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Late quaternary paleohydrology of the Gulf of St. Lawrence (Québec, Canada) based on diatom analysis

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Abstract

Postglacial sediments from three cores raised from the Gulf of St. Lawrence along the path of the Laurentian Channel, were analyzed for diatoms. A sequence of four distinct zones was defined from oldest to youngest:

1. Characterized by low diatom concentrations, this zone is mainly represented by heavily silicified species *Delphineis surirella*, *Stephanopyxis turris*, *Coscinodiscus radiatus* and *Paralia ornata* that were probably deposited by glacial drift in a glaciomarine environment from about 18 000 to 14 000 years BP.
2. This postglacial sedimentation zone deposited around 13 000 years BP, is marked by high diatom concentrations with cold-water marine species, *Thalassiosira antarctica* resting spores and *Porosira glacialis*. The upper part of the zone suggests a gradual warming with the appearance of temperate water species, *Bacterosira bathyomphala* and *Chaetoceros* spp., both resting spores and vegetative cells.
3. An important cooling of surface temperatures is noticed by the resurgence of cold species, *Porosira glacialis*, *Thalassiosira antarctica* resting spores and *Thalassiosira hyalina*. This zone is associated with the Younger Dryas chronozone dated from 10 800 to 10 300 years BP. This interval is also characterized by two marked freshwater pulses, coming from the outflow of Laurentide Ice Sheet meltwater, on the surface layer of the Goldthwait Sea. Although well-defined in the northwestern Gulf area (core 90-031-015), the influence of this meltwater decreases considerably or even disappears in Cabot Strait (core 89-007-111) and offshore (core 90-031-044). Evidence of reduced postglacial glacial runoff on surface water supports the conclusion that it could not have generated the Younger Dryas cooling episode.
4. The diatom assemblages from 10 000 years BP through Recent correspond to the progressive establishment of modern-like surface water conditions.

Keywords: diatoms; Gulf of St. Lawrence; Late Quaternary; Laurentide Ice Sheet meltwater; paleohydrology; younger dryas

1. Introduction

The Gulf of St. Lawrence, located in the north-eastern part of North America, is a complex semi-enclosed sea connecting the St. Lawrence River to the North Atlantic Ocean through Cabot Strait, along the Laurentian Channel. Being at the end of the St. Lawrence drainage basin, the Gulf provides great opportunities to study the history of freshwater and meltwater runoff over Eastern Canada, since the last glaciation.

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The evacuation of meltwater through the axis of the St. Lawrence River during the last deglaciation may have played an important role on the paleoceanography of the northwestern North Atlantic. According to Clayton (1983), Drexler et al. (1983) and Teller (1988, 1990), the drainage of proglacial Lake Agassiz is responsible for irregular and episodic runoff through the St. Lawrence River around 11 000 years BP and between 10 000 and 9600 years BP. As suggested by Broecker et al. (1989), such sudden meltwater discharge might have been the cause for a significant dilution of surface water salinity in the northwestern North Atlantic and the resultant decreased production rate of the North Atlantic Deep Water. It was implied that this flooding and capping of the North Atlantic Ocean induced the brief, global cooling of the Younger Dryas.

In order to examine this hypothesis and to evaluate the effect of meltwater discharge into the northwestern North Atlantic, several studies based mainly on foraminifera, pollen and dinoflagellate-cyst assemblages were undertaken (Rodrigues et al., 1993; Rodrigues and Vilks, 1995; de Vernal et al., 1996). Those studies showed a reduced influence of the meltwater in deep, intermediate and surface waters of the Gulf.

The hydrographical changes in the Gulf of St. Lawrence are documented during the course of the deglaciation and into the Holocene, based on diatom assemblages. Diatoms were successfully used as paleoceanic indicators in many studies, such as in the Atlantic sector of the Southern Ocean (Pichon et al., 1987; Zielinski, 1993), the North Atlantic (Koç Karpuz and Jansen, 1992; Koç et al., 1993), and the Arctic Seas (Polyakova, 1997). Furthermore, a previous analysis on surface sediments demonstrated that diatom assemblages allow the characterization of surface hydrographic conditions in the Gulf of St. Lawrence (Lapointe, 1998).

The main objectives of this research are (1) to define diatom zonations in postglacial sediments from three cores located along the path of the Laurentian Channel and (2) to define diatom paleohydrographic signals during the deglacial history of the Gulf of St. Lawrence, with a particular focus on surface water impact from the Laurentide Ice Sheet meltwater runoff, around the Younger Dryas period.

2. Studied area

The Gulf of St. Lawrence (Fig. 1) is a shallow submerged lowland shelf of Paleozoic sedimentary rocks, surrounded by Appalachian and Grenvillian orogenic uplands. Major physiographic features of the Gulf are outlined by central submarine troughs: the Laurentian Channel along with its tributaries, the Anticosti Channel and the northeastern Esquiman Channel (Piper et al., 1990). It is believed that this linear network is a result of glacial erosion modifying an older erosional path of a fluvial drainage system dating from late Cretaceous to early Tertiary (King and MacLean, 1970). Glacial erosion was developed along the contact between lower and upper Paleozoic strata (Loring and Nota, 1973).

Late Quaternary marine geology of the region was studied and synthesized by many authors (Dyke and Prest, 1987; Syvitski and Praeg, 1989; Piper et al., 1990; Piper, 1991; Zevenhuizen and Josenhans, 1992). From these papers, a general history of the late Wisconsinan Laurentide Ice Sheet retreat, based on radiocarbon years, can be summarized as follows:

1. The maximum extension of the Laurentide Ice Sheet was dated around 18 000 years BP (Fig. 2a);
2. The Laurentide Ice Sheet receded from its maximum position around 14 500 years BP;
3. Retreat of the ice sheet margin along the coast, was principally done by iceberg calving and started around 14 000 years BP. Initial retreat of the ice began while sea level was locally much higher than today, due to the isostatic depression which formed the Goldthwait Sea (Fig. 2b);
4. Retreat of a Laurentidian ice barrier near Québec City by 12 000 years BP, led to the marine transgression of the St. Lawrence Lowland and formed the Champlain Sea (Fig. 2b) (Parent and Occhietti, 1988; Rodrigues, 1992);
5. Overflow of episodic runoff (glacial drainage meltwater and precipitation) from proglacial

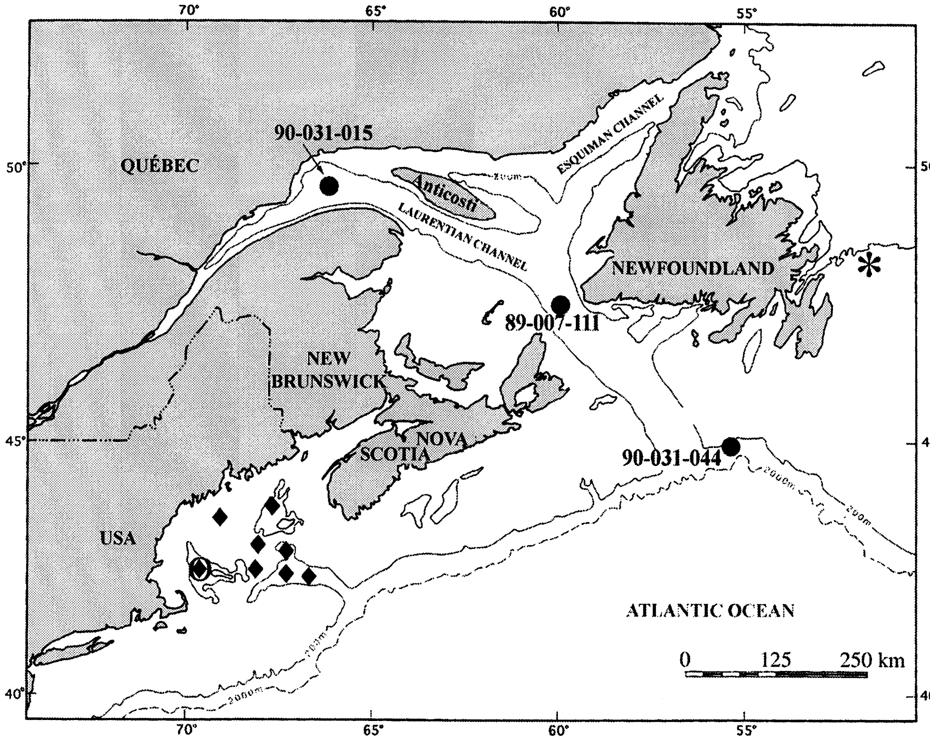

Fig. 1. Coring site locations: ●: this study; *: Palmer (1984); ◆ Popek (1993).

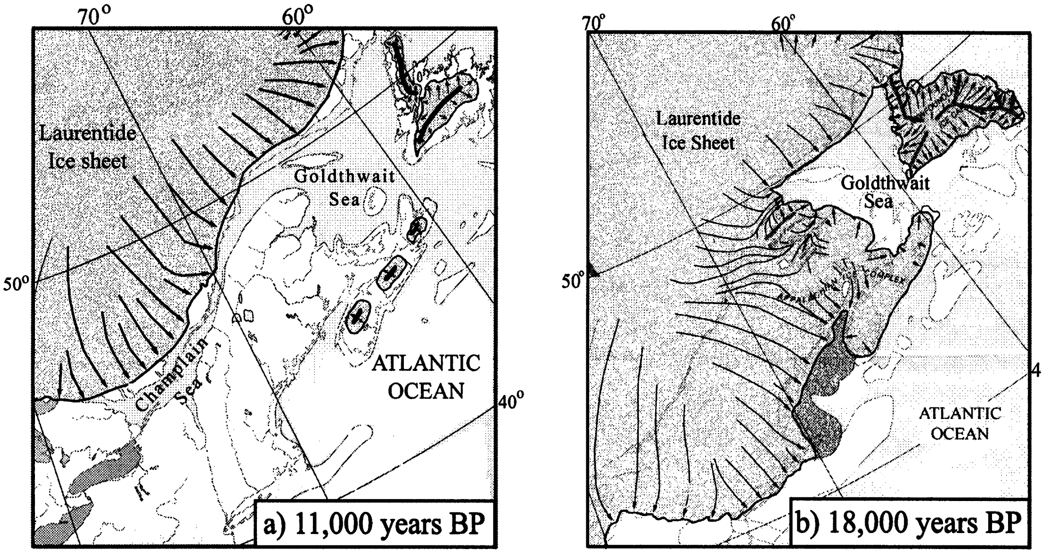

Fig. 2. Limits of the Laurentide Ice Sheet and proglacial Champlain and Goldthwait Seas: (a) 11 000 years BP and (b) 18 000 years BP [based on Dyke and Prest (1987)].

Lake Agassiz and the Great Lakes through the St. Lawrence drainage basin and the Goldthwait Sea were dated around 11 000 years BP, and 10 000–9600 years BP (Clayton, 1983; Drexler et al., 1983; Teller, 1988, 1990). During the same interval, a brief and important cooling event related to the Younger Dryas period (Mercer, 1969), was reported in Eastern Canada, for instance in Nova Scotia and New Brunswick (Mott et al., 1986) and in Gaspésie (Marcoux and Richard, 1995).

6. Between 10 000 and about 6 000 years BP, the modern marine conditions were gradually established.

Regional marine stratigraphy of the unconsolidated Quaternary sediments of the Gulf of St. Lawrence, based on seismic surveys, showed five major units overlying a sedimentary or crystalline bedrock (Syvitski and Praeg, 1989; Josenhans et al., 1990; Vilks et al., 1990). Unit 1 corresponds to a grounded glacial ice environment with ice-contact sedimentation, Unit 2 contains ice-proximal sediments, while the ice-distal sedimentation are included in Unit 3. Unit 4 is comprised of paraglacial deltaic sediments, and finally, Unit 5 represents the postglacial sequence.

3. Material and methods

A total of 152 samples were analyzed from three piston cores located along the Laurentian Channel: (1) in the Northwest Gulf, core 90-031-015, 49°25.42′ N, 66°19.45′ W, (2) in Cabot Strait, core 89-007-111, 47°31.00′ N, 59°53.06′ W, and (3) in the Northwest North Atlantic, core 90-031-044, 44°39.41′ N, 55°37.13′ W (Fig. 1).

The cored sediments consist principally of sandy and gravely mud overlain by hemipelagic mud. They correspond to seismic units 2 and 5, which are, respectively, associated with a glaciomarine environment and postglacial sedimentation. Further sedimentological descriptions (sediment texture and color) and seismic survey data are reported in Vilks et al. (1990) and Zevenhuisen and Josenhans (1992) for *Dawson* cruise core 89-007-111, in the preliminary report of onboard studies of the *Hudson* cruise 90-031 for core 90-031-044 (GÉOTOP, Université du Québec à Montréal, unpublished) and in Rodrigues et al. (1993) for core 90-031-015.

Diatom subsamples were taken in 10–30 cm intervals. One gram of dry sediment was chemically treated to clean and concentrate diatoms content. Concentrated HCl (10%) was added to remove calcium carbonate, and organic matter was oxidized using concentrated hydrogen peroxide H_2O_2 (30%). The sample was sieved using a 10 μm sieve to separate fine silt and clay. Both fractions (smaller and larger than 10 μm) were diluted in 25 ml of distilled water, and an average of, respectively, 0.2 and 0.5 ml were mounted for microscopic analysis on glass slides, using Hyrax as embedding medium. A light microscope (Leitz Aristoplan) with phase contrast and a magnification of up to 1600 × was used for the diatom identification of the fraction larger than 10 μm. The finer fraction was used for testing the efficiency of the sieving procedure, by searching for the presence of small species. For each sample, a minimum of 300 valves were counted along random transect lines of known surface area. The transect count was extrapolated to the total surface area of a known volume. Thus, the total number of valves per gram could be calculated.

Even though all preserved diatoms were counted, only summary diagrams of percentages are presented herein. Both the resting spores and the vegetative cells were included in the computation of diatom percentages and concentrations. Resultant diatom concentrations are given in number of valves or frustules per gram of dry sediment.

Core dating is by ^{14}C-AMS (accelerator mass spectrometry) based on gastropod shells for core 89-007-111 (de Vernal et al., 1993) and on foraminifera *Neogloboquadrina pachyderma* left coiling for core 90-031-044 (de Vernal et al., 1996). Ages were corrected by −400 years to account for the apparent age of dissolved inorganic carbon in high-latitude surface waters of the North Atlantic (Bard, 1988). The whole sedimentary sequence represents approximately the last 13 000 years.

3.1. Taxonomic note

Species identifications were based primarily on Cleve-Euler (1968: reprint of 1951–1955), Hendey

(1964), Germain (1981), Hustedt (1927–1933, 1937, 1959, 1976) (reprint of 1930), Patrick and Reimer (1966, 1975), Van Heurck (1981) (reprint of 1885), and Hartley et al. (1996). Details and further information about methodology, species description, illustration and taxonomy can be found in Lapointe (1998).

Thalassiosira antarctica resting spores could be easily confused with *Thalassiosira gravida*. According to Syvertsen (1979), the difference lies in part in the number of areolae in 10 μm, which is 10–14 for *T. antarctica* resting spores and about 20 for *T. gravida*. However, only *Thalassiosira antarctica* has produced resting spores in cultural experiments. To avoid confusion, although, in the literature of the area, *Thalassiosira gravida* is used (Jorgensen, 1984; Palmer, 1984; Williams, 1988, 1990; Schnitker and Jorgensen, 1990; Popek, 1993), herein, this morphological form was identified as the resting spores of *Thalassiosira antarctica*.

4. Diatom results and interpretation

4.1. Core 90-031-015: Northwestern Gulf

Core 90-031-015 is 10.7 m long and was taken in 322 m water depth. Sediments consist of dark gray to gray, silt- and clay-mud, from 0 to 6 m, dark gray clay-mud with sand, granules and gravels, from 6 to 7.5 m, and dark gray clay-mud from 7.5 to 10 m (preliminary report of the *Hudson* cruise 90-031, GÉOTOP, Université du Québec à Montréal, unpublished).

Located in the northwestern Gulf, this core lies within an area of very thin Late Quaternary sediment, where accumulation rates were about 0.1 cm/year or 100 cm/kyr (Syvitski, 1993). Modern surface circulation is dominated by the Anticosti Gyre, a stable anticlockwise circulation, and in the south part by Gaspé Current, which consists of freshwater runoff from the St. Lawrence River (Trites, 1971; Steven, 1974; El-Sabh, 1976). Modern surface conditions are characterized by mean summer temperatures of 11–12°C and salinities of 28–29‰.

A total of 107 samples were analyzed, and 94 diatom species in 37 genera were identified. Diatom preservation was generally very good, except from 8 to 10 m, where the core was barren. The mean diatom concentration was 1.7×10^5 with a median value of 1.4×10^5 and a maximum of 1.8×10^6 frustules/g. Four ecostratigraphic zones were defined, based on diatom abundance and the compositon of dominant species (Fig. 3).

4.1.1. Core 90-031-015, Zone 1 (≈780–1060 cm)

This zone consists of generally barren samples. Only rare, poorly preserved, heavily silicified and unidentifiable diatom valves were found in this interval. They were probably transported and deposited by glacial ice. The low number of diatoms and the highly detrital nature of the sediments suggest that it was deposited in a glaciomarine environment, perhaps under a cover of floating ice through much of the year.

4.1.2. Core 90-015-015, Zone 2 (≈440–780 cm)

This zone is defined by the following diatom assemblage: *Thalassiosira antarctica* resting spores, *Coscinodiscus curvatulus*, *Actinocyclus ehrenbergii*, *Thalassiothrix longissima*, and *Thalassiosira leptopus*. These species are characteristic of cold to temperate marine waters (Lohman, 1941; Williams, 1988, 1990).

There is a gradual warming upward in this zone suggested by the increase of *Thalassiosira* cf. *eccentrica*, *Nitzschia* aff. *arctica*, *Coscinodiscus asteromphalus*, *Coscinodiscus oculus-iridis*, *Chaetoceros* spp., *Chaetoceros* spp. resting spores, *Bacterosira bathyomphala* resting spores, *Thalassionema nitzschioides* and *Coscinodiscus divisus*. Amongst others, *Thalassionema nitzschioides* was described by Hendey (1964) as a cosmopolitan neritic and marine species living in temperate to cold water, such as in the North Atlantic and the North Sea.

This zone was separated in two parts, 2a and 2b, based on the diatom concentrations. The lower part 2a is characterized by the only major peak in diatom concentrations, with 1.8×10^6 frustules/g, while the mean concentration for subzone 2b is about 3×10^5 frustules/g.

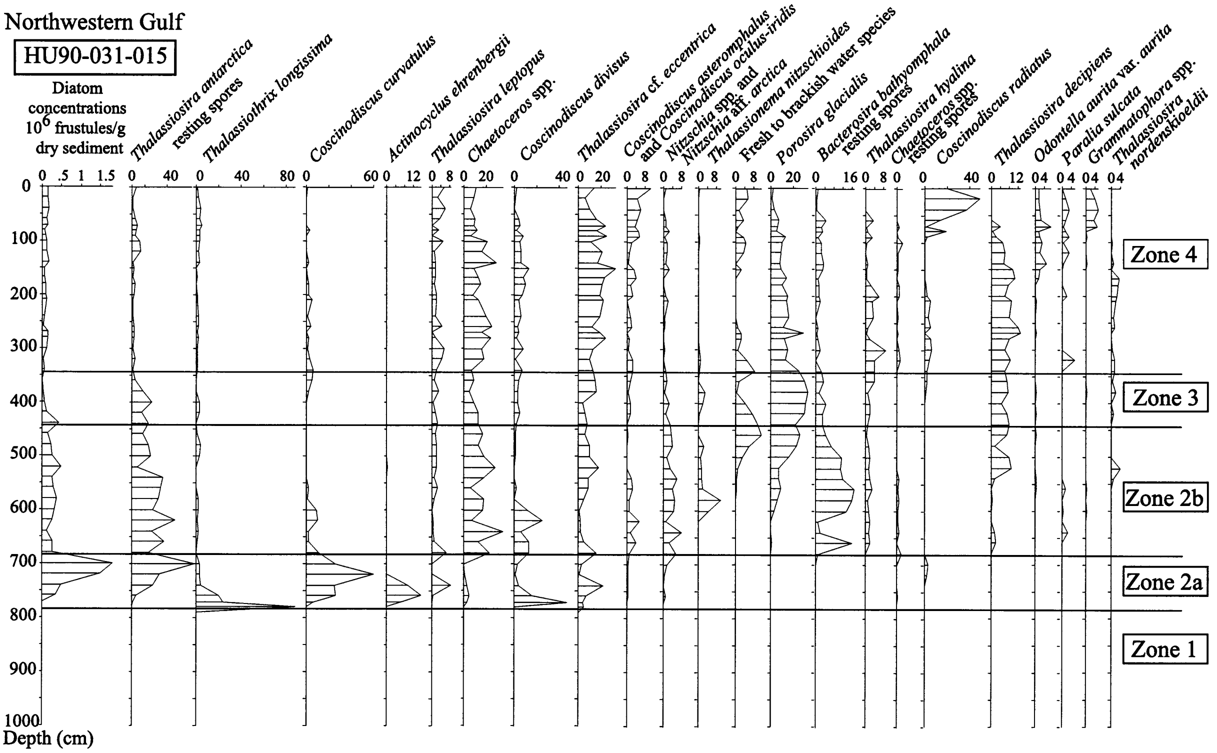

Fig. 3. Summarized diagram of diatom concentrations and species percentages from core 90-031-015. Zone 1: glaciomarine environment; Zone 2a: early Postglacial; Zone 2b: later Postglacial; Zone 3: Younger Dryas; Zone 4: Holocene and modern environments.

4.1.3. Core 90-031-015, Zone 3 (≈340–440 cm)

This zone is marked by the maximum abundance of *Porosira glacialis*, a cold-water species associated with ice (Carey, 1985). There is also a general decrease in concentrations for most species, with values as low as 24×10^3 frustules/g and the disappearance of others, such as *Chaetoceros* spp. resting spores.

This zone is delineated at the base and top by two small, but distinct, peaks of fresh and brackish water species such as *Cyclotella meneghiniana*, *Cyclotella bodanica* var. *affinis*, *Cyclotella astrea*, *Aulacoseira* spp. (such as *A. distans*, *A.* cf. *granulata*, *A. italica*, and *A. islandica*), *Tabularia* spp., *Stephanodiscus hantzschii* and *Tabellaria flocculosa* var. *linearis*. *Thalassiosira decipiens*, which is often found in waters with variable salinity such as great inland seas, estuaries, bays, shallow coastal waters and rivers influenced by the tide (Hasle, 1979), is also very common.

The whole diatom assemblage reveals particularly cold conditions with brief variations in surface salinity of the Goldthwait Sea, which coincides with the Younger Dryas chronozone.

4.1.4. Core 90-031-015, Zone 4 (≈0–340 cm)

This zone is marked by a major decreasing abundance of *Thalassiosira antarctica* resting spores and the recurrence of *Chaetoceros* spp. resting spores. Diatom concentrations remain relatively low throughout the zone with more or less 1.5×10^5 frustules/g. The other major species are characteristic of modern epicontinental marine and cold water conditions with *Thalassiosira* cf. *eccentrica*, *Thalassiosira hyalina*, *Chaetoceros* spp., *Coscinodiscus asteromphalus*, *Coscinodiscus oculus-iridis*, *Coscinodiscus radiatus*, *Odontella aurita* var. *aurita*, *Paralia sulcata*, *Grammatophora* spp., *Thalassiosira nordenskioeldii*, and *Thalassiosira leptopus*. A possible minor reduction in surface salinity is evident by the presence of *Thalassiosira decipiens*.

4.2. Core 89-007-111: Cabot Strait

Core 89-007-111, located in Cabot Strait, is 7.8 m long and was taken at a water depth of 503 m. Cabot Strait constitutes the end of the St. Lawrence system, and the surface circulation is characterized by a general two-way flow (1) outward flow from the Gulf of St. Lawrence and (2) inward flow from the northwest North Atlantic (Trites, 1971; El-Sabh, 1976).

The principal target of diatom analysis for this core was to focus on the Younger Dryas chronozone and to correlate it with the other two cores. Since the interval 3.8–4.8 m was identified previously by de Vernal et al. (1993) as the interval of the Younger Dryas episode, a total of 16 samples were taken between 2.8 and 7.3 m in the core. Sediments consist of gray, silt- to clay-mud overlying a dark gray clay-mud with sand and gravel layers. The apparent sedimentation rate for this core during deglaciation is around 170 cm/kyr (de Vernal et al., 1996).

Diatom preservation was generally very good with 57 diatom species and 22 genera identified. The mean diatom concentration is 4.9×10^5 with a median value of 3.4×10^5 and a maximum of 2.1×10^6 frustules/g. Three ecostratigraphic zones were defined, based on diatom abundance and the dominant species (Fig. 4).

4.2.1. Core 89-007-111, Zone 2 (≈460–730 cm)

The base of this zone is marked by higher concentrations of *Thalassiosira decipiens*, *Thalassiosira antarctica* resting spores and *Porosira glacialis* (at depths of 650–730 cm), which refer to a cold marine environment. *T. antarctica* resting spores gradually decrease and *P. glacialis* disappears, while marine temperate diatom assemblages develop, with the increasing abundance of vegetative cells and resting spores of both *Bacterosira bathyomphala* and *Chaetoceros* spp., *Thalassiosira* cf. *eccentrica* and *Paralia sulcata*. Such assemblages reveal a gradual warming from the base to the upper part of the zone.

4.2.2. Core 89-007-111, Zone 3 (≈400–460 cm)

For a brief period, percentages of temperate marine species of this zone, such as *Thalassiosira* cf. *eccentrica*, decreased significantly, even to the vanishing point for both vegetative cells and resting spores of *Bacterosira bathyomphala* and for the resting spores of *Chaetoceros* species. In the same interval, there is a decrease in relative abundance of *Paralia sulcata* toward the top of zone 3 and a brief recurrence of *Porosira glacialis*. These assemblages suggest a significant cooling of the surface water, which coincides with the Younger Dryas chronozone. However, persistence, and even a modest increase in *Thalassiosira decipiens* abundance, could be a reflection of variation in surface salinity.

4.2.3. Core 89-007-111, Zone 4 (≈280–400 cm)

This zone is characterized by a peak in diatom concentrations of more than 2×10^6 frustules/g. It is also marked by the recurrence of *Chaetoceros* resting spores and *Bacterosira bathyomphala* (both vegetative cells and resting spores) and the high abundance of *Chaetoceros* spp., *Coscinodiscus divisus*, *Paralia sulcata* and *Thalassiothrix longissima*. Such an assemblage represents the establishment of marine and temperate-boreal conditions, similar to the modern setting.

4.3. Core 90-031-044: Northwest North Atlantic

Core 90-031-044, located on the continental slope, is 9.41 m long and was taken at a water depth of 1381 m. Sediments consist of dark gray to greenish gray clay-mud overlying a dark gray clay-mud section with scattered granules. Postglacial apparent sedimentation rate for this core is of the magnitude of 90 cm/kyr (de Vernal et al., 1996). Modern surface circulation in the area is influenced by both the cold arctic Labrador current and the temperate water of the North Atlantic (Trites, 1971; El-Sabh, 1976), with a mean summer temperature of 12–14°C and a salinity of 31–32‰.

Ninety-three samples were analyzed, and 94 diatom species within 35 genera were identified. Diatom preservation was in general good, except for the interval of Zone 1 (from 5 m to the bottom

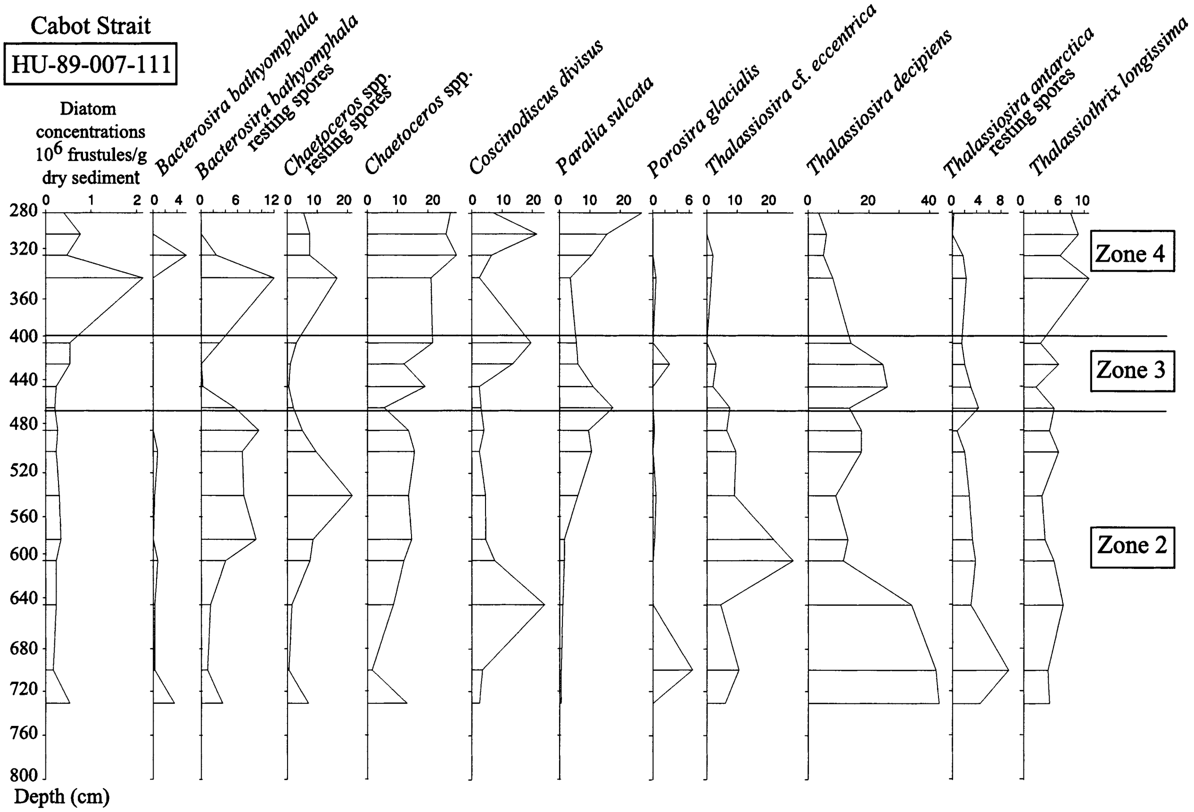

Fig. 4. Summarized diagram of diatom concentrations and species percentages from core 89-007-111. Zone 2: early Postglacial sedimentation; Zone 3: Younger Dryas; Zone 4: Holocene and modern environments.

of the core), where even the heavily silicified diatom species were broken. The mean diatom concentration was 2.5×10^5 with a median value of 1.8×10^5 and a maximum of 1.3×10^6 frustules/g. Four ecostratigraphic zones were defined, based on the diatom abundance and the assemblage of the dominant species (Fig. 5).

4.3.1. Core 90-031-044, Zone 1 ($\approx$500–941 cm)

This zone is marked by low diatom concentrations of about 1×10^5 frustules/g and poor preservation. The dominant species are *Delphineis surirella*, *Stephanopyxis turris*, *Coscinodiscus curvatulus*, *Coscinodiscus radiatus*, *Hyalodiscus scoticus*, *Thalassiosira* cf. *eccentrica* and *Paralia ornata*, which are all heavily silicified diatoms. Moreover, *D. surirella* has a long geological history and is known from deposits as old as middle Miocene (Andrews, 1981). This assemblage may have been transported and deposited by glacial ice in a glaciomarine environment. It could originate from either older Quaternary deposits of the Gulf of St. Lawrence or from the older Cenozoic geological strata of the Arctic. The latter of the two is most likely because the site is located along the path of icebergs coming from the Arctic and *D. surirella* was not encountered in the other cores of this study.

4.3.2. Core 90-031-044, Zone 2 ($\approx$270–500 cm)

This zone is characterized by an important increase in diatom concentrations with values $>6 \times 10^5$ frustules/g, and by the dominance of cold marine species *Odontella aurita* var. *aurita*, *Thalassiosira antarctica* resting spores, *Thalassiosira* cf. *eccentrica* and *Coscinodiscus curvatulus*, overlain by more temperate water associated species *Rhizosolenia* spp. (*Rhizosolenia borealis*, *Rhizosolenia hebetata* f. *hebetata* and *Rhizosolenia*

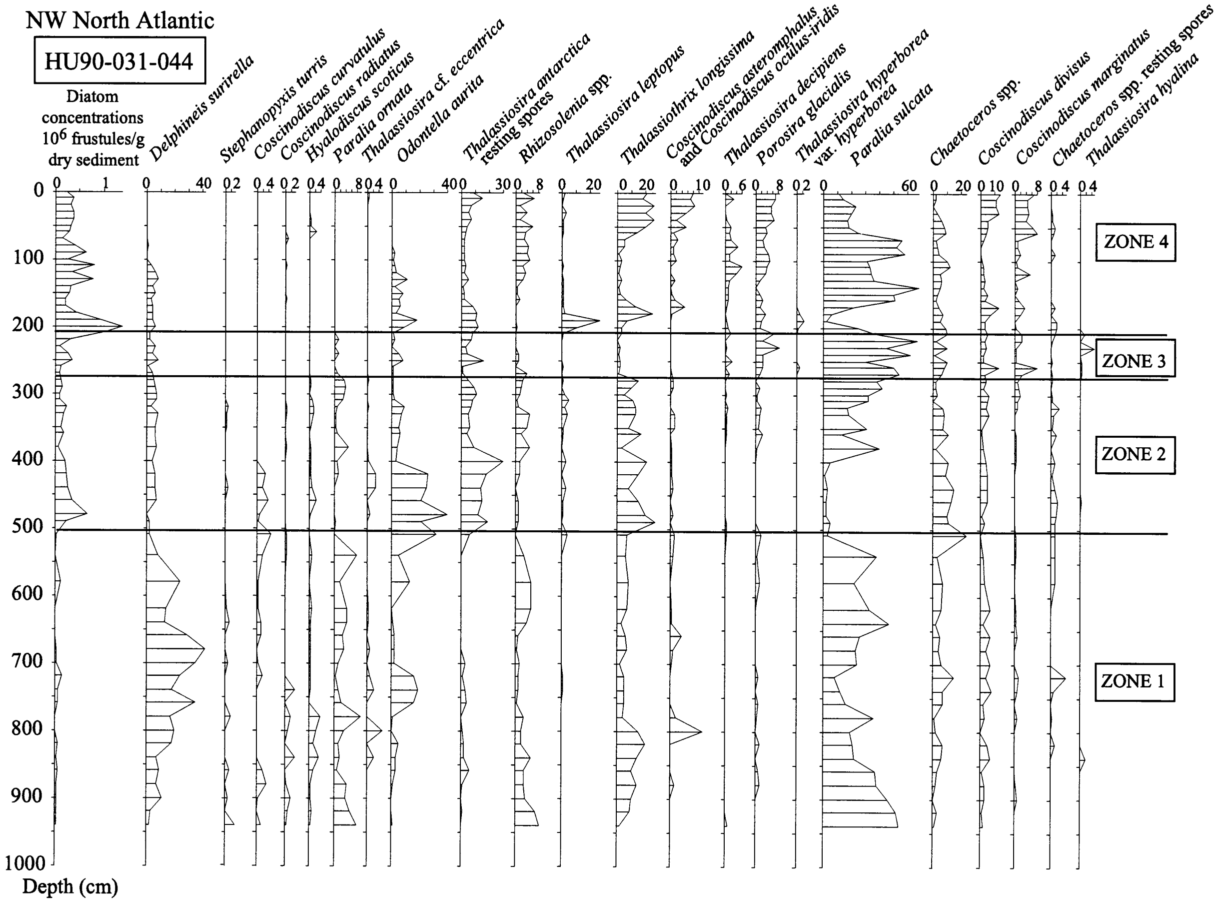

Fig. 5. Summarized diagram of diatom concentrations and species percentages from core 90-031-044. Zone 1: glaciomarine environment; Zone 2: early Postglacial sedimentation; Zone 3: Younger Dryas; Zone 4: Holocene and modern environments.

styliformis), *Thalassiothrix longissima*, *Actinocyclus* spp., *Coscinodiscus divisus* and *Chaetoceros* spp. (both vegetative cells and resting spores). This zone corresponds to a gradual improvement in sea-surface conditions, which suggests a higher availability of light to support the photosynthesis. Diatom assemblage succession in this interval shows a gradual gradient core warming.

4.3.3. Core 90-031-044, Zone 3 (≈210–270 cm)

A general low diatom concentration with a minimum value of 9.5×10^4 frustules/g and a significant diminution of species number are distinctive of this zone. It is also characterized by the disappearance of *Coscinodiscus asteromphalus*, *Coscinodiscus oculus-iridis* and *Thalassiosira leptopus* and by an important reduction in *Thalassiothrix longissima*, *Odontella aurita* var. *aurita*, *Rhizosolenia* spp. and *Chaetoreros* spp. resting spores.

Furthermore, the assemblages are dominated by the resting spores of *Thalassiosira antarctica* and *Paralia sulcata*, by an important peak of *Porosira glacialis*, *Coscinodiscus divisus*, *Coscinodiscus marginatus* and *Thalassiosira hyalina*, and by the omnipresence of *Chaetoceros* spp. and *Thalassiosira decipiens*. *Thalassiosira hyperborea* appears in two minor, but distinct, peaks bordering this zone. This species appears most frequently in marine areas influenced by rivers, and its habitat is associated with sea ice (Hasle and Lange, 1989).

Low diatom concentrations, disappearance of temperate water species and increased importance of cold and sea-ice associated species suggest a brief cooling period related to the Younger Dryas for this zone. The emergence of *Thalassiosira hyperborea* together with the presence of *Thalassiosira decipiens* could indicate a minor freshening of surface salinity.

Core 90-031-044, Zone 4 (≈0–210 cm): the beginning of zone 4 is marked by the most important diatom concentrations peak in the core with more than 1×10^6 frustules/g. Further up, concentrations fluctuate to finally stabilize with values around 3×10^5 frustules/g. The most abundant species are *Paralia sulcata*, *Thalassiothrix longissima*, *Chaetoceros* spp., *Coscinodiscus asteromphalus*, *Coscinodiscus divisus*, *Coscinodiscus oculus-iridis*, *Thalassiosira decipiens*, *Porosira glacialis*, *Chaetoceros* spp. and *Coscinodiscus marginatus*. Diatom assemblages of this zone indicate a gradual establishment of modern-like marine conditions.

5. Discussion

The biostratigraphic analysis of three cores located along the Laurentian Channel in the Gulf of St. Lawrence allow the definition of four ecostratigraphic zones based on diatom assemblage results. Although the diatom assemblages were in part dissimilar for the three cores, they infer concomitant changes in paleoenvironmental conditions, which lead to the late Quaternary paleohydrology evolution of the Gulf of St. Lawrence: (Zone 1) glaciomarine environment (Zone 2) early postglacial sedimentation (Zone 3) Younger Dryas and (Zone 4) modern environment.

A comparative regional ecostratigraphy of herein analyzed piston cores and published information on foraminifera (Rodrigues et al., 1993) and dinoflagellate cysts (de Vernal et al., 1993, 1996) is given in Fig. 6.

5.1. Deglaciation history of the Gulf of St. Lawrence

Postglacial diatom analysis of the area defined a succession of distinct assemblages suggesting four main paleohydrologic phases.

5.1.1. Glaciomarine environment (diatom zone 1)

Characterized by low diatom concentrations, this zone is mainly represented by heavily silicified species *Delphineis surirella*, *Stephanopyxis turris*, *Coscinodiscus radiatus* and *Paralia ornata* that were probably deposited by glacial drift in a glaciomarine environment from about 14 000 to 18 000 years BP. It also correlates with foraminiferal zone GS1A (GS: Goldthwait Sea) of core 90-031-015 (Rodrigues et al., 1993) and with the lower part of dinoflagellate cysts ecozone I of core 90-031-044 (de Vernal et al., 1993). All foraminiferal, palynological, dinoflagellate cyst and diatom assemblages relate to a glaciomarine depositional environment.

This period is synchronous with the active ice calving margin of the Gulf of Maine in a cold Atlantic water environment (see studied site locations, Fig. 1). Described as a deposition layer below a floating ice shelf by Jorgensen (1984) and Schnitker and Jorgensen (1990), it was also associated with a ‘Transitional Glacial Marine’ facies by Popek (1993).

5.1.2. Early postglacial sedimentation (diatom zones 2, 2a–b)

This zone, dated about 13 000 years BP, is marked by high diatom concentrations with cold-water marine species, *Thalassiosira antarctica* resting spores and *Porosira glacialis*. The upper part of this zone suggests a gradual warming gradient with the appearance of temperate-water species, *Bacterosira bathyomphala* and *Chaetoceros* spp., both resting spores and vegetative cells, as well as a higher availability of light to support the photosynthesis. In cores 89-007-111 and 90-031-044, it corresponds, respectively, to dinoflagellate cysts ecozone I and to the upper part of ecozone Ia (de Vernal et al., 1993), which relate to a glaciomarine and early postglacial sedimentation with a low salinity and cold temperature in surface waters (de Vernal et al., 1993).

Similar diatom assemblages (Distal glacial-marine facies) were described in the Gulf of Maine (Popek, 1993) and dated between 13 400 and 12 000 years BP. This facies, divided into lower and upper parts, was interpreted by the author as being an ice shelf edge environment, dominated by *Thalassiosira gravida* (identified herein as

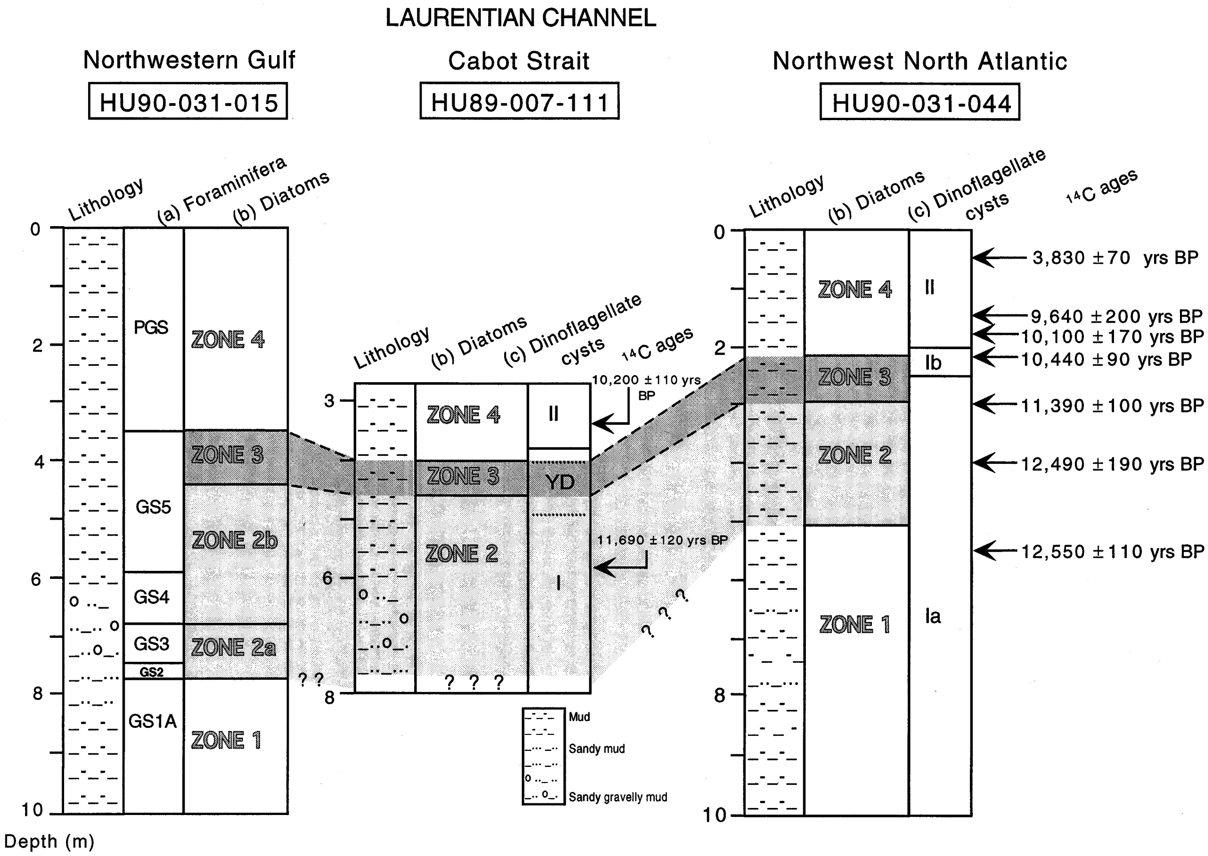

Fig. 6. Summarized ecostratigraphy for cores from the Gulf of St. Lawrence and proposed scheme of regional correlation (shaded areas), based on diatom analysis: (a) Foraminifera (deep and intermediate waters), based on Rodrigues et al. (1993), GS: Goldthwait Sea, GS1A: glaciomarine, 0°C and <20‰, GS2: 3°C and ~35‰, GS3: <3°C and 33.5–34.5‰, GS4: <3°C and 30–33‰, GS5: 3–4°C and 33.5–34.5‰, PGS: Post Goldthwait Sea, 4–6°C and 34.5–34.9‰ (b) Diatom zonations, this study, 1: glaciomarine environment, 2a: early postglacial, 2b: later postglacial, 3: Younger Dryas, 4: modern environment, and (c) Dinoflagellate cysts based on de Vernal et al. (1993) for core 89-007-111 and de Vernal et al. (1996) for core 90-031-044, I and Ia: glaciomarine and early postglacial sedimentation, Ib: Younger Dryas (YD), II: later postglacial. Cores 89-007-111 and 90-031-044 ages are AMS-^{14}C dates and were respectively measured on gastropod shells (de Vernal et al., 1993) and foraminifera *Neogloboquadrina pachyderma* left coiling (de Vernal et al. (1996). The ages were corrected by −400 years to account for the apparent age of dissolved inorganic carbon in high-latitude surface waters of the North Atlantic (Bard, 1988).

Thalassiosira antarctica resting spores) followed by boreal conditions with moderate to thin winter ice and ice-free conditions in spring and summer, as suggested by high concentrations of *Chaetoceros* spp.

In the northwestern Gulf, core 90-031-015, this zone is subdivided into two parts, based on diatom concentrations:

1. Subzone 2a (early postglacial sedimentation) is characterized by a peak in diatom concentrations, which suggests establishment of favorable surface water conditions for diatom growth, such as a higher light intensity and nutrient concentrations and/or shorter seasonal ice cover. Significant peaks in diatom concentrations were also found in core sediments of the Gulf of Maine and were interpreted as being the result of vigorous upwelling caused by strong katabatic winds blowing off the Laurentide Ice Sheet (Popek, 1993). This sub-

zone corresponds to the foraminiferal zones GS2 and GS3 dated around 13 500 years BP (Rodrigues et al., 1993), which are associated with a salinity decrease for deep and intermediate waters.

2. Subzone 2b (later postglacial sedimentation) is marked by sudden and major drop in diatom concentrations, from almost 2×10^6 down to 2×10^5 frustules/g, which represents about 70% fewer frustules. This event could a priori mean an important decrease in surface primary production due, for example, to increased turbid meltwater or to a brief readvance of Laurentide ice lobe, as suggested in the Gulf of Maine by Popek (1993). However, as Anderson (1990) pointed out, it is important to take into consideration the whole variability of diatom concentrations in view of sediment accumulation rates. In a small lake basin, Anderson (1990) demonstrated an inverse linear relationship between diatom concentration and linear sediment accumulation rate. A higher sediment accumulation rate corresponds to a diluted diatom concentration, without important changes in surface production.

Unfortunately, for core 90-031-015, no measurement is available regarding a variation in paleosedimentation rates, although, visual recognition of diluted samples and microscopic analysis showed increased sand and gravel components (more quartz and minerals fragments). However, this event coincides with the breakdown of sea ice around Québec City and the marine transgression that led to the formation of the Champlain Sea (Parent and Occhietti, 1988), opening a passage for more sediments to the site. These observations suggest a variation in the diatom concentration for that period reflecting a dilution caused by higher sediment accumulation rates instead of being an indication of the variation in surface production.

Diatom subzone 2b corresponds to the relatively low-salinity foraminireral zone GS4, dated approximately 12 000 years BP and part of transitional zone GS5 (Rodrigues et al., 1993).

5.1.3. *Younger dryas episode (diatom zone 3)*

This zone represents an important cooling of surface temperatures, as noticed by the resurgence of cold-water species, *Porosira glacialis*, *Thalassiosira antarctica* resting spores and *Thalassiosira hyalina* and an associated decrease in diatom concentrations and species diversity. Dated approximately 10 800–10 300 years BP, it is related to the Younger Dryas chronozone and coincides with dinoflagellate cysts ecozone Ib of de Vernal et al. (1996).

In the northwestern Gulf, core 90-031-015, the whole diatom assemblage suggests a cold period related to the Younger Dryas, with brief variations in surface salinity of the Goldthwait Sea, caused by two successive small, but distinct, peaks of fresh and brackish water species such as *Cyclotella meneghiniana, Aulacoseira distans*, *Aulacoseira italica* and *Tabellaria flocculosa* var. *linearis*. These events could be related to the meltwater pulses coming from the retreating Laurentide Ice Sheet through the drainage of proglacial Lake Agassiz and the St. Lawrence River, as recorded by Clayton (1983), Drexler et al. (1983) and Teller (1988, 1990).

This interval is associated with the upper part of foraminiferal zone GS5 (Rodrigues et al., 1993). Zone GS5 is interpreted as a transition between low-salinity zone GS4 and marine post-Goldthwait Sea interval (PGS). Rodrigues et al. (1993) and Rodrigues and Vilks (1995) reported that the foraminifera showed no evidence of mixing during the last deglaciation runoff episodes coming from proglacial lakes (in particular, Lake Agassiz) and the deep water mass. Diatom analysis confirms this suggestion, which is also supported by isotopic stratigraphy (de Vernal et al., 1996), about the postglacial outflow going through the surface layer of the Goldthwait Sea to the North Atlantic Ocean.

In the Cabot Strait and Northwest North Atlantic site, cores 89-007-111 and 90-031-044, diatom assemblages suggest a brief cold and marine period with only a minor fall-off and fluctuations in surface salinity for both sites. For these sites, de Vernal et al. (1993, 1996) developed a transfer function using dinoflagellate cysts, and quantified for this period, in comparison with modern conditions, a maximum decline of 10–15°C for the surface temperatures at both core sites, as well as a decrease in surface salinity on the order of 5‰ in core 89-007-111 and a lesser drop of 0.7‰ for core 90-031-044. They attributed the surface salinity lowering of core 89-007-111 to the discharge of deglaciation meltwater pulses coming through the St. Lawrence pathway.

Although well-defined in the northwestern Gulf area, the proglacial meltwater runoff pulses vanished in Cabot Strait and offshore sites, according to the diatom analysis of this study. These results support the conclusions of Rodrigues and Vilks (1995) and de Vernal et al. (1996), who found no, or only minor, fresh-water outflow at the time of the Younger Dryas. Broeker's hypothesis (Broeker et al., 1989) requires an important outflow of meltwater through the surface water of the Goldthwait Sea to generate the cooling event of the Younger Dryas. There is no evidence of a significant meltwater flux, in the studied area, to support this hypothesis.

In the Gulf of Maine, the Younger Dryas episode was not formally identified by Popek (1993), even though the data suggest a cooling interval around 10 000 years BP. However, Jorgensen (1984) and Schnitker and Jorgensen (1990) recognized the Younger Dryas cold period, in only one core, by a recurrence of glacial conditions bordered by two successive sharp peaks of *Thalassiosira gravida* (*Thalassiosira antarctica* resting spores) dated around 10 200 and 11 000 years BP. They also related this event to a possible influx of glacial meltwater coming from the St. Lawrence basin.

5.1.4. Establishment of modern environment (diatom zone 4)

This zone corresponds to the progressive establishment of modern-like surface water conditions that began at about 10 000 years BP, and correlates to foraminiferal zone PGS (Post Goldthwait Sea, Rodrigues et al., 1993) for core 90-031-015 and to dinoflagellate cysts ecozone II (de Vernal et al., 1993, 1996) for both cores 90-031-044 and 89-007-111. This interval is also described in the Gulf of Maine (Jorgensen, 1984; Schnitker and Jorgensen, 1990; Popek, 1993) and is dated to begin there around 8000 years BP.

6. Conclusions

Diatom analysis from late Quaternary sequences in the Gulf of St. Lawrence provides further information about postglacial paleohydrologic changes, particularly about the presence of two marked freshwater pulses, coming from the outflow of Laurentide Ice Sheet meltwater runoff, as a surface layer of the Goldthwait Sea during the Younger Dryas. Although well-defined in the northwestern Gulf area, the influence decreases considerably, or even disappears, in the Cabot Strait and offshore sites. Evidence of reduced postglacial glacial runoff on surface water supports the conclusions of Rodrigues and Vilks (1995) and de Vernal et al. (1996), which outlined no significant meltwater flux that could have generated the Younger Dryas cooling episode, as proposed by Broeker et al. (1989).

Furthermore, diatoms used along with various biological indicators (such as foraminifera, pollen, dinoflagellate cysts), showed complementary results, and together, they provide a better understanding of the global evolution of postglacial hydrology of the region. In the same way, both diatoms and foraminifera were used, respectively, as surface and intermediate-deep water indicators, to study Late Quaternary deposits of southern St. Lawrence Estuary area, by Lortie and Guilbault (1984). Their study showed similar paleoecological interpretations. This emphasizes the importance of bringing together various biological data and interpretations in order to obtain a better overview of the area as a whole.

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