deposited during relatively short periods of time. They have durations of a few hundred years (about 250-2000 years; Dowdeswell et al., 1995; Johnson et al., 1995) with recurrence intervals of a few thousands years (up to 10 ka; Andrews et al., 1993). Adopting an average sedimentation rate of $6 \text{ cm}/10^3 \text{ y}$ for the North Atlantic Heinrich layers, Broecker et al. (1992) estimated durations of Heinrich events 1, 2 and 3 of 1000, 500 and 1800 years, respectively. Using $^{230}\text{Th}_{\text{excess}}$ profiles, Thomson et al. (1995) estimated durations of 2000, 1120 and 710 years for the these same events, respectively. In the northwestern Labrador Sea, the sedimentation rates of Heinrich layers were an order of magnitude higher than those of normal hemipelagic sediment, e.g. 100 cm/ka for HL-1 (Andrews et al., 1994a). A similar rate of up to 110 cm/ka was obtained for HL-2 in this study.

There is a number of ice-rafted horizons which occur between Heinrich layers, mainly in isotopic stages 1 and 2. Similar to Heinrich layers, they contain abundant IRD (up to 20%), but unlike Heinrich layers they have low detrital carbonate (up to 150 grains/g) and high foram contents (up to 3700 forams/g). Among them, the ice-rafted layer associated with the Last Glacial Maximum (LGM) is best documented (Fig. 6.3). A different mineralogic composition of this zone (i.e. predominance of quartz and feldspar) indicates a Canadian Shield source (Fig. 6.3). This shows that, at least during isotopic stages 1 and 2, deposition of IRD continued between Heinrich events, but from different sources.

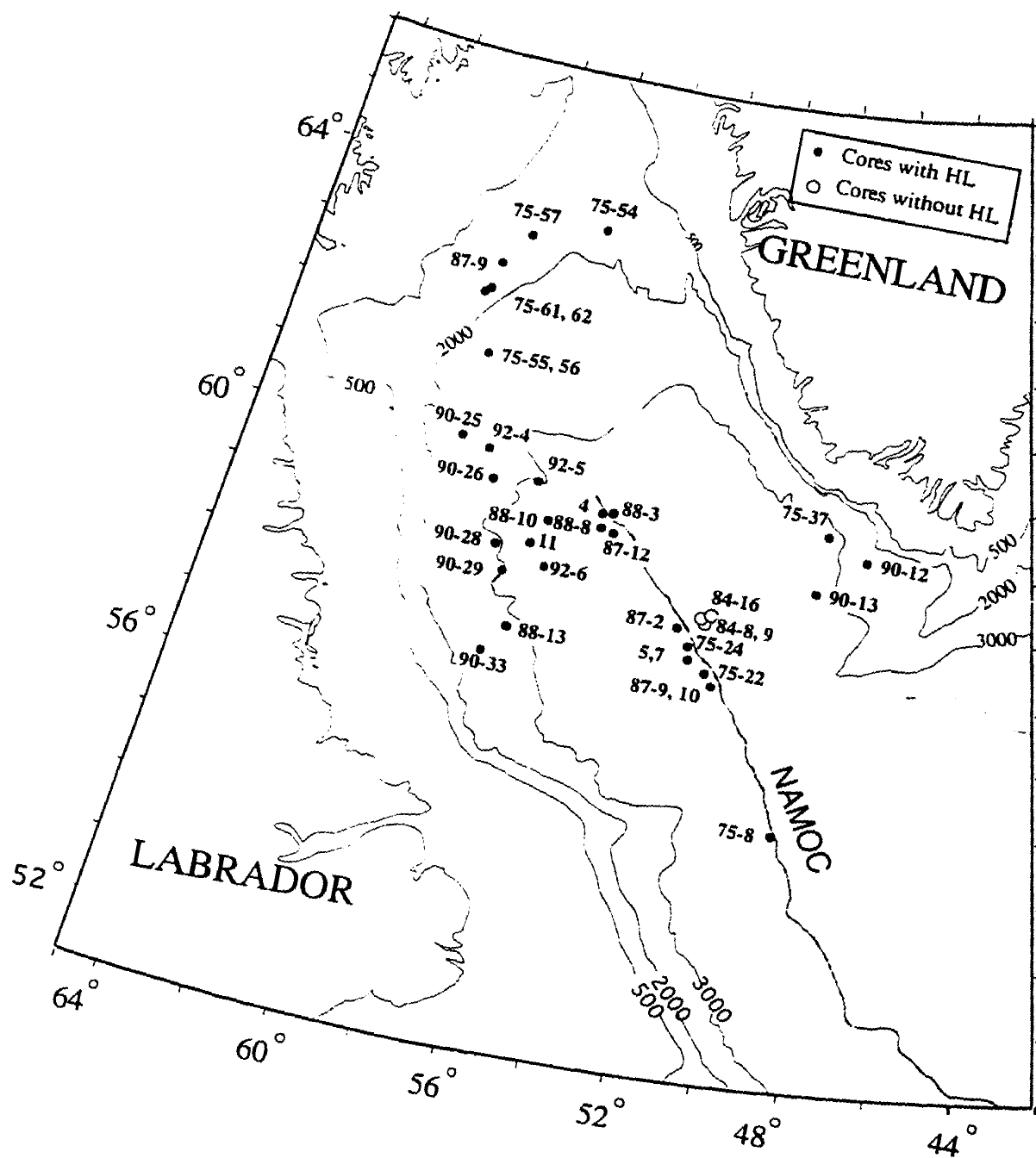
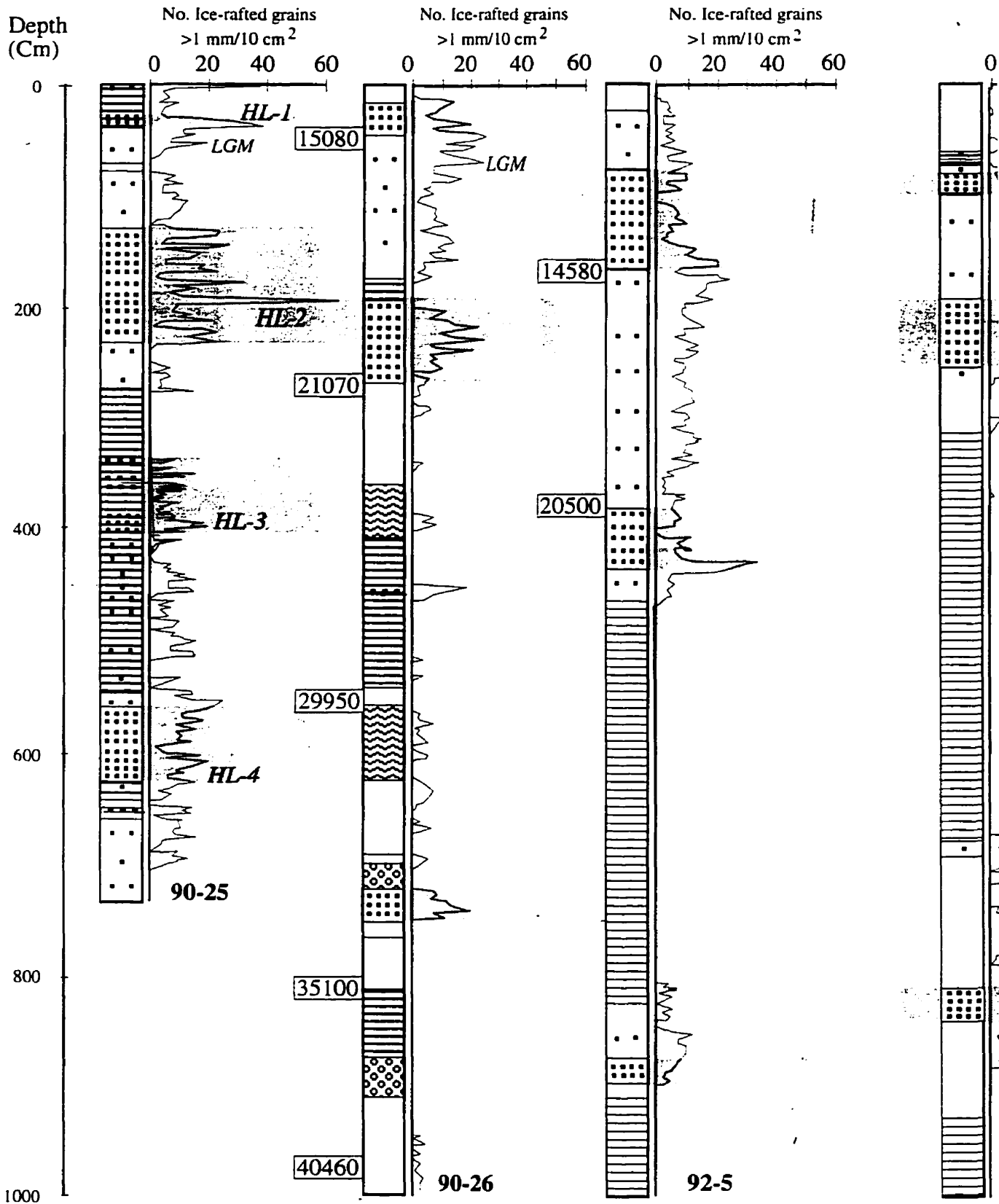
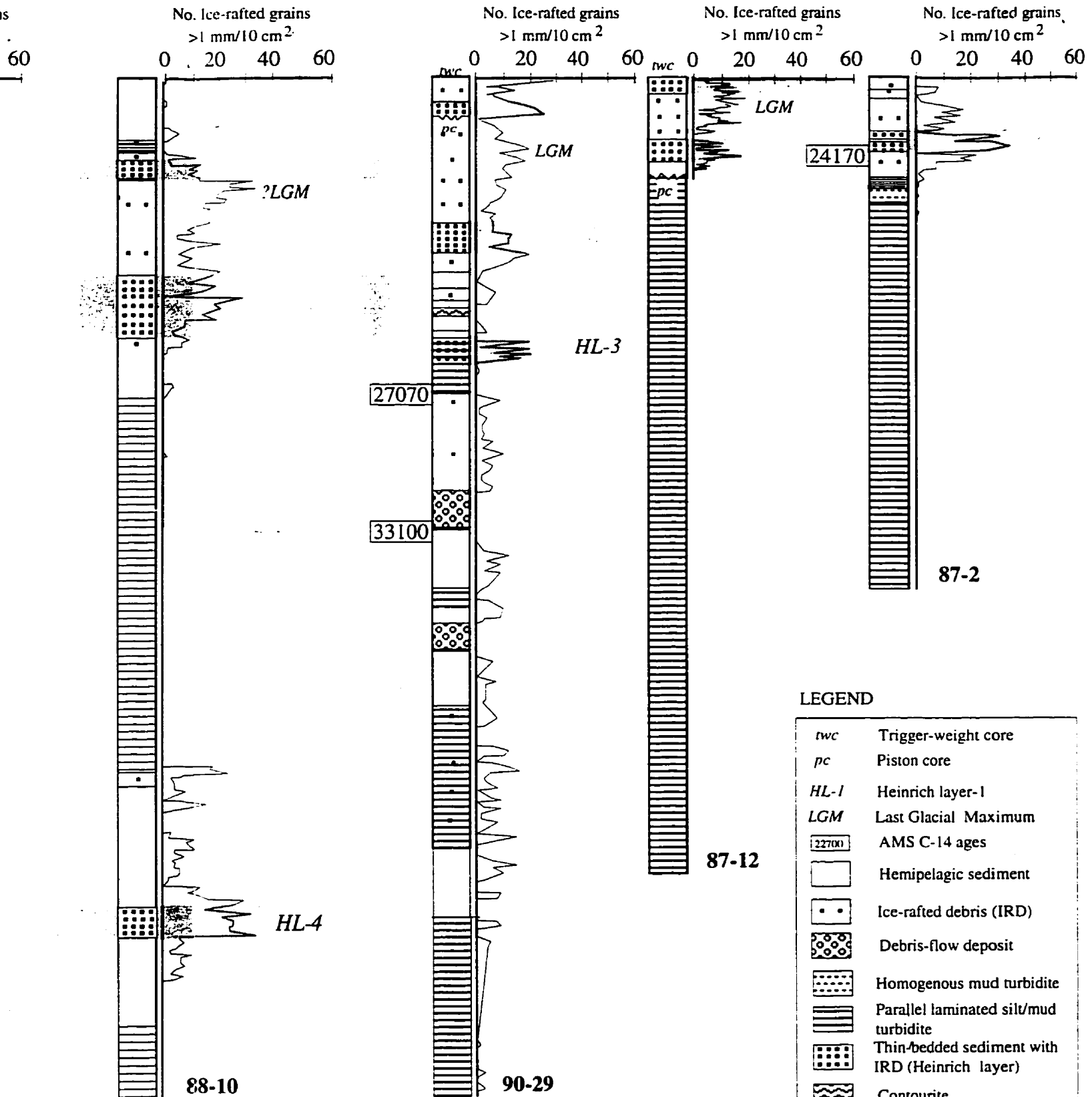
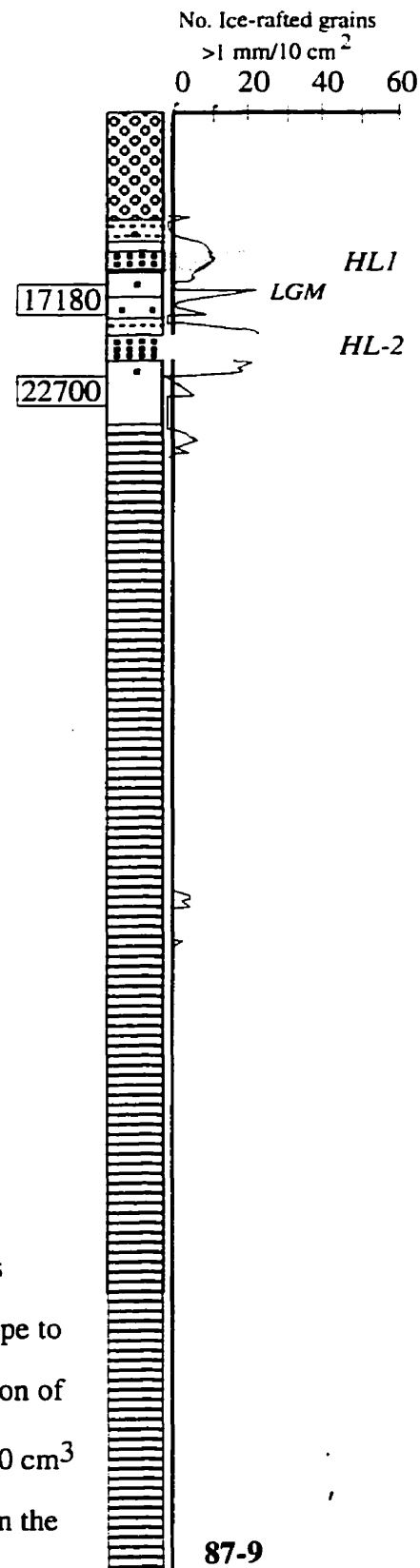
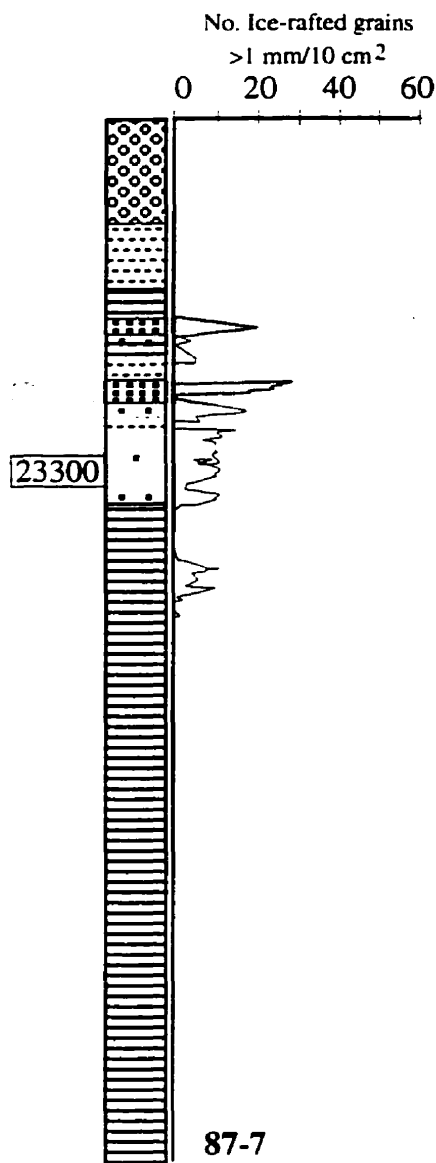
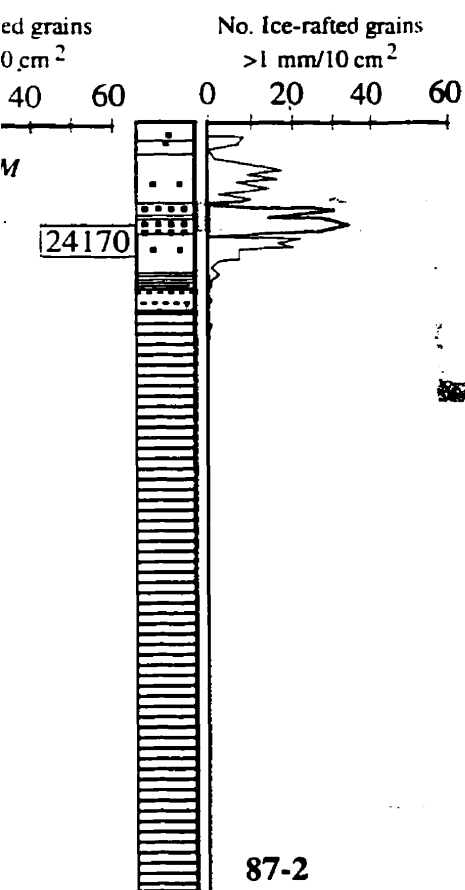


Fig. 6.1. Location map of cores used for the study of Heinrich layers.







LEGEND

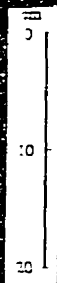
<i>twc</i>	Trigger-weight core
<i>pc</i>	Piston core
<i>HL-1</i>	Heinrich layer-1
<i>LGM</i>	Last Glacial Maximum
22700	AMS C-14 ages
	Hemipelagic sediment
	Ice-rafted debris (IRD)
	Debris-flow deposit
	Homogenous mud turbidite
	Parallel laminated silt/mud turbidite
	Thin-bedded sediment with IRD (Heinrich layer)
	Contourite
	Coring disturbance

Fig. 6.2. Correlation of Heinrich-layers

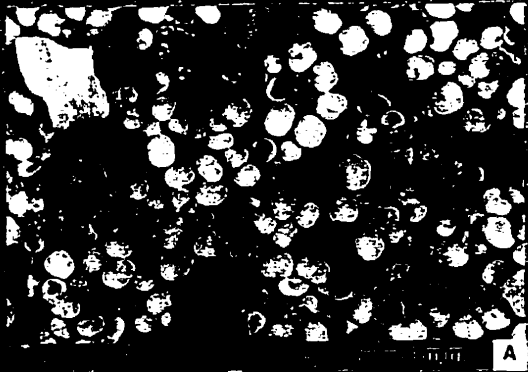
1 to 4 in 9 cores from the Labrador Slope to the basin centre. Abscissa: Concentration of IRD measured as the number of IRD/10 cm³ of sediment. Note basinward decrease in the IRD concentration and HL thickness (see Fig. 6.1 for core locations).

Fig. 6.3. Major constituents of coarse IRD

Major constituents of the coarse fraction (>125 micron) of IRD are compared between different facies in core 87-9, subbottom depths of 196, 234, 237 and 245 cm. Sediments deposited during the Last Glacial Maximum (LGM; sample A) have high contents of lithic fragments with few detrital carbonates (DC). Heinrich layers (sample B) have the highest DC (shown by arrows) and the lowest foram content. DC content is significantly reduced in the underlying ice-rafted hemipelagic sediment (sample C). Pure hemipelagic sediment without IRD (sample D) has the highest foram and the lowest lithic content.



HL-1

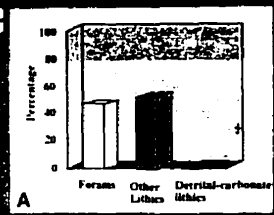


A

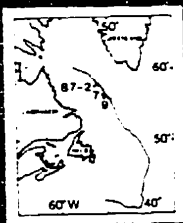


B

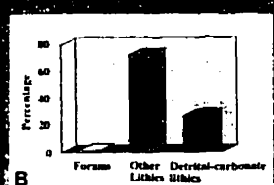
17500 (LGM)



A

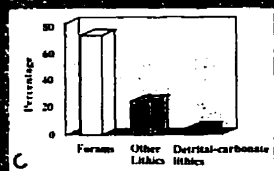


HL-2

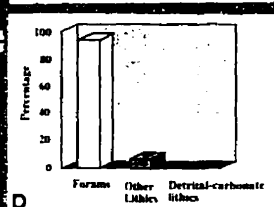


B

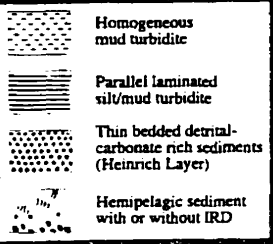
22700



C



D



250 cm

6.2. Distribution and depositional facies of Heinrich Layers in the Labrador Sea.

Study of the four most recent Heinrich layers in Northwestern Labrador Sea shows the presence of 4 types of Heinrich layers: Type I is represented by graded muds with floating coarse IRD throughout (facies N). Type II consists of millimeter- to centimeter-thick mud turbidites alternating with thin laminae of IRD (facies TI). Type III comprises centimeter-thick crudely laminated layers of IRD interbedded with mud turbidites (facies TH of Wang and Hesse, 1996). Type IV is made up of bioturbated hemipelagic sediments with IRD (facies HI; Hesse and Khodabakhsh, 1995; Khodabakhsh and Hesse, 1996; Figs. 6.4 and 6.9 to 6.12).

Type-I Heinrich layers predominate in the slope and upper-rise region. Type-II and III occur where the flow paths of spill-over turbidity currents lie under the iceberg drift route. They occur in the region of the middle slope (type II) and on the NAMOC levees (Type III; see Fig. 6.5). Compared to type-III, the number of turbidites and ice-rafted laminae is much greater in type-II. In the most distal regions (with respect to the Hudson Strait source), not reached by turbidity currents or nepheloid layers, type-IV is predominant (Fig. 6.5).

Previously, type-III has been interpreted as head-spill turbidites because of the lack of bioturbation and foram content, absence of grading, poor sorting and a close association with spill-over turbidites on the NAMOC levees (Chough and Hesse, 1980). However, these are also the characteristics of Heinrich layers (see section 6.1). The term headspill applies to large, channelized turbidity currents whose head is higher than the body, so that spillover from the head may occur on the levees (Hesse et al., 1987). While

Fig. 6.4. Depositional facies of Heinrich layers.

Type I: nepheloid-layer deposits consisting of graded carbonate-rich mud with floating IRD throughout (core 90-26, 240-260 cm); Type II: thin-bedded alternations of fine-grained millimeter- to centimeter-thick, carbonate-rich mud turbidites with laminae of ice-rafted debris, including dropstone structure (arrow; core 90-34, 255-275 cm). Type III: crudely laminated, centimeter-thick layers of IRD interbedded with mud turbidites (core 87-2, 57-77 cm); Type IV: bioturbated, detrital-carbonate rich hemipelagic sediments with IRD (core 88-7, 183-203 cm); the darker sediment in the lower half of the radiograph has a higher detrital carbonate content.



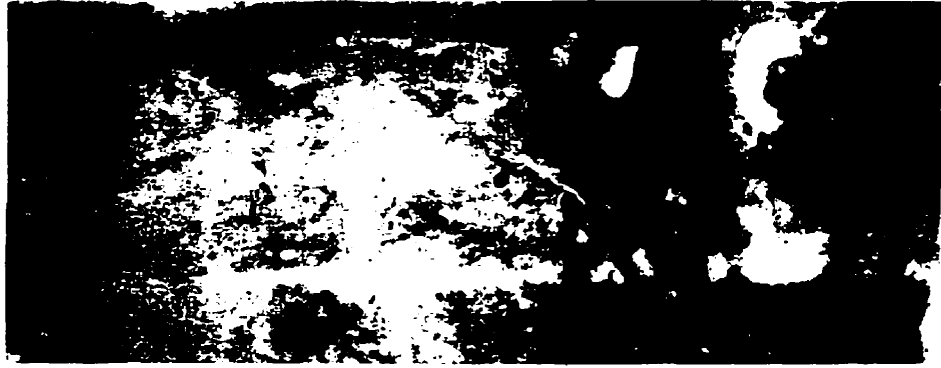
I



II



III

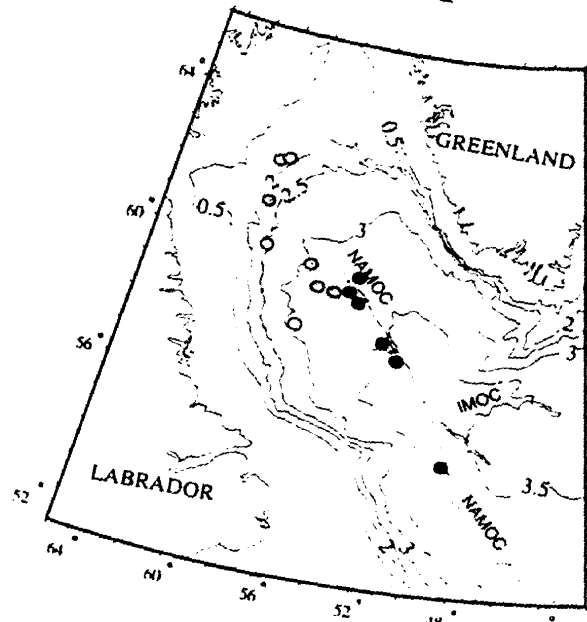


IV

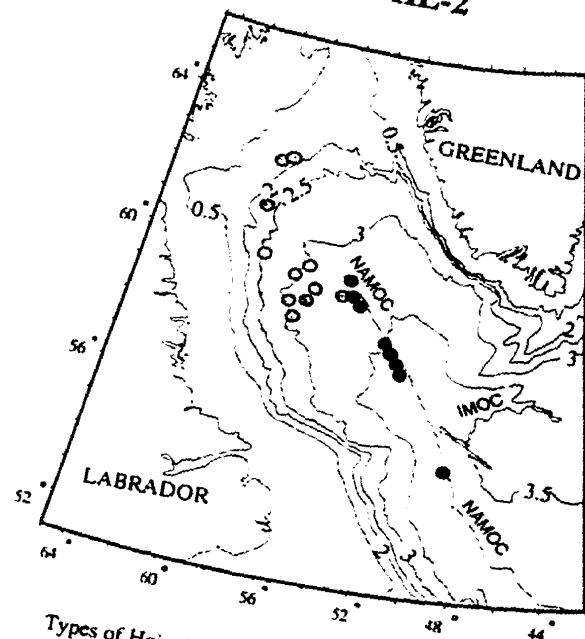
cm
0 5

Fig. 6.5. Thickness variation (lower part) and type (upper part) of Heinrich layers 1 to 4 (see text for details); Note: (i) a proximal-distal decrease (with respect to the Hudson Strait source) in the HL thickness, (ii) different distribution pattern for HL-3, (iii) occurrence of types II and III where the flow paths of spill-over turbidity currents lie under the iceberg drift route (i.e. the slope canyons and NAMOC), and (iv) the predominance of type-I in slope and rise cores proximal to the Hudson Strait, and type-IV in distal regions (i.e. HL-1).

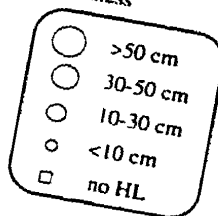
HL-1



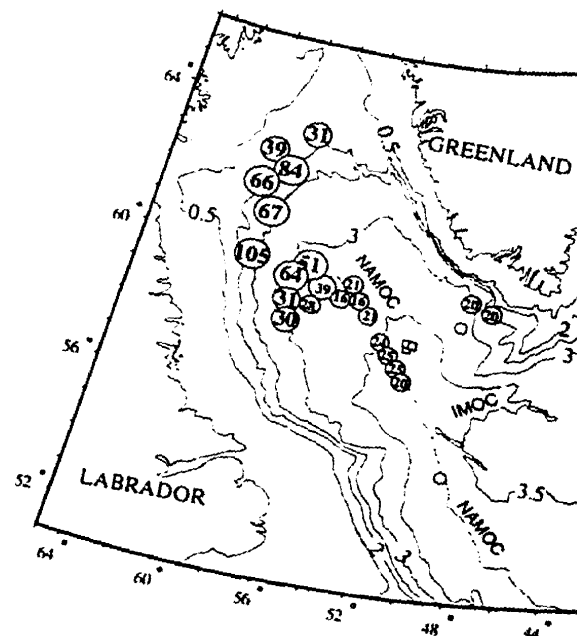
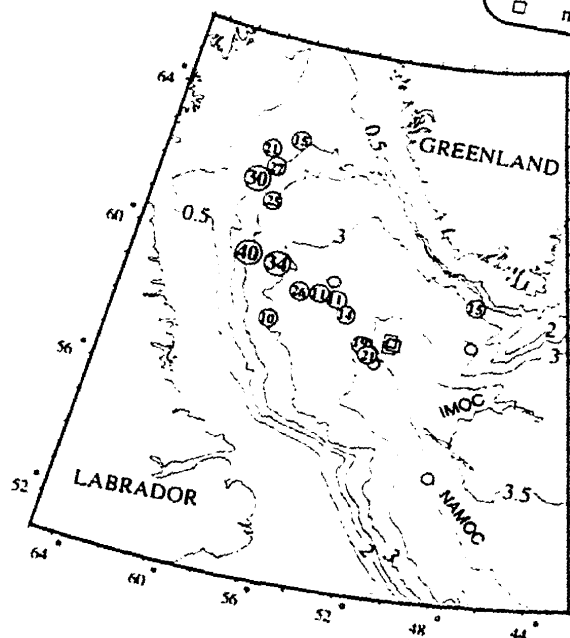
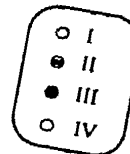
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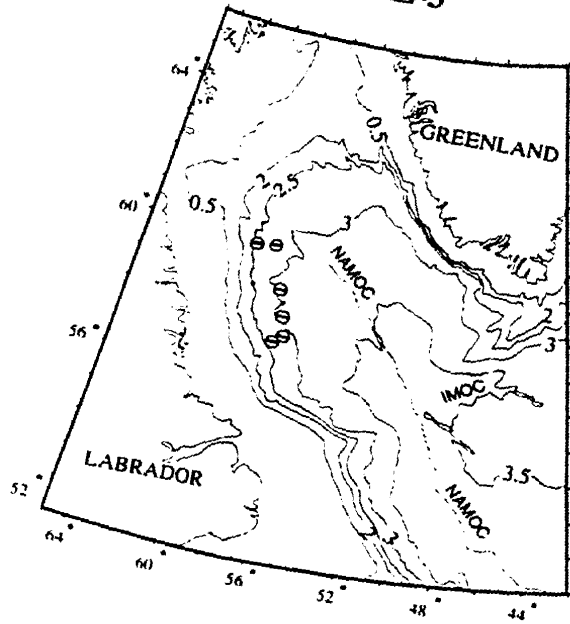
Thickness



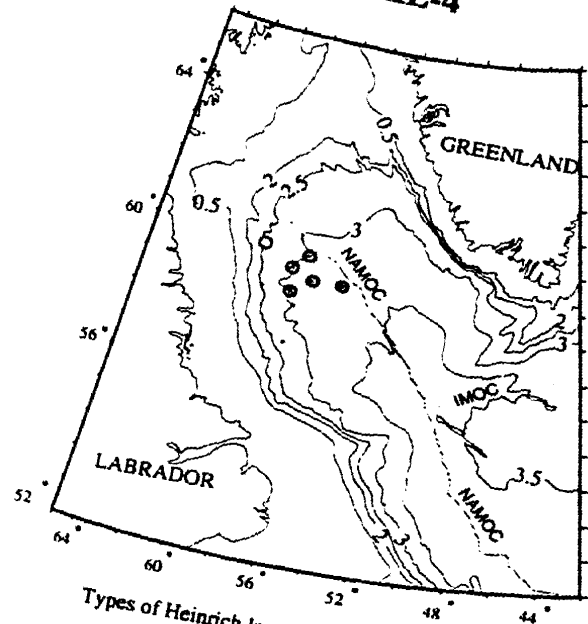
Types of Heinrich layers



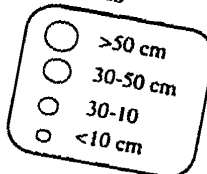
HL-3



HL-4



Thickness



Types of Heinrich layers

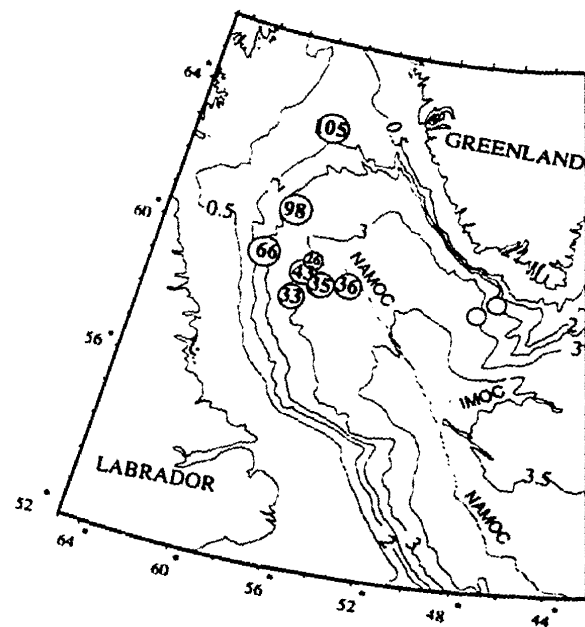
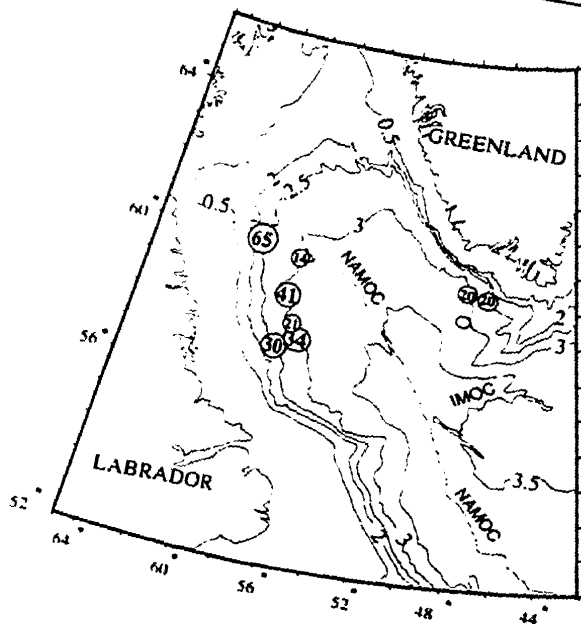


Fig. 6.6. Isopach maps showing thickness variations (in centimeter) for HL-1 and HL-2 in northwestern Labrador Sea, based on x-radiographs of 25 piston and trigger-weight cores (data for cores 75-54, -55, -56, -57 and 87-9 from Kirby, 1996; see Appendix 10 for details). Solid lines show areas of equal thickness of type I HL.

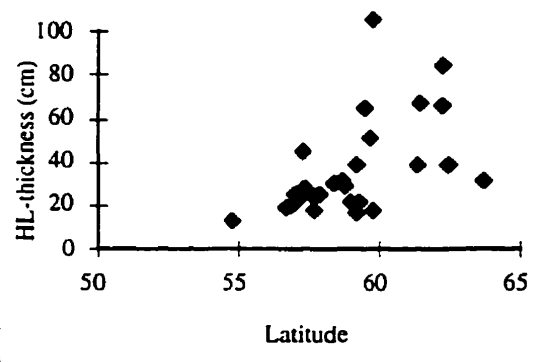
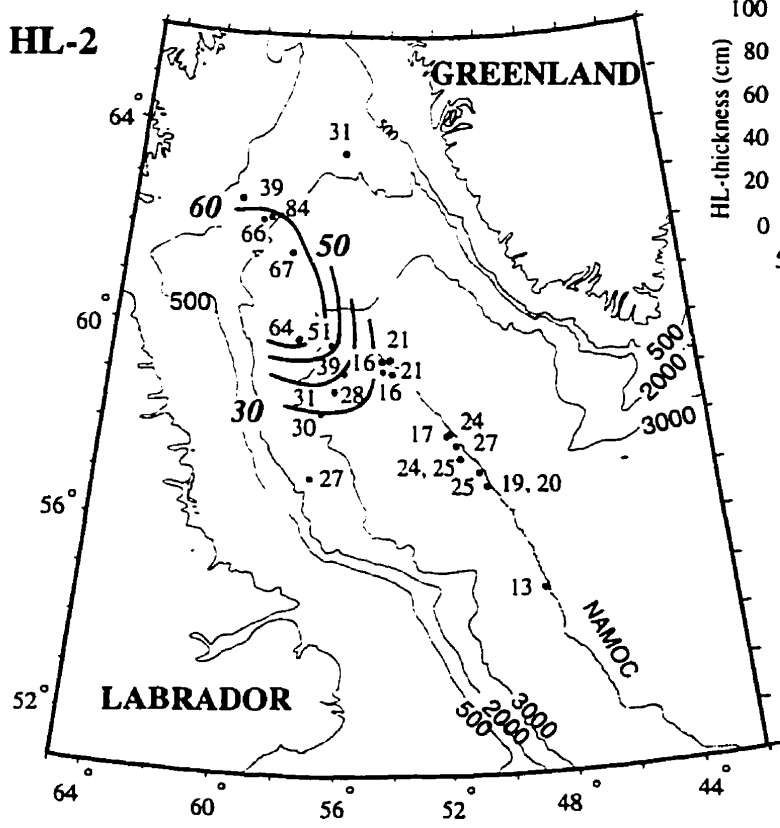
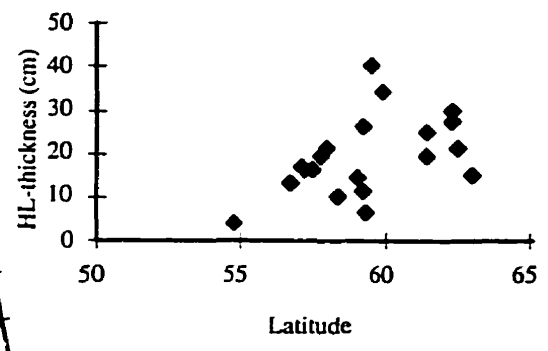
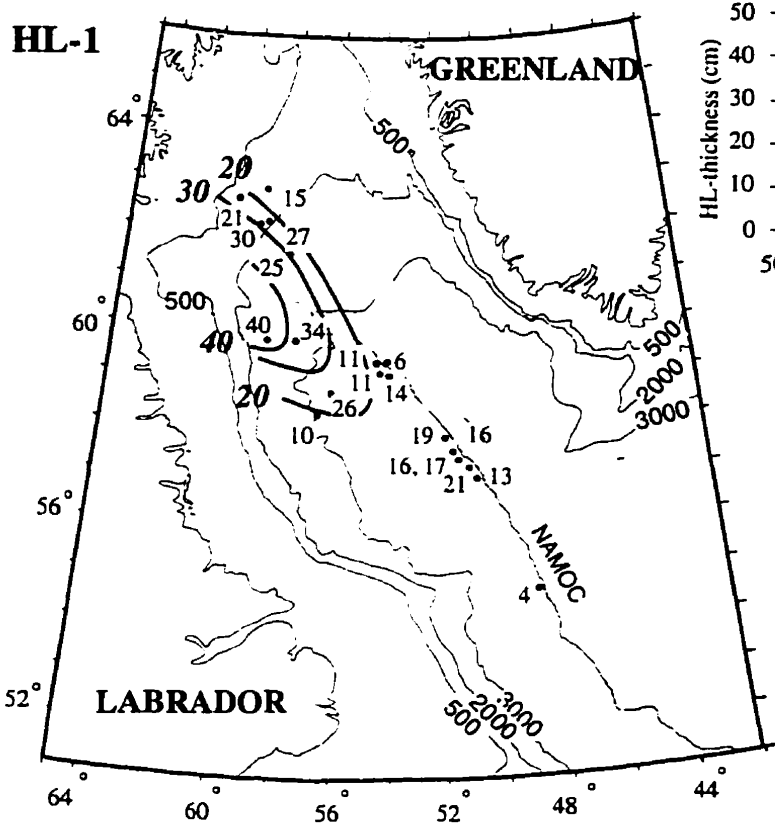
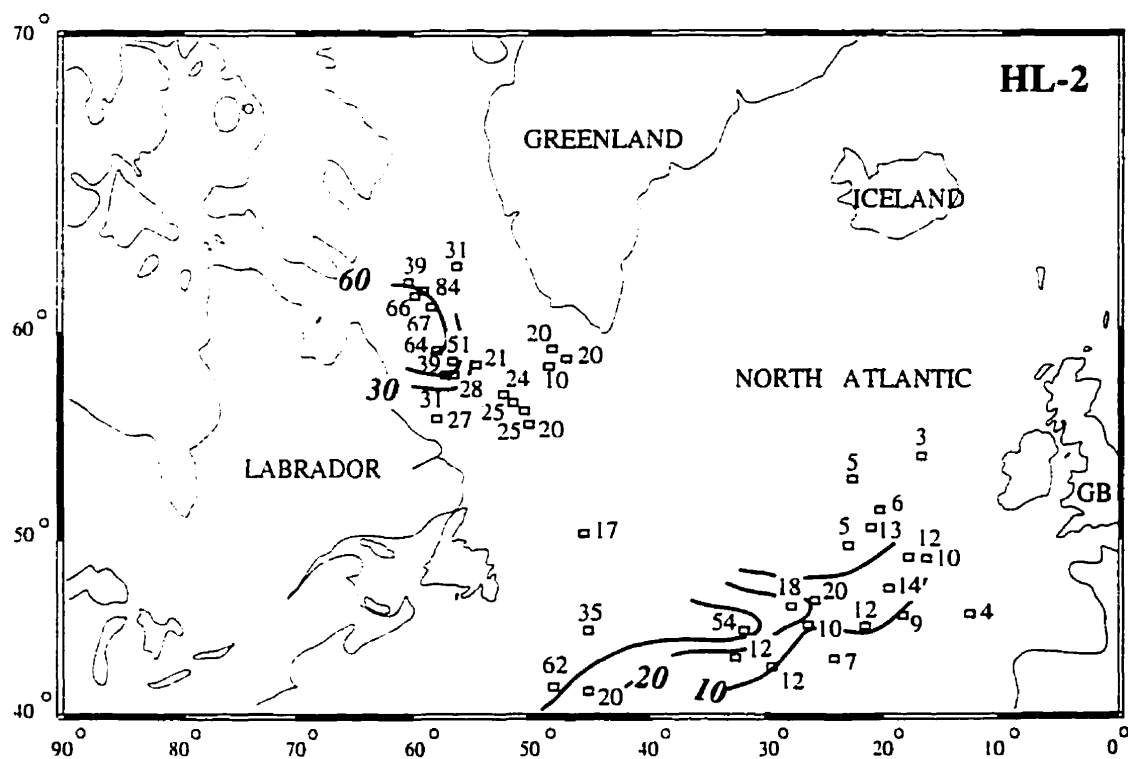
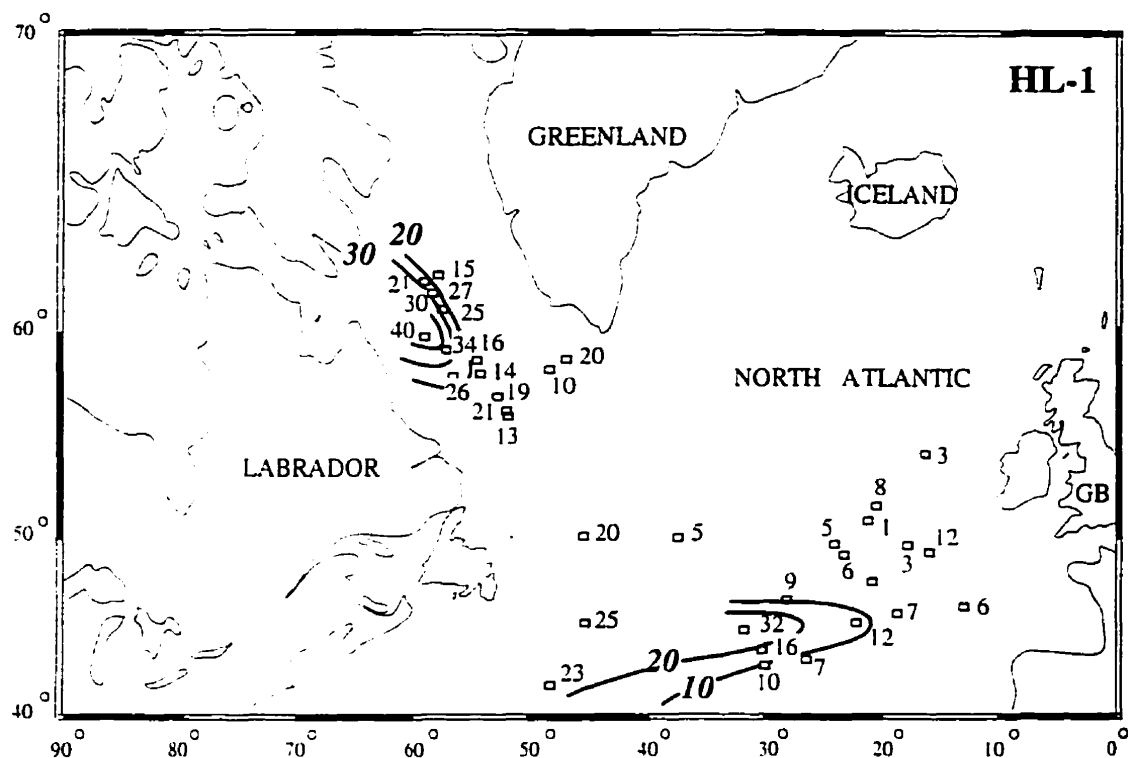


Fig. 6.6. Continued. Isopach map showing thickness variations (in centimetres) of HL-1 and HL-2 in northwestern Labrador Sea and North Atlantic (data for the North Atlantic cores from Bond et al., 1992 and Grousset et al., 1993). Solid lines show areas of equal thickness of type I HL in northwestern Labrador Sea and type IV HL (from Grousset et al., 1993) in the North Atlantic.



in type-III HL the parallel-laminated muds were deposited by turbidity currents, the gravelly-sand interbeds are ice-rafted in origin, evidenced by the presence of dropstone structures. Individual pebbles as large as 1.5 cm are present: an extraordinary turbidity current would be required to carry such grains and deposit them 200 m above the channel floor on the NAMOC levee. Both chronologically and lithologically these sediments are correlated with Heinrich layers in the slope and rise cores (see Ch. 7).

Compared to the remainder of the North Atlantic, the Labrador Sea Heinrich layers are distinct because of: (1) their greater thickness (up to 1 m, compared to a maximum thickness of 35 cm in core V23-16; Bond et al., 1992), (2) their complex depositional processes, and (3) high organic carbon content (up to 2.8%). 25-59% of the sediment is detrital carbonate. The coarse fraction ($>125\mu\text{m}$) comprises 13-27% of the sediment. Among the most recent four Heinrich layers, HL-2 is the thickest (up to 1 m thick in core 90-26; Fig 6.5, Appendix 10). The proximal-distal thickness variation of Labrador-Sea Heinrich layers with respect to the Hudson Strait is pronounced, particularly for HL-1 and 2, which were encountered in a large number of cores from the McGill core collection (Figs. 6.5, 6.6; see also Grousset et al., 1993; Dowdeswell et al., 1995). They have up to two orders-of magnitude higher detrital carbonate content in the sand fraction than the background hemipelagic sediments (see section 4.3.1). Compared to non-ice rafted sediments, rapid deposition of Heinrich layers resulted in better preservation of organic matter (see also Heinrich et al., 1989). Their organic-carbon content also shows a proximal-distal trend with respect to the Hudson Strait (see Fig. 4.10). A high proportion of type III kerogen in Heinrich layers indicates a dominant terrigenous (land

Table 6.1.
A: Sediment distribution in modern icebergs

Locality	sediment concentration of sediment-rich zone (%)			n
	<63 μ m	>63 μ m	Reference	
Antarctic	41.9	58.1	Anderson et al. (1980)	7
Spitsbergen	41.5	58.5	Dowdeswell and Dowdeswell (1989)	2
Alaska	30.9	69.1	Hoskin and Valencia (1976)	9
Average	36.4	63.6		

B: Carbonate concentration in coarse and fine fractions of Heinrich layer types. Data for type I from core 90-26 and 92-5; type II, core 90-34; type III, core 87-9 and type IV, cores 88-1, 88-7 and 90-29 trigger-weight core (see Appendix 5 for details).

HL type	CaCO ₃ %	<63 μ m	>63 μ m	n
Type I (nepheloid-layer deposits)	40.4	98.4	1.6	12
Type I (ice-rafted)	39.3	89.6	10.4	13
Type II	31.6	91.4	8.6	7
Type III (mud turbidite)	34.2	97.7	2.3	2
Type III (ice-rafted)	40.8	85.8	14.2	4
Type IV	32.6	82.4	17.6	6

Table 6.2. Comparison between detrital-carbonate content and the coarse fraction of Heinrich layers 1-4 in representative Labrador Sea cores. Data for cores 91-12, 13 and 94 from Hillaire-Marcel et al. (1994) and for core 75-56 from Kirby (1996).

Locality	Av. %CaCO ₃	Max. %CaCO ₃	Av. %>125 μ m	Max. %>125 μ m	n
Northern Labrador Slope (core 75-56)	40.5	53.9	7.3	14.8	11
Northern Labrador Slope (core 90-26)	39.7	59.4	11.2	27.4	12
Central Labrador Sea (core 87-9)	40.8	47.4	14.7	17.1	4
Southern Labrador Sea (core 91-94)	35.4	49.7	13.2	16.0	8
Greenland Rise (core 901-13)	17.1	32.4	23.2	40.0	6
Greenland Slope (91-12)	6.7	8.5	12.5	14.0	3

derived) source for the organic matter, in agreement with the findings of Muzuka and Hillaire-Marcel (1995) for a core in the southeastern Labrador Sea (core 91-94).

The distribution pattern and provenance of HL-3 in the North Atlantic is still not well established and its provenance debated. Andrews et al., (1994a) and Kirby (1996) suggested that HL-3 is absent in the Labrador Sea. However, the present thesis documents its presence in this basin (Fig. 6.11). The distribution pattern appears to be different from that of HL-1, 2 and 4, which may indicate a different iceberg trajectory during the time of deposition of this layer (possibly similar to that of HL-0; see Figs. 6.5 and 6.7).

Grousset et al. (1993) determined a different mineralogical composition (i.e. no carbonates) for the North Atlantic HL-3 and postulated a Greenlandian source for this layer. However, in the northwestern Labrador Sea, HL-3 has a high detrital carbonate content, which indicates a source similar to that for HL1, 2 and 4, i.e. the Hudson Strait

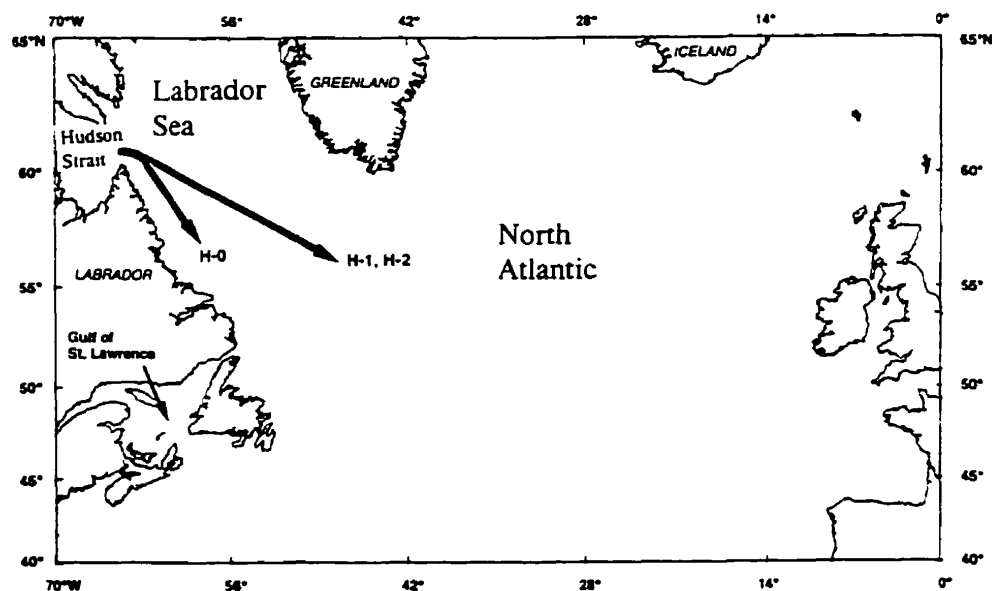


Fig. 6.7. Map of the North Atlantic showing probable transport pathways for Heinrich events 0, 1 and 2 (modified from Andrews et al., 1995).

(see Ch. 4). This is in agreement with findings of Hillaire-Marcel et al. (1994) and Bond et al. (1992) in the Labrador Sea and northwestern North Atlantic cores. It should be noted that the absence of HL-4 in the debris-flow dominated region of the DB, EA and EB canyon systems on Labrador Slope (i.e. cores 90-29, 88-11 and 92-6; Fig. 5.4) is likely due to erosion by mass flows.

6.3. Depositional mechanisms of the Labrador Sea Heinrich layers

Detrital carbonates in Heinrich layers occur both in the coarse and fine fractions. An unsolved problem is the high proportion of detrital carbonates in the fine fraction (<63 μm) of Heinrich layers. Observations on sediment distribution in modern icebergs indicate that >60% of the enclosed sediment are sand and gravel (Table 6.1). However, more than 84% of the detrital carbonate in type-I, -II and -III HL occur in the fine fraction and are unlikely, if not impossible, to have been exclusively supplied by icebergs (Table 6.1). It is notable that during the existence of the LIS, efficient grinding of bedrock might have increased the mud proportion over that seen in modern icebergs (see Hiscott and Aksu, 1996). The fine-grained detrital carbonate, which has been supplied as glacial flour to the Labrador Sea, has the same source as the coarse-grained detrital carbonate: Paleozoic carbonates underlying the Hudson Strait and adjacent regions (e.g. Baffin Bay; see section 6.1).

The coarse IRD may be randomly distributed throughout Heinrich layers (types I and IV) or may be concentrated in distinct layers, separated by sediments more or less free of IRD (types II and III). In the former case, deposition occurred by continuous rain-

out of coarse and fine material released from icebergs and finer sediment supplied simultaneously by nepheloid layers (type I) or hemipelagic settling (type IV). The high concentrations of carbonate-rich mud in type IV HL in Orphan Basin, south of the study area (44°N), indicate that Pleistocene icebergs supplied more mud compared to modern icebergs (see Hiscott and Aksu, 1996). During deposition of HLs the hemipelagic flux might have increased.

Concerning the latter case, deposition of coarse IRD was interrupted by episodic deposition from turbidity currents, which occurred at much higher frequency with type II than type III. Deposition of turbidite intervals was fast enough to form sediments free of IRD. Spill-over of turbidity currents occurred less frequently on the NAMOC levees

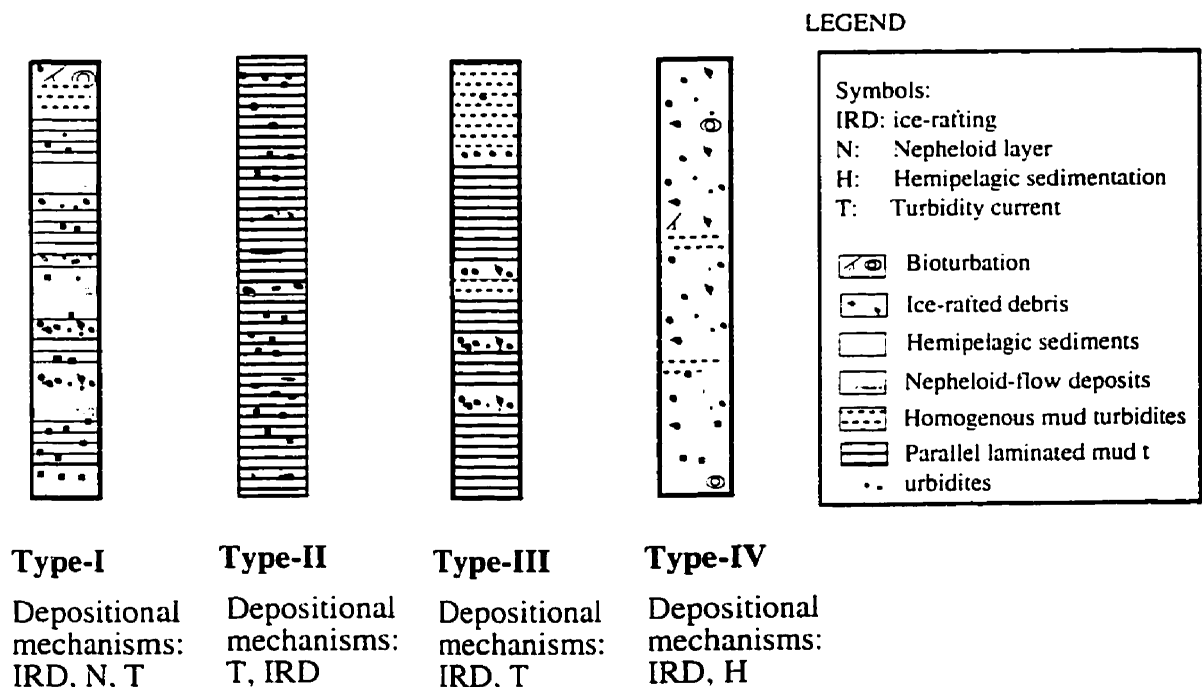


Fig. 6.8. A schematic illustration of depositional mechanisms of Heinrich layers in northwestern Labrador Sea (see section 6.3 for details).

than on the slope. In distal regions of the North Atlantic (with respect to the Hudson Strait source), deposition of coarse material from icebergs was the dominant source mechanism supplying terrigenous sediments to Heinrich layers of type IV. The fine fraction ($<63\mu\text{m}$) is subordinate in these regions (Fronval et al., 1995). In the Labrador Sea (with respect to the Hudson Strait source), detrital carbonate content of Heinrich layers shows a proximal to distal decrease (Table 6.2).

6.4. Origin of Heinrich events

Two models have been suggested for the causes of Heinrich events. The first is based on assumptions concerning geothermal heat flow and ice sheet thickness. During maximum glacial conditions the Laurentide Ice Sheet reached its greatest thickness. Increased thermal isolation resulted in geothermal heating under the ice producing wet-based glaciers. If this condition was accompanied by open-sea conditions in adjacent oceans, moisture-bearing storms would be guided poleward and the growth of the LIS would be enhanced (Ruddiman and McIntyre, 1981, Aksu et al., 1988). Glacial surges through the Hudson Strait and other outlets of the LIS would have lead to ice-rafting events (Oerlemans, 1991; binge-purge model of MacAyeal, 1993). The inherent unstable behavior of the LIS, overriding deforming sediments in the Hudson Strait-Hudson Bay region, may have enhanced the rapid ice surges across the Hudson Strait which triggered Heinrich events (Clark, 1994).

Glaciological evidence (e.g. Boyd et al., 1988) indicates a possible alternative senario. Hesse et al. (1994) and Johnson and Lauritzen (1995) suggested that subglacial

outburst floods (jökulhlaups) from a Hudson Bay lake dammed by ice at the mouth of Hudson Strait may have caused extensive iceberg discharges leading to Heinrich events. The binge-purge model would explain the periodic occurrence (i.e. 7-10 ka) of Heinrich layers, if they were not fed from the 3 or 4 northern hemisphere ice sheets synchronously. If ice sheet collapse occurred synchronously in North America, Greenland and Northern Europe, then external control is more likely, in which case outburst-flooding could have been the triggering event. Evidence supporting the subglacial outburst model includes the exposed canyons in the Hudson Strait on land (the York canyons on the Meta Incognita Peninsula), which presumably acted as spillways for the outburst events (Johnson and Lauritzen, 1995).

6.5. Discussion

Andrews et al. (1994b) and Kirby (1996) suggested meltwater plumes were one of the main supply mechanisms of fine detrital carbonates of Heinrich layers. However, as shown in section 5.1.1, this mechanism is insignificant in regions beyond the upper slope, while fine detrital carbonate forms a significant proportion of the fine grain-size fraction in all regions of the basin. An important depositional process for Heinrich layers is nepheloid-layers, which formed from sediment-laden meltwater from the LIS with high concentrations of suspended sediment spreading out in mid-water or on the sea floor and depositing Type I-HL. They are the most proximal Heinrich layers with respect to the Hudson Strait and can be traced for more than 300 km from the shelf break. Relatively slow deposition of the graded nepheloid-layer muds in type-I HL allowed incorporation

of IRD in sediment. Progressive loss of suspended material caused the Labrador-Sea nepheloid-layers to vanish basinward. Nepheloid-layer deposits do not occur in ice-rafted horizons between Heinrich layers, indicating that nepheloid layers were closely associated with Heinrich events and were the main transport mechanism for fine-grained detrital carbonate to proximal Labrador Sea sites during Heinrich events.

Recent studies have shown that spill-over turbidites of the NAMOC and its tributaries were derived from remobilization of detrital carbonate-rich sediments on the slope south of the Hudson Strait (see also Hesse et al., 1996; Ch.5). >50% of type-II and III HL are parallel-laminated mud turbidites. Therefore, turbidity currents are one of the processes responsible for the dispersal of fine detrital carbonates during Heinrich events in this region (Fig. 6.8). However, this mechanism is unlikely to be responsible for the supply of detrital carbonate to Heinrich layers in regions such as the Greenland Rise, although Hillaire-Marcel et al. (1994) proposed it spread to this region by turbidity currents.

Fig. 6.9. Correlation of Heinrich Layer 1.

X-radiographs of Heinrich Layer 1 (HL-1) in 7 piston and trigger-weight cores (two) from the Labrador Slope and Rise (see inset map for location). Numbers at top and bottom of X-radiographs = subsurface depths (in cm). The base of the HL-1 is used as reference level for the correlation. Two AMS ^{14}C ages give an extrapolated basal age for HL-1 of approximately 14 ky. HL-1 consists of an alternation of layers with a high concentration of ice-rafted debris (IRD) (darker layers indicating the coarser grain size of the sediment) and laminated turbidite muds with no IRD (e.g. core 90-25). Muddy graded layers with IRD correspond to type I HL (e.g. core 92-5, arrows). The highest number of ice-rafted layers (30) in the HL-1 was found in core 92-5. Note a downslope decrease in the HL thickness.

HEINRICH-LAYER 1

10 cm
0

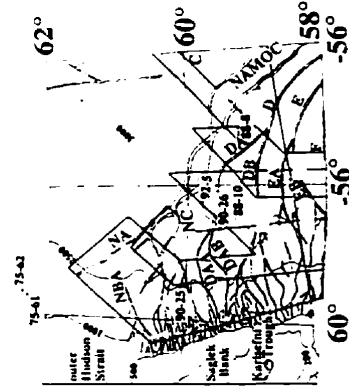




Fig. 6.9. Continued.

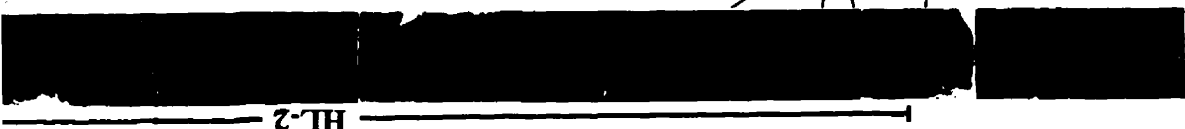
X-radiographs of HL-1 in a lower-slope piston core and 6 trigger-weight cores from the levees of the NAMOC levee (see inset map for location). Compared to the slope canyons, the number of ice-rafted layers and the thickness of HL-1 on the NAMOC levee are lower. This implies there were fewer turbidity currents coming through the NAMOC capable of spilling over during Heinrich Event-1 than there were turbidity currents coming through the slope canyons or nepheloid flows coming down the slope. An AMS ^{14}C age 25 cm below HL-1 in core 87-9 gave 17180 y. B.P. corresponding to the Last-Glacial Maximum (LGM).



Fig. 6.10. Correlation of Heinrich Layer 2.

X-radiographs of HL-2 in 10 piston and trigger-weight cores from the Labrador Slope and Rise (see inset map for location). Four AMS ^{14}C ages at the top and base of HL-2 give sedimentation rates of 41 (core 75-55) and 95 to 86 cm/ka (cores 90-26 and 92-5). The graded layers (arrows) in cores 90-26 and 92-5 from the lower slope are typical of type-I HL. Compared to more proximal middle-slope cores (e.g. cores 90-25 and 90-26), the HL thickness is significantly reduced on the rise (cores 88-10, 11) and distal lower-slope (cores 90-28, 29). Twenty one nepheloid-flow events can be tentatively traced from core to core in HL-2 on the lower slope.





HL-2

489 cm

75-61



747

75-62



21060

256

75-55



241

90-25



21070

285

90-26



20500

437

92-5



244

88-10



148

195

88-11
twc



33

81

90-28



113

160

90-29

HL-2

Fig. 6.10. Continued.

X-radiographs of HL-2 in 4 distal lower-slope piston cores and 4 trigger-weight cores from the right and left NAMOC levees (see inset map for location). Compared to more proximal middle-slope cores (e.g. cores 90-25 and 90-26) HL-2 is significantly thinner in this region. Cores 87-2, -5 and -9 from the NAMOC levee show typical type-III HL.

HEINRICH-LAYER 2

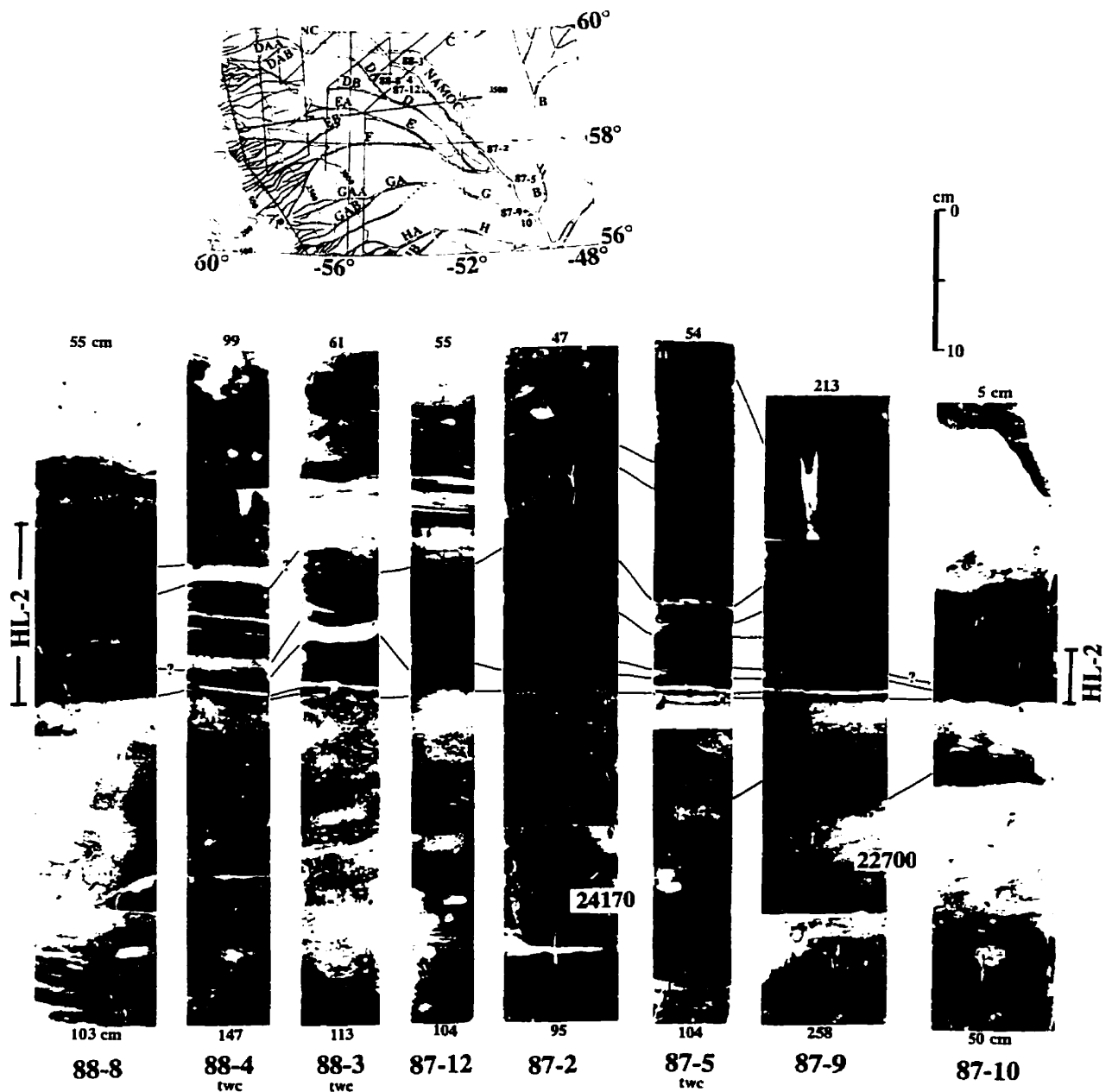
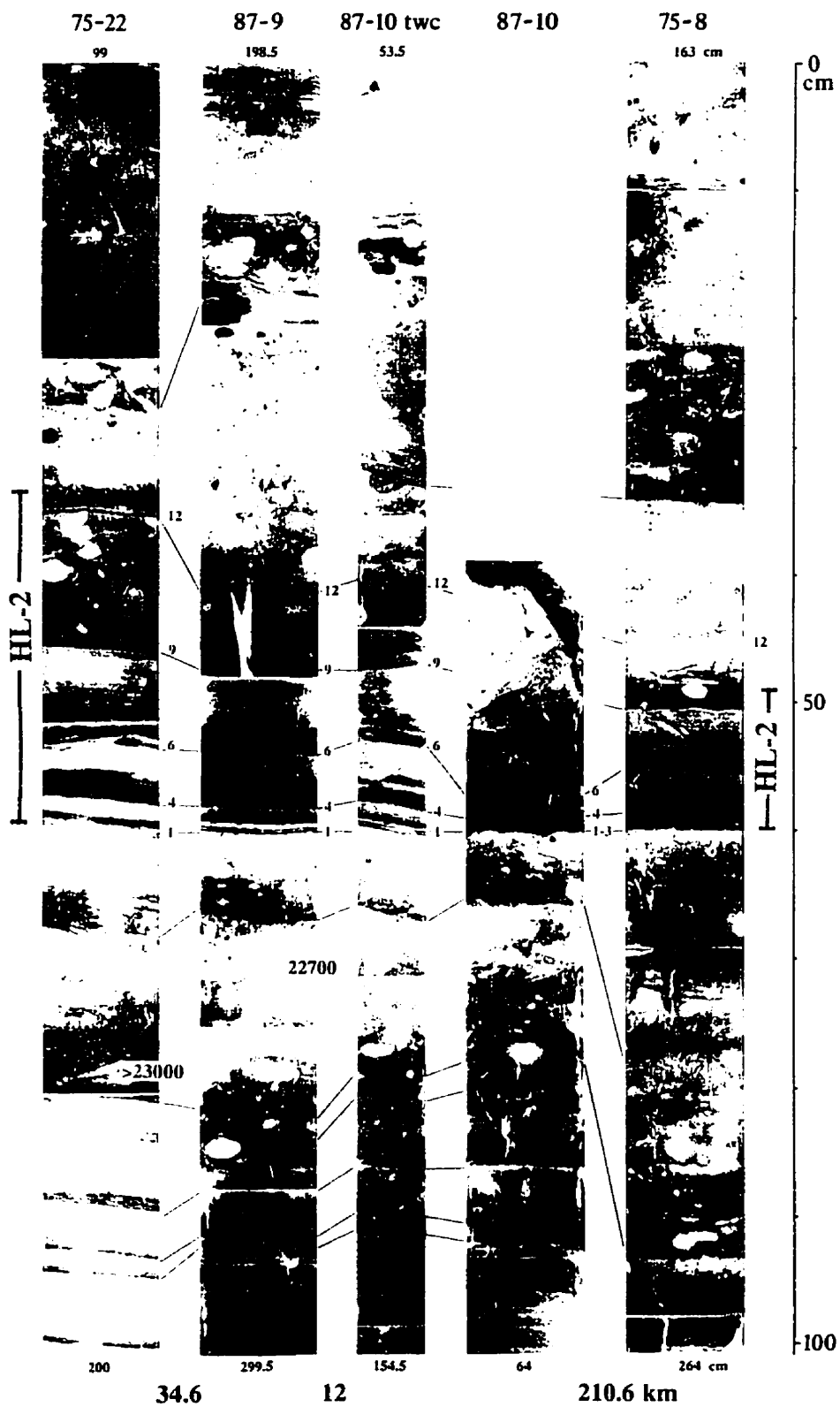


Fig. 6.10. Continued.

X-radiographs of HL-2 in 11 piston and trigger-weight cores from the right and left NAMOC levees (see inset map for location). Six layers of ice-rafted debris separated by thin mud turbidites can be traced from core to core (from Hesse, 1995a).



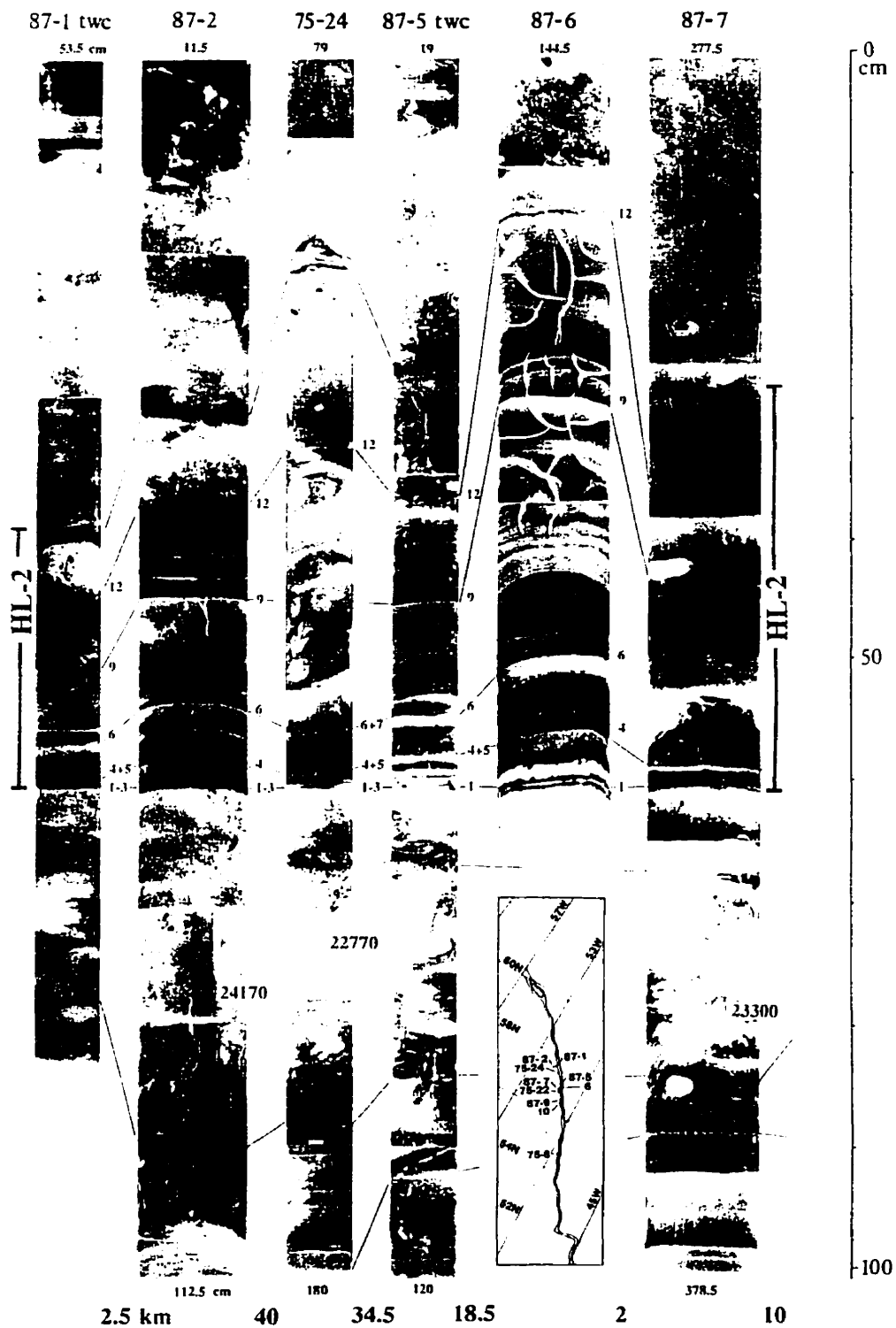


Fig. 6.11. Correlation of Heinrich-Layer 3.

A- X-radiographs of HL-3 in 5 piston cores from the middle and lower Labrador Slope (see inset map for location). Core 90-33 shows typical type-II HL. A 4-8 cm thick massive layer of IRD within HL-3 can be correlated in most cores. Distally, the HL thickness is reduced to 33 cm in core 90-33 from 58 cm in core 90-25.

B- Correlation of HL-3 in a lower slope core (92-4) with 3 lower-slope (90-26) and rise cores (88-11 and 92-6). HL-3 is 14 cm thick in slope core 92-4 and vanishes in the rise cores (except for rare mm thick layers of IRD, shown by arrows). The absence of HL-3 in this region may be due to a different iceberg trajectory during this period of time or slope erosion.

HEINRICH-LAYER 3

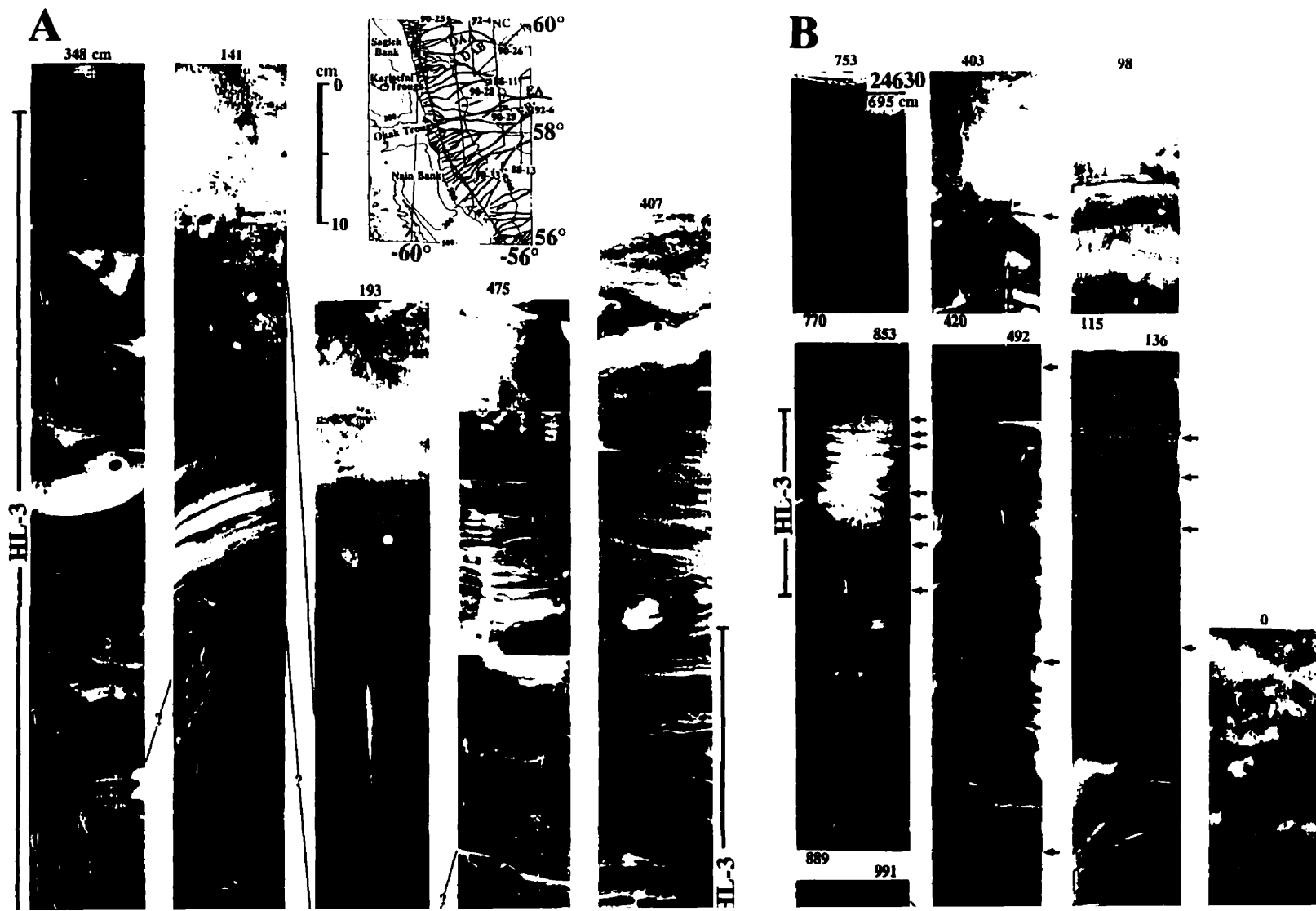




Fig. 6.12. Correlation of Heinrich-Layer 4.

X-radiographs of HL-4 in 6 piston cores from the mid-slope and rise (see inset map for location). The absence of HL-4 in the debris-flow dominated region (EB and F canyon systems, e.g. cores 90-29, 88-11 and 92-6) is likely due to erosion by mass flows. Numerous microfaults (? coring artifacts) in HL-4 hinders correlation between the cores. On the NAMOC levee, HL-4 is buried under a thick turbidite sequence and has not been penetrated by 15 m long piston cores.

HEINRICH-LAYER 4



CHAPTER 7: Stratigraphic correlation and glacial cycles

7.1. Glacial cycles and depositional processes

The stratigraphy of the northwestern Labrador Sea reflects the glacial history of the region. Most of isotopic stage 1 (13 ka to Recent; Fulton and Prest, 1987) represents the present Holocene interglacial climate. Some short re-advances of the LIS were reported between 11-8 ka (Miller and Kaufman, 1990; Andrews et al., 1987) before the final disappearance of glaciers from the Hudson Strait (8 ka, Josenhans et al., 1986; Dyke and Prest, 1987). Sediments deposited during most parts of stages 2 and 3 have high oxygen-isotope values (Fig. 4.1) indicating the presence of large ice sheets. In the southern Labrador Sea (core 91-94), oxygen-isotope values of stage 3 are lower than those of stage 2 (fig. 17 of Hillaire-Marcel et al., 1994), implying less intense glacial conditions or stronger meltwater input during this period. During stages 2 and 3, an open-sea condition with seasonal ice prevailed in the Labrador Sea (Fillon and Duplessy, 1980; Fillon and Aksu, 1985; Rahman and de Vernal, 1994). The persistent presence of IRD in sediments deposited during this time supports this interpretation. Compared to isotopic stage 3, deposition by ice-rafting intensified during stage 2 (Fig. 6.2). Maximum glacial conditions occurred around 18 ka (Dyke and Prest, 1987), characterized by high O-isotope values (Fig. 4.1) and abundant IRD (Fig. 6.2).

Three major deglaciations (10, 14 and 37 ka), a glacial advance (18 ka) and an ice sheet collapse (27 ka) were documented (Table 7.1). Deglaciation episodes coincide with Heinrich layers 0, 1 and 4(?). Prior to HL-1 and HL-2, oxygen-isotope values and proportion of *N. pachyderma* gradually decrease (Fig. 4.1). During isotopic stages 2 and

3, the foraminifera concentration is low in the slope sediments, probably due to dilution by rapidly accumulated IRD. Both prior to and after HL-2, oxygen isotope values were high ($>4.2\text{‰}$), suggesting intense glacial conditions (see also Andrews et al., 1994). Therefore, the light oxygen-isotope values associated with HL-2 are probably due to iceberg melting (Fig. 4.1, see also Andrews et al., 1994).

No distinct oxygen-isotope variation accompanies HL-4 (Fig. 4.1). However, in North Atlantic DSDP Site 609, HL-4 is associated with light oxygen-isotope values followed by a dramatic decrease in the proportion of *N. pachyderma* (Bond et al., 1993), which may indicate a deglaciation phase, as suggested by Andrews and Miller (1984). Kirby (1996), on the other hand suggested that prior to Heinrich Event 4, the LIS may have attained its maximum extent. This was inferred by the unusual thickness (up to 1 m) of HL-4 in the northwestern Labrador Sea. However, Dredge and Thoreifson (1987) suggested that compared to the Late Wisconsinan (23-12 ka) the LIS was smaller during the Middle Wisconsinan (65-23 ka). As shown in Chapter 6, the unusual thickness of HLs in the northwestern Labrador Sea is mainly due to incorporation of sediment supplied by nepheloid layers and turbidity currents and is, in all likelihood, not an indicator of ice extent.

It is noteworthy that depositional processes during Heinrich Event 4 may have been different from those of younger events. Deposition of extensive tills (the Lower Till unit of Josenhans et al., 1986; the Baffin Shelf Drift of Praeg et al., 1986 and MacLean et al., 1990), which extended to the shelf edge, may have occurred during this period of time. In this case the LIS may extended to the shelf break (as suggested by Kirby, 1996).

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[illegible]

References: 1, Andrews et al (1994); 2, Andrews and Miller (1984); 3, de Vernal and Hillaire-Marcel (1987); 4, Dredge and Thorleifson (1987); 5, Dyke and Prest (1987); 6, Josenhans et al. (1987); Wisconsinan Glaciation boundaries from Fulton and Prest (1984).

A significant portion of debris flow deposits in the Labrador Slope may have been deposited prior to and after Heinrich Event 4 (see cores 90-26, 29, 33, 34 and 92-6 in Fig. 7.1). They may indicate a high slope instability during Heinrich-Event 4. However, with presently available information the temporal relationship between these debris flow deposits and glacial cycles cannot be established beyond doubt. Sediments older than 43 ka were probably deposited during a glacier retreat phase (Dredge and Thorliefson, 1987), as marked by a decrease in oxygen-isotope values in sediments older than 45 ka (Ch. 4).

Facies H and C are predominant during low-sediment discharge periods (i.e. interglacial, interstadials or glacial times, Table 7.2). A significant portion of the Labrador Sea sediments was deposited during glacial and deglacial times, when nepheloid layer deposits and turbidites with abundant IRD were predominant (Tables 7.2 and 7.3). These sediments were deposited in short periods of time (<1000 years, Ch. 6) with high sedimentation rates (up to 100 cm/ka; Table 5.4). These periods may be associated with debris flow deposits. Deposition of facies N requires effective subglacial processes. The presence of plumites on the upper slope indicates that meltwater supply was significant in front of glaciers even during the cold isotopic stage 2. The presence of contourites in isotopic stages 2 and 3 indicates that deep-water production did not entirely cease during this period (Ch. 3), although it may have been substantially diminished at certain times (e.g. during Heinrich events).

7.2. Lithostratigraphic units

In contrast to the adjacent shelf, where major parts of the Quaternary stratigraphic

sequence have been eroded by the last Wisconsinan glaciation (e.g. Josenhans et al., 1986; Josenhans, 1990), sediments of the Labrador Slope, Rise and the Basin centre are relatively well preserved. On the Labrador margin, sedimentary facies change rapidly over short distances, but stratigraphic correlation is now possible in many cores with the aid of HLs. Correlation of local facies (e.g. plumites or contourites) with other facies can be achieved on a regional scale where ^{14}C dates are available.

Before 1992, a stratigraphic subdivision of the Quaternary sediments on the Labrador Slope that could be applied on a regional scale did not exist. Age controls were few, and most of the units could only be used locally (e.g. Chough et al., 1987; de Vernal and Hillaire-Marcel, 1987; Table 7.1). Attempts to obtain a detailed stratigraphy for the Labrador margin were thought to be doomed to failure because of the large terrigenous input during the last glaciation (e.g. Mudie and Hardy, 1990). However, Wang (1992) found the sedimentary sequences on the margin are relatively continuous and well preserved in deep sea cores. For the first time a lithostratigraphic subdivision of the Labrador Slope sediments into 15 stratigraphic units was proposed for the last 60 Ka (Wang and Hesse, 1996). These units were tentatively correlated in 13 cores up to 350 km apart on the Labrador Slope, although firm correlation was only possible for nearby cores (e.g., cores 90-28 and -29; cores 90-33 and -34). Wang (1992) was also the first to relate lithologic variations to glacial cycles during the Wisconsinan glaciation. Deposition of 6 hemipelagic units was tentatively attributed to 6 intervals of glacial retreat. Other local units had been suggested by Chough et al. (1987) and Hesse et al. (1987) for the NAMOC levees comprising four stratigraphic intervals: (i) the upper

hemipelagic sediments (<9 ka), (ii) the upper turbidites, (iii) the lower hemipelagic sediments (17-25 ka), and (iv) the lower turbidites (>25 ka).

Since 1992, the stratigraphy for the Labrador Slope has been significantly improved by additional radiocarbon ages (cores 92-1 to -6, 87-9, 84-8, -9 and -16), isotopic data (cores 90-26, 84-8, -9 and -16), and analysis of Heinrich layers (Khodabakhsh and Hesse, 1997). The latter are used here for the first time as principal markers to define the Quaternary lithostratigraphic units as their synchronicity across the Labrador Sea and North Atlantic has now been established beyond doubt (e.g. Grousset et al., 1993; Dowdeswell et al., 1995).

The lithostratigraphic units used in the present thesis (modified after Wang and Hesse, 1996), are correlated for the first time in a regional scale. In most cases, the lithostratigraphic boundaries of Wang and Hesse (1996) remain unchanged. For simplification, the labelling order of units is slightly modified, so that they can be directly related to Heinrich layers. Seven major lithostratigraphic units were identified. The base of the six most recent Heinrich layers (HL-0 to 5) was used for unit boundaries. Each unit consists of an upper and a lower subunit a and b respectively. Upper subunit a consists of hemipelagic sediments, whereas Heinrich layers or equivalents constitute lower subunit b (Fig. 7.1).

7.2.1. Unit 0

Unit 0 consists of two subunits. *Subunit 0a* is the most recent Holocene sediment deposited during isotopic stage 1 after deglaciation (10 ka, Andrews et al., 1987). It is

Table 7.2. Relationship between lithostratigraphic units and facies associations in the Labrador Slope, Rise and NAMOC levees. Cooling cycles from Dansgaard et al. (1993); numbers on these cycles are interstadials.

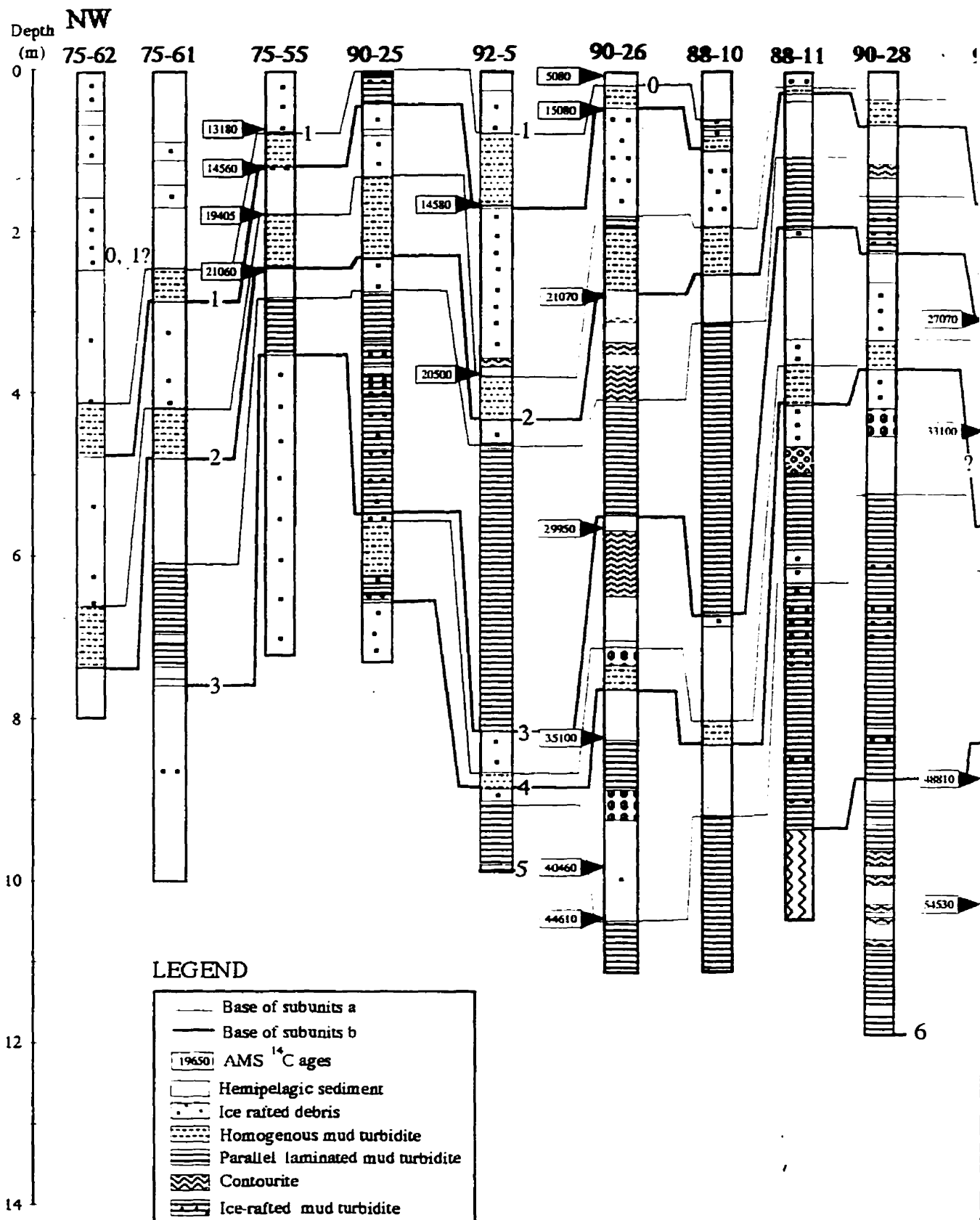
¹⁴ C ages	oxygen Isotopic stages	Cooling cycles	Heinrich layers	Lithostratigraphic units		Lithology		
						Slope	Rise	NAMOC levee
~14.5	1	YD	HL-1	Unit 0	0a	■ ■	■ ■	■ ■
					0b HL-0	■ ■ ■ ■	■ ■ ■ ■	■ ■ ■ ■
				Unit 1	1a	■ ■ ■ ■	■ ■ ■ ■	■ ■ ■ ■
					1b HL-1	■ ■ ■ ■	■ ■ ■ ■	■ ■ ■ ■
~20.5	2	2	HL-2	Unit 2	2a	■ ■ ■	■ ■ ■	■ ■ ■
					2b HL-2	■ ■ ■ ■	■ ■ ■ ■	■ ■ ■ ■
~27-29		4	HL-3	Unit 3	3a	■ ■ ■ ■	■ ■ ■ ■	■ ■ ■
					3b HL-3	■ ■ ■ ■	■ ■ ■ ■	■ ■ ■ ■
~35.5		8	HL-4	Unit 4	4a	■ ■ ■ ■	■ ■ ■ ■	?
					4b HL-4	■ ■ ■ ■	■ ■ ■ ■	?
~49	3	12	HL-5	Unit 5	5a	■ ■ ■ ■	■ ■ ■ ■	?
					5b HL-5	■ ■ ■ ■	■ ■ ■ ■	?
~55				Unit 6		■ ■ ■ ■	■ ■ ■ ■	?

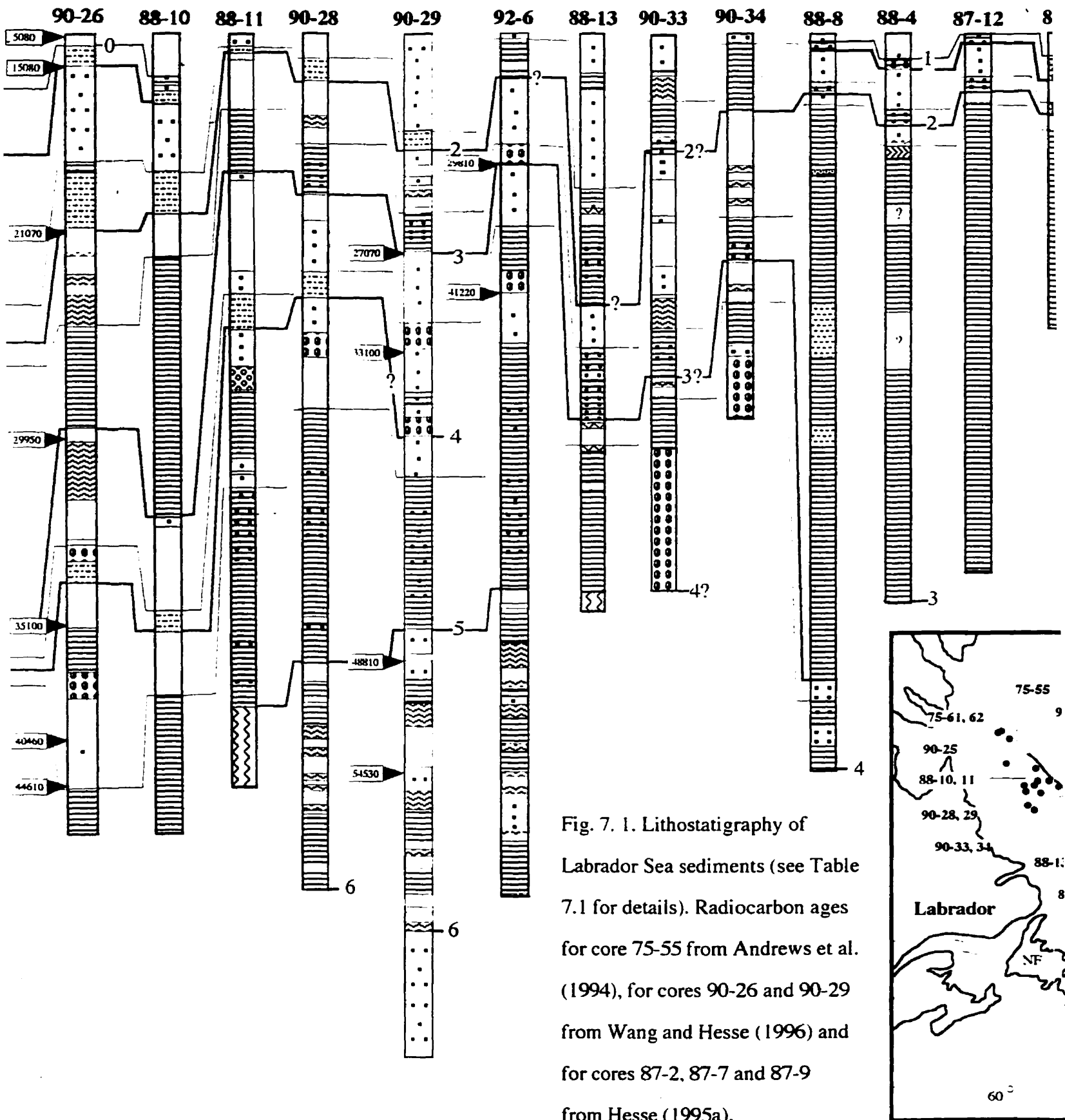
LEGEND

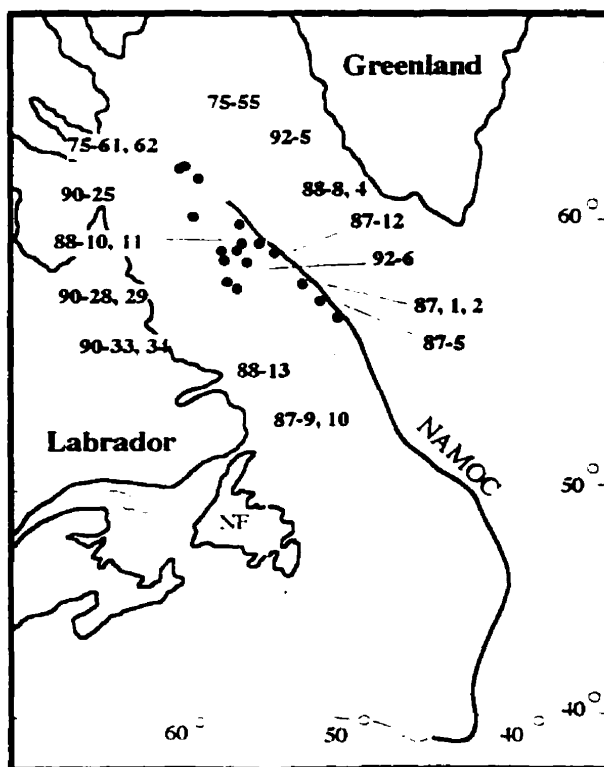
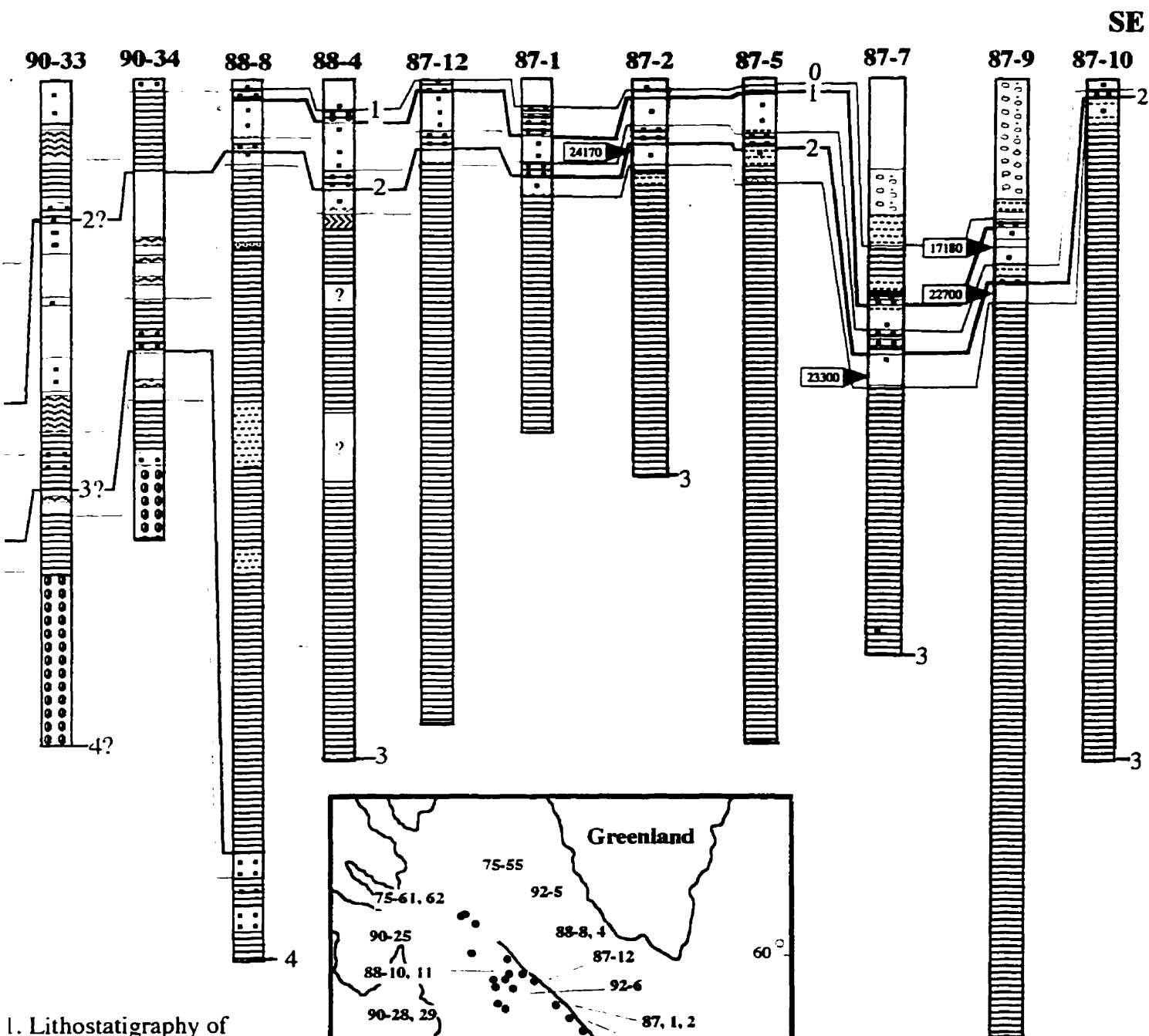
■ ■ Ice-rafted debris	□ Hemipelagic sediments	■ ■ Nepheloid-layer deposits	■ ■ Debris-flow deposits
■ ■ Plumites	■ ■ Parallel-laminated silt/mud turbidites	■ ■ Contourites	

Table 7.3. Relationship between sedimentary facies and glacial cycles.

Glacial unit	Sediment facies				
	C	H/Hi	N	T/Ti	
Interglacial	—?—	—			C Contourite
Deglacial	—?—	—	—	—	H, Hi Hemipelagic sediment (with/without IRD)
Glacial	—	—	—	—	N Nepheloid-layer deposit
					T, Ti Turbidite (with/without IRD)
					D Debris-flow deposits







1. Lithostatigraphy of
or Sea sediments (see Table
details). Radiocarbon ages
75-55 from Andrews et al.
for cores 90-26 and 90-29
ang and Hesse (1996) and
s 87-2, 87-7 and 87-9
esse (1995a).

absent or <50 cm thick in most cores because of heavy core-top loss (up to 1.1 m) during coring. This subunit consists of intensely bioturbated hemipelagic sediments with abundant foraminifera and siliciclastic IRD (facies HI). Agglutinated foraminifera predominate (Fig. 4.5). Three AMS ^{14}C ages for the top and middle of this unit gave values of 5850 ± 70 (core 90-26, Isotracer lab # TO-3145), 9450 ± 110 , and 9719 ± 140 years BP, respectively (cores 84-8 and -9, Isotracer lab # TO-5212 and TO-5213, respectively; Fig. 7.1). Equivalents of *subunit 0a* in adjacent regions are: (1) the Makkaq Clay on the Labrador Shelf (8-5 ka, Josenhans et al., 1986), (2) the upper hemipelagic unit on the NAMOC levees (<8.6 ka, Hesse et al., 1987), (3) probably Resolution Island lag and Tiniktartuq clays on Baffin Island (<11.3 ka, Praeg et al., 1986), and the hemipelagic silty mud unit (<11.5 ka) of de Vernal and Hillaire-Marcel (1987) on the Labrador Rise (core 84-21). The low detrital carbonate content of this subunit indicates that the Hudson Strait Ice stream, when it was still in existence prior to 8 ka (Josenhans and Zevenhuizen, 1990), had little influence on deposition of these sediments.

Subunit 0b corresponds to HL-0 with a basal age of 11391 ± 48 (Kirby, 1996). HL-0 was reported by Kirby (1996) for a nearby location (core 75-56). With present available data, it is not possible to differentiate this subunit from the overlying subunit *0a* in any of studied cores. This needs to be further elaborated with new radiocarbon dating in the future.

7.2.2. Unit 1

Unit 1 consists of two subunits, from top to bottom 1a and 1b. *Subunit 1a* consists

of ice-rafted hemipelagic sediments. A radiocarbon dating at the base of this subunit gave age of 13185 ± 190 years BP (core 75-55, Isotracer lab# AA6851; Andrews et al., 1994). Due to the lack of radiocarbon ages, it is not possible to differentiate this subunit with the overlying unit 0 in most cores (see section 7.2.1). *Subunit 1b* consists of facies N, TI and occasionally T (Table 7.2). It corresponds to HL-1 with bottom age around 14560 ± 105 , 14580 ± 90 and 15080 ± 120 years BP, respectively (cores 75-55, 92-5 and 90-26, Isotracer lab # AA-5999, TO-5215 and TO-3146; Andrews et al., 1994; Wang and Hesse, 1996, Fig. 7.1). *Subunit 1b* is equivalent of the Qeovik Silt (11-15 ka, Josenhans et al., 1986) on the adjacent shelf, the upper part of the Upper Davis Strait Silt (11-25 ka, Praeg et al., 1986) on Baffin Shelf, the upper turbidites on the NAMOC levee (Hesse et al., 1987, and Hesse, 1995a), and the upper part of the gravelly mud unit (11.5-17 ka) of de Vernal and Hillaire-Marcel (1987) on the rise. A high detrital carbonate content of *subunit 1b* indicates a Hudson Strait source. This subunit was deposited during a deglaciation phase (centred at 14 ka, Josenhans et al., 1986; Andrews and Miller, 1984; Andrews et al., 1994; Table 7.1).

7.2.3. Unit 2

Unit 2 consists of two subunits, from top to bottom 2a and 2b. *Subunit 2a* consists of hemipelagic sediments with low foram content, abundant siliciclastic IRD, and low detrital carbonate content. For the middle of the subunit an age of 17180 ± 130 years BP (core 87-9, Isotracer lab # TO-5214) was obtained (Fig. 7.1). A radiocarbon date from the base of this subunit gave age of 19405 ± 210 years BP (core 75-55, Isotracer lab # AA-

4700; Andrews et al., 1994). Based on this age this subunit correlates with the Upper Till (15-20 ka) of Josenhans et al. (1986) on the shelf. The detrital carbonate content of the Upper Till is also low, implying a similar sediment source on the Canadian Shield. Deposition of the lower part of these sediments occurred during the Last Glacial Maximum (18 ka, Dyke and Prest, 1987), when the glaciers had prograded to the shelf edge (Fillon and Harms, 1982; Fig. 2.2). The predominance of cold-water *N. pachyderma* (left coiling)(>95%) among the planktonic foraminifera supports this interpretation.

Subunit 2b corresponds to HL-2 and comprises facies N, TI, and rarely HI (Table 7.2). Detrital-carbonate lithics predominate. The bottom of this subunit has an age of 21060 ± 240 to 21070 ± 200 years BP (cores 75-55, 90-26 and 92-5; Andrews et al., 1996; Wang and Hesse, 1996; Fig. 7.1). *Subunit 2b* correlate stratigraphically with the Hudson Strait till (20-25 ka) of Josenhans (1990) on the adjacent shelf, and parts of the Upper Davis Strait Silt (20-25 ka, Praeg et al., 1986) on the Baffin Shelf.

7.2.4. Unit 3

Subunit 3a consists of hemipelagic sediments with relatively little IRD (facies H). The top and middle ages of this subunit range from 21060 ± 240 to 21070 ± 200 (cores 75-55, 90-26 and 92-5) and 22770 ± 190 years BP (cores 87-9, 75-4, Isotracer lab # TO-3144 and I-9814, respectively; Andrews et al., 1994; Hesse, 1995a; Hesse et al., 1987). On the lower slope and upper rise this subunit comprises facies C and H. *Subunit 3a* has been correlated with the lower hemipelagic sediments (22->25 ka; Hesse, 1995a) on the NAMOC levee.

The base of *subunit 3b* corresponds to HL-3; on the slope, this subunit consists of turbidites with layers of IRD (e.g. core 90-29; Fig. 7.1). On the basin centre, sediments of this subunit have no IRD (e.g. core 87-9; Fig. 7.1). Sediments immediately below the base of *subunit 3b* have ages between 27070 ± 270 to 29950 ± 270 years BP (cores 90-29, 90-26; Isotracer lab # TO-2994 and TO-2367, respectively). The upper slope plumes (core 92-1, 22-28 ka) are local equivalents of this subunit. Other stratigraphic equivalents are the Lower Till (top age >20-25 ka) of Josenhans et al. (1986) on the adjacent shelf, and the Baffin Shelf Drift and Lower Davis Strait Silt (top age >20-25 ka, Praeg et al., 1986) on the Baffin Shelf, and the lower turbidites (23-27 ka; Hesse, 1995a) on the NAMOC levee (Table 7.1). Sediments below *subunit 3b* were not penetrated in the NAMOC levees because of the great thickness of this subunit (up to 8 m).

7.2.5. Unit 4

Subunit 4a comprises hemipelagic sediments with low amounts of IRD (facies H). On the lower slope and upper rise, *subunit 4a* may contain contourites (e.g. core 90-26; Fig. 7.1).

The base of *subunit 4b* is correlated with the base of HL-4, characterized by facies N and TI with abundant detrital carbonates (Table 7.1). A radiocarbon date close to the base of this subunit gave an age of 35100 ± 360 years BP (core 90-26, Isotracer lab # TO-2437). Locally, in the middle slope region two debris-flow deposits occur in the upper and lower part of this subunit. This subunit may be the equivalent of the Lower Till of Josenhans et al. (1986) on the adjacent shelf and the Baffin Shelf Drift of Praeg et al.

et al. (1986).

7.2.6. Unit 5

Subunit 5a consists of hemipelagic sediments with very little IRD (facies H). A radiocarbon date in the middle of these sediments gave age of 40460 ± 530 years BP (core 90-26, Isotrace lab # TO-2438).

Subunit 5b is dominated by facies TI which may be correlated with HL-5 (Tables 7.1 and 7.2). A radiocarbon date 40 cm below the base of *subunit 5b* gave age of 48810 ± 1130 years BP, respectively (core 90-29; Isotrace lab # TO-2996). These sediments may have been deposited during similar conditions as those of subunit 3b, i.e. glacial advance. However, terrestrial glacier studies on adjacent lands indicate a glacial retreat phase prior to 43 ka (Dredge and Thorliefson, 1987).

7.2.7. Unit 6

Unit 6 is observed in three slope cores (90-28, 29 and 92-6). It consists of alternating hemipelagic sediments, turbidites and contourites. In general, compared to higher stratigraphic units, sediments are more intensely bioturbated with very little or no IRD. Hemipelagic sediments are more abundant in the upper part. A radiocarbon date on middle of unit 6 gave age of 54530 ± 2090 years BP (core 90-29; Isotrace lab # TO-2998). With the presently available information, further subdivision of this unit into subunits would be premature and requires additional cores.

CHAPTER 8: Conclusions and suggestions for future studies

The new findings of the present study are summarized in the following paragraphs.

8.1. Depositional regimes in northwestern Labrador Sea. The depositional processes in the Labrador Sea during the Late Pleistocene were grouped into two general categories according to the sediment-delivery processes: (1) depositional processes related to primary delivery mechanisms, whose deposits are not modified by other processes (turbid-surface plumes, nepheloid-layers, hemipelagic sedimentation, ice-rafting and primary turbidity currents); and (2) secondary delivery mechanisms, which involve the resedimentation of previously deposited materials (debris flows, muddy turbidity currents and contour currents).

Rhythmic deposition from turbid-surface plumes (TSP) seems to extend not more than a few tens of kilometres from the ice margin and to gradually change into hemipelagic sedimentation. Preferential occurrence of plumites south of the major glacial outlets implies the entrainment of the suspended load of TSP by the southward flowing Labrador Current. While the proportion of hemipelagic sediments decreases basinward, thin-bedded spillover turbidites predominate in the basin centre on the levees of NAMOC. Mud turbidites have high detrital-carbonate contents (up to 45%), originating from remobilization of fine detrital-carbonate rich sediments on the slope region adjacent to the Hudson Strait.

8.2. Possible linkage between subglacial outburst flooding events and Heinrich events. Sandy turbidites form an extensive floodplain, >600 km long and up to 150 km wide, east of NAMOC. The depositional mechanisms of the braided floodplain sands are still hypothetical. Their mineralogical composition indicates Canadian sources, rather than Greenlandian sources. Some horizons indicate a provenance from the Hudson Strait region; they may have been deposited during Heinrich events by sandy turbidity currents generated from bedload-rich meltwater discharges off the Hudson Strait. The apparent thickness and mineralogic variation indicate that the braidplain sands were deposited by numerous events. The time of deposition of the sands is constrained by a minimum age of about 10 ka for the top of the present sand surface which means they could have been deposited during Heinrich events 0, 1, 2 or earlier.

8.3. Depositional mechanism of Heinrich layers (HL). The Labrador Sea HLs are distinct from HLs in North Atlantic in general because of: (1) their greater thickness (up to 1 m), (2) their complex depositional processes, and (3) high organic carbon content (up to 2.8%, mainly terrigenous type) compared to sediments deposited between Heinrich events (average $C_{org}=0.5\%$). Up to 60% of the sediment is detrital carbonate, more than 80% of which occurs in the fine fraction (<63 μ m). For the first time, the present thesis revealed the complex depositional facies and mechanisms involved in the formation of HLs in northwestern Labrador Sea. Nepheloid layers were the most important process for the supply of fine detrital carbonates of HLs to the regions proximal to the Hudson Strait. This mechanism explains the exceptional thickness (up to 1 m) of HLs in this region.

Turbidity currents also supplied large quantities of detrital carbonates to the levees of NAMOC and its tributaries during Heinrich events where thin turbidites are intercalated in the HLs. Icebergs were the main source of detrital carbonates in HLs in distal regions with respect to the Hudson Strait.

8.4. Lithostratigraphy and glacial cycles. Six lithostratigraphic units were identified for the intervals spanning the last 60 ka. O-isotope stratigraphy indicates cold conditions prevailed during deposition of units which occur prior to HL-1. Light O-isotope peaks coincide with HL-1 and 2. Sediments deposited during the Last Glacial Maximum (18 ka; Dyke and Prest, 1987) are characterized by abundant IRD and high O-isotope values. The new approach of this study is the application of HLs as stratigraphic tools; the facies variation and stratigraphic correlation reflect the glacial history of the region. A significant portion of sediments were deposited mainly during glacial and deglacial times when nepheloid-layers and turbidites with abundant IRD were predominant. HLs were deposited in short periods of time (<1000 years) with sedimentation rates up to 100 cm/ka. Hemipelagic sediments and contourites were deposited dominantly during time intervals between Heinrich events, characterized by low sediment discharge.

8.5. Suggestions for future studies

The results of this study have raised a number of questions, which should encourage further investigations in this region.

1. One of the most important questions concerns the depositional mechanism of the

braidplain sands and their possible relationship with subglacial flooding events, which may be linked to Heinrich events. The paleoclimatic/paleoceanographic information obtained from this study could help to discriminate between the binge-purge and the subglacial outburst flood hypotheses for the origin of Heinrich events. Side-scan sonar images, especially covering the proximal region of this feature off the Hudson Strait outlet, could serve to investigate the evolution of this giant submarine feature. Additional cores from the region and the braidplain would give information about the provenance and depositional mechanisms of the braidplain sediments. Radiocarbon dating would be essential to tackle this problem.

2. Little is known about depositional mechanisms of HLs south of 56°. The distribution of type I HLs (nepheloid-layer deposits) in front of the Hudson Strait needs to be detailed with additional cores. Heinrich layers 3, 4 and older were not retrieved in NAMOC levee cores (<12 m long). On the slope, Heinrich-Layer 4 was also eroded in most cores located in debris-flow dominated regions. Additional long (>15 m) cores on NAMOC levees and the slope, not covered in previous cruises, would help to establish the regional distribution of Heinrich layers 3, 4 and older.

3. Due to the lack of radiocarbon ages in some cores, the relationship between sedimentary facies and glacial cycles is incompletely known. Additional radiocarbon dating in strategic sites (i.e. adjacent to the main glacier outlets) would aid to address this problem.

4. The Labrador Sea is a strategic site to study trigger mechanisms of Heinrich events. High resolution O-isotopic study and radiocarbon dating of sediments in regions not

influenced by resedimentation processes (i.e. intercanions) would provide insight to establish correlation between Quaternary climatic oscillations revealed in the Greenland Ice cores (i.e. Dansgaard et al, 1993) and Heinrich events. This may also improve our understanding about short duration oceanographic changes during these events in this region.

5. This study revealed the characteristics and occurrence of plumites on the upper Labrador Slope; however, their provenance, basinward extent and transition with other sedimentary facies needs to be further elaborated with new cores in the future. Preliminary results of this study showed that the Labrador Sea plumites may contain some signature of Quaternary climatic variations.

8.6. Contribution to knowledge

This study is a significant contribution to knowledge. The data presented in this study improves the understanding of the Late Pleistocene sedimentary facies in the Labrador Sea. The analysis of the anatomy of Heinrich layers in the Labrador Sea and the interpretations of their depositional mechanisms is a breakthrough, which is very significant for other workers in the field. The reinterpretation of turbidites on the NAMOC levees formerly considered to be "headspill turbidites" as ice-rafted sediments interlayered with thin muddy spill-over turbidites is one of the major discoveries of this thesis. Improvement of the Late Pleistocene stratigraphy of the Labrador Sea by systematic use of Heinrich layers is another important result of this study.

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Appendix 1. List of cores.

Core no.	Locality	Latitude	Longitude	Water depth (m)	Piston core length (cm)	Trigger-weight core length (cm)
75-55	Labrador Slope	61°, 30', 03"	58°, 38', 07"	2410	700	
75-56	Labrador Slope	61°, 26', 09"	58°, 33', 05"	2434	386	
75-61	Labrador Slope	62°, 18', 07"	59°, 36', 01"	1473	819	
75-62	Labrador Slope	62°, 23', 07"	59°, 18', 01"	1520	798	
84-7	NAMOC left levee	57°, 39', 01"	50°, 12', 06"	3512	855	153
84-8	NAMOC left levee	57°, 36', 05"	58°, 33', 05"	3521	834	146
84-9	NAMOC left levee	57°, 34', 05"	50°, 35', 07"	3528	646	73
84-11	NAMOC right levee	57°, 39', 07"	51°, 51', 00"	3437	550	158
84-12	NAMOC right levee	57°, 32', 04"	51°, 53', 05"	3453	762	111
84-14	NAMOC right levee	57°, 43', 06"	51°, 58', 01"	3435	818	228
84-15	NAMOC right levee	57°, 40', 07"	52°, 08', 02"	3438	710	112
84-16	NAMOC left levee	58°, 14', 05"	50°, 47', 01"	3438	322	60
84-19	NAMOC right levee	58°, 22', 06"	59°, 18', 01"	3352	837	146
87-1	NAMOC right levee	57°, 45', 45"	51°, 31', 50"	3498	411	139
87-2	NAMOC right levee	57°, 41', 50"	51°, 41', 45"	3525	373	200
87-5	NAMOC right levee	57°, 13', 53"	50°, 40', 28"	3577	668	140
87-7	NAMOC right levee	57°, 04', 37"	50°, 37', 96"	3592	840	121
87-9	NAMOC right levee	56°, 41', 62"	50°, 09', 38"	3619	687	126
87-10	NAMOC right levee	56°, 53', 54"	50°, 03', 23"	3686	819	183
87-12	NAMOC right levee	59°, 02', 55"	53°, 24', 00"	3444	686	133
88-1	Labrador Slope	57°, 22', 20"	57°, 07', 80"	3054	785	100
88-2	Labrador Slope	58°, 42', 40"	55°, 07', 61"	3220	735	112
88-3	NAMOC left levee	59°, 21', 82"	53°, 44', 80"	3266		136
88-4	NAMOC right levee	59°, 12', 29"	54°, 05', 69"	3266	621	154
88-7	Greenland Slope	60°, 24', 84"	49°, 52', 60"	2889	730	
88-8	NAMOC right levee	59°, 15', 55"	54°, 18', 24"	3252	1023	20
88-10	Labrador Rise	59°, 12', 47"	55°, 51', 31"	3131	1109	58
88-11	Labrador Slope	58°, 47', 70"	56°, 21', 51"	3027	1081	174
88-13	Labrador Slope	57°, 29', 10"	56°, 21', 54"	2798	1074	
90-24	Labrador Slope	58°, 40', 51"	58°, 35', 44"	2360	315	165
90-25	Labrador Slope	59°, 53', 32"	58°, 51', 39"	2450	725	166
90-26	Labrador Slope	59°, 31', 34"	57°, 16', 64"	2895	1105	25
90-28	Labrador Slope	58°, 45', 80"	57°, 06', 75"	2913	1175	128
90-29	Labrador Slope	58°, 23', 61"	56°, 45', 76"	2918	1402	95
90-33	Labrador Slope	57°, 16', 84"	56°, 50', 70"	2577	770	23
90-34	Labrador Slope	57°, 19', 17"	56°, 51', 68"	2586	537	170
92-1	Labrador Slope	56°, 09', 61"	57°, 07', 28"	1469	1250	139
92-2	Labrador Slope	57°, 00', 47"	58°, 10', 69"	1602	1236	194
92-4	Labrador Slope	59°, 48', 62"	58°, 08', 00"	2761	1350	161
92-5	Labrador Slope	59°, 49', 14"	56°, 27', 38"	2932	970	221
92-6	Labrador Rise	58°, 30', 69"	55°, 48', 38"	3135	1149	223

Appendix 2. Grain-size analyses of various sedimentary facies and lithologies.

Core	Depth (cm)	Facies	Size: mm	16.000	8.000	4.000	2.000	1.000	0.500	0.250	0.125	0.063	0.032	0.016	0.008	0.004	0.002	0.001
			Size: phi	-4.0	-3.0	-2.0	-1.0	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
84-8	36	H		0.00	0.00	0.00	0.00	0.02	0.29	1.79	1.69	2.86	14.89	22.44	25.20	13.51	12.03	5.08
"	306	MS		0.00	0.00	0.00	0.00	0.06	0.57	5.97	19.76	31.69	20.89	6.33	7.45	1.77	1.77	5.08
"	311	"		0.00	0.00	0.00	0.00	0.11	1.12	23.56	18.67	26.05	12.12	4.54	3.26	1.63	2.04	6.92
84-9	128	"		0.00	0.00	0.00	0.23	3.84	17.53	32.97	19.69	8.96	5.28	1.51	1.04	3.78	1.99	2.55
"	180	"		0.00	0.00	0.00	0.00	0.19	1.55	51.50	24.58	7.64	4.91	2.51	1.24	1.51	1.54	2.81
84-14	322	MS		0.00	0.00	0.00	0.00	1.06	7.61	9.30	10.39	12.07	11.31	14.70	15.17	9.16	4.11	4.30
"	370	D4		0.00	0.00	3.55	2.19	2.55	4.02	5.41	4.69	6.98	11.39	22.80	26.78	5.55	3.22	2.16
"	780	MS		0.00	0.00	0.00	0.00	0.20	4.11	13.64	31.56	19.11	9.19	9.27	1.86	1.58	2.21	6.33
"	790	"		0.00	0.00	0.00	1.00	4.72	14.61	26.26	27.88	15.01	6.28	3.68	1.98	0.00	0.00	0.00
84-15	251	D1		38.99	9.64	3.43	1.67	0.67	0.48	1.24	1.50	1.53	6.13	6.61	5.91	7.29	11.15	3.65
84-16	94	Tc		0.00	0.00	0.00	0.00	0.02	0.52	0.74	2.42	25.26	49.37	15.03	2.74	0.73	0.93	2.58
"	110	MS		0.00	14.09	36.97	42.71	4.42	0.98	0.78	0.81	0.25	0.00	0.00	0.00	0.00	0.00	0.00
87-9	115	D2		0.00	0.00	0.00	0.63	1.15	5.94	4.07	2.70	0.91	7.46	16.13	22.00	16.17	14.92	8.62
"	142	Td		0.00	0.00	0.00	0.00	0.00	0.00	0.44	0.51	11.35	45.04	16.99	7.76	4.46	6.72	6.56
"	194	HI		0.00	0.00	5.64	1.32	0.91	1.17	3.64	1.46	6.15	2.40	10.52	20.77	25.12	16.09	5.30
"	231	TI		0.00	0.00	0.00	0.09	0.25	0.70	1.62	1.78	1.66	6.54	19.43	14.79	11.45	9.55	31.15
"	232	TI		0.00	0.00	1.23	0.97	2.22	4.80	12.58	12.65	4.99	5.09	13.09	10.34	8.07	7.39	16.57
"	295	Te		0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.02	0.84	2.47	17.01	15.66	13.23	19.49	32.02
"	296	Td		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	1.74	6.84	20.33	15.48	11.98	9.99	32.60
"	297	Td		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	3.94	28.14	21.85	19.32	5.92	3.32	17.49
"	353	Tc		0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.23	5.68	46.98	29.11	6.58	3.70	2.95	5.72
90-25	197	TI		0.00	0.00	0.00	0.00	1.25	2.04	5.11	7.54	8.59	9.79	9.47	11.47	10.27	8.59	26.16
90-26	1	H		0.00	0.00	0.00	0.00	0.00	0.30	0.70	3.39	11.92	20.35	16.48	15.60	8.87	8.10	13.66
"	364	C		0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.21	3.77	4.34	18.25	19.87	9.23	7.88	37.83
"	415	Te		0.00	0.00	0.00	0.00	0.00	0.00	0.56	0.54	7.30	5.38	7.99	10.00	14.08	16.61	37.54
"	416	Tc		0.00	0.00	0.00	0.00	0.05	0.17	2.77	3.21	24.73	29.54	9.39	6.82	3.96	2.75	6.61
"	469	Te		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	2.26	4.24	8.48	14.27	15.81	13.22	41.69
"	470	Td		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.80	2.45	20.35	14.51	12.54	15.18	34.41
"	471	Td		0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.25	5.32	34.64	23.58	9.43	5.22	4.82	16.68

Appendix 2. continued.

Core	Depth (cm)	Facies	Size: mm	16.000	8.000	4.000	2.000	1.000	0.500	0.250	0.125	0.063	0.032	0.016	0.008	0.004	0.002	0.001
			Size: phi	-4.0	-3.0	-2.0	-1.0	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
90-26	592	C		0.00	0.00	0.00	0.00	0.21	0.10	0.12	0.58	3.29	13.40	18.26	13.24	9.99	6.46	33.86
"	603	H		0.00	0.00	0.00	0.36	0.59	1.48	2.19	1.99	2.02	7.51	9.53	13.07	11.04	10.32	40.35
"	624	C		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.66	6.66	15.90	23.13	16.83	9.60	2.22	26.07
"	686	H		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.94	1.35	5.62	3.25	13.70	14.25	12.57	48.38
"	1075	Tc		0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.03	1.58	2.26	10.74	16.22	13.17	15.76	39.72
"	1075.5	Td		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.90	14.59	29.52	16.22	8.63	14.27	16.57
"	1076	Tc		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	8.17	11.47	50.89	11.06	3.50	7.68	7.31
90-34	505	Td		0.00	0.00	0.00	0.00	0.48	0.52	1.08	1.15	9.71	11.37	10.51	13.38	10.86	35.41	4.96
"	506	D3		0.00	0.00	2.74	0.94	2.07	4.50	1.88	5.48	12.98	8.47	12.58	10.13	7.24	24.25	6.76
92-1	64	D4		0.00	0.00	2.81	2.25	3.36	4.76	5.49	7.72	6.51	7.59	36.24	17.77	1.04	1.00	3.00
"	207	Td		0.00	0.00	0.00	0.00	0.00	0.02	0.03	1.02	6.67	10.51	22.70	15.01	37.99	2.41	2.91
"	342	Tc		0.00	0.00	0.00	0.00	0.00	0.00	0.06	2.01	10.55	15.55	18.74	48.94	1.01	0.20	3.80
"	345	Te		0.00	0.00	0.00	0.00	0.00	0.00	0.20	2.51	13.69	16.53	13.11	10.20	8.22	14.26	22.47
"	550	H		0.00	0.00	0.09	0.44	0.63	1.30	1.41	9.11	14.18	22.99	10.58	7.53	6.26	4.68	21.08
"	979	"		0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.36	17.93	11.72	11.68	10.67	24.56	10.10	7.50
"	980	P		0.00	0.00	0.00	0.00	0.00	0.00	1.14	24.09	26.99	14.38	7.36	5.22	3.52	4.83	12.46
92-2	217	H		0.00	0.00	0.15	0.10	0.09	0.24	0.89	4.85	4.36	3.90	17.55	11.84	11.34	11.90	31.31
"	277	D4		0.00	0.00	0.96	1.27	1.72	2.60	4.61	2.96	6.62	10.62	12.90	12.01	8.17	9.40	26.14
"	360	HI		0.00	0.00	0.52	0.18	0.97	2.69	4.37	5.85	6.56	12.71	21.49	6.51	7.36	19.10	12.60
"	382	D4		0.00	0.00	1.29	1.46	2.07	3.94	6.16	6.83	7.42	9.45	9.86	13.83	33.88	1.01	2.78
"	482	"		0.00	0.00	1.71	1.35	1.63	3.30	6.10	7.49	11.84	11.26	10.43	9.48	6.02	7.35	24.05
"	541	HI		0.00	0.00	1.25	0.66	0.93	1.54	2.40	2.40	18.12	15.25	14.17	9.74	8.30	7.27	18.78
"	549	"		0.00	0.00	0.90	0.60	0.80	1.40	2.25	7.42	24.82	12.43	9.80	33.10	4.34	1.00	1.95
"	615	D4		0.00	0.00	4.36	1.25	1.75	3.26	5.65	8.92	9.91	8.40	11.03	9.25	7.94	9.56	19.53
"	695	D4		0.00	0.00	4.61	1.44	1.70	3.28	6.26	6.77	4.79	8.64	13.53	8.75	8.36	7.09	25.58
"	752	H		0.00	0.00	0.40	0.10	0.30	1.00	1.25	1.72	1.00	8.70	10.39	17.93	50.42	3.56	3.90
"	1192	"		0.00	0.00	0.00	0.00	0.00	1.27	0.03	17.44	22.94	14.13	10.61	29.87	1.31	0.52	1.35
92-4	180	C		0.00	0.00	0.00	0.00	0.00	0.07	0.22	1.76	20.50	25.22	15.12	14.47	4.72	6.63	11.28
"	200	Ta		0.00	0.00	0.00	0.00	0.00	0.92	8.36	51.25	28.70	3.45	3.38	2.78	1.14	0.00	0.00

Core	Depth (cm)	Facies	Size: mm	16.000	8.000	4.000	2.000	1.000	0.500	0.250	0.125	0.063	0.032	0.016	0.008	0.004	0.002	0.001
			Size: phi	-4.0	-3.0	-2.0	-1.0	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
92-4	204	Tb		0.00	0.00	0.00	0.00	0.00	0.00	1.95	36.07	43.11	6.86	4.96	3.62	1.44	1.00	0.00
"	675	"		0.00	0.00	0.00	0.00	0.00	0.15	0.30	0.72	0.61	14.53	16.90	13.38	12.31	7.87	34.25
"	1072	"		0.00	0.00	0.00	0.00	0.00	0.02	0.05	0.27	5.09	7.57	14.66	13.01	10.51	16.04	34.04
"	1112	"		0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.28	1.01	6.95	19.48	16.09	11.06	18.29	26.06
92-5	23	HI		0.00	0.00	0.18	0.27	0.51	1.11	5.34	9.89	21.43	24.56	13.90	7.90	4.59	2.70	7.57
"	125.5	N		0.00	0.00	0.00	0.00	0.50	0.50	0.38	1.40	2.80	8.34	17.58	15.29	12.94	9.30	31.08
92-5	163	HI		0.00	0.00	0.00	0.18	0.33	0.74	5.88	9.24	12.04	16.32	22.82	16.66	5.60	2.88	8.04
"	370	H		0.00	0.00	0.00	0.00	0.02	0.12	0.48	0.21	4.00	5.62	9.81	12.28	15.24	15.98	35.80
"	824	"		0.00	0.00	0.00	0.14	0.00	0.17	0.16	1.75	6.58	17.10	21.60	16.27	15.58	15.90	4.78
"	842	"		0.00	0.00	0.00	0.00	0.10	0.20	0.13	1.00	1.19	2.92	8.43	18.77	51.05	7.99	8.61
92-6	911	Tb		0.00	0.00	0.00	0.00	0.08	4.92	48.38	25.17	12.39	2.91	2.22	1.00	1.59	0.83	2.26
"	914	"		0.00	0.00	0.00	0.05	4.04	46.01	31.23	9.41	9.54	0.51	0.00	0.00	0.00	0.00	0.00
"	917	Ta		0.00	0.00	0.00	9.67	28.26	48.83	9.67	2.81	1.14	0.55	0.00	0.00	0.00	0.00	0.00

Appendix 2 (continued). Grain-size analyses of various sedimentary facies.

Core	Depth (cm)	Facies	Gravel%	Sand%	Silt%	Clay%	Md	MZ	MO	SD
84-8	36	H	0.00	3.79	78.90	17.11	6.25	6.35	6.7	1.68
"	306	MS	0.00	26.36	68.13	6.85	3.80	4.15	4	1.93
"	311	"	0.00	43.46	47.60	8.96	3.35	3.55	2	2.21
84-9	128	"	0.00	74.26	20.57	4.54	3.40	2.92	2	2.14
"	180	"	0.00	77.82	17.81	4.35	1.95	2.42	2	1.72
84-14	322	"	0.00	28.36	62.41	8.41	5.00	4.82	6.7	2.68
"	370	D4	3.55	18.86	73.50	5.38	6.00	4.95	6.7	2.51
"	780	MS	0.00	49.51	41.01	8.53	3.00	3.75	3	2.32
"	790	"	0.00	74.47	26.95	0.00	2.15	2.30	2.3	1.41
84-15	251	D1	52.06	5.56	27.47	14.80	-2.10	0.43	-4	5.23
84-16	94	Tc	0.00	3.70	93.13	3.51	4.45	4.48	5	1.18
"	110	MS	51.06	49.70	0.25	0.00	-2.00	-2.05	-2	0.92
87-9	115	D2	0.00	14.49	62.67	23.54	6.55	6.50	7	2.35
"	142	Tc	0.00	0.95	92.32	6.73	4.90	5.53	5	1.75
"	194	HI	5.64	8.50	64.96	21.39	6.90	6.28	8	2.85
"	231	TI	0.00	4.44	53.87	40.70	36.60	7.30	10	2.01
"	232	TI	1.23	33.22	41.58	23.96	32.31	5.41	10, 3	3.34
"	295	Te	0.00	0.06	49.21	51.51	8.05	7.78	10	1.63
"	296	Td	0.00	0.02	56.37	42.59	7.50	7.52	10	1.82
"	297	Td	0.00	0.03	79.17	20.81	5.90	6.41	5	1.86
"	353	Tc	0.00	0.27	92.05	8.67	4.98	5.21	5	1.35
90-25	197	TI	0.00	15.94	49.59	34.75	6.65	6.40	10	2.82
90-26	1	H	0.00	4.39	81.32	14.29	5.80	6.23	5	2.22
"	364	C	0.00	0.27	55.46	45.71	7.47	7.49	10	1.85
"	415	Te	0.00	1.10	44.75	53.15	8.20	7.70	10	1.98
"	416	Tc	0.00	6.20	81.44	7.36	4.71	4.90	5	1.77
"	469	Te	0.00	0.03	45.06	54.91	8.50	8.10	10	1.62
"	470	Td	0.00	0.20	50.65	49.59	8.00	7.75	10	1.68
"	471	Td	0.00	0.30	81.19	18.50	5.40	6.13	5	1.83
"	592	C	0.00	1.01	58.18	40.32	7.20	7.27	10	2.03
"	603	H	0.00	6.16	43.17	50.67	8.05	7.55	10	2.13
"	624	C	0.00	0.00	72.12	28.29	7.25	7.45	5, 10	1.74
"	686	H	0.00	0.88	38.17	60.95	8.90	8.32	10	1.62
"	704	C	0.12	2.41	92.55	4.36	6.50	6.42	7	1.15
"	1075	Te	0.00	0.07	43.97	55.48	8.45	8.15	10	1.57
"	1075.5	Td	0.00	0.00	75.86	30.84	6.00	6.45	6	1.79
"	1076	Tc	0.00	0.10	85.09	14.99	5.06	6.07	6	1.66
90-34	505	Td	0.00	3.23	91.24	5.53	6.95	6.62	9	1.89
"	506	D3	2.74	14.87	51.40	31.01	5.95	5.86	9	2.85
92-1	64	D4	2.81	24.58	68.15	5.00	5.30	4.60	6	2.36
"	207	Td	0.00	1.07	92.88	5.32	7.50	8.37	8	1.46
"	342	Tc	0.00	2.07	94.79	4.00	5.10	4.73	7	1.48
"	345	Te	0.00	2.71	61.75	36.73	5.80	5.80	10	2.73
"	550	H	0.00	12.45	61.54	25.76	6.00	6.50	5	2.29

Appendix 2. continued.

Core	Depth (cm)	Facies	Gravel%	Sand%	Silt%	Clay%	Md	MZ	MO	SD
92-1	979	P	0.00	5.36	76.56	17.60	7.30	8.20	3.4	2.20
"	980	"	0.00	25.23	57.47	17.29	7.15	7.52	4.8	2.35
92-2	217	H	4.36	20.83	46.53	29.09	7.70	7.50	10.00	2.15
"	277	D4	4.61	19.45	44.07	32.67	6.60	6.52	10.00	2.82
"	360	HI	0.40	13.06	54.63	7.46	5.80	5.93	6.00	2.64
"	382	D4	0.00	18.74	78.86	1.87	6.15	5.38	8.00	2.49
"	482	"	0.00	2.05	80.03	17.91	5.65	5.83	4.10	3.08
"	541	HI	0.00	60.53	39.45	0.00	5.62	6.07	10.00	2.65
"	549	"	0.90	12.47	84.49	2.95	5.00	4.97	7.00	1.77
"	615	D4	4.36	20.83	46.53	29.09	5.75	5.70	6.10	3.30
"	695	"	4.61	19.45	44.07	32.67	6.00	5.80	6.10	3.49
"	752	H	0.40	4.37	88.44	7.46	7.20	6.77	8.00	1.44
"	1192	"	0.00	18.74	78.86	1.87	4.00	4.32	7.00	1.51
92-4	180	C	0.00	2.05	80.03	17.91	5.21	5.76	5.00	2.06
"	200	Ta	0.00	92.68	7.32	0.00	2.80	2.85	3.00	0.98
"	204	Tb	0.00	87.99	11.01	1.00	3.10	3.33	4.00	1.15
"	675	C	0.00	1.17	57.73	42.12	7.45	7.33	10.00	1.99
"	1072	"	0.00	0.34	50.84	50.08	8.00	7.60	10.00	1.91
"	1112	"	0.00	0.39	54.59	44.35	7.20	7.20	10.00	1.69
92-5	23	HI	0.00	17.11	74.62	8.27	4.50	5.18	5.4	2.41
"	163	HI	0.00	16.37	73.44	10.92	5.30	5.13	6.00	2.12
"	370	H	0.00	0.83	46.95	51.78	8.20	7.83	10.00	1.83
"	824	"	0.00	2.22	77.13	20.68	6.20	6.35	6.00	1.77
"	842	"	0.00	1.43	82.36	16.60	7.37	7.19	8.00	1.08
92-6	911	Tb	0.00	78.55	22.86	3.49	2.95	3.25	2.00	1.28
"	914	"	0.00	90.74	10.05	0.00	1.00	1.23	1.00	1.06
"	917	Ta	0.00	99.24	1.69	0.00	0.25	0.18	1.00	0.93

Md=median; Mz=mean; Mo=mode; SD=standard deviation

Appendix 2 (ontinued). Grain-size analyses of plumites and nepheloid-layer deposits.

Core	Depth (cm)	Facies	Size: mm	4.000	2.000	1.400	1.000	0.700	0.500	0.355	0.25	0.162	0.140	0.121	0.104	0.0
			Size: phi	-2	-1		0		1		2	2.5	2.7	2.9	3.2	3
92-1	975	P		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.89	2.22	2.91	3.88	5.0
"	975.5	"		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.85	1.17	1.85	2.81	4.0
"	975.8	"		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.77	1.12	1.00	2.89	4.0
"	976.2	"		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	1.00	3.66	6.0
"	979	"		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.65	0.66	0.69	0.73	0.0
"	979.4	"		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.01	1.03	1.07	1.11	1.0
"	979.7	"		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.85	1.42	2.00	4.27	6.0
"	980	"		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.49	1.29	2.45	4.0
92-5	125	N		0.00	0.00	0.10	0.06	1.67	0.33	0.09	0.47	0.00	0.00	0.00	0.00	0.0
"	126	"		0.00	0.00	0.00	0.00	0.03	0.05	0.10	0.09	0.02	0.02	0.02	0.00	0.0
"	127.5	"		0.00	0.00	0.08	0.08	0.16	0.03	0.02	0.19	0.04	0.04	0.05	0.00	0.0
"	128	"		0.00	0.16	0.16	0.04	0.20	0.10	0.22	0.32	0.19	0.21	0.20	0.31	0.0
"	128.5	"		0.68	0.17	0.40	0.31	0.58	0.47	0.81	1.00	0.58	0.58	0.00	0.60	0.0
"	129	"		0.02	0.27	0.23	0.13	0.86	0.68	1.35	2.03	2.25	2.32	2.49	2.66	2.0
"	132.5	"		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.51	0.50	0.49	0.40	0.0
"	133	"		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0
"	134	"		0.00	0.00	0.00	0.00	0.04	0.01	0.03	0.29	0.00	0.00	0.00	0.00	0.0
"	134.5	"		0.00	0.00	0.02	0.08	0.05	0.06	0.05	0.09	0.07	0.13	0.26	0.44	0.0
"	134.8	"		0.00	0.00	0.00	0.17	0.11	0.27	0.23	0.88	0.16	0.17	0.20	0.00	0.0
"	135.2	"		0.00	0.00	0.00	0.12	0.11	0.29	0.22	1.25	0.73	0.81	0.99	1.16	1.0

posits.

0	0.121	0.104	0.090	0.078	0.067	0.058	0.050	0.043	0.037	0.032	0.028	0.024	0.021	0.018	0.015	0.013	0.011	0.010	0.008	0.007
1	2.9	3.2	3.4	3.6	3.8	4	4.2	4.4	4.6	4.9	5.1	5.3	5.5	5.7	5.9	6.1	6.3	6.6	6.8	7
2	2.91	3.88	5.23	6.75	7.50	6.92	5.11	3.44	3.12	3.64	4.30	4.12	3.83	3.22	3.28	3.52	3.00	2.76	2.38	2.18
7	1.85	2.81	4.15	5.66	6.53	6.28	4.97	3.70	3.42	3.74	4.39	4.43	4.61	4.25	3.82	3.64	3.40	3.23	2.97	2.68
2	1.00	2.89	4.33	5.97	6.95	6.76	5.48	4.20	3.85	3.99	4.27	3.87	3.54	3.58	3.58	3.82	3.62	3.19	2.82	2.62
5	1.00	3.66	6.15	8.97	10.20	8.83	5.39	4.30	4.20	4.01	4.10	3.70	3.57	3.13	2.76	2.72	2.00	2.64	2.24	1.93
6	0.69	0.73	0.79	1.73	3.59	4.58	4.67	4.36	3.94	3.36	3.61	3.93	4.56	4.58	4.07	3.93	4.20	4.28	4.10	3.88
3	1.07	1.11	1.18	2.34	4.50	5.36	4.95	4.17	3.75	3.46	3.67	3.72	4.45	4.79	4.34	4.07	4.00	4.09	3.90	3.65
2	2.00	4.27	6.59	9.20	10.32	9.00	5.74	4.69	4.57	4.27	3.95	3.07	2.91	2.78	2.51	2.35	2.20	2.05	1.89	1.72
9	1.29	2.45	4.04	5.86	6.90	6.62	5.08	3.57	3.17	3.49	4.06	4.05	4.35	4.18	3.73	3.57	3.60	3.55	3.33	2.93
0	0.00	0.00	0.00	0.01	0.02	0.04	0.07	0.32	1.01	1.77	2.02	1.51	1.19	1.20	2.02	2.98	3.43	3.56	3.75	4.34
2	0.02	0.00	0.02	0.02	0.05	0.14	0.31	0.68	1.44	2.27	2.88	2.87	3.22	3.92	5.56	6.61	5.00	5.07	5.30	5.67
4	0.05	0.00	0.09	0.12	0.20	0.52	0.55	1.07	2.17	3.29	3.63	2.82	2.65	3.03	4.27	5.02	4.13	3.33	3.34	4.05
1	0.20	0.31	0.40	0.50	0.65	0.84	1.08	1.58	2.59	3.61	4.13	3.60	3.50	3.55	4.19	4.73	4.00	4.11	4.30	4.77
3	0.00	0.60	0.62	0.64	0.70	0.79	0.91	1.33	2.35	3.48	4.19	4.01	3.87	4.04	4.99	5.68	5.05	4.45	4.46	4.80
2	2.49	2.66	2.99	3.32	3.39	3.07	2.37	1.88	2.15	1.82	3.52	3.47	3.14	2.45	2.40	2.72	2.85	2.92	2.95	3.02
0	0.49	0.40	0.43	0.39	0.41	0.49	0.64	0.90	1.31	1.69	1.96	1.80	1.66	1.74	2.78	3.89	4.17	4.21	4.47	5.13
0	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.17	0.61	1.24	2.07	2.63	3.19	3.58	4.37	4.97	4.65	4.28	4.39	5.08
0	0.00	0.00	0.00	0.02	0.06	0.09	0.13	0.58	1.86	3.56	5.24	5.81	6.17	6.22	7.49	7.88	5.00	3.64	3.20	3.50
3	0.26	0.44	0.70	0.99	1.25	1.40	1.78	4.04	7.50	10.63	12.48	11.02	9.50	6.84	4.85	3.50	2.00	1.67	1.66	1.73
7	0.20	0.00	0.27	0.35	0.62	1.13	1.87	3.14	5.22	7.14	7.96	6.60	5.96	5.09	4.36	3.86	3.29	3.10	3.31	3.42
1	0.99	1.16	1.60	2.00	2.23	2.17	1.84	1.83	2.70	3.86	4.52	3.85	3.07	2.38	3.15	3.94	3.51	2.92	2.77	3.33

0.021	0.018	0.015	0.013	0.011	0.010	0.008	0.007	0.006	0.005	0.005	0.004	0.004	0.003	0.003	0.002	0.002	0.001
5.5	5.7	5.9	6.1	6.3	6.6	6.8	7	7.2	7.4	7.6	7.8	8	8.3	8.5	8.7	8.9	10
3.83	3.22	3.28	3.52	3.00	2.76	2.38	2.18	2.07	1.96	1.82	1.61	1.46	1.20	1.08	0.91	0.69	1.77
4.61	4.25	3.82	3.64	3.40	3.23	2.97	2.68	2.42	2.28	2.14	1.90	1.73	1.43	1.29	1.10	0.85	2.24
3.54	3.58	3.58	3.82	3.62	3.19	2.82	2.62	2.47	2.31	2.10	1.82	1.66	1.37	1.20	1.03	0.80	2.10
3.57	3.13	2.76	2.72	2.00	2.64	2.24	1.93	1.74	1.70	1.62	1.43	1.25	0.98	0.84	0.71	0.56	1.45
4.56	4.58	4.07	3.93	4.20	4.28	4.10	3.88	3.72	3.70	3.49	3.03	2.79	2.36	2.13	1.92	1.59	4.33
4.45	4.79	4.34	4.07	4.00	4.09	3.90	3.65	3.41	3.28	3.05	2.64	2.38	1.99	1.84	1.65	1.34	3.62
2.91	2.78	2.51	2.35	2.20	2.05	1.89	1.72	1.58	1.50	1.39	1.20	1.08	0.88	0.79	0.68	0.53	1.42
4.35	4.18	3.73	3.57	3.60	3.55	3.33	2.93	2.57	2.50	2.40	2.13	1.89	1.51	1.38	1.26	1.04	2.86
1.19	1.20	2.02	2.98	3.43	3.56	3.75	4.34	5.31	6.58	6.83	5.97	5.64	5.20	5.46	5.78	5.30	16.69
3.22	3.92	5.56	6.61	5.00	5.07	5.30	5.67	5.87	5.80	5.37	4.54	3.88	3.19	3.24	3.44	3.16	9.69
2.65	3.03	4.27	5.02	4.13	3.33	3.34	4.05	5.89	5.43	5.31	4.62	4.30	3.87	4.07	4.46	4.21	13.56
3.50	3.55	4.19	4.73	4.00	4.11	4.30	4.77	5.19	5.36	5.14	4.51	4.16	3.60	3.51	3.42	2.96	8.66
3.87	4.04	4.99	5.68	5.05	4.45	4.46	4.80	5.04	4.94	4.49	3.76	3.36	2.82	2.62	2.47	2.09	5.86
3.14	2.45	2.40	2.72	2.85	2.92	2.95	3.02	3.14	3.34	3.01	2.78	2.78	2.43	2.51	2.70	2.53	8.03
1.66	1.74	2.78	3.89	4.17	4.21	4.47	5.13	5.87	6.41	6.26	5.41	4.94	4.37	4.51	4.72	4.28	13.20
3.19	3.58	4.37	4.97	4.65	4.28	4.39	5.08	5.93	6.57	6.33	5.28	4.84	4.36	4.49	4.58	4.06	12.28
6.17	6.22	7.49	7.88	5.00	3.64	3.20	3.50	3.74	3.37	2.71	2.04	1.94	2.03	2.55	3.42	3.66	13.57
9.50	6.84	4.85	3.50	2.00	1.67	1.66	1.73	1.70	1.53	1.34	1.17	1.14	1.09	1.21	1.44	1.41	3.25
5.96	5.09	4.36	3.86	3.29	3.10	3.31	3.42	3.37	3.28	3.07	2.70	2.57	2.28	2.26	2.32	2.13	6.56
3.07	2.38	3.15	3.94	3.51	2.92	2.77	3.33	4.02	4.33	4.02	3.22	2.85	2.52	2.66	3.23	3.33	11.41

Appendix 2. continued.

Core	Depth: cm	Facies	Gravel%	Sand%	Silt%	Clay%	Md	MZ	MO	SD
92-1	975	P	0.00	26.63	70.68	2.46	4.92	5.24	3.8	1.82
"	975.5	"	0.00	19.76	77.09	3.09	5.38	5.53	3.8	1.78
"	975.8	"	0.00	19.56	76.63	2.9	5.30	5.53	3.8	1.81
"	976.2	"	0.00	24.93	70.89	2.01	7.19	6.18	3.8	1.87
"	979	"	0.00	7.045	86.99	5.92	6.16	6.2	4	1.94
"	979.4	"	0.00	9.99	84.86	4.96	5.98	6.02	4.2,5.7	1.95
"	979.7	"	0.00	29.49	67.96	1.95	4.68	5.06	4	1.72
"	980	"	0.00	17.68	78.37	3.9	5.50	5.66	3.8	1.84
92-5	125	N	0.00	2.745	75.99	21.99	7.80	8.07	10	1.8
"	126	"	0.00	2.78	56.95	40.38	7.50	7.47	10.00	1.98
"	127.5	"	0.00	0.404	86.3	12.85	7.21	7.32	10	1.54
"	128	"	0.00	1.001	81.92	17.77	7.40	7.57	10	1.91
"	128.5	"	0.00	3.344	85.8	11.62	7.10	7.03	10	1.84
"	129	"	0.68	7.113	84.25	7.95	6.70	6.68	10	1.98
"	132.5	"	0.02	23.28	65.12	10.56	6.10	6.08	10	2.63
"	133	"	0.00	2.968	79.54	17.48	7.61	7.54	10	1.65
"	134	"	0.00	0.009	83.67	16.34	7.52	7.64	10	1.63
"	134.5	"	0.00	0.423	82.2	17.23	6.62	7.14	10	1.85
"	134.8	"	0.00	3.576	91.85	4.66	5.50	5.86	5.1	1.44
"	135.2	"	0.00	3.126	87.61	8.69	6.02	6.43	5.1	1.81

Appendix 3. Coarse fraction. foram content. %N. *pachyderma* and detrital carbonate lithic (DCL) content of two slope cores and a basin-centre core.

90-26

Depth (cm)	Weight% >125µm	no. of forams/g	%N. <i>pachyderma</i>	no. of DCL/g
1	1.00	433.26	76.76	0.00
9	4.85	340.57	76.74	504.32
18	7.42	11.04		837.82
31	8.33	71.10	84.37	2058.42
39	8.79	2.98	94.11	1237.12
50	3.24	269.85	83.72	21.11
60	1.47	13.43		3.57
69	2.50	6.31	90.47	1.87
80	1.03	1.76		4.47
90	1.56	6.61		17.54
100	1.70	105.48	92.64	19.89
110	1.10	10.00		4.42
120	1.37	2.82		0.00
130	2.66	75.72	89.04	133.76
140	0.74	3.55	90.47	6.49
150	1.04	0.33		0.00
160	1.41	0.66		1.94
170	2.74	0.00		14.26
194	0.23	19.31		0.00
200	0.14	57.93	95.34	0.00
207	0.04	124.96	95.65	0.00
221	13.36	0.00		3317.18
240	3.39	0.14		1037.33
248	27.36	2.77		3568.74
260	13.93	0.00		3485.38
269	17.99	70.39	92.86	3416.70
283	1.84	1060.20	94.66	0.00
289		428.16	89.86	0.00
300	1.39	314.32	99.37	9.95
320	0.25	26.02	93.91	1.19
335	0.00	12.62	98.94	0.00
342	0.00	43.82	98.52	0.00
352	1.19	69.48	100.00	10.15
404	1.15	126.21	96.58	0.00
410	1.08	612.80	92.98	0.00
552	2.84	479.12	94.59	0.00

90-29 (twc)

Depth (cm)	Weight% >125µm	no. of forams/g	%N. <i>pachyderma</i>	no. of DCL/g
1	14.66	3390.68	91.37	265.94
10	8.17	1570.79	83.19	1000.86
18	7.44	20.32	87.59	610.97
30	4.28	1780.04	92.12	0.00
40	4.77	1147.40	97.29	27.00
50	1.60	7.27		8.72

90-29

Depth (cm)	Weight% >125µm	no. of forams/g	%N. <i>pachyderma</i>	no. of DCL/g
50	1.03	2.30		6.90
90	0.64	2.68		5.36
105	1.14	631.72	96.44	1.56
122	14.27	113.96	86.50	1400.06
131	14.03	54.85	87.90	1272.44
140	19.78	32.80		4412.77
145	6.22	937.12	95.14	0.00
160	1.22	790.73	98.50	0.00
170	0.32	3.96		3.96
180	0.71	24.43	97.43	17.77
190	0.86	62.37	99.00	12.35
210	0.90	2.47		15.44
215	1.08	0.00	95.35	0.00
235	20.91	43.79		846.12
243	26.78	0.00		957.69
266	0.83	0.00		0.00
270	0.58	17.45	97.53	0.00
290	0.77	5.94	96.43	0.00
330	0.81	2.59		0.74
360	1.37	0.55		1.25
430	2.66	0.25		4.62
460	3.52	24.90		29.05
470	1.87	8.88		9.13
530	1.05	0.00		4.81
560	0.79	1.57		5.27

Appendix 3. Continued.

90-29

Weight%	no. of	%N.	no. of
>125µm	forams/g	<i>pachyderma</i>	DCL/g
2.23	716.98	97.13	9.97
4.64	773.78	97.74	0.00
0.35	0.00		2.52
1.89	0.00		4.84
0.32	17.40	94.97	8.00
0.13	0.38		0.00
1.84	0.00		0.00
0.13	8.69		21.70
1.04	29.94	92.22	27.25
25.67	3.45		3841.97
17.80	4.19		1885.08
15.05	3.50		2098.48
0.25	0.00		1735.85
0.51	0.00		1823.85
0.51	0.00		35.26
0.83	0.41		40.42
0.66	0.00		2.24
0.49	158.89	97.07	1.80
2.02	43.78	94.19	2.00
2.02	2.73		44.29
0.97	437.48	95.51	7.62
0.75	322.34	87.12	6.52
0.39	78.63	91.18	2.99
0.55	48.50	90.40	2.91
0.81	105.74	95.02	0.00
0.79	80.66	97.24	1.49
0.77	20.98	71.21	2.35
0.71	27.12	88.82	14.57
1.09	59.61	93.03	0.00
1.00	21.31	81.63	15.65
0.29	78.56	94.20	6.24

Depth	Weight%	no. of	%N.	no. of
(cm)	>125µm	forams/g	<i>pachyderma</i>	DCL/g
590	1.43	9.74	89.74	2.20
622	12.94	0.00		681.26
640	8.26	0.27		918.48
655	7.19	0.00		885.36
684	10.82	0.00		1063.84
696	9.38	8.87		745.06
725	9.24	0.00		846.92
738	2.33	0.00		253.52
765	9.42	0.00		662.52
822	0.68	5.36		2.98
832	0.96	2.09		1.31
870	0.58	68.01	98.30	68.01
924	1.36	855.66	98.53	9.44
948	1.24	391.36	97.89	0.00
987	3.66	1086.49	96.35	0.00
1001	1.31	35.27	89.80	0.00
1021	1.08	340.56	96.30	1.40
1030	8.06	1625.13	96.24	53.41
1050	3.61	1088.62	97.35	6.40
1074	1.61	804.61	97.29	1.28
1103	1.29	359.29	97.77	3.16
1127	0.92	524.72	97.37	0.00
1187	1.91	11.67		3.89
1210	0.91	248.97	98.95	0.00
1243	1.65	0.00		1.30
1282	1.07	0.00		1.37
1312	3.00	0.27		9.23
1322	3.14	11.97		4.79
1342	3.81	216.48	97.10	3.14
1362	0.91	3.02		7.94

Weight%	no. of	%N.	no. of
>125µm	forams/g	<i>pachyderma</i>	DCL/g
0.43	272.93	75.92	16.65
0.54	384.67	46.53	7.16

Appendix 3. Continued.

87-9

Weight% >125µm	no. of forams/g	%V. <i>pachyderma</i>	no. of DCL/g
0.14	61.82	63.72	6.93
14.82	297.45	100.00	3619.36
3.19	0.00		4382.85
2.87	1779.35	68.20	74.14
9.13	2090.00	83.74	106.77
4.83	2104.59	87.47	25.51
8.01	1194.15	84.10	24.65
1.85	902.37	90.48	20.45
0.67	243.11	83.33	9.47
1.11	180.16	98.39	4.85
5.37	2093.19	93.85	9.06
4.66	1810.86	99.41	62.90
2.61	795.40	98.27	0.00
2.63	899.72	99.12	15.35
3.68	1186.39	95.81	35.96
1.91	576.88	97.29	0.00
1.16	297.79	97.77	6.73
11.05	902.95	98.49	26.66
19.59	1672.28	99.61	95.84
6.97	2878.81	97.50	155.48
10.26	3175.62	99.09	76.45
7.73	2731.23	97.64	90.26
8.30	2753.94	99.00	31.60
8.92	3403.85	98.49	63.77
8.14	3321.74	99.40	40.56
5.80	3696.40	95.90	42.40
4.28	1439.42	97.16	69.06
2.10	3028.33	85.45	24.81
4.53	2638.16	89.33	13.47
12.36	104.30	95.00	2555.24
13.40	69.45	100.00	2708.36
13.60	35.75	97.10	4468.93
17.13	1428.20	77.58	1875.29
3.87	2929.77	77.63	404.11
2.13	1421.87	89.33	115.62
9.37	3527.92	85.26	8.09
7.73	5120.99	81.82	15.44
5.65	4156.65	85.90	5.30

Depth (cm)	Weight% >125µm	no. of forams/g	%V. <i>pachyderma</i>	no. of DCL/g
247	5.18	2957.57	90.54	9.34
249	4.17	3948.43	92.30	49.47
251	4.65	3833.47	88.21	28.98
253	4.70	7081.89	84.28	11.74
255	8.15	5616.97	80.91	34.36

Appendix 3. continued.

Core 87-2

Depth (cm)	Weight% >125µm	no. of DCL/g
22	13.24	41.76
23	13.60	41.97
24	15.26	0.00
27	6.92	12.31
29	6.28	0.00
30	6.34	8.28
33	3.56	24.72
34	5.94	15.11
36	2.05	0.00
42	4.78	0.00
43	4.68	0.00
44	4.49	9.93
45	4.90	43.45
46.5	2.54	61.67
55	19.37	1409.11
64	13.26	1995.42
66	19.15	2126.30
71	17.83	2857.51
72.5	7.80	65.88
74	7.91	81.40
75	4.64	159.44
76	8.29	69.23
77	9.85	77.69
78	8.16	22.19
80	7.15	9.03
82	6.52	0.00

Core 87-7

Depth (cm)	Weight% >125µm	no. of DCL/g
250	0.00	0.41
252	15.58	1575.18
254	12.19	2968.05
256	27.12	609.31
257	15.29	249.33
258	10.96	48.62
259	6.91	28.47
260	2.97	26.44
262	5.22	10.91
263	1.57	20.26
266	18.95	30.79
272	35.30	63.59
275	16.09	38.17
278	10.50	17.84
280	9.18	61.68
282	8.91	34.99
305.5	8.36	263.21
308	1.96	74.66
310	3.49	307.55
311	4.17	550.28
320	11.79	2000.00
332	16.13	2830.61
334	19.16	2522.94
337	15.18	2041.87
346	8.50	19.77
347	8.40	6.32
348	8.08	40.95
349	5.41	45.86
350	6.31	0.00
352	5.33	0.00
355	5.66	0.00

Appendix 4a. Isotopic analyses of Holocene muds in 3 braidplain cores (84, 8, 16), hemipelagic sediments of core 90-26 and plumites of core 92-1.

core 84-8

Depth (cm)	δ O18‰	δ C13‰
1	2.57	0.77
11	2.52	0.67
21	2.39	0.49
31	2.86	0.45
37	2.64	0.54
49	2.52	0.35
53	2.40	0.26
57	2.86	0.18
61	2.66	0.36
65	2.74	0.46
76	3.30	0.21
128	2.93	0.21
132	3.38	0.28
150	3.01	0.22
152	2.90	0.29

core 84-9

Depth (cm)	δ O18‰	δ C13‰
1	2.50	0.77
11	2.56	0.86
20	2.43	0.68
29	2.75	0.58
41	2.70	0.66
51	2.45	0.55
62	2.51	0.44
67	2.43	0.50
74	2.47	0.37
77	3.01	0.36
81	3.09	0.26
85	3.09	0.26
89	3.18	0.20

core 84-16

Depth (cm)	δ O18‰	δ C13‰
1	2.44	0.66
11	2.47	0.71
21	2.41	0.58

core 90-26

Depth (cm)	δ O18‰	δ C13‰
1	2.47	0.70
9	2.48	-0.12
18	2.50	-0.21
31	2.00	-0.25
39	3.10	-0.06
50	3.40	-0.21
69	3.29	-0.04
90	4.12	0.07
100	4.42	0.10
110	4.40	0.18
120	3.80	0.18
130	4.10	0.17
140	4.20	0.14
194	3.56	0.07
200	4.28	0.01
211	3.15	-0.07
221	3.54	-0.17
228	3.18	-0.10
248	3.20	-0.08
269	3.77	0.07
283	4.02	-0.14
290	4.10	0.13
300	4.20	0.40
320	4.04	0.31
335	3.87	0.06
344	4.14	0.15
352	3.73	0.10
404	3.88	-0.04
410	3.81	0.02
552	4.10	0.21
562	4.09	0.19
603	3.80	0.18
664	3.97	0.19
684	3.66	0.36
704	4.19	0.37
715	3.39	0.17
724	2.78	0.03
800	3.66	0.44
810	3.90	0.35

Appendix 4a. Continued.

core 84-16

Depth (cm)	δ O18‰	δ C13‰
30	2.51	0.56
41	2.53	0.56
49	2.55	0.55
56	2.55	0.41
65	2.97	0.25
69	3.01	0.35
71	2.85	0.31
73	3.16	0.40
75	3.02	0.30
79	3.31	0.33
83	3.27	0.26
87	3.51	0.18
88.5	3.50	0.26

core 90-26

Depth (cm)	δ O18‰	δ C13‰
820	3.64	0.44
923	4.18	0.51
933	4.07	0.32
943	4.26	0.31
953	4.15	0.37
963	4.19	0.35
973	4.23	0.23
983	4.24	0.21
991	4.29	0.20
1002	3.68	0.09
1013	3.55	-0.03
1023	3.45	-0.15
1033	3.52	0.01
1043	3.34	-0.13

core 92-1

Depth (cm)	δ O18‰	δ C13‰
765	3.82	0.24
766	3.90	0.31
767	3.76	0.17
768	3.80	0.26
769	3.79	0.16
770	3.84	0.14
771	3.81	0.11
772	3.94	0.28
773	3.88	0.3
774	3.86	0.17
775	3.89	0.24
776	4.05	0.25

Appendix 4b. List of AMS C14 ages (processed in Isotrache Laboratory, Toronto Marine reservoir corrections have not been applied to these results.

Core No.	Depth (cm)	Isotrache Lab. No.	AMS 14C dating	Reference
75-55	81	AA-6851	13185±190	Andrews et al (1994)
75-55	116	AA-5999	14560±105	Andrews et al (1994)
75-55	181	AA-4700	19405±210	Andrews et al (1994)
75-55	250	AA-3338	21060±240	Andrews et al (1994)
84-8	60	TO-5212	9450±110	This study
84-8	76	TO-4661	22680±240	This study
84-9	73	TO-5213	9719±140	This study
84-9	81	TO-4662	16000±200	This study
84-16	88	TO-4663	18590±180	This study
87-2	88	TO-3142	24170±200	Hesse (1995)
87-7	335	TO-3143	23300±190	"
87-9	195	TO-5214	17180±130	This study
87-9	246	TO-3144	22770±190	Hesse (1995)
90-26	1	TO-3145	5850±70	Wang and Hesse (1992)
90-26	51	TO-3146	15080±120	Wang and Hesse (1992)
90-26	276	TO-2366	21070±190	Wang and Hesse (1992)
90-26	560	TO-2367	29950±270	Wang and Hesse (1992)
90-26	817	TO-2437	35100±360	Wang and Hesse (1992)
90-26	981	TO-2438	40460±530	Wang and Hesse (1992)
90-26	1041	TO-2439	44610±920	Wang and Hesse (1992)
90-29	266	TO-2994	27070±270	Wang and Hesse (1992)
90-29	425	TO-2995	33100±330	Wang and Hesse (1992)
90-29	857	TO-2996	48810±1130	Wang and Hesse (1992)
90-29	1008	TO-2998	54530±2090	Wang and Hesse (1992)
92-1	550	TO-4930	21890±160	This study
92-1	1233	TO-4931	28100±290	This study
92-2	217	TO-4932	9640±70	This study
92-2	529	TO-4933	32530±450	This study
92-2	1152	TO-4934	35240±440	This study
92-4	213	TO-4935	9520±70	This study
92-4	696	TO-4936	24630±140	This study
92-5	161	TO-5215	14580±90	This study
92-5	369	TO-5216	20500±170	This study
92-6	185	TO-5217	29710±530	This study
92-6	367	TO-5218	41220±670	This study

Appendix 5a. Carbonate content in fine and coarse fractions.

Core 90-26

Depth (cm)	Facies	proportion of CaCO ₃		
		%CaCO ₃	<63 µm	>63 µm
1	HI	26.11	87.35	12.65
9	HI	19.40	92.1	7.9
18	N	42.76	96.62	3.38
31	N	59.42	94.85	5.15
39	N	57.13	93.1	6.9
50	HI	3.38	22.1	77.9
60	HI	2.26	100	0
69	HI	1.43	100	0
80	HI	0.96	100	0
90	HI	0.86	92.84	7.16
100	HI	0.03	100	0
110	HI	2.41	100	0
120	HI	1.7	100	0
130	HI	2.48	85.2	14.8
140	HI	1.59	100	0
150	HI	1.36	100	0
160	HI	0.6	100	0
170	HI	0.78	100	0
194	H	2.1	98.63	1.37
200	H	2.69	86.1	13.9
207	H	2.8	97.13	2.87
221	N	25.41	85.71	14.29
240	N	25.7	97.13	2.87
248	N	32.25	68.92	31.08
260	N	36.11	82.74	17.26
269	N	43.48	82.22	17.78
283	HI	6.88	74.09	25.91
290	HI	9.09	91.03	8.97
300	H	4.59	20	80
320	H	1.38	76.95	23.05
344	C	2.48	91.3	8.7
360	C	0.46	100	0
380	C	2.3	94.12	5.88
404	H	3.11	77.53	22.47
415	T	32.11	98.59	1.41
440	T	40.39	98.1	1.9
460	T	38.19	97.48	2.52
480	T	41.49	98.9	1.1
500	T	44.66	96.99	3.01

Core 87-9

Depth (cm)	Facies	proportion of CaCO ₃		
		%CaCO ₃	<63 µm	>63 µm
160	T	35.07	99.15	0.85
164	T	31.76	94.87	5.13
166	TI	40.41	88.89	11.11
167	TI	43.84	90.61	9.39
169	HI	21.78	79.61	20.39
170	HI	10.10	90.15	9.85
171	HI	6.88	56.97	43.02
172	HI	5.66	59.02	40.98
173	HI	4.44	76.74	23.26
174	HI	2.87	85.06	14.94
175	HI	2.61	85.64	14.36
179	T	8.01	61.54	38.46
180	HI	6.64	66.76	33.24
182	HI	5.86	62.54	37.46
183	HI	4.40	91.84	8.16
184	HI	4.89	89.88	10.12
185	HI	4.13	82.45	17.55
187	HI	5.70	58.80	41.20
194	HI	3.40	94.95	5.05
195	HI	7.33	67.84	32.16
196	HI	8.70	51.75	48.25
197	HI	9.03	73.56	26.44
198	HI	8.35	58.36	41.64
200	HI	8.46	59.10	40.90
201	HI	8.15	62.83	37.17
203	HI	9.36	55.84	44.16
204	HI	10.01	46.84	53.16
206	HI	8.79	76.75	23.25
208	HI	13.22	76.07	23.93
209	HI	15.56	69.24	30.76
210	HI	21.35	52.23	47.77
211	HI	23.20	56.74	43.26
212	HI	23.20	90.25	9.75
213	HI	14.35	89.36	10.64
218	T	30.29	96.23	3.77
222	T	51.32	70.19	29.81
229	TI	40.54	94.07	5.93
231	T	38.08	99.14	0.86
232	TI	38.07	85.76	14.24

Appendix 5a. continued

Core 90-26

Depth (cm)	Facies	proportion of CaCO ₃		
		CaCO ₃ %	<63 µm	>63 µm
520	T	44.26	99.04	0.96
540	T	32.42	98.9	1.1
552	H	1.99	21.45	78.55
562	H	0	100	0
570	C	0.64	100	0
592	C	0	100	0
603	C	6.12	80.22	19.78
610	C	1.38	100	0
630	C	1.79	100	0
674	H	0.82	100	0
694	H	2.54	100	0
715	HI	6.33	76.97	23.03
724	D	39.85	86.6	13.4
733	N	40.42	91.78	8.22
743	N	39.6	91.15	8.85
752	N	35.89	98.18	1.82
759	N	37.72	91.78	8.22
769	H	1.72	70.37	29.63
790	HI	1.91	100	0
810	HI	6.91	96.99	3.01
830	T	36.37	98.76	1.24
850	T	35.27	99.65	0.35
870	T	34.82	99.04	0.96
890	T	28.46	98.16	1.84
890	T	28.89	97.88	2.12
923	H	3.4	72.95	27.05
943	H	1.81	52.39	47.61
963	H	3.82	91.46	8.54
983	H	6.2	94.05	5.95
1002	H	5.78	97.04	2.96
1023	H	5.71	56.65	43.35
1043	T	13.75	97.18	2.82
1063	T	8.96	96.1	3.9
1083	T	25.03	97.73	2.27

Core92-5

Depth (cm)	Facies	proportion of CaCO ₃		
		CaCO ₃ %	<63 µm	>63 µm
125	N	34.45	9.18	90.82
126	N	39.00	3.88	96.12
127.5	N	41.68	1.77	98.23

Core 87-9

Depth (cm)	Facies	proportion of CaCO ₃		
		CaCO ₃ %	<63 µm	>63 µm
234	TI	47.42	90.99	9.01
236	TI	31.52	72.64	27.36
237	HI	17.02	88.36	11.64
239	HI	27.45	74.16	25.84
240	T	21.45	95.70	4.30
243	H	18.11	57.10	42.90
244	H	13.93	69.74	30.26
246	H	13.33	75.24	24.76
247	H	12.13	82.24	17.76
249	H	12.79	89.58	10.42
251	H	16.80	75.45	24.55
253	H	10.92	57.07	42.93
255	T	18.17	68.83	31.17
257	T	34.56	96.35	3.65
260	T	37.95	97.77	2.23

Core 88-1

Depth (cm)	Facies	proportion of CaCO ₃		
		CaCO ₃ %	<63 µm	>63 µm
208	HI	40.59	85	15.39
289	HI	39.27	84.00	16
349	HI	34.54	84.61	15.39

Core 88-7

Depth (cm)	Facies	proportion of CaCO ₃		
		CaCO ₃ %	<63 µm	>63 µm
197	HI	38.3	78.03	21.97
442	HI	33.66	83.49	16.51

Core 90-34

Depth (cm)	Facies	proportion of CaCO ₃		
		CaCO ₃ %	<63 µm	>63 µm
267	TI	40.80	91.06	8.94
276	TI	30.45	90.90	9.1
282	TI	28.15	90.06	9.94
287	TI	38.36	93.75	6.25
292	TI	26.12	90.78	9.22
304	TI	30.59	94.45	5.55
315	TI	26.41	88.78	11.22

Appendix 5a. continued.

Core 92-5

Depth (cm)	Facies	CaCO ₃ %	proportion of CaCO ₃	
			<63 μ m	>63 μ m
128	N	44.52	1.00	99.00
128.5	N	41.25	0.40	99.60
129	N	36.27	1.63	98.37
132	N	27.40	2.66	97.34
132.5	N	43.43	3.14	96.86
133	N	46.07	3.41	96.59
134	N	45.14	1.38	98.62
134.5	N	39.80	1.44	98.56
134.8	N	40.77	0.23	99.77
135.2	N	40.00	0.00	100.00

Appendix 5b. Total carbonate content in three slope cores

Core 90-25

Depth (cm)	Facies	%CaCO ₃
124	HI	25.91
130	N	33.15
133	N	33.32
138	N	33.32
142	N	26.66
149	N	23.16
153	N	33.82
159	N	27.41
160	N	36.65
166	N	17.91
172	N	29.57
177	N	27.82
182	N	26.66
187	N	26.24
194	N	45.32
197	N	28.91
201	N	32.40
206	N	33.82
209	N	34.99
216	N	40.32
220	N	32.90
224	N	34.74
228	N	28.49
232	HI	3.75
239	HI	6.91
245	HI	2.58
255	H	1.33

Core 88-10

Depth (cm)	Facies	CaCO ₃ %
187	HI	6.58
192	HI	18.74
197	N	32.07
201	N	31.65
206	N	30.65
209	N	22.49
214	N	27.99
219	N	31.32
223	N	34.74

Core 88-10 (continued)

Depth (cm)	Facies	%CaCO ₃
227	N	32.65
232	N	33.82
240	N	2.25
245	N	1.83
250	N	3.42
227	N	32.65
232	N	33.82
240	N	2.25
245	N	1.83
250	N	3.42

Core 92-1

Depth (cm)	Facies	%CaCO ₃
64	HI	37.98
270	T	8.19
342	T	7.94
345	T	8.67
566	P	2.17
567	P	3.25
722	P	1.25
724	P	1.83
759	P	1.25
760	P	1.25
774	P	1.92
775	P	1.00
874	P	1.83
875	P	0.00
979	P	2.17
979.3	P	0.83
979.6	P	2.25
979.9	P	1.67
1021	P	0.00
1023	P	0.83
1055	P	3.83
1056	P	2.58
1227	P	1.58
1229	P	1.50

Appendix 6. Organic and inorganic carbon content of sediments in four slope, rise and basin centre cores.

Core 90-25

Depth (cm)	Facies	%Organic C	%Inorganic C
124	HI	1.01	3.11
130	N	0.80	3.98
133	N	1.07	4.00
138	N	1.08	4.00
142	N	1.53	3.20
149	N	0.48	2.78
153	N	1.18	4.06
159	N	1.19	3.29
160	N	1.99	4.40
166	N	1.18	2.15
172	N	1.56	3.55
177	N	1.14	3.34
182	N	0.79	3.20
187	N	1.91	3.15
194	N	0.82	5.44
197	N	1.67	3.47
201	N	1.66	3.89
206	N	1.80	4.06
209	N	1.86	4.20
216	N	0.67	4.84
220	N	1.65	3.95
224	N	0.71	4.17
228	N	1.48	3.42
232	HI	1.03	0.45
239	HI	1.07	0.83
245	HI	0.91	0.31

Core 88-10

Depth (cm)	Facies	%Organic C	%Inorganic C
187	HI	2.02	0.79
192	HI	1.81	2.25
197	N	1.64	3.85
201	N	1.97	3.80
206	N	1.29	3.68
209	N	2.80	2.70
214	N	0.91	3.36
219	N	1.45	3.76
223	N	1.51	4.17

Core 90-26

Depth (cm)	Facies	%Organic C	%Inorganic C
1	HI	1.53	1.80
19	N	1.50	4.37
44	N	0.95	4.19
70	HI	0.48	0.16
99	HI	0.57	0.12
121	HI	0.45	0.20
150	HI	0.38	0.10
171	HI	0.59	0.07
186	T	0.61	0.12
194	H	0.48	0.05
200	H	0.67	0.04
207	H	1.13	0.08
211	N	1.43	3.20
215	N	1.47	2.86
221	N	0.78	3.05
228	N	1.28	4.21
233	N	1.41	3.64
240	N	1.13	3.54
244	N	1.43	3.08
247	N	0.65	2.96
248	N	1.73	2.39
251	N	1.39	4.71
254	N	1.83	3.87
262	N	1.28	3.37
264	N	1.45	4.33
269	N	1.07	5.22
275	H	1.02	0.27
283	H	0.71	0.83
290	H	1.12	1.09
300	H	0.60	0.16
310	H	0.26	0.00
320	H	0.38	0.05
350	H	0.23	0.18
360	H	2.05	0.10
391	C	0.46	0.12
420	T	2.19	2.21
445	T	2.20	3.16
479	T	2.03	3.64
500	T	1.37	4.06
520	T	2.08	2.35

Appendix 6. Continued.

Core 88-10

Depth (cm)	Facies	%Organic C	%Inorganic C
227	N	0.97	3.92
232	N	1.00	4.06
240	N	0.68	0.27
245	N	1.34	0.22
250	N	1.45	0.41
255	H	1.88	0.16

Core 87-12

Depth (cm)	Facies	%Organic C	%Inorganic C
58	HI	1.33	0.43
62	N	1.84	3.40
65	N	0.61	4.20
69	N	1.71	3.91
73	N	1.01	3.52
76	N	1.07	3.77
78	N	1.55	4.00
81	N	1.66	4.19
86	H	1.47	0.64
91	H	1.49	1.37
96	T	2.04	2.10

Core 92-5

Depth (cm)	Facies	%Organic C	%Inorganic C
125	N	0.90	4.13
125.3	N	1.43	4.68
125.6	N	1.64	5
125.9	N	1.41	5.34
126.2	N	1.87	4.95
126.5	N	2.04	4.35
131	N	1.67	3.29
131.3	N	0.97	5.21
131.6	N	0.92	5.53
131.9	N	1.21	4.6
132.2	N	1.76	4.77
132.5	N	1.85	4.89
132.8	N	1.77	4.8

Core 90-26

Depth (cm)	Facies	%Organic C	%Inorganic C
547	T	1.97	2.55
570	C	0.33	0.05
600	C	0.67	0.19
630	C	0.50	0.12
650	H	0.45	0.07
670	H	0.56	0.04
700	H	0.52	0.15
720	D	1.30	3.11
750	N	1.10	3.61
769	H	0.50	0.14
800	HI	0.46	0.15
826	T	2.07	2.32
830	T	2.31	1.81
851	T	1.69	2.86
870	T	1.90	2.35
884	T	2.11	1.91
891	D	1.10	3.53
906	D	0.72	3.26
920	D	0.80	0.19
950	H	0.46	0.10
980	H	1.17	0.07
1000	H	0.94	0.20
1020	H	1.03	0.03
1050	T	0.68	2.86
1070	T	1.98	2.44

Core 92-1

Depth (cm)	Facies	%Organic C	%Inorganic C
566	P	1.05	0.26
567	P	0.52	0.39
722	P	1.12	0.15
724	P	1.01	0.22
759	P	1.22	0.15
760	P	0.72	0.15
774	P	0.82	0.23
775	P	0.89	0.12
874	P	0.62	0.22
875	P	0.57	0
979	P	0.64	0.26
979.3	P	0.44	0.1

Appendix 6. Continued.

Core 92-1

Depth (cm)	Facies	%Organic C	%Inorganic C
979.6	P	0.48	0.27
979.9	P	0.74	0.2
1021	P	1.1	0
1023	P	0.66	0.1
1055	P	0.63	0.46
1056	P	0.34	0.31
1227	P	0.75	0.19
1229	P	0.65	0.18

Appendix 7. Rock-Eval analyses of core 90-26.

No. No.	Depth (cm)	Tmax	S1	S2	S3	PI	S2/S3	PC	TOC	HI	OI
1	1	375.00	0.10	0.23	1.88	0.31	0.12	0.02	0.16	143.50	1174.50
2	19	425.50	0.01	0.19	0.92	0.06	0.20	0.01	0.15	123.00	609.50
3	99	507.00	0.05	0.22	0.51	0.19	0.42	0.02	0.23	93.00	221.00
4	150	519.00	0.05	0.30	0.40	0.15	0.75	0.03	0.22	134.00	179.50
5	200	449.00	0.07	0.24	0.64	0.22	0.37	0.02	0.31	78.50	209.50
6	250	341.00	0.03	0.07	0.70	0.31	0.09	0.00	0.12	54.00	579.00
7	300	408.00	0.06	0.15	0.67	0.28	0.22	0.01	0.11	136.00	608.50
8	350	380.00	0.03	0.09	0.60	0.28	0.14	0.01	0.13	65.00	461.00
9	391	414.00	0.04	0.21	0.47	0.17	0.44	0.02	0.29	71.50	162.50
10	446	436.00	0.02	0.24	1.16	0.09	0.21	0.02	0.43	55.00	269.50
11	500	422.00	0.01	0.16	1.17	0.07	0.13	0.01	0.25	62.00	468.00
12	547	419.50	0.02	0.16	1.47	0.09	0.11	0.01	0.27	59.50	554.50
13	600	411.00	0.05	0.17	0.53	0.23	0.33	0.02	0.22	77.50	237.50
14	650	391.50	0.10	0.44	0.50	0.18	0.90	0.04	0.32	139.50	156.50
15	724	397.00	0.00	0.04	0.51	0.00	0.08	0.00	0.05	95.00	1137.50
16	750	425.00	0.00	0.09	0.73	0.00	0.12	0.00	0.09	99.50	810.50
17	800	371.00	0.08	0.38	0.49	0.18	0.77	0.04	0.12	325.00	422.50
18	850	419.00	0.01	0.12	1.12	0.04	0.11	0.01	0.25	48.00	448.00
19	890	426.00	0.01	0.12	0.86	0.05	0.13	0.01	0.15	80.00	590.00
20	950	445.50	0.13	0.58	0.45	0.19	1.30	0.06	0.27	214.00	165.00
21	1000	353.50	0.07	0.15	0.81	0.34	0.19	0.02	0.20	75.00	402.50
22	1050	405.00	0.02	0.11	1.06	0.16	0.10	0.01	0.22	46.50	480.00

Note: (1) All samples have been analyzed in duplicate and the average results are reported in the table.

(2) The geochemical parameters are:

Tmax: temperature in centigrade at the top of the pyrolysis peak: a thermal maturity indicator

S1: mg hydrocarbon (HC)/g sample evolved at 300°C: previously existing hydrocarbons

S2: mg HC/g sample yielded during pyrolysis experiment up to 600°C: potential HC

S3: mg CO₂/g sample evolved up to 390°C: organically derived CO₂

PI: production Index=S1/(S1+S2): a maturity indicator

S1/S2: organic matter type indicator

PC: Pyrolyzable Carbon: organic matter type indicator

TOC: Total organic carbon, percent by weight

HI: Hydrogen Index= 100*S2/TOC: organic matter type indicator

OI: Oxygen Index= 100*S3/TOC: organic matter type indicator

Appendix 7. continued.

The Rock-Eval pyrolysis

The rock-eval is a whole-rock pyrolysis technique to identify the type and maturity of organic matter. The pyrolysis technique involves a programmatic temperature gradient allowing gasification of organic material. During the pyrolysis cycle, CO₂ produced from organic matter is trapped at specific intervals for kerogen analysis. In addition, a maximum temperature value is obtained which corresponds to the maximum hydrocarbon produced from kerogen pyrolysis. Time duration for a complete pyrolysis is 20 minutes.

Measured parameters (from Dr. L. Snowdon, personal communication; Peters, 1986):

S1: the quantity of free hydrocarbons in the sample in mg hydrocarbon/g sample

S2: the quantity of hydrocarbons produced by thermal conversion of kerogen in the sample in mg hydrocarbons/g sample

S3: the quantity of organic CO₂ produced during pyrolysis from the organic carbon in the sample in mg CO₂/g sample

T_{max}: the temperature at which the maximum hydrocarbon generation occurs

TOC: Total organic carbon content of the sample is algorithmically calculated from the S1, S2 and S4 peaks. The S4 peak is the residual carbon determined on a second detector after oxidation in air at 600 degrees centigrade in a second oven.

Rock-eval interpretive guidelines

S1: indicative of light (extractable) hydrocarbons

S1 values (mg HC/g):

0-0.25: very poor

0.25-0.5: poor

0.5-1: fair

1-2.0: good

2.0-4.00: very good

>4.00: excellent

S2: an indicator of source rock genetic potential

S2 values (mg HC/g sample for immature to slightly mature source rocks):

<2.00: poor source rock

2.00-5.00: fair source rock

>5.00: good source rock

S1+S2= overall genetic potential of a source rock

PI= S1/(S1+S2) Production Index

S2/S3 Ratio: this ratio allows type classification of kerogen

0.00-2.50: Type III, gas

2.50-5.00: Type III, gas/oil

5.00-10.00: Type I or II, oil

Pyrolyzed carbon: PC

This index represents the organic richness of the source rock by kerogen type provided sufficient burial depth and time.

$$PC = K(S1 + S2)/10 \quad K=0.82$$

where $K=0.82$ (the average weight percent of carbon present in hydrocarbons)

type I: $PC=80\%$ of toc

type II: $PC=50\%$ of toc

type III: $PC=10-30\%$ of toc

Tmax: This index is indicator for the stage of maturation of organic matter.

<435°C: immature

435-465°C: oil zone

>465°C: gas zone

Kerogen typing:

HI: hydrogen index = $S2/TOC \times 100$

OI: oxygen index = $S3/TOC \times 100$

HI versus Tmax plot

Type I: $HI > 600 < 900$

Type II: $HI > 300 < 600$

Type III: $HI < 300$

Total Organic Carbon (TOC)

$$TOC = K(S1 + S2)/10 + S4/10$$

where $S4 = 10TOC\% - 0.82(S1 + S2)$

S4 is the value of the oxidized residual organic carbon portion of the TOC.

Appendix 8a. Concentration of ash particles.

Core 84-8

Depth (cm)	no. of rhyolitic ash/g	no. of basaltic ash/g
20	0.46	0.14
30	5.77	1.92
48	5.65	1.8
56	31.02	10.34
60	35.69	3.97
64	3	0
71	5.08	1.95

90-29 (twc)

Depth (cm)	no. of rhyolitic ash/g	no. of basaltic ash/g
1	0.00	0.00
10	41.70	0.00
18	0.00	0.00
30	0.00	4.99
40	0.00	0.00
50	0.00	0.00

Core 84-9

Depth (cm)	no. of rhyolitic ash/g	no. of basaltic ash/g
28	76.52	25.51
40	6.02	2
61	16.84	5.62
65	5.42	0.18
72.5	4.03	8.05
76	56.9	18.96

90-29

Depth (cm)	no. of rhyolitic ash/g	no. of basaltic ash/g
50	0.00	2.30
90	0.00	0.00
105	0.00	119.30
122	0.00	0.00
131	0.00	0.00
140	0.00	0.00
145	0.00	6.39
160	0.00	0.00
170	0.00	0.00
180	0.00	7.11
190	0.00	0.00
200	0.00	6.23
210	0.00	663.83
215	0.00	805.01
235	0.00	0.00
243	0.00	0.00
266	0.00	0.00
270	0.00	0.00
290	2.04	26.50
330	0.00	38.33
360	0.00	77.53
370	0.29	8.24
430	0.00	50.81
460	0.00	120.37
470	0.00	39.58
530	0.00	92.98
540	0.00	10.98

Core 87-7

Depth (cm)	no. of rhyolitic ash/g	no. of basaltic ash/g
257	22.23	66.70
258	6.08	18.23
259	0.00	8.74
260	0.00	40.30
262	8.31	33.26
263	0.00	10.13
266	0.00	57.65
277	24.81	0.00
275	9.54	28.64
278	0.00	17.84
280	0.00	15.42
308	0.00	6.92
310	0.00	5.04
311	0.00	6.19
347	0.00	6.32
350	0.00	18.82

Appendix 8a. Continued.

Core 84-9

Depth (cm)	no. of rhyolitic ash/g	no. of basaltic ash/g
352	0.00	6.33

Core 87-9

Depth (cm)	no. of rhyolitic ash/g	no. of basaltic ash/g
150	0.05	0.38
160	38.55	17.13
169	21.17	42.34
170	0.00	116.46
172	0.00	18.86
174	0.00	17.74
175	0.00	2.79
179	0.00	22.77
180	6.00	0.00
184	11.36	0.00
194	2.93	0.00
197	9.61	9.70
198	0.00	14.10
200	0.00	11.71
203	19.62	9.81
211	0.00	13.48
213	0.00	19.24
243	0.00	4.85
250	0.00	0.00

Core 90-26

Depth (cm)	no. of rhyolitic ash/g	no. of basaltic ash/g
1	0.00	0.00
9	0.00	0.00
18	0.00	9.89
31	0.00	0.00
39	0.00	0.00
50	0.00	9.76
60	0.00	64.78
69	0.00	9.36
80	0.00	8.96

90-29

Depth (cm)	no. of rhyolitic ash/g	no. of basaltic ash/g
560	0.00	4.52
580	1.16	12.13
590	72.50	17.58
622	0.00	0.00
640	0.00	0.00
655	0.00	0.00
684	0.00	0.00
696	0.00	0.00
725	0.00	0.00
738	0.00	0.00
765	0.00	0.00
822	0.00	0.00
832	1.31	3.26
870	0.00	6.95
924	0.00	3.15
948	0.00	0.00
1050	0.00	0.00
1074	0.00	0.00
1103	0.00	2.11
1127	0.00	1.06
1187	0.00	0.00
1210	0.00	6.52
1243	0.00	2.60
1282	0.00	5.47
1312	18.46	0.00
1322	0.00	0.00
1342	0.00	0.00
1362	0.00	0.00

Core 92-5

Depth (cm)	no. of rhyolitic ash/g	no. of basaltic ash/g
51	10.66	37.32
60	43.48	182.68
64	64.84	272.32
68	39	305.5
72	5.12	77.15
78	1.33	10.64

Appendix 8a. Continued.

90-26

Depth (cm)	no. of rhyolitic ash/g	no. of basaltic ash/g
90	0.00	11.69
100	0.00	14.21
110	1.11	3.32
120	4.36	8.74
130	0.00	16.05
140	0.00	12.98
150	2.36	0.00
160	0.90	15.51
170	3.56	3.56
194	31.61	7.51
200	0.19	26.79
207	0.00	174.06
221	0.00	0.00
240	0.00	0.00
248	0.00	0.00
260	0.00	0.00
269	0.00	0.00
283	0.00	19.31
289	0.00	0.00
300	0.00	82.91
320	0.00	32.12
335	0.00	17.92
352	0.00	17.05
404	0.00	10337.00
410	0.00	13.04
552	0.00	106.84
562	0.00	4.89
603	0.00	24.02
644	0.00	8.83
650	0.00	0.00
664	0.00	8.00
674	0.00	0.00
686	0.00	0.00
694	0.00	4.34
704	0.00	31.14
724	0.00	0.00
733	0.00	0.00
743	0.00	0.00
752	0.00	0.00

92-5

Depth (cm)	no. of rhyolitic ash/g	no. of basaltic ash/g
161	0	195.08
169	0	49.48
177	0	17.26
185	2.84	54.05
201	0	8.33
225	0	21.04
245	0	13.42
265	0	16.11
285	0	13.6
305	0	9.51
325	3.45	18.99
335	0	14.8
365	0	308.54
370	0	0
423	0	0
433	0	0
806	0	109.93
824	0	35.99
840	0.52	1.04
870	0	14.84
885	0	89.38

Appendix 8a. Continued.

90-26

Depth (cm)	no. of rhyolitic ash/g	no. of basaltic ash/g
759	0.00	0.00
769	2.14	43.81
780	0.00	40.42
790	0.00	6.72
800	0.00	12.59
806	0.00	2.00
810	0.00	24.16
923	0.00	1.91
943	0.00	9.78
963	0.00	8.97
973	0.00	10.19
983	0.00	0.00
991	32.74	0.00
1002	52.93	2.35
1013	311.77	11.66
1023	84.89	0.00
1033	90.00	0.00
1044	89.38	2.08

Appendix 8b. Geochemical analysis of ash particles.

A: Rhyolitic ash

Core	Depth (cm)	Na2O%	Mgo%	Al2O3%	SiO2%	K2O%	CaO%	TiO2%	FeO%
87-7	258	0.00	0.00	9.54	72.97	6.52	2.52	0.00	8.45
"	"	2.54	0.00	7.94	65.31	7.59	3.71	0.00	12.92
"	260	0.00	0.00	10.22	72.90	6.07	2.58	0.00	8.23
"	"	2.85	0.00	9.94	67.44	6.24	2.97	0.00	10.57
"	262	2.29	0.00	10.28	72.41	5.92	2.10	0.00	7.01
"	266	2.46	0.78	11.29	67.12	5.35	3.37	0.00	9.64
"	"	0.00	0.00	11.27	73.98	6.46	2.04	0.00	6.25
"	"	0.83	0.00	8.47	70.27	8.92	1.93	0.00	9.59
"	"	2.02	0.00	10.32	70.39	6.30	2.47	0.00	8.50
"	"	3.69	0.00	11.27	72.79	4.66	2.05	0.00	5.54
"	"	2.60	0.00	10.84	72.46	5.39	1.94	0.00	6.77
"	"	3.06	0.00	11.26	72.42	5.29	1.87	0.00	6.11
"	"	3.05	0.00	11.18	72.56	5.31	1.78	0.00	6.12
"	"	3.48	0.00	11.31	72.09	4.96	2.02	0.00	6.14
"	"	0.91	0.00	9.61	69.17	7.15	3.08	0.00	10.07
"	"	0.00	0.00	9.63	69.84	7.42	3.10	0.00	10.00
"	"	0.00	0.00	9.68	71.21	6.61	2.92	0.00	2.57
87-9	160	0.00	0.00	10.68	65.54	6.19	3.76	0.00	13.84
"	"	3.86	0.00	10.58	71.98	5.31	2.60	0.00	5.67
"	"	0.00	0.00	9.44	70.34	6.62	3.31	0.00	10.29
"	169	0.00	0.00	9.88	70.50	6.87	3.03	0.00	9.73
"	198	0.00	0.00	9.55	77.47	7.07	0.00	0.00	5.91
"	"	2.67	0.00	8.85	60.39	7.17	3.45	0.00	17.48
90-26	160	0.66	0.00	7.26	71.72	9.17	1.33	1.52	8.35
"	"	0.00	0.00	7.20	73.89	8.89	1.39	1.47	7.16
92-5	68	0.00	0.00	8.65	68.96	6.81	7.28	1.26	11.04
"	"	0.00	0.00	9.84	72.18	6.53	2.62	1.02	7.81
"	"	0.00	0.00	10.93	70.12	5.30	3.35	0.91	9.4
"	"	1.53	0.00	7.72	64.30	6.70	4.32	1.81	13.64
"	"	0.71	0.00	7.34	74.85	8.33	1.22	0.84	6.7
"	"	1.07	0.00	6.79	63.98	8.34	5.06	1.91	12.86
"	"	1.87	0.00	7.53	63.70	6.82	4.51	1.74	13.83
"	72	0.00	0.00	8.66	67.65	7.21	3.24	1.79	11.45
"	"	0.00	0.00	8.72	68.07	7.25	4.25	1.37	10.34
"	161	0.00	0.00	7.94	63.94	6.82	5.60	1.78	13.93
	Average	1.11	0.02	8.73	64.34	6.15	2.70	0.46	8.52

Appendix 8b. continued.

B: Basaltic ash

Core	Depth (cm)	Na2O%	Mgo%	Al2O3%	SiO2%	K2O%	CaO%	TiO2%	FeO%
"	"	0.92	1.17	11.26	39.25	0.58	19.66	2.91	24.24
87-7	259	0.00	1.93	7.58	37.51	0.81	18.58	4.51	29.07
"	"	0.00	0.00	9.16	42.91	0.00	16.93	2.97	28.02
"	"	0.00	3.13	10.57	37.67	0.69	16.62	5.61	25.70
"	"	0.00	0.00	7.68	40.62	0.45	16.77	4.02	30.28
"	"	1.46	0.00	7.98	33.59	1.00	18.48	0.00	37.48
"	"	1.43	3.29	8.86	43.98	0.33	15.67	0.00	26.45
"	"	1.22	3.29	11.39	42.93	0.54	16.02	0.00	24.60
"	"	2.86	2.24	10.01	44.38	0.36	17.15	0.00	23.00
"	260	0.87	2.84	8.13	38.58	0.60	15.85	3.85	29.28
"	261	0.00	4.65	12.53	44.18	0.53	14.04	3.86	20.21
"	"	0.00	0.00	8.55	43.65	0.57	16.13	5.08	26.03
"	"	2.65	1.74	8.45	42.69	0.91	12.77	6.22	24.58
"	"	1.81	2.09	8.60	42.61	0.51	11.92	4.51	27.94
"	"	0.94	0.93	8.31	42.87	2.49	12.05	8.10	24.31
"	"	1.03	3.03	9.69	47.61	0.63	14.79	2.80	20.37
"	261	1.12	0.00	7.26	59.57	7.78	5.25	0.00	19.02
"	262	1.05	1.35	9.88	40.68	3.70	14.49	5.81	23.02
"	"	1.90	3.09	8.37	38.59	0.58	18.85	3.00	25.62
"	280	0.98	0.00	7.58	50.77	2.24	9.34	3.99	25.10
87-9	160	0.00	0.00	9.84	52.35	3.99	9.56	6.50	17.75
"	195	1.21	4.35	13.37	47.21	0.53	13.36	3.46	16.51
90-26	90	1.18	1.94	7.11	35.13	0.94	13.77	8.75	31.20
"	160	1.34	0.87	7.74	45.21	1.40	10.75	5.70	27.00
"	300	0.89	1.26	7.58	41.70	1.42	12.49	6.47	28.18
"	"	0.78	2.31	7.50	39.65	0.37	14.92	4.06	30.41
"	"	0.50	2.62	7.74	41.37	0.30	16.07	3.38	28.03
"	"	0.61	1.31	7.05	39.60	0.63	16.28	4.83	29.69
"	404	0.00	0.00	7.84	43.83	0.00	14.37	6.83	27.14
"	"	0.00	4.00	9.39	38.68	0.82	12.96	6.48	27.66
"	"	0.00	3.50	10.78	47.25	0.34	13.39	3.29	21.46
"	"	0.00	0.76	6.14	43.11	1.45	12.11	6.36	30.07
"	552	1.01	1.74	7.45	36.53	1.18	15.87	7.69	28.52
"	"	0.76	0.98	5.54	30.48	1.55	16.57	8.46	35.65
"	"	0.95	1.62	7.87	38.65	1.14	15.03	7.91	26.84
"	"	1.02	1.86	7.11	34.68	0.93	15.09	8.61	30.29
92-5	60	1.60	3.73	9.58	43.05	0.60	14.60	3.93	22.90
"	68	0.00	0.00	9.64	45.80	1.40	11.72	6.26	25.18
"	"	0.44	2.34	8.61	40.41	0.54	17.95	3.87	25.83
"	161	2.87	1.33	9.22	48.34	3.06	12.32	3.75	19.12

Appendix 8b. continued.

B: Basaltic ash

Core	Depth (cm)	Na ₂ O%	MgO%	Al ₂ O ₃ %	SiO ₂ %	K ₂ O%	CaO%	TiO ₂ %	FeO%
92-5	"	0.54	2.46	8.63	41.75	0.51	16.83	4.37	24.90
"	"	2.26	2.87	10.37	47.31	0.98	16.48	2.20	17.16
"	"	1.10	1.70	9.02	46.55	0.76	11.75	5.59	23.54
"	806	1.28	1.48	7.13	35.31	0.95	16.36	7.14	30.35
"	"	1.41	1.71	7.70	36.87	0.92	15.57	6.73	29.09
"	"	0.55	1.52	6.92	33.39	0.98	16.43	8.44	31.77
"	"	0.78	1.33	7.50	35.17	1.03	16.14	8.49	29.56
"	885	0.85	1.82	8.88	46.25	0.62	12.94	4.64	24.01
"	"	1.26	1.55	8.70	47.68	0.85	12.18	3.94	23.84
"	"	1.32	1.37	8.73	41.89	0.89	12.81	4.77	28.21
"	"	1.29	1.27	7.54	39.88	1.16	12.75	6.24	29.88
	Average	0.92	1.65	7.87	38.87	1.09	13.12	4.52	24.10

Appendix 9a. Mineralogical composition of the sand fraction.

Core	Depth (cm)	Facies	Quartz	Microcline	Orthoclase	Plagioclase	Hornblende	Clino-pyroxene	Ortho-pyroxene	Epidote	Augite	Biotite	Ash	Opaque minerals
84-8	100	MS	38.1	8.3	17.9	3.6	2.4					1.2		
84-8	162	"	49.9	8.3	13.9	2.8	1.9		1.9	1.0		1.0		1.0
84-8	262	MS	47.9	10.6	17.0	1.1	1.1							
84-8	311	MS	46.6	3.3		3.3	0.5	2.3				16.4	25.0	
"	350	MS	49.7	1.3	8.7	6.7	14.1	0.7	0.7	1.3		1.3		0.7
"	400	MS	42.9	3.2	17.5	6.4	1.6					1.6		
"	450	MS	28.3		19.6	6.5	4.4				1.1			
"	490	MS	49.0		9.6	14.4	1.0							
84-9	128	MS	31.3	5.2	19.8	3.1	1.0	1.0						
"	180	MS	38.7	2.8	11.3	12.7	0.7	1.4				11.5	1.9	
84-14	322	MS	45.6	1.0	10.7	4.9	1.9	1.0		1.0		1.0		
84-14	370	D	27.5	2.0	5.9	9.8								
"	780	MS	32.0		13.9	12.5	5.6	1.4		2.8				
84-16	110	MS	21.1	1.3	11.8	4.0	4.0	7.9	2.6	1.3				
87-9	170	HI	21.8		3.9	3.9	3.9							
"	196	HI	13.9		13.9	7.6	5.1							2.5
"	237	HI	20.2	1.1	6.4	6.4				1.1				1.1
"	255	HI	42.3	3.9	5.1	12.8			2.6	1.3			12.8	
88-8	212	HI	63.2	3.5	1.1	8.0	1.1	2.3	2.3	1.1		1.6	3.1	
"	417	HI	53.1	6.3	6.3	1.6	2.3	0.8	3.1			0.8		
"	500	HI	44.9	8.2	8.2	4.1				4.0			4.0	
90-26	39	N	39.1	1.6	3.3	4.4	1.1	3.8	0.5	3.8				0.5
"	248	N	63.8	1.9	3.3	1.9	2.4	2.9	3.8	2.4				1.0
"	752	N	48.7	2.0	6.6	5.3	3.9	2.6	0.7	2.6				
90-29	235	N	56.0	1.0	2.9	5.3	4.8	1.9	1.4	3.8				
92-1	979	P	71.4	5.7	2.9	5.7	2.9					4.3		
92-1	980	P	57.0	0.6	14.7	10.9	1.3					4.5		
92-2	1152	H	53.3	2.8	14.0	4.7						4.7		0.9

Appendix 9a. Continued.

Core	Depth (cm)	Facies	Rock fragments												n
			Carbonate	Granite	Granodiorite	Diorite	Anorthosite	Gabbro	pyroxenite	Amphibolite	Basalt	Andesite	Schist	others	
84-8	100	MS	1.2	21.4							6.0				84
84-8	162	"	1.9	12.0	4.6			1.0							108
84-8	262	MS		16.0							6.4				94
84-8	311	MS		1.4	1.4										203
"	350	MS	0.7	10.1			0.7	1.3		1.3	0.7				149
"	400	MS		25.4				1.6							63
"	450	MS	1.1	23.9	5.1		4.4	2.5	2.2	1.1					92
"	490	MS	10.6	9.6			2.9				2.9				104
84-9	128	MS	2.1	13.8	12.8			2.1	1.0			4.2	1.0		94
"	180	MS	3.5	3.5						0.7	9.9		1.4		141
84-14	322	MS	21.4	7.8			1.0	1.0			1.9				103
84-14	370	D	33.3	15.7			3.9		2.0						51
"	780	MS	5.8	16.7			0.0	4.2		1.4	1.4			1.4	72
84-16	110	MS	25.0	3.5			3.5	3.5			10.5				78
87-7	170	HI	2.6	9.0			2.6	2.6			50.0				78
"	196	HI	3.8	11.4	1.3		1.3	7.6			31.7				79
"	237	HI	9.6	23.5	2.1		3.2				22.3			1.1	94
"	255	HI		16.7	1.3		1.3								78
88-8	212	HI		3.1				1.1			3.1			2.3	109
"	417	HI	1.6	8.6			0.8		0.8		11.7				128
"	500	HI	6.1	10.2							11.3				98
90-26	39	N	37.5	1.6								2.7			184
"	248	N	14.8	1.4								0.5			211
"	752	N	19.1	6.6		1.3						0.7			152
90-29	235	N	16.8	4.3		0.5		0.5	0.5			4.3			199
92-1	979	P	1.4	1.4							4.3				70
92-1	980	P	2.5	5.8							2.0	1.3			153
92-2	1152	H	15.0	4.7											107

Appendix 9b. Chemical analysis of feldspars in the braidplain massive sands.

Core No.	Depth (cm)	SiO ₂ %	Al ₂ O ₃ %	FeO%	MgO%	CaO%	Na ₂ O%	K ₂ O%	BaO%	Or %	Ab %	An %	Mineral
84-8	100	68.56	16.19	5.65	1.12	2.93	4.03	1.41	0.00	14.11	61.20	24.69	oligoclase
84-8	100	65.14	15.20	0.40	0.00	0.54	0.75	17.66	0.00	91.70	5.97	2.34	sanidine
84-8	100	68.51	16.97	3.64	0.22	0.90	9.04	0.00	0.27	0.00	94.76	5.24	albite
84-8	100	65.14	19.97	1.08	0.00	5.68	8.06	0.00	0.06	0.00	71.96	28.04	oligoclase
84-8	100	64.35	15.39	0.10	0.09	1.28	2.00	16.17	0.62	79.66	15.01	5.33	sanidine
84-8	100	62.44	22.44	0.00	0.00	6.66	7.42	0.07	0.68	0.41	66.53	33.06	andesine
84-8	311	68.41	19.69	0.00	0.03	3.16	8.67	0.00	0.00	0.00	83.30	16.70	oligoclase
84-8	311	66.67	20.22	0.00	0.00	2.92	9.94	0.00	0.00	0.00	86.00	14.00	oligoclase
84-8	311	64.53	17.72	0.00	0.00	0.90	0.54	14.08	1.89	89.90	5.26	4.83	sanidine
84-8	450	64.16	21.20	0.08	0.00	6.04	7.65	0.31	0.34	1.87	68.36	29.77	oligoclase
84-8	450	66.04	15.55	0.20	0.00	0.21	0.93	16.79	0.00	91.32	7.68	1.01	sanidine
84-8	450	72.90	16.79	0.01	0.12	0.13	9.60	0.00	0.00	0.00	99.26	0.74	albite
84-8	450	66.34	14.91	0.18	0.00	0.19	0.60	17.47	0.00	94.21	4.88	0.90	sanidine
84-8	450	57.60	24.60	0.72	0.00	12.23	4.36	0.00	0.00	0.00	39.24	60.76	labradorite
84-8	450	65.82	15.44	0.00	0.00	0.73	0.59	17.04	0.00	91.78	4.88	3.34	sanidine
84-8	450	66.42	15.13	0.03	0.00	0.44	0.63	16.48	0.00	92.55	5.37	2.07	sanidine
84-8	450	73.43	16.20	0.00	0.23	0.15	9.54	0.00	0.36	0.00	99.13	0.87	albite
84-8	450	65.35	20.18	0.88	0.12	5.97	7.24	0.17	0.02	89.90	5.26	4.83	andesine
84-8	490	67.92	19.20	0.22	0.08	3.87	8.03	0.07	0.50	0.46	78.60	20.94	oligoclase
84-8	490	71.41	17.36	0.00	0.00	0.52	10.50	0.00	0.12	0.00	97.35	2.65	albite
84-8	490	65.62	15.42	0.12	0.00	0.31	0.64	17.31	0.51	93.32	5.23	1.44	sanidine
84-8	490	66.79	20.43	0.24	0.00	4.45	7.66	0.21	0.04	1.37	74.68	23.94	oligoclase
84-8	490	64.38	15.02	0.25	0.38	0.45	0.46	17.49	1.30	94.21	3.74	2.05	sanidine
84-8	490	64.77	14.52	0.16	0.07	1.00	0.97	18.24	0.00	88.79	7.18	4.03	sanidine
84-8	490	63.00	21.81	0.16	0.00	7.92	6.60	0.00	0.22	0.00	60.13	39.87	andesine
84-8	490	65.48	14.66	0.47	0.00	0.55	0.92	17.14	0.78	90.26	7.28	2.46	sanidine
84-9	180	65.98	15.57	0.21	0.00	0.18	0.51	16.82	0.00	94.81	4.34	0.85	sanidine
84-9	180	65.07	16.04	0.34	0.00	0.13	0.69	17.70	0.00	93.87	5.60	0.53	sanidine
84-9	180	65.18	15.71	0.00	0.00	0.38	0.80	17.36	0.56	91.87	6.45	1.68	sanidine

Appendix 9b Continued.

Core No.	Depth (cm)	SiO ₂ %	Al ₂ O ₃ %	FeO%	MgO%	CaO%	Na ₂ O%	K ₂ O%	BaO%	Or %	Ab %	An %	Mineral
84-9	180	64.01	15.14	0.72	0.00	0.08	0.61	18.37	1.08	94.89	4.77	0.34	sanidine
84-9	180	65.15	19.38	2.66	1.59	2.99	7.88	0.02	0.00	0.12	82.50	17.38	oligoclase
84-9	180	65.87	15.71	0.62	0.01	0.29	0.58	16.92	0.00	93.84	4.85	1.31	sanidine
84-9	180	65.60	16.88	0.21	0.00	0.31	2.18	13.69	0.60	79.26	19.18	1.57	sanidine
84-16	110	63.67	22.32	0.18	0.00	6.76	6.75	0.08	0.00	0.55	63.98	35.47	andesine
84-16	110	64.68	14.48	0.00	0.00	0.48	0.75	18.96	0.19	92.51	5.56	1.93	sanidine
84-16	110	65.77	15.74	0.23	0.00	0.31	0.32	17.50	0.12	95.86	2.67	1.47	sanidine
84-16	110	55.38	26.11	1.43	0.00	13.22	3.25	0.12	0.00	0.74	30.53	68.72	labradorite
84-16	110	64.95	15.38	1.22	0.00	0.15	0.64	16.45	0.94	93.74	5.59	0.66	sanidine
84-16	110	65.18	22.15	0.04	0.00	7.10	5.38	0.15	0.00	1.00	57.20	41.80	andesine
84-16	110	65.93	15.48	0.23	0.00	0.54	0.37	16.60	0.00	94.29	3.14	2.57	sanidine
84-16	110	63.80	22.10	0.14	0.00	7.97	5.53	0.17	0.29	1.00	54.99	43.85	andesine

Appendix 9c. Chemical analysis of feldspars in the Greenlandian Slope sediment.

Core No.	Depth (cm)	SiO ₂ %	Al ₂ O ₃ %	CaO%	Na ₂ O%	K ₂ O%	Or %	Ab %	An %	Mineral
88-7	212	70.86	17.18	9.12	2.84	0.00	0.00	36.10	63.90	labradorite
88-7	212	58.94	12.51	0.00	0.00	28.55	100.00	0.00	0.00	sanidine
88-7	212	80.82	15.45	0.00	3.73	0.00	0.00	100.00	0.00	albite
88-7	212	50.98	22.53	25.53	0.97	0.00	0.00	6.40	93.60	anorthite
88-7	212	59.22	12.48	0.00	0.00	28.30	100.00	0.00	0.00	sanidine
88-7	212	58.98	11.53	0.00	0.00	29.49	100.00	0.00	0.00	sanidine
88-7	212	54.18	22.40	22.30	0.00	0.00	0.00	0.00	100.00	anorthite
88-7	417	68.75	17.98	10.14	3.13	0.00	0.00	35.86	64.14	labradorite
88-7	417	60.17	12.80	0.00	0.00	27.03	100.00	0.00	0.00	sanidine
88-7	417	66.28	18.49	12.41	2.82	0.00	0.00	29.11	70.89	bytownite
88-7	417	57.52	20.44	20.73	1.30	0.00	0.00	10.16	89.84	labradorite
88-7	417	61.15	13.52	0.00	0.00	25.32	100.00	0.00	0.00	sanidine
88-7	417	78.75	14.98	0.00	3.71	2.56	31.22	68.78	0.00	orthoclase
88-7	417	63.24	13.75	0.00	0.96	22.04	93.78	6.22	0.00	sanidine
88-7	417	60.73	13.12	0.00	0.21	25.95	98.80	1.20	0.00	sanidine
88-7	417	56.19	21.65	20.46	1.71	0.00	0.00	13.11	86.89	bytownite
88-7	417	53.09	22.38	23.32	1.22	0.00	0.00	8.64	91.36	anorthite
88-7	500	79.70	14.53	1.48	4.29	0.00	89.90	5.26	4.83	sanidine
88-7	500	60.12	12.76	0.00	0.00	27.12	100.00	0.00	0.00	sanidine
88-7	500	78.74	14.31	1.70	4.06	1.18	13.50	70.25	16.24	oligoclase
88-7	500	60.89	12.79	0.00	0.00	26.32	100.00	0.00	0.00	sanidine
88-7	500	62.15	13.01	0.00	0.19	24.64	98.85	1.15	0.00	sanidine
88-7	500	64.46	13.34	0.00	0.83	21.38	94.44	5.56	0.00	sanidine
88-7	500	61.09	13.19	0.00	0.00	25.72	100.00	0.00	0.00	sanidine
88-7	500	61.39	12.95	0.00	0.00	25.66	100.00	0.00	0.00	sanidine
88-7	500	62.74	13.02	0.00	0.00	24.25	100.00	0.00	0.00	sanidine

Appendix 10. Thickness of Heinrich layers 1 to 4 in a sequence from the Labrador Slope to the NAMOC levee and Greenland Slope. Data for cores 75-54, 55, 56 and 87-9 from Kirby (1996) and Andrews et al. (1994b); for cores 75-37, from Hillaire-Marcel et al. (1996); radiocarbon ages for cores 87-2, -7, 90-12 and -13 and -9 from Hesse (1995).

Core no.	Locality	Latitude	Longitude	Depth	HL-1	Age: top	HL-2	Age: top	HL-3	Age: top	HL-4	Age: top
					Thick.	Age: bottom	Thick.	Age: bottom	Thick.	Age: bottom	Thick.	Age: bottom
75-54	Labrador Slope	63°, 46', 00"	55°, 97', 08"	1169			31	20760±190		29725±590	105	
75-57	Labrador Slope	63°, 00', 09"	58°, 10', 97"	999	15							
87-9	Labrador Slope	62°, 30', 99"	59°, 26', 82"	1120	21	14400±205	39					
75-61	Labrador Slope	62°, 18', 07"	63°, 01', 00"	1473	30		66					
75-62	Labrador Slope	62°, 23', 07"	59°, 18', 01"	1520	27		84					
75-55	Labrador Slope	61°, 30', 03"	58°, 38', 07"	2410	25	13185±190 14560±105	67	19405±210 21060±240				
75-56	Labrador Slope	61°, 26', 09"	58°, 33', 05"	2434	19		38	21520±195			98	
90-25	Labrador Slope	59°, 53', 32"	58°, 51', 39"	2450	40		105		59		66	
90-26	Labrador Slope	59°, 31', 34"	57°, 16', 64"	2895	34	15080±120	64	21070±190			43	35100±360
92-4	Labrador Slope	59°, 48', 62"	58°, 08', 00"	2761			17		14			
92-5	Labrador Slope	59°, 44', 14"	56°, 27', 38"	2932	86	14580±90	51	20500±170			26	
88-10	Labrador Slope	59°, 12', 47"	55°, 51', 31"	3131	26		39				35	

Appendix 10. Continued.

Core no.	Locality	Latitude	Longitude	Depth	HL-1	Age: top		HL-2	Age: top		HL-3	Age: top		HL-4	Age: top	
					Thick.	Age: bottom		Thick.	Age: bottom		Thick.	Age: bottom		Thick.	Age: bottom	
90-28	Labrador Slope	58°, 45', 80"	57°, 06', 75"	2913				31			41			33		
90-29	Labrador Slope	58°, 23', 61"	56°, 45', 76"	2918	10			30			21	27070±270				
88-13	Labrador Slope	57°, 29', 10"	56°, 21', 54"	2798				41			34					
90-33	Labrador Slope	57°, 16', 84"	56°, 50', 70"	2577				27			43					
88-11	Labrador Slope	58°, 47', 70"	56°, 21', 51"	3025				28								
88-8	NAMOC right l	59°, 15', 55"	54°, 18', 24"	3250	11			16						36		
88-4	NAMOC right l	59°, 12', 29"	54°, 05', 69"	3266	11			16								
88-3	NAMOC left lev	59°, 21', 82"	53°, 44', 80"	3266	6			21								
87-12	NAMOC right l	59°, 02', 55"	53°, 24', 00"	3444	14			21								
87-1	NAMOC right l	57°, 45', 45"	51°, 31', 50"	3498	19			17								
87-2	NAMOC right l	57°, 41', 50"	51°, 41', 45"	3525				24	24170±200							
75-24	NAMOC right l	57°, 27', 00"	51°, 65', 04"	3507	16			27								
87-5	NAMOC right l	57°, 13', 53"	50°, 40', 28"	3577	16			24								
87-7	NAMOC right l	57°, 04', 37"	50°, 37', 96"	3592	17			25	23300±190							

ABBREVIATIONS:

AMS: Accelerated Mass Spectrometry

DCL: Detrital-carbonate lithics

DFD: debris-flow deposits

HL: Heinrich Layer

IRD: Ice-rafted debris

LGM: Last Glacial Maximum

NAMOC: Northwest Mid-Atlantic Channel

TSP: Turbid-surface plumes

FACIES SYMBOLS:

C: Contourites

D: Debris-flow deposits

H: Hemipelagic sediments

HI: Ice-rafted hemipelagic sediments

MS: Massive sands

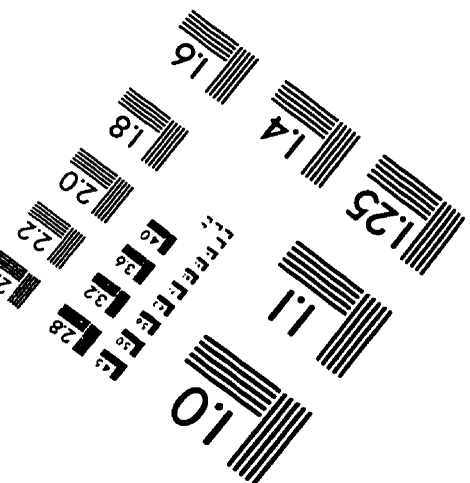
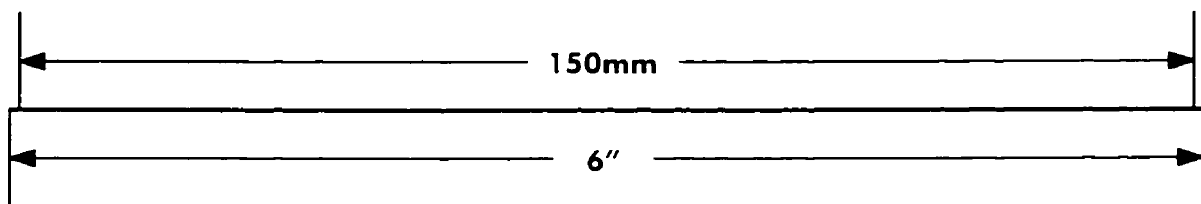
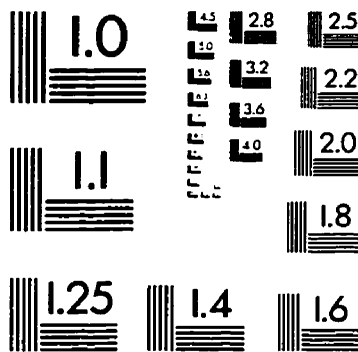
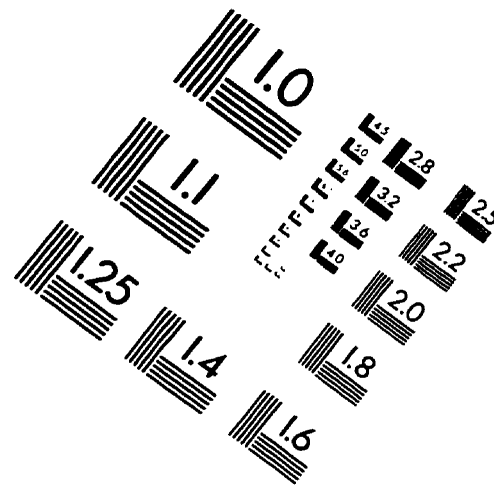
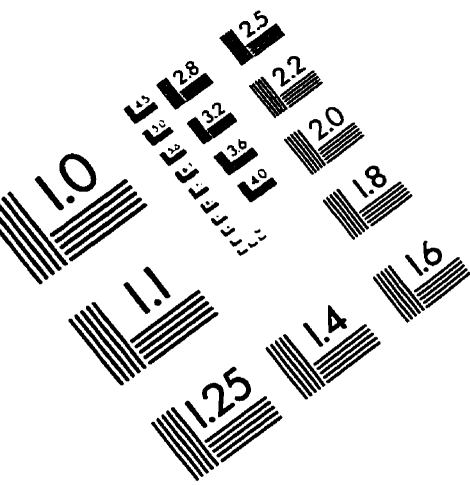
N: Nepheloid-layer deposits

P: Plumites (TSP deposits)

T: Turbidites

TI: Ice-rafted hemipelagic sediments

IMAGE EVALUATION TEST TARGET (QA-3)



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