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PALEOENVIRONMENTS ALONG THE EASTERN LAURENTIDE ICE SHEET MARGIN AND TIMING OF THE LAST ICE MAXIMUM AND RETREAT

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ABSTRACT Palynological and isotopic analysis in a few deep-sea cores from the Labrador Sea reveals strong environmental changes related to the Late Pleistocene glacial fluctuations over eastern Canada. On the whole, the Labrador Sea was characterized by strong exchanges between North Atlantic water masses, Arctic outflows, and meltwater discharges from Laurentide, Greenland and Inuitian ice sheets. The penetration of temperate Atlantic waters persisted throughout most of the Late Pleistocene, with a brief interruption during the Late Wisconsinan. During this glacial substage, a slight but continuous meltwater runoff from the Laurentide ice margins grounded on the northern Labrador Shelf is indicated by relatively low ^{18}O values and low-salinity ($<$ 30‰) dinocyst assemblages. The calving of the ice margin, the melwater outflow and the subsequent dilution of surface waters offshore Labrador probably contributed to the dispersal of floating ice and, consequently, to a southward displacement of the polar front restraining the penetration of North Atlantic waters into the Labrador Sea. The advection of southern air masses along the Laurentide ice margins, shown by pollen assemblages, was favourable to abundant precipitation and therefore, high ice accumulation rates, especially over northern Labrador during the Late Wisconsinan. The deglaciation is marked by a brief, but significant, melting event of northern Laurentide ice shortly after 17 ka. The main glacial retreat occurred after *ca.* 11 ka. It allowed restoration of WSW-ENE atmospheric trajectories, increased phytoplanktonic productivity, and penetration of North Atlantic water masses into the Labrador Sea.

RÉSUMÉ *Les paléo-milieux le long des marges orientales de l'inlandsis laurentidien pendant le dernier maximum glaciaire et la déglaciation.* L'analyse palynologique et isotopique de forages de la mer du Labrador révèle des changements des paléo-milieux du Pléistocène supérieur, en relation étroite avec les glaciations de l'est du Canada. De façon générale, la mer du Labrador a connu des échanges importants entre les masses d'eaux nord-atlantiques, celles des bassins septentrionaux de l'est du Canada et celles d'apports d'eaux de fonte des grandes calottes de l'hémisphère nord (laurentidienne, groenlandaise et inuitienne). La mer du Labrador fut influencée par la pénétration des masses d'eaux tempérées de l'Atlantique Nord au cours de la majeure partie du Pléistocene supérieur, à l'exception du Wisconsinien supérieur. Pendant cet épisode, des apports discrets mais continus d'eaux de fonte le long des marges glaciaires immergées dans le secteur ouest de la mer du Labrador sont indiqués par de faibles teneurs en ^{18}O et par les assemblages de dinokystes associés à de faibles salinités ($<$30‰). Le vêlage le long des marges glaciaires, l'évacuation des eaux de fonte et la dilution subséquente des masses d'eaux superficielles ont sans doute favorisé une dispersion méridionale des glaces flottantes pendant le Wisconsinien supérieur, provoquant ainsi une descente latitudinale du front polaire et limitant la pénétration de la dérive nord-atlantique dans la mer du Labrador. Par ailleurs, l'advection de masses d'air d'origine méridionale le long des marges de l'inlandsis, révélée par les influx polliniques, a certainement contribué à d'abondantes précipitations induisant un bilan positif des glaces laurentidiennes, en particulier au nord du Labrador. Le déclin de l'inlandsis laurentidien est marqué par un premier épisode de fonte, bref mais considérable, peu après 17 ka. La déglaciation principale, postérieure à 11 ka, fut suivie du rétablissement de trajectoires atmosphériques WSW-ENE, d'une augmentation notable de la productivité phytoplanctonique et d'une influence accrue de la dérive nord-atlantique dans la mer du Labrador.

ZUSAMMENFASSUNG *Paleoumgebungen entlang des östlichen laurentischen Eisdeckenrands und zeitliche Abfolge der letzten maximalen Eisausdehnung und der Enteisung.* Aus der palynologischen und isotopischen Analyse einiger Tiefseebohrungen im Meer von Labrador ergeben sich starke Umweltveränderungen in enger Beziehung zu den glacialen Schwankungen in Ostkanada im späten Pleistozän. Im Ganzen gesehen gab es im Meer von Labrador einen bedeutenden Austausch zwischen den Wassermassen des Nordatlantik, arktischem Abfließen und dem Schmelzwasser von den Eisdecken. Über fast das ganze späte Pleistozän mit kurzer Unterbrechung im späten glacialen Wisconsin dauerte das Eindringen wärmeren Wassers aus dem Atlantik an. Relativ niedrige ^{18}O-Werte und der geringe Salzgehalt ($<$30%) der Dinokyst-Ansammlungen weisen darauf hin, daß während dieser glazialen Zwischenphase ein geringer aber fortlaufender Schmelzwasserabfluß von den laurentischen Eisrändern, die auf dem nördlichen Labrador-Schelf festsitzen, stattfand. Das Kalben des Eisrands, das Schmelz-wasserabfließen und die anschließende Verdünnung des Oberflächenwassers vor der Küste Labradors trug vermutlich zu der Auflockerung des schwimmenden Eises bei und führte als Folge davon zu einer Verschiebung der Polarfront und schränkte so das Vordringen des Nordatlantikwassers in das Meer von Labrador ein. Das Entlangstreichen südlicher Luftmassen an den laurentischen Eisrändern, was durch Pollen-Ansammlungen erkennbar ist, begünstigte starke Niederschläge und dadurch große Eiszuwachsraten, besonders über dem nördlichen Labrador während des späten glazialen Wisconsin. Die Enteisung ist durch eine kurze aber bedeutende Schmelzphase des nördlichen laurentischen Eises kurz nach 17 ka gekennzeichnet. Der Haupteisrückzug geschah nach ungefähr 11 ka. Er führte zu der Wiederherstellung der WSW-ONO Luftströmungen, vergrößerte die phytoplanktonische Produktivität und das Vordringen nordatlantischer Wassermassen in das Meer von Labrador.

INTRODUCTION

Eastern Canada experienced the development and retreat of huge ice masses, notably the Laurentide and Inuitian ice sheets, during the Late Pleistocene. These ice sheets account for a large part of the mass transfers within the hydrosphere, that are recorded on a global scale by the oceanic ^{18}O stratigraphy (*e.g.* DANSGAARD and TAUBER, 1969; SHACKLETON and OPDYKE, 1973). Ice sheet growth was related to oceanic and atmospheric paleocirculation patterns that allowed the penetration of humid air masses to high latitudes (*cf.* ANDREWS *et al.*, 1972; BOULTON, 1979, RUDDIMAN and McINTYRE, 1979, 1981a; RUDDIMAN *et al.*, 1980). Consequently, the eastern Canadian seas, notably the Labrador Sea, played a major role in ice sheet development. They also constitute the primary "transitional" basins between ice sheets and open oceans into which large amounts of meltwater had to flow. From this viewpoint, the study of Quaternary sediments in the Labrador Sea is essential for the understanding of land/sea/atmosphere interactions over eastern Canada during the last ice ages. We report here on palynological and isotopic analyses of piston cores collected in the southern (84-030-003), eastern (HU-75-037) and western (84-030-021) parts of the Labrador Sea (Fig. 1). Because palynological records lead to the reconstruction of atmospheric (pollen and spores) and oceanic (dinocysts) paleocirculations, and because ^{18}O changes in planktonic foraminifera directly relate to meltwater discharge episodes, this study provides an insight into the glacial history of eastern Canada, notably that of fluctuations of the eastern part of the Laurentide Ice Sheet.

THE SOUTHERN LABRADOR SEA STRATIGRAPHY (CORE 84-030-003)

Cores 84-030-003TWC and −003P were collected at the southern margin of the Labrador Sea, at the boundary between the subpolar and polar bioclimatic zones (IMBRIE and KIPP, 1971; BÉ and TOLDERLUND, 1971). Surface waters are influenced here by both the temperate North Atlantic Drift flowing eastward and the cold Labrador current flowing southward and sinking because of its density.

The coring site is located on the abyssal plain (water depth = 3771 m) adjacent to the NAMOC (North Atlantic Mid Ocean Channel) and the Gloria Drift (Fig. 1). The site is characterized by hemipelagic sedimentation (CHOUGH *et al.*, 1985). Sediments consist mainly of foraminifera oozes alternating with grayish and brownish silty muds (Fig. 2).

$\delta^{18}O$ STRATIGRAPHY

The ^{18}O record in cores 84-030-003 (Fig. 2; *cf.* de VERNAL and HILLAIRE-MARCEL, 1987) does not differ considerably from those originating from "open" oceans (*e.g.* Caribbean Sea, North Atlantic and Pacific oceans; *cf.* EMILIANI, 1966; SHACKLETON, 1977; SHACKLETON and HALL, 1984; SHACKLETON and OPDYKE, 1973). It therefore allows direct correlation with the reference isotopic stratigraphy of core V28-238 (SHACKLETON and OPDYKE, 1973). In cores 84-030-003, the ^{18}O record spans isotopic stages 8 to 1, *i.e.* ca. 300,000 years. A mean sedimentation rate of *ca.* 5 cm/10^3 yrs may be interpolated. When compared to other "global" ^{18}O records, that of cores 84-030-003 shows a relatively greater amplitude of $^{18}O/^{16}O$ fluctuations: isotopic stages 2/1 and 6/5 transitions are marked by a depletion in ^{18}O of respectively 2.2‰ and 3.1‰. In view of the location of the coring site, these high values may be attributed to meltwater inputs from the Laurentide Ice Sheet and its satellitic ice caps, which fed

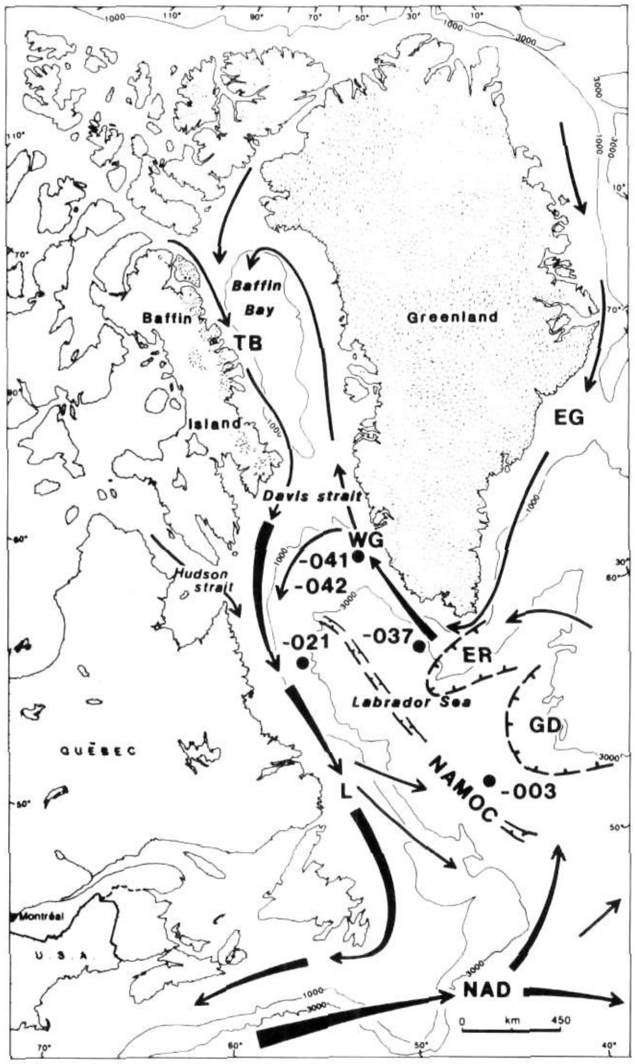

FIGURE 1. Location map. All site locations of cores discussed in the text are indicated. The present-day surface water circulation is indicated by arrows (*cf.* ICHIYE, 1966; PICKARD and EMERY, 1982): NA = North Atlantic Drift; EG = East Greenland current; WG = West Greenland current; L = Labrador current. The main physiographic features of the Labrador Sea floor are indicated: NAMOC = North West Atlantic Mid Ocean Channel; ER = Eirik ridge; GD = Gloria Drift.

Carte de localisation. La localisation des sites de forages auxquels il est fait référence dans le texte est indiquée. La circulation océanique actuelle est indiquée par des flèches (cf. ICHIYE, 1966; PICKARD et EMERY, 1982): NA = dérive nord-atlantique; EG = courant de l'est du Groenland; WG = courant de l'ouest du Groenland; L = courant du Labrador. Les principaux caractères physiographiques de la mer du Labrador sont indiqués: NAMOC = Chenal médio océanique de l'Atlantique Nord; ER = «Eirik ridge»; GD = «Gloria Drift».

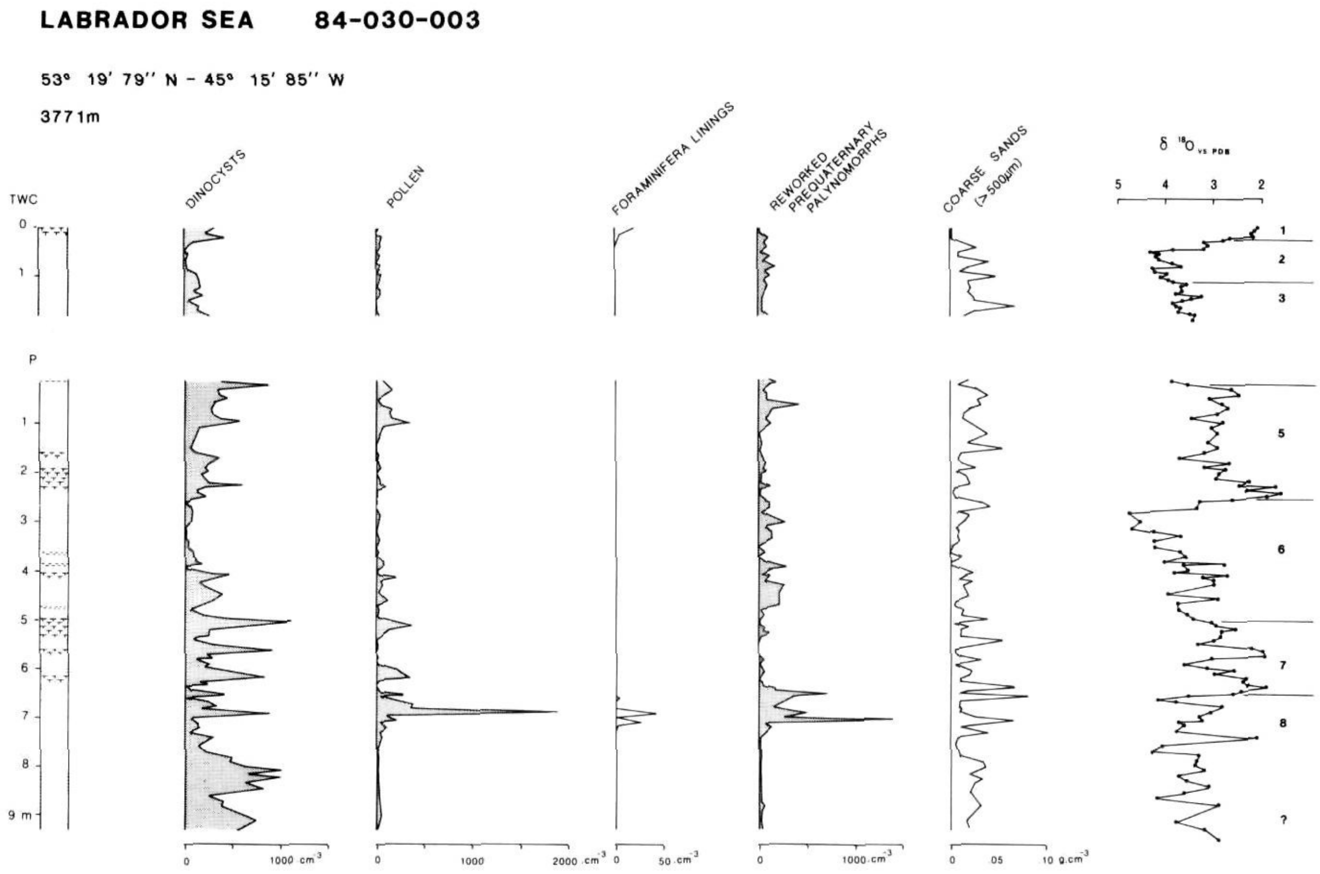

Figure 2. Lithostratigraphy, palynomorph concentrations and $\delta^{18}O$ stratigraphy of core 84-030-003 (53°19'79N-45°15'85W; 3771 m).

Lithostratigraphie, concentration des palynomorphes et stratigraphie isotopique du forage 84-030-003 (53°19'79N-45°15'85W; 3771 m).

the Labrador current before mixing with the global oceanic water masses (within *ca.* 3000 years; *cf.* MIX and RUDDIMAN, 1984). Hence, during glacial/interglacial transitions, the southward outflow of the Labrador current appears to have increased because of the meltwater transit and, consequently, surface waters in south central Labrador Sea were more diluted. Both the larger outflow and the lower salinity of the Labrador current may have resulted in a southward displacement of its sinking zone in the North Atlantic Ocean. It could be mentioned that this short-lived paleocirculation pattern of the Labrador current and its influence on the Gulf Stream/North Atlantic Drift trajectory may be the cause of a southward displacement of the polar front (RUDDIMAN and McINTYRE, 1981b) that resulted in the younger Dryas climatic cooling over western Europe (WATTS, 1980). This would also explain the fact that with the exception of the easternmost margin of the continent (MOTT *et al.*, 1986), the younger Dryas is not clearly recorded in North America.

PALYNOSTRATIGRAPHY

Dinocyst assemblages in cores 84-030-003 (Fig. 3) are characterized by a high taxonomic diversity but low concentrations, the latter averaging *ca.* 100 to 500 cysts/cm^3. Extrapolated from sedimentation rates, the corresponding influxes (*ca.* ½ to 3 cysts/cm^2.year) indicate a low local dinoflagellate productivity, probably due to the offshore location of the coring site. Since the reproduction of dinoflagellates by the excystment of dinocysts lying at the abyssal floor is highly improbable, a large part of the dinocyst flux over the abyssal plain is doubtless related to oceanic transportation (*cf.* de VERNAL, 1986; de VERNAL and HILLAIRE-MARCEL, 1987). Because subtropical (*Impagidinium patulum, I. aculeatum, I. strialatum, Spiniferites mirabilis, Lingulodinium machaerophorum*) to Arctic (*Multispinula minuta, S. elongatus*) species are complementary throughout the sedimentary sequence, inputs through both the North Atlantic Drift and the Labrador current have to be considered. Indeed, the concentration of warm-water taxa (notably the *Impagidinium* genus; *cf.* Fig. 3) indicates an almost continuous penetration of the North Atlantic Drift into the Labrador Sea during the Middle and Late Pleistocene, with a single interruption during the last glacial maximum (*i.e.* isotopic stage 2). The abundance of cold temperate to subarctic taxa (notably *Operculodinium centrocarpum*), mainly associated with the Labrador current contribution, varies significantly throughout the sequence. The dominance of subarctic to cold temperate dinocyst flora, notably during isotopic stages 7, 5

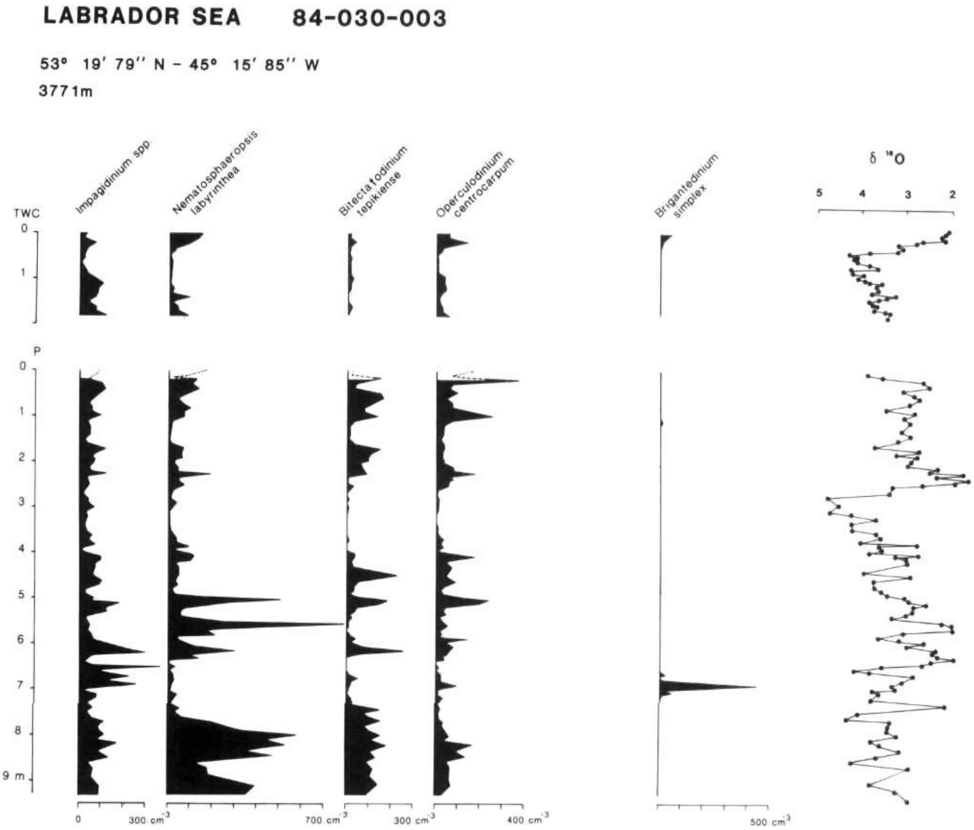

FIGURE 3. Summarized diagram of dinocyst concentrations in core 84-030-003. Several species that occur frequently, but in low concentration, are not reported on this diagram. These taxa are notably *Spiniferites elongatus, S. ramosus, S. mirabilis, Lingulodinium machaerophorum, Tectatodinium pellitum, Polysphaeridium zoharyi* and *Multispinula minuta.* In addition we have grouped the *Impagidinium* species together (*I. sphaericum, I. aculeatum, I. patulum, I. paradoxum* and *I. strialatum*). More detailed data are reported by de VERNAL and HILLAIRE-MARCEL (1987).

Diagramme résumé de la concentration des dinokystes dans le forage 84-030-003. Plusieurs espèces présentes, mais en de faibles concentrations, n'apparaissent pas sur ce diagramme. Il s'agit notamment de Spiniferites elongatus, S. ramosus, S. mirabilis, Lingulodinium machaerophorum, Tectatodinium pellitum, Polysphaeridium zoharyi *et* multispinula minuta. *Nous avons par ailleurs regroupé les espèces appartenant au genre* Impagidinium (I. sphaericum, I. aculeatum, I. patulum, I. paradoxum et I. strialatum). *Des résultats plus détaillés sont déjà publiés (cf. de VERNAL et HILLAIRE-MARCEL; 1987).*

and 1, may be interpreted as a response to higher phytoplanktonic productivity along the eastern Canadian margin as well as to stronger Labrador current outflows during each interglacial episode.

The pollen content in sediments of core 84-030-003 is very low (Fig. 2): the concentration rarely exceeds 100 grains/cm^3 and leads to the calculation of an influx averaging ½ grain/cm^2.year. The paucity of pollen assemblages does not allow detailed interpretation. Nevertheless, the dominance of *Pinus* (Fig. 4) which has a morphology favourable to atmospheric transportation over a long distance (MUDIE, 1982; HEUSSER, 1983) reveals influx from southern areas. The very low concentrations and the dominance of *Pinus* suggest long-distance influxes controlled mainly by SW-NE or SSW-NNE air mass trajectories. Such an atmospheric circulation pattern probably prevailed over south central Labrador Sea, with slight variations, during most of Late Quaternary.

THE EASTERN LABRADOR SEA STRATIGRAPHY (CORE HU-75-37)

Core HU-75-37 was collected on the continental rise off southwest Greenland. This core and a few others from the west Greenland margin have been described by FILLON and DUPLESSY (1980) with special emphasis on microfaunal content, tephrostratigraphy and lithostratigraphy. FILLON and DUPLESSY (1980) also included $\delta^{18}O$ records on two cores (HU-75-41 and HU-75-42; Fig. 1) from the north-east Labrador Sea.

Surface water circulation at the coring site is dominated by the west Greenland current flowing northward. This subarctic current is formed by the polar east Greenland current flowing westward along the south Greenland margin and by a northward branch of the Atlantic Drift.

Several AMS ^{14}C dates on hand-picked foraminifera samples (de VERNAL and HILLAIRE-MARCEL, 1986) and correlations established by FILLON and DUPLESSY (1980) indicate that core HU-75-37 spans approximately 60,000 years. The deposits are mainly hemipelagic. However, the occurrence of coarse sands (>125 μm; Fig. 5) reveals ice rafting activity especially before *ca.* 10 ka.

PALYNOSTRATIGRAPHY

In core HU-75-37 the taxonomic composition and concentration of dinocyst assemblages fluctuate (Fig. 6), indicating that significant changes in surficial water masses occurred throughout the last 60,000 years. Three main dinocyst assemblage zones can be distinguished (Fig. 6):

1) the basal zone (DI) corresponds to isotopic stage 3, that is, the Middle Wisconsinan substage. It is characterized by highly variable concentrations that suggest discontinuous phytoplanktonic productivity. The high concentration peaks correspond to assemblages dominated by *Brigantedinium*

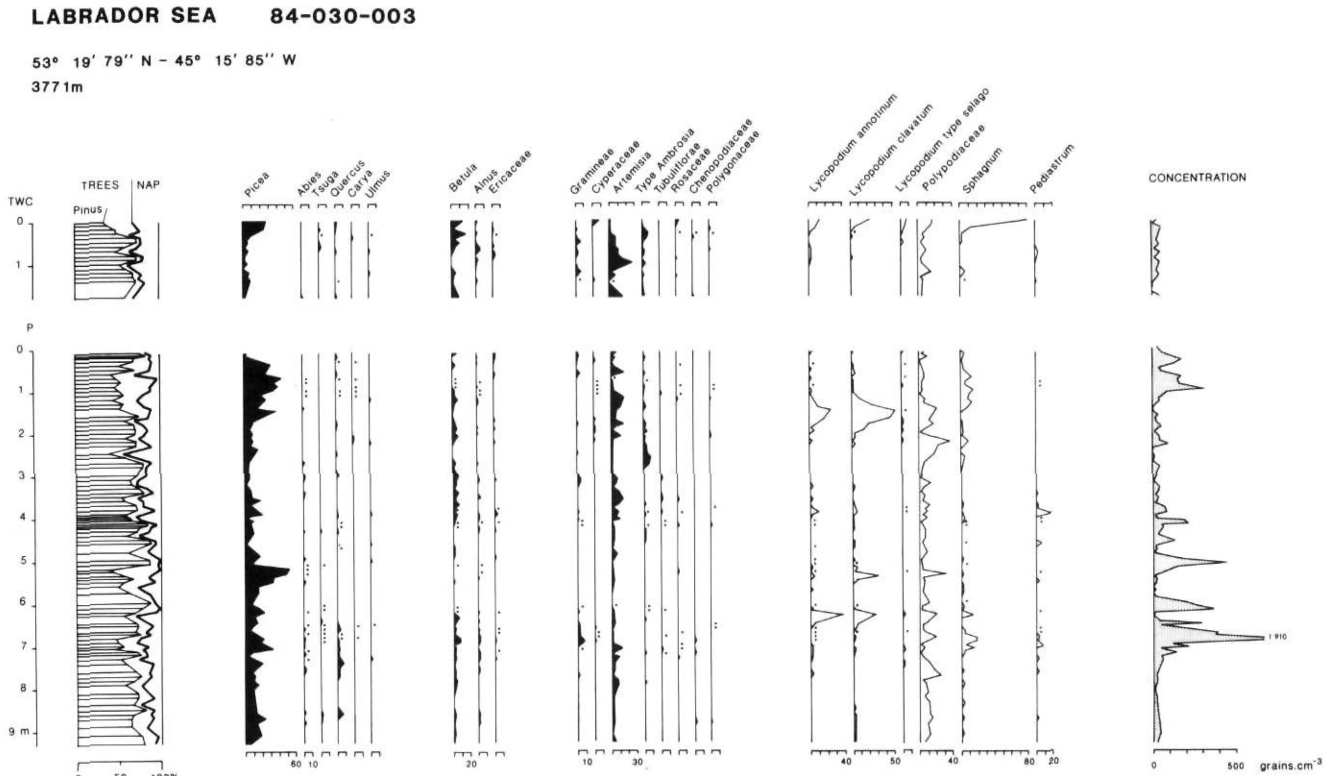

FIGURE 4. Diagram of pollen and spore percentages in core 84-030-003.

Diagramme sporo-pollinique de pourcentage: forage 84-030-003.

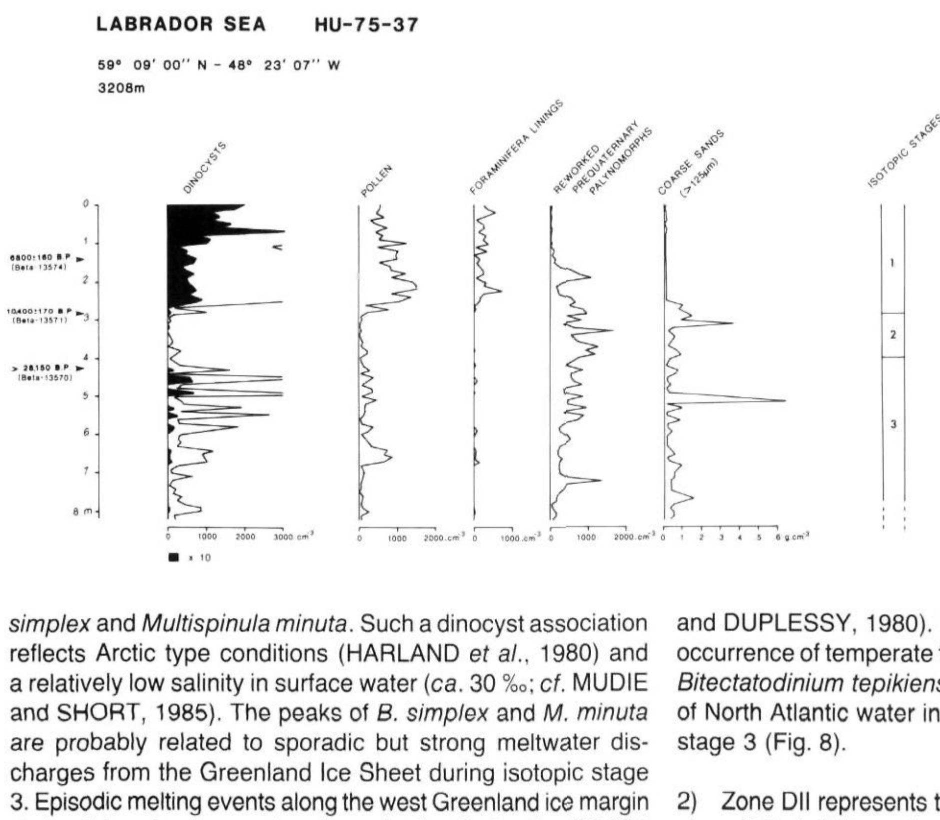

FIGURE 5. Palynomorphs and coarse sand concentrations in core HU-75-37 (59°09'00N-48°23'70W; 3208 m); proposed correlative isotopic stages are indicated.

Concentration des palynomorphes et des sables grossiers dans le forage HU-75-37 (59°09'00N-48°23'70W; 3208 m); les stades correspondants sont indiqués.

simplex and *Multispinula minuta*. Such a dinocyst association reflects Arctic type conditions (HARLAND *et al.*, 1980) and a relatively low salinity in surface water (*ca.* 30 ‰; *cf.* MUDIE and SHORT, 1985). The peaks of *B. simplex* and *M. minuta* are probably related to sporadic but strong meltwater discharges from the Greenland Ice Sheet during isotopic stage 3. Episodic melting events along the west Greenland ice margin during this episode are also shown by the fluctuating $^{18}O/^{16}O$ ratios recorded in cores HU-75-41 and HU-75-42 (FILLON and DUPLESSY, 1980). In addition, the slight but consistant occurrence of temperate taxa such as *Impagidinium* spp. and *Bitectatodinium tepikiense* reveals a continuous penetration of North Atlantic water into the Labrador Sea during isotopic stage 3 (Fig. 8).

2) Zone DII represents the last glacial maximum, *i.e.* isotopic stage 2 (Late Wisconsinan). It is marked by very low dinocyst concentrations suggesting a minimal phytoplanktonic pro-

ductivity, probably due to the extension of a dense sea ice cover along the Greenland margin. The paucity of dinocyst assemblages confirms that the penetration of North Atlantic waters into the Labrador Sea was interrupted during the glacial maximum of isotopic stage 2 (*cf. supra*).

3) Zone DIII covers the postglacial period. It is characterized by rich dinocyst assemblages dominated by *Operculodinium centrocarpum* and *Nematosphaeropsis labyrinthea*, which indicate a high primary productivity and subarctic conditions in surface waters. The occurrence of temperate taxa such as *Impagidinium* spp. again reveals the penetration of North Atlantic water masses into the Labrador Sea shortly after 10,400 BP. However, the noticeable occurrence of *Multispinula minuta* and of Cyst P (Mudie, *in* SCOTT *et al.*, 1984) at the base of the zone (DIIIa) constitutes an Arctic component that probably resulted from meltwater transit through the Greenland current.

The pollen and spore assemblages of core HU-75-37 are relatively rich (Fig. 7). Although *Pinus* remains a dominant taxon throughout most of the sequence, variations in concentration and assemblage composition make it possible to define the following zones (Fig. 7):

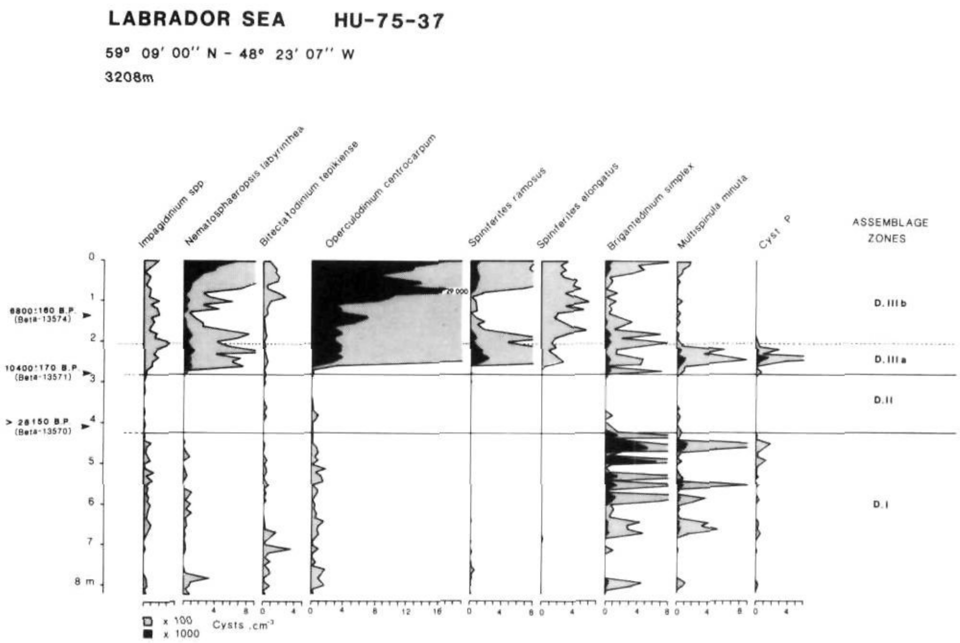

FIGURE 6. Dinocyst stratigraphy of core HU-75-37. Results are expressed in terms of concentrations.

Stratigraphie des dinokystes dans le forage HU-75-37. Les résultats sont exprimés en terme de concentrations.

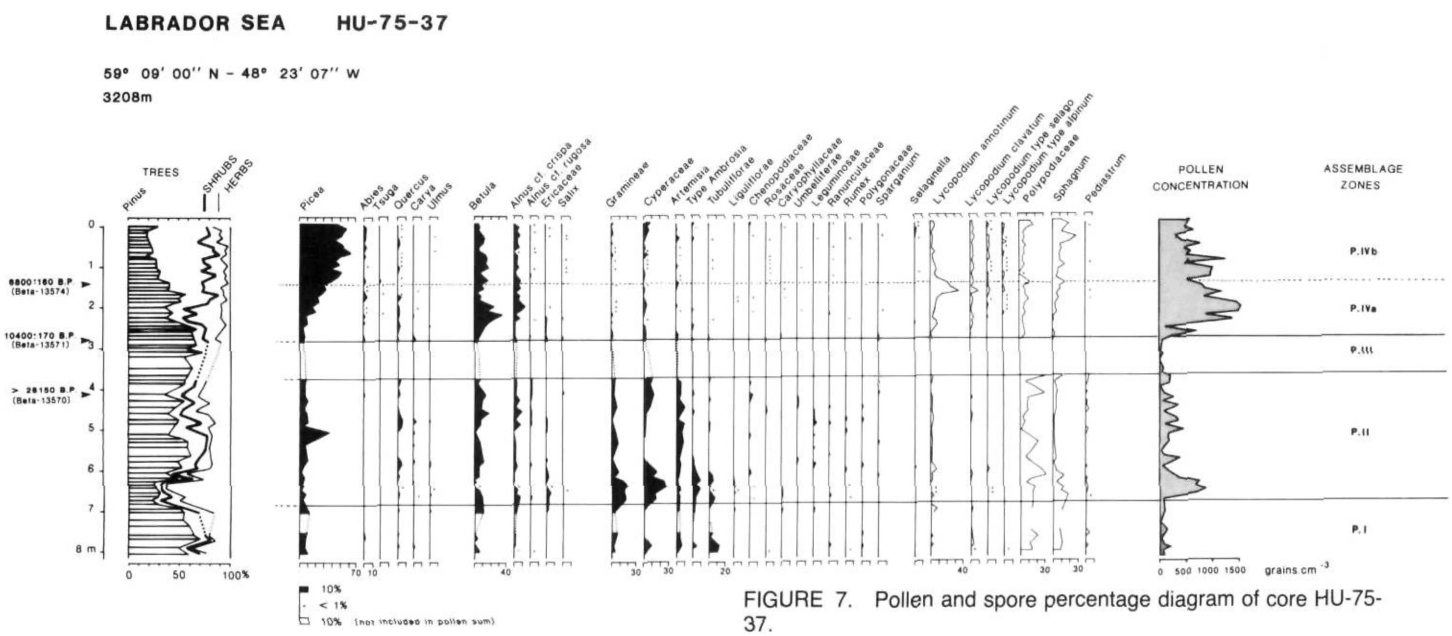

FIGURE 7. Pollen and spore percentage diagram of core HU-75-37.

Diagramme sporo-pollinique de pourcentage du forage HU-75-37.

1) At the base, zone PI is marked by low concentrations and assemblages dominated by *Pinus*. It indicates long-distance air transportation from southern areas.

2) Zone PII corresponds to most of the isotopic stage 3 and is characterized by relatively high percentages of herb taxa (Compositae, Gramineae and Cyperaceae). It reflects the extension of an open vegetation of tundra or forest tundra within the source area, which is *a priori* unknown. However, on the basis of correlative palynologic records from eastern Canada (de VERNAL *et al.*, 1986; MOTT and GRANT, 1986) and from core 84-030-003, pollen influxes from southeastern Canada, controlled by SSW-NNE atmospheric trajectories, may be deduced (*cf.* de VERNAL and HILLAIRE-MARCEL, 1986; Fig. 8).

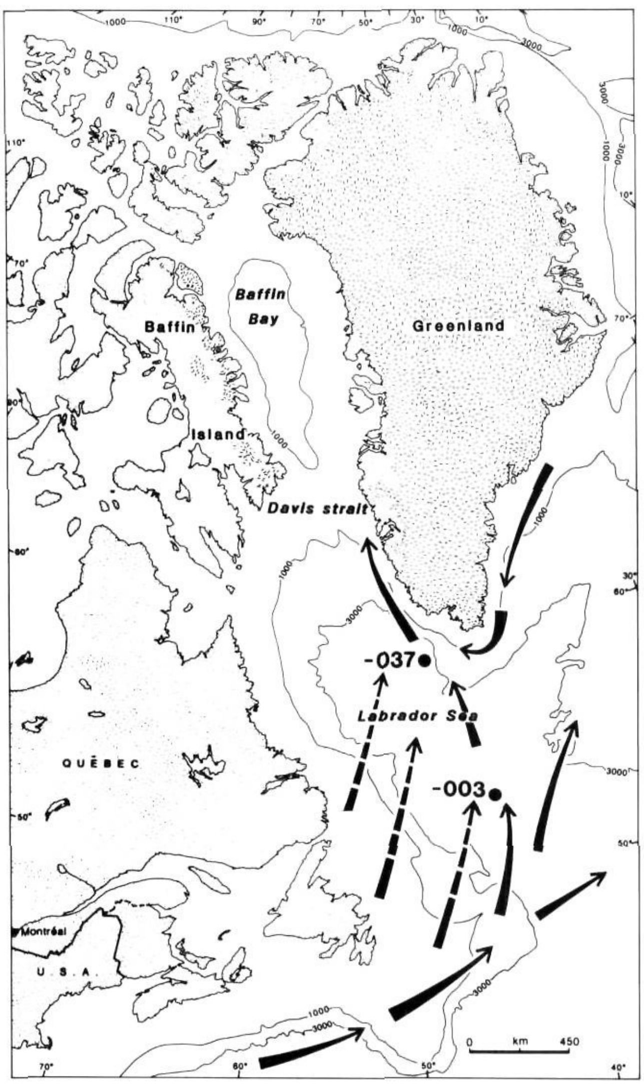

FIGURE 8. Schematic reconstruction of atmospheric (dashed arrows) and oceanic (arrows) paleocirculations during the Middle Wisconsinan substage.

Reconstitution schématique des paléocirculations atmosphériques (tireté) et océaniques (trait plein) du Wisconsinien moyen.

3) In zone PIII, which corresponds to isotopic stage 2, pollen and spore concentrations are very low and most assemblages are largely dominated by *Pinus*. The pollen record suggests therefore a southern source and long-distance atmospheric transportation over vegetation-free areas.

4) Zone PIV covers the postglacial period. It is characterized by relatively high pollen concentrations. In addition to *Pinus*, its pollen assemblages are mainly marked by the occurrence of *Betula* at the base, followed by increasing *Picea* percentages. This palynosuccession allows direct correlation with the postglacial palynostratigraphy of southern Labrador (LAMB, 1980; ENGSTROM and HANSEN, 1985). An atmospheric circulation dominated by WSW-ENE trajectories, similar to the present, therefore prevailed over the Labrador Sea during the Holocene.

THE WESTERN LABRADOR SEA STRATIGRAPHY (CORE 84-030-021)

Core 84-030-021 was collected on the continental rise off northern Labrador (Fig. 1). Surface water circulation is controlled by the cold Labrador current flowing southward. The latter is formed by Arctic water outflowing through Davis Strait and Hudson Strait, combined with a westward branch of the subpolar Greenland current. Because meltwater discharges from the Laurentide and Inuitian ice sheets necessarily flowed in large part through the Labrador current, the western Labrador Sea is a strategic area for the study of the Quaternary glacial history in eastern Canada. However, with the exception of the shelf area (JOSENHANS, 1983; JOSENHANS *et al.*, 1986; FILLON and HARMES, 1982; OSTERMAN *et al.*, 1985), the northwest Labrador Sea remains virtually unexplored from a paleoclimatic viewpoint.

Sediments of core 84-030-021 consist of sandy to gravelly clayey mud (Unit I; Fig. 9), with no stratification, overlain by hemipelagic silty mud (Unit II). The coring site remained apparently little influenced by the western boundary undercurrent (WBUC; *cf.* CHOUGH *et al.*, 1985): a thin layer of sorted sand lying between the two main lithologic units (2.54-2.27 m sub-bottom) is the sole indication of any accumulation under deep-current effects. AMS ^{14}C dates on hand-picked foraminifera samples reveal a chronology spanning *ca.* 20,000 years. The lithostratigraphy of core 84-030-021 points to a direct relationship with the glacial history of the eastern Canadian continental margin. The coarse sediments of the lower unit, older than *ca.* 11,000 BP, reflect very intense ice rafting, likely related to glacio-marine activity; these deposits doubtless correlate with the upper till observed along the central Labrador shelf (FILLON and HARMES, 1982; JOSENHANS, 1983; JOSENHANS *et al.*, 1986). The upper unit, consisting of hemipelagic sediments, represents the postglacial interval. The glacial/interglacial transition is marked at a depth of 2.27 m in core −021 and is dated at *ca.* 11,000 BP.

$\delta^{18}O$ STRATIGRAPHY

The glacial/interglacial transition is characterized by a shift in the $^{18}O/^{16}O$ ratios (Fig. 9): it corresponds to the isotopic stage 2/1 transition (SHACKLETON and OPDYKE, 1973; DUPLESSY *et al.*, 1986).

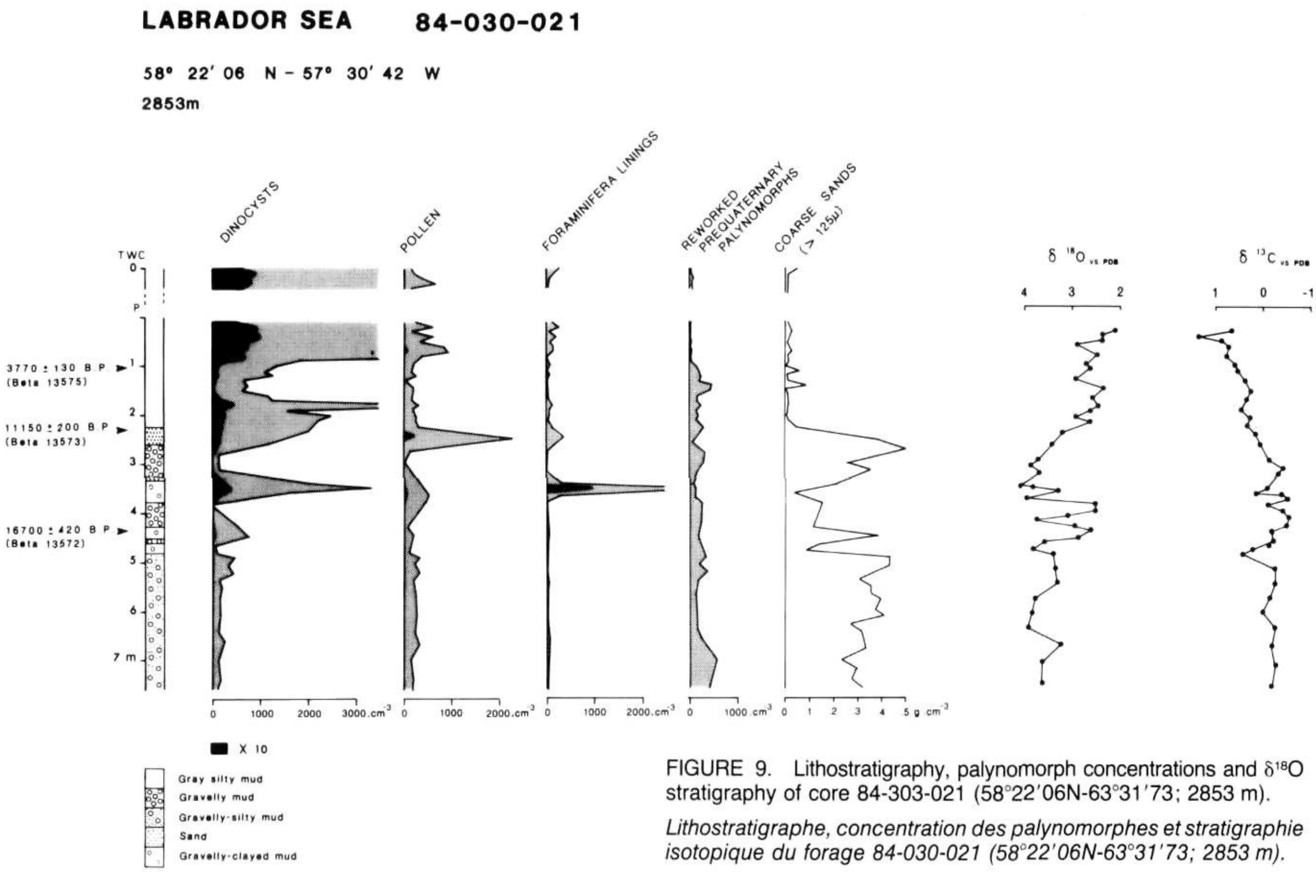

FIGURE 9. Lithostratigraphy, palynomorph concentrations and $\delta^{18}O$ stratigraphy of core 84-303-021 (58°22'06N-63°31'73; 2853 m).

Lithostratigraphe, concentration des palynomorphes et stratigraphie isotopique du forage 84-030-021 (58°22'06N-63°31'73; 2853 m).

Although partly correlative with the "global" ^{18}O stratigraphy, the $\delta^{18}O$ record of core 84-030-021 shows some peculiarities, the first one being the relatively low $\delta^{18}O$ values ($\leq$ 4.0 ‰) of isotopic stage 2. By comparison, other records from the southern Labrador Sea (*cf.* core 84-030-003; Fig. 2) and from the northwest Greenland slope (*cf.* cores HU-75-41 and HU-75-42; FILLON and DUPLESSY, 1980) yield $\delta^{18}O$ values of *ca.* 4.1-4.3 ‰ and *ca.* 4.1-4.8 ‰ respectively. The relatively low $^{18}O/^{16}C$ ratios observed off Labrador may be attributed to a slight but continuous meltwater runoff from the Laurentide ice sheet margin during the last glacial maximum. As discussed below, the persistence of slightly diluted surface waters during the isotopic stage 2 is also shown by the dominance of *Brigantedinium simplex* in dinocyst assemblages.

The high-resolution ^{18}O profile of core 84-030-021 is also unique because it recorded short but significant events related to the Wisconsinan glacial history. A 1.0 ‰ to 1.5 ‰ shift in ^{18}O is notably observed between 4.47 and 3.75 m sub-bottom. It indicates a strong but brief episode of dilution in surface waters initiated shortly after 17,000 BP. This isotopic event probably correlates with a late glacial ^{18}O drop recorded in deep sea cores from lower latitudes (KENNETT and SHACKLETON, 1975; LEVENTER *et al.*, 1982; MIX and RUDDIMAN, 1985; *cf.* also core 84-030-003TWC). However, in core 84-030-021, this event is marked by a much larger shift in $\delta^{18}O$ values (a difference of *ca.* one order of magnitude). The attenuated response of the global ocean is probably due to the homogenization (within *ca.* 3000 years according to MIX and RUDDIMAN, 1984) of the large meltwater input through the Labrador current. This transit responded therefore to a significant melting of the northeastern Laurentide ice margin and possibly of Inuitian ice margins as early as *ca.* 17,000 BP. This melting event could account for the early deglaciation of high altitude areas in the Torngat mountains (north Labrador; *cf.* SHORT, 1981; SOMMA, 1984). It is certain however that the Laurentide ice volume remained large enough to allow offshore glacio-marine activity as shown by the abundant ice-rafted debris in the sediments. Furthermore the subsequent recurrence of high $\delta^{18}O$ values (*ca.* 4 ‰) also indicates a restabilized ice sheet. According to the lithostratigraphy and the ^{18}O stratigraphy in core 84-030-021, the deglaciation of the northernmost Labrador Shelf and the main retreat of the Laurentide ice resumed after *ca.* 11,000 BP.

PALYNOSTRATIGRAPHY

Dinocyst assemblages in core 84-030-021 are characterized by a low taxonomic diversity (Fig. 10). Abrupt changes in the assemblage composition and concentration, however, make it possible to distinguish three main zones:

1) The lowest one (DI) is older than 11,000 BP and corresponds therefore to isotopic stage 2. On the whole, its dinocyst assemblages are dominated by *Brigantedinium simplex* accompanied by *Multispinula minuta* and the Cyst P, suggesting Arctic type and low-salinity conditions in surface water during

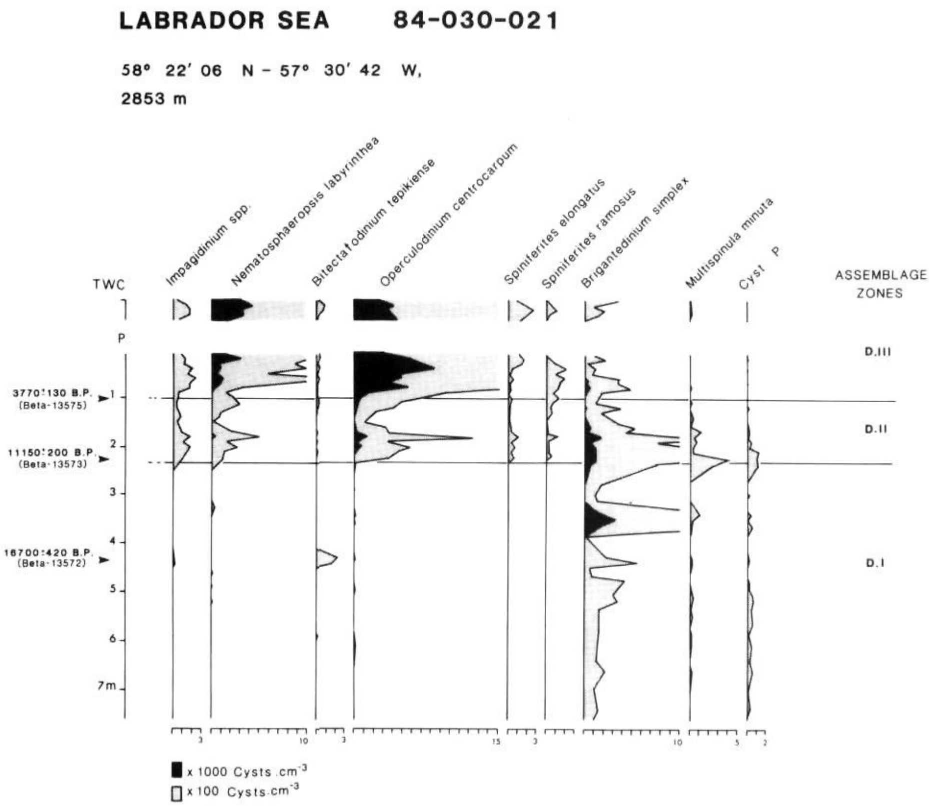

FIGURE 10. Dinocyst stratigraphy of core 84-030-021. Results are expressed in terms of concentrations.

Stratigraphie des dinokystes dans le forage 84-030-021. Les résultats sont exprimés en termes de concentrations.

summer (< 30 ‰; MUDIE and SHORT, 1985). This dilution, also shown in the $\delta^{18}O$ record, is probably related to melting along the ice margin, on the continental shelf throughout the Late Wisconsinan (FILLON and HARMES, 1982; JOSENHANS, 1983; JOSENHANS *et al.*, 1986). The occurrence of *B. simplex* in the Late Wisconsinan deposits of the western Labrador Sea is indicative of continuous phytoplanktonic production, which invalidates the hypothesis of a continuous sea ice cover over the Labrador Sea during the last glacial maximum (*e.g.* DENTON and HUGHES, 1981). Nevertheless, the existence of very diluted surface waters feeding the Labrador current probably contributed to a southward dispersion of sea ice, which may have restricted the North Atlantic Drift penetration into the Labrador Sea (Fig. 12) and induced a southward displacement of the polar front (McINTYRE *et al.*, 1976). Noticeable also in the dinocyst record is the peak of *Bitectatodinium tepikiense* appearing at the beginning of the first melting event dated at *ca.* 17,000 BP. The occurrence of *B. tepikiense*, which has a present-day temperate distribution (HARLAND, 1983), may result from an increasing insulation and/or attenuated seasonal variations (TURON, 1984). The proliferation of *B. tepikiense* as well as the melting event initiated at *ca.* 17,000 BP probably responded to a brief but significant climatic warming at high boreal latitudes.

2) Zone DII, dated between *ca.* 11,000 and 4000 BP, is marked by an increase in dinoflagellate cyst concentrations and diversity. The assemblages reveal relatively high phytoplanktonic production and subarctic conditions in surface water masses. The occurrence of cold temperate taxa suggests a slight influence of North Atlantic waters *via* the west Greenland current (Fig. 13). The low-salinity species *Brigantedinium simplex* remains dominant, however, indicating significant freshwater or meltwater runoff through the Labrador current until *ca.* 4000 BP. This runoff could have been partly related to a late melting of the northernmost ice caps of the Canadian Arctic Archipelago, in addition to an outflow of diluted water from the Arctic Ocean during this episode. Abundant driftwood collected along Arctic island coasts attests to the penetration of subpolar water between 9000 and 4000 BP (BLAKE, 1972; STEWARD and ENGLAND, 1983). Such a subpolar influence could have induced melting of Arctic pack-ice and consequently the dilution of the Arctic surface waters that fed the Labrador current.

3) Zone DIII is younger than 4000 BP. It is characterized by rich assemblages dominated by *Nematosphaeropsis labyrinthea* and *Operculodinium centrocarpum*, which reveal subarctic conditions in the superficial water masses. They indicate the establishment of modern "interglacial" conditions.

The pollen and spore assemblages of core 84-030-021 show distinct associations that led to the definition of three main assemblage zones (Fig. 11):

1) The first zone (PI) corresponds to lithologic unit I, *i.e.* to the Late Wisconsinan episode. It is marked by moderately high concentrations and by the dominance of *Pinus, Picea* and Asteraceae. It reveals the existence of a coniferous vegetation, probably forest tundra, in the source area. Because of the glacial cover across Labrador (*e.g.* PREST, 1984), long-distance atmospheric transportation may be inferred. Thus the pollen assemblages in zone PI suggest a northern

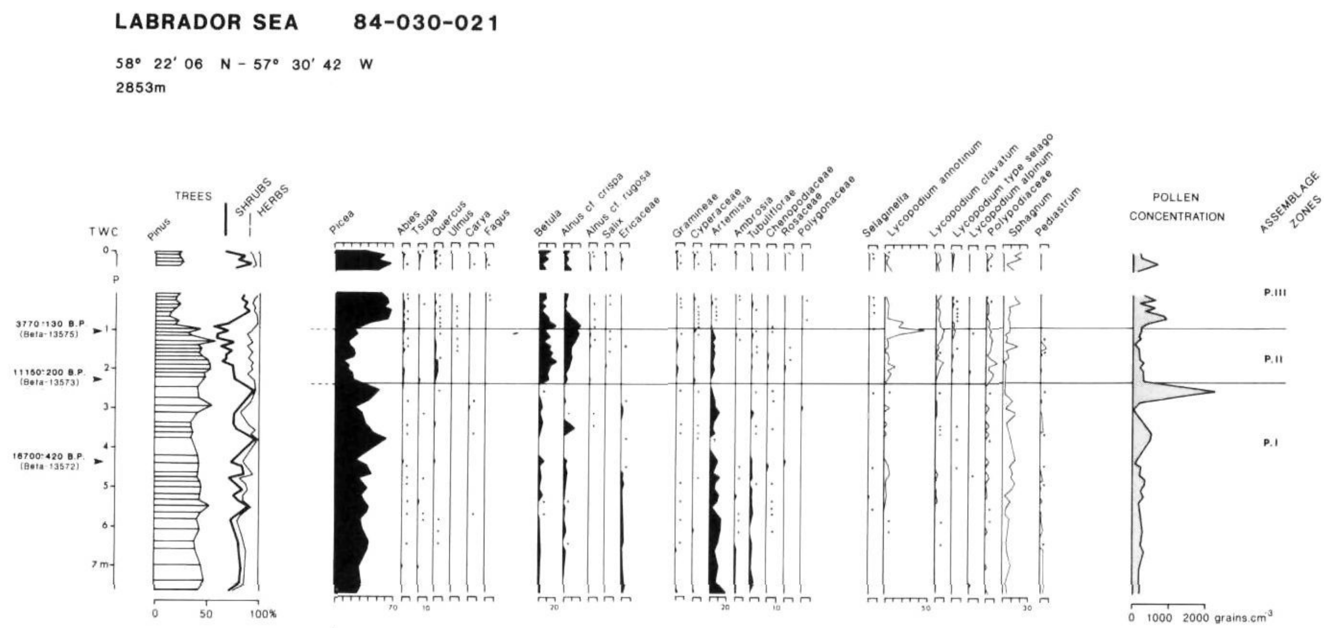

FIGURE 11. Pollen and spore percentage diagram of core 84-030-021.

Diagramme sporo-pollinique de pourcentage du forage 84-030-021.

advection of air masses coming from the southern Laurentide ice margin (Fig. 12). Such an atmospheric paleocirculation pattern has already been proposed on theoretical grounds by RUDDIMAN and McINTYRE (1981a) in order to explain rapid ice sheet growth mechanisms. Indeed, an atmospheric paleocirculation from south to north along the ice margin, controlled by pressure and temperature gradients, is favourable to the transportation of humid air masses toward high latitudes, and therefore to abundant precipitation and ice accumulation. The palynological record of core 84-030-021 tends to demonstrate that such an atmospheric paleocirculation pattern prevailed, at least during summer time (when flowering occurs), throughout the last glacial maximum, *i.e.* until *ca.* 11,000 BP.

2) Zone PII is dated between approximately 11,000 and 4000 BP. It is distinguished by an abrupt change in microfloristic assemblages. *Betula, Alnus* and *Lycopodium* are well represented while a decrease in *Picea* percentages is recorded. This assemblage reflects the existence of a shrub tundra in the source area. It allows correlation with the Early Holocene palynostratigraphy of northern Labrador (*e.g.* SHORT and NICHOLS, 1977; RICHARD, 1981) and suggests influxes mainly governed by WSW-ENE air mass trajectories, similar to the modern ones (Fig. 13). The change in pollen assemblages at the PI/PII transition, dated at *ca.* 11,000 BP, is probably related to a change in air mass trajectories as a result of the Laurentide Ice Sheet desintegration. This change in the atmospheric circulation pattern could be responsible for the Late-glacial climatic oscillation recorded in the Atlantic provinces of Canada (MOTT *et al.*, 1986).

3) Zone PIII is marked by an increase in pollen concentrations and by the dominance of *Picea*. The pollen influx originates from a coniferous boreal forest vegetation. The *Picea* maximum occurring shortly after 4000 BP likely correlates to that observed in the Labrador-Ungava palynostratigraphy (*e.g.* SHORT and NICHOLS, 1977; RICHARD, 1981).

CONCLUSION

Palynologic and isotopic analyses of deep-sea cores from the Labrador Sea reveal that major changes in the paleoceanography and atmospheric paleocirculations occurred in relation to late Quaternary ice fluctuations on eastern Canada and adjacent areas.

A significant penetration of North Atlantic waters into the Labrador Sea persisted throughout most of the Late Pleistocene. During isotopic stage 3, in particular, the Labrador Sea area also experienced atmospheric paleocirculation with a dominant SW-NE trend. Such oceanic and atmospheric circulation patterns may account for northward movements of relatively warm and humid air masses responsible for abundant precipitation and consequently high ice accumulation rates. Simultaneously, the temperate influence of the North Atlantic waters induced stabilization of the ice margins through melting, notably those of southern Greenland. Isotopic stage 3, which spans over *ca.* 30,000 years, corresponds to a long-term stationary regime when ice accumulation was equilibrated by ice ablation.

During the glacial maximum of isotopic stage 2, the northward penetration of temperate Atlantic waters into the Labrador Sea was interrupted. The advection of southern air masses along the Laurentide ice margin, however, allowed precipitation to occur, especially over Québec-Labrador. As a result, the Laurentide Ice Sheet reached its maximum extent. Although full glacial conditions then characterized eastern Canada, meltwater runoff persisted into the western Labrador Sea along the marine ice margins on the continental shelf. The calving of the ice margin, the meltwater outflow and the subsequent dilution of surface waters may have been responsible for a southward dispersal of floating ice, restraining the northward influence of Atlantic surface waters and inducing a southward shift of the polar front. These environmental conditions apparently persisted until *ca.* 11,000 BP.

The deglaciation of northern Labrador occurred in two main steps. A first melting event of the Laurentide Ice Sheet was initiated shortly after 17,000 BP, apparently in response to a brief but noticeable climatic warming. This melting event may have led to the ice wastage of high altitude areas in northern Labrador, notably in Torngat Mountains. The Laurentide ice volume nevertheless remained large enough for ice advance on the northermost Labrador shelf until *ca.* 11,000 BP, when the main ice retreat finally resumed. This transition is notably marked off northern Labrador by an interruption in glacio-marine activity. At the same time, WSW-ENE atmospheric trends developed as a consequence of the Laurentide ice dislocation. The restoration of the North Atlantic divergence into the Labrador Sea is also recorded shortly after *ca.* 11,000 BP.

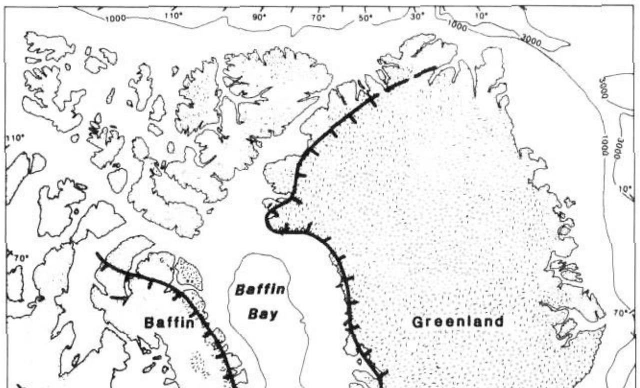

FIGURE 12. Schematic reconstruction of atmospheric (dashed arrows) and oceanic paleocirculation during the Late Wisconsinan (before 11,000 BP). Probable ice limits (ππ) are based on a compilation of several studies (GRANT, 1977; ROGERSON, 1981; MILLER and DYKE, 1974; BOULTON, 1979; PREST, 1984; JOSENHANS *et al.*, 1986).

Reconstitution schématique des paléocirculations atmosphériques (tireté) et océaniques (trait plein) du Wisconsinien supérieur (avant 11 000 BP). Les limites glaciaires probables (ππ) sont dessinées d'après la compilation de plusieurs travaux (GRANT, 1977; ROGERSON, 1981; MILLER et DYKE, 1974; BOULTON, 1979; PREST, 1984; JOSENHANS et al., *1986).*

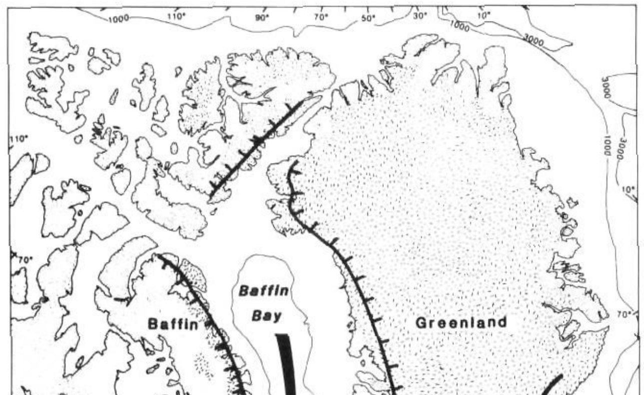

FIGURE 13. Schematic reconstruction of atmospheric (dashed arrows) and oceanic paleocirculations shortly after the deglaciation (after 11,000 BP). Probable ice limits (ππ) are essentially based on PREST (1984).

Reconstitution schématique des paléocirculations atmosphériques (tireté) et océaniques (trait plein) au moment de la déglaciation, peu après 11 000 BP. Les limites glaciaires probables (ππ) sont dessinées en référence à la carte de PREST (1984).

The establishment of modern subarctic interglacial conditions in the surface waters of the Labrador Sea shows a diachronic pattern: it occurred shortly after 10,000 BP in the eastern Labrador Sea and only after 4000 BP in the western Labrador Sea. The contribution of the North Atlantic Drift to the west Greenland current was probably strong enough as early as 10,000 BP to allow subarctic conditions to prevail in the eastern Labrador Sea. In the superficial water masses of western Labrador Sea, however, the increased outflow from the Arctic throughout the "hypsithermal" was probably responsible for the late establishment of full "interglacial" conditions.

These Late Quaternary surface water conditions in the Labrador Sea point to a highly sensitive system in space and time. Indeed, major variations of atmospheric and oceanic paleocirculations occurred; their close relationship with the glacial history of eastern Canada is an example of complex feedback mechanisms and of the general complexity of paleoclimatic reconstruction.

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