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DIATOM PALEOLIMNOLOGY OF TWO FLUVIAL LAKES IN THE ST. LAWRENCE RIVER: A RECONSTRUCTION OF ENVIRONMENTAL CHANGES DURING THE LAST CENTURY[1]

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ABSTRACT

Water quality degradation is a serious concern for the St. Lawrence River. While some environmental data are available for the St. Lawrence ecosystem, long-term monitoring data are generally lacking. To infer past environmental changes, we undertook a paleolimnological assessment of diatom assemblages preserved in four ^{210}*Pb- and* ^{137}*Cs-dated sediment cores from two fluvial lakes in the river, and used diatom transfer functions to infer past shoreline habitat characteristics. At sites in Lake Saint-François, a fluvial lake downstream from Cornwall, water quality decreased this century in response to human impacts (e.g. macrophyte density and nutrient levels increased). These trends were apparent from an increase in epiphytic diatom taxa, followed by an increase in eutrophic planktonic taxa. Water quality, however, appears to have improved somewhat in response to rehabilitation measures during the last two decades. From a sediment core near Montréal (Lake Saint-Louis), we also noted a large proportion of eutrophic and epiphytic taxa, but less evidence was recorded of a recent improvement in water quality. The diatom-based inference model for habitat characteristics appeared to reconstruct environmental conditions in the St. Lawrence River during the last century. The most notable shift has been an increase in diatom taxa commonly associated with macrophyte substrates. Trends in some of the planktonic diatoms were similar to those recorded in paleolimnological investigations from Lake Ontario, but cores from the river also may be reflecting local environments. This study shows that diatom-based paleolimnological studies are possible in large river systems, if coring sites (e.g. fluvial lakes) are carefully selected.*

Key index words: *cores; diatoms; fluvial lakes; habitat; human impacts; microfossils; paleolimnology; sediments; St. Lawrence River; water quality*

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The St. Lawrence River (Canada, U.S.A.) has experienced extensive degradation in water quality as a result of human influences, such as excessive nutrient inputs, organic pollution, and physical disturbances resulting from the construction of the St. Lawrence Seaway (St. Lawrence Centre 1996). There is now considerable interest in attempts to restore the river. However, preimpact conditions are unknown, and in order to set effective rehabilitation goals, it is important to determine the causes, timing, and extent of deterioration. While some historical environmental data exist for the St. Lawrence River (e.g. Germain and Janson 1984, Rondeau 1993), measurements tend to be sporadic, and little monitoring was undertaken before the 1960s. Paleolimnological approaches, however, can be used to identify some of the chemical, physical, and biological changes that have occurred in the past, without an extensive database of historical environmental measurements (Smol 1992).

Major advances have been made in biological paleolimnology in recent years (reviewed in Smol 1992, 1995). For example, considerable progress has been made in the quantitative estimates of the environmental optima and tolerances of indicator taxa (Birks 1995) using primarily surface sediment calibration sets in lakes (Charles and Smol 1994). The most commonly used biological indicators in paleolimnological analyses are diatoms (class Bacillariophyceae). For decades, diatoms have been used successfully to describe the environmental histories of lake systems (e.g. Dixit et al. 1992). In addition, many studies exist concerning the taxonomy of river diatoms (e.g. Sreenivasa and Duthie 1973, Wujek and Rupp 1980, Zalocar de Domitrovic and Maidana 1997), and several others (e.g. De Sève and Goldstein 1981, Juggins 1992, Hay et al. 1997) have considered the relationships between diatoms and environmental conditions in rivers. However, to date, diatoms have not been used in detailed paleoecological analyses of recent river sediment cores. This is not surprising, because the sedimentary regimes of many lotic systems are not conducive to paleolimnological approaches (e.g. obtaining a core with a consistent sedimentary sequence). Fortunately, the St. Lawrence River system contains a number of fluvial lakes, where the river widens, flow rates decrease, and adequate sedimentation of diatom remains occurs. Two such fluvial areas are the focus of this paleolimnological study.

Surface sediment calibration sets are used extensively in lentic systems. However, since many lotic systems do not accumulate sediments, modern diatom assemblages must be collected from living periphytic communities. For example, Juggins (1992) assessed living periphytic diatom communities (e.g. attached to macrophytes and rocks) in the Thames Estuary (U.K.) and developed a diatom-based transfer function to infer salinity from diatom assemblages. In the St. Lawrence River, Reavie and Smol (1997) determined the affinities of diatom taxa to their substrate habitats, and constructed a simple model to infer habitat characteristics from diatom assemblages.

The main objective of this study was to use sedimentary fossil diatoms to infer past trends in limnological variables and shoreline habitat characteristics for two fluvial lakes in the St. Lawrence River: Lake Saint-François and Lake Saint-Louis (Fig. 1). Two of our sediment cores were previously subjected to extensive geochemical analyses by Carignan et al. (1994), who recorded changes in pollutant concentrations (metals, PCBs, mirex, DDT derivatives) in the sedimentary record for the last 50 years. In addition to comparing our diatom results to the 1994 Carignan et al. findings, we analyze two longer cores that contain diatom microfossils from as far back as the late 19th century. We also use the previously described (Reavie and Smol 1997) diatom-based transfer function for the St. Lawrence River to infer changes in shoreline habitat characteristics from fossil diatom assemblages. Our study shows that human influences affected water quality in the St. Lawrence River, although some recovery is evident in our upstream site.

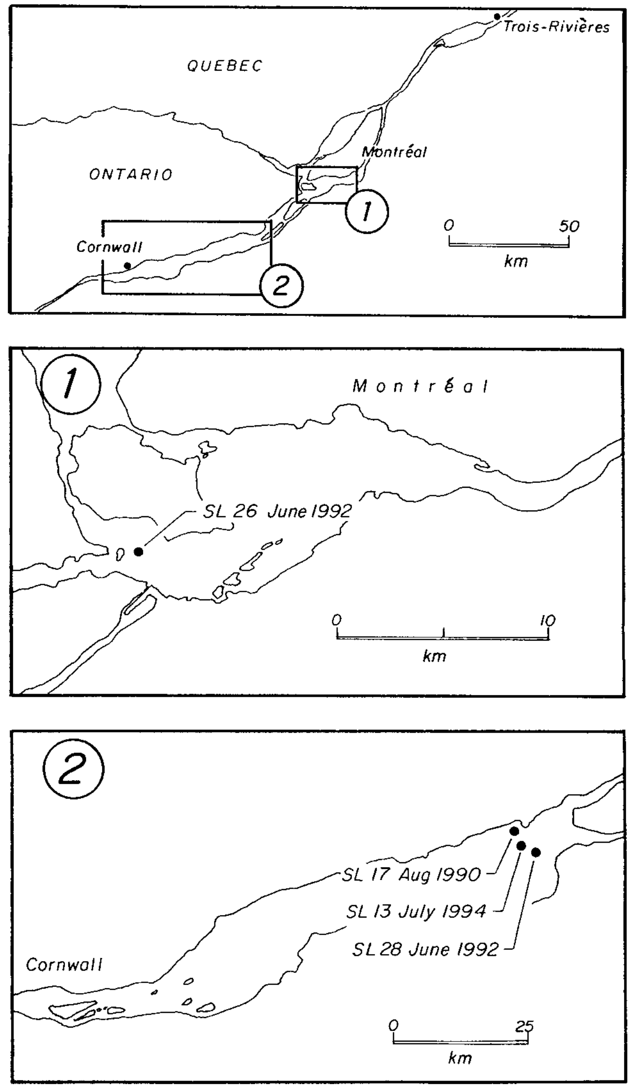

FIG. 1. Locations and sampling dates of the four cores taken from Lake Saint-Louis (1) and Lake Saint-François (2) in the St. Lawrence River.

STUDY AREA

The St. Lawrence River (Fig. 1) is one of the world's most important waterways, as it links the Laurentian Great Lakes to the Atlantic Ocean. The St. Lawrence has been subjected to several waves of anthropogenic disturbance (St. Lawrence Centre 1996). First, during the period of rapid European colonization and expansion (starting in the 19th century), most of the forests were cleared for timber and agriculture. Second, rapid agricultural expansion in the 19th and early 20th centuries resulted in significant increases in nutrient loading to the river and its tributaries. Third, canal construction (primarily the Beauharnois Canal during the 1920s and 1930s) and the ensuing rapid industrialization of populated areas (e.g. Cornwall, Montréal) over the past century have resulted in localized degradation of water quality. Fourth, the construction of the St. Lawrence Seaway in the 1950s modified the hydrologic regime of the river, reducing the average flow rate and the amplitude of water level fluctuations (Morin et al. 1994). These changes have, in turn, provided a more favorable environment for aquatic macrophytes.

The St. Lawrence River is considered a major world river according to its discharge (12,600 $m^3 \cdot s^{-1}$ at Québec City) (Milliman and Meade 1983), but it has a relatively low solid load, 87% of which originates from tributaries (measured at Québec City; Frenette et al. 1989). Accumulation rates of sediment vary by as much as an order of magnitude between Cornwall and Trois-Rivières, and close to a factor of 7 within Lake Saint-François. Furthermore, the deep Seaway "channel" acts as a hydrodynamic

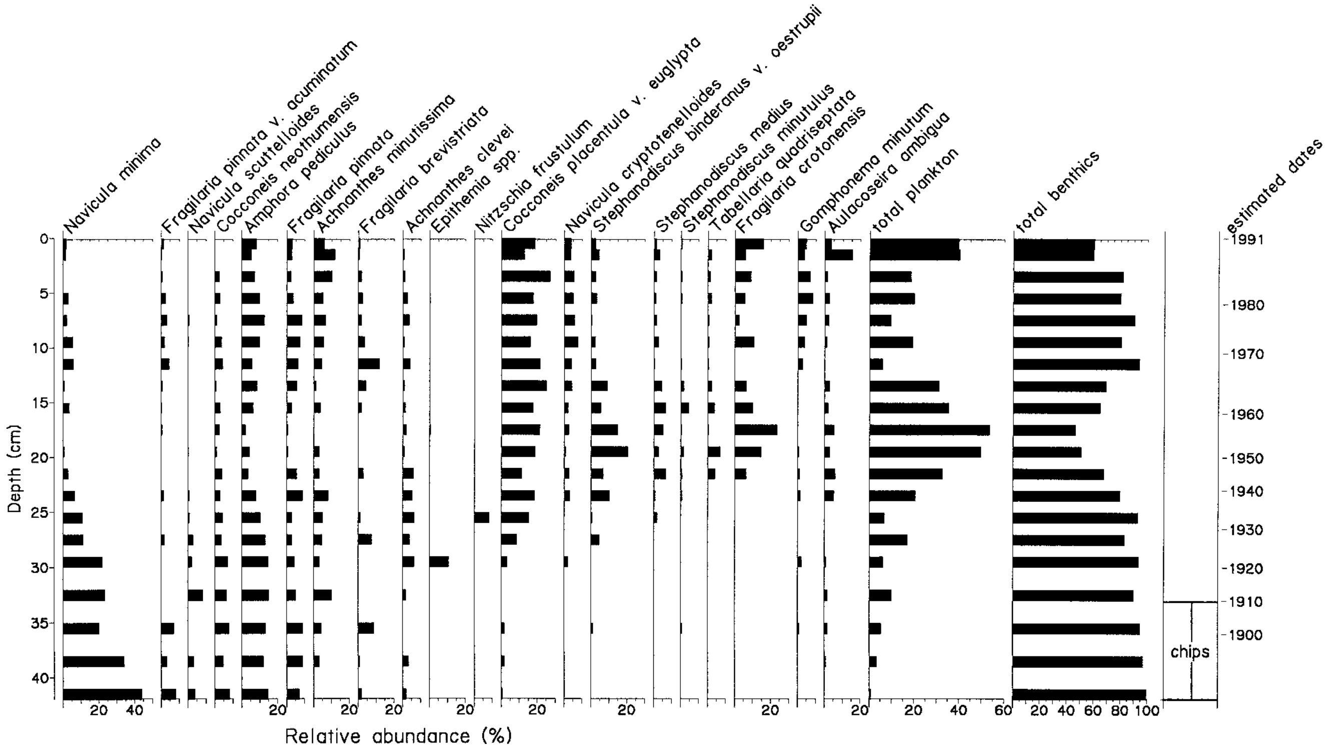

FIG. 2. Diatom microfossil profiles for the SL-17 core from Lake Saint-François, St. Lawrence River. Estimated dates were calculated using ^{210}Pb and ^{137}Cs dating techniques. Samples analyzed were from 1-cm-thick sections. Intervals containing wood chips (chips) are indicated at the right side of the diagram.

barrier, hindering lateral mixing between the north and south sectors of the river.

The portions of the river investigated in this study are two fluvial regions (Fig. 1): Lake Saint-François, downstream from the city of Cornwall, is the first broad, shallow basin in the river; and Lake Saint-Louis, just south and upstream of the city of Montréal, is located just downstream from the Beauharnois Canal. Both sites are located in the ''fluvial section'' of the river (St. Lawrence Centre 1996), which has its source in the Great Lakes, but also drains the Ottawa, Châteauguay, Nicolet, Richelieu, and Saint-François rivers. The fluvial section is the largest area of shoreline wetlands in the river, with abundant submerged and emergent aquatic plant communities. Over three million inhabitants are concentrated along the shoreline stretch between the cities of Cornwall and Trois-Rivières, and most drinking water intakes for these communities are located in the fluvial section. Several industrial plants (primarily pulp and paper, metallurgy, and chemical industries) are also located along the shoreline.

MATERIALS AND METHODS

Coring procedures. Sediment cores were taken by scuba divers from deep water areas at four stations (Fig. 1; dates of coring shown), using butyrate tubes (12-cm internal diameter). The tubes were pushed into the sediments, and core compaction was measured as the difference between the inside and outside sediment–water interfaces. Compaction never exceeded 3% of total core length (Carignan et al. 1994). On shore, the cores were immediately sectioned into intervals of 1 cm (SL-26, SL-17), 2 cm (SL-28), or 5 cm (SL-13). The sections were freeze dried in plastic containers and subsampled for particle size, radioisotope, nutrient, trace metal, algal pigment, and diatom analyses (Carignan et al. 1994). The four cores assessed here were selected from a large suite of St. Lawrence River cores because they had the best preserved stratigraphic records (according to ^{210}Pb analysis, below). The present study focuses on the diatom assemblages preserved in these sediments.

Sediment dating. Radioisotopes (^{137}Cs and ^{210}Pb) were measured by low-background gamma spectrometry (as described in Carignan et al. 1994), using equipment and procedures similar to those described by Appleby et al. (1986).

Diatom preparation and identification. Diatom valves were separated from the organic matrix of the sediments using standard techniques (Battarbee 1986). Small samples of dry sediment (0.5–1 g) were digested in a solution of 50:50 concentrated sulfuric and nitric acid. Digestion was accelerated by placing the samples in a boiling water bath for 1 h. Digested slurries were rinsed several times in distilled water until neutral pH was reached (approximately six rinse cycles). On a slide warmer, slurries were dried overnight on coverslips, and then mounted onto microscope slides using Naphrax®, a permanent mounting medium.

Diatom valves were enumerated and identified under oil immersion (1000× magnification) using a Leitz DMRB microscope (N.A. objective = 1.3). For each slide, a minimum of 300 valves was counted along a transect. Species identifications were based primarily on the Krammer and Lange-Bertalot (1986–1991) book series, as well as Camburn et al. (1984–1986) and Lange-Bertalot (1993).

Habitat reconstruction. Diatom taxa that exhibit an affinity for a specific substrate type are likely to provide information on past habitat status in the river, based on the diatom taxa found in fossil assemblages. For example, if a taxon known to occur predominantly associated with macrophytes increases in a sedimentary profile, one may assume that macrophyte density also increased during that time. The relative contributions of three major habitats (i.e. *Cladophora,* macrophytes, rocks) to the sedimentary diatom assemblages were calculated using a reconstructive model developed by Reavie and Smol (1997). Briefly, using correspondence analysis (CA), the computer program CANOCO (ter Braak 1988, 1990) ordinates fossil assemblages relative to modern periphytic diatom assemblages. Based on the relative proximity of any one fossil sample to the modern samples, the influence of each substrate on that fossil diatom assemblage can be estimated. Fossil samples were run through three "submodels" (one for each habitat), and for each submodel, a logistic regression equation calculates a relative contribution (between 0 and 1) of that habitat to the fossil assemblage. Details of this method are described in Reavie and Smol (1997).

RESULTS AND DISCUSSION

Lake Saint-François (core SL-17). Of the four cores considered in this study, the SL-17 core (Fig. 2) contains the longest temporal record. Sediments from ~1910 and earlier contained wood chips, indicating the end of the period of extensive logging in the 19th and early 20th centuries. The pre-20th century sediments were dominated by small benthic taxa (Reavie and Smol 1998a), primarily *Navicula minima* Grunow, *Cocconeis neothumensis* Krammer, *Amphora pediculus* (Kützing) Grunow, and *Fragilaria pinnata* Ehrenberg. Beginning in the ~1920s, *C. placentula* v. *euglypta* Ehrenberg, a primarily epiphytic taxon in the river (Reavie and Smol 1998b), increased in abundance. Shortly thereafter, during the 1930s and 1940s, eutrophic planktonic taxa (e.g. *Stephanodiscus binderanus* v. *oestrupii* Cleve-Euler, *S. medius* Håkansson, and *Fragilaria crotonensis* Kitton) also increased. According to records from the 1950s (Brunel 1956), *S. binderanus* v. *oestrupii* was a nuisance alga that bloomed in the St. Lawrence River. During the period from ~1950 to ~1960, planktonic taxa were relatively more common than benthic taxa. However, planktonic taxa began to decrease in abundance at ~1960, and many of the small benthics once again increased. *C. placentula* v. *euglypta* maintained a relatively high abundance to the surface of the core (1990), but in the late 1980s, plankton were more common. These plankton were primarily *Aulacoseira ambigua* and *Fragilaria crotonensis,* two taxa that generally occur under high nutrient conditions; however, at this point, it is difficult to make conclusions regarding recent trophic shifts. It is possible that a recent decline in planktonic cyanobacteria and green algae has allowed planktonic diatoms to be more competitive.

Diatom-inferred (DI) periphytic habitat reconstruction (Fig. 3) indicates that rock-type diatoms dominated the assemblages until the 1930s, when epiphytic taxa also began to make a significant contribution. This apparent sudden increase in macrophytes reflects increased littoral habitat, coinciding with physical disruption of the river, such as the construction of the Beauharnois Canal. During the plankton dominance of the mid-century, the relative contribution by rock taxa decreased temporarily, but increased again as plankton decreased around

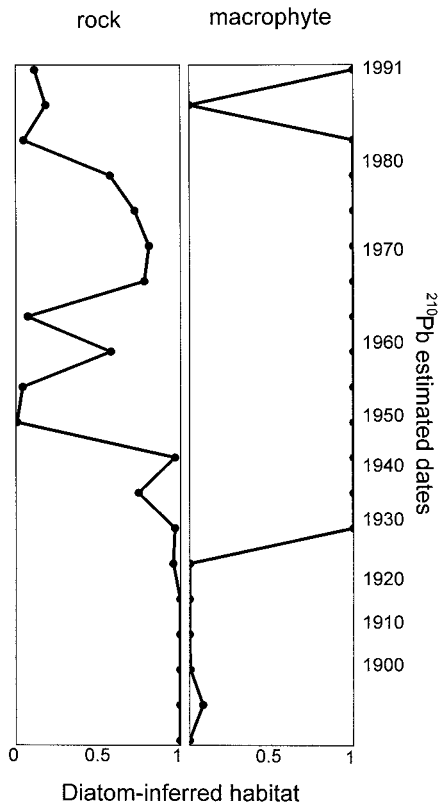

FIG. 3. Diatom-inferred periphytic habitat profiles for the SL-17 core from Lake Saint-François, St. Lawrence River, using the logistic regression model developed by Reavie and Smol (1997). Each "diatom-inferred habitat" reconstruction is a calculated value between 0 and 1, which represents the relative contribution of that habitat to the diatom assemblage. Values do not represent percentages, so a value close to 1 would represent a "high" contribution. The temporal scale corresponds to that used in Figure 2.

the mid-1960s. Again, as plankton increased in relative abundance in the 1980s (Fig. 2), contributions by rock taxa decreased, as well as one very low contribution by epiphytic taxa at the 1–2-cm interval. Such a significant drop in macrophyte populations is unlikely and was probably caused by a relative increase in planktonic taxa (e.g. *Aulacoseira ambigua*), which were uncommon in the periphyton calibration samples (Reavie and Smol 1997). Hence, none of the periphytic habitats made a significant contribution to the diatom assemblage in the 1–2-cm interval.

In summary, analyses of the SL-17 core suggest that macrophyte density increased early this century and has since been an important component of shoreline habitat. Eutrophication was also severe between ~1940 and ~1965, but during the last few decades, eutrophic indicator taxa (e.g. *S. binderanus* v. *oestrupii, F. crotonensis*) decreased in relative abundance, indicating a slight improvement in nutrient status. Reasons for the recent increase in planktonic diatoms (e.g. *F. crotonensis, A. ambigua*) in the uppermost two intervals are still unclear.

Lake Saint-François (SL-28). The SL-28 core (Fig.

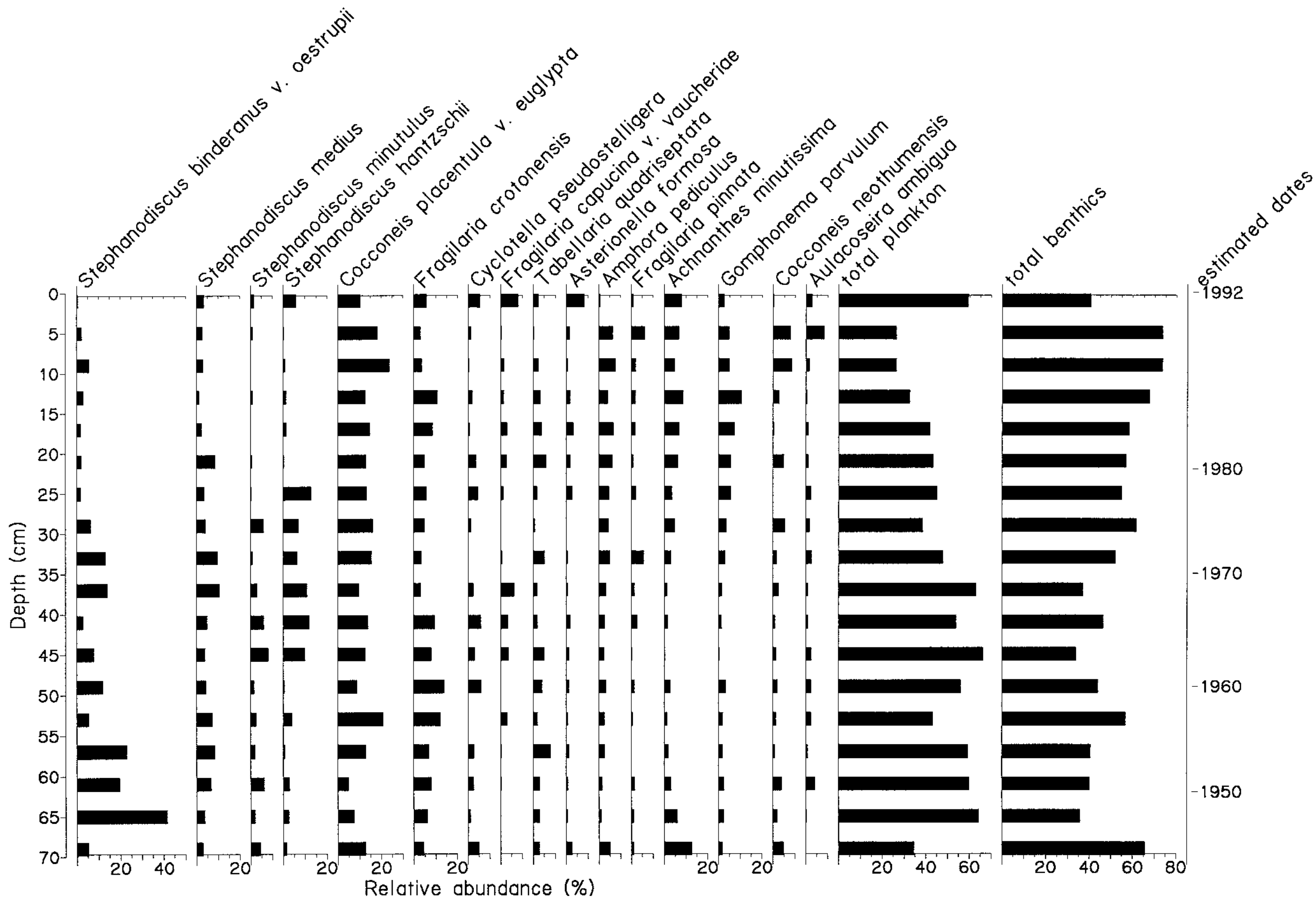

FIG. 4. Diatom microfossil profiles for the SL-28 core from Lake Saint-François, St. Lawrence River. Estimated dates were calculated using ^{210}Pb and ^{137}Cs dating techniques. Samples analyzed were from 2-cm-thick intervals.

4) dates back to only the ~1940s, and so represents a shorter temporal profile than SL-17 (Fig. 2). The early assemblages (late 1940s and early 1950s) were dominated by the eutrophic diatom *Stephanodiscus binderanus* v. *oestrupii.* From the late ~1950s to the ~1970s, *S. binderanus* v. *oestrupii* was gradually replaced by other planktonic taxa (e.g. *S. medius, S. minutulus* (Kützing) Round, *S. hantzschii* Grunow, *Fragilaria crotonensis*). The epiphytic *Cocconeis placentula* v. *euglypta,* which was abundant throughout the core, also increased slightly during this time. Similar to core SL-17, eutrophic, planktonic taxa decreased in relative abundance during the last two decades, and were replaced by small benthic taxa (e.g. *Achnanthes minutissima* Kützing, *Amphora pediculus, Gomphonema parvulum* Kützing). This trend suggests that water quality in Lake Saint-François may have improved in the last few decades. In the surface (0–2 cm) interval, however, benthics decreased as total planktonic diatoms suddenly increased 27%–59% of the diatom assemblage. This trend is similar to that in SL-17 (Fig. 2), but this time, the plankton comprised several taxa, each represented by low relative abundance (e.g. *Fragilaria crotonensis, Cyclotella pseudostelligera, F. capucina* v. *vaucheriae, Asterionella formosa,* and several small *Stephanodiscus* taxa). This occurrence might suggest a sudden nutrient increase this decade, but since some of these taxa have broad tolerances to trophic variables, other factors, such as a decline in other planktonic algae (greens, blue-greens), might be responsible.

Diatom-inferred habitat for SL-28 (Fig. 5) describes a substantial contribution by epiphyton throughout this core, although epilithic diatoms also were common until the 1970s, after which their contribution was relatively less. The major increase in macrophyte density (in response to excess nutrient inputs and hydrologic modification) likely occurred prior to 1950, so high contributions by epiphyton were inferred, but since the core only extends back to the 1940s, the original increase was not recorded.

The diatom profiles show little relationship to measured pollutant trends in the core. Carignan et al.'s (1994) measurements of organic contaminants (PCBs, mirex, DDT derivatives) and metals in the SL-28 core indicate a pollutant maximum between ~1954 and ~1980. Some *Stephanodiscus* taxa also were higher in relative abundance during this peri-

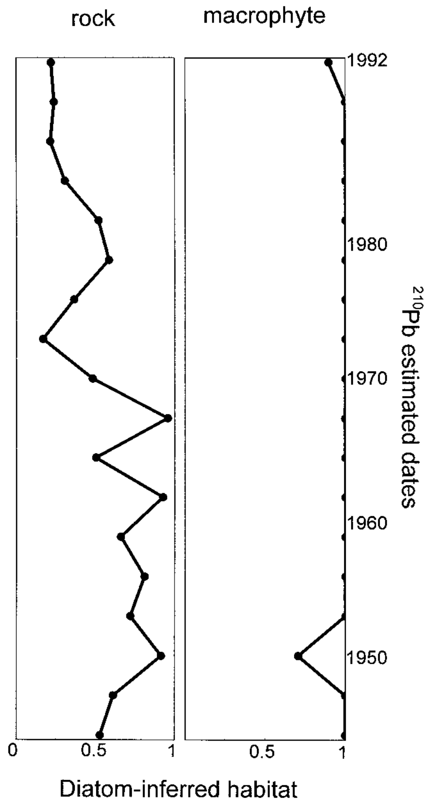

FIG. 5. Diatom-inferred periphytic habitat profiles for the SL-28 core from Lake Saint-François, St. Lawrence River, using the logistic regression model developed by Reavie and Smol (1997). Details on interpreting inferred habitat values are in Figure 3. The temporal scale corresponds to that used in Figure 4.

od, but trends in the diatoms were most likely determined by trophic status variables (e.g. nutrients).

Lake Saint-François (SL-13). In the longest core (physically, but not temporally) from Lake Saint-François (SL-13; Fig. 6), patterns in the most recent diatom assemblages correspond to the profiles in the previously described shorter core for this lake (SL-28; Fig. 4). This core, similar to SL-17 (Fig. 2), contained a basal section (below 60 cm) with abundant wood chips, corresponding to the time when the area was extensively logged in the 19th and early 20th centuries.

The fossil diatoms present during the late 19th century were primarily benthic taxa with an affinity for relatively clean water in the river (e.g. *Fragilaria pinnata, Navicula minima;* Patrick and Reimer 1966, pers. observ.). This is not surprising because extensive degradation of water quality probably did not occur until the early 1900s, with the increases in population and industry. By the 1920s, the diatom assemblage was dominated by forms associated with extensive macrophyte and filamentous algal growth (i.e. epiphytic diatoms, such as *Cocconeis placentula* v. *euglypta*). By the 1950s, many eutrophic planktonic forms (particularly *Stephanodiscus* species) became dominant. As mentioned above, one species in particular, *Stephanodiscus binderanus* v. *oestrupii,* was previously recognized as a nuisance alga in the Great Lakes system during that time (Brunel 1956). The trend toward planktonic taxa continued until ca. 1970, when benthic taxa increased again in relative frequency. Interestingly, the present diatom assemblages have some affinities to the late 19th-/early 20th-century diatom communities, indicating that mitigation efforts might be improving water quality in this fluvial lake.

In the late 19th and early 20th centuries, DI-habitat (Fig. 7) indicated that diatoms characteristic of rock habitats were relatively common. From 1925 to the surface of the core, however, epiphytic habitats were relatively more common. Between 1950 and 1980, contributions by rock taxa declined slightly, probably in response to eutrophication, and the consequent increase in plankton in the system. Overall, the DI-habitat profile for SL-13 describes an increase in macrophytes early this century, and macrophyte concentrations have been maintained at this high level until recently. This trend is corroborated by measured macrophyte abundance data from Lake Saint-François (Morin, unpubl.).

Lake Saint-Louis (core SL-26). Some trends inferred in the Lake Saint-Louis core (SL-26; Fig. 8) correspond to those in other cores from Lake Saint-François (e.g. SL-28; Fig. 4). The gradual decrease in *Stephanodiscus* taxa, for example, seems to be a consistent trend in all of the cores. However, in most intervals since ~1970, *Fragilaria capucina* Desmazières and *F. crotonensis* dominated, in marked contrast to the profiles from the Lake Saint-François cores. Additionally, the surface interval of SL-26 shows a marked increase in *Stephanodiscus binderanus* v. *oestrupii,* indicating a recent eutrophication event. Aside from dramatic shifts in *S. binderanus* v. *oestrupii,* diatom assemblage shifts in the SL-26 core are relatively minor. Benthic taxa (primarily *Cocconeis placentula* v. *euglypta* and several small epilithic taxa) maintained moderate and relatively stable abundances (29%–52%) throughout the core.

Diatom-inferred habitats (Fig. 9) fluctuate at the bottom of the core, but for the most part describe a diatom community composed of primarily epilithic and some epiphytic taxa. In the 1950s and during the mid-1970s, peaks in macrophyte-type habitat occurred, but contributions by epiphytic taxa never persisted. It is noteworthy that SL-26 is the only core to show a significant abundance of primarily *Cladophora*-associated diatoms in the fossil assemblages (from approximately 1970 to 1980, and at one interval in the mid-1980s). This calculation likely occurred due to the rare occurrences of *Cladophora*-specific (Reavie and Smol 1997) diatoms such as *Navicula kuelbsii* Lange-Bertalot and *Navicula tripunctata* (Müller) Bory (not shown in Fig. 8). Although we are certain that *Cladophora* has been present in high abundance throughout the Great Lakes/St. Lawrence system (Ontario Water Resources Commission 1959, Shear and Konasewich 1975), it is possible

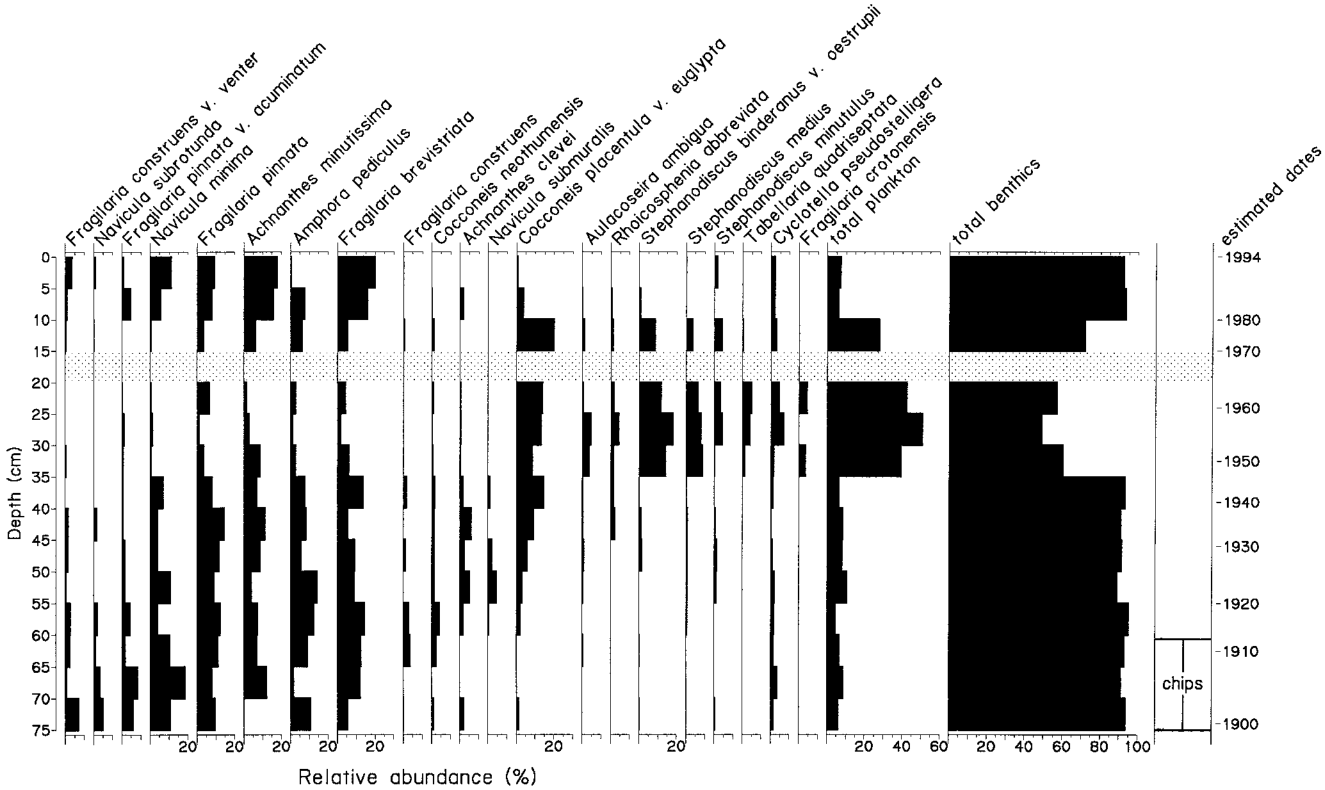

FIG. 6. Diatom microfossil profiles for the SL-13 core from Lake Saint-François, St. Lawrence River. Estimated dates were calculated using ^{210}Pb and ^{137}Cs dating techniques. Intervals containing wood chips (chips) are indicated at the right side of the diagram. All sedimentary material from the 15–20-cm interval (shaded) was used in other analyses by Environment Canada (Centre Saint-Laurent), so diatom data were unavailable. Samples analyzed were from 5-cm-thick intervals.

that *Cladophora* density might have been relatively minor in comparison to macrophyte communities. *Cladophora glomerata* often occurs close to shore (Shear and Konasewich 1975), whereas dense growths of macrophytes such as *Myriophyllum* and *Potamogeton* can extend into much deeper water. Therefore, it is not overly surprising to have epiphytic diatoms from macrophytes overwhelming the number of diatoms associated with *Cladophora*.

Geochemical analyses of the SL-26 core (Carignan et al. 1994) indicate that organic contaminants peaked between ~1950 and ~1968, and metals increased starting in the late 1950s, and have been gradually decreasing until the present. As occurred in Lake Saint-François (Fig. 4), diatom assemblage changes did not coincide with these pollutant concentrations. Organic and metal contaminants have probably had no detectable effects on diatom assemblages, as the diatom communities are more likely responding to trophic status variables, similar to studies from the Great Lakes (Stoermer et al. 1985, 1996, Wolin et al. 1991).

In summary, the shifts in diatom assemblages in the Lake Saint-Louis core are less pronounced than in the Lake Saint-François cores (Figs. 2, 4, 6), and only a minor recovery, if any, is inferred.

Comparison among cores. Most paleolimnological investigations in lentic systems have been based on a single core, typically obtained from the deepest portion of the study lake. However, a number of multiple-core analyses from single lakes have been undertaken (e.g. Charles et al. 1991, Dixit et al. 1996) to ensure spatial replication of stratigraphic trends. Such studies have illustrated that single-core analyses are usually sufficient to describe the environmental history of a lake ecosystem. However, river systems are much more complex for three main reasons: (1) sedimentary regimes vary significantly along a river's length; (2) point sources of pollutants can occur along a river, and hence there can be marked local differences in environmental variables; and (3) the source of sedimented materials in rivers can be uncertain (e.g. from upstream sites). The present study indicates that some replication of trends occurs among cores in the river, particularly within the same reach (i.e. Lake Saint-François), but a single core would not have been sufficient for an accurate description of the paleolimnology of the St. Lawrence River.

The four cores considered here share many stratigraphic trends. Nineteenth- and early 20th-century sediments in both longer cores (Figs. 2, 6) were dominated by small benthic taxa. In response to a river-wide increase in macrophyte abundance during the ~1920s and 1930s (Morin, unpubl.), *Cocconeis placentula* v. *euglypta* increased in relative abun-

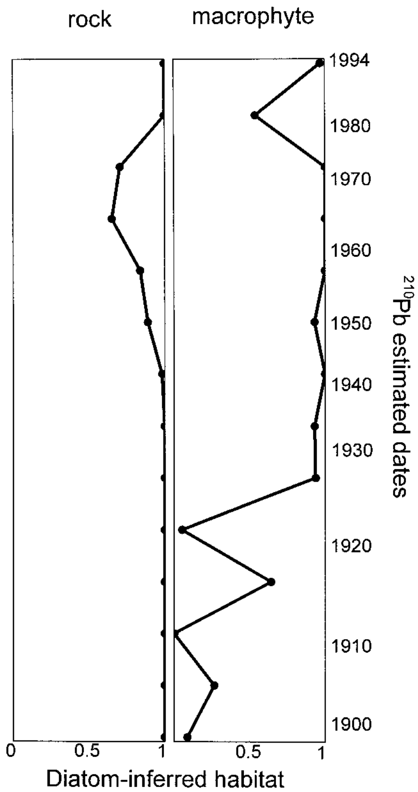

FIG. 7. Diatom-inferred periphytic habitat profiles for the SL-13 core from Lake Saint-François, St. Lawrence River, using the logistic regression model developed by Reavie and Smol (1997). Details on interpreting inferred habitat values are in Figure 3. The temporal scale corresponds to that used in Figure 6.

dance. Eutrophic plankton, represented primarily by *Stephanodiscus* taxa, were most abundant between ~1940 and ~1970. In three of the cores (Figs. 2, 4, 8), the surface intervals show an abrupt peak in planktonic taxa, indicating further limnological changes in the late 1980s or early 1990s.

Similarities such as those above are expected from analyses of replicate cores from a specific aquatic ecosystem (e.g. Charles et al. 1991). However, it is clear that replicate cores in the St. Lawrence River, even those taken in close proximity (SL-17, 13, 28), do not necessarily record all the same compositional and temporal trends in diatom microfossils. Aside from *C. placentula* v. *euglypta,* the composition of benthic taxa since ~1970 in Lake Saint-François differs significantly among the three cores: SL-17 (Fig. 2) was dominated by *Amphora pediculus, Achnanthes minutissima* and *Gomphonema minutum* (Agardh) Agardh; SL-28 (Fig. 4) was dominated by *A. pediculus, A. minutissima, G. parvulum,* and *C. neothumensis*; SL-13 (Fig. 6) was dominated by *Navicula minima, Fragilaria pinnata, A. minutissima,* and *F. brevistriata* Grunow.

The distribution of settling material in a river often depends a great deal on current speed and the physical nature of bottom sediments. These characteristics may result in varying size selection mechanisms (size fractionation) of sediments and diatom microfossils. Local current speeds in Lake Saint-François and Lake Saint-Louis have periodically shifted due to changes in water level, discharge, and human activities (e.g. channel construction and dredging). Furthermore, the structure of bottom sediments in Lake Saint-François can vary considerably on a scale as small as 5 m, with bottom coverings of sand, gastropod shells, and mats of the macroalga *Chara,* all of which likely result in varying size fractionation regimes. It is also possible that these differences in diatom composition may have been influenced by the proximity of each core to the main channel of the river, with cores nearer to the channel (e.g. SL-28) recording many taxa from upstream sources, whereas cores further from the channel (e.g. SL-17) contain taxa that better represent local shoreline communities, or diatoms from nearby tributaries. Further multicore studies are clearly warranted.

The core from Lake Saint-Louis (SL-26; Fig. 8) also shows many similarities to cores from Lake Saint-François. However, *Fragilaria capucina* var. *vaucheriae* occurred at abundances of 4%–20% throughout the Lake Saint-Louis core, while this diatom was rarely observed in upstream sites. Additionally, the planktonic diatoms *Aulacoseira italica* (Ehrenberg) Simonsen, *Melosira lineata* Agardh, and *A. alpigena* (Grunow) Krammer were relatively common in Lake Saint-Louis, but were only observed in trace amounts in cores from Lake Saint François. Since ~1950, planktonic diatoms were relatively more common (50%–70%) in Lake Saint-Louis (Fig. 8) than in Lake Saint-François. Lake Saint-Louis is fed by many adjacent tributaries, such as the Ottawa River, which may be providing diatoms that do not occur upstream in the St. Lawrence River.

Lorrain et al. (1993) also observed dissimilarities among replicate cores between Cornwall and Trois-Rivières, noting that the timing of metal contamination did not correspond among geochemical profiles of St. Lawrence River cores.

Intercore comparisons confirm some expected similarities in diatom trends at various sites in the St. Lawrence River. However, in a system as large as the St. Lawrence River, local conditions also influence the stratigraphic microfossil composition. Based on our observations of diatoms, more spatial heterogeneity occurs in river sediments than lake sediments, so we recommend that replicate- and multiple-coring techniques be used for paleolimnological studies in complex river systems.

Evaluation of the habitat model. Based on our knowledge of past habitat shifts in the St. Lawrence River system, it appears that DI reconstructions can track past habitat characteristics. For example, it is widely believed that nutrient increases and the construction of the St. Lawrence Seaway resulted in an increase in macrophyte density (Morin, unpubl.). Diatom-inferred habitat reconstructions that date back

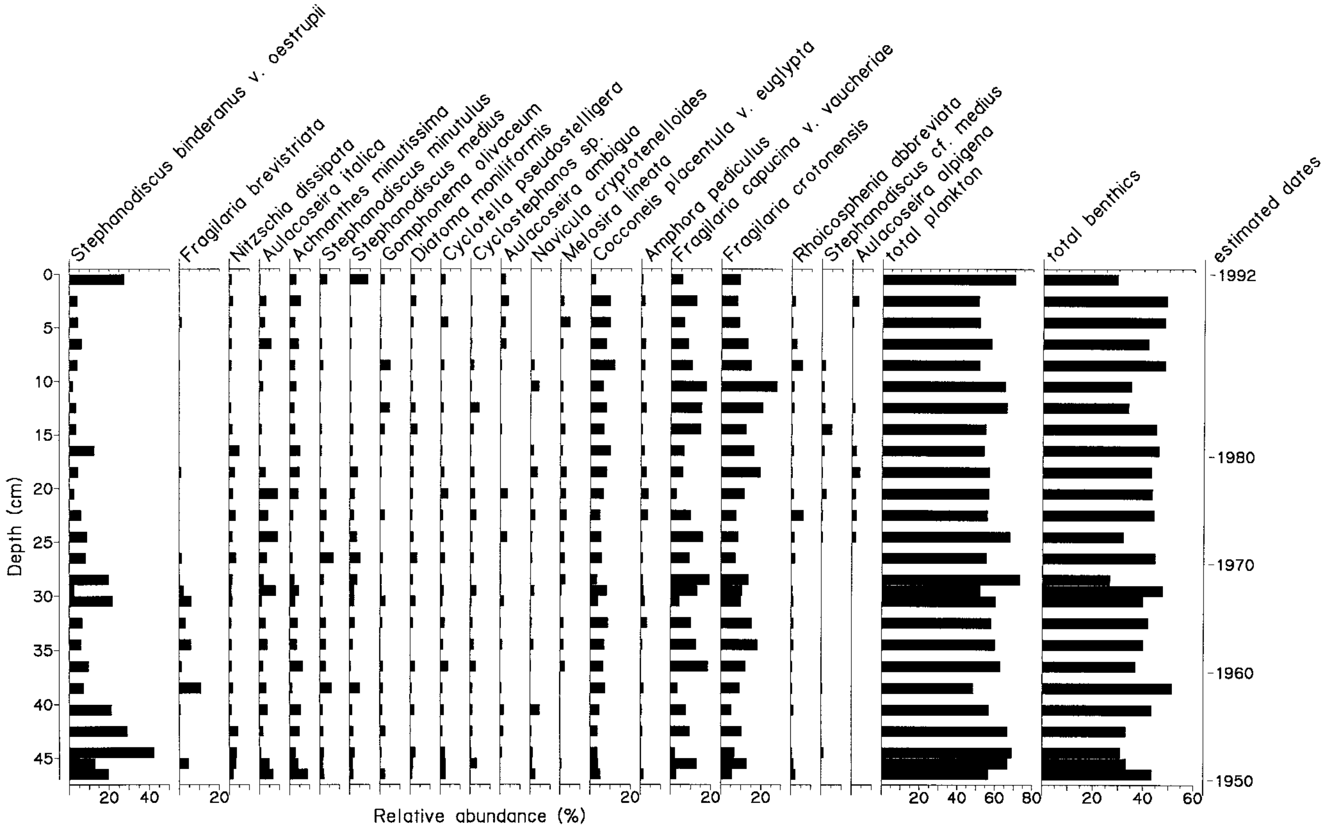

FIG. 8. Diatom microfossil profiles for the SL-26 core from Lake Saint-Louis, St. Lawrence River. Estimated dates were calculated using ^{210}Pb and ^{137}Cs dating techniques. Samples analyzed were from 1-cm-thick intervals.

to the 19th century also indicate that macrophytes increased this century. Decreases in the relative contributions of rock taxa also corroborate times when other forms of diatoms (primarily plankton and epiphyton) dominated. While the model can be applied with some confidence to fossil data, some refinements and further expansion of the calibration set (Reavie and Smol 1997) would likely improve our inferences. For example, the model is presently limited to three possible habitats, and neglects other diatom communities such as epipsammon, epipelon, and taxa associated with other substrates. Additionally, because fossil assemblages incorporate taxa from all seasons, the sampling of habitats at other times of peak diatom growth (e.g. autumn) might also improve the model's reliability. Some changes, such as the sudden drop in DI-macrophyte density near the surface of SL-17 (Fig. 3), were likely not as drastic as they appear in our reconstructions, and future model expansion will probably reduce these erratic fluctuations in DI values. As outlined by Reavie and Smol (1997), comparisons should be made among the various DI-habitat profiles to determine the relative contributions by each periphytic habitat to the diatom assemblages.

GENERAL DISCUSSION

Through diatom-based paleolimnological analysis, we were able to track recent degradation in water quality and the timing of events leading to major ecosystem changes in the St. Lawrence River. Intense agricultural practices, population growth in the catchment, and the construction of the Beauharnois Canal and the St. Lawrence Seaway coincide with the increase in growth of littoral macrophytes and algae. Fossil remains in the sediment cores indicate that an increase in macrophytes occurred early this century, and the high relative abundance of *Stephanodiscus binderanus* v. *oestrupii* indicates a temporary state of very high nutrient conditions from the ~1940s to the late 1960s. It is likely that the resulting significant reduction in the seasonal fluctuations in water level has allowed a more stable environment for the growth of aquatic plants. Furthermore, extensive settlement and development of the river watershed caused the system to become more eutrophic. Unfortunately, it is difficult to distinguish the specific effects of increased nutrients and Seaway construction, probably because they would have occurred at the same time and would have had a combined effect on water quality degradation.

Inferred eutrophication events correspond to those recognized in paleoecological analyses of the Great Lakes (e.g. Stoermer et al. 1985, 1987, 1996, Schelske 1991, Wolin et al. 1991, Schelske and Hodell 1995). In Lake Ontario (Stoermer et al. 1985) and Lake Erie (Stoermer et al. 1996), past increases

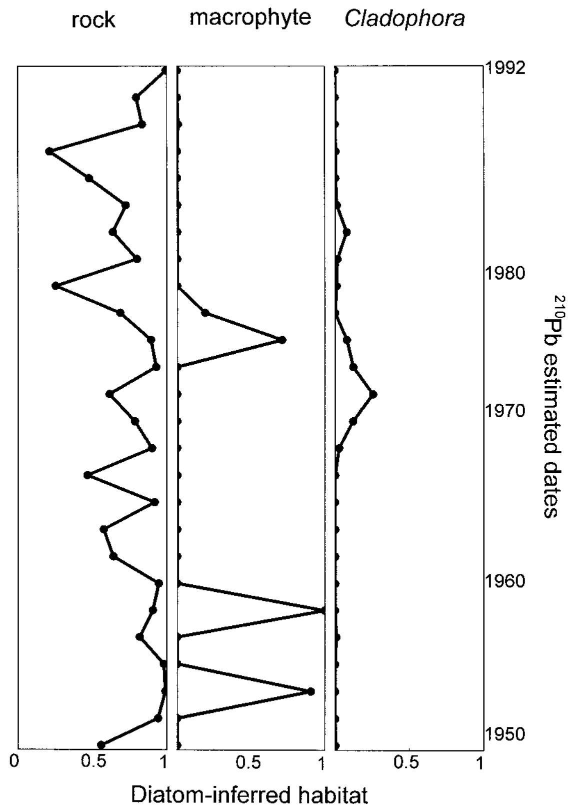

FIG. 9. Diatom-inferred periphytic habitat profiles for the SL-26 core from Lake Saint-Louis, St. Lawrence River, using the logistic regression model developed by Reavie and Smol (1997). Details on interpreting inferred habitat values are in Figure 3. The temporal scale corresponds to that used in Figure 8.

in *Stephanodiscus* taxa were noted at the same time as in the St. Lawrence River, indicating serious eutrophication problems during the mid-20th century. Although some diatom trends in cores from the Great Lakes correlate well with trends in this study, a comparison of specific downcore diatom assemblages among studies shows that assemblages preserved in the St. Lawrence River record are unique. For example, within the last 100 years, *S. binderanus* v. *oestrupii* never exceeded 2% of the diatom assemblage in Lake Ontario (Stoermer et al. 1985), but it appeared in relative abundances as high as 42% in the St. Lawrence River. Conversely, taxa such as *S. alpinus* Hustedt occurred at relative abundances as high as 25% in Lake Ontario, but this taxon was rarely observed in St. Lawrence River sediments. When compared to fossil assemblages from the St. Lawrence River, Great Lakes assemblages were, not surprisingly, largely planktonic. Therefore, although some bioindicators from upstream locations are accumulating in St. Lawrence sediments, and although inferred nutrient trends are similar to those observed in paleoecological investigations of the Great Lakes, most fossil specimens are likely from the river itself.

This study also documents some recent recovery of water quality in Lake Saint-François. Although historical measurements of pollution are scarce for the river, nutrient levels (USGS, unpubl.; St. Lawrence Centre, unpubl.) have been documented in the last few decades and indicate some water quality improvement. In some cases (e.g. in cores SL-13 and SL-17), it appears that rehabilitation measures (e.g. removal of phosphates from detergents, sewage treatment) in the last two decades may have been effective. This corresponds well with nutrient trends from the St. Lawrence River (USGS, unpubl.) and Lake Ontario, where measurements indicated a 42% decrease in total phosphorus concentrations between 1973 and 1982 (Stevens and Neilson 1987). Our data indicate, however, that not all regions in the St. Lawrence River have followed identical trajectories in their recent history. The core from Lake Saint-Louis (SL-26), for example, indicates that water quality has improved since the 1950s (according to a decrease in the eutrophic indicator *S. binderanus* v. *oestrupii*), but apparently not to the extent of upstream locations. Relatively less improvement has been recorded near Montréal, which is not surprising, as this portion is nearer to very large industrial centers.

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Appleby, P. G., Nolan, D. W., Gifford, D. W., Godfrey, M. J., Oldfield, F., Anderson, N. J. & Battarbee, R. W. 1986. ^{210}Pb dating by low background gamma counting. *Hydrobiologia* 143: 21–7.

Battarbee, R. W. 1986. Diatom analysis. *In* Berglund, B. E. [Ed.] *Handbook of Holocene Palaeoecology and Palaeohydrology.* J. Wiley, New York, pp. 527–70.

Birks, H. J. B. 1995. Quantitative palaeoenvironmental reconstructions. *In* Maddy, D. & Brew, J. S. [Eds.] *Statistical Modelling of Quaternary Science Data.* Technical Guide 5, Quaternary Research Association, Cambridge, pp. 161–254.

Brunel, J. 1956. Addition du Stephanodiscus binderanus á la flore diatomique de l'Amérique du Nord. *Nat. Can.* 83:89–95.

Camburn, K. E., Kingston, J. C. & Charles, D. F. 1984–1986. PIRLA Diatom Iconograph. *PIRLA Unpublished Report Series* 3. Indiana University, Bloomington.

Carignan, R., Lorrain, S. & Lum, K. R. 1994. A 50-year record of pollution by nutrients, trace metals and organic chemicals in the St. Lawrence River. *Can. J. Fish. Aquat. Sci.* 51:1088–100.

Charles, D. F., Dixit, S. S., Cumming, B. F. & Smol, J. P. 1991. Variability in diatom and chrysophyte assemblages and inferred pH: paleolimnological studies of Big Moose Lake, New York, USA. *J. Paleolim.* 5:267–84.

Charles, D. F. & Smol, J. P. 1994. Long-term chemical changes in lakes. Quantitative inferences from biotic remains in the sediment record. *In* Baker, L. [Ed.] *Environmental Chemistry of Lakes and Reservoirs.* American Chemical Society, Washington, D.C., pp. 3–31.

De Sève, M. A. & Goldstein, M. E. 1981. The structure and composition of epilithic diatom communities of the St. Lawrence and Ottawa Rivers in the Montréal area. *Can. J. Bot.* 59:377–87.

Dixit, A. S., Dixit, S. S. & Smol, J. P. 1996. Setting restoration goals for an acid and metal-contaminated lake: a paleolimnological study of Daisy Lake (Sudbury, Canada). *J. Lake Res. Manage.* 12:323–30.

Dixit, S., Cumming, B. F., Smol, J. P. & Kingston, J. C. 1992. Monitoring environmental changes in lakes using algal microfossils. *In* McKenzie, D. H., Hyatt, D. E. & MacDonald, V. J. [Eds.] *Ecological Indicators.* Volume 2. Elsevier Applied Science Publishers, Amsterdam, pp. 1135–55.

Frenette, M., Barbeau, C. & Verrette, J.-L. 1989. *Aspects quantitatifs, dynamiques et qualitatifs des sèdiments du Saint-Laurent.* Tech. report to Environment Canada and the Government of Quèbec, 185 pp.

Germain, A. & Janson, M. 1984. *Qualité des eaux du fleuve Saint-Laurent de Cornwall à Québec (1977–1981).* Environnement Canada, Direction générale des eaux intérieures, région du Québec, Québec City, 232 pp.

Hay, M. B., Smol, J. P., Pipke, K. J. & Lesack, L. F. W. 1997. A paleohydrological model for the Mackenzie Delta, N.W.T. (Canada): a diatom-based approach for evaluation of past river discharge. *Arct. Alp. Res.* 29:430–44.

Juggins, S. 1992. Diatoms in the Thames Estuary, England: ecology, palaeoecology, and salinity transfer function. *Bibliotheca Diatomologica* Band 25, J. Cramer, Berlin, 216 pp.

Krammer, K. & Lange-Bertalot, H. 1986–1991. Bacillariophyceae. *In* Ettl, H., Gerloff, J., Hyenig, H. & Mollenhauer, D. [Eds.] *Süsswasserflora von Mitteleuropa 2/1–4.* Fischer, Stuttgart.

Lange-Bertalot, H. 1993. *85 New Taxa and much more than 100 taxonomic clarifications supplementary to Süßwasserflora von Mitteleuropa Vol. 2/1–4.* J. Cramer, Berlin, Stuttgart, 454 pp.

Lorrain, S., Carignan, R. & Lum, K. 1993. Trace metal profiles in the fluvial lakes of the St. Lawrence River, Canada. *In* 9th International Conference on Heavy Metals in the Environment, Toronto, Canada, September, 1993.

Milliman, J. D. & Meade, R. H. 1983. World-wide delivery of river sediment to the oceans. *J. Geol.* 91:1–21.

Morin, J., Boudreau, P. & Leclerc, M. 1994. *Réhabilitation de L'écosystème du Saint-Laurent. Lac Saint-François: les bases de la modélisation hydrodynamique.* Report to the INRS-Eau, Ottawa.

Ontario Water Resources Commission. 1959. *Cladophora* Investigations: Observation on the Nature and Control of Excessive Growth of *Cladophora* sp. in Lake Ontario. Report Number 1. Ontario Water Resources Commission, Ontario.

Patrick, R. & Reimer, C. W. 1966. *The Diatoms of the United States Exclusive of Alaska and Hawaii.* Monograph 13, Volume 2, Part 1. Academy of Natural Science, Philadelphia, 688 pp.

Reavie, E. D. & Smol, J. P. 1997. Diatom-based model to infer past littoral habitat characteristics in the St. Lawrence River. *J. Gt. Lakes Res.* 23:339–48.

——— 1998a. Epilithic diatoms from the St. Lawrence River and their relationships to water quality. *Can. J. Bot.*

——— 1998b. Diatom epiphyton in the St. Lawrence River (Canada): characterization and relation to environmental conditions. *In* Proceedings of the 14th International Diatom Symposium, Tokyo, Japan, September 2–8, 1996.

Reavie, E. D., Smol, J. P. & Carmichael, N. B. 1995. Postsettlement eutrophication histories of six British Columbia (Canada) lakes. *Can. J. Fish. Aquat. Sci.* 52:2388–401.

Rondeau, B. 1993. *Qualité des eaux du fleuve Saint-Laurent (1985–1990) tronçon Cornwall-Québec.* Centre Saint-Laurent, Environnement Canada, Région du Québec, 150 pp.

Schelske, C. L. 1991. Historical nutrient enrichment of Lake Ontario: paleolimnological evidence. *Can. J. Fish. Aquat. Sci.* 48: 1529–38.

Schelske, C. L. & Hodell, D. A. 1995. Using carbon isotopes of bulk sedimentary organic matter to reconstruct the history of nutrient loading and eutrophication in Lake Erie. *Limnol. Oceanogr.* 40:918–29.

Shear, H. & Konasewich, D. E. 1975. *Cladophora* in the Great Lakes. Internation Joint Commission. Great Lakes Research Advisory Board, Windsor, Ontario.

Smol, J. P. 1992. Paleolimnology: an important tool for effective ecosystem management. *J. Aquat. Ecosyst. Health* 1:49–58.

——— 1995. Paleolimnological approaches to the evaluation and monitoring of ecosystem health: providing a history for environmental damage and recovery. *In* Rapport, D. J., Gaudet, C. L. & Calow, P. [Eds.] *Evaluating and Monitoring the Health of Large-Scale Ecosystems.* Springer-Verlag, Berlin, pp. 301–18.

Sreenivasa, M. R. & Duthie, H. C. 1973. Diatom flora of the Grand River, Ontario, Canada. *Hydrobiologia* 42:161–224.

St. Lawrence Centre. 1996. *State of the Environment Report on the St. Lawrence River. Volume 1: The St. Lawrence Ecosystem.* Environment Canada—Quebec Region, Environmental Conservation, and éditions Multimondes, Montreal.

Stevens, R. J. J. & Neilson, M. A. 1987. Response of Lake Ontario to reductions in phosphorus load, 1967–82. *Can. J. Fish. Aquat. Sci.* 44:2059–68.

Stoermer, E. F., Emmert, G., Julius, M. L. & Schelske, C. L. 1996. Paleolimnologic evidence of rapid recent change in Lake Erie's trophic status. *Can. J. Fish. Aquat. Sci.* 53:1451–8.

Stoermer, E. F., Kociolek, J. P., Schelske, C. L. & Conley, D. J. 1987. Quantitative analysis of siliceous microfossils in the sediments of Lake Erie's central basin. *Diatom Res.* 2:112–34.

Stoermer, E. F., Wolin, J. A., Schelske, C. L. & Conley, D. J. 1985. An assessment of ecological changes during the recent history of Lake Ontario based on siliceous algal microfossils preserved in the sediments. *J. Phycol.* 21:257–76.

ter Braak, C. J. F. 1988. *CANOCO—A FORTRAN Program for Canonical Community Ordination by [partial] [detrended] [canonical] Correspondence Analysis, Principal Components Analysis and Redundancy Analysis (version 2.1).* Agricultural Mathematics Group, Wageningen.

——— 1990. *Update Notes: CANOCO Version 3.10.* Agricultural Mathematics Group, Wageningen.

Wolin, J. A., Stoermer, E. F. & Schelske, C. L. 1991. Recent changes in Lake Ontario 1981–1987: microfossil evidence of phosphorus reduction. *J. Gt. Lakes Res.* 17:229–40.

Wujek, D. E. & Rupp, R. F. 1980. Diatoms of the Tittabawassee River, Michigan. *Bibliotheca Phycologica,* Band 50. J. Cramer, Vaduz, 100 pp.

Zalocar de Domitrovic, Y. & Maidana, N. I. 1997. Taxonomic and ecological studies of the Paraná River diatom flora (Argentina). *Bibliotheca Diatomologica,* Band 34. J. Cramer, Berlin, 122 pp.