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Comparing limnological changes associated with 19th century canal construction and other catchment disturbances in four lakes within the Rideau Canal system, Ontario, Canada

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ABSTRACT

Paleolimnological analysis of microfossils and physical sediment characteristics in ^{210}Pb and Ambrosia *dated sediment cores, along with diatom-inferred total phosphorus concentration [TP] reconstructions, were used to determine the trophic histories (*ca *200 years) of four lakes within the Rideau Canal system, Ontario, Canada. Paleoecological information of the dominant diatom taxa that flourished during the pre-settlement period indicated that these lakes were naturally oligo-mesotrophic. At the estimated time of canal construction, all lakes demonstrated an increase in nutrients but their responses varied in magnitude. These differences were likely related to a number of variables, but the surface-area:watershed ratio appeared to be an important explanatory variable. Additionally, the similar trophic response of the control lake (not part of the canal), Otter Lake, illustrated the regional impact of past watershed disturbance (e.g. logging, settlement, mining, agriculture), not directly related to canal construction. In more recent years (~1970 to present), less productive planktonic species (e.g.* Cyclotella comensis *and* Cyclotella aff. gordonensis*) increased in all the study lakes. These recent water quality changes were attributed to improved nutrient retention of developing soils in secondary growth forests, the potential effects of climate warming, as well as mitigation efforts (e.g. decreased phosphorus concentrations in detergents, etc.). Eutrophication patterns determined for the deeper study lakes were similar to paleolimnological studies of other deep lakes in the canal system. However, the trophic response in the shallow lake, Lower Rideau Lake, is more pronounced at the time of canal construction than those of other shallow canal lake responses (e.g. nearby Lake Opinicon) and suggests that both alternative equilibrium states have occurred. This heightened response was attributed to increased nutrient export in Lower Rideau Lake's limestone catchment and/or higher watershed disturbance. Finally, results from this study furthers our understanding of impacts in an integrated system of lakes and this information can be used to help set realistic mitigation targets for these and other lakes in the Rideau Canal system.*

Key words: eutrophication, total phosphorus, diatoms, climate change, alternative equilibrium theory, water levels, Rideau Canal

1. INTRODUCTION

The Rideau Canal is a 202 km-long waterway linking Ottawa and Kingston (Ontario) (Fig. 1). The canal was built between 1826 and 1832 for military purposes providing an alternative supply route to Kingston from Montreal. Twenty-nine kilometres were excavated and twenty-three lock stations, with forty-seven locks, were constructed to connect the rivers and lakes of the waterway (Legget 1975). The transport of goods thereafter subsided and the canal was subsequently used for local commercial transport. From the late-1800s until the present, the canal has mainly served recreational purposes. Today, next to tourism, the canal is also used for hydroelectric power, water supply, flood abatement, and runoff dilution associated with agricultural activities (Acres 1994).

Recently, eutrophication concerns have been raised regarding lakes within the Rideau Canal system (Michael Michalski Associates 1992), similar to other areas within southeastern Ontario (Reavie & Smol 2001). Long-term limnological data highlight the extent of past human disturbances and pre-impact limnological conditions to help lake managers set realistic mitigation targets for future restoration and management decisions (Smol 1995, 2002). However, such data are unavailable for the lakes within the canal system and so indirect proxy methods must be used.

Paleolimnology uses the physical, chemical and biological information archived in lake sediments to reconstruct and interpret past environmental conditions over many time scales (Smol 2002). Diatoms (Class Bacillariophyceae) have been widely used as bioindicators of environmental conditions in lakes (Stoermer & Smol 1999). They have silicified cell walls (frustules) that are taxonomically diagnostic (species-specific or lower), abundant in a wide range of aquatic habitats, and remain well preserved in most lake sediments. Additionally, diatom species generally have well-defined optima and tolerances to many environmental variables. These

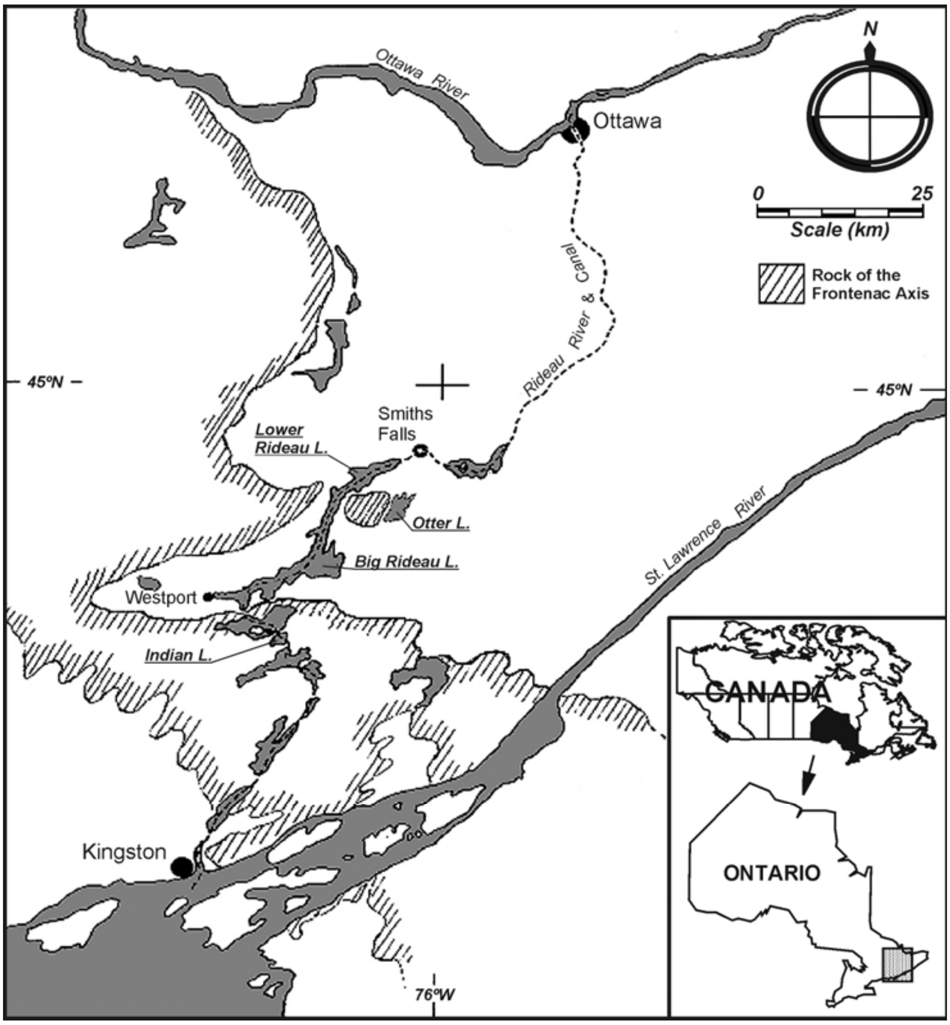

Fig. 1. Map of southeastern Ontario showing location of the study lakes (underlined).

characteristics allow for the development of transfer functions, mathematical equations that describe the relationships between biological species and environmental variables. With these functions, past values of an environmental variable (e.g. [TP]) can be inferred from the composition of fossil assemblages. Additionally, diatoms have rapid replication rates, enabling them to track changes in the aquatic environment (Dixit *et al*. 1992). Diatoms have proven to be reliable indicators of eutrophication problems in lakes (reviewed in Hall & Smol 1999).

A diatom-based water quality model recently developed from 64 alkaline southeastern Ontario lakes across a [TP] gradient of 4 to 54 µg l^{-1} (Reavie & Smol 2001) was applied to down-core diatom data to infer past lake-water spring [TP]. This transfer function was generated using weighted-averaging regression and calibration techniques (reviewed in Birks 1995). The model provided a relatively robust reconstructive relationship for spring TP (r^2 = 0.64; RMSE = 0.01 mg l^{-1}; r^2_{boot} = 0.47; $RMSE_{boot}$ = 0.01 mg l^{-1}) (Reavie & Smol 2001).

Previous paleolimnological studies have been conducted for several lakes within the canal system to assess historical eutrophication patterns (e.g. Christie & Smol 1996; Karst & Smol 2000; Little & Smol 2000). These studies have highlighted different limnological responses to disturbances following canal construction. Using fossil diatom assemblages from Upper Rideau Lake, a large, relatively deep lake (surface area (SA) = 13.6 km^2, mean depth = 8.1 m, maximum depth (Z_{max}) = 22.0 m), Christie & Smol (1996) reconstructed past limnetic total nitrogen [TN]. Results indicated that Upper Rideau Lake has always been productive, but that nutrient levels increased markedly with settlement and canal construction. In contrast, a paleolimnological study of Lake Opinicon, a large, shallow, macrophyte-dominated lake (SA = 7.8 km^2, mean depth = 4.9 m, Z_{max} = 9.2 m), recorded no major changes in trophic state following canal construction (~1826 - 1832) (Karst & Smol 2000; Little & Smol 2000), consistent with the clear-water state of the alternative equilibrium hypothesis (Scheffer *et al*. 1993). This hypothesis describes an

Tab. 1. Physical and chemical characteristics of the study lakes. Physical data compiled from lake survey reports from the Ministry of the Environment, Kingston District Office and Fisheries Assessment Unit report 90-4, M.N.R. Rideau Lake Map (1972). Water chemistry data for Indian and Big Rideau lakes is from 1998 (Little 1999) and from 1999 for Lower Rideau and Otter lakes (Lake Partner Program, unpublished data; Canadian Museum of Nature, unpublished data; and field sampling). Average values indicate an annual average of spring (May) and summer (Aug./Sept.) values. (n.d. = no data). [1] Michael Michalski Associates (1992); [2] I. Patterson, pers. comm.; [3] Kennedy (1984).

	Indian	Big Rideau	Lower Rideau	Otter
Latitude	44º 60' N	44º 49' N	44º 52' N	44º 47' N
Longitude	76º 32' W	76º 14' W	76º 07' W	76º 07' W
Elevation (m a.s.l.)	122	124	124	124
Mean depth (m)	10.1	16.3	2.8	10.0
Maximum depth (m)	26	95	23	37
Surface area (SA) (km^2)	2.7	44.6	13.0	6.0
Volume (V) ($\times 10^6$ m^3)	26.8	726.8	36.4	60.5
Watershed area (W) (km^2)	359	128.5	478.9	46.6
SA:W	0.01	0.35	0.03	0.13
V:W	0.07	5.66	0.08	1.30
Shoreline (km)	17	154	47	20
Residences and commercial properties	166 [2]	1268 [1]	302 [1]	291 [3]
Average Secchi (m)	4.9	5.2	2.5	4.2
Spring Chl-*a* ($\mu g\ l^{-1}$)	1.2	1	n.d.	2
Spring TP ($\mu g\ l^{-1}$)	10	8	19	11
Average TN ($\mu g\ l^{-1}$)	420	330	465	433
pH	8.4	7.9	8.7	8.6

equilibrium between a clear-water macrophyte-dominated state and a turbid, phytoplankton-dominated state for shallow lakes. Natural buffers maintain these two states (e.g. macrophytes), however it is hypothesized that a substantial addition or reduction in nutrients can switch the equilibrium to the alternate state. Therefore, Karst & Smol (2000) hypothesized that nutrient additions were insufficient to switch Lake Opinicon to the turbid state from the macrophyte-dominated clear-water state.

These previous canal studies have provided important historical eutrophication trends, however it is still uncertain how other canal and nearby lakes have been impacted by similar past anthropogenic disturbances. In order to expand on these original studies, the overall objectives of this study were to reconstruct and compare the past trophic state histories (~200 years) of three canal lakes and one control lake in the Rideau Canal area using paleolimnological techniques. Data gathered from the trophic reconstruction of the shallow canal study lake were also hoped to further our understanding of the alternative equilibrium theory. Trophic changes were tracked using diatom assemblages, cyst to diatom ratios, and physical sediment characteristics of the ^{210}Pb- and *Ambrosia*-dated sediment cores.

2. SITE DESCRIPTIONS

The Rideau Canal region has a temperate climate with generally cool winters (Jan. max. -5.5 ºC, min. -15.3 ºC), warm summers (July max. 26.5 ºC, min. 14.3 ºC) and an average annual precipitation of 914.7 mm (at Kemptville, Ontario, Environment Canada 1998). The canal crosses Phaerozoic limestone and Precambrian igneous and metamorphic bedrock (Chapman & Putnam 1984), which influences the physiography of the area. Four lakes from the Rideau Canal region were chosen for detailed paleolimnological analysis. Indian, Big Rideau and Lower Rideau lakes are part of the canal waterway, whereas Otter Lake is not (Fig. 1). Otter Lake was selected to serve as a temporal control as it is independent of the canal waterway, yet it is within the Rideau Watershed and was subjected to similar land-use changes that occurred in the other study lakes (with the exception of canal construction).

Indian, Big Rideau and Otter lakes are deep, thermally stratified, and oligo-mesotrophic lakes. Lower Rideau Lake is shallow and mesotrophic. Physical and chemical characteristics of the study lakes are presented in table 1. Detailed lake descriptions and historical catchment disturbances have been summarized in Forrest (2001).

2.1. *Past watershed disturbances within the Rideau Canal system*

Lakes within the Rideau Canal have received increased nutrient loads from multiple anthropogenic sources (e.g. logging, settlement, flooding, agriculture, industry, cottage development) since European settlement began in the area in the early-1800s.

With canal construction (1826 - 1832), lakes and rivers were flooded (~2 - 3 m) to create navigable depths for steamboat transport. The flooding of lowland areas and other hydrologic changes likely increased nutrients in the canal lakes. The construction of dams and locks altered the natural hydrology of the lakes and rivers in the Rideau system by controlling the inflow and outflow of upstream canal lakes. Despite occasional repairs, water levels within the canal lakes have been maintained within annual water-level restrictions (~1 m) to ensure downstream navigation depths, water supply, hydroelectricity and runoff dilution requirements. The hydrological controls on these lakes may have also increased nutrient addition by augmenting natural water-residence times, providing more time for the lakes to accumulate nutrients in the water column and release phosphorus from the sediments.

Most settlement in the area came following the construction of the canal. Trees were cut back for miles on each side of the canal during this time (Passfield 1982). By the 1860s, two-thirds of the area was cleared for agricultural and settlement purposes (CHPC 1996). Nutrient concentrations in agricultural runoff are often substantial and can create eutrophic conditions in receiving water bodies (Lennox *et al*. 1997).

By the 1880s, there were several industries along the canal. These industries included several mills (producing lumber, flour, wool, bricks, and cement), cheese factories, maple sugar factories (still operating today) and extraction operations (apatite, mica, iron ore, graphite, limestone and sandstone). Mining (phosphate and mica) occurred in the area from 1855 to the 1950s (Snyder 1977). The resulting industrial discharges also likely added nutrients to the Rideau Canal system.

Following the 1890s, the tourism industry took on a major role in the Rideau area. Improved roads and railways in the early-1900s brought more people to the area (Kennedy 1984; Legget 1975). From 1900 until 1950, resident populations decreased and the economy changed. Many farmers left the area during this time for the more fertile soils located in the Canadian West (Warren 1997). Farmers who remained in the area became more involved in the dairying and livestock husbandry industries (Kennedy 1984). At this time, large-scale lumbering also came to an end (Fleming 1981).

Cottage development began in the 1930s and has since increased along the canal. In 1951, there were less than 1,000 cottages along the canal and by 1996 there were over 6,000 cottages and permanent homes (CHPC 1996). Today, a number of canal communities, along with rural and seasonal residents, reside along the Rideau Canal system. Cottage development, along with sewage effluent from private sewage tank systems and a secondary sewage treatment plant at Perth (serving a population of 5,646), have also added nutrients to the Rideau Lakes basin (Michael Michalski Associates 1992).

3. MATERIALS AND METHODS

3.1. Field work

Sediment cores (38 - 49 cm in length) were retrieved from the four study lakes using a 7.5 cm internal diameter gravity corer (Glew 1988). Sediment cores were taken from the central, flat deep-water regions of Indian and Big Rideau lakes in October of 1998, in Otter Lake in July 1999 and Lower Rideau Lake in February 2000. At Lower Rideau Lake, both a 47-cm long gravity core and a 1-m long modified Livingstone piston core were retrieved (Wright 1991). The cores were sectioned on-site into 1-cm intervals for Indian, Big Rideau and Lower Rideau lakes and 0.5-cm intervals for Otter Lake, using an upright extruder (Glew 1988). The piston core was extruded horizontally and subsampled in the laboratory. All sediment samples were refrigerated at 4 ºC in Whirl-pak bags until processing of microfossils and physical sediment analysis.

3.2. Sediment characterization and chronology

Organic matter content was estimated in the laboratory for Indian, Big Rideau, Lower Rideau and Otter lakes' sediment cores by drying one gram of wet sediment for two hours at 550 ºC. Sediment chronologies for Big Rideau, Lower Rideau, Indian and Otter lakes were based on ^{210}Pb activity and sediment color changes (see below). *Ambrosia* (ragweed) pollen abundances (see below), recorded in bottom sediment intervals also helped confirm chronologies for Big Rideau, Lower Rideau and Otter lakes.

An EG&G Ortec germanium well-detector was used to count naturally occurring isotopic decays for ^{210}Pb and results were obtained by applying the constant rate of supply model (CRS) (Appleby & Oldfield 1983).

The *Ambrosia* pollen rise served as an additional independent chronological marker of European encroachment. The rise in *Ambrosia* and grass pollen is related to widespread vegetation disturbance from the onset of human activities (European settlement), which occurred in the area in the early1800s (Bassett & Terasmae 1962).

3.3. Microfossil preparation and analysis

For each core, selected intervals were prepared for diatom analysis following standard techniques (Battarbee 1986). Diatom valves and chrysophyte cysts were enumerated under oil immersion (1000× magnification) along parallel vertical transects using a Leica DMRB microscope. A minimum of 300 fossil diatom valves were enumerated and identified for each sediment interval. Taxonomy was primarily based on floras described by Krammer & Lange-Bertalot (1986-1991), Reavie & Smol (1998), and Cumming *et al*. (1995). To ensure taxonomic consistency with Reavie & Smol (2001), joint taxonomic sessions were completed between the authors.

Approximately ten intervals were prepared for pollen analysis in each sediment core from Big Rideau, Lower Rideau and Otter lakes. Pollen preparation followed standard techniques described by Faegri & Iversen (1975), with the exception that the hydrofluoric acid step was not used, as siliciclastics were not often common in the sediment, and only important during erosion events (see below). For each sample, a minimum of 300 pollen grains was enumerated and *Ambrosia* pollen grains were identified and recorded to provide further geochronological control (J. Smol, unpublished data).

3.4. Statistical analysis

Stratigraphic diatom profiles were constructed using the program TILIA version 1.09 (Grimm unpublished program) for dominant (≥3% relative abundance in Lower Rideau Lake and ≥5% relative abundance in all other study lakes) taxa. The squared-chord dissimilarity index was used in the program CONISS (Grimm 1987) to perform stratigraphically-constrained cluster analysis in TILIA so as to define intervals containing similar species assemblages.

Statistical analyses were performed on those diatom taxa that exceeded ≥2% relative abundance in at least one sediment interval within the downcore fossil assemblages. However, down-core diatom data were screened according to the calibration model criteria for analogue analysis. Diatom species data were included if: a) they were present in a minimum of five intervals and achieved ≥1% abundance of in at least one interval, or b) they were present ≥5% abundance in at least one interval (Reavie & Smol 2001). The similarity of diatom assemblages within study lake cores and down-core gradient lengths were examined using detrended correspondence analysis (DCA), a non-linear ordination technique.

3.5. Inferring total lakewater phosphorus

Using the computer program WACALIB 3.2 (Line *et al*. 1994) and a 64-lake southern Ontario calibration set (Reavie & Smol 2001), historical diatom-inferred lake-water spring TP concentrations were calculated for the four study lakes. Spring lake water [TP] was reconstructed because this is the index value used by the Ontario Ministry of the Environment. Additionally, the weighted-averaging spring [TP] transfer function is relatively strong ($r^2_{\text{bootstrapped}} = 0.43$) and has been used to track changes in trophic state conditions of several other deep southeastern Ontario lakes (K. Neill, unpublished data).

Comparisons between the diatom-inferred spring TP reconstructions for the surface sediments of the four study lakes and recent measurements of spring TP were done to evaluate the accuracy of the TP transfer function. Other steps taken to evaluate the reconstructions were: 1) 'goodness-of-fit' tests (Birks 1998), 2) 'analogue' measures (Birks 1998), and 3) correlation analyses of DCA axis one sample scores and inferred variables.

The 'goodness of fit' test consisted of running a CCA on the southeastern Ontario lakes, constrained to the TP variable and plotting down-core fossil samples passively. Fossil samples were deemed to have a "poor" or "very poor" fit to the calibration set's TP axis if their squared residual lengths (SRL) exceeded the 90% and 95% SRL confidence limits of the modern samples (Birks *et al*. 1990). However, as we found, the distribution of squared residual distances of the modern samples to be skewed, the modern and fossil distances were log-transformed before determining 90% and 95% confidence limits.

The computer program ANALOG version 1.6 (Line & Birks unpublished program) was used to identify the fossil diatom assemblages with poor analogues to those found in the modern calibration data-set. The Bray-Curtis dissimilarity coefficient (DC) was used to compare the fossil samples to the calibration lake set (Clarke & Warwick 1994). The 90% and 95% confidence limits (CLs) from the calibration set, determined by calculating the best match (lowest dissimilarity) within the calibration set, were applied to the fossil DCs in their evaluation (modified from Hall & Smol 1993). Any fossil samples with minimum DCs above the extreme 10% and 5% of the calibration samples were considered to have poor and very poor analogue matches, respectively (Hall & Smol 1993).

Correlation analyses were performed between inferred spring TP values (i.e. mean boot values) and DCA axis one sample scores to determine whether this variable was tracking the main direction of variation in the fossil samples.

4. RESULTS AND DISCUSSION

4.1. Chronologies

Chronologies for the sediment cores were based on ^{210}Pb activity, the rise in *Ambrosia* and sediment color changes. The short sediment cores for Indian, Big Rideau, Lower Rideau and Otter lakes show typical exponential declines in ^{210}Pb activity with sediment depth suggesting cores contained undisturbed chronological sediment profiles (Fig. 2). Strong relationships between the log of excess ^{210}Pb activity (dpm g^{-1}) and cumulative dry mass (g cm^{-2}) suggest that the flux of ^{210}Pb activity has remained relatively constant in all the cores (Forrest 2001). The rise in *Ambrosia* pollen determined in Big Rideau, Lower Rideau and Otter lakes closely matched the ^{210}Pb-estimated dates (Forrest 2001).

Color changes were also observed in all the canal lake cores around the estimated time of canal construction. There was a sharp color change from light brown pre-disturbance sediments to dark-brown sediments observed in the deep canal lakes, and a more gradual color change in the shallow canal lake around the time of ca-

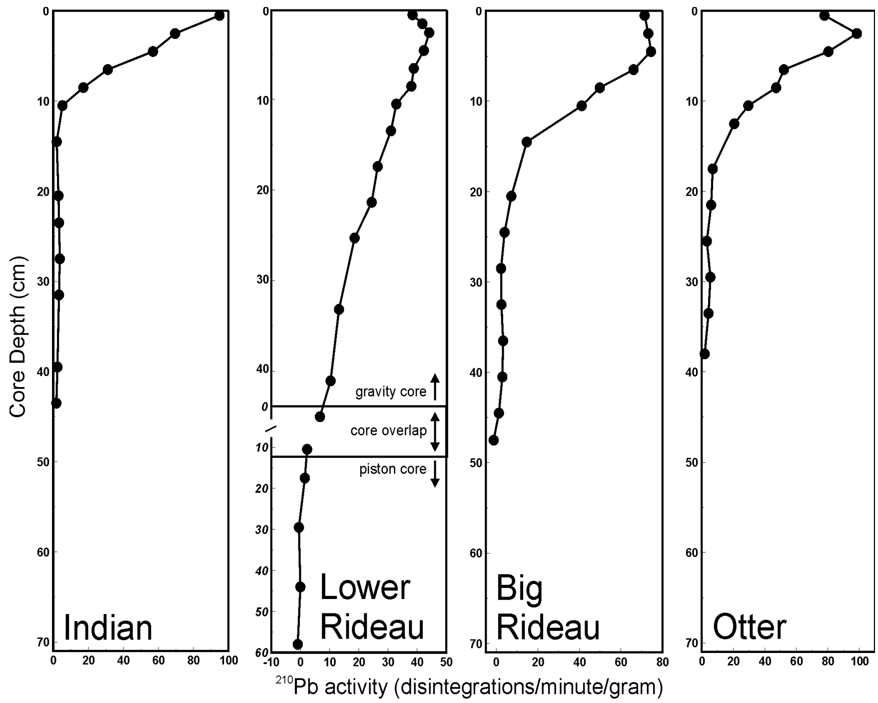

Fig. 2. Profile of ^{210}Pb activity *vs* sediment core depth for the four study lakes.

nal construction (Figs 3-5). A similar color change was observed in the sediment core from Upper Rideau Lake (Christie & Smol 1996), another lake within the canal system. Unlike the sediment cores from the canal lakes, the Otter Lake sediment core had unique color changes and they did not correspond to the time of canal construction (Fig. 6).

The initial ^{210}Pb activity profile from Lower Rideau Lake using only the 7.5 cm diameter gravity core suggested that the lake had a high sedimentation rate and therefore the 47-cm long core was not of sufficient length to span the entire period of interest (~200 y). Subsequent coring of the lake using a Livingstone corer resulted in the retrieval of a 1-m long core which reached background ^{210}Pb activity (0.143 dpm g^{-1}). Matching ^{210}Pb activity, diatom and pollen relative abundances in both the long and short cores suggested that the top 5 cm of the piston core overlapped with the bottom interval (46 - 47 cm) of the short core. Using a sedimentation rate of 0.5 cm per year, calculated from the excess activity and cumulative mass curve (Forrest 2001), the sediment interval of 37 cm on the long core was estimated as ~1830, the time of canal construction. As the sedimentation rate likely varied over this time period, this sedimentation rate estimate can only be considered as an approximation of ~1830. Therefore, other lines of evidence (e.g. *Ambrosia* and sediment color changes) further identified the timing of canal construction. *Ambrosia* increased around the 39 - 40 cm interval in the long core, providing evidence of moderate human activity in the area and a color change occurred just prior to the *Ambrosia* rise (46 cm). Together, these lines of evidence suggest that 46 cm in the piston core was approximately the time of canal construction in Lower Rideau Lake.

4.2. Sediment characteristics

Percent organic content, estimated by loss-on-ignition at 550 °C, decreased at the estimated time of canal construction in the study lakes with predominantly flat, limestone basins (Figs 4, 5, 6). This decrease in loss-on-ignition was believed to reflect an increase in siliciclastic material associated with watershed disturbances occurring during this period of canal construction and settlement (Rowan *et al.* 1992).

4.3. TP model evaluation

Diatom-inferred [TP] values were generally supported by direct and indirect lines of evidence. Direct comparisons between diatom-inferred [TP] values and recent (1970s until present) spring epilimnetic [TP] were similar in all the deep lakes (Indian, Big Rideau, Otter lakes) (Forrest 2001). Not surprisingly, the [TP] model did not perform as well in reconstructing recent [TP] for the shallow, Lower Rideau Lake. The recent inferred value for [TP] was slightly overestimated (inferred [TP] = 25 µg l^{-1} > actual [TP] = 19 µg l^{-1} in 1999; Canadian Museum of Nature, unpublished data). Over estimations of diatom-inferred [TP] in shallow lakes have previously been related to high relative abundances of *Fragilaria pinnata*, which generally has a high [TP] optimum in calibration sets (Reavie *et al.* 1995). Additionally, the relationship between benthic taxa and open water nutrient concentrations is thought to be more

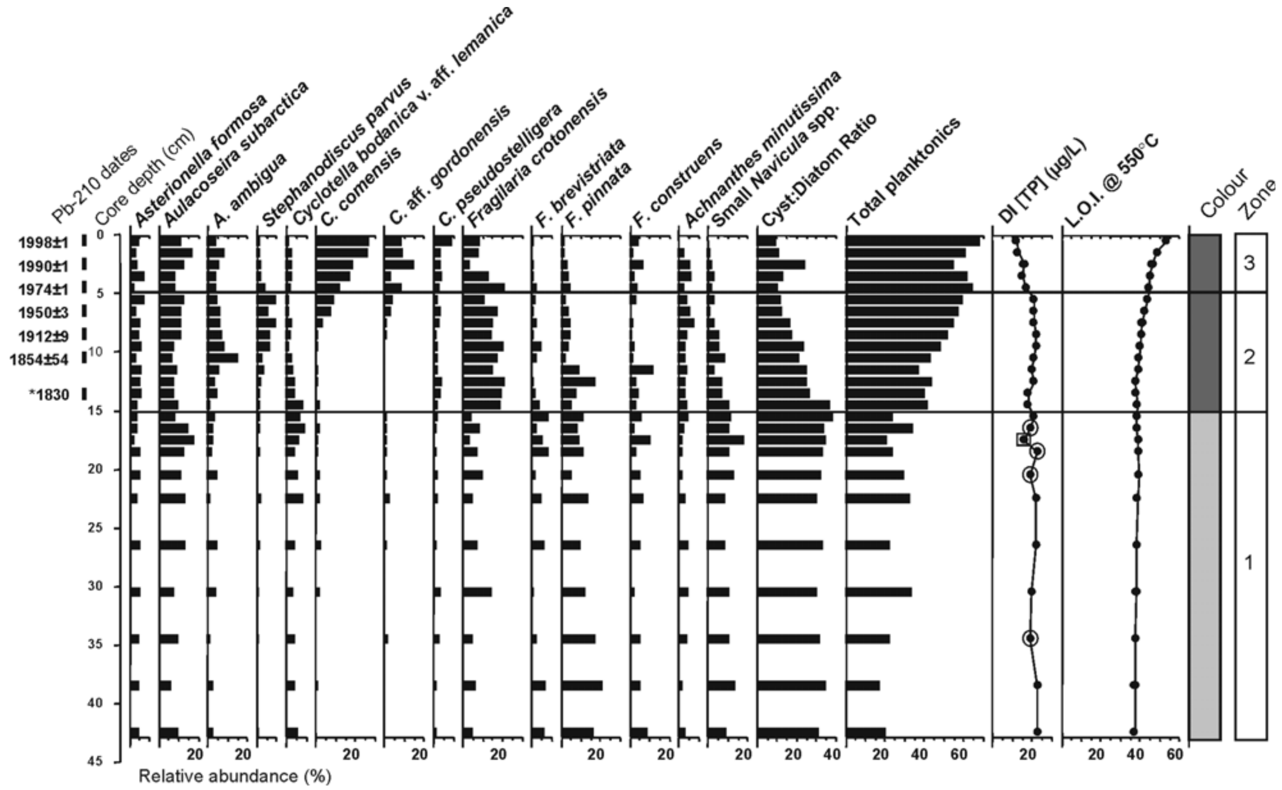

Fig. 3. Profiles of siliceous microfossils, diatom-inferred [TP], estimated percent organic matter as L.O.I. and sedimentary color profiles for Indian Lake. Assemblages are designated as poorly fitted to TP (squares) and poor analogues to the calibration set (circles); see text for details. The light grey colour represents light brown gyttja and dark grey colour represents dark brown gyttja. * extrapolated ^{210}Pb date.

complicated than that for planktonic taxa (Bennion *et al*. 2001). Benthic taxa are also affected by changes in substrate and light, and may have access to enhanced nutrient levels at the sediment-water interface or substrate (e.g. macrophytes) (Bennion *et al*. 2001). Sampling more shallow lakes and including more taxa in the surface sediment calibration set may overcome these inference differences.

Three indirect lines of evidence also suggested that our reconstructions of [TP] provided reliable [TP] inferences for post-canal diatom assemblages in sediment cores from Indian, Lower Rideau, and Big Rideau lakes (Figs 3, 4, 5). First, analogue matching performed well as indicated by good analogues for most of the cores. Poor analogues were generally only found before the time of canal construction. Second, few sample intervals had "poor" or "very poor" fits to TP. Third, there was generally significant correlations between DCA axis one sample scores and inferred [TP] (Forrest 2001). Therefore, diatom inferences were considered to be good approximations of [TP] following canal construction.

However, the model performed poorly for Otter Lake's [TP] reconstruction (Fig. 6). First, DCA axis one sample scores were weakly correlated to inferred [TP] values and were not significant (r^2 = 0.12, p = 0.27). Additionally, three samples had "poor fit" to [TP] in a constrained CCA of the southeastern Ontario calibration set. Additionally, more than half of the fossil diatom assemblages had "poor" to "very poor" modern analogues (>95% CLs) within the calibration lake-set. With the exception of the more recent assemblage inferences (~1965 to present), [TP] inferences were generally considered unreliable. For these reasons, the core from Otter Lake will be discussed qualitatively using autecological information available for the dominant diatom species.

4.4. Lake comparisons

Cluster analysis, sediment color, *Ambrosia* pollen (not analyzed in Indian Lake) and ^{210}Pb dates delineated the sediment cores into three zones of diatom species assemblages: Zone 1 is the pre-disturbance period (before European settlement); Zone 2 is the settlement and canal construction period; and Zone 3 is the recent past (~1970 - present).

4.4.1. Pre-disturbance conditions (Zone 1: before ~1830)

Prior to the extrapolated ^{210}Pb date of 1830, the microfossil evidence for all study lakes suggests that conditions were naturally somewhat productive (Figs 3-6). Generally, the assemblages in the deep lakes were dominated by oligo-mesotrophic species such as *Cy-*

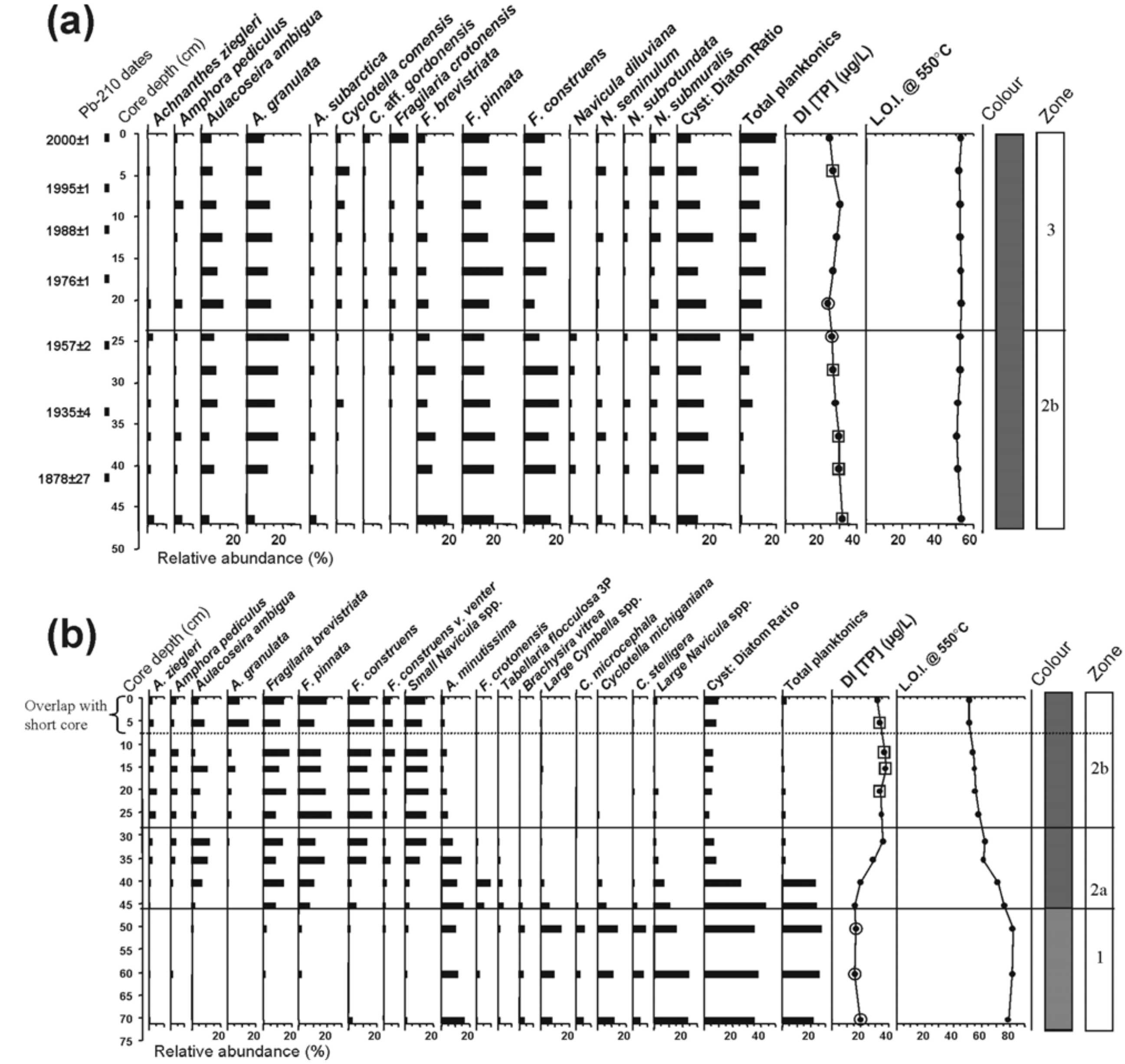

Fig. 4. Profiles of siliceous microfossils, diatom-inferred [TP], estimated percent organic matter as L.O.I. and sedimentary color profiles for Lower Rideau Lake (**a**: short core and **b**: long core). Assemblages are designated as poorly fitted to TP (squares) and poor analogues to the calibration set (circles); see text for details. The light grey colour represents light brown gyttja and dark grey colour represents dark brown gyttja.

clotella bodanica var. *aff. lemanica* (spring [TP] optima = 11 µg l^{-1}), *Cyclotella stelligera* (spring [TP] optima = 13 µg l^{-1}), *Aulacoseira subarctica* (spring [TP] optima =14 µg l^{-1}), *Fragilaria pinnata* (spring [TP] optima = 16 µg l^{-1}), *F. construens* (spring [TP] optima = 18 µg l^{-1}), *F. brevistriata* (spring [TP] optima = 17 µg l^{-1}) and *Stephanodiscus medius* (spring [TP] optima = 16 µg l^{-1}) ([TP] optima obtained from Reavie & Smol (2001)). The small *Fragilaria* taxa have wide ranges of ecological tolerances (Bennion *et al*. 1995; Christie & Smol 1993) and habitats, and therefore provided only some general ecological information (Bennion *et al*. 2001). The assemblages were also dominated by some benthic taxa, such as *Navicula minima*, *N. seminulum* and *N. submuralis*. Their presence illustrates the importance of the littoral habitat at this time. These species were also found in mesotrophic conditions with TP optima of 15 µg l^{-1} (*N. minima*), 16 µg l^{-1} (*N. seminulum*) and 17 µg l^{-1} (*N. submuralis*) in southeastern Ontario lakes (Reavie & Smol 2001). The cyst to diatom ratios were also relatively high in this zone for all lakes, which also suggested oligo-mesotrophic conditions for Ontario waters (Smol 1985). Despite poor analogues in the transfer function in this zone, we can confidently conclude that

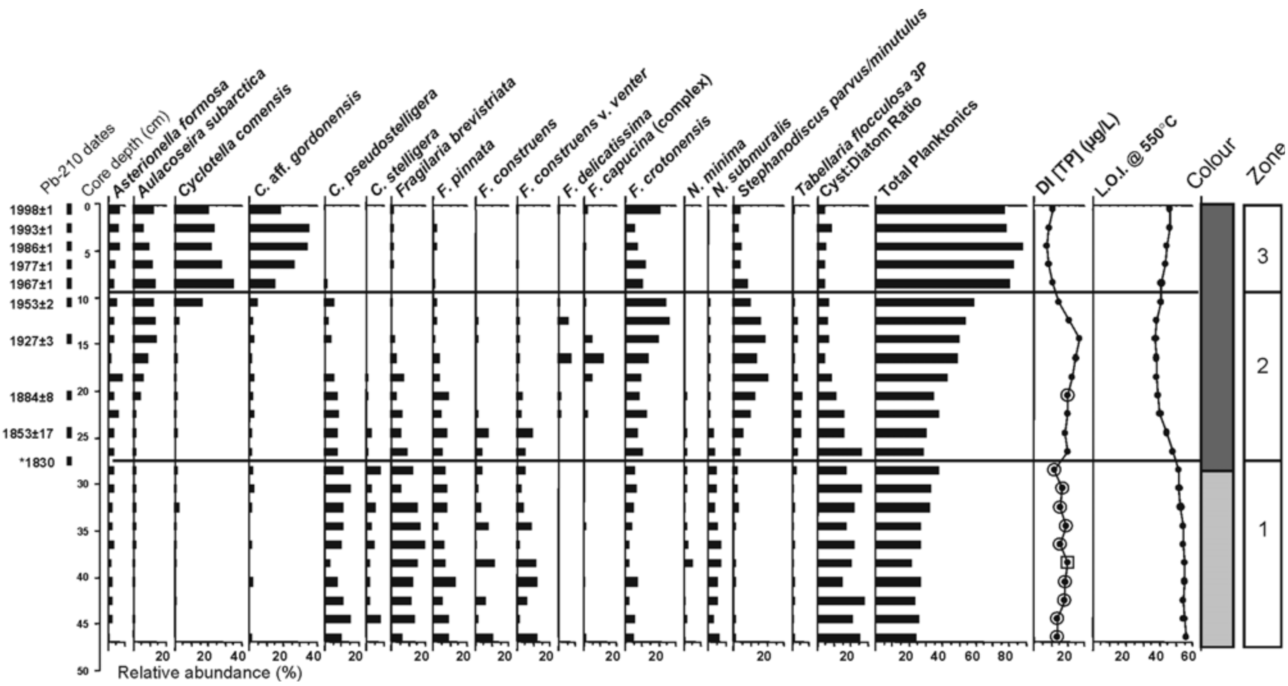

Fig. 5. Profiles of siliceous microfossils, diatom-inferred [TP], estimated percent organic matter as L.O.I. and sedimentary color profiles for Big Rideau Lake. Assemblages are designated as poorly fitted to [TP] (squares) and poor analogues to the calibration set (circles); see text for details. The light grey colour represents light brown gyttja and dark grey colour represents dark brown gyttja. * extrapolated ^{210}Pb date.

lakes were oligo-mesotrophic and had moderate littoral areas based on the known autecology of the dominant diatom taxa and the relatively high cyst to diatom ratios.

Slightly productive conditions have previously been reported in the pre-disturbance assemblages of other Rideau Canal paleolimnological studies (Karst & Smol 2000; Christie & Smol 1996) and some other, nearby southeastern Ontario lakes (K. Neill unpublished data; Christie 1993). These findings reflect the relatively nutrient-rich soils in the region. Knowledge of these background trophic conditions is important for lake managers in determining the impacts of watershed disturbances and providing realistic targets for future lake management (Smol 2002).

4.4.2. Historical anthropogenic disturbance (Zone 2: ~1830 to the ~1970s)

Microfossil evidence from all the study lakes recorded microfossil changes around the time of European settlement and canal construction (~1830). However, trophic state responses varied in magnitude. These differences were thought to be related to a number of variables, such as surface area: watershed ratio (SA:W), watershed topography (e.g. slope of catchment), and magnitude of catchment disturbances. The lakes will be discussed in order of increasing SA:W: Indian 1%, Lower Rideau 3% and Big Rideau 35% (Tab. 1), as this ratio provides a general estimate of phosphorus export relative to catchment area (Prairie & Kalff 1986), given the relatively similar watershed disturbances that occurred. Otter Lake had the second highest SA:W ratio of 13%, but it will be discussed last because it was considered the temporal control for canal construction.

Generally, the study lakes with small SA:W ratios experienced more pronounced changes in trophic state around the time of canal construction. Trophic responses were compared between lakes quantitatively through analysis of DCA axis one sample scores and [TP] inference relationships, and qualitatively through microfossil changes around the time of canal construction. Therefore, a high correlation between [TP] and DCA axis one sample scores suggests that [TP] is explaining most of the variance in the diatom assemblages. Indian Lake demonstrated an abrupt increase in the eutrophic indicator, *Fragilaria crotonensis*, around the time of canal construction (Fig. 3). *F. crotonensis* is a common indicator of cultural disturbance associated with increased nutrient loading in many paleolimnological studies (e.g. Reavie *et al*. 1995; Bradbury 1975). Similarly, the cyst:diatom ratio and total planktonic species decreased and increased at that time, respectively. Additionally, Indian Lake had a significant and moderate correlation between inferred TP and DCA axis one sample scores (r^2 = 0.41, p <0.001). This trophic response was not surprising, as Indian Lake has a relatively small SA:W ratio (1%) and its steep-sided slopes likely facilitated nutrient transport to the lake. A dramatic trophic response to canal construction was also observed in the paleolimnological study of Upper Rideau Lake, another deep canal lake within the Rideau system with a relatively low SA:W (9%) (Christie & Smol 1996).

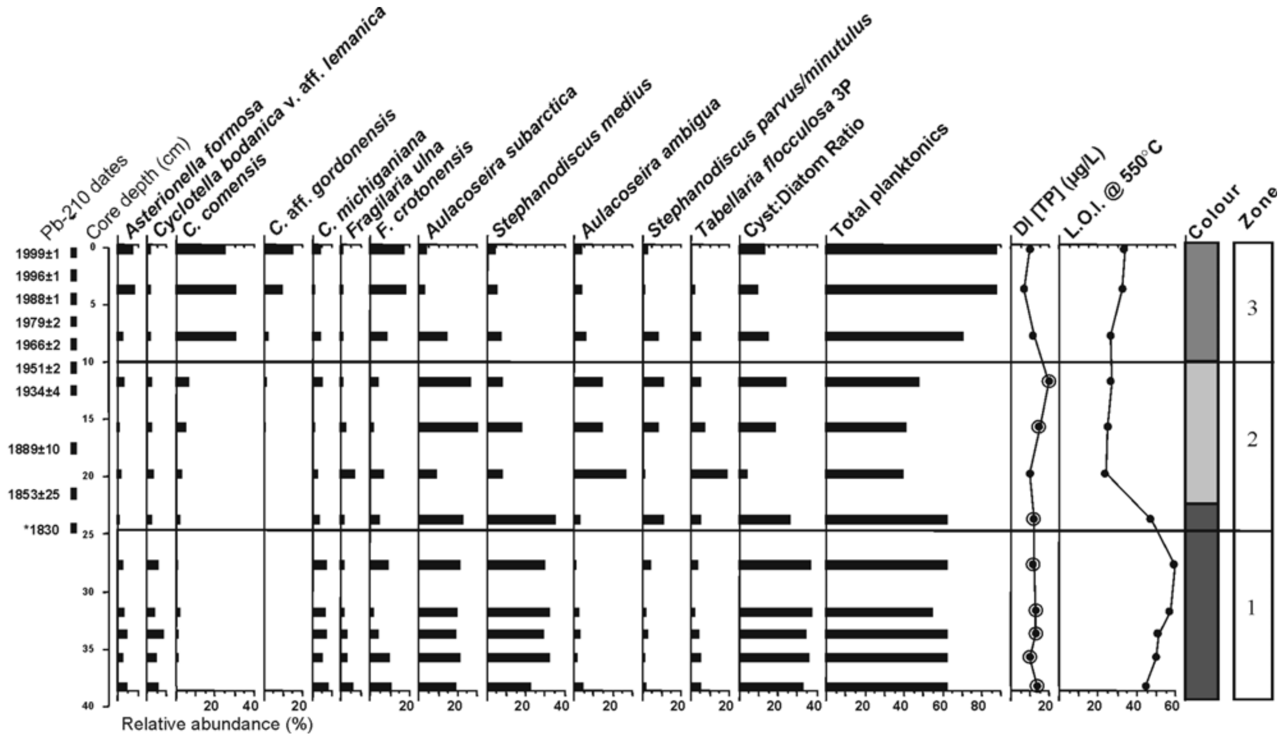

Fig. 6. Profiles of siliceous microfossils, diatom-inferred [TP], estimated percent organic matter as L.O.I. and sedimentary profiles for Otter Lake. Assemblages are designated as poor analogues to the calibration set (circles); see text for details. The medium grey colour found in zone 1 represents medium brown coloured gyttja, the light grey found in zone 2 represents light brown gyttja and the dark grey found in zone 3 represents greenish-brown gyttja. * extrapolated ^{210}Pb date.

Lower Rideau Lake, the shallow lake, also experienced a marked increase in trophic state at the time of canal construction. The trophic response was illustrated by an increase in the productive planktonic species, *Fragilaria crotonensis* and *Aulacoseira ambigua* (a meso-eutrophic species, TP opt. 16 µg l^{-1} and TN opt. 469 µg l^{-1}; Reavie & Smol 2001), around the time of canal construction (Fig. 4b, Zone 2a), and the significant and strong correlation between DCA axis one sample scores and inferred TP ($r^2 = 0.89$, $p < 0.001$). This lake also had a low SA:W (3%), however its catchment area was gently sloped.

The abrupt trophic response in Lower Rideau Lake was surprising as other paleolimnological data from shallow Rideau canal lakes, Sand Lake (E. Reavie, unpublished data) and Lake Opinicon (Karst & Smol 2000), demonstrated only modest shifts in their diatom assemblages during this time period. Furthermore, Lake Opinicon had an even lower SA:W (1%), suggesting a potentially greater nutrient contribution from its watershed given similar watershed activities (Prairie & Kalff 1986). These differences in trophic state response are possibly related to greater nutrient contributions associated with geology and the magnitude of watershed disturbance. Lower Rideau Lake likely received higher nutrient loads from its predominantly limestone catchment than the other shallow lakes with predominantly granitic catchments (Soil Research Institute 1968). Additionally, this lake potentially received greater nutrients from local and upstream watershed disturbances, as Perth was a thriving settlement at the time of canal construction (Kennedy 1984).

The deep, Big Rideau Lake recorded only a slight trophic state response at the time of canal construction. The cyst to diatom ratio decreased indicating an increase in nutrients; however, eutrophic planktonic species (e.g. *F. crotonensis* and *S. parvus/minutulus*) only slightly increased in abundance (Fig. 5). These *Stephanodiscus* species are common indicators of eutrophication with high nutrient optima (*S. parvus*, TP 28 µg l^{-1}, TN 568 µg l^{-1}; *S. minutulus* TP 15 µg l^{-1}, TN 461 µg l^{-1}) (Reavie & Smol 2001). This lake had a significant but small correlation between DCA axis one samples scores and inferred TP ($r^2 = 0.29$, $p < 0.05$) around the time of canal construction. This minor trophic response was likely related to its relatively large SA:W ratio (35%) and gentle sloping catchment area (Soil Research Institute 1968). Despite major watershed disturbances (Forrest 2001) the high volume of the lake likely diluted the increased nutrient input at this time, relative to the other lakes.

Otter Lake, the control lake, also experienced a moderate increase in productivity during this time (~1830). Qualitatively, there was an increase in productivity demonstrated by a decrease in the cyst to diatom ratio and an increase in the eutrophic indicators, *Aula-*

coseira ambigua and *Stephanodiscus parvus/minutulus* (Fig. 6). This lake has a moderate SA:W (13%), a gentle to steeply sloping catchment (Soil Research Institute 1968), and experienced moderate disturbances during this period (~1830) (Kennedy 1984). The trophic state response of this lake is important as it illustrates the regional impact of watershed disturbance in the ~1830s and the relatively minimal impact from canal construction *per se*.

In summary, the four lakes experienced an increase in productivity at the estimated time of canal construction and associated watershed disturbances. The magnitude of their trophic responses varied, however, and this appeared to be mainly related to SA:W ratios, water depth and relative watershed disturbance.

4.4.3. Recent trophic state inferences (Zone 3 ~1970s until present)

In recent years, there is a general shift to less productive diatom assemblages (Figs 3-6). The relative abundances of eutrophic, planktonic taxa, such as *S. parvus* and *F. crotonensis* generally decrease, and oligo-mesotrophic, planktonic species increase, such as *C. comensis* and *C. aff. gordonensis*. The ecology of these *Cyclotella* species is not well known; however, according to a recent diatom-based model from southeastern Ontario, *C. comensis* has a low [TP] opt. (10 $\mu g\ l^{-1}$), high pH opt. (8.29), high [TN] opt. (0.406 $mg\ l^{-1}$), high maximum depth opt. 30.7 m and moderate chlorophyll-*a* (Chl-*a*) opt. (1.53 $mg\ l^{-1}$) (Reavie & Smol 2001). *C. aff. gordonensis* is also characterized as an oligo-mesotrophic indicator with a [TP] opt. of 10 $\mu g\ l^{-1}$ and was found in similar conditions as *C. comensis* (pH opt. 8.28, [TN] opt. 0.423 $mg\ l^{-1}$, maximum depth opt. 37.5 m, Chl-*a* opt. 1.64 $mg\ l^{-1}$). Although the cyst to diatom ratio generally fluctuate during this zone, there is a general increase in planktonic taxa and decline in inferred [TP] values from ~1960 until present day oligo-mesotrophic conditions. Independent water quality improvements (increased Secchi disk measurements and decreased chlorophyll-*a* concentrations) have been recorded since the early 1970s (Lake Partner Program, unpublished data). Additionally, the 1998 inferred spring [TP] concentrations closely match the actual measured values taken during the spring of that year in the deep lakes (Little 1999).

The oligo-mesotrophic conditions of the recovery zones (1970 until present) are surprisingly similar to those inferred in the pre-disturbance zones, indicating a recovery to apparently near 'natural' conditions. This recovery suggests that recent (~1970s) cottage development under current government regulations (e.g. mitigation of septic tank placement, decrease in phosphorus concentration in detergents etc.) appears to be improving the lakes' trophic state conditions.

The distribution of the two planktonic species, *Cyclotella comensis* and *C. aff. gordonensis*, is interesting because they are present in all the study lakes around the 1970s, despite differences in lake morphometry and hydrological control associated with the canal. Furthermore, on a larger scale, they are prevalent in recent assemblages of many other paleolimnological studies in southeastern Ontario lakes (K. Neill, unpublished data; Christie 1993; Hall 1993), Lake Erie (Stoermer *et al.* 1996), a lake in the Northwest Territories, Canada (K. Rühland, unpublished) and in a subarctic lake in Finnish Lapland (Sorvari & Korhola 1998).

Increased abundances of *C. comensis* have been previously attributed to nutrient reductions associated with the invasion of zebra mussels (*Dreissena polymorpha*) in the mid-1980s in Lake Erie and the institution of effective phosphorus loading controls in the early-1970s (Stoermer *et al.* 1996). Zebra mussels were first noticed in the Rideau Canal near Ottawa in 1990 (Martel 1995) and have since been identified in some of the study lakes for several years now (Canadian Museum of Nature 1999), but the *Cyclotella* increase pre-dates their arrival in most of the study lakes and it also occurs in lakes with no zebra mussels (M. Chaisson, unpublished data). Additionally, the decrease in use of phosphate detergents is probably partly responsible for some of the recent nutrient reductions, however the *Cyclotella* increase once again pre-dates the mitigation in some lakes (e.g. Indian Lake, these *Cyclotella* species were first observed ~1950). Furthermore, other paleolimnological studies of lakes within the immediate area with no cottage development have experienced a similar shift to these less productive conditions (K. Neill, unpublished data). Increased retention of soils in secondary growth forests may also play a key role in nutrient reductions (Borman *et al.* 1974). Forests in the catchment area have been left to regrow, as many agricultural activities were abandoned in the 1950s (Warren 1997) and fertilizer use has declined over the past 20 years (Chambers *et al.* 2001). Over time, soils in the area have had time to redevelop and perhaps aid in nutrient retention, as nutrients can be strongly retained by aggrading soils of redeveloping forests (Borman *et al.* 1974).

The increase in these *Cyclotella* species in all the study lakes may also be related to climate warming and possibly longer periods of stratification. A recent rise in abundance of *Cyclotella comensis* in a remote subarctic lake in Finnish Lapland has previously been attributed to climate change (Sorvari & Korhola 1998). In addition, Schindler *et al.* (1996) observed recent (last 30 years) increases in thermocline depths (1 - 1.5 m) in lakes within southwestern Ontario and has related these occurrences to climate warming. An increased epilimnion volume may promote the growth of these planktonic *Cyclotella* species, however this possible relationship requires further exploration. Recent increases in temperature may also cause shallower lakes to stratify and develop a more suitable epilimnion habitat for these *Cyclotella* species. This reasoning may explain the recent occurrence of these *Cyclotella* species in Lower Rideau and other shallow lakes in Ontario (M. Chaisson, unpublished data). Hausmann & Lotter (2001) recently separated *Cyclotella comensis* into six ecomorphs and reported two to be good indicators of warm summer air temperatures. However, despite the need for greater ecological information on these *Cyclotella* species, these recent diatom assemblages are indicating oligo-mesotrophic conditions.

4.4.4. Shallow and deep lake trophic differences

The diatom-inferred trophic patterns differed between the shallow, macrophyte-dominated Lower Rideau Lake and those of the deep study lakes. These differences in responses were attributed to a shift in equilibria, in accordance with the alternative equilibrium theory for shallow lakes (Scheffer & Jeppesen 1998).

Prior to canal construction, the diatom assemblages in Lower Rideau Lake suggest that conditions were oligo-mesotrophic and the lake supported macrophytes, as benthic diatoms (*Achnanthes minutissima*, *Brachysira vitrea*, *Cymbella cesatii*, *Cymbella microcephala* and large *Navicula* species including *N. cryptotenella*, *N. densilineolata*, *N. diluviana*, *N. pupula*, and *N. vulpina*) and epiphytic taxa were dominant (e.g. *Cymbella microcephala*; Reavie & Smol 1997) (Fig. 4b). The high cyst to diatom ratio further indicates relatively unproductive conditions (Smol 1985). According to pre-canal surveys, conditions were described as relatively shallow and likely unproductive (lake is described as 'beautiful'; Welch 1979). Therefore, the lake was likely in a clear-water, macrophyte-dominated state (*sensu* Scheffer & Jeppesen 1998).

Around the estimated time of canal construction (Zone 2a), there was an increase in the more productive and planktonic species *Fragilaria crotonensis* and *Tabellaria flocculosa* strain IIIp. A concurrent decrease in the cyst to diatom ratio and an increase in reliable TP inferences (good fit and analogue matches) from 20 $\mu g\ l^{-1}$ to 36 $\mu g\ l^{-1}$ also indicated an increase in nutrients during this period. Also, at this time, there was a decrease in organic matter (~80 to 55%) with a relative increase in siliciclastic material (Forrest 2001). This inferred increase in nutrient concentrations and siliciclastic material coincided with a period of watershed disturbances and rise in water levels (~1 m) associated with canal construction (Forrest 2001). The combination of these disturbances is thought to have shifted the lake to a turbid state (*sensu* Scheffer & Jeppesen 1998). Interestingly, a Swedish shallow lake also demonstrated a switch from a clear to a turbid state following 0.5-m increase in water level associated with dam construction (Wallstein & Forsgren 1989).

Following the 1860s, Lower Rideau Lake is believed to have returned to the clear-water state (similar to pre-canal conditions), once again supporting macrophyte growth. The productive and planktonic diatom species disappear from the diatom record, and the assemblages become dominated by a benthic community with some species known to colonize macrophytes (e.g. *Amphora pediculus*; Reavie & Smol 1997). This increase in periphyton indicates an increase in water clarity necessary to support macrophyte growth and abundance. Additional macrophyte habitat was likely created with flooding of lowland areas during canal construction (~1 m) and more recent water level increases with dam repair in 1865 (0.6 m) (Parks Canada, undated documents). This periphytic assemblage remains dominant until the present-day, which suggests clear-water, macrophyte-dominated conditions. The mechanism for this second switch between states is, however, less certain. A reversion back to the clear-water, macrophyte-dominated state is perhaps related to decreased erosion from the catchment (organic content stabilizes at this time; Fig. 4b), once again creating favourable light conditions for benthic diatoms and macrophyte growth.

Unlike the deep lakes' diatom assemblages that recorded increases in eutrophic taxa in the 1930s and decrease in the 1970s, the diatom assemblages of Lower Rideau Lake remained relatively stable during this period. The diatom assemblages in these zones were dominated by small benthic *Fragilaria* species (*F. brevistriata*, *F. pinnata*, *F. construens*, *F. construens* var. *venter*), and small productive *Navicula* species (*N. minima*, *N. pseudoventralis*, *N. schadei*, *N. seminulum*, *N. subumuralis*, *N. vitabunda*), and meso-eutrophic tychoplanktonic taxa, *Aulacoseira ambigua* and *A. granulata* (Fig. 4a). *A. granulata* is a well-known indicator of nutrient-rich and turbulent conditions (e.g. Kilham *et al*. 1986; Bennion 1994). A similar, modest nutrient response to watershed activities was previously demonstrated in the paleolimnological study of Lake Opinicon, another shallow lake in the Rideau Canal system (Karst & Smol 2000; Little & Smol 2000). As argued by Karst & Smol (2000), the minimal diatom changes during this period of high watershed activity are thought to reflect the stabilizing effect of macrophytes, characteristic of the clear-water state of the alternative equilibrium theory. In summary, Lower Rideau Lake is thought to have experienced a clear-water, macrophyte-dominated state, a turbid-productive state, and then a return to the clear-water stable state over the past ~200 years. Macrophytes have likely played an important role in maintaining present-day water clarity and moderate nutrient conditions.

5. CONCLUSIONS

This study tracked the recent (~200 years) trophic histories of Indian, Big Rideau, Lower Rideau and Otter lakes. Based on the microfossil evidence, the lakes had similar oligo-mesotrophic conditions prior to European settlement. Nutrient loading increased with human activities; however, the magnitude of the trophic state response varied and was attributed to SA:W ratios and the magnitude of catchment disturbance. Otter Lake, the temporal control lake, also demonstrated a moderate trophic state response around the time of canal construction, emphasizing the heightened impact of watershed disturbances during this time and not just that of the canal. Recovery from eutrophication over the last ~30 years is evident in all of the study lakes. This recovery is believed to be attributed to the improved nutrient retention of soils in secondary growth forests and/or the effects of climate warming, as well as nutrient mitigation programs. However, the regional increase in *Cyclotella comensis* and *C. aff. gordonensis* species, and their relationship with stratification patterns and climate warming, warrants further investigation.

The trophic responses of Lower Rideau Lake, the shallow lake, suggest that it has changed trophic equilibrium states over the last two centuries. The lake is thought to have maintained a clear-water state throughout past anthropogenic disturbances with the exception of the period during canal construction. During the 1830s, the lake's sediments recorded a marked increase in productivity and planktonic diatoms, and this response is thought to reflect a switch to the turbid state. The lake subsequently returned to the macrophyte-dominated clear-water state. Macrophytes have likely played an important role in water clarity and nutrient uptake in Lower Rideau Lake.

The trophic patterns determined from these study lakes have provided further insights on the pre-disturbance conditions of these canal lakes and determined the impact of numerous human activities on lakes with differing morphometries. Recent regional trophic trends highlight the importance of external factors, likely climate warming or vegetation regrowth in the catchments on these and surrounding systems. This information should help lake managers set realistic mitigation targets to maintain their current oligo-mesotrophic conditions and sustain the ecological future of the Rideau Canal system.

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