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Late and Postglacial Paleoenvironments of the Gulf of St. Lawrence: Marine and Terrestrial Palynological Evidence

Évolution des environnements marins et terrestres du golfe du Saint-Laurent au cours du tardi- et postglaciaire à partir d'analyses palynologiques

Spät- und postglaziale Umwelt des Sankt-Lorenz-Golfs: palynologische Belege von Meer und Festland

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Article abstract

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LATE AND POSTGLACIAL PALEOENVIRONMENTS OF THE GULF OF ST. LAWRENCE: MARINE AND TERRESTRIAL PALYNOLOGICAL EVIDENCE

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ABSTRACT Cored sediments from Anticosti and Esquiman channels and from Cabot Strait have been analyzed for their palynological content, which includes pollen and spores and dinoflagellate cysts. The dinoflagellate cyst assemblages led to the establishment of a regional ecostratigraphy and to quantitative reconstruction of changes in sea-surface conditions using transfer function (best analogue method). Prior to about 10,000 BP, assemblages dominated by *Brigantedinium* are associated with relatively cold (4-10°C in August) surface water and extensive seasonal sea-ice cover (up to 8 months/yr.); in Cabot Strait low salinity conditions (25-27‰) were recorded from about 11,800 to 10,000 BP as the result of outflow of meltwater discharge from the Laurentide Ice Sheet. Between *ca.* 11,000 and 10,500 BP a cooling phase in surface water probably corresponds to the Younger Dryas event. At about 10,000 BP, a sharp transition marked by the occurrence of abundant Gonyaulacales, corresponds to the establishment of conditions similar to the present with summer temperatures up to 16°C, salinity of ~31‰ and a seasonal extent of sea-ice of about 2 months/yr. During the Holocene, slight fluctuations of sea-surface temperature are reconstructed, and a thermal optimum is recorded at about 6000 BP. The pollen and spore assemblages led to direct correlations with the onshore palynostratigraphy. In the northern Gulf region, *Picea* migration apparently rapidly followed the early Holocene surface water warming although the development of closed coniferous forests occurred much later. In the southern part of the Gulf, the *Picea* forest expansion coincides with the early Holocene increase of temperature, and the significant occurrence of *Tsuga* followed the middle Holocene thermal optimum as recorded in sea-surface water.

RÉSUMÉ *Évolution des environnements marins et terrestres du golfe du Saint-Laurent au cours du tardi- et postglaciaire à partir d'analyses palynologiques.* Des sédiments carottés ont fait l'objet d'analyses palynologiques, (pollen et dinoflagellés). Les assemblages de kystes de dinoflagellés ont permis l'établissement d'une écostratigraphie régionale et la reconstitution des changements de conditions dans les eaux de surface en exploitant la méthode des meilleurs analogues. Avant 10 000 BP, les assemblages dominés par *Brigantedinium* révèlent des conditions froides (4-10°C en août) et un couvert de glace de mer relativement dense (jusqu'à 8 mois/an); au détroit de Cabot, de faibles salinités (~25-27‰) sont enregistrées de 11 800 à 10 000 BP en réponse à l'évacuation d'eaux de fonte de la calotte laurentidienne. Entre 11 000 et 10 000 BP, un refroidissement des eaux de surface correspond sans doute au Dryas récent. Vers 10 000 BP, une transition abrupte, marquée par le développement de populations à Gonyaulacales, correspond à l'établissement de conditions semblables à celles de l'Actuel dans les eaux superficielles, avec des température et salinité d'environ 16°C et 31‰ respectivement, et un couvert de glace de mer d'environ 2 mois/an. Pendant l'Holocène, des fluctuations mineures des températures sont retracées et un optimum thermique est enregistré vers 6000 BP. Les assemblages autorisent des corrélations directes avec la palynostratigraphie continentale Dans le secteur nord du Golfe, la migration de *Picea* suivit de peu le réchauffement postglaciaire initial, bien que le développement des forêts conifériennes fermées soit plus tardif. Dans le secteur méridional du Golfe, le développement de pessières coïncide avec le début de l'Holocène et le développement des forêts à *Tsuga* a suivi l'optimum thermique de l'Holocène moyen enregistré dans les eaux de surface.

ZUSAMMENFASSUNG *Spät- und postglaziale Umwelt des Sankt-Lorenz-Golfs: palynologische Belege von Meer und Festland.* Sedimentbohrkerne der Kanäle von Anticosti und Esquiman sowie der Cabot-Meerenge wurden auf ihren palynologischen Gehalt untersucht einschließlich der Pollen, Sporen und der Beutel der Dinoflagellaten. Mit Hilfe der Ansammlungen von Dinoflagellatenbeuteln ließen sich die regionale Ökostratigraphie sowie die Wechsel in den Meeresoberflächenbedingungen quantitativ bestimmen unter Benutzung von Transfer-Funktionen (Methode des besten Analogons). Vor etwa 10,000 v.u.Z. werden die von Brigantedinium beherrschten Einheiten auf relativ kaltes (4-10°C im August) Oberflächenwasser und eine extensive Meereseisdecke (bis zu 8 Monate pro Jahr) zurückgeführt; in der Cabot-Meerenge sind wegen der Menge des Abflusses von Schmelzwasser von der laurentidischen Eisdecke niedrige Salzgehaltbedingungen (~25-27‰) von etwa 11,800 bis 10,000 v.u.Z. belegt. Zwischen etwa 11,000 und 10,500 v.u.Z. entspricht eine Abkühlungsphase im Oberflächenwasser wahrscheinlich dem jüngeren Dryas. Um etwa 10,000 v.u.Z. entspricht eine abrupte Übergangszeit, die sich durch reichliches Vorkommen von Gonyaulacales auszeichnet, der Verbreitung von der Gegenwart ähnlichen Bedingungen mit Sonnentemperaturen bis zu 16°C, Salzgehalt von ~31‰ und einer saisonbedingten Ausdehnung des Meereises von etwa 2 Monaten pro Jahr. Man hat geringfügige Temperaturschwankungen an der Meeresoberfläche rekonstruiert, und ein thermisches Optimum wird um etwa 6000 v.u.Z. belegt. Die Pollen- und Sporeneinheiten weisen auf eine direkte Wechselbeziehung mit der Küsten Palynostratigraphie, die ihrerseits mit der Vegetation sentwicklung in den Landgibieten um den Sankt-Lorenz-Golf verbunden ist.

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INTRODUCTION

The Gulf of St. Lawrence is a large epicontinental sea, which constitutes a transitional marine environment between the St. Lawrence River and the North Atlantic Ocean. Despite the penetration of North Atlantic water masses into deep and intermediate layers, the sea-surface water of the Gulf of St. Lawrence have a particular temperature and salinity signature that is largely controlled by the regional climatic regime in addition to freshwater runoff through the St. Lawrence River (*e.g.* Koutitonsky and Bugden, 1991). To document the regional evolution of the marine and terrestrial environments in relation to late and postglacial climate changes, sediment cores from the Gulf of St. Lawrence were studied for their palynological content. The palynological samples contain abundant marine microfossils, notably cysts of dinoflagellates which result from planktonic production and closely relate to sea-surface temperature and salinity conditions. Palynological assemblages also include pollen and spores which originate from the onshore vegetation of adjacent lands and allow direct correlation with the terrestrial palynostratigraphy. Therefore, the palynology of an epicontinental environment such as the Gulf of St. Lawrence allow the reconstruction of several climatic and oceanographic parameters, which identify the evolution of both the marine and terrestrial environments in response to regional climatic changes.

Four cores collected during the Dawson cruise 89-007 were selected for palynological analysis: cores 89-007-016 and 89-007-021 from the Anticosti Channel, core 89-007-36 from the Esquiman Channel, and core 89-007-111 from the distal end of the Laurentian Channel in Cabot Strait (Fig. 1). The sedimentary sequences at coring sites appear representative of regional stratigraphy established on the basis of airgun and Huntec seismic surveys (Vilks *et al.*, 1990; Zevenhuisen and Josenhans, 1992). The cored sediments consist of sandy-gravelly mud overlain by hemipelagic mud. These facies are respectively assigned to stratified and semi-transparent seismic units, which are associated with ice distal glacio-marine accumulations and postglacial sedimentation (Vilks *et al.*, 1990; Zevenhuisen and Josenhans, 1992).

METHODS

Details of the onboard sampling and seismic survey procedures can be found in the cruise 89-007 report (Vilks and Rodrigues, 1989). Sedimentological descriptions and seismic survey data are reported by Vilks *et al.* (1990) and *Zevenhuisen and Josenhans (1992)*. The trigger weight (TWC) and piston (P) cores have been systematically sampled at 20 cm intervals. Samples were prepared for palynological analyses using procedures that consist of HCl (10%) and HF (48%) treatments in addition to wet sieving at 10 and 125 μm (*e.g.* de Vernal, 1986). A minimum of 300 pollen grains and 300 dinoflagellate cysts were identified and counted for percentage calculation in most samples. However, lower counts were obtained in several samples with sparse palynomorph content at the base of the cores; in such cases only occurrences are reported. Although all identifiable palynomorphs were counted, only summary diagrams of percentages are presented herein. Detailed results are archived at the GEOTOP and available on request. Palynomorph concentrations were determined by the marker-grains method (Matthews, 1969), which provides estimates with a standard deviation of about 10% (de Vernal *et al.*, 1987). The nomenclature of dinoflagellate cysts conforms to the index of

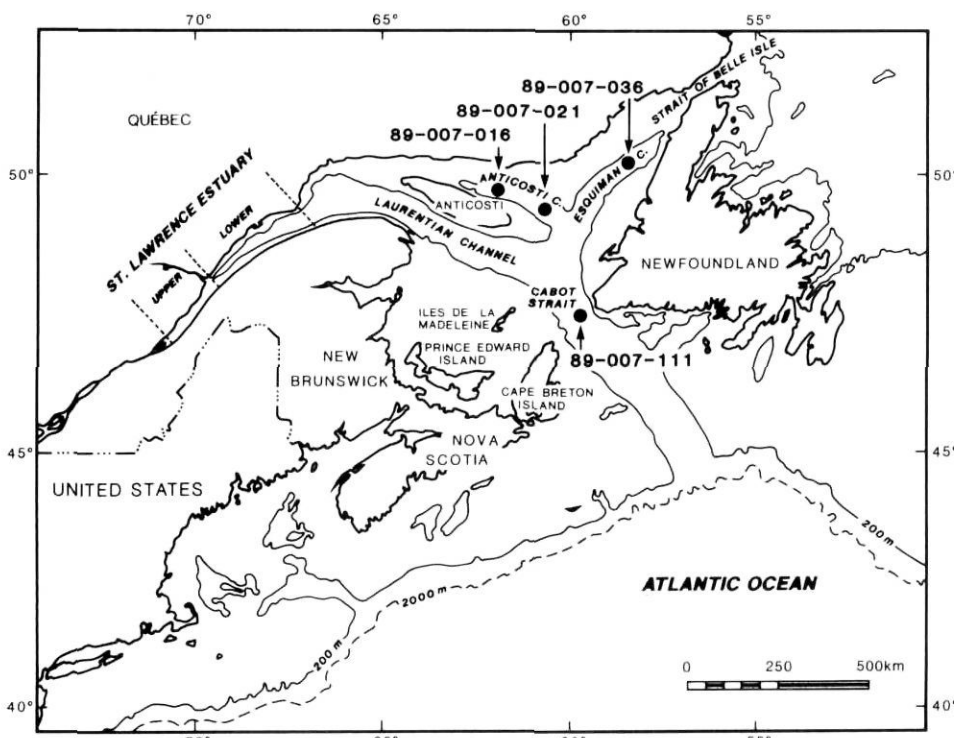

FIGURE 1. Location map of cores 89-007-016 (49°42.80′N-61°56.91′W, water depth = 258), 89-007-021 (49°31.28′N-60°48.13′W, water depth = 281 m), 89-007-036 (50°06.92′N-58°43.59′W, water depth = 300 m), 89-007-111 (47°31.00′N-59°53.06′W, water depth = 503 m).

Carte de localisation des carottes 89-007-016 (49°42.80′N-61°56.91′W, profondeur = 258 m), 89-007-021 (49°31.28′N-60°48.13′W, profondeur = 281 m), 89-007-036 50°06.92′N-58°43.59′W, profondeur = 300 m), 89-007-111 (47°31.00′N-59°53.06°W, profondeur = 503 m).

Quaternary taxa updated by de Vernal *et al.* (1992) after the index of genera and species of Lentin and Williams (1989).

Four ^{14}C-AMS (accelerator mass spectrometry) dates on gastropods from core 89-007-111 provide a chronostratigraphic framework. The ages were corrected for fractionation to a base of $\delta^{13}C = -25‰$. The ages were also corrected for a 410 years reservoir effect corresponding to air-sea ^{14}C difference. Correlations with terrestrial palynostratigraphy yield relative time marks. The sedimentary sequences span about the last 12,000 years.

DINOFLAGELLATE CYST RECORDS

In marine sediments, the most common palynomorphs are generally organic-walled cysts of dinoflagellates, one of the main primary producers in marine environments (*e.g.* Parsons *et al.*, 1984). The abundance and distribution of dinoflagellate cysts depend upon the primary production and the physico-chemical conditions in surface water of the photic zone. Studies of the modern dinoflagellate cyst distribution throughout the North Atlantic have shown a latitudinal zonation closely related to sea-surface temperature (Wall *et al.*, 1977; Turon, 1981; Harland, 1983; Mudie, 1980). In addition, the palynological study of modern sediments from transitional marine environments off eastern Canada shows close relationships between the dinoflagellate cyst distribution and the salinity of surface water (Mudie and Short, 1985; Giroux, 1990; de Vernal and Giroux, 1991). Surface sediments from the Estuary of St. Lawrence are characterized by a distinct upstream-downstream zonation that clearly corresponds to salinity gradients (Giroux 1990; de Vernal and Giroux, 1991). The relationship between the dinoflagellate cyst asssemblages and sea-surface temperature and salinity can be quantitatively defined through transfer functions (*e.g.* Mudie, 1984; Edwards *et al.*, 1991; de Vernal *et al.*, 1993). Therefore, dinoflagellate cyst analyses of Gulf of St. Lawrence sediments can be used to establish a regional ecostratigraphy in addition to quantitative estimates of surface water temperature and salinity changes since deglaciation.

REGIONAL ECOSTRATIGRAPHY

The water masses of the Gulf of St. Lawrence are characterized by three main components: (1) cold water from the Labrador Current that penetrates into the Gulf through the Belle-Isle Strait and Cabot Strait, which occurs in the intermediate layer; (2) relatively warm and saline North Atlantic water flowing through Cabot Strait that contributes mainly to the deep water masses; (3) freshwater outflow from the St. Lawrence River that results in a buoyant low saline sea-surface water mass (*cf.* salinity-temperature profiles, in Vilks and Rodrigues, 1989). Thus, the sea-surface salinity and temperature of the Gulf of St. Lawrence are strongly dependant upon regional hydroclimatic conditions: salinity is controlled by freshwater outflow resulting from precipitation throughout the St. Lawrence drainage basin, whereas temperature is mainly determined by heat exchanges at the water-atmosphere interface (*e.g.* Koutitonsky and Bugden, 1991). Because of intense horizontal mixing (*e.g.* El-Sabh, 1976), surface water masses in the Gulf of St. Lawrence are relatively uniform, except in the nearshore and shallow water regions: by the end of the summer season (August), sea-surface temperatures range between 13 and 16°C from north to south, and salinity is 30 to 31‰. Consequently, the dinoflagellate cyst assemblages are relatively uniform throughout the Gulf, at least in the hemipelagic sediments from the deep channels (Giroux, 1990). Therefore, a regional ecostratigraphy can be defined from the analyses of cores 89-007-016 (Fig. 2), 89-007-021 (Fig. 3), 89-007-36 (Fig. 4) and 89-007-111 (Fig. 5).

Two main ecozones comprise the ecostratigraphy. The lower ecozone (I) corresponds to the late-glacial interval (>10,000 BP). It is characterized by the dominance of Peridiniales (notably *Brigantedinium* spp.) accompanied by *Operculodinium centrocarpum* and rare Gonyaulacales. It reflects low salinity and cold temperature in surface water (*e.g.* Mudie and Short, 1985). This assemblage zone corresponds to the glacio-marine and early postglacial sedimentation. The upper ecozone (II) belongs to the later postglacial time. It is marked by increased percentages of Gonyaulacales, relatively high species diversity, and by the notable occurrence of *Bitectatodinium tepikiense* and *Alexandrium excavatum*. Another particularity of the postglacial dinoflagellate cysts assemblages is the successive occurrence of *Spiniferites ramosus* (SR) and *Nematosphaeropsis labyrinthus* (NL) which apparently constitute regional ecostratigraphic marks throughout the Gulf of St. Lawrence. On the whole, the dinoflagellate cyst assemblages of ecozone II suggest temperature and salinity conditions similar to modern ones.

SEA-SURFACE TEMPERATURE AND SALINITY CHANGES

A data base of 165 reference points from the northwest North Atlantic and adjacent basins (Labrador Sea, Baffin Bay, Hudson Bay, Gulf and Estuary of St. Lawrence) was established in order to develop transfer functions for quantitative reconstruction of sea-surface temperature and salinity based on dinoflagellate cyst assemblages (de Vernal *et al.*, 1993). The data base notably includes 86 points from the Estuary and Gulf of St. Lawrence. It consists of systematic dinoflagellate cyst counts in surface sediments and average instrumental measurements of selected environmental parameters. Three parameters are considered herein: the average sea-surface (water depth = 0 m) temperature and salinity in August, and the seasonal duration (months/year) of the sea-ice cover. Temperature and salinity data in marine regions adjacent to eastern Canada were provided by Environment-Canada. The compilation of >1,000,000 items of data collected up to 1989 is archived at UQAM. Salinity and temperature data for the North Atlantic are from the Atlases by Levitus (1982) and Isemer and Hasse (1985). The seasonal duration of the sea-ice cover was estimated after Atlases by Markham (1980, 1988).

The best analogue method (Guiot, 1990a-b) was used to reconstruct environmental parameters from the fossil dinoflagellate cyst assemblages. This method consists of three steps: (1) a paleobioclimatic analysis of the fossil sequence

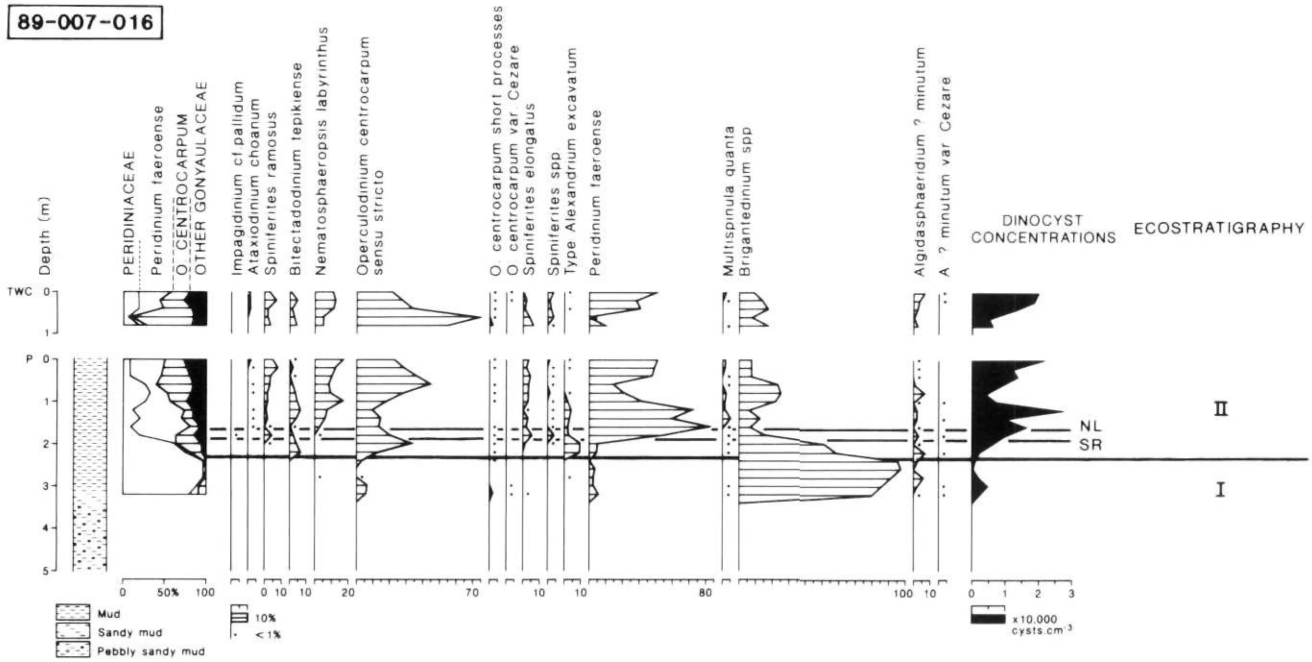

FIGURE 2. Summary diagram of dinoflagellate cyst taxa percentages in core 89-007-016 from the Anticosti Channel. The cyst concentrations are indicated in the right of the diagram. The ecostrastigraphy is indicated in the right margin: SR and NL refer to the occurrence of significant numbers of *Spiniferites ramosus* and *Nematosphaeropsis labyrinthus*, which constitute regional ecostratigraphic markers.

Diagramme résumé des pourcentages des espèces de kystes de dinoflagellés dans la carotte 89-007-016 prélevée dans le chenal d'Anticosti. Les concentrations sont indiquées à droite du diagramme. Un schéma écostratigraphique paraît en marge de droite: SR et NL font référence à l'apparition en grand nombre de Spiniferites ramosus *et* Nematosphaeropsis labyrinthus *qui constituent des marquèurs écostratigraphiques à une échelle régionale.*

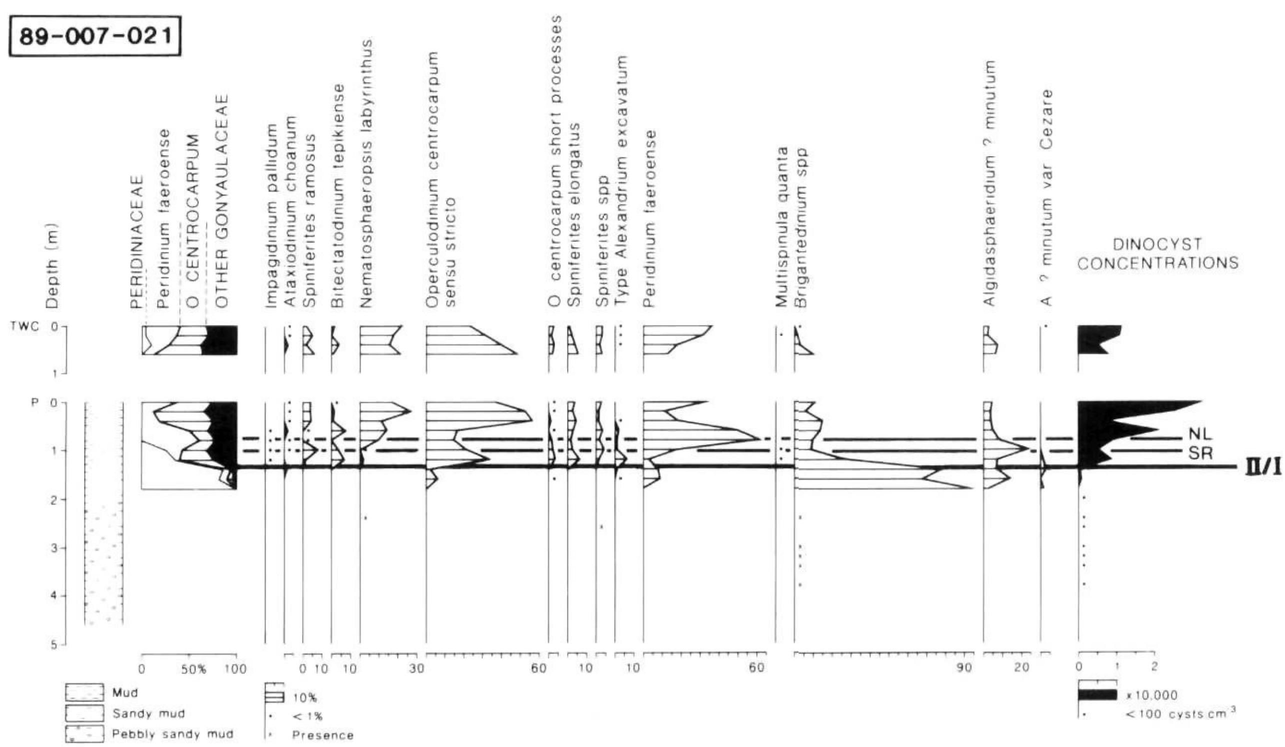

FIGURE 3. Summary diagram of dinoflagellate cyst distribution in core 89-007-021 from the Anticosti Channel (same caption as in Fig. 2).

Diagramme résumé de la distribution des kystes de dinoflagellés dans la carotte 89-007-021, prélevée dans le chenal d'Anticosti (même légende que celle de la fig. 2).

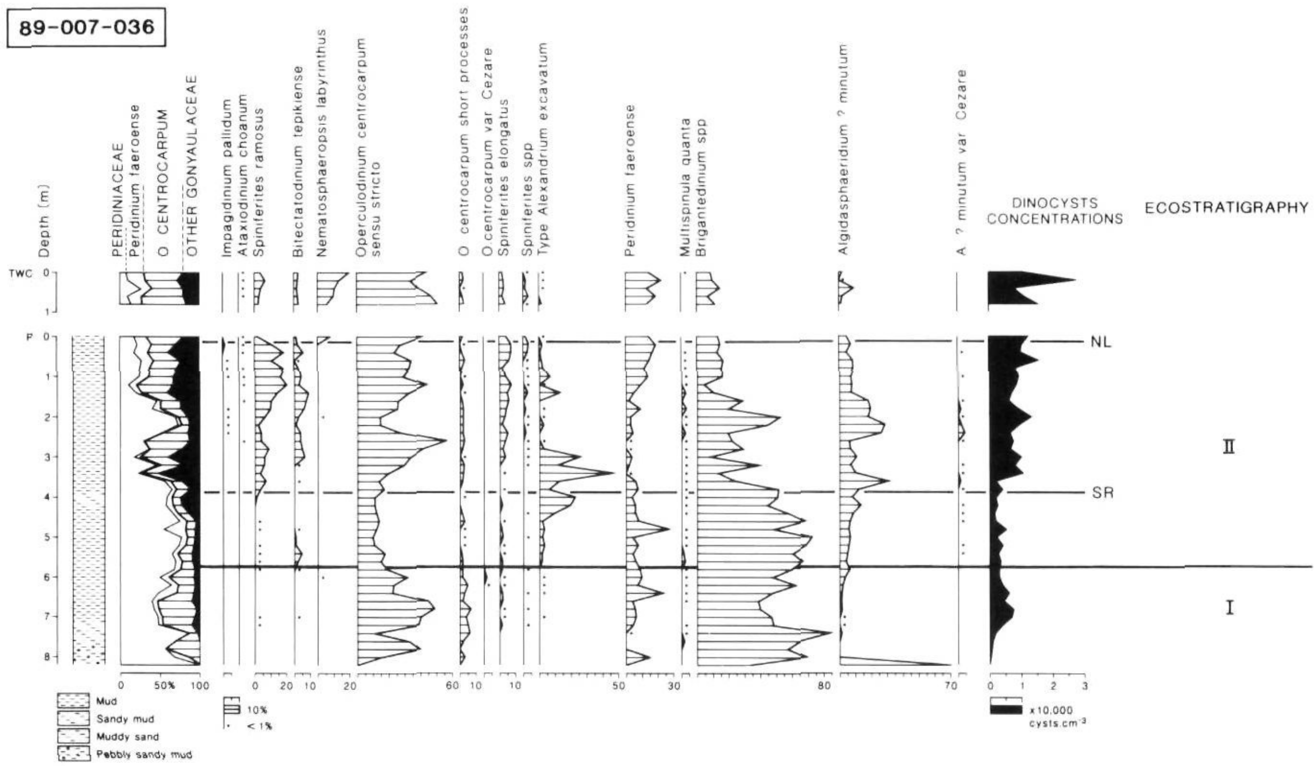

FIGURE 4. Summary diagram of dinoflagellate cyst distribution in core 89-007-036 from the Esquiman Channel (same caption as in Fig. 2).

Diagramme résumé de la distribution des kystes de dinoflagellés dans la carotte 89-007-036, prélevée dans le chenal des Esquimans (même légende que celle de la fig. 2).

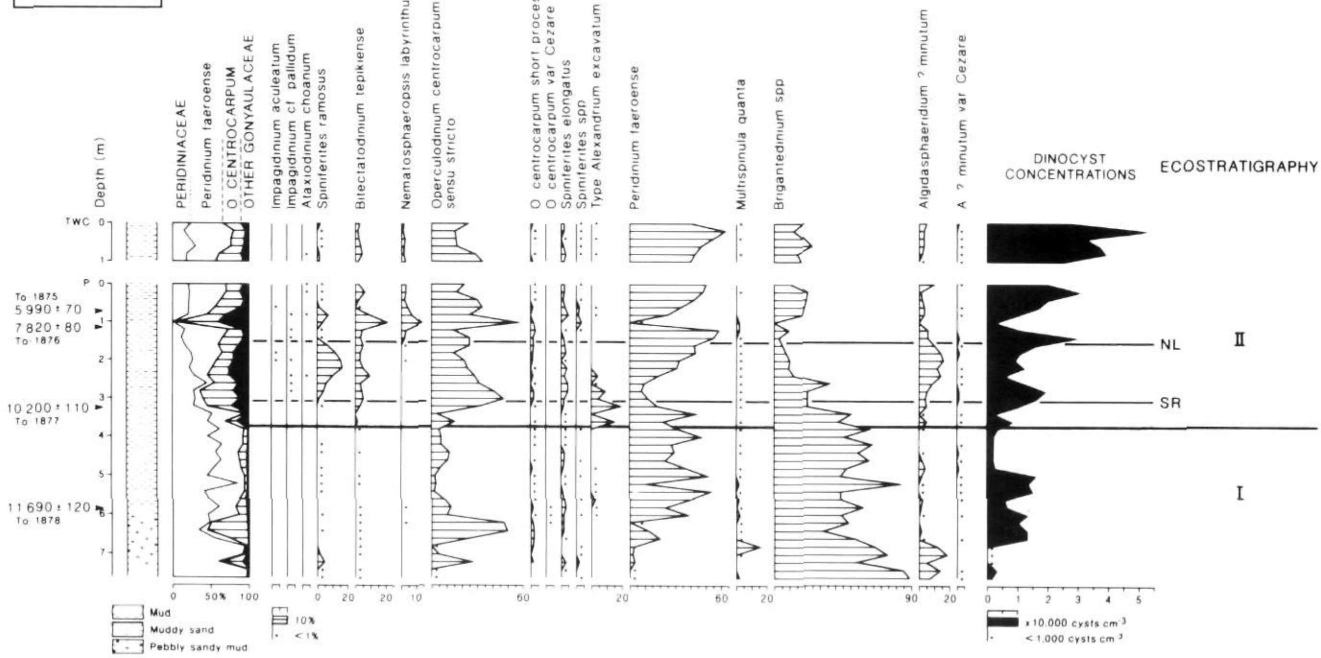

FIGURE 5. Summary diagram of dinoflagellate cyst distribution in core 89-007-111 from Cabot Strait (same caption as in Fig. 2).

Diagramme résumé de la distribution des kystes de dinoflagellés dans la carotte 89-007-111, prélevée sur le détroit de Cabot (même légende que celle de la fig. 2).

through multiple autocorrelation weights the taxa in the assemblages; (2) the distance between the fossil spectra, as weighted above, and the modern spectra is calculated to identify the closest modern analogues; (3) finally, the distance between the closest modern analogues and each fossil spectrum gives the most probable paleoenvironmental values within confidence interval. The accuracy of the method was verified by estimating modern environmental parameters from the dinoflagellate cyst assemblages (in the procedure, the analysed spectrum is of course excluded from the data base for the search of analogue; *cf.* Guiot, 1990b). The comparison of the instrumental data and the estimated values yielded the following correlation coefficients (R): 0.87 for temperature, 0.93 for salinity, and 0.97 for the seasonal duration of sea-ice cover (de Vernal *et al.*, 1993).

The application of the best analogue method to the postglacial dinoflagellate assemblages revealed important changes in sea-surface temperature and salinity (Figs. 6-9). The quantitative reconstructions show that significantly different salinity and temperature conditions characterize ecozones I and II respectively.

Ecozone I is characterized by temperature estimates that vary between 4 and 10°C (Figs. 6-9) and by a relatively long seasonal sea-ice cover extent, up to 8 months/yr. Ecozone I no doubt reflects cool subarctic conditions in surface water throughout the Gulf of St. Lawrence. It is also characterized by variable salinities ranging from 24 to 31‰. In cores from the Anticosti and Esquiman channels, the minimum salinities that correspond to phases of increased sea-surface temperatures probably resulted from stronger meltwater events of the adjacent ice margins. In Cabot Strait, low salinity estimates (25-27‰) reflect dilution of surface water for the interval spanning about 11,800 BP to 10,000 BP. Such a dilution is no doubt related to the outflow of meltwater from the Laurentide Ice Sheet through the Laurentian Channel after the deglaciation of the St. Lawrence lowlands and the development of the Champlain Sea (*e.g.* Hillaire-Marcel, 1988; Lewis *et al.*, 1989).

The upper part of ecozone I is marked by decreasing summer temperatures accompanied by increased seasonal duration of the sea-ice cover in all cores . This cooler interval that spans about 11,000-10,500 BP (*cf.* Figs. 9-10) coincides with the Younger Dryas event (*cf.* Mott *et al.*, 1986) Ecozone II is associated with the establishment of sea-surface conditions similar to the present ones. A significant increase of temperature from about 7° to about 15° C is indeed recorded at the base of the ecozone II throughout the Gulf (Figs. 6-9). The record of core 89-007-036 from the Esquiman channel (Fig. 8), which shows an expanded early postglacial stratigraphy, suggests a transition marked by oscillations in sea-surface temperature and salinity. On the whole, the postglacial interval corresponds to cool temperate conditions in surface water, with salinity of about 30‰ and a seasonal sea-ice cover spanning about 2 months/yr. Temperature and salinity fluctuations were minor. Notable peaks of sea-surface temperature are however recorded in core 89-007-016 (Fig. 6) and core 89-007-111 (Fig. 9). The latter sequence (Fig. 9) indicates that this thermal optimum spanned 8000 to 6000 BP.

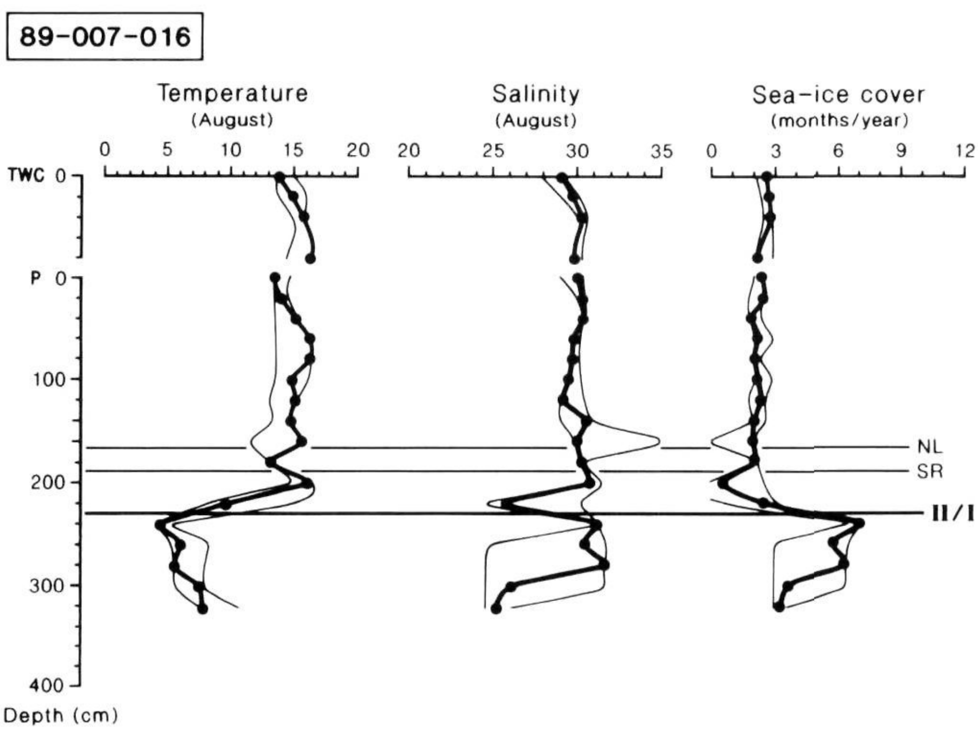

FIGURE 6. Reconstruction of sea-surface temperature and salinity in August, and seasonal duration of the sea-ice cover based on dinoflagellate cyst assemblages in core 89-007-016. The thick line is the most probable value that corresponds to the average of the values for the ten best modern analogues, weighted according to their distance from the fossil spectrum. The envelope is defined on the basis of minimum and maximum values possible in reference to the best analogues (*cf.* Guiot, 1990a-b).

Reconstitution des température et salinité de surface du mois d'août et de la durée saisonnière du couvert de glace à partir des assemblages de kystes de dinoflagellés dans la carotte 89-007-016. La ligne médiane indique la valeur la plus probable qui correspond à la moyenne des valeurs caractérisant les 10 meilleurs analogues modernes, pondérée selon leur distance par rapport au spectre fossile. L'enveloppe couvre les valeurs minimales et maximales possibles en référence aux meilleurs analogues (voir Guiot, 1990).

POLLEN AND SPORES RECORDS

Pollen and spores in marine sediments constitute long distance fluvial and/or atmospheric inputs originating from the terrestrial vegetation of adjacent land (*e.g.* Mudie, 1982; Heusser, 1983). Studies of surface sediments collected in the Estuary and the Gulf of St. Lawrence revealed abundant pollen and spores, primarily resulting from fluvial transport and moderately high atmospheric inputs (Giroux, 1990; de Vernal and Giroux, 1991). Assemblages show some regionalism (Giroux, 1990): those in nearshore regions are associated with the vegetation domains of adjacent lands as a result of dominant inputs by tributaries. In contrast, assemblages throughout the deep Laurentian Channel are uniform reflecting the homogenized input from several sources accross southeastern Canada (fluvial input through the St. Lawrence and tributaries, in addition to atmospheric input). Spectra from Gulf of St. Lawrence cores are used to identify the main

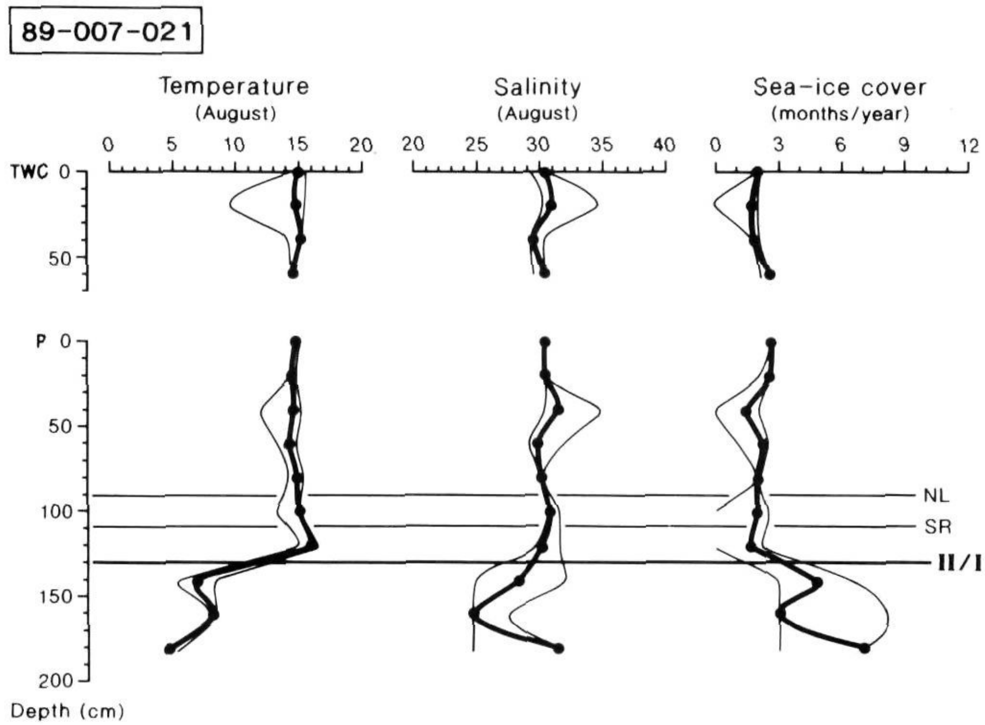

FIGURE 7. Reconstruction of sea-surface temperature and salinity in August, and seasonal duration of the sea-ice cover based on dinoflagellate cyst assemblages in core 89-007-021 (same caption as Fig. 6).

Reconstitution des température et salinité de surface du mois d'août et de la durée saisonnière du couvert de glace à partir des assemblages de kystes de dinoflagellés dans la carotte 89-007-021 (même légende que celle de la fig. 6).

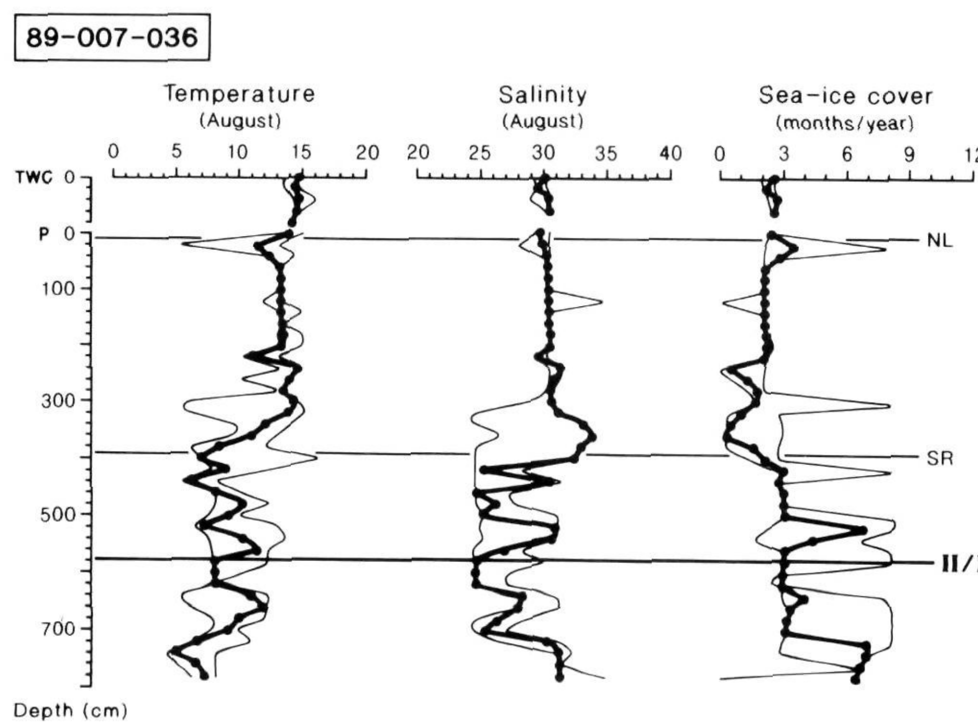

FIGURE 8. Reconstruction of sea-surface temperature and salinity in August, and seasonal duration of the sea-ice cover based on dinoflagellate cyst assemblages in core 89-007-036 (same caption as Fig. 6).

Reconstitution des température et salinité de surface du mois d'août et de la durée saisonnière du couvert de glace à partir des assemblages de kystes de dinoflagellés dans la carotte 89-007-036 (même légende que celle de la fig. 6).

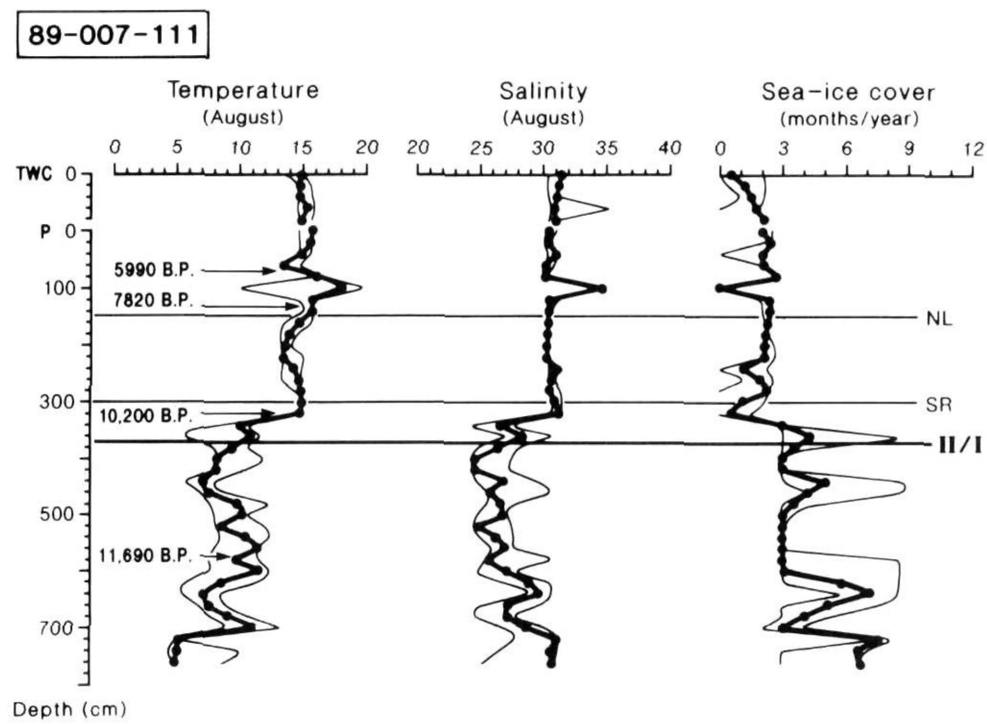

FIGURE 9. Reconstruction of sea-surface temperature and salinity in August, and seasonal duration of the sea-ice cover based on dinoflagellate cyst assemblages in core 89-007-111 (same caption as Fig. 6).

Reconstitution des température et salinité de surface du mois d'août et de la durée saisonnière du couvert de glace à partir des assemblages de kystes de dinoflagellés dans la carotte 89-007-111 (même légende que celle de la fig. 6).

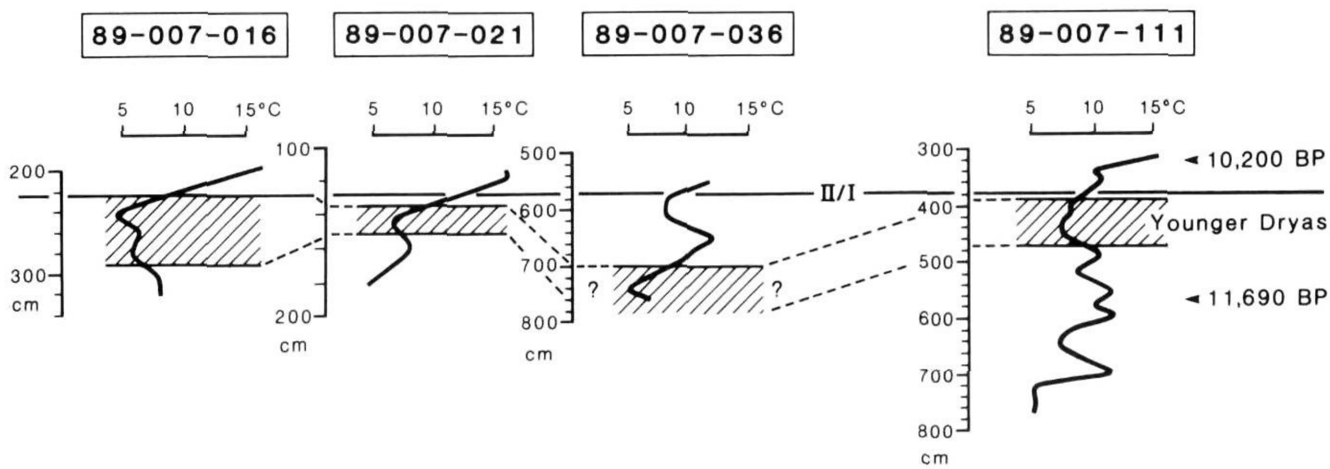

FIGURE 10. August sea-surface temperature reconstructions in the Gulf of St. Lawrence, which may be used as a regional paleoclimatic framework for the late-glacial (Ecozone I in the dinoflagellate cyst records).

Reconstitutions des températures d'août dans les eaux de surface du golfe du Saint-Laurent, fournissant un cadre climatostratigraphique régional du Tardiglaciaire (Ecozone I dans les assemblages de kystes de dinoflagellés).

regional changes of vegetation and to establish direct correlations with the terrestrial palynostratigraphy.

NORTHERN GULF OF ST. LAWRENCE

Recent pollen and spore spectra from the Anticosti and Esquiman channels show a regional signature with high *Picea* percentages related mostly to input from the coniferous boreal forest vegetation along the northern coast of the Gulf (*cf.* Giroux, 1990; see also Figs. 11-13).

The succession of pollen and spore assemblages in cores from the Anticosti Channel (89-007-016: Fig. 11; 89-007-021: Fig. 12) and the Esquiman Channel (89-007-036: Fig. 13) show similar palynostratigraphical trends which allows the establishment of a zonation on a regional scale.

The lower part of the cores is characterized by sparse pollen assemblages with concentrations lower than 10^3 grains/cm^3. As a consequence, low pollen counts did not allow percentage calculations. Such sparse pollen content probably reflect low input due to sparse vegetation, in addition to a dilution of microfossils related to abundant detrital sediment supply. These assemblages indeed occur in the sandy-gravelly mud deposits with abundant ice-rafted debris which correspond to the stratified sismic unit associated with ice distal glaciomarine sedimentation (Vilks *et al.*, 1990).

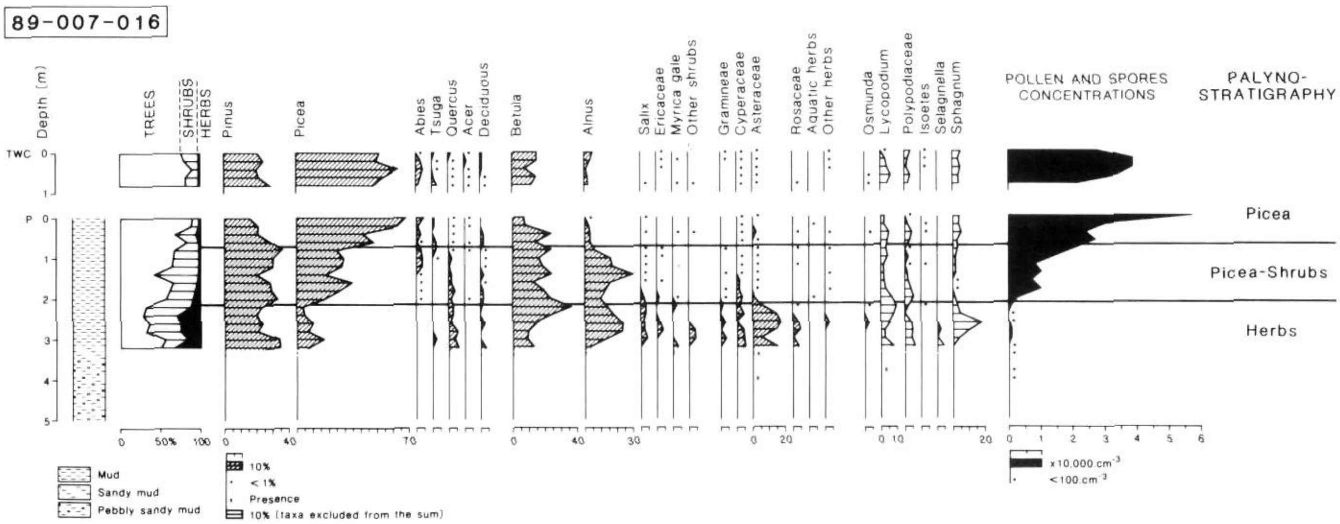

FIGURE 11. Summary diagram of pollen and spore assemblages in core 89-007-016 from the Anticosti Channel. The palynostratigraphic scheme illustrated in the right margin of the diagram can be directly correlated with the onshore palynostratigraphy of the terrestrial region north of the Gulf of St. Lawrence (*cf.* Mott, 1976; Lamb, 1980; Engstrom and Hansen, 1985).

Diagramme résumé des assemblages sporo-polliniques dans la carotte 89-07-016 prélevée dans le chenal d'Anticosti. La zonation palynostratigraphique illustrée en marge de droite autorise des corrélations directes avec la palynostratigraphie continentale des régions adjacentes du nord du golfe du Saint-Laurent (voir Mott, 1976; Lamb, 1980; Engstrom and Hansen, 1985).

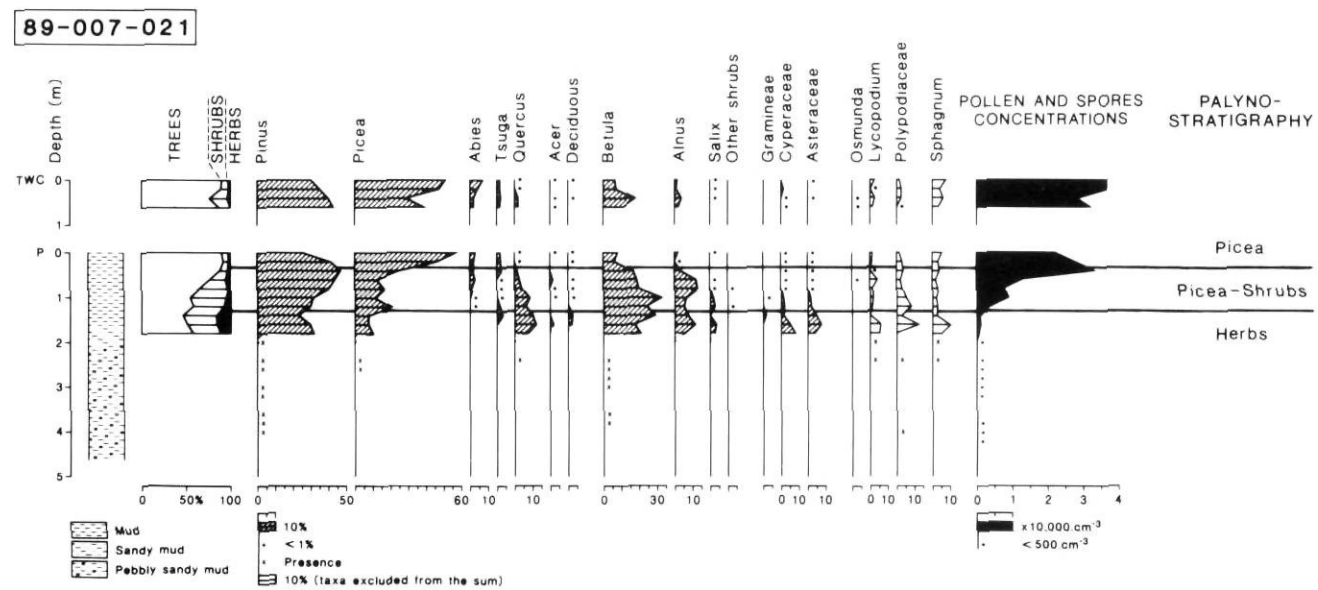

FIGURE 12. Summary diagram of pollen and spore assemblages in core 89-007-021 from the Anticosti Channel (same caption as Fig. 11).

Diagramme résumé des assemblages sporo-polliniques dans la carotte 89-007-021 prélevée dans le chenal d'Anticosti (même légende que celle de la fig. 11).

Overlying the sandy-gravelly mud deposits, the base of the hemipelagic sediments is characterized by moderately low pollen and spore content, with concentrations of the order of $10^3/cm^3$. High percentages of herb (Asteraceae, Cyperaceae) and shrub (*Salix*, *Alnus*) taxa define an "herb" zone (Fig. 11-14). This zone most probably reflects the development of shrub tundra vegetation in surrounding lands after the regional ice retreat. It may be correlated with the early postglacial (~11,000-9500 BP) tundra zone identified in the terrestrial palynostratigraphy of southern Labrador and along the northern coast of the Gulf of St. Lawrence (Lamb, 1980; Engstrom and Hansen, 1985; Mott, 1976). In the marine cores, the occurrence of tree pollen taxa (*Pinus, Picea, Quercus*) no doubt relates to southern atmospheric input, which is over-represented due to low regional pollen fluxes from the adjacent open tundra-type vegetation.

A significant increase in pollen concentrations (to about $10^4/cm^3$) accompanied by increased of *Picea* relative to

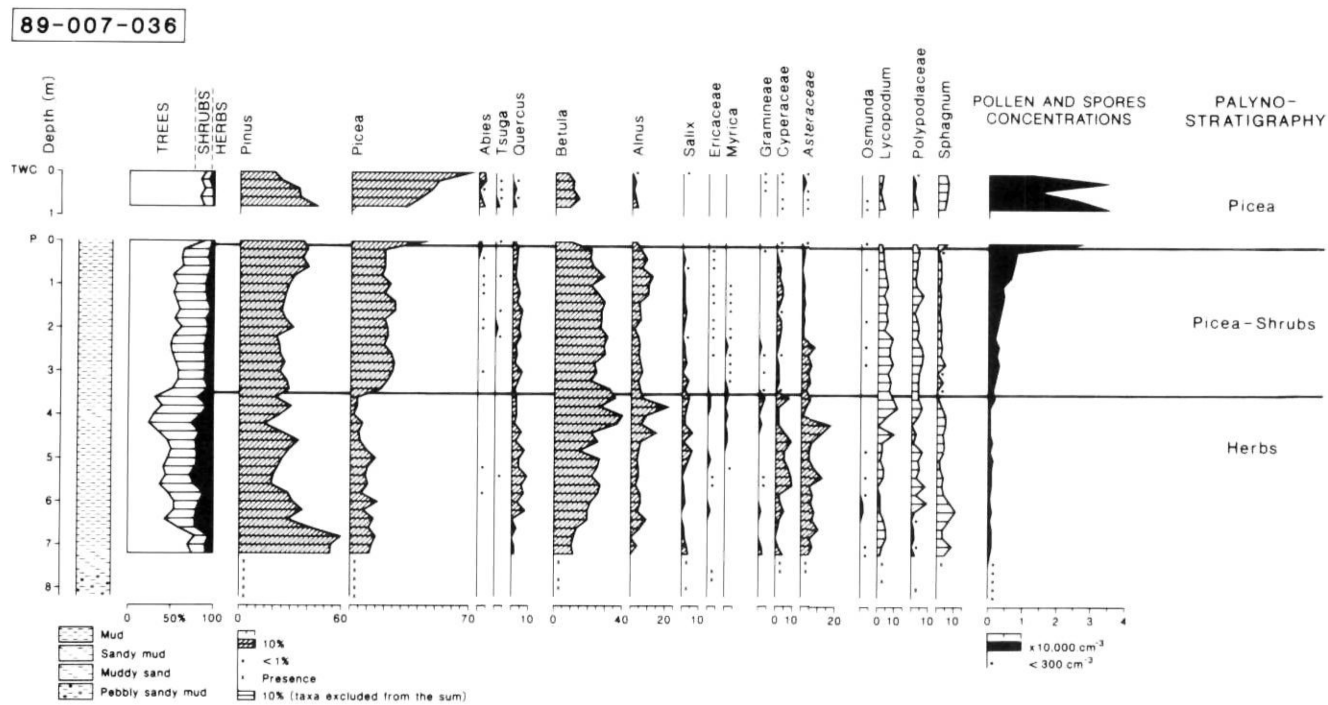

FIGURE 13. Summary diagram of pollen and spore assemblages in core 89-007-036 from the Esquiman Channel (same caption as Fig. 11).

Diagramme résumé des assemblages sporo-polliniques dans la carotte 89-007-036 prélevée dans le chenal des Esquimans (même légende que celle de la fig. 11).

decreasing herb taxa percentages occurs higher in the core. This trend led to definition of a "*Picea*-shrubs" zone (Figs. 11-13), which is characterized by the co-dominance of shrub taxa (*Betula* and *Alnus*) and *Picea*. In cores from the Anticosti Channel, this zone is also marked by the occurrence of *Abies* (Figs. 11-12). The "*Picea*-shrub" zone reflects the enrichment of the vegetational cover and the development of open forest vegetation over adjacent lands. It correlates with the early Holocene zone (*ca.* 9500 to 6500 BP) characteristic of the palynostratigraphy of terrestrial regions north of the Gulf (Lamb, 1980; Engstrom and Hansen, 1985; Mott, 1976).

Finally, the upper part of the sequences are marked by maximum pollen concentrations (up to about $3.10^4/cm^3$) and by the dominance of *Picea*. This "*Picea*" zone corresponds to the regional extension of the spruce forest along the northern coast of the Gulf and over Labrador at about 6500 BP (*cf.* Lamb, 1980; Engstrom and Hansen, 1985; Mott, 1976).

CABOT STRAIT DATA

Cabot Strait constitutes the end-member of the St. Lawrence system, where pollen fluxes integrate fluvial input from the drainage basin of the St. Lawrence river in addition to atmospheric input from the adjacent Atlantic provinces. Modern pollen assemblages of the Cabot Strait are similar to those observed throughout the Laurentian Channel: they are dominated by *Pinus* and characterized by significant percentages of *Tsuga*, and represent a large scale source from southeastern Canada (*cf.* Giroux, 1990).

Core 89-007-111 is marked by the succession of five distinct pollen assemblage zones (Fig. 14). The base of the core spanning approximately 12,000 to 10,000 BP, is characterized by relatively low pollen concentrations and relatively high percentages of herb (Asteraceae, Cyperaceae, Gramineae) and shrub (*Alnus, Salix, Betuta,* Ericaceae) taxa. This "Herbs" zone (Fig. 14) can be associated with an open tundra-type vegetation over southeastern Canada, as also observed in the terrestrial palynostratigraphy of southern Québec and Atlantic provinces (*e.g.* Anderson, 1985). It is of note that the pollen diagram does not show unequivocal evidence of large scale vegetational changes correlative with the Younger Dryas as locally observed in sequences from Nova Scotia (Mott *et al.*, 1986).

A second zone is distinguished by increasing pollen concentrations and maximum *Picea* percentages (*cf.* "*Picea*" zone, Fig. 14). It corresponds to the regional afforestation after *ca.* 10,000 BP that is marked by the development of spruce forests over southeastern Canada (*cf.* Anderson, 1985).

Above the "*Picea*" zone, the assemblages are characterized by increasing *Pinus* percentages and the significant occurrence of *Abies*, while *Picea* is decreasing. Such a transition is also observed in the palynostratigraphy of southern Québec and Atlantic provinces at about 9000 BP (*e.g.* Anderson, 1980; Mott, 1975, 1977; Richard, 1978). The "*Pinus*" zone (Fig. 14) would correspond to the enrichment of forest cover in southeastern Canada.

The fourth zone is characterized by maximum *Pinus* percentages, minimum herb and shrub percentages and by the significant occurrence of *Tsuga* (*cf.* "*Pinus-Tsuga*" zone, Fig. 14). The base of this zone has an age of about 6000 BP. The "*Pinus-Tsuga*" zone is certainly correlative with the palynostratigraphic *Tsuga* assemblage zone of southeastern Canada

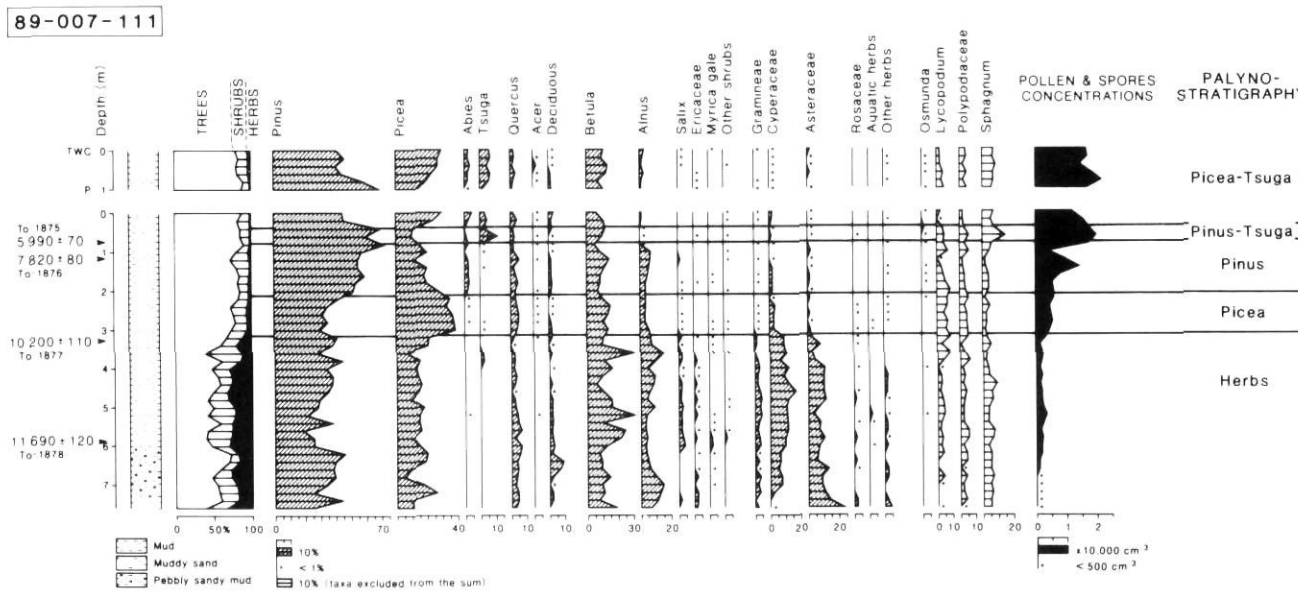

FIGURE 14. Summary diagram of pollen and spore assemblages in core 89-007-111 from Cabot Strait. The palynostratigraphic scheme illustrated in the right margin of the diagram allow correlation with onshore palynostratigraphic trends observed throughout southeastern Canada (*cf.* for ex. Anderson, 1985).

Diagramme résumé des assemblages sporo-polliniques dans la carotte 89-007-111 prélevée sur le détroit de Cabot. La zonation palynostratigraphique illustrée en marge de droite autorise des corrélations avec la palynostratigraphie continentale du sud-est canadien (voir par ex. Anderson, 1985).

(*e.g.* Anderson, 1985), which is commonly associated with the Holocene thermal optimum (*e.g.* COHMAP, 1988).

The upper zone is marked by decreasing *Pinus* percentages concomitant with increased *Picea* percentages ("*Picea-Tsuga*" zone, Fig. 14). This trend might reflect spruce forest development in response to regional climate cooling, as proposed on the basis of the terrestrial palynostratigraphy of southeastern Canada (*e.g.* Anderson, 1985; COHMAP, 1988).

DISCUSSION

The assumption that the dinoflagellate cyst assemblages respond rapidly to environmental changes in surface water as any phytoplankton organisms and constitute ecostratigraphical markers on a regional scale led to direct correlations between the sedimentary sequences recovered in cores 89-007-16, 89-007-021, 89-007-036 and 89-007-111. These correlations are supported by the zonation based on benthic foraminifer assemblages (Vilks *et al.*, 1990) and allow definition of a relatively well constrained stratigraphical scheme on a regional scale (Fig. 15). The dinoflagellate cyst stratigraphy in the Gulf of St. Lawrence shows significant changes in sea-surface salinity related to freshwater outflow, in addition to changes in summer temperature. Because the conditions in the buoyant surface water layer of the Gulf of St. Lawrence are to a large extent controlled by heat exchanges at the water-atmosphere interface (Koutitonsky and Bugden, 1991), sea-surface temperature reconstructions may be used as indicators of regional climates. On these grounds, the comparison of the pollen records with the dinoflagellate cyst ecostratigraphy and the related paleoclimates reconstructions may contribute to a better understanding of the relationship between vegetation dynamics and regional climate changes.

In the Gulf of St. Lawrence, the late-glacial (>10,000 BP) interval corresponds to dinoflagellate cyst ecozone I (Figs. 2-5). Ecozone I is associated with cool subarctic conditions in surface water, while adjacent terrestrial regions were occupied by an open tundra vegetation. This interval was marked by fluctuations in sea-surface temperatures and salinity, in response to climate changes and/or meltwater outflow. An early episode in ecozone I, probably older than 12,000 BP (*cf.* core 89-007-111) and representative of ice proximal conditions, is marked by cold sea-surface temperature (~4°C in August), extensive sea-ice cover (~8 months/yr.) and relatively high salinity (>30‰). This episode was followed by a significant warming (up to 11°C in August) concomitant with a notable dilution in surface water. Cabot Strait that constitute the distal end of the Laurentian Channel experienced low salinities (24-27‰) from about 11,800 BP to 10,000 BP, as a consequence of meltwater discharges from the Laurentide Ice. The upper part of the ecozone I is marked by decreasing summer temperatures (down to 5-7°C; Fig. 10) accompanied by an increased seasonal sea-ice cover. This cooling in surface water had an amplitude of about 3°C and spanned from *ca.* 11,000 to *ca.* 10,500 BP (cf. Figs. 9-10): it apparently corresponds to the Younger Dryas event.

The postglacial interval corresponds to the ecozone II of the dinoflagellate cyst record. The base of this ecozone (*ca.* 10,000 BP) is marked by a sharp change toward cool temperate, conditions in surface water with August temperature and salinity of about 15°C and 30‰ respectively, and seasonal duration of sea-ice averaging 2 months/yr. In terrestrial regions adjacent to the southern part of the Gulf, this transition was accompanied by the afforestation and the development of spruce forests. In the northern part of the Gulf, this transition was closely followed by the migration of coniferous trees and by the development of open forest tundra-type

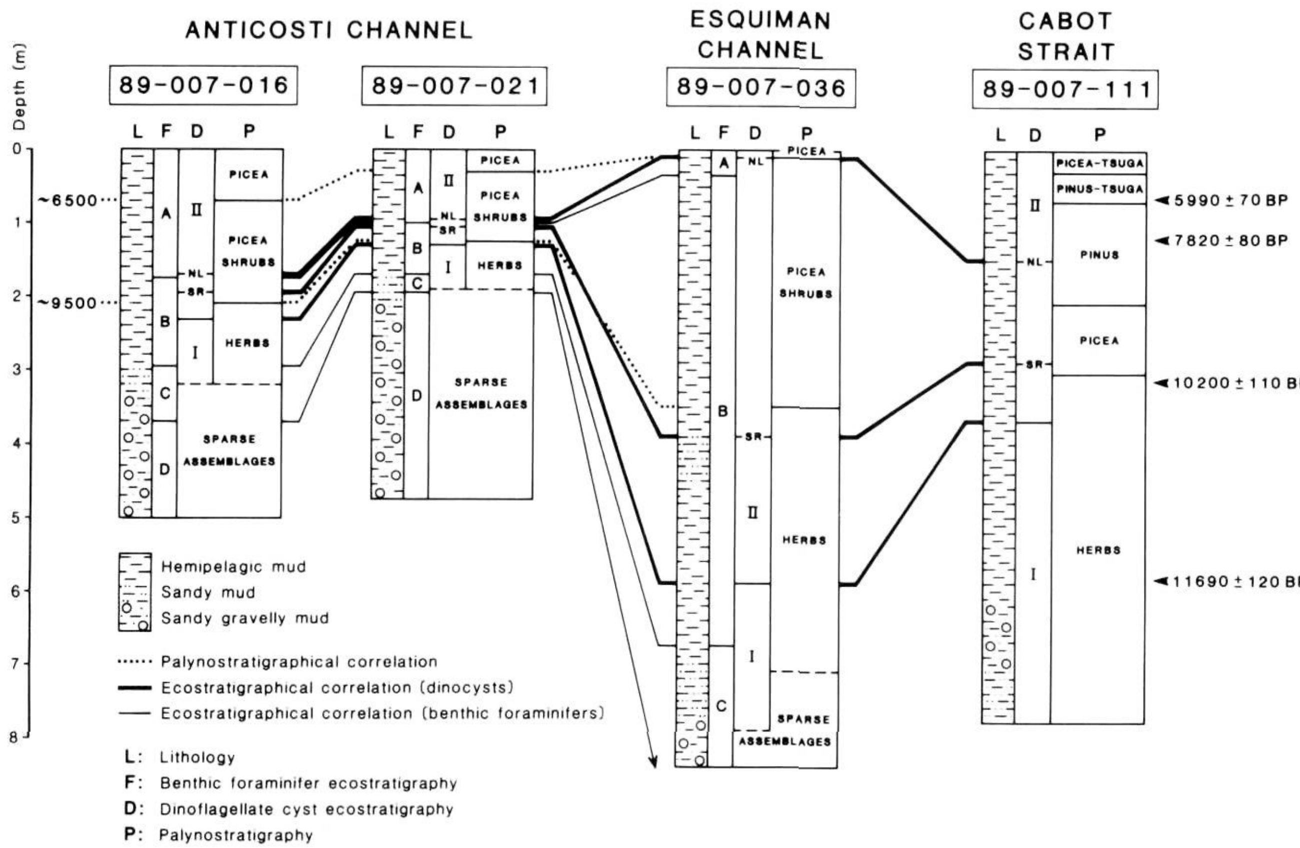

FIGURE 15. Summarized stratigraphy of cores from the Gulf of St. Lawrence and proposed scheme of regional correlations based on ecostratigraphic boundaries. The ages in the right margin of the stratigraphical scheme correspond to AMS-^{14}C dates on gastropods sampled in core 89-007-111; the approximate ages in the left margin of the scheme are from correlations with the onshore palynostratigraphy of the terrestrial region north of the Gulf of St. Lawrence (*cf.* Mott, 1976; Lamb, 1980; Engstrom and Hansen, 1985).

Stratigraphie simplifiée des carottes du golfe du Saint-Laurent et schéma de corrélations régionales s'appuyant sur les transitions écostratigraphiques. Les âges indiqués à droite du schéma stratigraphique sont issus de mesures AMS-^{14}C de gastropodes échantillonnés dans la carotte 89-007-111; les âges approximatifs indiqués à gauche du schéma proviennent de corrélations directes avec la palynostratigraphie continentale des régions adjacentes du nord du golfe du Saint-Laurent (voir Mott, 1976; Lamb, 1980; Engstrom and Hansen, 1985).

vegetation. The development of forest tundra was apparently delayed toward the east, as shown by the palynostratigraphic boundary that occurred later in the Esquiman Channel than in the Anticosti Channel, with reference to the dinoflagellate cyst ecostratigraphy (*cf.* Fig. 15). The time transgressive development of forest tundra from the west to the east can be attributed to tree migration delay (*cf.* also Lamb, 1980).

The establishment of sea-surface conditions similar to the present by about 10,000 BP appears to be a consistent feature throughout the Gulf of St. Lawrence. Sea-surface temperature of about 15°C in August indicates that cool temperate conditions existed by the beginning of the Holocene. However, the development of closed coniferous forests north of the Gulf of St. Lawrence occurred much later, by about 6500 BP, suggesting a delayed response of the regional vegetation to climate changes. The late afforestation may alternatively reflect local "periglacial" conditions on land, which are not recorded in the marine environment because of water mass homogenization. Prior to 7000 BP, the residual ice dome centred on Québec-Labrador may have resulted in catabatic winds, thus responsible for cold and dry climate on land (*cf.* Richard and Labelle, 1988) notably north of the Gulf of St. Lawrence.

On the whole, the Holocene was characterized by sea-surface conditions similar to present throughout the Gulf of St. Lawrence, with only slight fluctuations of reconstructed sea-surface temperatures. In particular, an increase of August temperature in surface water (>16°C) can be identified between about 8000 and 6000 BP in Cabot Strait (Fig. 9), and around 6500 BP in the Anticosti Channel (Fig. 6). Although this warming event is barely observed in the other records (Figs. 7-8), probably because of compressed middle and late Holocene stratigraphy (Fig. 15), it probably constitutes the regional signature of the "hypsithermal" (*e.g.* COHMAP, 1988). This slight warming in surface water coincides with the northward development of closed coniferous forest to the north. It was followed by the significant occurrence of *Tsuga* in pollen assemblages of Cabot Strait.

A tenuous cooling, trend of 1-2°C apparently characterized surface water masses during the late Holocene (Figs. 6 and 9). This cooling might be associated with the slight impoverishment of the forest cover north to the Gulf (*cf.* Lamb, 1980, 1985; Engstrom and Hansen, 1985) and to the decline of *Tsuga* and recurrence of *Picea* in southeastern Canada (*e.g* Anderson, 1985).

CONCLUSION

Palynological analyses in sedimentary sequences from epicontinental basins, such as the Gulf of St. Lawrence, provide two complementary records of proxy-climatic data. The dinoflagellate cyst assemblages relate to regional sea-surface conditions, notably the summer temperature that is primarily controlled by heat exchanges at the water-atmosphere interface. The pollen and spore assemblages originate from the vegetation of adjacent land, which is dependant upon climatic conditions. The palynological results illustrate important changes following the regional deglaciation in both marine and terrestrial environments.

After regional ice retreat, cold conditions with extensive seasonal sea-ice prevailed throughout the Gulf, while adjacent regions were occupied by an open tundra-type vegetation. The outflow of meltwater through the Laurentian Channel resulted in particularly low salinity conditions from about 11,800 to 10,000 BP. A regional cooling in surface water between *ca.* 11,000 and 10,500 BP apparently corresponds to the Younger Dryas event.

The beginning of the Holocene (~10,000 BP) was marked by a significant warming in surface water which led to the development of dinoflagellate populations with abundant Gonyaulacales. This early postglacial warming was accompanied by coniferous tree growth around the Gulf of St. Lawrence. However, there are notable discrepancies between the temperature changes that are recorded in surface water and the rate of forest development in adjacent terrestrial regions. Although sea-surface temperatures rather similar to present prevailed since the early Holocene, closed coniferous forests developed only at about 6500 BP north to the Gulf. Similarly, *Picea* remained the dominant component of the forest vegetation over southern Canada until about 9000 BP, prior to the succession of more diversified forest associations. The forest vegetation appears, therefore, to have been marked by delayed development in response to climate changes, that might be attributed to local constraints on terrestrial climate (*e.g.* catabatic winds) and/or to intrinsic dynamic processes within the forest ecosystem. The lag in response of the vegetation to large scale climate changes might explain the discrepancies between the postglacial pollen data and climate model simulations proposed by COHMAP (1988) for northeastern North America.

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