

Three hundred years of human-induced change in an urban lake: paleolimnological analysis of Lac Saint-Augustin, Québec City, Canada

Reinhard Pienitz, Karine Roberge, and Warwick F. Vincent

Abstract: Lac Saint-Augustin provides a unique record of anthropogenic change during the settlement and evolution of Québec City, one of North America's oldest cities. Lac Saint-Augustin is an urban lake that has been subject to three centuries of direct human impacts, with the most pronounced changes in trophic status and chemistry occurring within the last few decades. This accelerated eutrophication has greatly limited the present recreational opportunities for lake visitors and residents. A paleolimnological study of Lac Saint-Augustin was undertaken to identify the causes of this degradation and to place these changes within the context of historical development in the lake's catchment. Biological and chemical indicators identified three major periods in the recent history of Lac Saint-Augustin. The first period (1670–1750) corresponds to the arrival of the first settlers at the lake and the construction of a diversion canal; at that time, the lake was characterized by oligo- to meso-trophic conditions (as indicated by diatom species of the genus *Aulacoseira*) and low concentrations of chlorophyll *a*, total carotenoids, total phosphorus, and metals. The second period (1750–1904) corresponds to increased human colonization and was marked by slight increases in sedimentary metal and total phosphorus concentrations. The third period (1904–2002) coincides with an intensification of agriculture, the expansion of Québec City, and the urbanization of the catchment. At this time, there was a complete change in the diatom flora (predominance of *Stephanodiscus hantzschii*) as well as major increases in fossil pigment concentrations, nutrients, and sedimentary chemical levels. Diatom species typical of saline waters also appeared coincident with the use of road salts on a highway that passes through the lake's catchment. With the increasing demands for greater use of inland waters, multiproxy, long-term data of the kind provided here are essential to make informed management decisions.

Key words: lake eutrophication, paleolimnology, diatoms, fossil pigments, geochemistry, Québec.

Résumé : Le lac Saint-Augustin (en banlieue de la ville de Québec) connaît depuis quelques décennies une eutrophisation rapide. En conséquence, les activités récréatives pratiquées par les nombreux riverains sont aujourd'hui limitées. La présente étude paléolimnologique a comme principal objectif de déterminer les principales causes de la dégradation de la qualité de l'eau de cet écosystème lacustre important. Ainsi, des indicateurs biologiques (diatomées et pigments fossiles) et chimiques (géochimie des sédiments) ont permis de distinguer trois périodes majeures dans l'histoire récente du lac Saint-Augustin. La première période (1670–1750), qui correspond à l'arrivée des premiers colons Européens et la construction d'un canal de dérivation vers le lac, est représentée par une flore diatomifère oligo- à mésotrophe (dominance d'espèces du genre *Aulacoseira*) et des concentrations faibles en chlorophylle *a*, caroténoïdes totaux, phosphore total et métaux. La deuxième période (1750–1904) correspond à la colonisation humaine et est caractérisée par une légère augmentation des concentrations en phosphore total et en métaux. La troisième période (1904–2002), qui coïncide avec une agriculture intensive, l'expansion de l'agglomération de la ville de Québec et l'urbanisation du bassin, versant du lac est représentée par un changement complet de la flore diatomifère (dominance de *Stephanodiscus hantzschii*) et une augmentation majeure des pigments fossiles, des nutriments et des métaux. L'apparition de diatomées typiques des eaux salées coïncide avec l'utilisation de sels de déglçage pour l'entretien d'une autoroute qui passe à travers le bassin versant du lac. Les activités anthropiques ont donc eu un impact important sur la qualité de l'eau du lac. À l'heure d'une pression grandissante sur les écosystèmes d'eau douce, cette étude montre que ces données paléolimnologiques sont essentielles pour assurer une gestion efficace et à long terme du lac Saint-Augustin et de son bassin versant.

Mots clés : eutrophisation des lacs, paléolimnologie, diatomées, pigments fossiles, géochimie, Québec.

Received 28 June 2005. Published on the NRC Research Press Web site at <http://canjbot.nrc.ca> on 11 April 2006.

R. Pienitz¹ and K. Roberge. Department of Geography and Centre d'études nordiques, Université Laval, Québec City, QC G1K 7P4, Canada.

W.F. Vincent. Department of Biology and Centre d'études nordiques, Université Laval, Québec City, QC G1K 7P4, Canada.

¹Corresponding author (e-mail: reinhard.pienitz@cen.ulaval.ca).

Introduction

Lake eutrophication is an increasingly common problem throughout the world and is often associated with agricultural, industrial, and urban activities. However, historical monitoring information is often insufficient to quantify the extent of changes in water quality or to identify long-term trends (Kumagai and Vincent 2003). Paleolimnological analyses, based on studies of the biological, chemical, and phys-

ical information preserved in lake sediments, provide a valuable approach to fill this gap by allowing the reconstruction of natural and anthropogenic changes for periods predating instrumental observations (Pienitz and Vincent 2003). Fossil diatom assemblages preserved in lake sediments have proven to be especially valuable indicators given their species richness and strong correlations with lake water variables including nutrient concentrations, acidity, temperature, and salinity. In eutrophication studies, the paleolimnological approach has linked changes in lake trophic status to specific anthropogenic effects such as inputs of waste water generated by urbanization (e.g., Bartsh 1970; Hall et al. 1999; Dixit et al. 2000), fertilizer inputs from intensive agriculture (e.g., Anderson 1997; Hall et al. 1997; Pan and Brugam 1997; Lotter 2001), and industrial waste water (e.g., Olsson et al. 1997; Guilizzoni et al. 2001).

In the present study, we examine long-term water quality trends in a lake from a region of North America that has one of the longest histories of European colonization. Lac Saint-Augustin is located at the edge of the municipality of Québec City, Canada (Fig. 1). This lake has experienced serious deterioration of its water quality in recent decades to the point that water sport activities are now prohibited between July and September owing to the massive proliferation of cyanobacteria (blue-green algae) during this period. Our aim was to determine the preanthropogenic state of the lake as well as the timing and cause of eutrophication to aid future management decisions. We used a range of paleolimnological proxies as indicators of water quality, with emphasis on fossil diatoms, pigments, and geochemical analyses. In addition, we applied an inference model based on diatoms from 81 lakes in the northeastern United States (Köster et al. 2004) to the fossil diatom assemblages to quantitatively reconstruct past trends in total phosphorus (TP) concentrations.

Study site

Lac Saint-Augustin (46°42'N, 71°22'W) is located in suburban Québec City along the north shore of the St. Lawrence River (Fig. 1). It lies in the St. Lawrence Lowlands south of the Canadian Shield. Lac Saint-Augustin's drainage basin covers an area of 7.64 km², of which 8.8% is occupied by the lake itself. The maximum fetch length is 2.1 km with a maximum width of approximately 300 m (Meunier and Alain 1979). The average depth of the lake basin is 3.6 m with a maximum depth of 6.1 m (Fig. 1). The lake has few small surface inflows and underground sources with a water renewal time within the basin of about 6 months (Roberge et al. 2002). It has a relatively high conductivity (750 µS/cm) and its pH varies within the alkaline range of 8.5–9.2. The lake currently experiences summer blooms of cyanobacteria with total phosphorus (TP) concentrations in excess of 50 µg/L and peak chlorophyll *a* (Chl *a*) concentrations greater than 100 µg/L (Bouchard-Valentine et al. 2004).

The Québec City region was settled by Europeans at the beginning of the 17th century (1608). The lake is located within the municipality of Saint-Augustin-de-Desmaures that was established by French colonists in 1691 (Arcand 1991). The population and land use of the catchment have changed markedly over the last 300 years, with the greatest change occurring during the second half of the 20th century.

From 1960 onwards, the urbanization of the catchment has accelerated, with summer cottages located on the lake shore being replaced by permanent residences (Fig. 2). A major highway (Felix-Leclerc Highway 40) (Figs. 1 and 2) was built through part of the lake's catchment in 1977. This construction also corresponded to a demographic explosion experienced by the municipality at the end of the 1970s (Arcand 1991). At present, agricultural land makes up approximately 20%–25% of the catchment (Fig. 2), whereas the forested and residential zones occupy 20% and 30%–35%, respectively (Ministère des Ressources Naturelles et de la Faune du Québec 2002).

Materials and methods

Sampling and sediment analysis

A 76 cm sediment core was retrieved on 25 June 2002 from the bottom sediments near the maximum depth of the lake (Fig. 1) using a Kajak–Brinkhurst-type gravity corer (Kajak et al. 1965). The core was subsectioned at 0.5 cm intervals between 0 and 30 cm and at 1 cm intervals between 31 and 76 cm to attain high temporal resolution.

The sedimentary particle size of 0.2–0.5 g subsamples taken at 10 cm intervals in the core was determined using a radiation counter with laser diffraction (Malvern Instruments Masterizer). Sediment lithology was described according to particle size distribution in conformity with the scale of Wentworth (1922).

Sediments were freeze-dried for 4 d and reweighed to determine water content, while sediment organic matter (OM) content was determined by loss-on-ignition using the method outlined in Dean (1974). Approximately 1 cm³ of wet sediment was dried overnight at 95 °C and then weighed before and after combustion at 550 °C for 1 h.

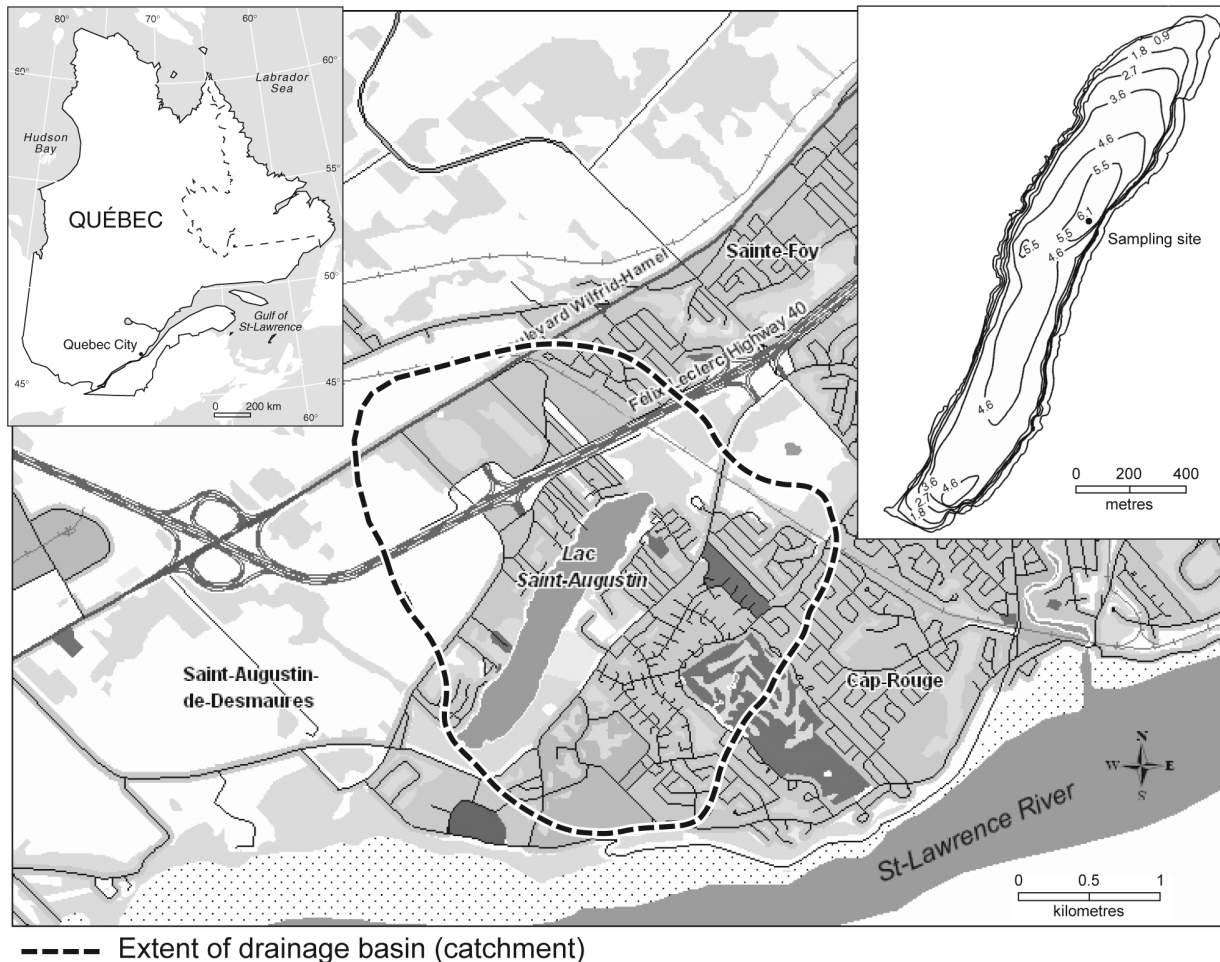
Core chronology

To estimate age and mean sediment accumulation rates for the past 100–150 years, 18 samples from the uppermost part of the core were analyzed for ²¹⁰Pb at the GEOTOP Laboratory (Université du Québec à Montréal). A minimum of 0.5 g of dry sediment was used for each sample, and ²¹⁰Pb concentrations were determined by measuring the radioactive granddaughter decay product ²¹⁰Po using alpha spectrometry. Unsupported isotopes and the constant rate of supply model were then used to transform the data into age AD (Binford 1990). A wood sample from the 75–76 cm level was analyzed for its ¹⁴C age at Beta Analytic Inc. Laboratories (Florida) by accelerator mass spectrometry.

Diatom analysis

Sample pretreatment for diatom analysis followed standard protocols (Pienitz et al. 1995) at the Paleolimnology–Paleoecology Laboratory, Université Laval. To calculate diatom concentrations, a known number of microspheres were added to the diatoms (Battarbee and Kneen 1982). The diatom–microsphere suspensions were applied on ethanol-cleaned cover glasses and, after drying at room temperature, mounted with Naphrax[®] mounting medium on microscope slides. Diatom counts (total of 500 valves per sample) were carried out using a Leica DMRB light microscope at a magnification of 1000× using differential inter-

Fig. 1. Map showing the location of Lac Saint-Augustin within western suburban Québec City (bathymetric contours are indicated in metres).



ference contrast optics. To facilitate the identification of diatom species, photographs were taken with a digital camera system (Leica DC 300). Taxonomic identifications followed those of several relevant reference works (Krammer and Lange-Bertalot 1986, 1988, 1991a, 1991b; Reavie and Smol 1998; Fallu et al. 2000). The computer programs C^2 (Juggins 2003) and ZONE (Juggins 1992) were used to graphically present the diatom stratigraphy and to identify major zones in the composition of the diatom assemblages based on the 40 most common taxa (see below).

Reconstruction of TP

A diatom-based inference model developed from a series of lakes located in the northeastern United States (Köster et al. 2004) was used to quantitatively reconstruct TP concentrations from the fossil diatom assemblages using weighted averaging partial least squares regression techniques. This model is based on modern surface sediment diatom assemblages from 81 lakes in New England states, including New Hampshire, Vermont, Connecticut, and Massachusetts (Dixit et al. 1999). These lakes had TP concentrations that varied between 0.9 and 109.5 $\mu\text{g/L}$ when sampled between 1991 and 1994.

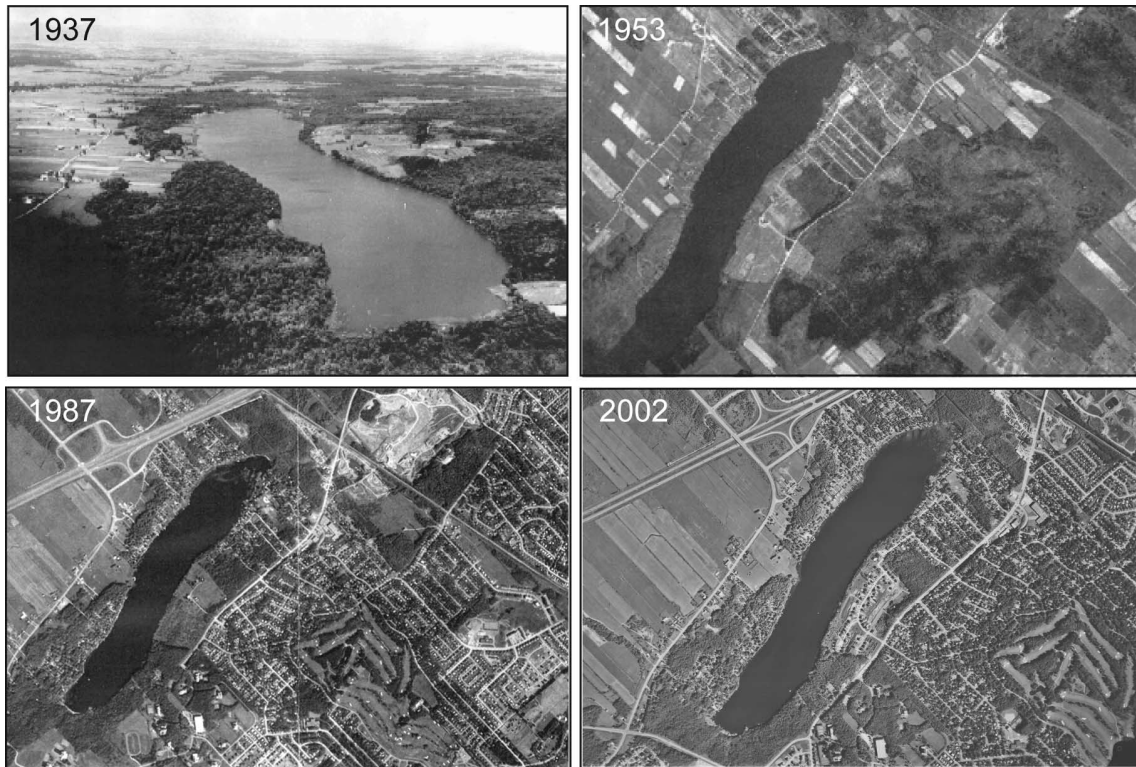
The degree of similarity (analogy) between the modern (calibration model) and fossil (core) samples from Lac

Saint-Augustin was tested with the program ANALOG (H.J.B. Birks and J.M. Line, unpublished program). Based on the mean minimum dissimilarity coefficient within the model data (modern samples), the 75% and 95% confidence intervals were calculated (Laird et al. 1998). Fossil samples with a dissimilarity coefficient lower than the 75% confidence interval were deemed to have good analogs in the calibration set, whereas dissimilarity coefficients between 75% and 95% indicated poor analogs and dissimilarity coefficients outside the 95% interval indicated no analogs (Laing et al. 1999). Furthermore, using the software CANOCO (ter Braak and Šmilauer 1998), the goodness-of-fit of the fossil assemblages to the reconstructed variable was evaluated by a canonical correspondence analysis with the first axis constrained to TP as sole explanatory variable in the modern samples and the fossil samples run passively. Fossil samples having residual lengths (distances) to the first axis outside the 95% confidence interval of the modern samples' distances were considered to have very poor fit to the variable being reconstructed (Birks et al. 1990).

Fossil pigment stratigraphy

Fossil pigments were analyzed in 38 sediment samples from the Lac Saint-Augustin core (at 2 cm intervals) using the methods outlined in Golterman (1971) and Britton

Fig. 2. Aerial photographs showing the extent of urban and agricultural development within the catchment of Lac Saint-Augustin during the years 1937–2002 (Source: Ministère de l'Énergie, des Mines et des Ressources, Québec City, Québec).



(1985). Two extractions of the pigments were necessary by sonication in 90% acetone. The extracts were cleared by centrifugation and absorption scans and then measured using a Varian Cary 300 spectrophotometer.

Geochemistry

Samples from 20 sedimentary levels evenly distributed throughout the core were freeze-dried and analyzed for geochemical constituents at the Institut National de la Recherche Scientifique – Eau, Terre et Environnement in Québec City. Analysis of metals was carried out by inductively coupled plasma atomic emission spectrometry (Varian Vista ICP-AES), and sediment nitrogen, carbon, and sulphur were measured in a Leco CHNS analyzer.

Results

Core chronology

The uppermost 30 cm of sediment corresponded to approximately 180 years of deposition (Fig. 3) where ^{210}Pb reached background levels between 24.5 and 30.5 cm depth. The ^{14}C age determined by accelerator mass spectrometry dating of the sample from the bottom of the core was 280 ± 30 calendar years B.P. (or AD 1670 \pm 30).

Sediment characteristics

At the time of sampling, three lithological units could be distinguished through visual inspection: organic and watery olive gyttja between 0 and 10 cm, fine and clayey organic mud between 10 and 50 cm, and clayey and cohesive grey and dark mud between 50 and 76 cm (Fig. 4). The OM profile agrees well with lithological changes in the sediment

Fig. 3. Age–depth curve for the sediment core from Lac Saint-Augustin based on results obtained through radioisotopic dating (^{210}Pb and ^{14}C). All dates are indicated in years AD, and only the basal date was obtained through accelerator mass spectrometry ^{14}C dating techniques (280 ± 30 calendar years B.P.).

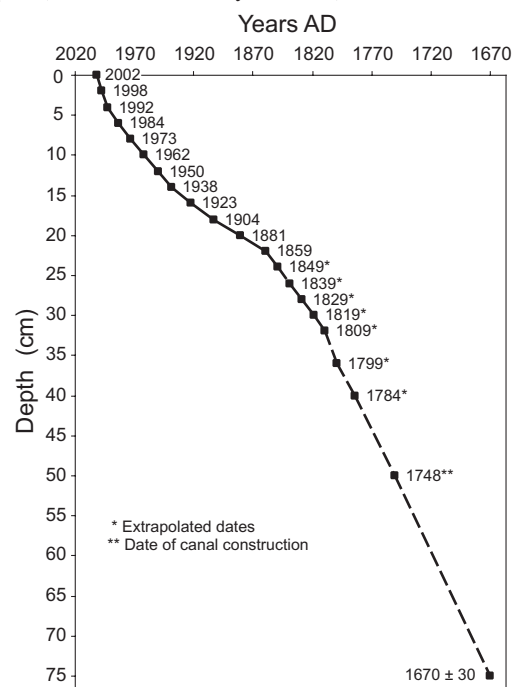
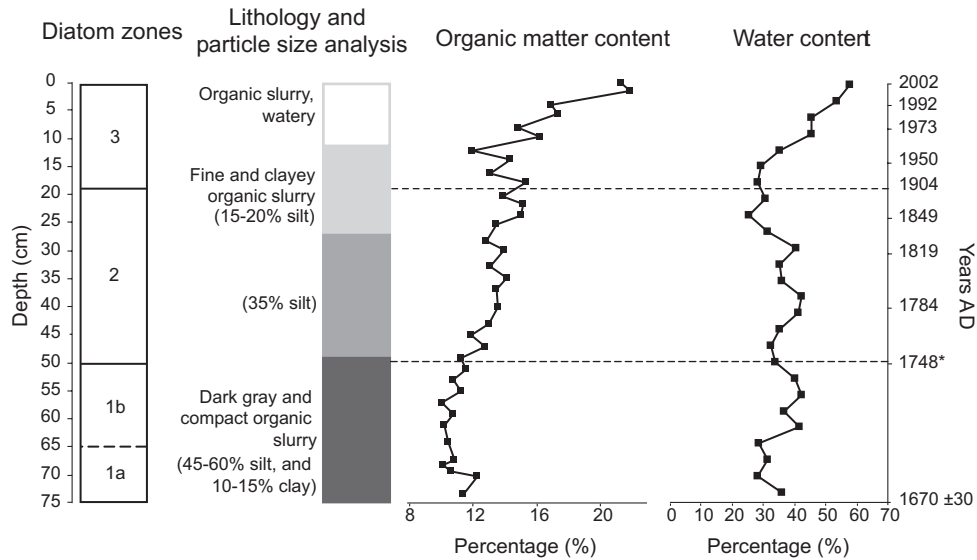


Fig. 4. Summary of sediment core characteristics. Organic matter content was estimated through loss-on-ignition analysis at 550 °C. *, date of canal construction; horizontal broken lines, diatom assemblage zone limits.



core. OM content (estimated through loss-on-ignition) was relatively low in the clay-rich sediments below 10 cm. Near the surface, OM exceeded 20%, roughly twice the concentration of sediments from the bottom of the core (Fig. 4).

Diatom assemblage zones (DAZ)

A total of 216 diatom taxa were identified in the 53 strata sampled from the Lac Saint-Augustin sediment core (Appendices A and B). Of this number, 40 were present with at least 1% relative abundance in at least five strata. After eliminating the species with lower abundances, the 21 most common diatom taxa were included in the stratigraphic diagram of the core (Fig. 5). The stratigraphy of the diatom assemblages was divided into three principal zones using a grouping analysis (optimal partitioning), the first being divided into two subzones (DAZ 1a and DAZ 1b). These diatom zones corresponded to the years AD 1670–1750 (DAZ 1), AD 1750–1904 (DAZ 2), and AD 1904–2002 (DAZ 3).

Zone 1 (76 – 50 cm, AD 1670 ± 30 to AD 1750)

The diatoms that characterized subzone 1a (76–65 cm) included four species within the genus *Aulacoseira*: *Aulacoseira alpigena*, *Aulacoseira perglabra*, *Aulacoseira ambigua*, and *Aulacoseira distans*. Among these, *Aulacoseira ambigua* had the highest relative abundance (15%–50% of total valve counts in a given sample) and was accompanied by *Tabellaria flocculosa*, *Cyclotella stelligera*, *Fragilaria construens*, *Fragilaria pinnata*, and *Fragilaria capucina* var. *vaucheriae*. *Stephanodiscus medius* was present at 5%–8% abundance.

Subzone 1b corresponds to the clayey layer found near the bottom of the core (65–50 cm). Many species found in the first subzone diminished to trace levels in 1b (i.e., *Aulacoseira alpigena*, *Aulacoseira perglabra*, *Tabellaria flocculosa*, *Stephanodiscus medius*, and *Fragilaria capucina* var. *vaucheriae*) and the relative abundance of *Aulacoseira distans* decreased considerably, declining from 10%–20% to less than 5%. Conversely, *Aulacoseira ambigua* increased substantially, reaching relative abundances exceeding 60%.

Stephanodiscus niagarae was present in abundances of 10%–12% in two levels only (i.e., 62 and 63 cm).

Zone 2 (50 – 18 cm, AD 1750 to AD 1904)

Zone 2 was characterized by the dominance of *Aulacoseira ambigua* (60%–80%). *Fragilaria pinnata* relative abundances varied between 1% and 10%. Several species were present at low relative abundances (1%–5%), such as *Aulacoseira distans*, *Stephanodiscus medius*, *Cocconeis placentula* var. *euglypta*, *Fragilaria construens*, and *Fragilaria crotonensis*.

Zone 3 (18 – 0 cm, AD 1904 to AD 2002)

Aulacoseira ambigua relative abundances declined abruptly in zone 3, decreasing from 50% to approximately 10%. Several taxa appeared for the first time, notably *Aulacoseira granulata*, *Asterionella formosa*, *Fragilaria capucina* var. *mesolepta*, *Fragilaria brevistriata*, *Diatoma tenuis*, and *Stephanodiscus hantzschii*. *Stephanodiscus hantzschii* largely dominated this zone, with abundances varying between 20% and 50%. Diatom concentrations reached peak values during this interval, particularly in the mid-1990s (Fig. 5).

Brackish diatom stratigraphy

Several species typical of brackish water conditions and saline lakes (Pienitz et al. 2000), such as *Epithemia sorex* and *Cyclotella meneghiniana*, were present in the core (Fig. 6). They did not occur before the 20th century but formed almost 11% of the diatom assemblage in the 1970s. Noteworthy is the sporadic occurrence of the marine diatom *Actinocyclus normanii* in Lac Saint-Augustin waters from about 50 years ago onwards.

Epiphytic diatom stratigraphy

Many epiphytic species were also present in the sediments of the Lac Saint-Augustin core (Fig. 6). They accounted for approximately 25% of diatom assemblages in the clay-rich sections of the core and reached maximum abundances (up

Fig. 5. Stratigraphic changes in diatom assemblage composition preserved within the Lac Saint-Augustin sediment core. The relative abundances of the most common taxa are based on counts of 500 diatom valves, whereas diatom concentration data were calculated from a known number of microspheres. Diatom assemblage zone limits were determined through optimal partitioning in the program ZONE (Juggins 1992), with solid and broken horizontal lines representing first- and second-order separations of zones, respectively. *, date of canal construction.

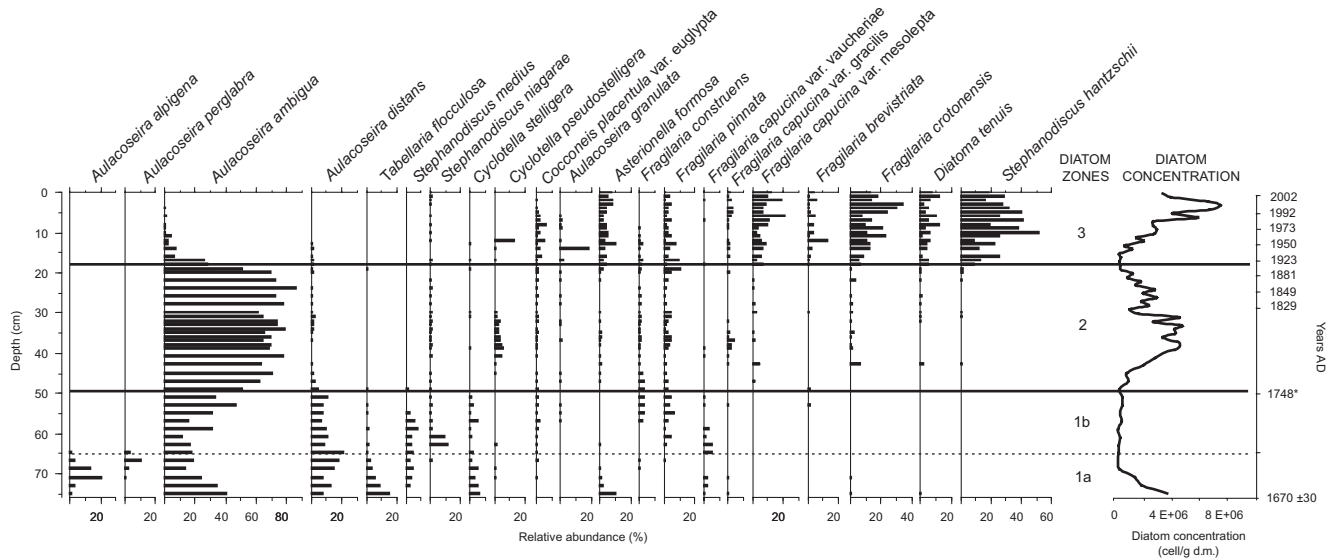
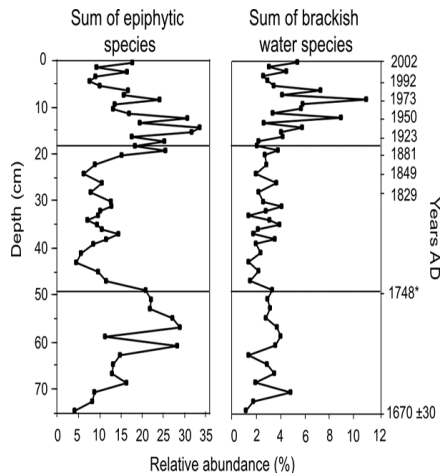


Fig. 6. Stratigraphic changes within the epiphytic and brackish water diatom components. *, date of canal construction; horizontal broken lines, diatom assemblage zone limits.



to 35%) between 1950 and 1960. As with the brackish water species, their percent abundance tended to decrease somewhat during the recent years.

Quantitative reconstructions of TP and model tests

A weighted averaging partial least squares model with one component and square root transformed species data (Köster et al. 2004) was applied to our sedimentary diatom assemblages. The jackknifed coefficient of determination for this model is $r^2_{\text{jack}} = 0.65$ with a jackknifed root mean squared error of prediction of $0.19 \mu\text{g/L}$. About 50% of the fossil diatom samples had poor modern analogues in the model data set (Fig. 7). Thirty out of a total of 53 samples were outside the 95% confidence limit, indicating little similarity between the model and fossil diatom assemblages, 20 strata placed between the confidence limits of 75% and

95%, indicating moderately good analogues for these samples, and three samples had close analogues inside the 75% confidence limit.

The generally weak analogies are likely due to the lower modern relative frequencies of some diatom taxa that were historically present at high relative abundances. For example, *Aulacoseira ambigua*, which occurred at up to 80% relative abundance in the lower part of the core, had a maximum abundance of 26% in the training set lakes on which the model is based. Similarly, *Stephanodiscus hantzschii*, which varied between 20% and 50% in the uppermost 15 samples of the core, was present in only three of the 81 training set lakes. However, reasonable reconstructions of phosphorus were possible in strata between 0 and 55 cm. Two strata (at 59 and 65 cm) with no-analogue situations and where the data exceeded the 95% limit for the goodness-of-fit test were excluded from the quantitative reconstructions (Fig. 7). Model reconstructions indicate that TP concentrations were close to $20 \mu\text{g/L}$ at the time of arrival of the European settlers, after which they rose to reach peak concentrations of almost $90 \mu\text{g/L}$ at 7 cm depth (approx. 1985). Post-1985 to the present, model reconstruction estimates imply that concentrations have decreased, varying between 45 and $56 \mu\text{g/L}$.

Fossil pigments

Chl *a* showed major variations within the sediment core (Fig. 8). Concentrations below 38 cm in the core varied between 25 and $95 \mu\text{g/g}$ dry mass, above which concentrations gradually decreased to reach a minimum of $25 \mu\text{g/g}$ dry mass at 20 cm depth near the end of the 19th century. From 1938 to 2002 (i.e., 14–0 cm core depth), Chl *a* concentrations increased by a factor of 4, reaching a maximum concentration of $180 \mu\text{g/g}$ dry mass in the mid-1990s (3 cm depth); however, a slight reduction in Chl *a* was measured in the uppermost 2 cm of the core (post-1998).

Fig. 7. Diatom-based quantitative reconstructions of total phosphorus (TP) concentrations in the water column of Lac Saint-Augustin. Analysis of the goodness-of-fit of the TP reconstruction model to the fossil diatom assemblage in the sediment core was done using the program ANALOG (H.J.B. Birks and J.M. Line, unpublished data). (A) Analogs between modern and fossil diatom assemblages. Percentages indicate the percentile based on minimum dissimilarity coefficients for the modern samples to evaluate whether sufficient analogs exist in the fossil assemblages. (B) Squared residual lengths for axis 1 determined through canonical correspondence analysis constrained to TP. (C) Diatom-inferred TP concentrations. *, date of canal construction; **, levels where data exceeded the 95% confidence limit for the goodness-of-fit test and with no-analog situations between modern and fossil diatom samples; horizontal broken lines, diatom assemblage zone limits.

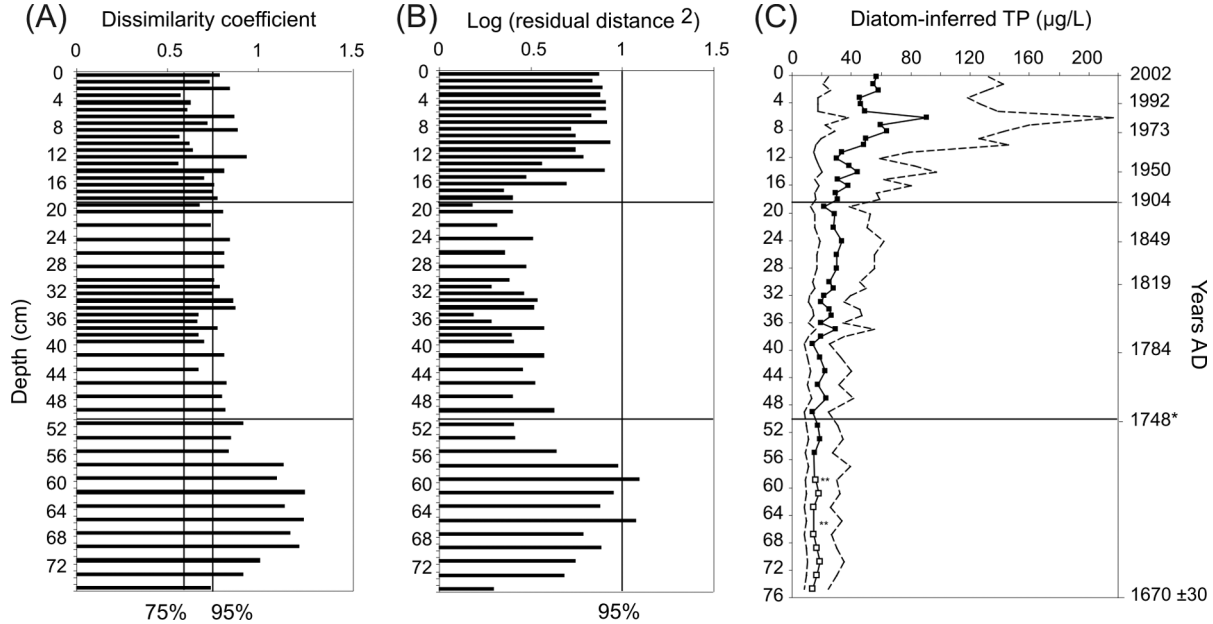
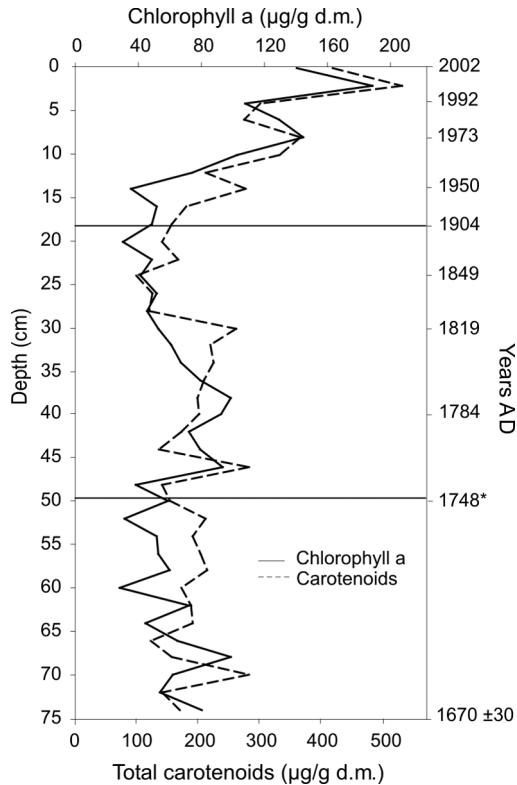


Fig. 8. Stratigraphic changes in fossil pigment (Chl *a* and total carotenoid) concentrations within the Lac Saint-Augustin sediment core. *, date of canal construction; horizontal broken lines, diatom assemblage zone limits.



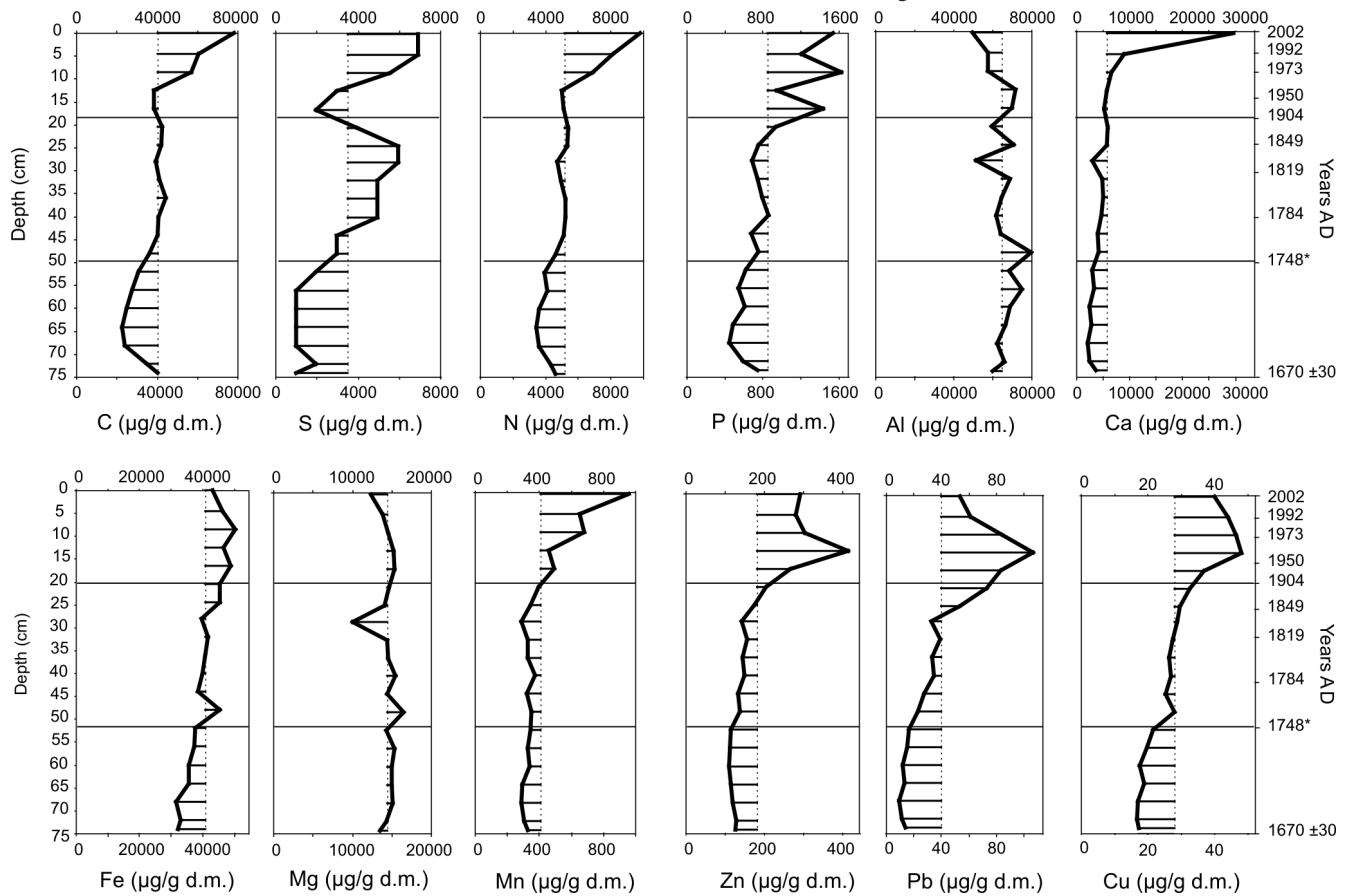
The general trends in total carotenoid concentrations were similar to those of Chl *a* (Fig. 8). Below 14 cm core depth (pre-1938), the concentrations fluctuated between 90 and 250 µg/g dry mass. Between 14 and 8 cm, the total carotenoid concentrations increased to 350 µg/g dry mass and then decreased to 5 cm (approx. 1990). From 5 cm onwards, the concentrations increased until a maximum of 510 µg/g dry mass was reached at 3 cm depth. Like Chl *a*, the total carotenoid concentrations decreased in the top 2 cm of the core.

Geochemistry

The aluminum and magnesium concentrations varied little over time compared with other elements (Fig. 9). Throughout the core, the concentrations of aluminum fluctuated between 49 000 and 79 000 µg/g dry sediment, whereas those of magnesium varied between 9000 and 16 000 µg/g dry sediment. A slight reduction in the concentration of these two elements started at approximately 15 cm depth (ca. 1930s).

Of all elements analyzed, calcium showed the greatest stability through much of the core, particularly between 76 and 8 cm. However, in the uppermost few centimetres of the core (ca. 1985 until the present-day), there was a dramatic increase in its concentration (from 2000 to 29 000 µg/g dry sediment). The sediment profiles of zinc, lead, and copper were almost identical, showing large increases at 30 cm (ca. 1820) to reach peak concentrations at about 15 cm depth (ca. 1930s). Concentrations declined steadily thereafter. Throughout the sediment profile, zinc concentrations varied between 108 and 290 µg/g dry sediment, lead between 8 and 107 µg/g dry sediment, and copper between 17 and 48 µg/g dry sediment (Fig. 9).

Fig. 9. Stratigraphic changes in geochemical characteristics (carbon, sulphur, nitrogen, phosphorus, and metals) within the Lac Saint-Augustin sediment core. *, date of canal construction; horizontal broken lines, diatom assemblage zone limits.



Sulphur concentrations varied greatly throughout the core from 1000 $\mu\text{g/g}$ dry sediment in the lowest core sections to a maximum of 7000 $\mu\text{g/g}$ dry sediment at the sediment surface. There was also a broad secondary peak in sulphur concentrations of about 6000 $\mu\text{g/g}$ dry sediment between 25 and 30 cm depth.

Manganese varied between 295 and 967 $\mu\text{g/g}$ dry sediment. The profile of this element showed stability below 30 cm depth (ca. 1820), after which a steady increase in its concentration to the core surface was evident. The concentration of iron was 32000 $\mu\text{g/g}$ dry sediment at the base of the core and subsequently increased until approximately 10 cm (early 1960s), where it reached the highest concentration at 50000 $\mu\text{g/g}$ dry sediment. Thereafter, concentrations decreased slightly, reaching 43000 $\mu\text{g/g}$ dry sediment in the uppermost sediments.

The profiles of phosphorus, carbon, and nitrogen were generally quite similar, although phosphorus showed more variability in the upper sediments. Carbon and nitrogen remained relatively stable until 15 cm (ca. 1930s), after which they increased considerably towards the sediment surface. Carbon concentrations rose from 38000 to 78000 $\mu\text{g/g}$ dry sediment, while those of nitrogen doubled, increasing from 5000 to 10000 $\mu\text{g/g}$ dry sediment. Above the 18 cm level (early 1900s), phosphorus concentrations varied considerably, fluctuating from 700 to 1400 $\mu\text{g/g}$ dry sediment and from 1400 to 900 $\mu\text{g/g}$ dry sediment within a few years.

Concentrations measured of carbon, nitrogen, and phosphorus in the surface sediments were at or near their highest level in the core, with levels of 78000 $\mu\text{g/g}$ dry sediment for carbon, 9900 $\mu\text{g/g}$ dry sediment for nitrogen, and 1500 $\mu\text{g/g}$ dry sediment for phosphorus.

Discussion

Three distinct zones were identified in the sedimentary diatom profiles of Lac Saint-Augustin (Fig. 5). These biological zones were mirrored by trends in our physical and geochemical proxies and are consistent with periods of historical change and human activity in the lake's catchment.

Zone 1: Pre- and early settlement period and canal construction (ca. AD 1670 to AD 1750)

This first zone can be subdivided into two subzones: 1a representative of the pre- and early colonial period and 1b corresponding to the construction of a diversion canal providing the water for a nearby mill (AD 1748). In this latter subzone, large amounts of sediments would have been transported into the lake basin within a very short time span. Consistent with the prevalence of fine clays, the construction of the canal likely led to increased inputs of sediments into the lake basin.

The diatom flora of this zone is typical of oligo- to mesotrophic waters, thus a moderately productive ecosystem. The

species *Aulacoseira ambigua*, which dominates the diatom assemblages, is usually found in freshwater plankton. It is known to occur in important concentrations in several rivers of western France (Germain 1981). According to several studies, *Aulacoseira ambigua* is common in mesotrophic waters throughout the United States (i.e., at TP concentrations between 8 and 39 µg/L; Diatom Paleolimnology Data Cooperative 2003). This species has been associated with periods of human colonization and settlement and, in certain cases, with precolonization periods (Karst and Smol 1998). The marked predominance of *Aulacoseira ambigua* relative to subsequent zones thus implies that the prevailing limnological conditions were very different from those of the present day.

Several taxa that were abundant in subzone 1a (i.e., *Aulacoseira alpigena*, *Aulacoseira perglabra*, *Tabellaria flocculosa*, and *Fragilaria capucina* var. *vaucheriae*) decreased to trace amounts in subzone 1b. These species, in particular *Tabellaria flocculosa*, are usually found in dilute, oligotrophic waters (Germain 1981) as well as in alkaline sites (Stevenson et al. 1996). The extremely low diatom concentrations (Fig. 5), as determined by microsphere counts, may also indicate that this zone was less productive and that dilution by the allochthonous inorganic matter fraction was important. Low productivity was also mirrored by the lowest diatom-inferred (Fig. 7) and sedimentary values (Fig. 9) for phosphorus in the entire core. However, this interpretation will require more precise chronological control within the sediment core.

The concentrations of Chl *a* and total carotenoids in this first zone remained relatively stable and low relative to recent sediments. These weak concentrations can be explained partly by oxidation of the pigments prior to their incorporation into the sediments (Sanger 1988) or through dilution by allochthonous OM. However, the generally strong correlation between sedimentary pigments and diatom-inferred TP appears to follow the expected positive relationship between phosphorus concentrations and primary productivity. As shown by Guilizzoni et al. (2001) in a sediment core from Lake Orta (northern Italy), these two factors (weak preservation and weak primary production) can occur simultaneously.

All paleolimnological indicators combined (diatoms, pigments, diatom-inferred phosphorus concentrations, and chemical elements) simultaneously indicate oligo- to mesotrophic lake conditions during the early colonial period and construction of the canal. Human occupation of the catchment surrounding Lac Saint-Augustin was in its beginnings; thus, human activities did not yet have major impacts on the trophic state of the lake ecosystem.

Zone 2: Human settlement period (ca. AD 1750 to AD 1904)

Diatom zone 2 corresponds to human settlement and the onset of deforestation in parts of the lake's catchment for agriculture and residential construction. As in systems elsewhere (e.g., Lotter 2001), deforestation would have accelerated soil erosion and increased the OM inputs into the lake (as evidenced by the loss-on-ignition results shown in Fig. 4).

Diatom assemblages in zone 2 had overall species compo-

sition similar to those in the earlier period; however, there were pronounced differences in the relative abundance of taxa. The settlement period was largely dominated by the taxon *Aulacoseira ambigua* (about 80% of the assemblage), with moderate abundances of benthic *Fragilaria pinnata* (up to 10%), suggesting that the ecosystem had remained in a mesotrophic state. Diatom concentrations were still relatively low in this zone, possibly owing to dilution by external OM inputs from deforestation and erosion of soils within the catchment area.

Concentrations of sedimentary Chl *a* and total carotenoids also remained low during the settlement period, reinforcing the mesotrophic status suggested by our diatom taxa. However, the concentrations of several metals (i.e., aluminum, magnesium, iron, zinc, lead, and copper) started to increase. This rise in metal concentrations is likely due to increased soil erosion in the catchment caused by deforestation.

During this period of human colonization, small increases in the concentrations of geochemical indicators coincided with changes in the relative importance of diatom taxa. The enrichment of copper, zinc, and lead probably resulted from erosion caused by deforestation (for construction) of certain parts of the catchment. Although this period of the sedimentary record corresponds to the earliest responses of the lake to direct anthropogenic activities, it is important to note that the population of the municipality of Saint-Augustin-de-Desmaures was still relatively small, which explains why our proxy indicators suggest that the impact at this time was minimal.

Zone 3: Agricultural, industrial, and urban period (ca. AD 1904 to AD 2002)

The third zone and uppermost section of the sediment record coincides with the expansion of agriculture within the drainage basin of Lac Saint-Augustin, the industrialization of nearby Québec City and its environs, and the rapid population growth in the municipality of Saint-Augustin-de-Desmaures. The second half of the 20th century corresponded to a period of intensive artificial fertilizer use in agriculture (Gouvernement du Québec 1954) as well as to considerable increases in residential construction that brought about pollution problems owing to raw sewage inputs and defective septic tanks (Ministère des Richesses Naturelles 1979). Also, the addition of a local industrial park in 1969 and the opening of a major highway through the catchment in 1977 have increased anthropogenic impacts on Lac Saint-Augustin.

The sharp increase in the relative abundance of the planktonic diatom species *Stephanodiscus hantzschii* in this third zone marked the onset of major change in the limnology of Lac Saint-Augustin and the transition towards advanced eutrophy. *Stephanodiscus hantzschii* is particularly common in strongly polluted waters (Germain 1981; Hall and Smol 1992) and often forms spring blooms in eutrophic and hypereutrophic lakes (Reynolds 1984; Stevenson et al. 1996). As in other lake ecosystems affected by intense human activities in their catchment, the replacement of *Aulacoseira ambigua* by *Stephanodiscus hantzschii* in the sediments suggests a phosphorus-driven succession of diatoms (Anderson 1990). Other species also increased in abundance in this zone, such as *Asterionella formosa* and *Fragilaria crotonen-*

sis (5%–15%), which are also characteristic of lakes that became eutrophic owing to anthropogenic processes (Wessels et al. 1999; Garrison and Wakeman 2000; Bennion et al. 2001; Köster et al. 2005).

During the second half of the 20th century, the diatom flora was made up almost exclusively of species typical of eutrophic waters. In addition, there was an unexpected presence of some “exotic” brackish water and marine species. This is likely the result of increasingly saline conditions from road and highway salting, a standard practice for road maintenance in Québec during winter. It is also consistent with the currently high conductivity of the lake (750 $\mu\text{S}/\text{cm}$) relative to other lakes of the region (e.g., 63 $\mu\text{S}/\text{cm}$ in Lac St-Charles; Tremblay et al. 2001).

Epiphytic species increased to approximately 30%–35% of the total diatom assemblage during the period 1940–1950 (Fig. 6), likely reflecting higher abundances of macrophytes in the littoral zone. With increasing eutrophication, planktonic taxa and diatom concentrations (Fig. 5) reached their maxima in 1992. This pattern of succession from epiphytic to planktonic diatoms recorded in the sediments of Lac Saint-Augustin generally agrees with the model of nutrient enrichment in shallow lakes, showing that macrophytes typically dominate when phosphorus loading is low and that phytoplankton dominate as phosphorus loading increases above a critical threshold (e.g., Scheffer et al. 1993; Wetzel 2001).

In Lac Saint-Augustin, there appears to be a connection between metal pollution and the abundance of the taxon *Stephanodiscus hantzschii*. Similar to our study of Lac Saint-Augustin, Reavie et al. (1998) found metals indicative of maximum pollution from the 1950s onwards in Lac Saint-François to coincide with peak abundances of *Stephanodiscus hantzschii*. As in other studies (e.g., Engstrom and Swain 1986; Guilizzoni et al. 2001), Lac Saint-Augustin sediments recorded a major and sudden increase of calcium concentrations during the 1980s, possibly as a result of increased primary production and eutrophication. An increase in primary production would have changed the carbonate equilibrium as CO_2 consumption increased through photosynthesis, thus favouring precipitation of CaCO_3 in mid-summer.

The shift towards eutrophic diatom assemblages in Lac Saint-Augustin was accompanied by increases in Chl *a* and carotenoids. This is consistent with the observations of Sabater and Haworth (1995), who suggested a link between the appearance of *Stephanodiscus hantzschii* and the abundance of fossil carotenoids in Lake Windermere (England). In part, this may represent an upshift in the production of total algal biomass, but it may also signal changes in the nondiatom flora of the lake. These authors found that in the mid-1950s, there was a synchronous increase in sedimentary myxoxanthophyll and oscillaxanthin, two carotenoids specific to cyanobacteria, and an increased abundance of *Stephanodiscus hantzschii*. Similarly, Hall et al. (1999) showed that pigments of bloom-forming cyanobacteria peaked at the time of maximum abundance of *Stephanodiscus hantzschii* (1930–1960) in lakes of the Canadian Great Plains. It is therefore possible that our observed increase in *Stephanodiscus hantzschii* in Lac Saint-Augustin at the beginning of the 20th century may have been accompanied by an increase in

cyanobacteria; however, this will require direct confirmation by high-performance liquid chromatography pigment analysis.

From the period of colonization (deforestation) onwards, major increases in diatom-inferred phosphorus (with maxima between 32 and 90 $\mu\text{g}/\text{L}$ in the second half of the 20th century) corresponded to increased primary production (indicated by a rise in Chl *a*), thereby confirming the close relationship between TP and Chl *a* as observed in numerous previous studies (e.g., Engstrom and Wright 1984; McCauley et al. 1989). Since ca. AD 1938, total carotenoid concentrations have doubled, which may be partly explained by a better preservation of these pigments under anoxic conditions at the sediment–water interface or by increased productivity of the phytoplanktonic community.

Starting in the early 1900s, the phosphorus and iron concentrations slightly increased and were more variable. Agricultural activities in lake catchments have strong impacts on the concentrations of these elements in lake waters (Arbuckle and Downing 2001). The use of artificial fertilizers to improve agricultural outputs after the Second World War is a worldwide phenomenon with known effects on the trophic state of aquatic ecosystems (Anderson 1997). On the other hand, according to a study based on interviews carried out by Pilote et al. (2002), it would seem that the use of fertilizers and pesticides was not the main source of phosphorus, since local farmers declared to have used negligible quantities of artificial fertilizers, but may explain significant increases in nitrogen in recent sediments (Fig. 9).

Both Chl *a* and carotenoids decreased in concentration in the surface strata of the core. This reduction could be potentially related to the disturbance of surface sediments, which, in this shallow lake, can be caused either by waves or by bioturbation caused by the large number of bottom-dwelling organisms (e.g., red *Tubifex* sp. worms were found within the first 5 cm of the core at the time of sampling). The decrease could also be due to the presence and increase of a third group of pigments, the phycobilins, which are associated with cyanobacteria.

Metals contained in the sediments provide indicators of industrial inputs (Blais and Kalff 1993; Boyle 2001) and in Lac Saint-Augustin reflect the growing industrialization of the Québec City region. The principal source of lead is often attributed to the combustion of leaded fuel. For example, in a study of Lac Saint-François (Québec), lead concentrations increased in the sediments until 1970 and declined thereafter (Carignan et al. 1994), coinciding with the maximum use of leaded fuel in North America between 1969 and 1974 (Trefry et al. 1985). In Lac Saint-Augustin, the maximum lead peak occurred in the 1960s, with a subsequent decline. This suggests a deviation from the typical trend and perhaps a local source of lead pollution. Atmospheric deposition may also be responsible for the increase in sulphur emissions starting at the beginning of the 20th century (Olsson et al. 1997), primarily originating from industrial pollution (Mitchell et al. 1988; Carignan 1989; Horne and Goldman 1994). The timing of the sharp rise of this element within the sediments of zone three is consistent with the onset of atmospheric deposition and acid rain effects.

In summary, the time interval represented by zone 3 was one of profound agricultural, industrial, and urban changes

that brought about the accelerated deterioration of Lac Saint-Augustin waters. The industrialization of nearby Québec City likely played a role in the enrichment of metals, as did the construction of a major highway route through the catchment. These results contrast somewhat with a study of another lake in the Québec City region, Lac Saint-Charles (Tremblay et al. 2001). However, this lake basin was much less impacted by industrial activities in Québec, possibly because of its much greater hydraulic renewal rate (less than 1 month) coupled with less impact by highway development.

This multiproxy paleolimnological study reveals a clear link between several human activities (e.g., deforestation, agriculture, urbanization, and recreational use of the lake) that have occurred and intensified in a relatively short interval and the associated deterioration of water quality. Thus, the abrupt changes in the diatom flora, the peak concentrations of most nutrients and metals, and the maximum concentrations of fossil pigments corroborate that, during the agricultural and industrial period (beginning of the 20th century), major changes in the chemical and biological water properties occurred since the early 1900s, particularly after 1950. Considering that the percentage of the catchment area occupied by agricultural lands is relatively low (approximately 20%), it seems that degradation of the water quality in Lac Saint-Augustin is mainly attributable to the intensification of urbanization of the lake shores and catchment, with associated problems of defective septic systems and an increasingly intensive residential and recreational use of the lake.

Conclusions

Our multiproxy paleolimnological study of the recent history of Lac Saint-Augustin shows that this lake was formerly much less productive than it is today, although as suggested by its shallow basin morphometry, it was unlikely to have even been highly oligotrophic. Over the course of the last three centuries, biological and geochemical indicators in the lake have responded in a sensitive and coherent way to environmental change. As a consequence of nutrient enrichment, the diatom flora has undergone major changes: the typical oligomesotrophic water species were replaced by eutrophic taxa at the beginning of the last century. Chl *a* and carotenoids have responded to increased nutrient input by a fourfold increase since the beginning of the human colonization period. Brackish water species of diatoms have appeared in parallel with the development of a highway and the major use of road salt in the catchment. Similarly, metal concentrations increased greatly from the bottom of the core towards the sediment surface, reflecting local as well as longer range sources. Diatom-inferred reconstructions of TP concentrations also revealed considerable increases through time.

Collectively, both biological and chemical indicators provide evidence that Lac Saint-Augustin was oligo- to mesotrophic less than 300 years ago and that eutrophication was largely accelerated by human activities around the lake and within its catchment. The main causes of this accelerated ecosystem eutrophication are inputs of nutrients (especially TP) owing to deforestation and urbanization of the catchment and, to a lesser degree, expansion of agricultural activities. Lake restoration and management measures will need

to target these three principal causes. The reduction of nutrient inputs to Lac Saint-Augustin thus constitutes a necessary first step to the long-term improvement of water quality within this ecosystem.

Acknowledgements

We thank the municipality of Saint-Augustin-de-Desmaures for facilitating access to the lake. Thanks also to the Centre d'études nordiques for logistic support, the Natural Sciences and Engineering Research Council of Canada, and the Fonds québécois de la recherche sur la nature et les technologies for the research grants provided to R. Pienitz and W.F. Vincent. We also would like to acknowledge Marie-Josée Martineau for her help with the fossil pigment analyses, Stéfane Prémont of the Institut National de la Recherche Scientifique – Eau, Terre et Environnement for the geochemical analyses, Dermot Antoniadis, Kathleen Rühland, and an anonymous reviewer for their valuable comments on the manuscript.

References

- Anderson, N.J. 1990. The biostratigraphy and taxonomy of small *Stephanodiscus* and *Cyclostephanos* species (Bacillariophyceae) in a eutrophic lake, and their ecological implications. *Br. Phycol. J.* **25**: 217–235.
- Anderson, N.J. 1997. Historical changes in epilimnetic phosphorus concentrations in six rural lakes in northern Ireland. *Freshw. Biol.* **38**: 427–440. doi: 10.1046/j.1365-2427.1997.00249.x.
- Arbuckle, K., and Downing, J. 2001. The influence of watershed land use on lake N:P in a predominantly agricultural landscape. *Limnol. Oceanogr.* **46**: 970–975.
- Arcand, B. 1991. A l'aube d'un quatrième siècle: Saint-Augustin-de-Desmaures, 1691–1991. Municipalité de Saint-Augustin-de-Desmaures, Québec.
- Bartsh, A.F. 1970. Accelerated eutrophication in lakes in the United States: ecological response to human activities. *Environ. Pollut.* : 133–140.
- Battarbee, R.W., and Kneen, M.J. 1982. The use of electronically counted microspheres in absolute diatom analysis. *Limnol. Oceanogr.* **27**: 184–188.
- Bennion, H., Appleby, P.G., and Phillips, G.L. 2001. Reconstructing nutrient histories in the Norfolk Broads, UK: implications for the role of diatom-total phosphorus transfer functions in shallow lake management. *J. Paleolimnol.* **26**: 181–204. doi: 10.1023/A:1011137625746.
- Binford, M.W. 1990. Calculation and uncertainty analysis of ²¹⁰Pb dates for PIRLA project lake sediment cores. *J. Paleolimnol.* **3**: 253–267.
- Birks, H.J.B., Line, J.M., Juggins, S., Stevenson, A.C., and ter Braak, C.J.F. 1990. Diatoms and pH reconstruction. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **327**: 263–278.
- Blais, J.M., and Kalff, J. 1993. Atmospheric loading of Zn, Cu, Ni, Cr, and Pb to lake sediments: the role of catchment, lake morphometry, and physico-chemical properties of the elements. *Biogeochemistry*, **23**: 1–22.
- Bouchard-Valentine, M., Vincent, W.F., and Pienitz, R. 2004. Stratification à courte terme et dynamique de mélange dans un lac eutrophe: implications pour les études de suivi de la qualité de l'eau. *In* Eau et changements climatiques: comprendre pour mieux s'adapter. Proceedings of the Annual Conference of the Canadian Water Research Association, Montréal, Qué. CWRA, Ottawa.

- Boyle, J.F. 2001. Inorganic geochemical methods in palaeolimnology. *In* Tracking environmental change using lake sediments. Vol. 2. Physical and geochemical methods. *Edited by* W.M. Last and J.P. Smol. Kluwer Academic Publishers, Dordrecht, Netherlands. pp. 83–141.
- Britton, G. 1985. General carotenoid methods. *In* Methods in enzymology. *Edited by* J.H. Law and H.C. Rilling. Academic Press, New York. pp. 113–149.
- Carignan, R. 1989. Géochimie et géochronologie sédimentaire récente de huit lacs du Témiscamingue. Gouvernement du Québec, Ministère de l'environnement, Québec, Qué.
- Carignan, R., Lorrain, S., and Lum, K. 1994. A 50-yr record of pollution by nutrients, trace metals, and organic chemicals in the St. Lawrence River. *Can. J. Fish. Aquat. Sci.* **51**: 1088–1100.
- Dean, W.E., Jr. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. *J. Sediment. Petrol.* **44**: 242–248.
- Diatom Paleolimnology Data Cooperative 2003. The Academy of Natural Sciences, Philadelphia, Pa. <http://diatom.acnatsci.org/dpdc/>.
- Dixit, A.S., Hall, R.I., Leavitt, P.R., Quinlan, R., and Smol, J.P. 2000. Effects of sequential depositional basins on lake response to urban and agricultural pollution: a palaeoecological analysis of the Qu'Appelle Valley, Saskatchewan, Canada. *Freshw. Biol.* **43**: 319–337. doi: 10.1046/j.1365-2427.2000.00516.x.
- Dixit, S.S., Smol, J.P., Charles, D.F., Hugues, R.M., Paulsen, S.G., and Collins, G.B. 1999. Assessing water quality changes in the lakes of the northeastern United States using sediment diatoms. *Can. J. Fish. Aquat. Sci.* **56**: 131–152. doi: 10.1139/cjfas-56-1-131.
- Engstrom, D.R., and Swain, E.B. 1986. The chemistry of lake sediments in time and space. *Hydrobiologia*, **143**: 37–44. doi: 10.1007/BF00026642.
- Engstrom, D.R., and Wright, H.E. 1984. Chemical stratigraphy of lake sediments as a record of environmental change. *In* Lake sediments and environmental history: studies in palaeolimnology and palaeoecology in honour of Winifred Tutin. *Edited by* E.Y. Haworth and J.W.G. Lund. University of Minnesota Press, Minneapolis, Minn. pp. 11–67.
- Fallu, M.-A., Allaire, N., and Pienitz, R. 2000. Freshwater diatoms from northern Québec and Labrador (Canada). *In* Bibliotheca Diatomologica. Vol. 45. J. Cramer, Berlin and Stuttgart.
- Garrison, P.J., and Wakeman, R.S. 2000. Use of paleolimnology to document the effect of lake shoreland development on water quality. *J. Paleolimnol.* **24**: 369–393. doi: 10.1023/A:1008107706726.
- Germain, H. 1981. Flore des diatomées, eaux douces et eaux saumâtres. Société Nouvelle des Éditions Boubée, Paris.
- Golterman, H.L. 1971. Methods for chemical analysis of fresh waters. IBP Handbook No. 8, Blackwell, Oxford.
- Gouvernement du Québec, G. 1954. Annuaire statistique du Québec. Ministère de l'Industrie et du Commerce, Archives Nationales du Québec, Québec City, Qué.
- Guilizzoni, P., Lami, A., Marchetto, A., Appleby, P., and Alvisi, F. 2001. Fourteen years of paleolimnological research of a past industrial polluted lake (L. Orta, northern Italy): an overview. *J. Limnol.* **60**: 249–262.
- Hall, R.I., and Smol, J.P. 1992. A weighted-averaging regression and calibration model for inferring total phosphorus concentration from diatoms in British Columbia (Canada) lakes. *Freshw. Biol.* **27**: 417–434.
- Hall, R.I., Leavitt, P.R., Smol, J.P., and Zirnelt, N. 1997. Comparison of diatoms, fossil pigments and historical records as measures of lake eutrophication. *Freshw. Biol.* **38**: 401–417. doi: 10.1046/j.1365-2427.1997.00251.x.
- Hall, R.I., Leavitt, P.R., Quinlan, R., Dixit, A.S., and Smol, J.P. 1999. Effects of agriculture, urbanization, and climate on water quality in the northern Great Plains. *Limnol. Oceanogr.* **44**: 739–756.
- Horne, A.J., and Goldman, C.R. 1994. *Limnology*. McGraw-Hill, New York and Montréal.
- Juggins, S. 1992. TRAN (version 1.8) and ZONE (version 1.2) user manual. University of Newcastle, Newcastle upon Tyne, UK.
- Juggins, S. 2003. C² user guide. Software for ecological and palaeoecological data analysis and visualisation. University of Newcastle, Newcastle upon Tyne, UK.
- Kajak, Z., Kacprzak, K., and Polkowski, R. 1965. Chwytać rurowy do pobierania prób dna. *Ekol. Pol. Ser. B*, **11**: 159–165.
- Karst, T.L., and Smol, J.P. 1998. Tracking the cultural eutrophication history of Collins Lake (southeastern Ontario, Canada) using paleolimnological techniques. *J. Lake Reservoir Manag.* **14**: 456–465.
- Köster, D., Racca, J.M.J., and Pienitz, R. 2004. Diatom-based inference models and reconstructions revisited: methods and transformations. *J. Paleolimnol.* **32**: 233–246.
- Köster, D., Pienitz, R., Wolfe, B.B., Barry, S., Foster, D.R., and Dixit, S.S. 2005. Paleolimnological assessment of human-induced impacts on Walden Pond (Massachusetts, USA) using diatoms and stable isotopes. *J. Aquat. Ecosyst. Health Manage.* **8**: 117–131.
- Krammer, K., and Lange-Bertalot, H. 1986. Bacillariophyceae 1. Teil: Naviculaceae. *In* Süßwasserflora von Mitteleuropa. Band 2/1. *Edited by* H. Ettl, J. Gerloff, H. Heynig, and D. Mollenhauer. Gustav Fischer Verlag, Stuttgart and New York.
- Krammer, K., and Lange-Bertalot, H. 1988. Bacillariophyceae 2. Teil: Bacillariophyceae, Epithemiaceae, Surirellaceae. *In* Süßwasserflora von Mitteleuropa. Band 2/2. *Edited by* H. Ettl, J. Gerloff, H. Heynig, and D. Mollenhauer. Gustav Fischer Verlag, Stuttgart and New York.
- Krammer, K., and Lange-Bertalot, H. 1991a. Bacillariophyceae 3. Teil: Centrales, Fragilariaceae, Eunotiaceae. *In* Süßwasserflora von Mitteleuropa. Band 2/3. *Edited by* H. Ettl, J. Gerloff, H. Heynig, and D. Mollenhauer. Gustav Fischer Verlag, Stuttgart and Jena.
- Krammer, K., and Lange-Bertalot, H. 1991b. Bacillariophyceae 4. Teil: Achnantheaceae, Kritische Ergänzungen zu Navicula (Lineolata) and Gomphonema. *In* Süßwasserflora von Mitteleuropa. Band 2/4. *Edited by* H. Ettl, G. Gärtner, J. Gerloff, H. Heynig, and D. Mollenhauer. Gustav Fischer Verlag, Stuttgart and Jena.
- Kumagai, M., and Vincent, W.F. (Editors) 2003. Freshwater management: global versus local perspectives. Springer-Verlag, Tokyo.
- Laing, T.E., Rühland, K., and Smol, J.P. 1999. Past environmental and climatic changes related to tree-line shifts inferred from fossil diatoms from a lake near the Lena River Delta, Siberia. *Holocene*, **9**: 547–557. doi: 10.1191/095968399675614733.
- Laird, K.R., Fritz, S.C., and Cumming, B. 1998. A diatom-based reconstruction of drought intensity, duration, and frequency from Moon Lake, North Dakota: a sub-decadal record of the last 2300 years. *J. Paleolimnol.* **19**: 161–179. doi: 10.1023/A:1007929006001.
- Lotter, A.F. 2001. The palaeolimnology of Soppensee (central Switzerland), as evidenced by diatom, pollen, and fossil-pigment analyses. *J. Paleolimnol.* **25**: 65–79. doi: 10.1023/A:1008140122230.
- McCauley, E., Downing, J.A., and Watson, S. 1989. Sigmoid rela-

- tionships between nutrients and chlorophyll among lakes. *Can. J. Fish. Aquat. Sci.* **46**: 1171–1175.
- Meunier, P., and Alain, J. 1979. La diagnose écologique en milieu lacustre. Direction régionale des eaux. Ministère des Richesses Naturelles, Québec, Qué.
- Ministère des Richesses Naturelles 1979. Rapport de la diagnose écologique du lac Saint-Augustin. Direction Générale des Eaux, Québec, Qué.
- Mitchell, M.J., Schindler, S.C., Owen, J.S., and Norton, S.A. 1988. Comparison of sulfur concentrations within lake sediment profiles. *Hydrobiologia*, **157**: 219–229. doi: 10.1007/BF00004199.
- Olsson, S., Regnell, J., Persson, A., and Sandgren, P. 1997. Sediment-chemistry response to land-use change and pollutant loading in a hypertrophic lake, southern Sweden. *J. Paleolimnol.* **17**: 275–294. doi: 10.1023/A:1007967832177.
- Pan, Y., and Brugam, R. 1997. Human disturbance and trophic status changes in Crystal Lake, McHenry County, Illinois, USA. *J. Paleolimnol.* **17**: 369–376.
- Pienitz, R., and Vincent, W.F. 2003. Generic approaches towards water quality monitoring based on paleolimnology. In *Freshwater management: global versus local perspectives*. Edited by M. Kumagai and W.F. Vincent. Springer-Verlag, Tokyo. pp. 61–82.
- Pienitz, R., Smol, J.P., and Birks, H.J.B. 1995. Assessment of freshwater diatoms as quantitative indicators of past climatic change in the Yukon and Northwest Territories, Canada. *J. Paleolimnol.* **13**: 21–49. doi: 10.1007/BF00678109.
- Pienitz, R., Smol, J.P., Last, W.M., Leavitt, P.R., and Cumming, B.F. 2000. Multiproxy Holocene palaeoclimatic record from a saline lake in the Canadian Subarctic. *Holocene*, **10**: 673–686. doi: 10.1191/09596830094935.
- Pilote, R., Buon, E., and Arsénault, S. 2002. Portrait agroenvironnemental du bassin versant du lac Saint-Augustin. Prepared for the Conseil de Bassin du lac Saint-Augustin by EXXEP Environnement, Québec, Qué.
- Reavie, E.D., and Smol, J.P. 1998. Freshwater diatoms from the St. Lawrence River. In *Bibliotheca Diatomologica*. Vol. 41. J. Cramer, Berlin and Stuttgart.
- Reavie, E.D., Smol, J.P., Carignan, R., and Lorrain, S. 1998. Diatom paleolimnology of two fluvial lakes in the St. Lawrence River: a reconstruction of environmental changes during the last century. *J. Phycol.* **34**: 446–456. doi: 10.1046/j.1529-8817.1998.340446.x.
- Reynolds, C.S. 1984. The ecology of freshwater phytoplankton. Cambridge University Press, Cambridge, UK.
- Roberge, K., Pienitz, R., and Arsénault, S. 2002. Eutrophisation rapide du lac Saint-Augustin, Québec: étude paléolimnologique pour une reconstitution de la qualité de l'eau. *Nat. Can.* **126**: 68–82.
- Sabater, S., and Haworth, E.Y. 1995. An assessment of recent trophic changes in Windermere South Basin (England) based on diatom remains and fossil pigments. *J. Paleolimnol.* **14**: 151–163. doi: 10.1007/BF00735479.
- Sanger, J.E. 1988. Fossil pigments in paleoecology and paleolimnology. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **62**: 343–359. doi: 10.1016/0031-0182(88)90061-2.
- Scheffer, M., Hosper, S.H., Meijer, M.-L., Moss, B., and Jeppesen, E. 1993. Alternative equilibria in shallow lakes. *Trends Ecol. Evol.* **8**: 275–279. doi: 10.1016/0169-5347(93)90254-M.
- Stevenson, R.J., Bothwell, M.L., and Lowe, R.L. 1996. *Algal ecology: freshwater benthic ecosystems*. Academic Press, San Diego and Toronto.
- ter Braak, C.J.F., and Šmilauer, P. 1998. CANOCO reference manual and user's guide to Canoco for Windows. Software for Canonical Community Ordination (version 4). Centre for Biometry Wageningen, Wageningen, Netherlands, and Microcomputer Power, Ithaca, N.Y.
- Trefry, J.H., Metz, S., Trocine, R.P., and Nelson, T. 1985. A decline in lead transport by the Mississippi River. *Science* (Washington, D.C.), **230**: 439–441.
- Tremblay, R., Légaré, S., Pienitz, R., Vincent, W.F., and Hall, R.I. 2001. Étude paléolimnologique de l'histoire trophique du lac Saint-Charles, réservoir d'eau potable de la Communauté Urbaine de Québec. *Rev. Sci. Eau*, **14**: 489–510.
- Wentworth, C.K. 1922. A scale of grade and class terms for clastic sediments. *J. Geol.* **30**: 377–392.
- Wessels, M., Mohaupt, K., Kuemmerlin, R., and Lenhard, A. 1999. Reconstructing past eutrophication trends from diatoms and biogenic silica in the sediment and the pelagic zone of Lake Constance, Germany. *J. Paleolimnol.* **21**: 171–192. doi: 10.1023/A:1008080922586.
- Wetzel, R.G. 2001. *Limnology*. 3rd ed. Academic Press, San Diego, Calif.

Appendix A. Taxonomic list of all of the diatom taxa encountered in the sediment core from Lac Saint-Augustin

Achnanthes

- A. bottnica* (Cleve) Cleve
A. clevei var. *bottnica* Cleve
A. clevei Grunow
A. conspicua Mayer
A. exigua Grunow
A. joursacense Heribaud
A. lanceolata (Brébisson) Grunow
A. lanceolata var. *frequentissima* Lange-Bertalot
A. lanceolata var. *rostrata* (Østrup) Hustedt
A. laterostrata Hustedt
A. minutissima Kützing
A. oblongella (Østrup)
A. peragalli Brun & Heribaud
A. pusilla Grunow (Cleve & Grunow)
A. saccula Carter
A. subatomoides (Hustedt) Lange-Bertalot & Archibald
A. suchlandtii Hustedt
A. ventralis (Krasske) Lange-Bertalot
A. sp. (2)

Actinocyclus

- A. normanii* (Gregory) Hustedt

Amphora

- A. fagediana* Krammer
A. ovalis (Kützing) Kützing
A. pediculus (Kützing) Grunow

Anomoconeis

- A. brachysira* (Brébisson) Grunow

Asterionnella

- A. formosa* Hassall

Aulacoseira

- A. alpigena* (Grunow) Krammer

A. ambigua (Grunow) Simonsen
A. distans (Ehrenberg) Simonsen
A. granulata (Ehrenberg) Simonsen
A. perglabra (Østrup) Haworth
A. tenuior (Grunow) Krammer

Brachysira

B. apanina (Ehrenberg) Cleve

Caloneis

C. molaris (Grunow) Krammer
C. silicula (Ehrenberg) Cleve
C. schumanniana (Grunow) Cleve

Cocconeis

C. placentula var. *euglypta* Ehrenberg
C. placentula var. *lineata* (Ehrenberg) Van Heurck

Cyclotella

C. bodanica var. *lemanica* (O. Müller ex Schröter) Bachmann
C. meneghiniana Kützing
C. pseudostelligera Hustedt
C. stelligera (Cleve & Grunow) Van Heurck

Cymatopleura

C. elliptica (Brébisson) W. Smith
C. solea (Brébisson) W. Smith

Cymbella

C. caespitosa (Kützing) Brun
C. cistula (Ehrenberg) Kirchner
C. cuspidata Kützing
C. microcephala Grunow
C. minuta Hilse ex Rabenhorst
C. naviculiformis (Auerswald) Cleve
C. cf. proxima
C. proxima Reimer
C. silesiaca Bleisch in Rabenhorst
C. sinuata Gregory
C. sp. (1)

Diatoma

D. mesodon (Ehrenberg) Kützing
D. tenuis Agardh
D. vulgaris Bory

Diploneis

D. elliptica (Kützing) Cleve
D. finnica (Ehrenberg) Cleve
D. oblongella (Naegeli) Cleve-Euler

Epithemia

E. adnata (Kützing) Brébisson
E. argus (Ehrenberg) Kützing
E. argus var. *alpestris* (W. Smith) Grunow
E. frickei Krammer
E. turgida (Ehrenberg) Kützing
E. turgida var. *granulata* (Ehrenberg) Brun
E. sorex Kützing

E. sp. (1)

Eunotia

E. bilunaris (Ehrenberg) Mills
E. circumborealis Lange-Bertalot & Nörpel
E. incisa Gregory
E. minor (Kützing) Grunow
E. muelleri Hustedt
E. praerupta Ehrenberg
E. pectinalis (Dillwyn) Rabenhorst
E. pectinalis var. *undulata* (Ralfs) Rabenhorst
E. formica Ehrenberg
E. flexuosa (Brébisson) Kützing
E. serra var. *tetraodon* (Ehrenberg) Nörpel
E. sp. (1)

Fragilaria

F. brevistriata (Grunow) Van Heurck
F. capucina var. *gracilis* (Østrup) Hustedt
F. capucina var. *mesolepta* (Rabenhorst) Rabenhorst
F. capucina var. *vaucheriae* (Kützing) Lange-Bertalot
F. capucina Desmazières
F. constricta, *stricta* Cleve
F. construens (Ehrenberg) Grunow
F. construens var. *binodis* (Ehrenberg) Grunow
F. construens var. *pumila* Grunow
F. construens var. *venter* (Ehrenberg) Grunow
F. crotonensis Kitton
F. elliptica Schumann
F. exigua Grunow
F. famelica (Kützing) Lange-Bertalot
F. fasciculata (Agardh) Lange-Bertalot
F. leptostauron (Ehrenberg) Hustedt
F. nanana Lange-Bertalot
F. neoproducta Lange-Bertalot
F. parasitica (W. Smith) Grunow
F. parasitica var. *subconstricta* Grunow
F. pinnata Ehrenberg
F. pinnata var. *intercedens* (Grunow) Hustedt
F. pulchella (Ralfs) Lange-Bertalot
F. ulna (Nitxsch) Lange-Bertalot
F. virescens var. *exigua* (Grunow) Van Heurck
F. sp. (4)

Frustulia

F. rhomboides (Ehrenberg) De Toni

Gomphonema

G. acuminatum Ehrenberg
G. angustatum Kützing
G. amoneum Lange-Bertalot
G. augur Ehrenberg
G. clavatum Ehrenberg
G. clevei Fricke
G. globiferum Meister
G. grovei M. Schmidt
G. minutum (Agardh) Agardh
G. parvulum (Kützing) Kützing
G. subtile Ehrenberg
G. truncatum Ehrenberg
G. (girdle view)

G. sp. (7)

Gyrosigma

G. acuminatum (Kützing) Rabenhorst

Mastogloia

M. smithii Thwaites

Meridion

M. circulare var. *constrictum* (Ralfs) Van Heurck

Navicula

N. cf. *absoluta* Hustedt

N. accomoda Hustedt

N. capitata Ehrenberg

N. capitatoradiata Germain

N. cocconeiformis (Greville) Gregory

N. diluviana Krasske

N. hambergii Hustedt

N. helensis Schulz

N. ignota var. *palustris* (Hustedt) Lund

N. laterostrata Hustedt

N. lesmonensis Hustedt

N. minima Grunow

N. peregrina (Ehrenberg) Kützing

N. pupula Kützing

N. phyllepta Kützing

N. placentula (Ehrenberg) Grunow

N. porifera var. *opportuna* Lange-Bertalot

N. pusilla W. Smith

N. pseudoscutiformis Hustedt

N. radiosa Kützing

N. rhynchocephala Kützing

N. seminulum Grunow

N. schadei Krasske

N. slesvicensis Grunow

N. submuralis Hustedt

N. tenelloides Hustedt

N. tripuncta (O.F. Müller) Bory

N. ventralis Krasske

N. viridula var. *linearis* Hustedt

N. viridula var. *rostellata* (Kützing) Cleve

N. sp. (14)

Neidium

N. ampliatum (Ehrenberg) Krammer

N. iridis (Ehrenberg) Cleve

Nitzschia

N. acuminata (W. Smith) Grunow

N. amphibia Grunow

N. amphibia f. *frauenfeldii* (Grunow) Lange-Bertalot

N. capitellata Hustedt

N. dissipata (Kützing) Grunow

N. frustulum (Kützing) Grunow

N. recta Hantzsch

N. sp. (1)

Pinnularia

P. brandelii Cleve

P. gibba (Ehrenberg) O. Müller

P. nodosa (Ehrenberg) W. Smith

P. maior (Kützing) Rabenhorst

P. rupestris Hantzsch

P. viridis (Nitzsch) Ehrenberg

P. sp. (2)

Rhoicosphenia

R. abbreviata (Agardh) Lange-Bertalot

Rhopalodia

R. gibba (Ehrenberg) O. Müller

Stauroneis

S. acuta W. Smith

S. phoenicenteron (Nitzsch) Ehrenberg

S. nobilis Schumann

S. smithii Grunow

Stephanodiscus

S. hantzschii Grunow

S. niagarae Ehrenberg

S. medius Håkansson

Surirella

S. angusta Kützing

S. sp. (1)

Synedra

S. ulna (Nitzsch) Ehrenberg

Tabellaria

T. fenestrata (Lyngbye) Kützing

T. flocculosa (Roth) Kützing

Tetracyclus

T. glans (Ehrenberg) Mills

Tryblionella

Tryblionella sp.

Appendix B. Photographic plates of the diatom taxa most abundant in the sediment core from Lac Saint-Augustin

Plates 1–3 show some of the diatom taxa that were most abundant in the respective diatom assemblage zones 1–3 (see text and Fig. 5).

Plate 1. Select diatom taxa typical of diatom assemblage zones 1 and 2. **Fig. 1.** *Aulacoseira alpigena* (Grunow) Krammer. **Fig. 2.** *Aulacoseira distans* (Ehrenberg) Simonsen. **Fig. 3.** *Aulacoseira perglabra* (Østrup) Haworth. **Fig. 4.** *Aulacoseira tenuior* (Krammer) Grunow. **Fig. 5.** *Stephanodiscus medius* Håkansson. **Fig. 6.** *Cyclotella stelligera* Cleve & Grunow. **Fig. 7.** *Tabellaria flocculosa* (Roth) Kützing. **Fig. 8.** *Tabellaria fenestrata* (Lyngbye) Kützing. **Fig. 9.** *Fragilaria capucina* var. *vaucheriae* (Kützing) Lange-Bertalot. **Fig. 10.** *Eunotia incisa* Gregory. **Fig. 11.** *Eunotia minor* (Kützing) Grunow in Van Heurck. **Fig. 12.** *Eunotia muelleri* Hustedt. **Fig. 13.** *Eunotia praeupta* Ehrenberg. **Fig. 14.** *Eunotia pectinalis* var. *undulata* (Ralfs) Rabenhorst. **Fig. 15.** *Eunotia formica* Ehrenberg. **Fig. 16.** *Cymbella silesiaca* Bleisch. **Fig. 17.** *Achnanthes pusilla* Grunow. **Fig. 18.** *Achnanthes joursacense* Héribaud. **Fig. 19.** *Achnanthes clevei* Grunow. **Fig. 20.** *Achnanthes exigua* Grunow. **Fig. 21.** *Gomphonema acuminatum* Ehrenberg. **Fig. 22.** *Gomphonema parvulum* Kützing. **Fig. 23.** *Frustulia rhomboides* (Ehrenberg) De Toni. **Fig. 24.** *Navicula laevis* Kützing. **Fig. 25.** *Navicula radiosa* Kützing. **Fig. 26.** *Caloneis silicula* (Ehrenberg) Cleve. **Fig. 27.** *Neidium ampliutum* (Ehrenberg) Krammer. Magnification $\times 1300$.

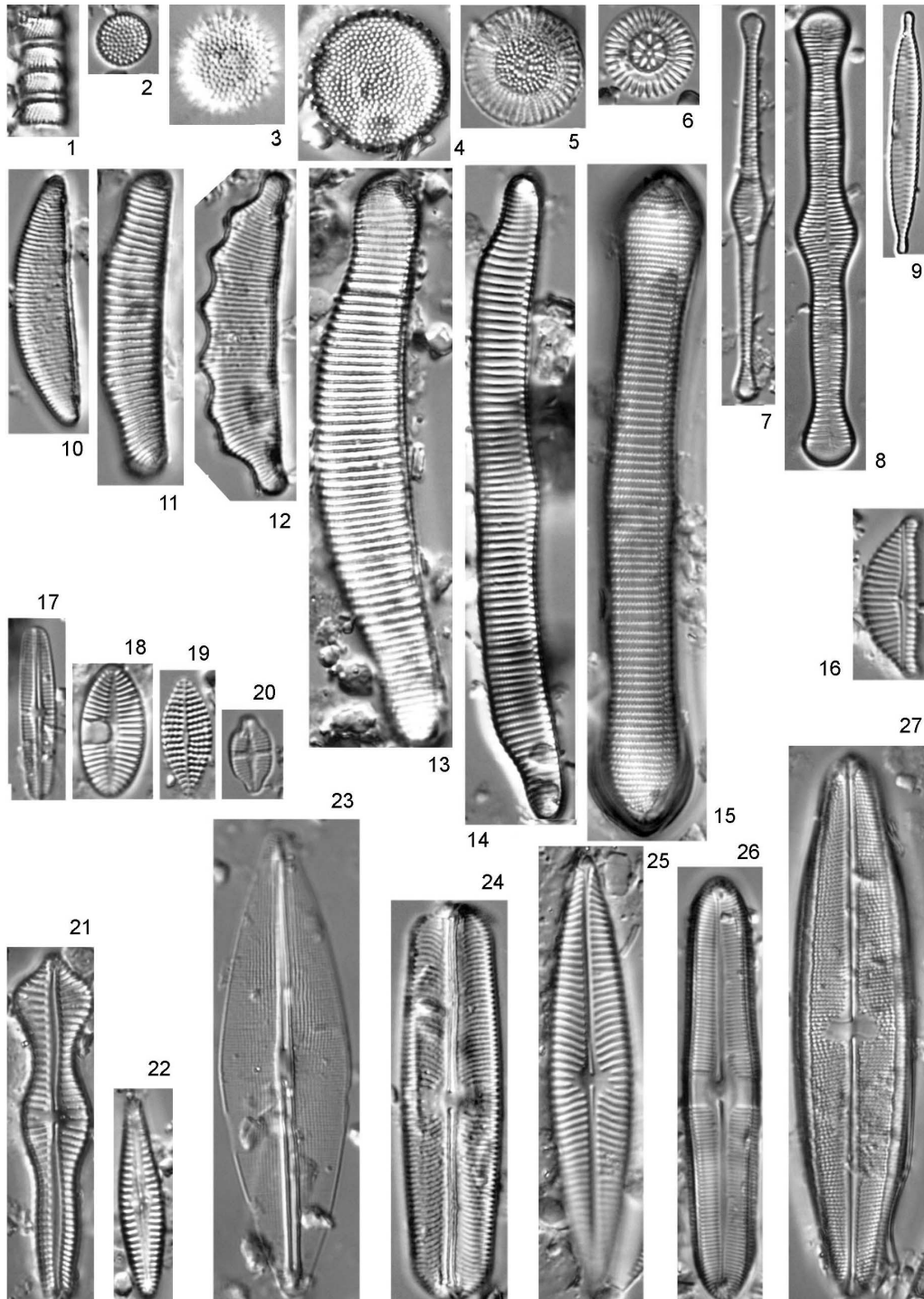


Plate 2. Select diatom taxa typical of diatom assemblage zones 1 and 2. **Fig. 1.** *Aulacoseira ambigua* (Grunow) Simonsen. **Fig. 2–2'.** *Stephanodiscus niagarae* Ehrenberg. **Fig. 3.** *Achnanthes peragalli* Brun & Héribaud. **Fig. 4.** *Diploneis elliptica* Kützing (Cleve). **Fig. 5.** *Fragilaria leptostauron* (Ehrenberg) Hustedt. **Fig. 6.** *Epithemia frickey* Krammer. **Fig. 7.** *Eunotia circumborealis* Nörpel & Lange-Bertalot. **Fig. 8.** *Eunotia serra* var. *tetraodon* (Ehrenberg) Nörpel. **Fig. 9.** *Navicula peregrina* (Ehrenberg) Kützing. **Fig. 10.** *Navicula capitata* Ehrenberg. **Fig. 11.** *Navicula pupula* Kützing. **Fig. 12.** *Cymbella sinuata* Gregory. **Fig. 13.** *Caloneis molaris* (Grunow) Krammer. **Fig. 14.** *Stauroneis phoenicenteron* (Nitzsch) Ehrenberg. **Fig. 15–15'.** *Nitzschia acuminata* (W.Smith) Grunow. **Fig. 16.** *Gyrosigma acuminatum* (Kützing) Rabenhorst. Magnification $\times 1300$.

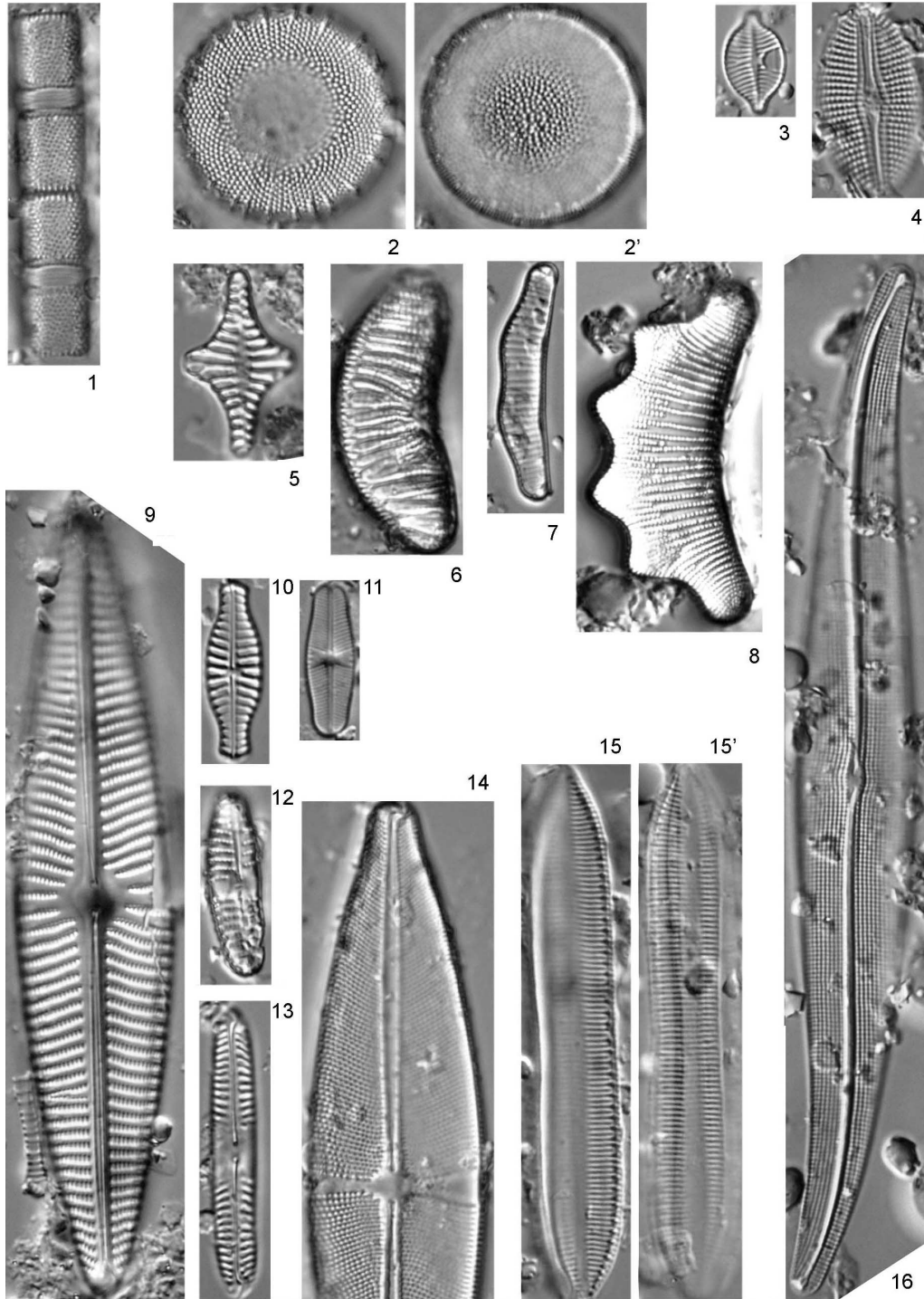


Plate 3. Select diatom taxa typical of diatom assemblage zone 3. **Fig. 1.** *Actinocyclus normanii* (Gregory) Hustedt. **Fig. 2.** *Cyclotella meneghiniana* Kützing. **Fig. 3.** *Stephanodiscus hantzschii* Grunow. **Fig. 4.** *Diatoma vulgare* Bory. **Fig. 5.** *Diatoma tenuis* Agardh. **Fig. 6.** *Asterionella formosa* Hassall. **Fig. 7.** *Cocconeis placentula* var. *lineata* Ehrenberg. **Fig. 8.** *Fragilaria crotonensis* Kitton. **Fig. 9.** *Fragilaria pinnata* Ehrenberg. **Fig. 10.** *Fragilaria brevistriata* Grunow. **Fig. 11.** *Fragilaria parasitica* (W.Smith) Grunow. **Fig. 12.** *Fragilaria parasitica* var. *subconstricta* Grunow. **Fig. 13.** *Fragilaria construens* Ehrenberg. **Fig. 14.** *Fragilaria construens* f. *venter* (Ehrenberg) Hustedt. **Fig. 15.** *Fragilaria capucina* var. *mesolepta* (Rabenhorst). **Fig. 16.** *Epithemia sorex* Kützing. **Fig. 17.** *Caloneis schumanniana* (Grunow) Cleve. **Fig. 18.** *Navicula capitatoradiata* Germain. **Fig. 19.** *Navicula schadei* Krasske. **Fig. 20.** *Gomphonema truncatum* Ehrenberg. **Fig. 21.** *Gomphonema grovei* var. *lingulatum* (Hustedt) Lange-Bertalot. **Fig. 22.** *Gomphonema augur* Ehrenberg. **Fig. 23.** *Nitzschia recta* Hantzsch in Rabenhorst. **Fig. 24.** *Nitzschia amphibia* Grunow. **Fig. 25.** *Surirella angusta* Kützing. Magnification $\times 1300$.

