RECONSTRUCTING THE TROPHIC HISTORIES (ca. 200 years) OF FOUR LAKES WITHIN THE RIDEAU CANAL SYSTEM, ONTARIO

by

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ABSTRACT

Diatom-based paleolimnological techniques were used to track the eutrophication histories (ca. 200 years) of four lakes within the Rideau Canal system, Ontario, Canada. The Rideau Canal waterway links Kingston and Ottawa and was constructed in 1832 for military purposes. Recent water quality concerns, as well as differing trophic responses to anthropogenic disturbances observed in past paleolimnological studies, prompted this investigation. Stratigraphical analysis of microfossils and physical sediment characteristics in ^{210}Pb and *Ambrosia* dated sediment cores, along with diatom inferred total phosphorus and maximum depth reconstructions, were used to determine the trophic histories in Indian, Big Rideau, Lower Rideau and Otter lakes.

Paleoecological information of the dominant diatom taxa that flourished during the pre-settlement period indicates 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 surface-area-to-watershed ratio appeared to be one of the more important ones. In additional, the similar trophic response of the control lake (not part of the canal), Otter Lake, illustrated the regional impact of the watershed disturbance (e.g. logging, settlement, mining, agriculture) and minimal impact from the canal per se. In more recent years (~1970 to present) there is an increase in less productive planktonic species (e.g. *Cyclotella comensis* and *Cyclotella* aff. *comta* v. *unipunctata)* observed in all the study lakes. These recent improvements in water quality are attributed to the mitigation of phosphate detergents, improved nutrient retention of developing soils in secondary growth forests and the potential effects of climate warming.

Eutrophication patterns determined for the deep lakes were similar to the other deep lake paleolimnological study in the canal. However, the trophic response in the shallow lake, Lower Rideau Lake, is more pronounced at the time of canal construction than those demonstrated in previous shallow canal lake studies. This heightened response was attributed to increased nutrient export from watershed disturbances within its limestone catchment. Trophic patterns from this shallow lake study support the alternative equilibrium theory. Results from this study can now be used to help set realistic mitigation targets for these lakes.

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TABLE OF CONTENTS

TABLE OF CONTENTS (cont'd)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (con't)

LIST OF COMMON ABBREVIATIONS

CCA - Canonical Correspondence Analysis

CRS - Constant Rate of Supply

DCA - Detrended correspondence analysis

MZ - maximum depth

RMSE - root mean squared error

$\text{RMSE}_{\text{boot}}$ - Bootstraped RMSE

SD - standard deviation

TP - Total phosphorus

CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

LAKE EUTROPHICATION

Eutrophication describes the progression of a lake from nutrient poor to nutrient rich conditions (i.e. an increase in trophic state) (Whiteside, 1983). Phosphorus is considered to be the key nutrient in stimulating algal and plant growth in almost all temperate lakes (Schindler, 1974). There are both natural and anthropogenic causes of eutrophication. Natural sources are often relatively minor, and include tree die-off (Hall and Smol, 1993) and limnological effects of climate shifts (Webster et al., 1996). Anthropogenic sources of eutrophication, or cultural eutrophication, are more common and include nutrient enrichment from agricultural, urban run-off, industries, and sewage.

Globally, cultural eutrophication is one of the most widespread forms of lake pollution and results in many negative impacts on lake ecosystems (Lampert and Sommer, 1997). The most commonly cited problems include: increased algae and macrophyte growth; phytoplankton community shifts from green algae and diatoms to cyanobacteria; hypolimnetic oxygen depletion, causing changes in dominant fish species (e.g. salmonids to cyprinids) or fish kills if severe; general reduction in diversity (e.g. benthic invertebrates, macrophytes, fish); and anoxic conditions at the sediment-water interface, promoting phosphate release (Mehner and Benndorf, 1995). Together, these ecosystem changes can decrease the aesthetic (recreation) and economic (water treatment, water supply, recreation and fisheries) quality of the water, and seriously affect ecosystem function (Mehner and Benndorf, 1995).

Some lakes are more susceptible to eutrophication because of their location and regional characteristics (e.g. climate, hydrology, geography and physiography, natural trophic status, lake depth, industrialization and urbanization) and the degree and duration of past pollution (Hall and Smol, 1999). For example, the local geology can influence lake productivity. Dillon and Kirchner (1975) found that mean phosphorus export from forested catchments with igneous bedrock in the Precambrian Shield was less (4.8 mg $m^{2}a^{-1}$) than exports from catchments in sedimentary areas (10.7 mg $m^{-2}a^{-1}$). For example, Dixit et al. (1999) attributed high background TP values in New England Uplands and Coastal Lowlands/Plateau ecoregions to nutrient-rich runoff from calcareous catchment soils and lower background TP values in the Adirondacks ecoregion to nutrient-poor runoff in predominantly granite regions.

Furthermore, lakes with large, steep catchment areas are generally more susceptible to eutrophication (Prairie and Kalff, 1986). For example, in a paleolimnological study of five Ontario lakes, Hall and Smol (1993) found that the strongest eutrophication response to the hemlock decline and recovery (4,800 - 3,500 years BP) occurred in lakes with the largest and steepest catchments.

Additionally, the susceptibility of shallow lakes to eutrophication may be quite different from that of deep lakes. Shallow lakes tend to be naturally more productive. Internal loading is generally higher in shallow lakes, as there are often increased nutrients in the water column from mixing and wind-resuspension of nutrients (Jeppesen et al., 1997). Additionally, Scheffer et al. (1993) have described an alternative equilibrium theory to explain the trophic dynamics of shallow lakes. At one end of the equilibrium, lakes are characterized as being in a clear-water state, dominated by aquatic vegetation, whereas at the other end of the equilibrium, lakes display a turbid state characterized by high phytoplankton biomass and the absence of aquatic vegetation. These states are buffered by food-web and lake-water sediment interactions (Jeppesen, 1998). It is hypothesized that abundant macrophyte vegetation in shallow lakes can sustain a clear-water state even with relatively high nutrient loads. However, there is a critical point where the phytoplankton will outcompete the macrophytes and the water will become turbid. In the turbid state, it would take a substantial nutrient reduction to allow for the recolonization by aquatic plants. A decrease in macrophytes can further change the structure of the ecosystem, by decreasing spawning habitat for fish and invertebrates, and by influencing chemistry of open waters by decreasing sediment anchoring (Balls et al., 1989). These characteristic effects of the turbid state are undesirable from a lake-management perspective.

Eutrophication is a complex issue and so long-term data are required to characterize the varying susceptibilities of lakes to eutrophication and address water quality concerns. For example, long-term 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). However, such data are generally unavailable for most lake systems, and so indirect proxy methods must be used.

PALEOLIMNOLOGY AND LAKE EUTROPHICATION

Paleolimnology uses the physical, chemical and biological information archived in lake sediments to reconstruct and interpret past environmental conditions over many time scales (Smol, 1992). Paleolimnological indicators include geochemical markers, pigment degradation products, and the morphological remains of many lacustrine organisms, such as diatoms.

Diatoms (Class Bacillariophyceae) have been widely used as bioindicators of environmental conditions in lakes (Stoermer and Smol, 1999). They have silicified walls (frustules) that are taxonomically diagnostic (species-specific or lower), are abundant in a wide range of aquatic habitats, and remain well-preserved in most lake sediments (Charles and Smol, 1994; Battarbee, 1986). Diatom species generally have well-defined optima and tolerances to many environmental variables (Dixit et al., 1992). Further, diatoms have rapid replication rates, enabling them to track fine temporal changes in the aquatic environment (Dixit et al., 1992). For these reasons, diatoms can provide indications of environmental conditions.

Diatoms and eutrophication

Diatoms have proven to be good indicators of eutrophication problems in lakes (reviewed by Hall and Smol, 1999). As primarily photoautotrophic organisms, diatoms are directly affected by changes in nutrient and light availability, two variables associated with eutrophication (Tilman et al., 1982). Individual species have specific habitat and nutrient requirements (Round et al., 1990). Diatoms can also be used to track littoral to planktonic shifts in algal production, which may occur during light-limiting, eutrophic conditions (Osborne and Moss, 1977). For example, in some oligotrophic lakes, the photic zone has been found to extend well below the summer thermocline (Lowe, 1996). However, in some productive lakes, heightened nutrient inputs can lead to turbid conditions with light limitations for macrophytes and periphyton growth (Burkholder and Cuker, 1991). Because of these qualities, stratigraphic analysis of diatoms can be used to interpret historical trophic state changes associated with human activities or natural processes (e.g. Hall and Smol, 1999).

DIATOMS AND MULTIVARIATE STATISTICS

Quantitative inferences of various limnological variables, such as those related to trophic state, can be determined using multivariate statistics in paleoecological investigations (Birks, 1995). Basically, a calibration or training set is constructed by collecting benthic surface-sediment samples (0.5 - 1 cm assumed to represent the last few years of accumulation), water chemistry and other limnological data from a number of lakes across an environmental gradient of interest (e.g. total phosphorus (TP)). Multivariate statistics are then used to quantify the relationship between the limnological conditions and diatom assemblages (Birks, 1995). Ordination techniques are used to determine environmental variables that best explain the variance in the diatom species data. Subsequently, environmental optima of common diatom taxa for limnologically important variables are then calculated using regression techniques. Transfer functions are then generated with calibration techniques and subsequently applied to down-core diatom data. Diatom transfer functions have been used to reconstruct a number of limnological variables such as pH (Batterbee et al.,1999) and salinity (Fritz et al., 1999). Trophic-related transfer functions, such as total phosphorus, have also been developed in a number of regions around the world (Hall and Smol, 1999).

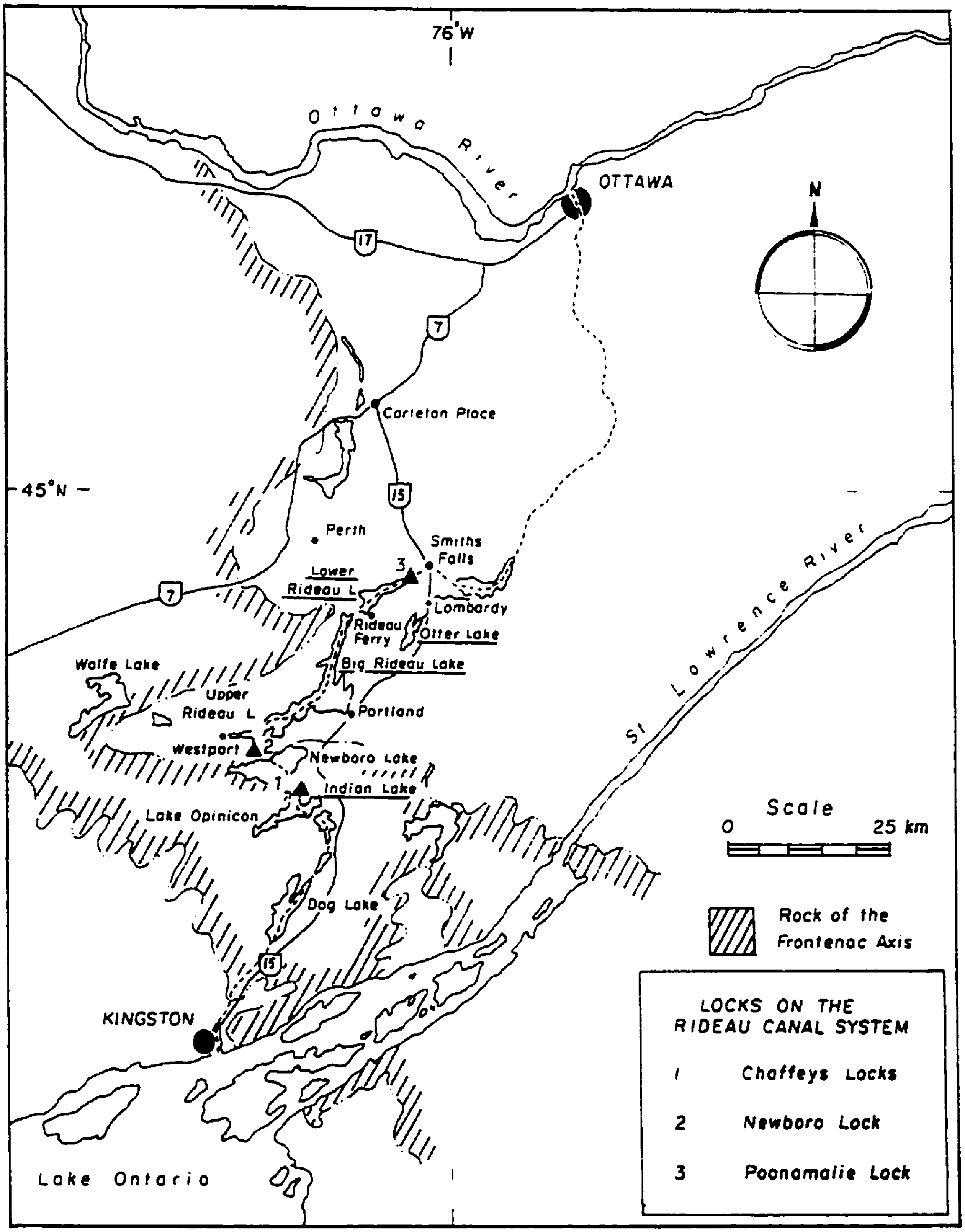
Southeastern Ontario diatom model for TP reconstruction

Recently, Reavie and Smol (2001) developed a diatom-based water quality model from 64 alkaline southeastern Ontario lakes across a TP gradient of 4 to 54 μg/L. Transfer functions were generated using weighted-averaging regression and calibration techniques to determine the environmental optima of common diatom taxa for several limnologically important variables (e.g. total phosphorus (TP)). The diatom inference 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}). This TP model has been used to reconstruct the recent trophic histories of four lakes within the southern Ontario region (Neill et al., in progress). The model was generally considered reliable as inferred total phosphorus [TP] concentrations closely matched recent available water chemistry measurements for the study lakes (Neill et al., in progress).

EUTROPHICATION IN THE RIDEAU CANAL SYSTEM

The Rideau Canal is a 202 km-long waterway linking Ottawa and Kingston through a series of lakes, rivers and canal cuts (Figure 1.1). The canal was built between 1826 and 1832 for military purposes. It provided an alternative route to Kingston from Montreal, as opposed to travelling on the international waters of the St. Lawrence River.

Figure 1.1. Map of southeastern Ontario showing the geology of the area and the location of the Rideau Canal waterway (dotted line) and study lakes (underlined).


76°W
Ottawa River
OTTAWA
N
17
7
Carleton Place
45°N
15
Perth
Smiths Falls
3
Lower Rideau L
Lombardy
Rideau Ferry
Otter Lake
Big Rideau Lake
Wolfe Lake
Upper Rideau L
Portland
Westport
2
Newboro Lake
1
Indian Lake
Lake Opinicon
St Lawrence River
Scale
0
25 km
Dog Lake
Rock of the Frontenac Axis
KINGSTON
LOCKS ON THE RIDEAU CANAL SYSTEM
1 Chaffeys Locks
2 Newboro Lock
3 Poonamalie Lock
Lake Ontario

High dams were built to raise the water levels of lakes and rivers and create navigable depths for steamboat travel (Turner and Visser, 1995). 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. From 1832 to 1848, the canal was mainly used for the transport of goods from Montreal to Kingston (Legget, 1975). However, the transport of goods subsided with the construction of the St. Lawrence Waterway (1848) and railway (Toronto to Montreal completed in 1856) (Heisler, 1973), and the canal was subsequently used primarily for local commercial transport. From the late-1800s until the present, the canal has mainly served recreational purposes (Legget, 1975).

Tourism is currently the main industry along the canal. People visit the canal for lake and river recreation, sport fishing, waterfowl and small game hunting, and for its historical importance. Land-based visitation to the lock stations is estimated at one million people per year (Canadian Heritage Parks Canada (CHPC), 1996). An additional estimated 84 000 boats travel on the canal (in 1998; Canadian Museum of Nature, 1999). Approximately 12 million dollars is generated annually from canal visitors (CHPC, 1996). Apart from tourism, the canal is also used for hydroelectric power, water supply (e.g. Smith Falls), flood abatement, and runoff dilution associated with agricultural activities (Acres International Ltd., 1994).

Recently there have been environmental concerns about the future of the Rideau Waterway (Michael Michalski Associates, 1992; Ecological Services, 1998). These concerns include increased urban development, loss of shoreline and wetland habitat for fish and wildlife, increased fishing pressures, and diminishing water quality. The water quality concerns have prompted several limnological initiatives within the Rideau Canal System, such as the Biodiversity Study, a five-year study being conducted by the Canadian Museum of Nature (1999). Eutrophication has been identified as the main water quality concern in the recreational lakes within the canal system (Michael Michalski Associates, 1992).

Past and present watershed disturbances within the Rideau Canal system

The Rideau Canal has received increased nutrient loads from multiple anthropogenic sources throughout its history (e.g. flooding, logging, agriculture, industry, cottage development). With canal construction (1826 - 1832), lakes and rivers were flooded (~2 - 3 m) to create navigable depths. The flooding of lowland areas likely increased nutrients in the canal lakes. In a paleolimnological study of diatom succession in an urban reservoir in Michigan, Donar et al. (1996) attributed an increase in productivity to increased nutrients from flooded areas. The construction of dams and locks also 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 control on these lakes may have also increased nutrient addition by increasing natural water-residence times, providing more time for the lakes to accumulate nutrients in the water column and release phosphorus from the sediments. For example, accelerated eutrophication in a small eutrophic lake in Northern Ireland was attributed to reduced flushing and sudden increase in the sediment phosphorus release rate (Rippey et al., 1997).

From the early 1800s until the 1870s, forests in the Rideau Canal area were cleared for lumber and settlement purposes. Cleared land likely resulted in heavy spring runoff with increased soil erosion and siltation of the waters. Forest cover can function as a sink or source for nutrients and the removal of terrestrial vegetation generally leads to the leaching of nutrients to a lake (Bormann and Likens, 1979).

Despite generally unproductive soils, agricultural activities have occurred in the Rideau area since settlement. By the 1860s, two-thirds of the area was cleared for agricultural and settlement purposes (CHPC, 1996). Today, only one-third of the area supports major agricultural activities (dairy and beef farming, and row cropping), particularly the more fertile soils between Merrickville and Ottawa, Westport and Newboro, and south of Seeley's Bay (CHPC, 1996). Nutrient concentrations in agricultural runoff are substantial and often sufficient to create eutrophic conditions in receiving water bodies (Lennox et al., 1997). Phosphorus inputs from agriculture vary due to differences in land-use management, climate, and soil type (Holtan et al., 1988). Poor agricultural practices decrease water quality by adding excess nutrients and pesticides to receiving water bodies through erosion and runoff. Sources of nutrient loss to waterbodies include overfertilizing, feed lots, grazing, decreased vegetation cover, and increased soil tilling (Daniel et al., 1998).

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 used for fertilizer, mica used for insulation and unbreakable glass, iron ore used for steel production, graphite and limestone and sandstone used for construction purposes). The resulting industrial discharges likely added nutrients to the Rideau Canal system.

Cottage development generally began in the 1930s and has increased significantly along the canal since the 1950s. In 1951, there were fewer 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 (e.g. Portland (population 275), Rideau Ferry (population 150), Newboro (population 253)), along with rural and seasonal residents, reside along the Rideau Canal System (Township of Rideau Lakes Office, pers. comm.). Most canal communities have private sewage tank systems. However, a secondary sewage treatment plant at Perth, serving a population of 5 646, discharges treated effluent into the Rideau Lakes basin (Michael Michalski Associates, 1992). There is no storm-water treatment facilities within these communities (CHPC, 1996). These sewage sources have also contributed nutrients to the canal system.

Previous paleolimnolgical studies of eutrophication patterns in the Rideau Canal

Previous paleolimnological studies have been conducted on several lakes within the canal system to assess historical eutrophication patterns (Christie and Smol, 1996; Karst and Smol, 2000; Reavie and Smol, in progress; Little and Smol, 2000). These studies have highlighted different responses to disturbance following canal construction. Using fossil diatom assemblages from Upper Rideau Lake, a large, deep lake (surface area (SA) = 13.62 km^2, mean depth = 8.05 m, maximum depth (MZ) = 22 m), Christie and Smol (1996) reconstructed past limnetic total nitrogen [TN]. Results indicated that Upper Rideau Lake has always been productive, but that nutrient levels increased with settlement and especially with 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, MZ = 9.2 m), recorded no major changes in trophic state following canal construction (~1826 - 1832) (Karst and Smol, 2000; Little and Smol, 2000). Sand Lake, which is a relatively large, shallow, canal lake (SA = 7.3, mean depth = 5.2 m, MZ = 14.3 m), located down stream of Lake Opinicon, also recorded minimal changes in diatoms around the time of canal construction (Reavie and Smol, in progress).

Karst and Smol (2000) suggested that the "dampened" response to nutrient inputs at Lake Opinicon might be due to its abundant macrophyte community, supporting the stable state of the alternative equilibria hypothesis (Scheffer et al., 1993). They argued that Lake Opinicon remained in the clear-water, macrophyte-dominated state despite past increases in nutrient inputs throughout canal construction and other past anthropogenic disturbances. Given that Upper Rideau, Opinicon and Sand lakes have responded quite differently to canal construction, the responses of other lakes within the canal system are uncertain, and so prompted this comparative study.

PURPOSE AND OBJECTIVES

The overall objectives of this thesis 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 techiques. Trophic state responses were determined for two deep (Indian and Big Rideau) and one shallow (Lower Rideau) canal lakes during the period of canal construction (~1830), as well as subsequent changes due to anthropogenic activities in the watersheds. Otter Lake, the control lake, is not a part of the canal, but is in the greater Rideau watershed and therefore would have experienced similar watershed disturbances, such as logging, settlement, agriculture and mining, but not flooding and canal construction.

Chapter 2 describes the study lakes (e.g. basin morphology, geology and catchment area) and summarizes the historical anthropogenic disturbances in the study region. The methodology and materials used to determine the trophic state histories of the study lakes are discussed in Chapter 3. Trophic changes observed in the diatom assemblages, cyst to diatom ratios and physical sediment content of the ^{210}Pb- and *Ambrosia*-dated sediment cores from Big Rideau, Indian, Lower Rideau, and Otter lakes are described in Chapter 4. Trophic state histories are described in terms of pre-disturbance conditions, historical disturbance conditions, and recent water quality conditions. Results from the application and evaluation of total phosphorus and maximum depth transfer functions are also discussed (Chapter 4). Finally, trophic state histories were compared between the study lakes and previous paleolimnological studies in the canal system (Chapter 5).

This study has important implications in terms of lake management. It provides historical trophic reconstructions for the four study lakes and assesses the effects of natural and anthropogenic changes on trophic state conditions in Big Rideau, Indian, Lower Rideau, and Otter lakes for future water-quality studies. This information is important from a water quality perspective as it establishes: 1) background, pre-impact limnological conditions; 2) natural background variability; 3) the onset of eutrophication; 4) the extent of ecological degradation; and 5) any recent recovery. This information will be useful to lake managers for setting realistic mitigation targets. Additionally, results from this study provide useful information on the management of lakes with different morphometry in relation to eutrophication and hydrological changes. Furthermore, the paleolimnoligical investigation of Lower Rideau Lake will further evaluate the alternative equilibrium hypothesis for shallow lakes. Finally, this information contributes to the growing body of knowledge that will help secure the future of the Rideau Canal system.

CHAPTER 2: SITE DESCRIPTIONS

The Rideau Canal region has a temperate climate with generally cool winters (Jan. max. -5.5 °C, min. -15.3 °C), warm summers (July max. 26.5 °C, min. 14.3 °C) and an average annual precipitation (Kemptville) of 914.7 mm per year (Environment Canada, 1998). The Rideau Canal is located within the Great Lakes St. Lawrence Region dominated by *Pinus strobus* (eastern white pine), *P. resinosa* (red pine), and *Tsuga canadensis* (eastern hemlock) coniferous species, along with *Betula lutea* (yellow birch), *Acer saccharum* (sugar maple), *Acer rubrum* (red maple), *Tilia icana* (basswood), *Quercus rubra* (red oak) and *Ulmus americana* (white elm) deciduous trees (Scott, 1995). The canal crosses Phaerozoic limestone and Precambrian igneous and metamorphous bedrock which influences the physiography of the area. The two physiographic regions: 'The Smith Falls Limestone Plain' and the 'Leeds Knobs and Flats' describe most of the surrounding area. The Leeds Knobs and Flats region is characterized by knobs of exposed or shallow-covered granite bedrock among clay beds (Chapman and Putnam, 1984). The Smith Falls Limestone Plain, between Merrickville and Rideau Ferry, consists of shallow soils over limestone, dolomite and sandstone (Chapman and Putnam, 1984).

The canal links 16 lakes within two river basins: the Cataraqui River Watershed (drainage area 910 km^2) and the Rideau River Watershed (drainage area 3730 km^2) (Acres International Ltd., 1994). Four lakes from the Rideau Canal region were chosen for detailed paleolimnological analysis. Big Rideau, Lower Rideau and Otter lakes are within the Rideau watershed and Indian Lake is located within the Cataraqui Watershed.

Indian, Big Rideau and Lower Rideau lakes are part of the canal waterway, whereas Otter Lake is not (Figure 1.1). 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.

The study lakes lie within the townships of North Burgess and North Elmsley in Lanark County and the Township of Rideau Lakes (formerly known as the townships of Bastard and South Burgess, South Elmsley and South Crosby) in the United Counties of Leeds and Grenville. The former township names will be used in the lake descriptions to facilitate the historical land-use descriptions of the watershed areas.

Indian, Big Rideau and Otter lakes are deep, thermally stratified, and classified asa oligotrophic to mesotrophic. Lower Rideau Lake is a shallow, polymictic, mesotrophic lake. Physical and chemical characteristics of the study lakes are presented in Table 1. Further lake descriptions are provided below along with historical perspectives of past anthropogenic activities occurring within their watersheds.

CATARAQUI WATERSHED

Indian Lake

Indian Lake (44° 60' N, 76° 32' W; 122 m a.s.l.; United Counties of Leeds and Grenville, South Crosby Township) is located upstream of Chaffey's Locks (Figure 2.1). Indian Lake is a small (2.7 km^2), deep lake (maximum depth 26 m) with a relatively large watershed (359 km^2) (Ontario Ministry of the Environment, unpublished data) (Figure 2.1, Table 1).

Table 1. Physical and chemical characteristics of the study lakes.

	Indian	Big Rideau	Lower Rideau	Otter
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) (x 10^6 m^3)	26.8	726.8	36.5	60.5
Catchment area (C) (km^2)	359	128.4 (1)	308.8 (1)	47
SA:C	0.01	0.35	0.04	0.13
V:C	0.07	5.66	0.12	1.29
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* (μg/L)	1.2	1	n.d.	2
Spring TP (μg/L)	10	8	19	11
Average TN (μg/L)	420	330	465	433
Average pH	8.4	7.9	8.7	8.6

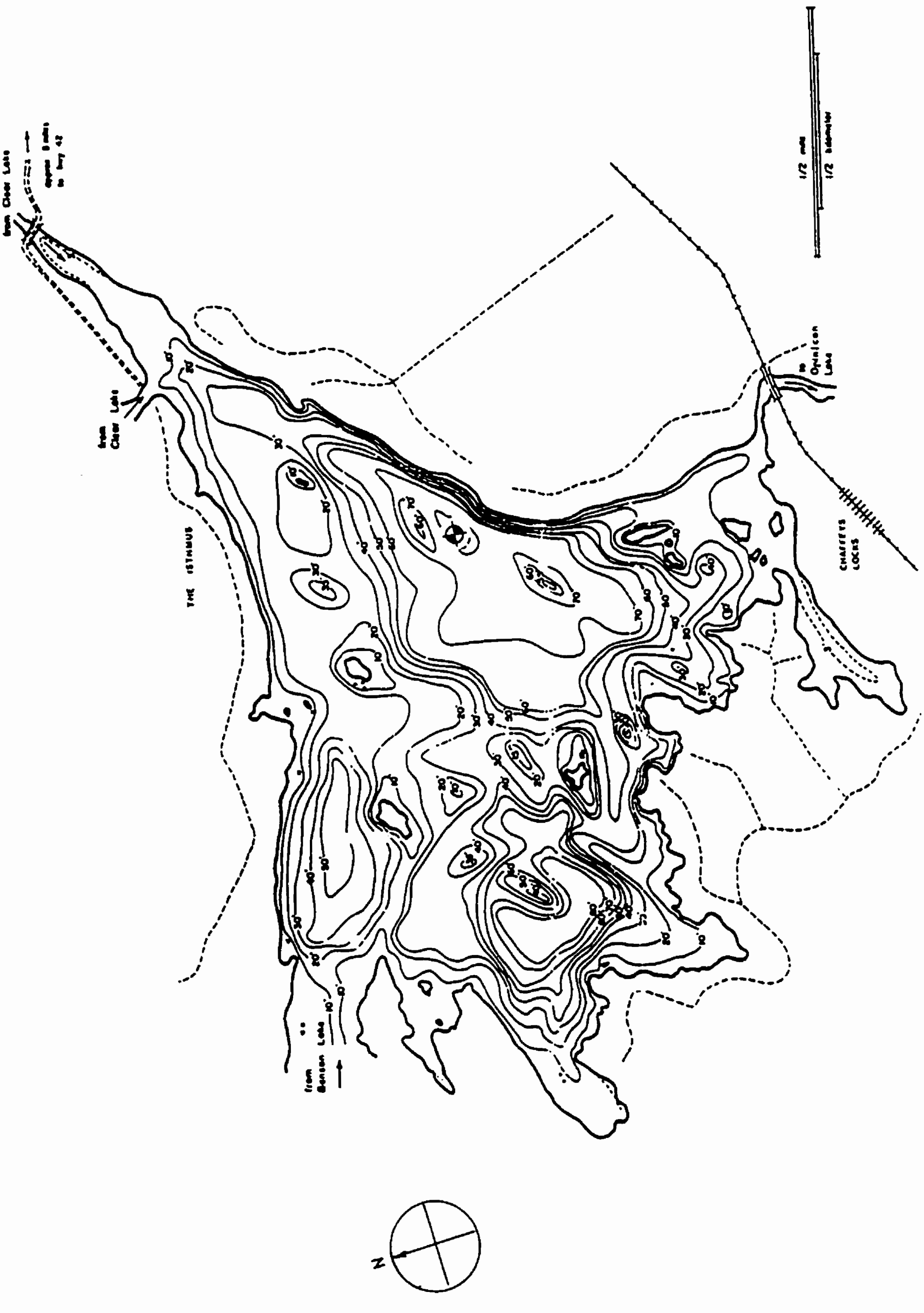
Physical data compiled from lake survey reports from the Ministry of the Environment, Kingston District Office and Fisheries Assessment Unit report 90-4, M.N.R. Rideau Lake Map (1972).

(1) Michael Michalski Associates, 1992; (2) I. Patterson, pers. comm.; (3) Kennedy, 1982

Water chemistry data for Indian and Big Rideau lakes from 1998 from Little (1999) and for Lower Rideau and Otter lakes from O.M.O.E. Lake Partner Program (1999), Canadian Museum of Nature (unpublished data) and 1999 field sampling.

Average indicates an annual average of spring (May) and summer (Aug./Sept) values. (n.d. = no data)

Figure 2.1. Bathymetric map of Indian Lake, Ontario. Approximate position of the coring site is marked by the '+' symbol. Depth contours are in feet. (modified from the Ministry of the environment, Kingston District office, unpublished data).


from Clear Lake
approx 8 miles to Hwy 42
from Clear Lake
THE ISTHMUS
from Benson Lake
to Opinicon Lake
CHAFFEYS LOCKS
1/2 mile
1/2 kilometer
N
10
20
30
40

Most of the shoreline consists of Precambrian rock and is part of the Leeds Knobs and Flats physiographic region (Chapman and Putnam, 1984). The Monteagle sandy loam-rock soil complex makes up the soil type found on the strongly sloping southwest shores of the lake (Soil Research Institute, 1968). This rock soil complex is described as shallow, well drained and with numerous granite outcroppings (Soil Research Institute, 1968). Rockland is the discriptor for the bare rock soil type found on the north and east shores of the lake (Soil Research Institute, 1968).

Based on spring water chemistry data (1998), the lake is classified as oligotrophic to mesotrophic (Table 1) (Wetzel, 1983). Sporadic Secchi depth and chlorophyll *a* measurements from the past 30 years have also suggested oligotrophic to mesotrophic conditions ranging from 3.5 - 5.5 m and 1.5 - 4 μg/L, respectively (Appendix A). A slight increase in Secchi depth and decrease in chlorophyll *a* measurements suggest that nutrient conditions may be improving over recent years (Appendix A).

Two lakes, Clear and Benson, drain into Indian Lake, which subsequently drains into Opinicon Lake at Chaffey's Locks. To maintain navigable depths in downstream lakes, the water level of Indian Lake is drawn down from an early summer level of 122.05 m to a winter holding level of 121.59 m (Acres International Ltd., 1994). Therefore, flow rates are controlled and range from ~18 m^3/s in the spring to about 5 m^3/s in the summer (Acres International Ltd., 1994).

Indian Lake History

Prior to European settlement, the area surrounding Indian Lake was covered by forests of cedar, white pine, birch and poplar (Fleming, 1981). Chaffey's Mills, located on the downstream southeast end of Indian Lake, was settled with 126 people in 1815 and was moderately developed by 1825, with many township roads (Fleming, 1981). At this time, a distillery, as well as grist, woolen and saw mills harnessed energy from the rapids flowing from Indian Lake (Passfield, 1982). According to the diary of an early surveyor, MacTaggart, the mill dam had an estimated fall of nine feet three inches (2.82 m) and backed up an estimated three and a half feet (1.02 m) of water in Indian and other Newboro lakes (Welch, 1979).

Canal construction began in this area in 1827, when a 55 m long and 2 m deep canal was cut through the northeast shore of Indian Lake to provide a direct route from Clear Lake (Passfield, 1982). In 1828-1829, malaria struck the canal workers at both locks above and below Indian Lake, Newboro and Chaffey's Locks (Fleming, 1981). It was believed that malaria was caused by bad air and, in an attempt to rid the canal of the disease, trees were cut back for miles on each side of the canal to better circulate the air (Passfield, 1982). As a result, large sections of the forest were cleared. Around the time of canal completion, a painting of Chaffey's Locks, shows the foreground slopes of Indian Lake denuded of trees (Fleming, 1981).

Chaffey's Locks was completed in 1830. A single lock with a ten foot two inch (3.10 m) lift was built just below the former site of the mill dam (Passfield, 1982). The water flow throught the weir was regulated with stop logs.

Following canal construction, land clearing along the Rideau Waterway mirrored the timber demand and settlement of the area. Around 1815, there was a great demand for timber in Britain and later (1830-1840) the United States (Warren, 1997). Fifty sawmills were identified within the Rideau Corridor after the completion of the canal, seventeen of which were located in the townships away from the settled areas (Snyder, 1977). In 1840, the canal was in regular use for the passage of rafts of logs; this traffic continued well into the twentieth century (Legget, 1975). Forests of the canal region were heavily logged until the 1870s (Sadler, 1977). During this time, stands of white pine, hemlock and oak were cut in the late fall, close to the water for easy hauling to the shoreline (Warren, 1997). In the 1830s, this logging activity occurred within the Indian Lake area as three sawmills were reported to be in operation at this time (Lot 9 Con. 2, Elgin, Lot 17 Con. 6 and Lot 24 Con. 10) (Warren, 1997).

A large number of people were brought to the lock areas surrounding Indian Lake (Chaffeys and Newboro locks) during the canal construction period. In the few decades following construction, the community size increased. In 1830, a small village with more than 60 log-buildings sprang up near the canal cut at the Newboro Lock. By 1850, Newboro had a population of 300 people (Passfield, 1982), and by 1861 there was an ashery, a furniture factory, a cabinet shop, a carriage shop, and a tannery in the Newboro area (Snyder, 1977). During these years, most of these settlers farmed potatoes, white corn, cabbages and turnips, oats and wheat (Warren, 1997).

After the 1850s, mining and quarrying activities occurred within the Rideau waterway. The Chaffey Iron Mine (Lot 26 Con. 6) was the first mine identified in the Rideau corridor (Snyder, 1977). It was located on an island in Newboro Lake and mined intermittently from 1850-1870s, with 11,000 tons of ore extracted between 1870 and

1871 (Snyder, 1977). In the 1890s, test pits on the west side of Indian Lake (Lot 19 Con. 8) were mined for mica (Warren, 1997). At the time, mica was used for making insulation and unbreakable glass products.

During 1880-1890, small-scale wheat farming was still common, although the dairy industry was becoming more important. In the Rideau Corridor, especially within the principal dairying areas of Leeds and Grenville counties, there were 33 cheese factories in 1887, which increased to 37 by 1927 (Snyder, 1977). The number of cows on Leeds farms increased from 17 000 in 1861 to 48,000 in 1901 (Moore, 1982). A cheese factory operated on the east side of Clear Lake (just north of Indian Lake) from 1900 - 1920 (Fleming, 1981) and a gristmill operated at Chaffey's Locks between 1873 and 1922 (Warren, 1997).

From 1900 until 1950 the township population decreased and the economy changed. Young people were deserting the area in a quest for the more fertile soils located in the Canadian West (Warren, 1997). At this time, large-scale lumbering also came to an end, with the last large raft of timber passing north through Chaffey's Locks to a sawmill in Portland on Big Rideau Lake in 1933 (Fleming, 1981).

Despite declines in resident populations, people have been visiting Indian and other canal lakes for the excellent fishing and relaxing atmosphere since the late-1800s. Improved roads and railways have brought more people to the area. A section of Canadian Northern Railway was constructed through Chaffey's Mills in 1911 (Legget, 1975). In 1900, there were nine cottages in the township and by 1950 there were 163 cottages along the shores of the township lakes (Warren, 1997). More recently, the summer population has double the number of year-round residents (a resident population of 1,771 in 1997) (Warren, 1997). Indian Lake currently has 165 residents/cottages in its catchment (I. Patterson, pers. comm.).

Dam History:

As previously mentioned a pre-canal mill dam existed in 1825 (unknown construction date) which is estimated to have raised the water level of Indian lake by three and a half feet (1.1 m) (Welch, 1979). The replacement lock and weir erected with canal construction (Chaffey's Lock) was known to have been built in a similar location and with a similar but slightly greater lift height to the mill dam (canal lock lift -ten foot two inches (3.1 m) and mill dam lift of nine foot three inches (2.8 m)) (Passfield, 1982; Welch, 1979). Therefore Chaffey's Lock must have raised the water level at least three and a half feet (1.1 m). A local resident of the area estimated a five to six foot (1.5 to 1.8 m) increase in water-level from canalization based on depths of tree stumps found in flooded areas (D. Warren, pers. comm.). Despite uncertainties, these increases in water-levels flooded low-shoreline areas and altered the "natural" conditions of Indian Lake.

RIDEAU WATERSHED

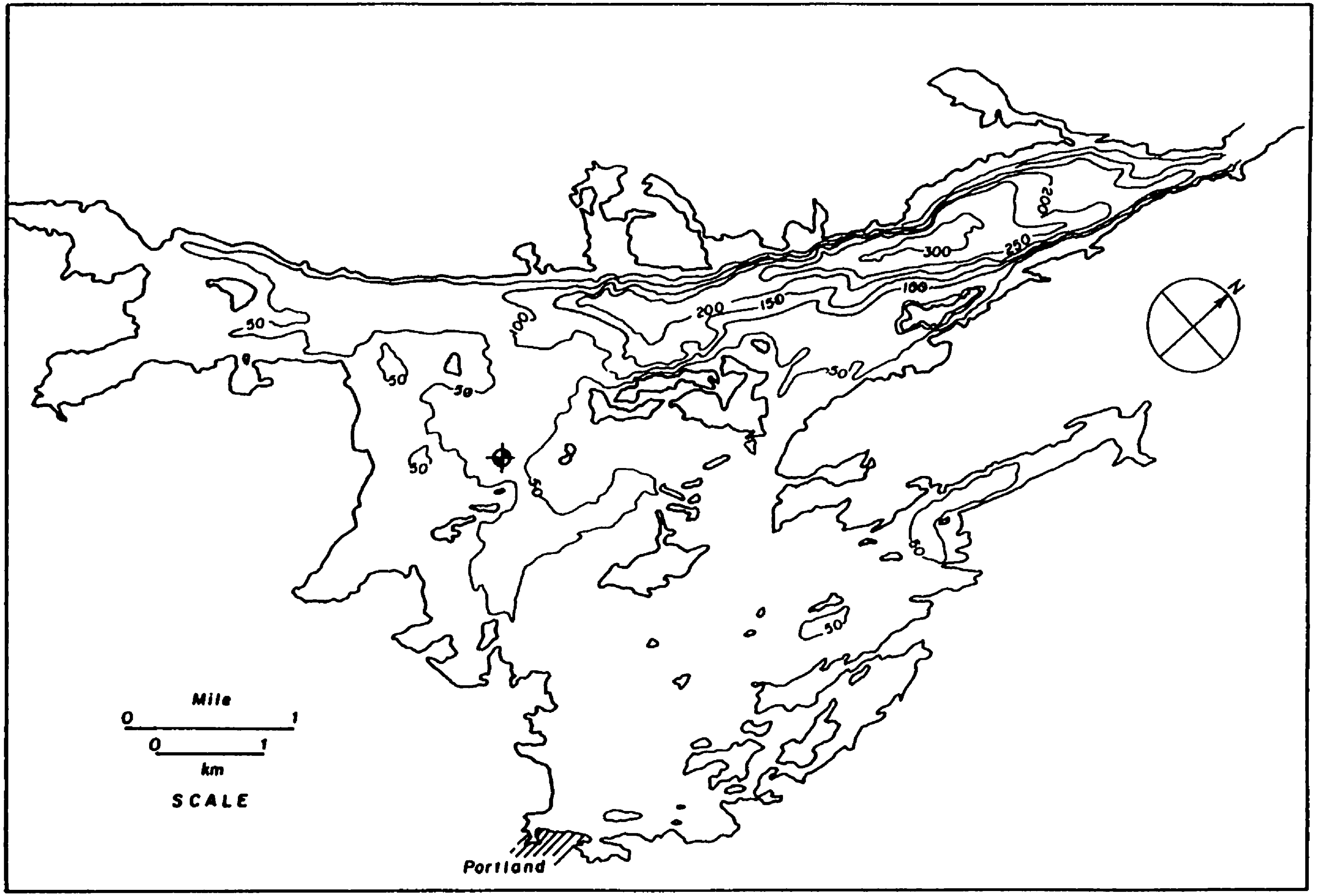
Big Rideau Lake

Big Rideau Lake (44° 49' N, 76° 14' W; 122 m a.s.l.; United Counties of Leeds and Grenville and County of Lanark, North Burgess and Bastard and South Burgess townships) is located next to the town of Portland and extends from Narrows Locks to the village of Rideau Ferry. It is the largest (S.A. = 44.6 km^2) and deepest waterbody in the Rideau Canal System (maximum depth (MZ) = 95 m) with over 300 islands (Ontario Ministry of the Environment (O.M.E.), 1989) (Figure 2.2, Table 1).

Geologically, Big Rideau Lake lies between granite and limestone bedrock. The moderately sloping northwest shore is part of the Leeds and Knobs Flats physiographic region and supports native white pine and oak forests. A tweed sandy loam-rock soil complex makes up the soils on this side of the lake (Soil Research Institute, 1966). This soil complex is described as well-drained with frequent chrystalline limestone and granite outcroppings. The southeast shores are part of the Smith Falls Limestone Plain region and are extensively cleared for agriculture (O.M.E., 1989; Chapman and Putnam, 1984). The Farmington loam and sandy-loam complex make up these stone-free and gently sloping shores (Soil Research Institute, 1968). Farmington soils are described as well drained, shallow (<0.3 m) sand-loam till over limestone or sandstone bedrock (Soil Research Institute, 1968).

Presently, Big Rideau Lake is oligotrophic to mesotrophic (spring TP 8 µg/L and average TN 370 µg/L) (Table 1). The lake is fed by numerous sources including Upper Rideau Lake, Round Lake, Loon Lake, and Millpond Land. The only outflow is into Lower Rideau Lake at Rideau Ferry (Acres International Ltd., 1994). The water quality remains satisfactory as the large volume of the lake likely dilutes nutrients and contributes to high oxygen levels in the hypolimnion (Ecological Services, 1998). Historical Secchi depth and chlorophyll *a* values suggest a decline in nutrients over the past few decades (Appendix A).

Figure 2.2. Bathymetric map of Big Rideau Lake, Ontario. Approximate position of the coring site is marked by the '+' symbol. Depth contours are in feet. (modified from Canadian Hydrographic Service (CHS), 1971).


N
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250
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50
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50
Mile
0
1
0
1
km
SCALE
Portland

Big Rideau Lake is unique to the canal in that it serves as the only cold-water fishery in the system supporting lake trout. The Big Rideau Lake fish community was surveyed in 1932, 1947, and 1972 (MacLean and Hooper, 1981). The lake was first stocked in 1897. Over the years, eight species have been stocked in attempts to augment the natural populations or introduce new species (MacLean and Hooper, 1981). Lake trout are the only fish species currently being stocked (MacLean and Hooper, 1981).

The Poonamalie Lock regulates the water-level of Big Rideau Lake and Lower Rideau Lake. Poonamalie is a particularly important dam in the canal because it retains the waters of the Rideau lakes and controls water supply for the northern agricultural end of the canal between Smith Falls and Ottawa (Kennedy, 1984). Low downstream water levels can be detrimental to public health, dairying, fishing, trapping, and tourism (Kennedy, 1984).

To maintain navigation depths and water quality downstream of Poonamalie, Big Rideau and Lower Rideau lakes are drawn down, from a summer level of 123.9 m to 123.62 m by August 31. The minimum desirable discharge is about 8.5 m^3/s during the summer months. Maximum discharges are restricted to a flow-rate of less than 42 m^3/s during the navigation season. The drawdown rate is then accelerated to reach its winter holding level of 123.10 m. This acceleration in drawdown is an attempt to reduce the incidence of exposed trout spawn in the winter months. The minimum flow is generally 2.8 m^3/s for the rest of the year (Acres International Ltd., 1994).

History:

Big Rideau Lake was used as a traffic-way to Perth before the canal was constructed. Perth was a Scottish and military community established by the British in 1816 to accomodate United Empire Loyalists leaving rebelling American colonies. Britain purchased land in the Rideau area from the Missassauga Indians in the late-1700s (Kennedy, 1984). Children of United Empire Loyalists held thousands of acres of land in the Rideau area but few came to claim it (Kennedy, 1984). With the depression in Europe in 1815-1822, British troops and families, and families from Scotland, were sent to three planned settlements: Perth, Richmond and Franktown. Three roads were also established at this time: Old Kingston Road (Kingston to Perth), Perth or Ferry Road, and Brockville Road (Brockville to Perth) (Hwy 29) (Kennedy, 1984). The Brockville to Perth Road and Kingston to Perth Road joined at Oliver's Ferry (Kennedy, 1984).

In 1824, on one of the survey maps for the Rideau Canal, Portand was described as a transfer point with a small settlement of seven houses (Haskins, 1985). Most settlement in the area came following the construction of the canal. In attempts to settle the Rideau area, free land was offered to 161 men of the Royal Sappers and Miners who helped build the canal (Kennedy, 1984). Both workmen and soldiers later settled in the area with their families when the project was complete (Haskins, 1985).

During canal construction the area surrounding the upstream lock 'the Narrows' was cleared. Similarly to Newboro and Chaffeys locks, malaria was a major problem at the Narrows, and this lock was considered one of the worst areas (Sadler, 1977). For this reason the surrounding area was also cleared of trees in attempts to better circulate the air, with hopes of improving the malaria conditions for the workers (Passfield, 1982).

With the completion of the canal, commercial trade thrived around Portland. Industries included tanneries, cheese factories, sawmills, and furniture factories. By 1839, there was a mercantile business and later a shoe making business, tannery and potash factory situated along the waterfront (Haskins, 1985).

Agricultural and industrial activities were similar to those occurring in the county of Leeds. In a census carried out in 1852 in the county of Lanark, there were butter (297,558 kg), cheese (17,927 kg) and maple sugar (34,880 kg) being produced (Snyder, 1977). In Lanark County in 1861, there are records of five shingle mills, two distilleries and one brewery (Snyder, 1977).

Mining also occured in the area from 1855 to the 1950s (Snyder, 1977). The first phosphate mine recorded in the area was opened in the North Burgess Township in 1855 (Snyder, 1977). Phosphate was easy to locate and mine. Twenty-four of the 34 identified mines were located in North Burgess. One of several examples of phosphate mines found in the area was operating about 60 ft (18.2 m) from the shore of Big Rideau Lake (Lots 3 and 4, Con. 5) in 1867 (Snyder, 1977). The local market for phosphate increased with the interest in soil improvement around 1870 (Warren, 1997). During the 1880s, when American markets were open for high quality phosphate, mining companies took over private operations and Ontario exports rose from 3701 tons in 1878 to 14,478 tons in 1883 (Snyder, 1977). However, the global demand for phosphate was short-lived and it decreased in the early 1890s after large deposits were discovered in Florida (Warren, 1997).

Mica was generally found in the same area as phosphate and by the mid-1890s a demand for mica had developed and many of the phosphate ventures were reopened for mica extraction. Thirty-five of the fifty-nine mica mines were identified in the Rideau Corridor and were located in the North Burgess Township. There are numerous references to mica mines between 1900 and 1914 and between 1935 and 1950 (Snyder, 1977). Murphy's Point, on the north end of Big Rideau Lake, has the remnants of the Silver Queen Mica Mine, which operated between 1903 and 1920 (Turner and Visser, 1995).

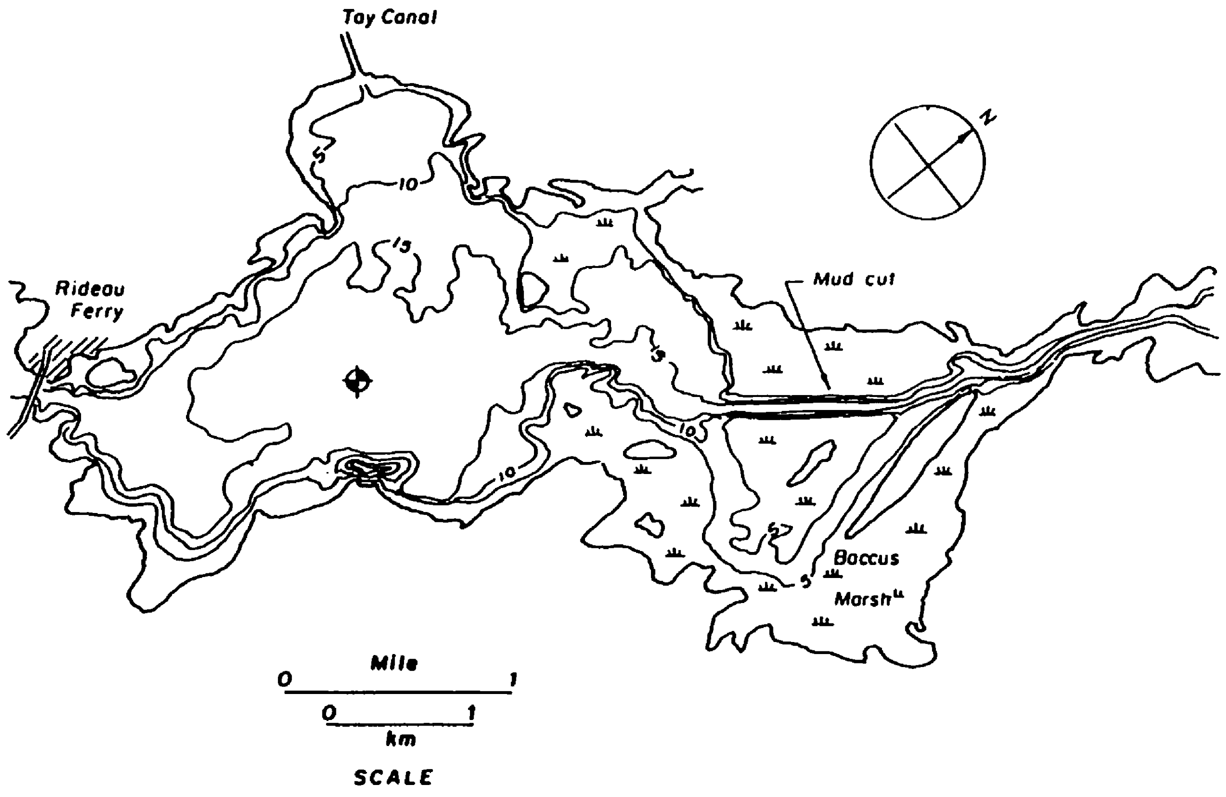
As previously mentioned, the counties of Leeds and Grenville were important dairying area, in the late 1800s and early 1900s (Snyder, 1977). In 1929, there were three cheese factories in operation in Portland (Snyder, 1977). Lanark County also had its share of dairy activity. In 1896, eight cheese factories were recorded in the Rideau Corridor townships located in Lanark County (Snyder, 1977). In 1967, there were five cheese factories remaining in Leeds County (Snyder, 1977).

Following the 1890s, the tourism industy mostly took over the Portland area. Building of a railway in the early 1900s between Brockville and Ottawa, by way of Smiths Falls, provided an easy source of local transportation for the village of Portland (Kennedy, 1984). Catering to sports fishermen, the area remains tied to tourism today.

Lower Rideau Lake

Lower Rideau Lake (44° 52' N, 76° 07' W; 122 m a.s.l.; United Counties of Leeds and Grenville and County of Lanark, North and South Elmsley townships) extends from

Figure 2.3. Bathymetric map of Lower Rideau Lake, Ontario. Approximate position of the coring site is marked by the '+' symbol. Depth contours are in feet. . (modified from Canadian Hydrographic Service (C.H.S.), 1971).


Tay Canal
Rideau
Ferry
5
10
15
15
10
10
Mud cut
N
Baccus
Marsh
5
Mile
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1
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km
SCALE

Rideau Ferry to the Poonamalie Dam, just south east of Smith Falls (Figure 2.3). This lake is the northern shallow basin of Big Rideau Lake.

Lower Rideau Lake lies in the physiographic region of the Smiths Falls Limestone Plain. The shoreline around the lake is generally flat with shallow (<1.5 m) soil cover over limestone bedrock (Ontario Water Resources Commission, 1971). The Monteagle sandy-loam rock-soil complex make up the soils along the northwest shore, from Rideau Ferry to Stuart's Point (Soil Research Institute, 1966). The remainder of the shoreline is described as either muck, organic and poorly drained soils, or Farmington sandy loam, shallow, well-drained stoney loam till (Soil Research Institute, 1968).

This lake is shallow, mesotrophic, polymictic and has an extensive littoral zone (Table 1). Periodic historical Secchi and chlorophyll *a* records suggest that the Lower Rideau Lake has remained moderately productive (chlorophyll *a* 4 - 10 µg/L) over the last 30 years (Appendix A).

The Tay River, Tay Canal, Black Creek, Big Rideau Lake, and Bass Lake Creek drain into Lower Rideau Lake. Beveridge Locks controls the inflow from the Tay Canal and Tay River to Lower Rideau Lake. The Rideau River is the only outflow and, as previously mentioned, water levels and flow-rates are regulated at the Poonamalie Dam just south of Smiths Falls.

Treated sewage effluent from the Town of Perth discharges into the Tay River and thereafter into Lower Rideau Lake. Residences in Rideau Ferry and Port Elmsley have private septic tank systems, which are regulated by the local public health authorities.

History:

As Lower Rideau Lake is the downstream basin of Big Rideau Lake, it has experienced the same flooding and watershed disturbances as Big Rideau Lake with the addition of some localized influences in the North and South Elmsely Townships. Smiths Falls is located at the outlet of Lower Rideau Lake; therefore, its development has not directly impacted the water quality of the lake. However, its history provides further information on the timing of settlement and industry in the area.

In 1827, an early canal surveyor, John Burrows, described Lower Rideau Lake as "indescribably beautiful.. its surface as smooth as a mirror" (Welch, 1979, p. 22). The shores were vegetated at the time and a house is recorded (Olivers Ferry) on a point at the southeast side of the lake. The depth of the lake was recorded as 16 ft deep (4.8 m) near Olivers Ferry (Welch, 1979).

The Olivers Ferry started up in 1816, ferrying settlers across Lower Rideau Lake on their way to Perth (Kennedy, 1984). Delays in the surveying of rear townships of the Perth settlement brought the first settlers to South Elmsley (Kennedy, 1984). Twenty-eight men and their families were given lands during 1815-1819 in the area now known as South Elmsley (Kennedy, 1984). In 1820, there were 138 inhabitants recorded in the Township of Elmsley in 1820 (Kennedy, 1984). The quality of the land in the South Elmsley Township was considered fair for agricultural use. The Ontario Commission Report of 1881 claimed that about half of the township had rock too close to the surface to be "profitably cultivated" (Kennedy, 1984). Farmers in South Elmsley cleared land at a rate of nearly two acres per year in the early-1820s (Kennedy, 1984). Cleared land was planted with wheat, potatoes and turnips (Kennedy, 1984). Also at this time, livestock husbandry was a small, but important farming activity in Elmsley (Kennedy, 1984). Perth held agricultural fairs as early as the 1820s facilitating the sales of horned cattle, horses and sheep (Kennedy, 1984).

Logging activities also occurred in the area. In 1825, a sawmill was in operation at Smiths Falls (Passfield, 1982). The operation was taken down because of canal construction. It is thought to have been a large one as it was purchased for a substantial sum of money at that time (Legget, 1975).

Active work on this part of the canal began in 1827 (McGill, 1974). Large pines used for canal construction were removed from areas near Lombardy and near the Lower Rideau Lake water front (Kennedy, 1984). Stone used for canal construction came from a quarry half a mile above Oliver's Ferry, on the banks of Lower Rideau Lake which opened between 1826 and 1829 (Kennedy, 1984). Another quarry was later opened eight miles from the works to meet the construction demands (near present Bay Road on Lot 12, Con. 3) (Kennedy, 1984).

At the end of the canal construction period, South Elmsley had between 20-30 people per square mile (6-9 people per km^2) and the settlements, now known as Smiths Falls and Lombardy (near Otter Lake), were moderately developed (Kennedy, 1984). Over the next 15 years (1830 and 1845), the population of South Elmsley increased four-fold (Kennedy, 1984). By 1840, Rideau Ferry included a small tavern and storehouse (McGill, 1974). At this time, there were seven lots occupied along Lower Rideau Lake

(Kennedy, 1984).

Over the years, Smiths Falls and Perth provided many services to township settlers. In 1851. there were flour, oat, saw, carding, and fulling mills in operation for local use in Smiths Falls (Kennedy, 1984). Perth had also become a thriving settlement around this time with a population of 1800 in 1846 including brewers. tin smiths. blacksmiths. shoemakers. wagon makers and axe makers (McGill. 1974). A carding mill. saw mill and pork packing industry were also in operation in Perth at this time (McGill. 1974). Later a bridge was built in 1874 at Oliver's Ferry to better link township settlers to the commercial benefits found in Perth (Kennedy. 1984).

Logging activities continued in the area. Much of the timber passing through Perth from the mills in Lanark went down the Rideau Canal to Kingston. In the 1850s. it was estimated that 200,000 to 300.000 square ft (18.600 to 27.900 m^2) of timber was being cut annually (McGill, 1974). In 1895. Rideau Ferry was becoming an important establishment with two churches, a store. a hotel. and a graphite factory (Kennedy. 1984). This graphite operation was apparently quite large as "the mill has a 10 stamp battery and five HP engines, and employed nearly 50 hands, manufacturing from three to four tons of material daily" (Snyder, 1977 p. 178). The graphite mine was also in operation earlier during the 1870 to 1880s and reopened in the 1890s (Snyder. 1977).

Some mining was occurring on the land near the boundary of South Elmsley and South Burgess townships, despite being a relatively small part of the economy in South Elmsley. This area was regarded as having the best potential for mica and graphite in the township (Kennedy, 1984). Local landowners allowed entrepreneurs to mine their lands for a price. Two landowners in South Elmsley leased their land on the north end of Lower Rideau Lake (Lot 29, Con. 3 and Lot 29, Con. 4), but only four tons of graphite or plumago were extracted in 1870 (Kennedy, 1984). By 1893, most of the mineral lands around Rideau Ferry were leased by the Northern Graphite Company (Kennedy, 1984). At this time, 100 acres of land on Lot 29, Con. 3 were once again leased for mining purposes (Kennedy, 1984).

From the 1880s to the 1940s, many people moved away from the township to other parts of the country offering better land or greater employment (Kennedy, 1984). Farmers who remained no longer profited from just growing crops, such as corn and wheat on their mediocre soils, and many became involved in the dairying and livestock husbandry industries. Cheese factories operated in South Elmsley from the 1870s to the 1950s (Kennedy, 1984). The Rideau Star Butter and Cheese Factory processed local milk at Rideau Ferry from 1904 to 1952 (Kennedy, 1984).

Cottages began to appear on the lakeshore and islands of Lower Rideau Lake in the late-1880s (Kennedy, 1984). By 1931, the shoreline of Lower Rideau Lake was moderately developed with 116 cottages on its South Elmsley shore (Kennedy, 1984). According to environmental studies of the area in the 1970s, the shoreline development on Lower Rideau Lake was found to be one of the heaviest compared to other shorelines of lakes on the Rideau Canal (Kennedy, 1984).

Poonamalie Dam history

Both a mill dam (pre-canal) and the Poonamalie Dam have altered the water-levels and hydrology of Big Rideau and Lower Rideau lakes. Water-levels of these lakes were initially altered with a sawmill dam constructed in 1823 (Passfield, 1982). With canalization these lakes are estimated to have been flooded three feet (0.9 m) with the initial construction of the Poonamalie Dam in 1830 (Parks Canada, undated). Tree stumps observed in the swamp between Bacchus Island and the mainland on Lower Rideau Lake are evidence that lowland areas were indeed flooded (Kennedy, 1984).

Since construction, the Poonamalie Dam has always been vulnerable to spring floods (Smith, 1983). In 1865, the weir was raised by two feet (0.6 m) (Parks Canada, undated) to allow more water to be retained for a longer period of time (Tullock, 1981). There were spring floods in 1869 causing an embankment to be washed out and flooding of low-lying lands around Smith Falls (Tullock, 1981). In 1904, ice broke and washed out the dam (Tulloch, 1981). By the fall of 1904, a new concrete weir was constructed, 1.5 ft (0.46 m) lower than the 1865 weir height, and 0.5 ft (0.15 m) higher than the 1832 weir height (Watson, 2000; URL:www.rideau-info.com/canal/locks/h32-poonamalie.html). In 1910, water levels dropped because it was a hot and dry summer and reported high water-use of electric light companies (Parks Canada, undated). As a result of low water levels, there was extensive dredging carried out two miles (3.7 km) above Poonamalie Lock station (Tulloch, 1981). Flashboards were added to the weir in 1911 to increase the upstream water level by an additional six to eight inches (0.15 - 0.20 m) (Tulloch, 1981). A dry year in 1920 caused water shortages downstream of the Poonamalie Lock (Tullock, 1981). In 1971, a replacement dam was constructed at the Poonamalie lockstation, equiped with flashboards (elevation of 406.58 ft; 123.9 m) 0.96

ft (0.29 m) higher than the original 1832 dam (elevation 405.62 ft; 123.6 m) (Parks Canada, undated).

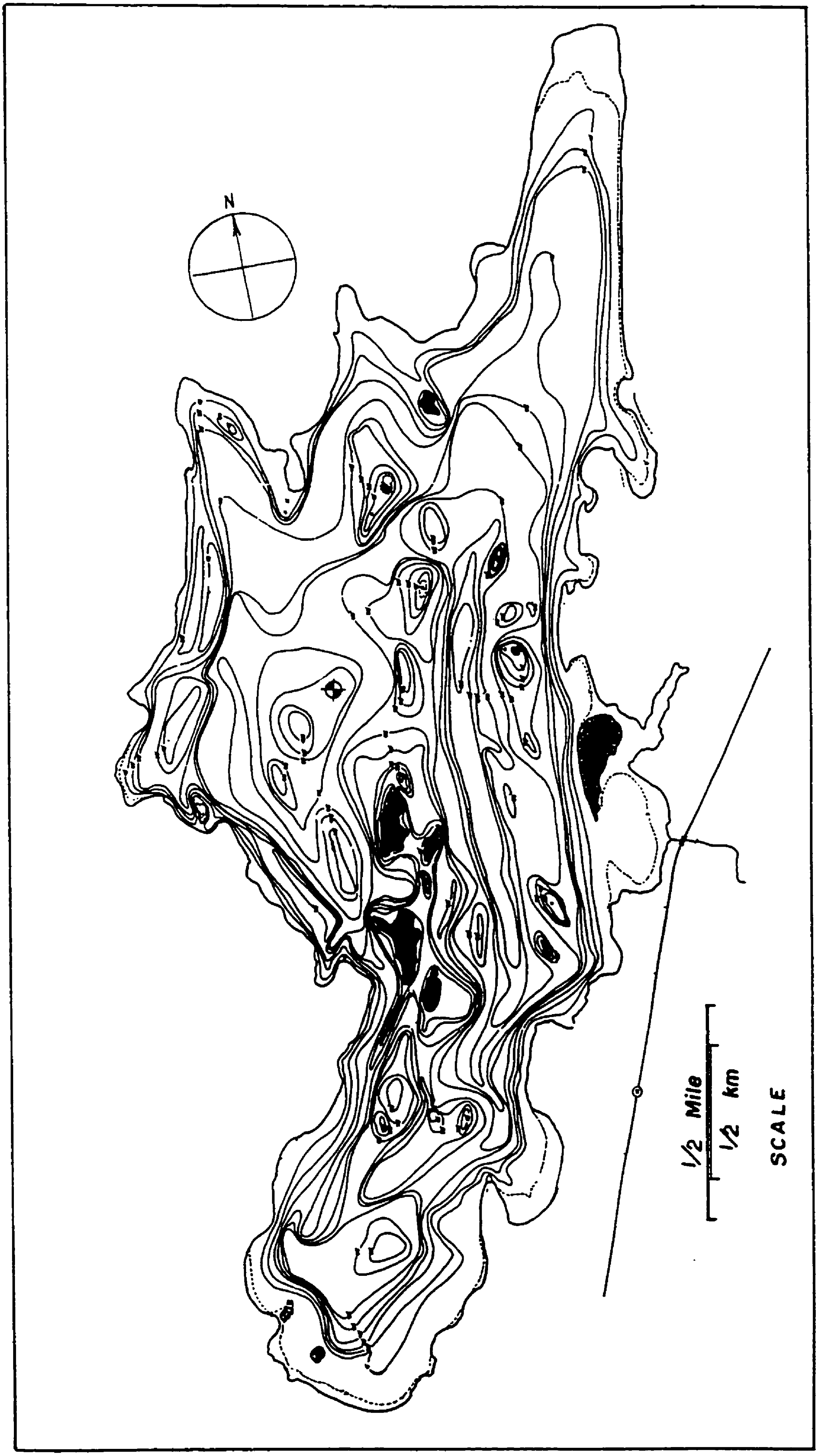
Otter Lake

Otter Lake (44° 47' N, 76° 07' W; 124 m a.s.l.; United Counties of Leeds and Grenville, South Elmsley and Bastard and South Burgess townships), my temporal control study lake, is located just west of Highway 15 and 13 kilometres south of Lombardy. Most of the lake lies within the physiographic region of the Smiths Falls Limestone Plain. The southwestern shores are characterized by the physiographic region of the Leeds Knobs and Flats (Chapman and Putnam, 1984). Farmington loam soils type are found on the gentle slopes of the north and east shores of the lake (Soil Research Institute, 1968). The Monteagle and Tweed sandy loam-rock soil complexes are found on the hilly slopes on the west side of the lake (Soil Research Institute, 1968).

Otter Lake is a relatively small (S.A. = 6 km^2), oligotrophic to mesotrophic, deep lake (MZ = 36.6 m) (O.M.O.E., unpublished) (Figure 2.4, Table 1). Averaged historical Secchi depths and mean chlorophyll *a* values show a gradual increase in water quality from 1986-1998 with the exception of a more recent chlorophyll *a* value of 4 µg/L (Appendix A). The lake is spring fed and drains into Otter Creek (MOE, unpublished).

Lake trout, smallmouth bass, northern pike, yellow perch, and lake herring have been recorded in Otter Lake (Kennedy, 1984). The restocking of whitefry began in the early-1900s, and Kamloops trout fingerlings were stocked in 1953 (Kennedy, 1984).

Figure 2.4. Bathymetric map of Otter Lake, Ontario. Approximate position of the coring site is marked by the '+' symbol. Depth contours are in feet. (modified from the Ministry of the Environment, Kingston District Office, unpublished data).


N
1/2 Mile
1/2 km
SCALE

History

The general history previously discussed for the Township of South Elmsley and Bastard and South Burgess also applies to the history of Otter Lake.

Settlement was delayed in the catchment of Otter Lake, as most of the soil is shallow and stoney and was considered only suitable for grazing (Kennedy, 1984). Some settlers were reported to have exchanged their lots on Otter Lake for other lots with better soils (Kennedy, 1984). However, there are records of a few settlers on the north banks of Otter Lake in 1829 and several more in the mid-1830s (Kennedey, 1984). By the 1850s, remaining vacant lands surrounding the lake and the rest of South Elmsley were filled and being cleared (Kennedy, 1984).

Logging and wheat farming activities were important to the local economy in the late-1800s. A total of 6 100 acres were farmed in South Elmsley in 1851 and 10 700 acres were under plow ten years later (Kennedy, 1984). Otter Creek, draining Otter Lake, was dammed (approximately 2 km from Otter Lake) in 1841 to facilitate the operation of a saw mill in 1843. This operation was later (in 1862) converted to a grist mill to satisfy local demands for flour (Kennedy, 1984). Timber demands increased in 1871 and the sawmill was reopened along with a second sawmill (Kennedy, 1984). The water level of Otter Creek was low in the late-1880s because of irrigation and cattle use and mill operations ceased (Kennedy, 1984). In 1893, the saw mill was restored and converted to steam operation and continued to operate from 1896 to 1910 (Kennedy, 1984). In 1910 the operations ceased and the dam was removed.

At the beginning of the 20th century, mica was mined on the south end of the lake in the Bastard Township (Lot 1, Con. 1) (Kennedy. 1984). The Bennett Mica Mine operated nearby on Lot 30, Con. 3, from 1908 to 1911, and from 1925 to 1944 (Kennedy. 1984).

Increased erosion from roads and railway construction in the watershed might have influenced the water quality in the 1900s. In 1912. a clearing was made for the railroad near Otter Lake (Kennedy, 1984). The Portland Road. running along the east side of the lake. was improved and designated Highway 15 in 1921. The road surface was further improved in 1927 (Kennedy, 1984).

In the early-1930s. people began purchasing land on Otter Lake for recreation (Kennedy. 1984). Many farmers sold their waterfront property to cottagers for extra income and wrote into deeds the continued access to the water for their cattle (Kennedy. 1984). After the 1950s, the rest of the lake's catchment filled up with cottages. and by 1976 there was almost complete coverage of lakefront property (Kennedy. 1984). In 1982. there were 291 cottages. five permanent residences, 299 campground sites and 46 vacant lots (O.M.O.E.. unpublished data). Also in that year, its watershed was described as being substantially cleared for agriculture (O.M.O.E., unpublished data).

CHAPTER 3: MATERIALS AND METHODS

FIELD WORK

Sediment cores (38 - 49 cm in length) were retrieved from the four study lakes using a Glew (1989) gravity corer with a 7.6 cm internal diameter core tube. Lakes were cored in their central, flat deep-water regions, which were located using a depth sounder and a bathymetric map. Big Rideau and Indian lakes were cored in October of 1998 (Figures 2.2 and 2.3). Big Rideau Lake was cored in its second deepest basin (34 m) to avoid problems associated with gravity coring in deep lakes greater than 50 m. Lower Rideau and Otter lakes were cored in June of 1999. Lower Rideau and Otter lakes were re-cored in less steep, deep basins in July, 1999 and February 2000, respectively, as unusual sediment colour changes and ^{210}Pb activity profiles indicated that sediment slumping may have been a problem in the original cores. At Lower Rideau Lake, both a 47-cm long gravity core and a 1-m long modified Livingstone (Wright, 1991) piston sediment core were retrieved at this time.

The cores from Indian, Big Rideau, and Lower Rideau lakes were sectioned into 1-cm intervals onsite using an upright extruder (Glew, 1988). The sediment core from Otter Lake was sectioned at 0.5 cm intervals. The piston core was extruded horizontally and subsampled in the laboratory. Sediment samples were refridgerated at 4°C in Whirl-pak® bags until processing of microfossil and physical sediment analysis.

PHYSICAL SEDIMENT CHARACTERISTICS

Percent water and organic matter content were estimated in the laboratory for all the sediment cores using standard techniques (Dean, 1974). Water contents were determined by weight loss after oven-drying 1 g of wet sediment subsamples in sterilized crucibles in a Ney muffle furnace at 105°C for 24 hours. Subsequent weight loss associated with heating the sediment to 550°C for two hours was used to estimate the percent organic matter. The remaining sediment was thereafter heated to 925°C for four hours, and this final weight loss was used to determine the percent carbonates (modified from Dean, 1974). A Mettler analytical balance (accurate to 0.0001g) was used for weighing sediments.

SEDIMENT CHRONOLOGY

Sediment chronologies of Big Rideau, Lower Rideau and Otter lakes were based on ^{210}Pb activity, sediment colour changes, as well as *Ambrosia* (ragweed) pollen abundances found in bottom sediment intervals. The sediment chronology of Indian Lake was based on ^{210}Pb activity and sediment colour changes.

Sediment preparation procedures for ^{210}Pb dating followed Schelske et al. (1994). Briefly, about twelve samples were selected along the length of each core to deterimine age-depth profiles. Sediment subsamples were oven-dried at 105°C for 24 hours, crushed into a fine powder, and reheated to 105°C for another 24 hours. Sediment was then distributed into labelled polypropylene tubes to heights of 2 cm, weighed, sealed with epoxy resin, and capped. Sealed sediments were left for two to three weeks to allow ^{214}Bi elements to equilibriate with ^{226}Ra.

An EG &G Ortec germanium well-detector was used to count naturally occurring isotopic decays for ^{210}Pb, ^{214}Bi, and ^{137}Cs within the sediment samples. ^{214}Bi activity provided a direct measure of supported ^{210}Pb activity for each sample. ^{210}Pb dates were calculated by applying the constant rate of supply model (CRS) (Appleby and Oldfield, 1983) and using Binford's (1993) computer program.

The *Ambrosia* pollen rise served as an additional independent chronological marker of European encroachment. The rise in *Ambrosia* and grass pollen was related to widespread vegetation disturbance from the onset of human activities (European settlement), which occurred in the area primarily between 1825 and 1850 (Mott and Farley-Gill, 1981).

MICROFOSSIL PREPARATION AND ANALYSIS

Approximately 0.5 g of wet sediment from each interval was placed in a glass scintillation vial and treated with a mixture of 50:50 nitric and sulfuric acid to remove organic material. These acid slurries were heated in a water bath at approximately 90°C for an average of four hours. Following heating, slurries were rinsed with de-ionized water and aspirated every 24 hours until their pH became neutral. Slurries were then pipetted onto coverslips at four different dilutions. Once dry, the coverslips were mounted onto glass slides with Naphrax® (refractive index = 1.74).

Diatom valves and chrysophyte cysts were enumerated under oil immersion (1000 x magnification) along parallel vertical transects using a Leica DMRB microscope for brightfield equipped with differential interference contrast optics. A minimum of 300 (an average of 350) fossil diatoms were enumerated and identified for each level based primarily on floras described by Krammer and Lange-Bertalot (1986-1991), Reavie and Smol (1998), and Cumming et al. (1995). To ensure taxonomic consistency with Reavie and Smol (2001), taxonomic sessions were completed with Dr. E. Reavie using light microscopy and prepared slides.

Five to thirteen pollen slides were prepared from each sediment core from Big Rideau, Lower Rideau and Otter lakes. Pollen preparation followed standard techniques described by Faegri and Iversen (1975) with the exception of using hydrofluoric acid, as clastics were not common in the sediment. Briefly, subsamples of 1 mL wet sediment were placed in polypropylene centrifuge tubes and treated with 12 mL of 10% potassium hydroxide to deflocculate the organic matrix and disperse the humic acids. Samples were then stirred and heated at 90°C in a water bath for 15 minutes. Following heating, sediment slurries were cooled and then centrifuged in a clinical centrifuge for one minute at approximately 7000 rpm. The supernatant liquid was decanted and the samples were rinsed with deionized water and re-centrifuged for one minute, and then decanted again. Subsequently, samples were treated with 10 mL of 10% hydrochloric acid and then heated, centrifuging, rinsing and decanting steps were then repeated. Three mL of glacial acetic acid were next added to dehydrate the samples. Samples were stirred, centrifuged and decanted. Finally, 5.0 mL of acetolysis solution (9:1 sulphuric acid to acetic anhydride) were added to break down cellulose structures. Samples were heated for two minutes in the water bath and the centrifuging, rinsing, and decanting steps were repeated.

The remaining sediment was plated on glass slides with corn syrup. For each sample, a minimum of 300 pollen grains were enumerated and *Ambrosia* pollen grains were identified and recorded. Dr. John Smol undertook the pollen counts.

STATISTICAL ANALYSIS

Diatom species counts were converted to percent relative abundances. 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 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. This index was chosen because it gives rare taxa moderate weight but still less than that given to the dominant taxa (Overpeck et al., 1985).

Statistical analyses were performed on those taxa that exceeded ≥ 2% relative abundance in at least one sediment interval within the downcore fossil assemblages (Appendix B and C). All ordination analyses were conducted using CANOCO version 4.0. The similarity of diatom assemblages within study lake cores and down-core gradient lengths were examined using the non-linear ordination technique, detrended correspondence analysis (DCA). Gradient lengths greater than two standard deviation units suggest that taxa demonstrate a unimodal relationship to environmental variables and therefore unimodal techniques are appropriate (e.g. CA); gradient lengths less than two standard deviation units suggest taxa follow linear relationships to environmental variables, and therefore linear techniques are appropriate (e.g. PCA) (Birks, 1998).

Using the computer program WACALIB 3.2 (Line et al., 1994) and a 64 southern Ontario calibration set (Reavie and Smol, 2001), historical diatom-inferred spring lake-water spring total phosphorus concentrations were calculated for the four study lakes. The weighted-averaging spring [TP] transfer function from the Reavie and Smol (2001) calibration set is of moderate predictive ability (r^2_{boot} of 0.43) and has been used to track changes in trophic state conditions of several other deep southeastern Ontario lakes (Reavie et al., unpublished, Neill et al., in progress).

Comparisons between the diatom-inferred TP reconstructions for the surface sediments of the four study lakes and recent measurements of spring TP were drawn 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 environmental variables of interest (i.e. TP) and plotting down-core fossil samples passively. This analysis was used to calculate the squared residual distance of each diatom fossil sample from the TP axis. The fossil samples' squared residual distances were compared to those of the modern samples used to derive the transfer functions. 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 (Jager and Looman, 1995).

The computer program ANALOG version 1.6 (Line and Birks, unpublished program) was used to identify the fossil diatom assemblages with poor analogues to those found in the modern calibration data-set. A reconstructed environmental value is considered more reliable if the fossil sample has close modern analogues with the calibration data-set (Birks, 1998). Analogue matching was performed on the screened data. Data were screened according to the calibration model criteria, where diatoms 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 and Smol, 2001). The Bray-Curtis dissimilarity coefficient (DC) was used to compare the fossil samples to the calibration lake set (Clarke and 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 and 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 analog matches, respectively (Hall and 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.

CHAPTER 4: RESULTS AND DISCUSSION

CORE CHRONOLOGIES

Chronologies for the four short sediment cores were based on ^{210}Pb activity, the rise in *Ambrosia* and sediment colour changes. ^{137}Cs peaks appeared to migrate in the sediments and therefore were considered unreliable for calculating dates. Cesium migration has been previously reported in sediments with high organic content (Davis et al., 1984). Additionally, ^{226}Ra activity measurements seemed to underestimate supported ^{210}Pb estimates and therefore were not used to confirm estimates of supported ^{210}Pb activity. Low estimates of ^{226}Ra activity have been previously encountered in other paleolimnological studies (Schelske et al., 1994). ^{210}Pb activity, the rise in *Ambrosia* and sediment colour changes are discussed separately for each lake.

SEDIMENTARY CHARACTERISTICS

In all four sediment cores, water content decreased gradually down-core. This common trend may reflect the increased compaction of lower sediments, and is a typical trend of surficial sediments. However, individual lake differences were noted in estimates of percent organic matter, carbonate content and clastic content. Therefore, interesting sedimentary characteristics are discussed independently for each lake.

ORDINATIONS

First axis gradient lengths determined from DCA ordinations of the diatom data from the four lakes were: Indian 1.9, Otter 1.9, Big Rideau 3.1, and Lower Rideau 2.9

SD-units for ≥ 2% relative abundance data untransformed, indicating that the use of both linear and unimodal techniques would be appropriate (Birks, 1995). However, an arch was apparent in the PCAs of Indian and Otter lakes and in the CAs of Big Rideau and Lower Rideau lakes' ordinations, which suggested that artificial structure of the second axis was introduced using these ordination techniques. Therefore, DCA ordinations were performed on all lakes for correlation calculations between axis one sample scores and corresponding inferred values.

RECONSTRUCTIONS

The correlations between the DCA axis one sample scores and inferred spring TP values were generally significant, but only moderately strong for the most of the study lakes, suggesting that this variable was not solely tracking the main direction of variation of the fossil diatoms (r^2 values ranged from 0.89 to 0.13). Therefore the maximum depth (MZ) transfer function ($r^2 = 0.55$; RMSE = 1.05; r^2_{boot} 0.38; $RMSE_{boot} = 1.49$ m) (Reavie and Smol, 2001) was also applied to fossil diatom data and high correlations (r^2 values ranged from 0.83 to 0.95) were identified between fossil samples and DCA axis one sample scores. This suggests that the fossil diatoms have also been tracking a variable related to depth. Therefore, the MZ reconstructions were further evaluated with 'goodness-of-fit' tests and 'analogue' measures for each lake.

The inferred MZ values gradually increased in the deep study lakes and were therefore not considered to be direct measures of water-level changes. As following initial flooding with canal construction (~1830), the water-levels of the canal lakes have been controlled and generally kept stable until present (Chapter 2). Additionally, MZ inferences were found to be strongly correlated to the sum of planktonics (r^2 ranged from 0.82 - 0.94; Appendix D). As previously discussed (Chapter 1) with eutrophication, phytoplankton abundance generally increases and water clarity may decrease depending on nutrient additions and macrophyte abundance. Additionally, phytoplankton biomass may be increasing with increased stratification due to recent climate warming (Schindler et al., 1996). Therefore the maximum depth reconstructions were thought to reflect water clarity and stratification patterns in the study lakes following canal construction.

MICROFOSSIL AND TROPHIC INFERENCES FOR THE STUDY LAKES

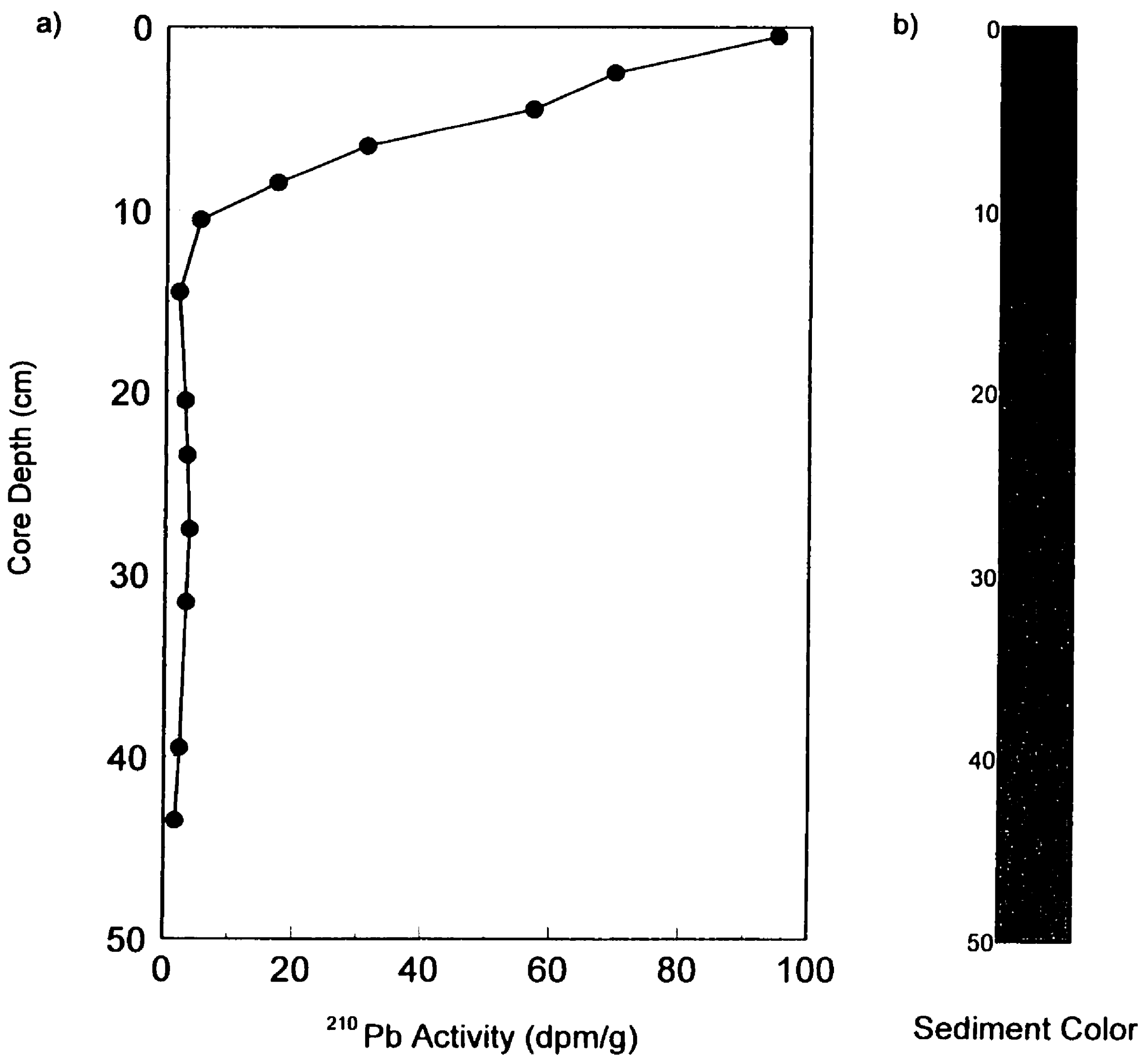
Indian Lake

Chronology:

The ^{210}Pb activity profile decreases exponentially with sediment depth, illustrating that the core is likely not disturbed by mixing (Figure 4.1). Supported levels of ^{210}Pb activity (2.91 dpm/g) are reached below 14 cm in the 44 cm long sediment core (Figure 4.1). Using the CRS model and assuming a constant flux of ^{210}Pb to the sediment, the 13 - 14 cm sediment interval is estimated as the approximate time of canal construction, 1830. Despite the uncertainty associated with older ^{210}Pb dates (Binford, 1990), this estimate is considered reasonable as it is in close proximity to the changes in sediment colour and microfossil zones (see below) observed in the sediment core.

There is an obvious change in sediment colour, from light brown to dark brown

Figure 4.1. a) Profile of ^{210}Pb activity vs. sediment core depth for Indian Lake.
b) Profile of sediment colour changes for Indian Lake (light (bottom sediments) to dark brown (upper sediments)).


a)
Core Depth (cm)
0
10
20
30
40
50
0
20
40
60
80
100
^{210}Pb Activity (dpm/g)
b)
0
10
20
30
40
50
Sediment Color

organic sediment at 15 cm in the 44 cm long sediment core from Indian Lake (Figure 4.1b). Similar lithological changes have been observed in other deep lakes in the Rideau Canal, coinciding with the estimated time of canal construction (Christie and Smol, 1996). Christie and Smol (1996) attributed this change to increased nutrient and sediment loads from flooded portions of the watershed.

Microfossil and Physical Sediment Analysis:

Cluster analysis and ^{210}Pb dates delineated three zones of diatom species assemblages: Zone 1 is the pre-disturbance era (before ~1815) (44 - 15 cm); Zone 2 is the settlement and canal construction era (15 - 5 cm); and Zone 3 is the recent past (~1970) until present (5 - 0 cm).

Paleoenvironmental Reconstructions:

Three lines of evidence suggest that our reconstructions of [TP] and maximum depth (MZ) provide reliable inferences (Figures 4.2 and 4.3). First, analogue matching performed well as indicated by good analogues in [TP] and MZ for most of the core. Poor analogues were only found before the time of canal construction (Figure 4.2). Second, only one sample interval, 17.5 cm, had poor fits to TP (Figure 4.2b) and maximum depth (Figure 4.2d). Finally, a moderate but significant correlation existed between DCA axis one sample scores and inferred [TP] ($r^2 = 0.41$, $p < 0.001$, $n = 26$) (Figure 4.3a). For these reasons, diatom inferences were considered to be moderate approximations of [TP] following canal construction. Additionally, there was a strong

Figure 4.2. Diatom reconstructions and model evaluations for Indian Lake (zones indicated).

a) Diatom inferred TP reconstruction (dotted lines indicate error estimates).

b) The fit of fossil samples to the TP axis of calibration samples, determined through canonical correspondence analysis (CCA) constrained to TP, with passive analysis of Indian Lake samples. Lines indicate the upper and lower 90 and 95% confidence limits. Indian Lake samples with poor and very poor fit fall beyond the 90% and 95% confidence limits (CL).

c) Diatom inferred MZ reconstruction (dotted lines indicate error estimates).

d) The fit of Indian Lake fossil samples to the MZ axis of calibration samples, determined through canonical correspondence analysis (CCA) constrained to TP, with passive analysis of Indian Lake samples. Lines indicate the upper and lower 90 and 95% confidence limits. Indian Lake samples with poor and very poor fit fall beyond the 90% and 95% confidence limits.

e) The analogue profile indicating the strength of the match between the Indian Lake fossil samples and the S.E. Ontario calibration set samples (Reavie and Smol, 2001), using the Bray-Curtis dissimilarity coefficient. Solid lines indicate upper 90 and 95% confidence limits. Indian Lake samples falling outside of the 90 and 95% confidence limits are deemed as having poor and very poor analogues.

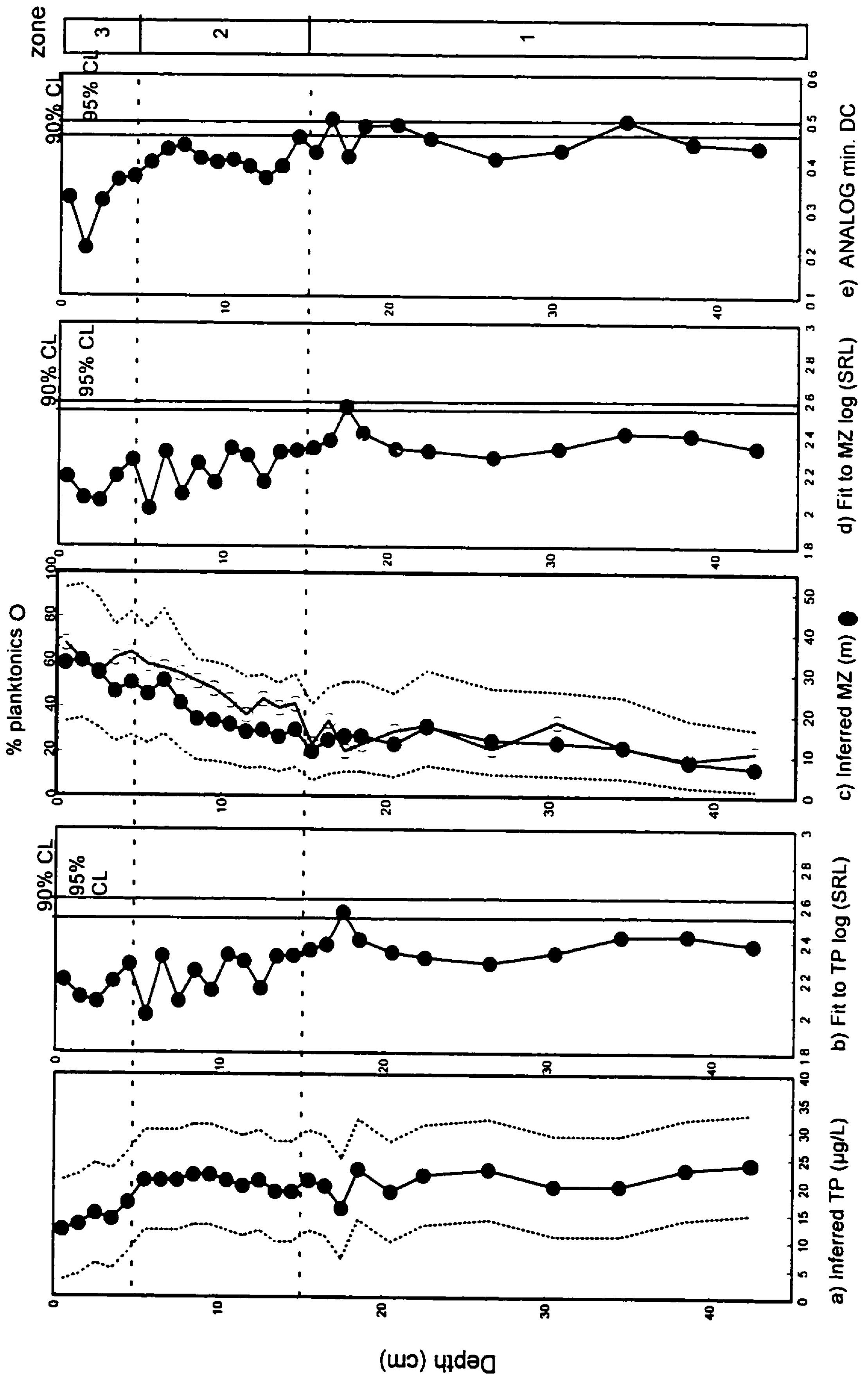
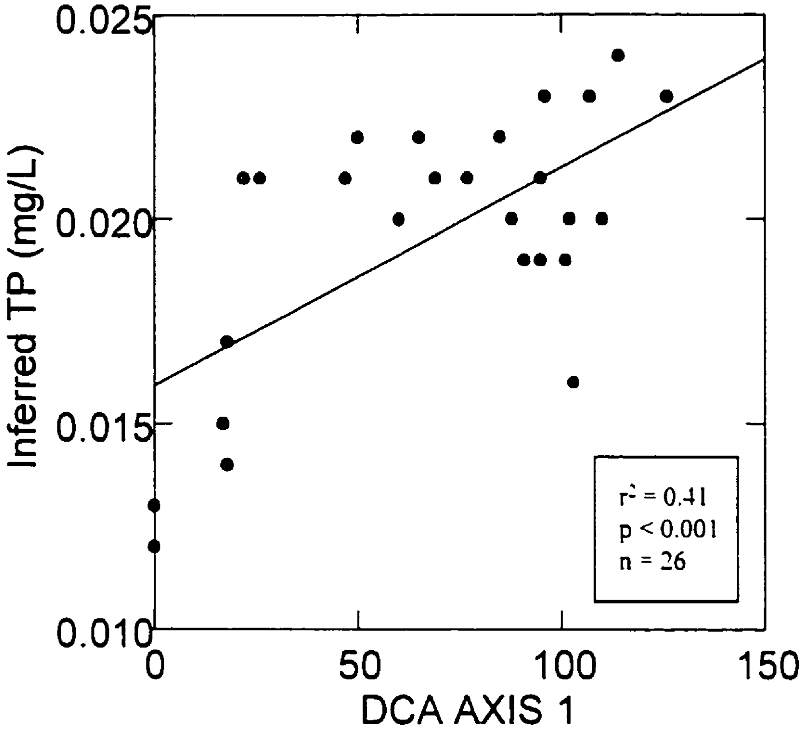
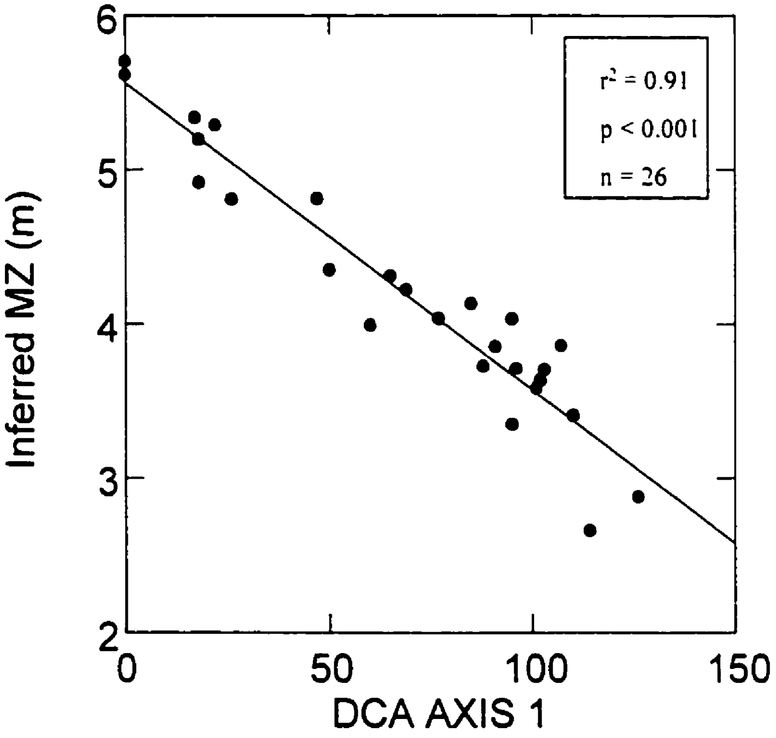

zone
3
2
1
90% CL
95% CL
e) ANALOG min. DC
0.1 0.2 0.3 0.4 0.5 0.6
d) Fit to MZ log (SRL)
1.8 2 2.2 2.4 2.6 2.8 3
% planktonics O
0 20 40 60 80 100
c) Inferred MZ (m) ●
0 10 20 30 40 50
b) Fit to TP log (SRL)
1.8 2 2.2 2.4 2.6 2.8 3
a) Inferred TP (µg/L)
0 5 10 15 20 25 30 35 40
0 10 20 30 40
Depth (cm)

Figure 4.3. The correlation between DCA axis one sample scores and inferred variables: a) TP values b) transformed MZ values for Indian Lake.

a)


0.025
0.020
0.015
0.010
Inferred TP (mg/L)
0
50
100
150
DCA AXIS 1
r² = 0.41
p < 0.001
n = 26

b)

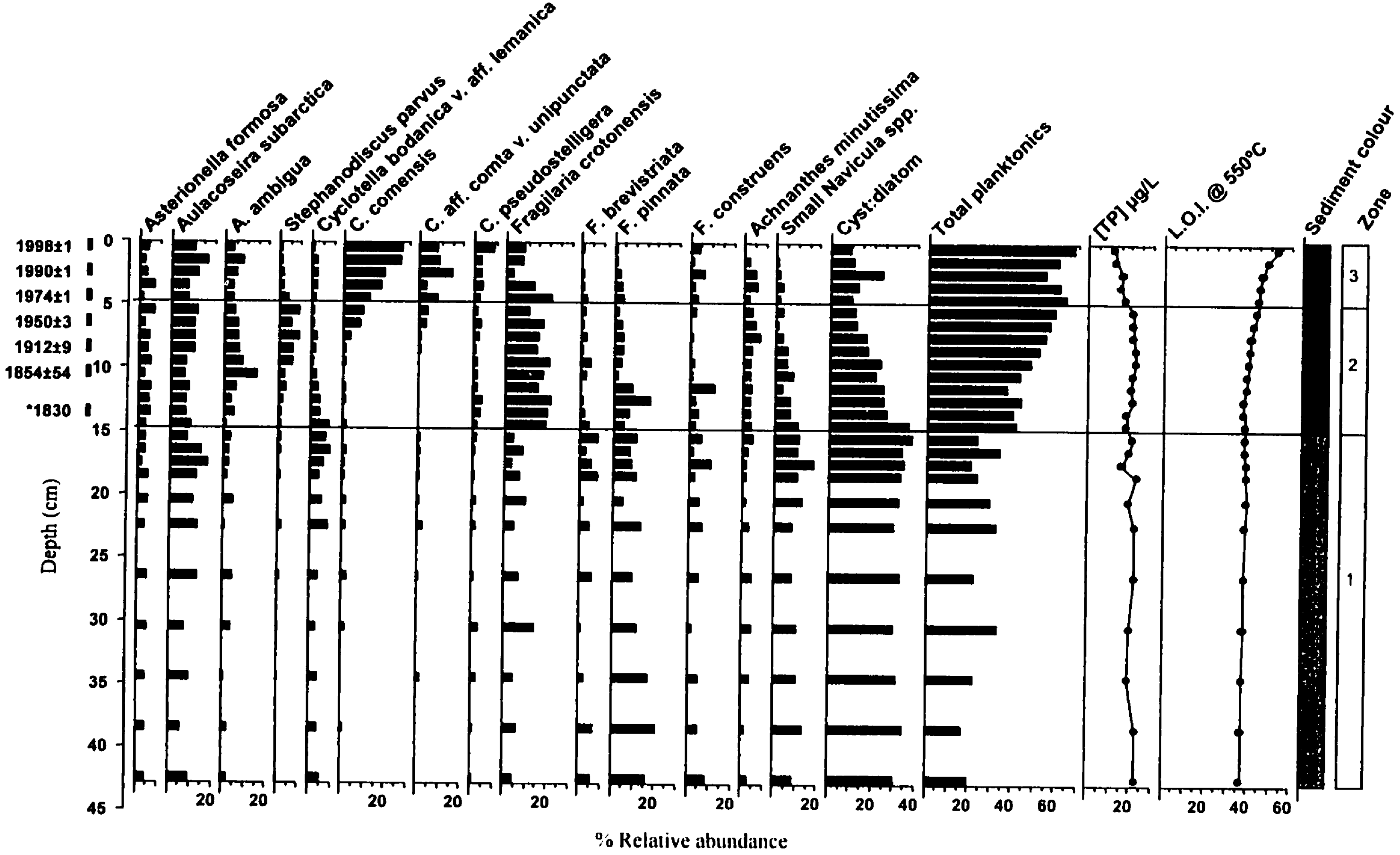

6
5
4
3
2
Inferred MZ (m)
0
50
100
150
DCA AXIS 1
r² = 0.91
p < 0.001
n = 26

correlation ($r^2 = 0.91$, $p < 0.001$, $n = 26$) between DCA axis one sample scores and inferred MZ (Figure 4.3b).

Zone 1: pre-settlement era (before ~1815)

Prior to the estimated ^{210}Pb date of 1815, the diatom assemblage was dominated by *Cyclotella bodanica* var. aff. *lemanica*, *Aulacoseira subarctica*, *Fragilaria pinnata*, *Fragilaria construens* and *F. brevistriata* (Figure 4.4). These taxa are most commonly associated with oligo-mesotrophic environments, primarily because of the presence of *C. bodanica* var. aff. *lemanica* (spr. [TP] optima = 11 µg/L) and the heavy, mesotrophic tychoplankton, *A. subarctica* (Reavie et al., 1995) (spr. [TP] optima = 14 µg/L; Reavie and Smol, 2001). Despite mesotrophic spring TP optima (*F. pinnata* = 16 µg/L; *F. construens* = 18 µg/L; *F. brevistriata* = 17 µg/L; Reavie and Smol, 2001), these small *Fragilaria* taxa have wide ranges of ecological tolerances (Bennion, 1994; Christie and Smol, 1993) and can be found in epiphytic, epipelic, epilithic or epipsammic communities (Sayer, in progress). Therefore, these species provide minimal information regarding the lake's trophic status (Bennion et al., 2001). The assemblage is 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 are also found in mesotrophic conditions with TP optima of 15 µg/L (*N. minima*), 16 µg/L (*N. seminulum*) and 17 µg/L (*N. submuralis*) in southeastern Ontario lakes (Reavie and Smol, 2001). The cyst to diatom ratio is relatively high in this zone, suggesting the conditions are still relatively unproductive, as chrysophytes tend to

Figure 4.4. Dominant diatom taxa ($\geq$ 5% in at least one interval). L.O.I. @ 550 °C and cyst:diatom ratio profiles of Indian Lake. (pre-disturbance- Zone 1, historical anthropogenic disturbance - Zone 2 and recent - Zone 3 delineated). * = extrapolated ^{210}Pb date.


Asterionella formosa
Aulacoseira subarctica
A. ambigua
Stephanodiscus parvus
Cyclotella bodanica v. aff. lemanica
C. comensis
C. aff. comta v. unipunctata
C. pseudostelligera
Fragilaria crotonensis
F. brevistriata
F. pinnata
F. construens
Achnanthes minutissima
Small Navicula spp.
Cyst:diatom
Total planktonics
[TP] µg/L
L.O.I. @ 550°C
Sediment colour
Zone
3
2
1
1998±1
1990±1
1974±1
1950±3
1912±9
1854±54
*1830
Depth (cm)
0
5
10
15
20
25
30
35
40
45
20
40
60
% Relative abundance

be more abundant in oligo-mesotrophic waters (Smol, 1985). Despite poor analogues in this zone, creating uncertain TP inferences, the known autoecology of the dominant diatom taxa, and the cyst to diatom ratio, suggest that there was a large littoral area and the conditions were oligo-mesotrophic.

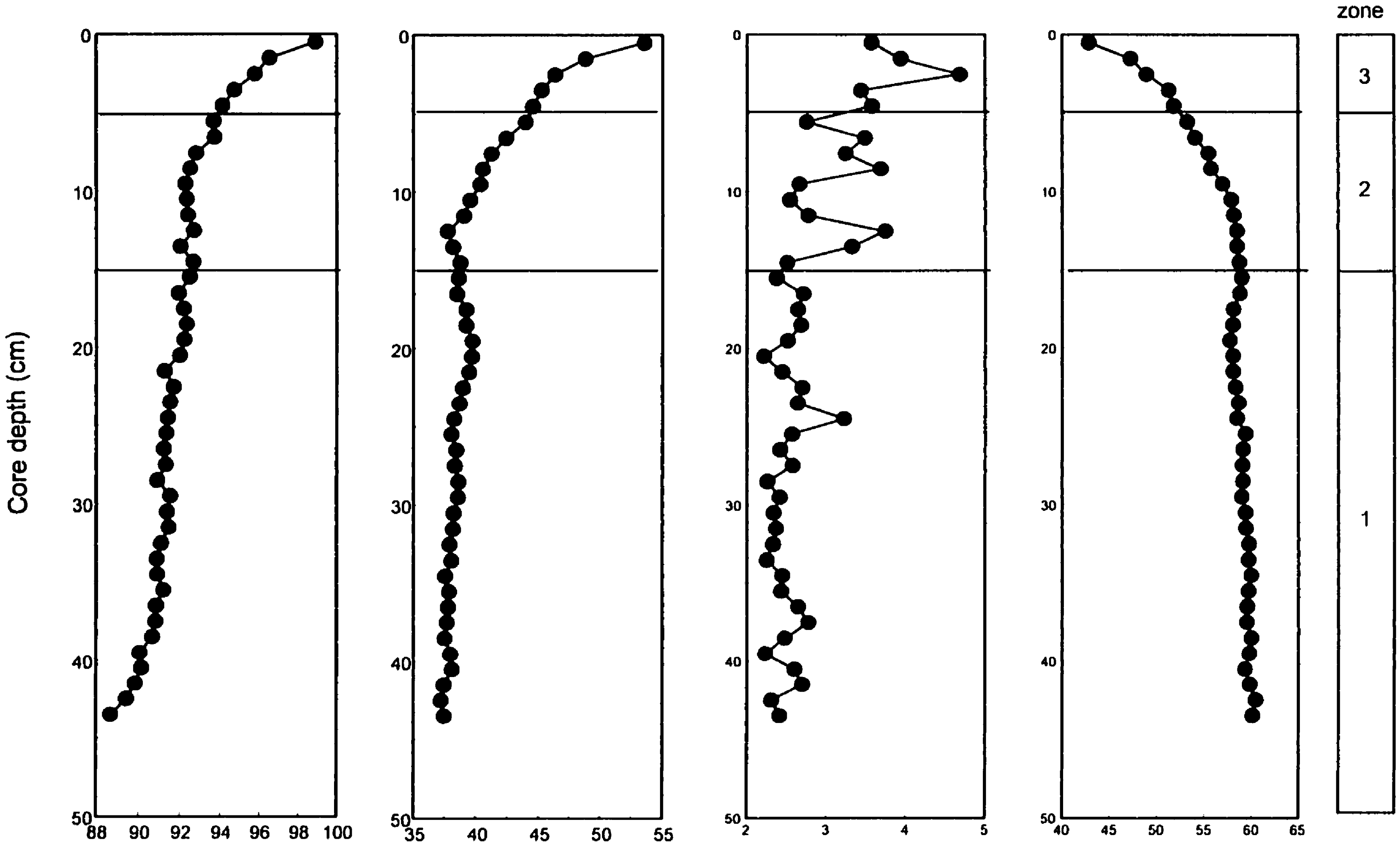
Zone 2: Early settlement and canal construction (~1830 - 1970)

At the estimated time of settlement and canal construction (14 - 15 cm), coinciding with the sediment colour change, there is a shift in the dominant diatom assemblage to one of more productive conditions (Figure 4.4). There is a 16% increase in the eutrophic species *Fragilaria crotonensis*, and a concurrent decrease in the less productive *Cyclotella bodanica* var. *aff. lemanica*. *Fragilaria 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).

Additionally, at this time, there is a decrease in the cyst to diatom ratio, providing further evidence of eutrophication (Smol, 1985). TP inferences are uncertain during this period, as analogue matching is poor (> 90% CL) (Figure 4.2e). However, the autoecological information of the dominant diatom taxa, and the decrease in the cyst to diatom ratio, indicates an increase in productivity. Estimates of percent organic matter and carbonate content gradually begin to decrease during this period and conversely clastic content increases (Figure 4.5).

These changes coincide with deforestation, settlement, and canal construction

Figure 4.5. Physical sediment characteristics for Indian Lake. (pre-disturbance- Zone 1, historical anthropogenic disturbance - Zone 2 and recent - Zone 3 delineated).



a) % Water

b) L.O.I. @ 550ºC estimating % organic matter

c) Weight loss after heating @ 925ºC estimating % carbonate content

d) % Clastics (remaining material)

activities. as European settlement is known to have occured in this drainage basin at the begining of the 1800s. The Chaffey's Mills area, located on the south end of Indian Lake, was established with 126 people in 1815 and was moderately developed by 1825 with many township roads (Fleming, 1981). Pre-canal survey reports from the early-1820s describe Chaffey's Mill as "a very extensive establishment. consisting of saw. grist. and fulling-mills, carding-machines, stores, barns. distillery. &c..." (Welch, 1979 p. 39). This description illustrates the moderate amount of logging. settlement and agricultural disturbances that were occurring in the catchment at this time. A mill dam is also described at the Chaffey's Mills location. which was estimated to have backed up approximately 1 metre of water in Indian and other Newboro lakes (Welch. 1979). This increase in water level likely inundated lowland areas around Indian Lake. and likely further contributed nutrients to the lake at this time.

In the 1830s. there was major logging associated with canal construction. Nearby areas surrounding both locks above and below Indian Lake were deforested to increase air circulation in attempts to rid the lock area of malaria (Fleming, 1981). A sketch of the bare slopes at the south end of Indian Lake illustrates the extent of logging in the catchment around this time (1833 - 1840) (Fleming, 1981). Erosion also likely increased with this deforestation and further canal construction, as a large canal cut (54.5 m long and 1.8 m deep) was made in the northeast side of the lake to provide a more direct route from Clear Lake to Indian Lake (Passfield, 1982). Finally, further nutrient addition was likely associated with flooding, as water levels were estimated to have increased an additional 1 metre with the canal weir (~1830) (Warren, pers. comm.). The combination of these disturbances likely contributed to the increase in nutrients detected by the microfossils.

Aulacoseira ambigua, a meso-eutrophic species (TP opt. 16 µg/L and TN opt. 469 µg/L; Reavie and Smol, 2001), increased abruptly to 10% relative abundance around 1850. The inferred increase in nutrients coincides with the combination of mining and further lumbering activities occurring at this time. Chaffey's Iron Mine, located on an island in Newboro Lake, was mined intermittently during the 1850s to 1870s (Snyder, 1977). Further erosion from logging practices and log drives passing through the lake to nearby sawmills also likely contributed to the increased productivity of the lake.

The diatom inferred [TP] values remain relatively stable and productive during the ~1850s to ~1960s. Inferred TP concentrations reached a maximum of 22 µg/L during the early-1900s, with increased abundances of *Stephanodiscus parvus*, a eutrophic indicator with a TP optima of 28 µg/L and a TN optima of 568 µg/L (Reavie and Smol, 2001). This eutrophication is likely related to additional runoff associated with dairying, mica mining (1890; Warren, 1997) and railway construction (1911; Fleming, 1981).

Zone 3: Recent era (~1970s to the present)

In recent years, there is a second major shift in the diatom assemblage (Figure 4.4). The relative abundance of eutrophic, planktonic taxa, such as *S. parvus* and *F. crotonensis* decrease, and oligo-mesotrophic, planktonic species increase, such as *C. comensis* and *C.* aff. *comta* var. *unipunctata*. 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 μg/L), high pH opt. (8.29), high TN opt. (0.406 mg/L), high MZ opt. 30.7 m and moderate chlorophyll *a* (Chl *a*) opt. (1.53 mg/L) (Reavie and Smol, 2001). *Cyclotella.* aff. *comta* var. *unipunctata* is also characterized as an oligo-mesotrophic indicator with a TP opt. of 10 μg/L and was found in similar conditions as *C. comensis* (pH opt. 8.28, TN opt. 0.423, MZ opt. 37.5 m, Chl *a* opt. 1.64 mg/L). Although the cyst to diatom ratio fluctuates 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. The 1998 inferred spring TP concentration of 12 μg/L closely matches the actual measured value of 10 μg/L taken during the spring of that year (Little, 1999).

These recent inferred water quality improvements are possibly related to: 1) decrease in use of phosphorus detergents, 2) better absorption of nutrients by soils in redeveloping forests, and 3) climate warming. As these recent water quality improvements are inferred in all the study lakes, reasons for this regional occurrence are discussed in Chapter 5.

Big Rideau Lake

Chronology:

The sediment core from Big Rideau Lake demonstrates a typical exponential decline in ^{210}Pb activity, suggesting that sedimentation rates have remained fairly constant and the core is likely not significantly mixed (Figure 4.6). Supported ^{210}Pb activity (2.11 dpm/g) was reached after the 28 cm interval in the sediment core. Using the CRS model, and assuming a constant flux of ^{210}Pb to the sediment, the 28 - 29 cm interval was approximately dated as 1830, the time of canal construction.

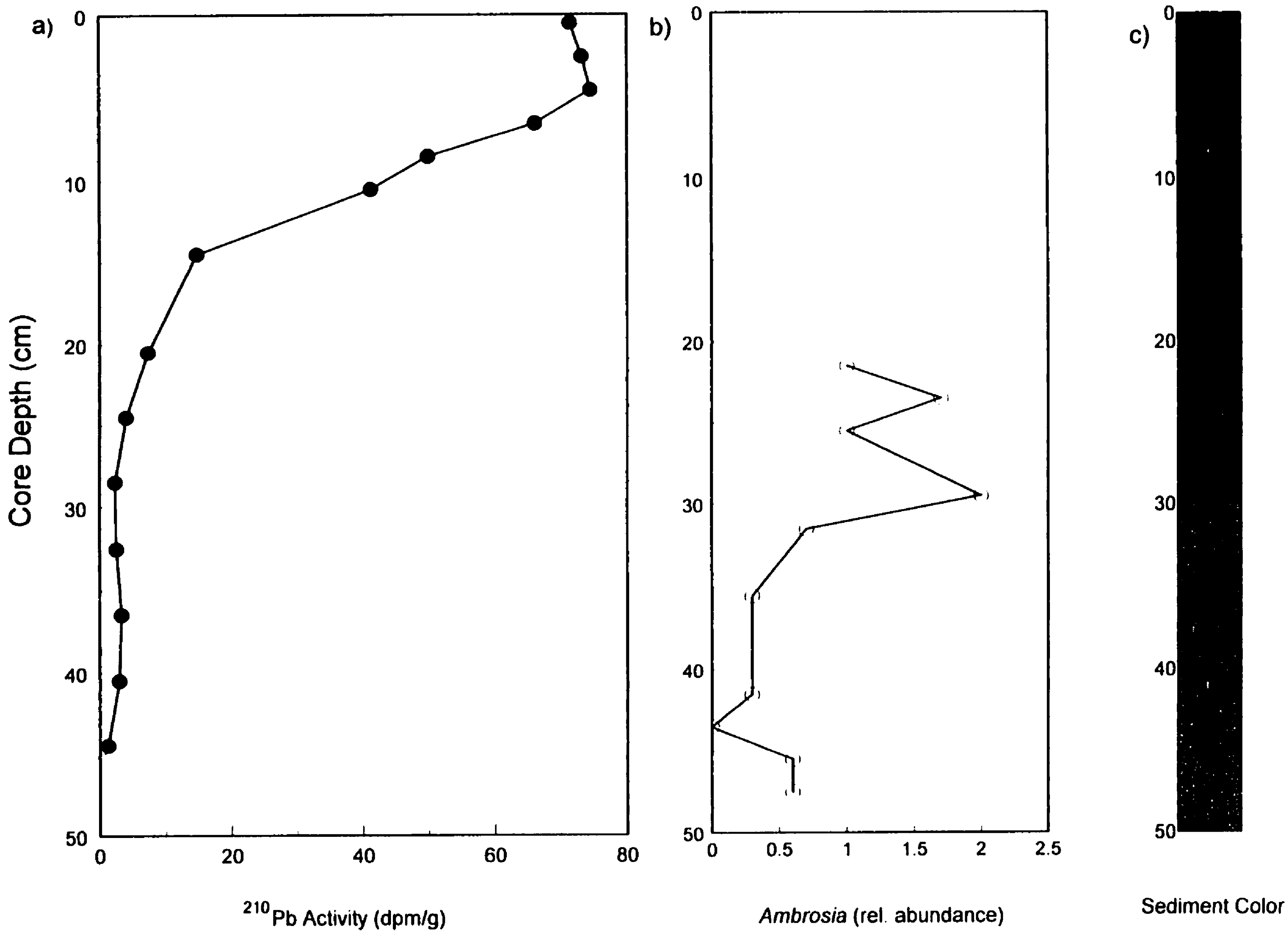
The rise of *Ambrosia* around this sediment interval provides further confirmation of this estimated ^{210}Pb date of 1830 (Figure 4.6). In the 29 - 30 cm interval, there is an increase in *Ambrosia* (0.6 - 2%) and the introduction of grass pollen (Smol, pers. comm.). The rise in *Ambrosia* is related to widespread vegetation disturbance from settlement and logging activities between 1825 and 1850 (Mott and Farley-Gill, 1981). *Ambrosia*, however, is present in trace abundances (0 - 0.7%) in the bottom sediments of the core (31 - 48 cm). These smaller abundances likely represent long disturbance transport of ragweed pollen from earlier disturbed regions to the south, as well as natural ragweed populations in the area.

A change in sediment colour is also observed around the estimated time of canal construction, 1830 (30 cm). Similar to the lithological change observed in Indian Lake, the Big Rideau Lake sediment core exhibits a change from light to dark brown organic sediments (Figure 4.6).

Microfossil and Sediment Analysis:

Cluster analysis of diatom assemblages, ^{210}Pb dates, sediment colour and *Ambrosia* pollen delineate the 48 cm sediment core into three distinct zones (Figure 4.6): Zone one represents the pre-disturbance era (before ~1820) (48 - 28 cm); Zone 2 includes the canal construction and settlement of era ~1820 to ~1967 (28 - 9 cm); and Zone 3 represents the recent past (~1970) until present (9 - 0 cm). Following total phosphorus

Figure 4.6. a) Profile of ^{210}Pb activity vs. sediment core depth for Big Rideau Lake.
b) Profile of *Ambrosia* pollen rise in Big Rideau Lake (relative abundance). Analyst: J.P. Smol.
c) Profile of sediment colour changes for Big Rideau Lake (light brown bottom sediments and dark brown upper sediments).


a)
Core Depth (cm)
0
10
20
30
40
50
0
20
40
60
80
^{210}Pb Activity (dpm/g)
b)
0
10
20
30
40
50
0
0.5
1
1.5
2
2.5
Ambrosia (rel. abundance)
c)
0
10
20
30
40
50
Sediment Color

[TP] and maximum depth (MZ) reconstruction analyses, the microfossil, physical sediment characteristics and model inferrences will be discussed and related to the known history of the area.

Paleoenvironmental Reconstructions:

Three lines of evidence suggest that the TP and MZ reconstructions are reliable in zones two and three. First, significant correlations were found between DCA axis one values and inferred TP ($r^2 = 0.29$, $p<0.05$, $n = 15$) and MZ ($r^2 = 0.95$, $p<0.001$, $n = 24$) values, suggesting that these variables were influencing the diatom assemblage (Figure 4.7a and 4.7c). However, the significant correlation found between DCA axis one and inferred TP values only occurred if the intervals prior to canal construction (below 30 cm) were excluded in the analysis. A poor correlation was found between DCA axis one and inferred TP values ($r^2 = 0.13$, $p>0.05$, $n = 24$) if values from the entire core were used in the analysis (Figure 4.7b). The second line of evidence was that post-canal sediment diatom samples exhibited 'good fit' to [TP] and MZ in a constrained CCA of the SE Ontario calibration set. Most pre-canal diatom assemblages demonstrated 'poor fit' to [TP] and MZ inferences, particularly intervals 28 - 29, 36 - 37, 38 - 39, 42 - 43, 44 - 45 and 46 - 47 cm, which exceeded 90% confidence limits (Figures 4.8b and 4.8d). Finally, there were good modern analogues between modern and fossil samples in post-canal assemblages with the exception of the 20 - 21 cm interval. In the pre-canal assemblages, there were poor degrees of correspondence between modern and fossil diatom assemblages in all samples except the 38 - 39 cm interval (Figure 4.8e). In summary,

Figure 4.7. Big Rideau Lake correlations between DCA axis one sample scores and TP and transformed maximum depth (MZ) inferences.

a) The correlation between DCA axis one sample scores and inferred TP values (including fossil samples following canal construction, 0-30 cm).

b) The correlation between DCA axis one sample scores and inferred TP values (including all fossil samples).

c) The correlation between DCA axis one sample scores and inferred square-root MZ values (including all fossil samples).

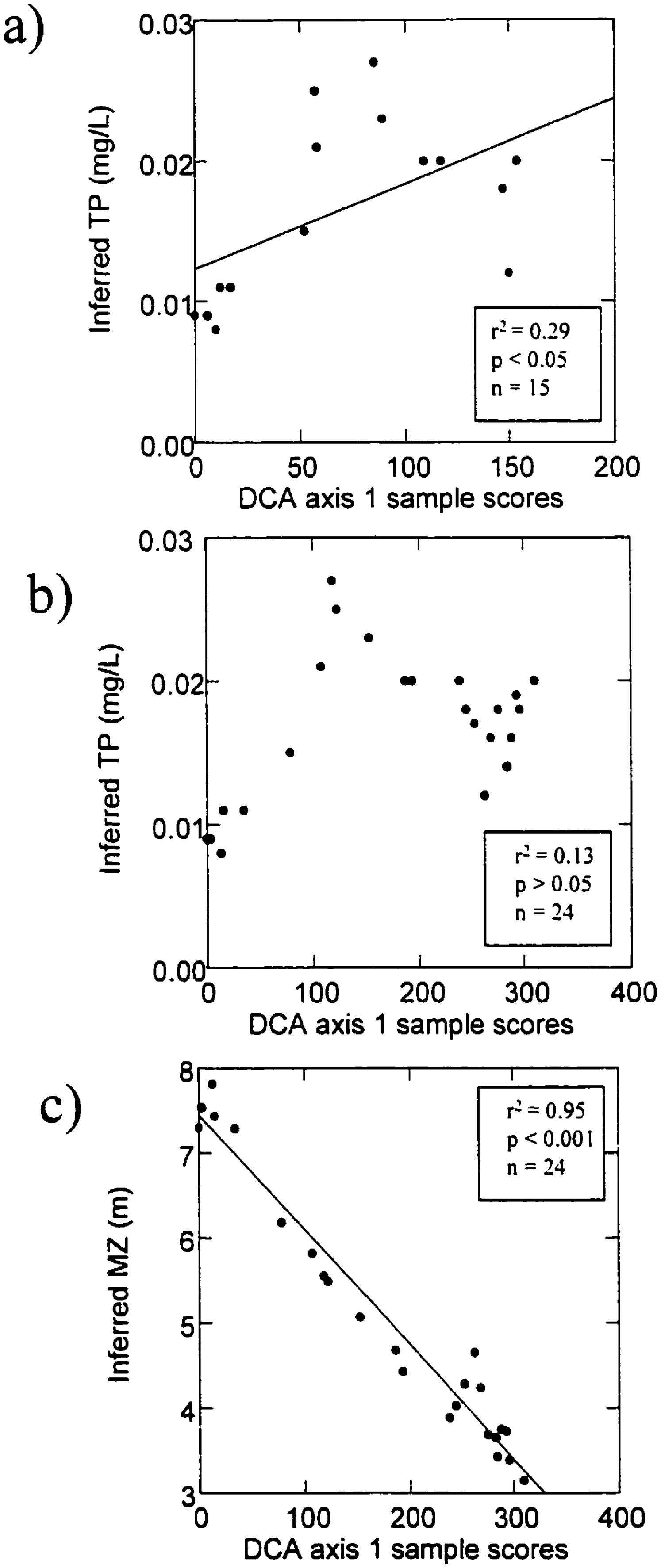

a)
Inferred TP (mg/L)
0.03
0.02
0.01
0.00
0
50
100
150
200
DCA axis 1 sample scores
$r^2 = 0.29$
$p < 0.05$
$n = 15$
b)
Inferred TP (mg/L)
0.03
0.02
0.01
0.00
0
100
200
300
400
DCA axis 1 sample scores
$r^2 = 0.13$
$p > 0.05$
$n = 24$
c)
Inferred MZ (m)
8
7
6
5
4
3
0
100
200
300
400
DCA axis 1 sample scores
$r^2 = 0.95$
$p < 0.001$
$n = 24$

Figure 4.8. Diatom reconstructions and model evaluations for Big Rideau Lake (pre-disturbance- Zone 1, historical anthropogenic disturbance - Zone 2 and recent - Zone 3 delineated)

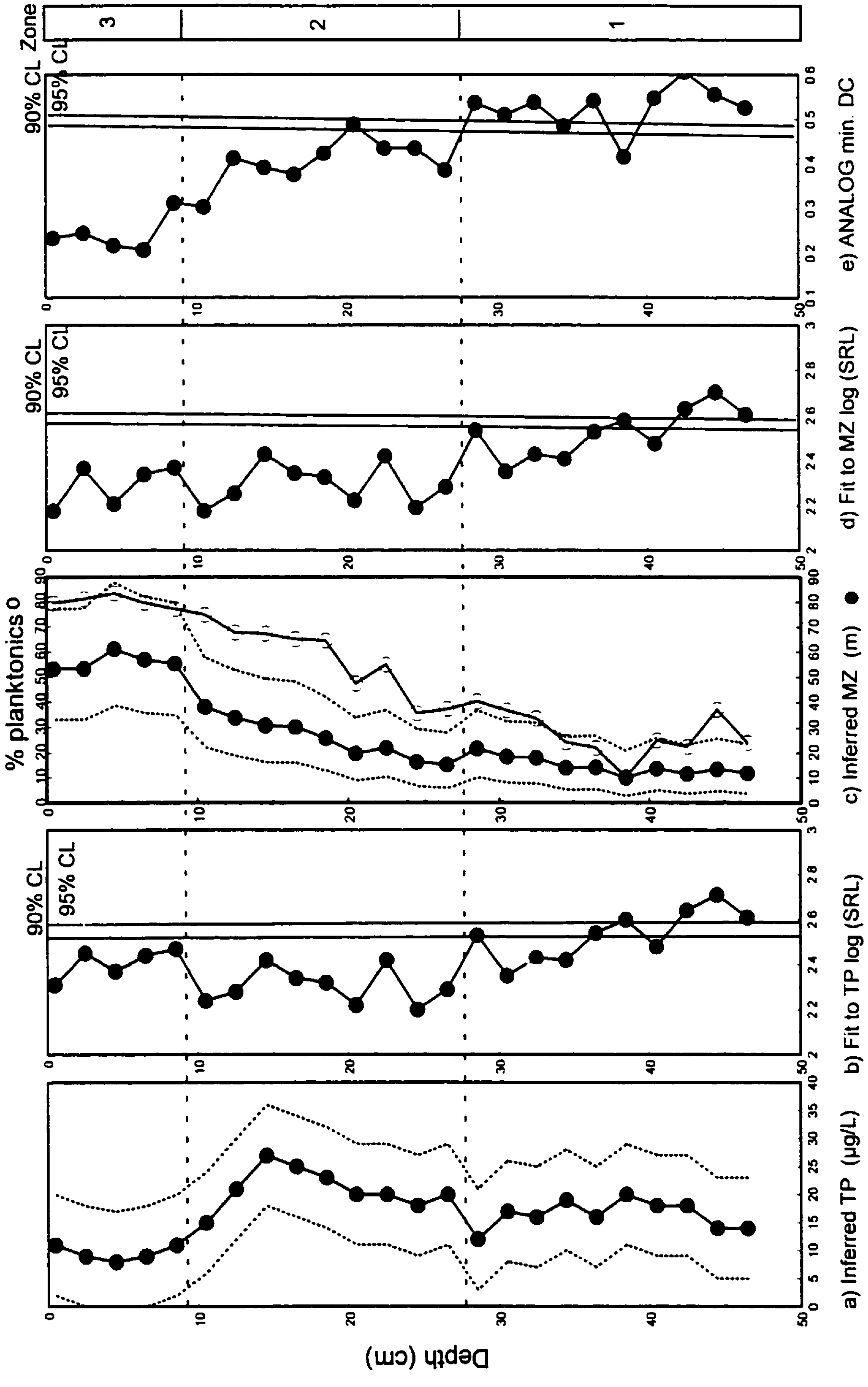
a) Diatom inferred TP reconstruction (dotted lines indicate error estimates).

b) The fit of Big Rideau Lake fossil samples to the TP axis of calibration samples, determined through canonical correspondence analysis (CCA) constrained to TP, with passive analysis of Big Rideau Lake samples. Lines indicate the upper and lower 90% and 95% confidence limits. Big Rideau Lake samples with poor and very poor fit, fall beyond the 90% and 95% confidence limits (CL).

c) Diatom inferred MZ reconstruction (dotted lines indicate error estimates).

d) The fit of Big Rideau Lake fossil samples to the MZ axis of calibration samples, determined through canonical correspondence analysis (CCA) constrained to TP, with passive analysis of Big Rideau Lake samples. Lines indicate the upper and lower 90% and 95% confidence limits. Big Rideau Lake samples with poor and very poor fit, fall beyond the 90% and 95% confidence limits.

e) The analogue profile indicating the strength of the match between the Big Rideau Lake fossil samples and the S.E. Ontario calibration set samples (Reavie and Smol, 2001), using the Bray-Curtis dissimilarity coefficient. Solid lines indicate upper 90% and 95% confidence limits. Big Rideau Lake samples falling outside of the 90% and 95% confidence limits are deemed as having poor and very poor analogues.



Depth (cm)
a) Inferred TP (µg/L)
b) Fit to TP log (SRL)
c) Inferred MZ (m) ●
% planktonics o
d) Fit to MZ log (SRL)
e) ANALOG min. DC
90% CL
95% CL
Zone
3
2
1

these results suggest that [TP] inferences are generally reliable following canal construction, but unreliable for pre-canal conditions. In addition, a variable related to maximum depth (e.g. water clarity) is greatly influencing the diatom assemblage.

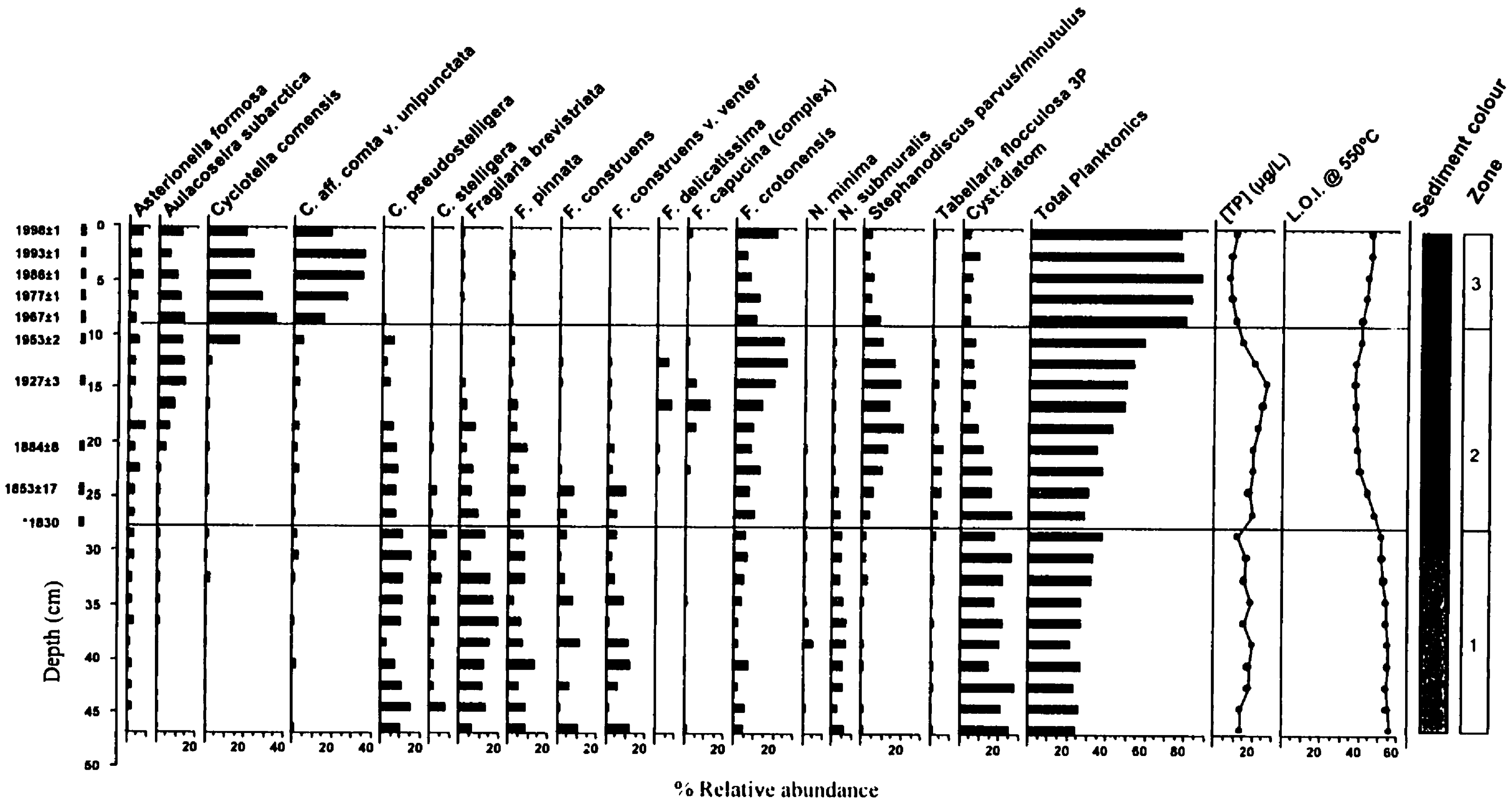
Zone 1: Pre-canal construction (before ~1830)

The pre-canal assemblage is dominated by *Fragilaria brevistriata*, *F. construens*, *F. construens* f. *venter*, *Cyclotella pseudostelligera* and *C. stelligera* (Figure 4.9). As previously mentioned, these small benthic *Fragilaria* species are considered to be generalists with broad nutrient tolerances and are found in a variety of habitats. Therefore, their occurrences are difficult to interpret (Bennion et al., 2001). However, the *Cyclotella* species provide evidence of oligo-mesotrophic conditions with respective TP and TN optima of 13 µg/L and 394 µg/L for *C. pseudostelligera* and 11 µg/L and 355 µg/L for *C. stelligera* (Reavie and Smol, 2001). Furthermore, the cyst to diatom ratio is relatively high (25%), also suggesting that the conditions were relatively unproductive at this time (Smol, 1985). Benthic diatom taxa (e.g. *N. submuralis*, *A. minutissima*) were also common, indicating a high percentage of littoral habitats. Despite uncertain TP inferences (poor analogues and fit to TP), the microfossil evidence suggests that lake conditions prior to European settlement were oligo-mesotrophic with a large littoral area.

Zone 2: Canal construction and land clearance

This zone is marked by a gradual change in the diatom species assemblage. There is an slight increase in the planktonic, eutrophic taxa *Tabellaria flocculosa* strain *IIIp*,

Figure 4.9. Dominant diatom taxa (≥ 5% in at least one interval), L.O.I. @ 550°C and cyst:diatom ratio profiles of Big Rideau Lake. (pre-disturbance- Zone 1, historical anthropogenic disturbance - Zone 2 and recent - Zone 3 delineated). * = extrapolated ^{210}Pb date.

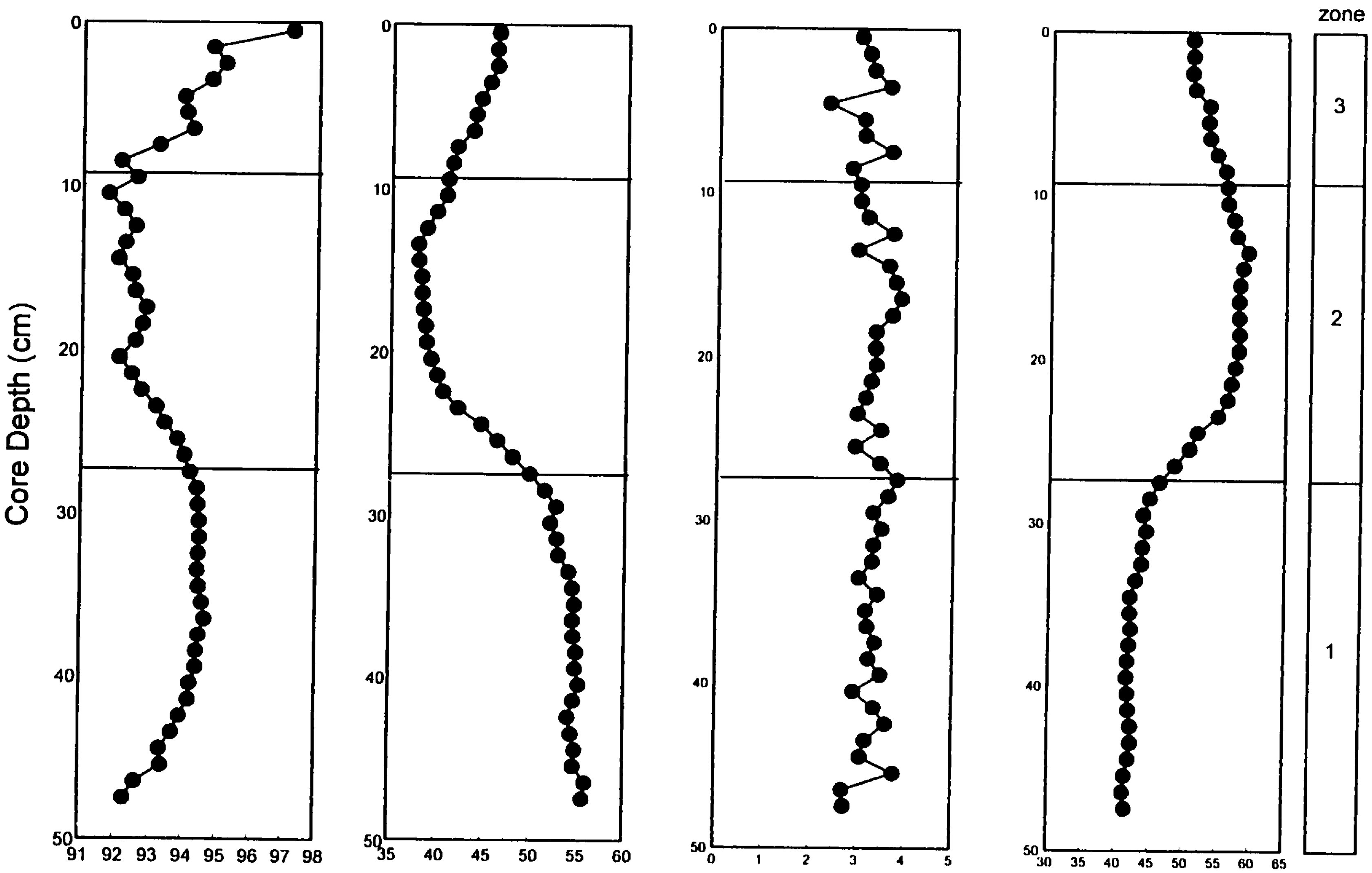

Asterionella formosa
Aulacoseira subarctica
Cyclotella comensis
C. aff. comta v. unipunctata
C. pseudostelligera
C. stelligera
Fragilaria brevistriata
F. pinnata
F. construens
F. construens v. venter
F. delicatissima
F. capucina (complex)
F. crotonensis
N. minima
N. submuralis
Stephanodiscus parvus/minutulus
Tabellaria flocculosa 3P
Cyst:diatom
Total Planktonics
[TP] (µg/L)
L.O.I. @ 550°C
Sediment colour
Zone
3
2
1
1998±1
1993±1
1986±1
1977±1
1967±1
1953±2
1927±3
1884±8
1853±17
*1830
0
5
10
15
20
25
30
35
40
45
50
Depth (cm)
% Relative abundance
20
40
60
80

Stephanodiscus parvus/minutulus, and *Fragilaria crotonensis* commencing at the estimated time of canal construction (1830). These *Stephanodiscus* species are common indicators of eutrophication with high nutrient optima (*S. parvus*, TP 28 µg/L, TN 568 µg/L; *S. minutulus* TP 15 µg/L, TN 461 µg/L) (Reavie and Smol, 2001). Coinciding with this assemblage change, there is a decrease in the cyst to diatom ratio, providing further evidence of nutrient enrichment. Diatom inferred TP is ~20 µg/L around this time (~1830). Additionally, estimated percent organics and carbonate content begin to decrease at this time and clastic content increases (Figure 4.10). This increase in clastics is likely related to heightened erosion associated with watershed disturbances. Microfossil and sediment composition changes suggest that the conditions became more productive at this time.

This trend in increased productivity coincides with deforestation, flooding and settlement activities known to have occurred in the 1830s. There was extensive clearing of the area surrounding Narrows' Lock during the time of canal construction, as the area was endemic with malaria and increasing the air circulation was thought to improve conditions (Passfield, 1982). The flooding of lowland areas associated with canal construction also likely contributed nutrients to the lake at this time, as Big Rideau and Lower Rideau lakes were estimated to have been flooded 3 ft (0.9 m) with the construction of the canal (Tulloch, 1981). Settlement activity also increased with the completion of the canal, as the Royal Sappers and Miners who helped build the canal were granted free land (Kennedy, 1984).

Following canal construction, there is an increase in planktonic taxa

Figure 4.10. Physical characteristics of Big Rideau Lake recent sediments (~200 years) (pre-disturbance- Zone 1, historical anthropogenic disturbance - Zone 2 and recent - Zone 3 delineated).



a) % Water

b) L.O.I. @ 550°C estimating % organic matter

c) Weight loss after heating @ 925°C estimating % carbonate content

d) % Clastics (remaining material)

(e.g. *Tabellaria floculosa* strain *IIIp, Stephanodiscus* species) and decrease in benthic species (e.g. *N. submuralis*). In the 1860s, there is a further increase in the eutrophic *Stephanodiscus* species and a decrease in small benthic *Fragilaria* species. The heavy, tychoplankton, *Aulacoseira subarctica* also increases at this time, which may be related to catchment erosion and increased turbulence. Reavie et al. (2000) suggest that the success of this genus is related to its high requirement for silica, which are usually associated with catchment erosion activities. This heavily silicified genus also requires turbulent conditions to maintain its presence in the photic zone (Round et al., 1990).

The increase in productivity and possibly turbulence, coincides with a time of mining, dairying and further flooding activities. Mining is known to have occurred in the region from 1855 to the 1950s (Snyder, 1977). A total of 24 of the 34 phosphate mines were identified in the North Burgess Township, which includes the northern watershed of Big Rideau Lake (Snyder, 1977). Dairying activities were also common, with local cheese factories operating in Portland (Snyder, 1977). In 1865, the Poonamalie Dam was increased 0.6 m in height (Parks Canada, undated) and flooded lowland areas, thus increasing nutrients to the lake and the lake's surface area. This increase in surface area would increase the fetch of the lake and relative wind-induced turbulence.

The early-1900s marks the most productive time of the lake's ~200-year history. The eutrophic species *S. parvus, F. crotonensis,* and *S. minutulus* further increase in abundance and the inferred TP peaks at 27 µg/L in ~1927. This coincides with increased mining and agricultural watershed disturbances. One mine located near the water's edge (north side of lake at entrance to Adams Lake) was mined for mica in 1909, 1916, 1939 and 1940 (Snyder. 1977). Another nearby mica mine (Murphy's Point) was operated between 1903 and 1920. and dairying activities were also common in the area at this time (Turner and Visser. 1995).

Zone 3: Recent era (~1970s to the present)

In the 1970s. there is shift to an assemblage dominated by less eutrophic species. such as *C. comensis and C.* aff. *comta* var. *unipunctata.* with low inferred [TP] values ranging from 8 - 11 μg/L. The 1998 inferred TP value of 11 μg/L closely matches the actual spring TP measured value of 8 μg/L (Little. 1999). However. there is also an increase in *F. crotonensis* in 1998. Since *F. crotonensis* is an eutrophic indicator. its occurrence is perhaps an early warning that water quality may be changing. Therefore. lake managers should continue monitoring and mitigation programs.

This zone of general recovery. as observed in the other study lakes. is also probably associated with: 1) decrease in use of phosphate detergents. 2) better absorption of soils from redeveloping forests. and 3) climate warming (discussed in Chapter 5).

Lower Rideau Lake (shallow lake)

Chronology:

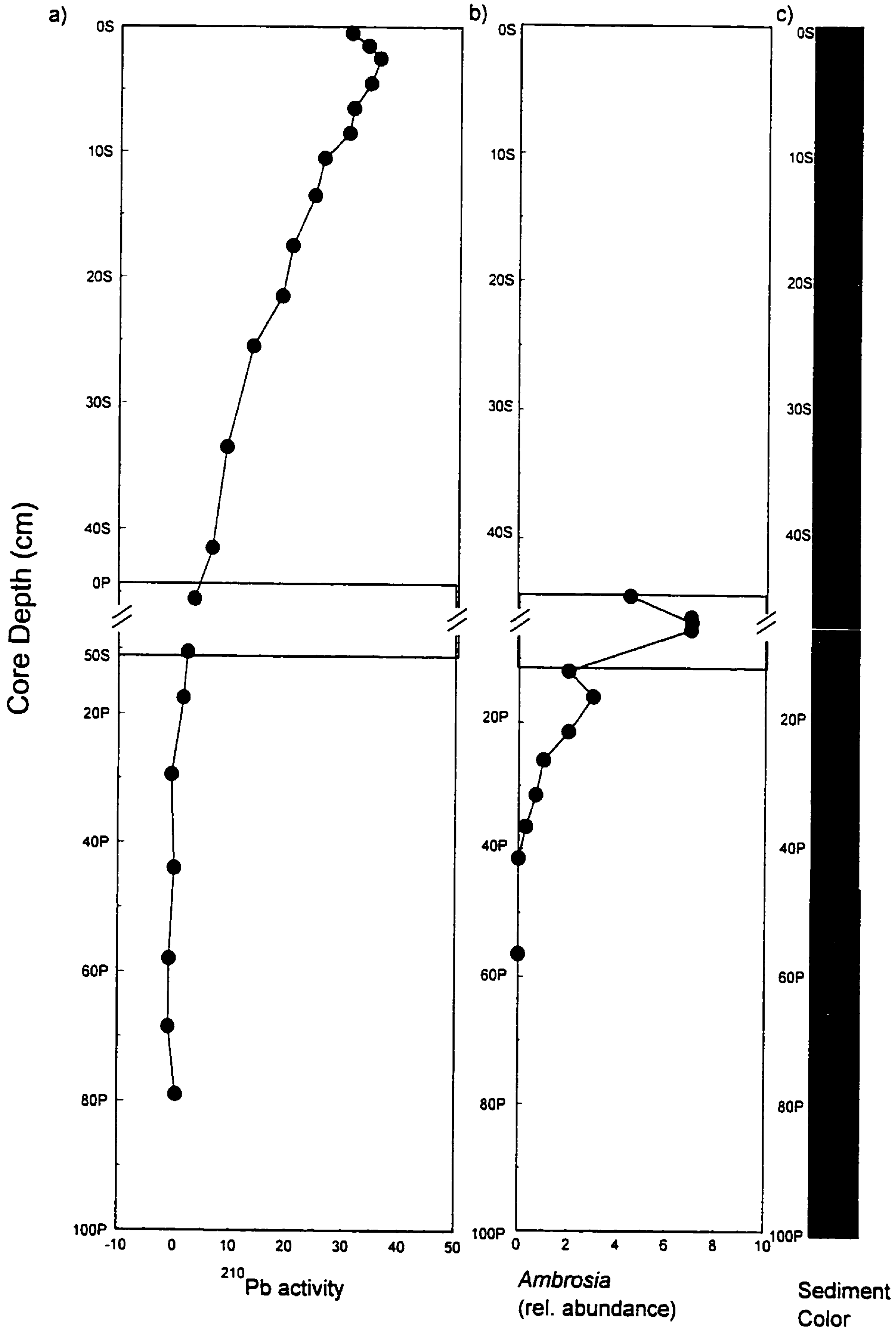
The ^{210}Pb activity profile suggests that the sediment core had not experienced significant mixing; however. the profile also indicated that the core was not of sufficient length to span the entire ~200 year period of interest. Lower Rideau Lake has a high

Figure 4.11. Sediment chronology of Lower Rideau Lake. (s = short core, super glew and p = long core, piston)

a) Profile of ^{210}Pb activity vs. sediment core depth.

b) Profile of *Ambrosia* pollen rise (relative abundance). Analyst: J.P. Smol.

c) Profile of sediment colour changes (medium (bottom sediments) to dark brown (upper sediments)).


a)
b)
c)
Core Depth (cm)
0S
10S
20S
30S
40S
0P
50S
20P
40P
60P
80P
100P
-10
0
10
20
30
40
50
^{210}Pb activity
0
2
4
6
8
10
Ambrosia
(rel. abundance)
Sediment
Color

sedimentation rate illustrated by its initially low ^{210}Pb activity (30.73 dpm/g) and long activity profile (supported activity reached after 42 cm) (Figure 4.11). Replicate dating of the surficial sediment in a second short core further confirmed the surprisingly low initial ^{210}Pb activities. Subsequent coring of the lake using a modified Livingstone corer (Wright, 1991) resulted in the retrieval of a 1 metre long core. This core reached background activity (0.143 dpm/g) and confirmed that supported activity was not reached in the short core. Matching ^{210}Pb activity, diatom and pollen relative abundances in both the long and short cores identified that the top 5 cm of the piston core likely overlapped with the bottom interval (46 - 47 cm) of the short core. A sedimentation rate of 0.5 cm per year was estimated from the excess activity and cumulative mass graph using the 1935 ^{210}Pb date (SD of ± 4 years) (34 cm = 1935). This sedimentation rate was used to estimate that the sediment interval of 84 cm (37 cm on the piston core) was ~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. However, the other lines of evidence (e.g. *Ambrosia* and sediment colour changes) discussed below, help confirm the timing of canal construction.

Ambrosia increased around the 39 - 40 cm interval in the long core, likely representing human activity after the 1830s (Chapter 2). Grass pollen also increased in abundance after 32 cm, providing further evidence of increased local watershed disturbances.

There was a slight change in colour from light to medium brown sediments after 46 cm in the long core. This colour change has been observed in other canal lakes around the estimated time of canal construction (1830) and therefore is considered another marker of the time of canal construction (this study; Christie and Smol, 1996).

Microfossil and Sediment Analysis:

Cluster analysis, *Ambrosia* pollen counts and sediment colour changes helped delineate the long and short sediment cores into three zones: Zone 1 is the pre-disturbance era (before 1830; 68 - 46 cm, long core); Zone 2 is the canal construction and settlement era (~1830 - ~1970; 46 - 0 cm long core; 47 - 21 cm short core); and Zone 3 is the recent past (~1970 - present; 21 - 0 cm short core). The microfossil assemblages, physical sediment characteristics, and TP and MZ inferences will be discussed in the context of the known history of the catchment area of Lower Rideau Lake (previously discussed in Chaper 2).

Paleoenvironmental Reconstructions:

Diatom-inferred [TP] and MZ reconstructions were only considered reliable in certain sections of the Lower Rideau Lake sediment core based on three lines of evidence: fit tests, analogue matches, and correlation analysis between the main direction of variation and TP and MZ reconstructions. The fossil assemblages exhibited a poor fit to TP in a constrained CCA of the calibration set. Fourteen of the 25 fossil samples in the diatom assemblages had poor or very poor fit to TP (SRLs > 90% or 95% CLs) in both the short and long core (Figures 4.12b and 4.13b). Sediment diatom samples mainly demonstrated a good fit to MZ in a constrained CCA of the southeastern Ontario training

Figure 4.12. Diatom reconstructions and model evaluations for Lower Rideau Lake (piston core) (pre-disturbance- Zone 1. historical anthropogenic disturbance - Zone 2a and 2b delineated).

a) Diatom inferred TP reconstruction (dotted lines indicate error estimates).

b) The fit of Lower Rideau Lake fossil samples to the TP axis of calibration samples, determined through canonical correspondence analysis (CCA) constrained to TP, with passive analysis of Lower Rideau Lake samples. Lines indicate the upper and lower 90% and 95% confidence limits. Lower Rideau Lake samples with poor and very poor fit fall beyond the 90% and 95% confidence limits (CL).

c) Diatom inferred MZ reconstruction (dotted lines indicate error estimates).

d) The fit of Lower Rideau Lake fossil samples to the MZ axis of calibration samples, determined through canonical correspondence analysis (CCA) constrained to TP, with passive analysis of Lower Rideau Lake samples. Lines indicate the upper and lower 90% and 95% confidence limits. Lower Rideau Lake samples with poor and very poor fit fall beyond the 90% and 95% confidence limits. (piston core) (diatom zones indicated).

e) The analogue profile indicating the strength of the match between the Lower Rideau Lake fossil samples and the S.E. Ontario calibration set samples (Reavie and Smol, 2001), using the Bray-Curtis dissimilarity coefficient. Solid lines indicate upper 90% and 95% confidence limits. Lower Rideau Lake samples falling outside of the 90% and 95% confidence limits are deemed as having poor and very poor analogues.

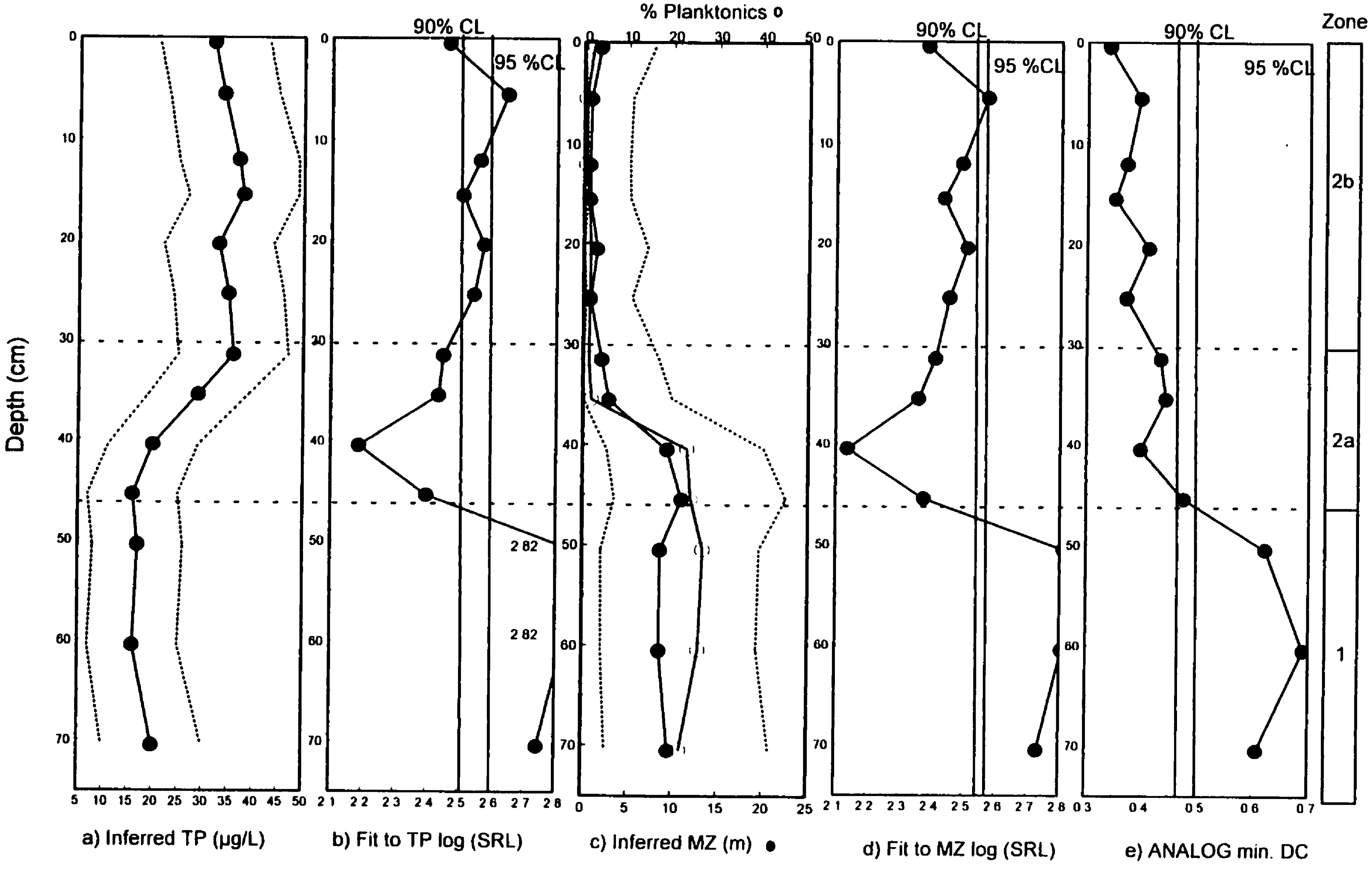

a) Inferred TP (µg/L)
b) Fit to TP log (SRL)
c) Inferred MZ (m) ●
d) Fit to MZ log (SRL)
e) ANALOG min. DC

Figure 4.13. Diatom reconstructions and evaluations for Lower Rideau Lake (short core) (pre-disturbance- Zone 1, historical anthropogenic disturbance - Zone 2 and recent - Zone 3 delineated).

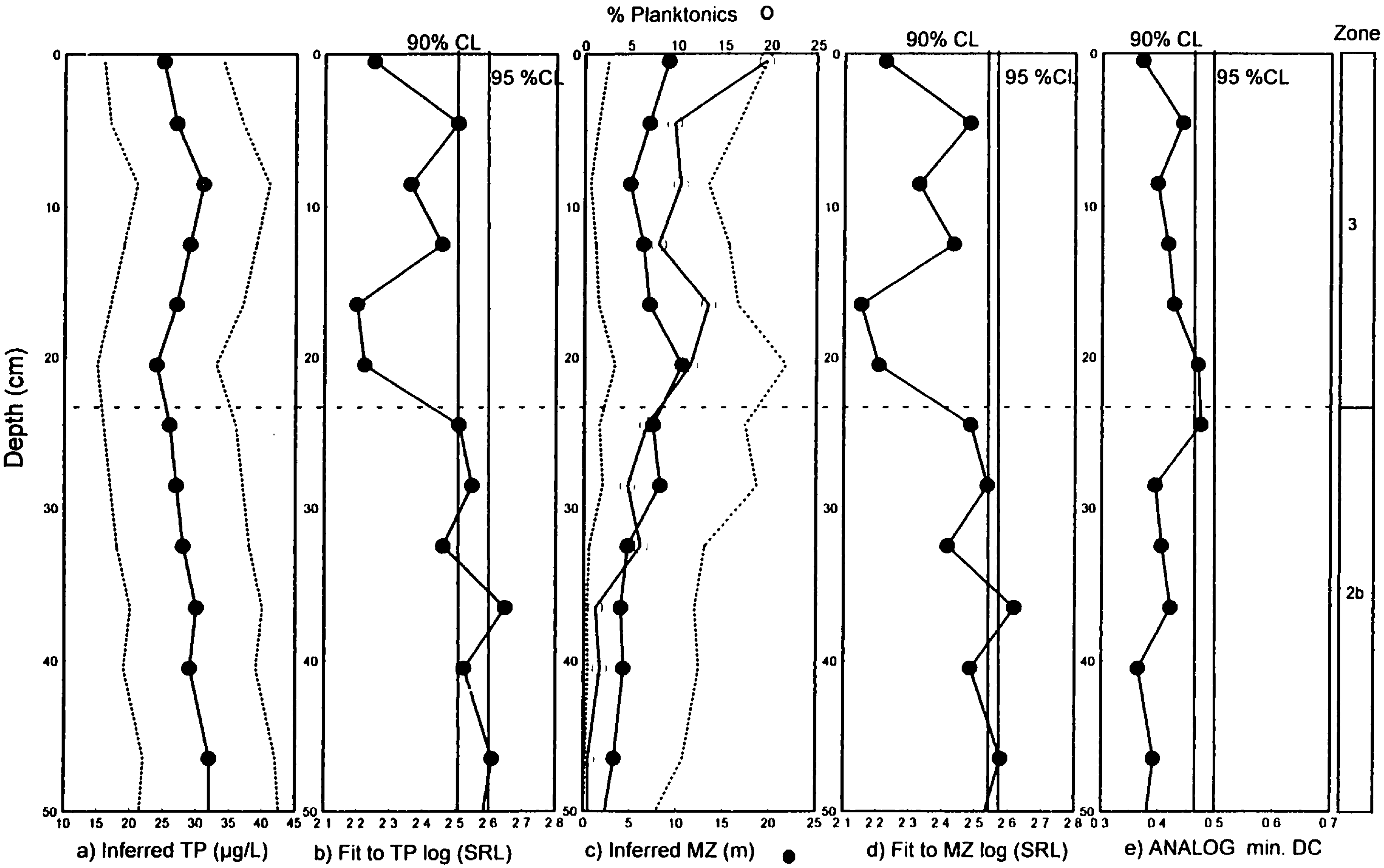
a) Diatom inferred TP reconstruction.

b) The fit of Lower Rideau Lake fossil samples to the TP axis of calibration samples, determined through canonical correspondence analysis (CCA) constrained to TP, with passive analysis of Lower Rideau Lake samples. Lines indicate the upper and lower 90% and 95% confidence limits. Lower Rideau Lake samples with poor and very poor fit fall beyond the 90% and 95% confidence limits (CL).

c) Diatom inferred MZ reconstruction.

d) The fit of Lower Rideau Lake fossil samples to the MZ axis of calibration samples, determined through canonical correspondence analysis (CCA) constrained to TP, with passive analysis of Lower Rideau Lake samples. Lines indicate the upper and lower 90% and 95% confidence limits. Lower Rideau Lake samples with poor and very poor fit fall beyond the 90% and 95% confidence limits.

e) The analogue profile indicating the strength of the match between the Lower Rideau Lake fossil samples and the S.E. Ontario calibration set samples (Reavie and Smol, 2001), using the Bray-Curtis dissimilarity coefficient. Solid lines indicate upper 90% and 95% confidence limits. Lower Rideau Lake samples falling outside of the 90% and 95% confidence limits are deemed as having poor and very poor analogues.


Depth (cm)
0
10
20
30
40
50
a) Inferred TP (µg/L)
10 15 20 25 30 35 40 45
b) Fit to TP log (SRL)
21 22 23 24 25 26 27 28
90% CL
95 %CL
% Planktonics O
0 5 10 15 20 25
c) Inferred MZ (m) ●
0 5 10 15 20 25
d) Fit to MZ log (SRL)
21 22 23 24 25 26 27 28
90% CL
95 %CL
e) ANALOG min. DC
03 04 05 06 07
90% CL
95 %CL
Zone
3
2b

set, with only three intervals of poor fit and four intervals with no fit to maximum depth (Figures 4.12d and 4.13d). Secondly, most fossil diatom assemblages had good modern analogues in the calibration set, with the exception of poor analogues in intervals 20.5, 24.5 (short core) and 45.5 cm (long core), and very poor analogues in the bottom intervals of the long core (50.5 cm, 60.5 cm, 70.5 cm) (Figure 4.12e and 4.13e). Therefore, TP and MZ inferences were only considered reliable for recent sediments in the short core (0 - 25cm) and during the period of canal construction and early settlement (30 - 40 cm in the long core). Interestingly, correlations between DCA axis one sample scores and inferred [TP] values were found to be significant in the long core ($r^2 = 0.89$, $p<0.001$, $n = 13$), but not in the short core ($r^2 = 0.27$, $p>0.05$, $n = 12$) (Figure 4.14a and 4.14c). Significant correlations were also found between inferred MZ and DCA axis one sample scores in the long and short core reconstructions (long core, $r^2 = 0.87$, $p<0.001$, $n = 13$; short core, $r^2 = 0.04$, $p<0.05$, $n = 12$). The significant correlations between DCA axis one sample scores and inferred [TP] and MZ in the long core suggest that these variables are influencing the changes of the fossil diatoms in this part of the chronology. In summary, TP inferences were likely reliable within recent periods (~1970 to present) and following canal construction (TP ~1830 - ~1860) (Figures 4.12 and 4.13). A variable related to MZ (e.g. water clarity) is also strongly influencing the fossil diatom assemblages during these periods (Figures 4.12 and 4.13).

Zone 1: Pre-settlement era (before ~1830)

The diatom assemblage in this zone was dominated by *Achnanthes minutissima*.

Figure 4.14. Correlations between DCA axis one samples scores and TP and MZ inferences in the short and piston cores from Lower Rideau Lake.

a) The correlation between DCA axis one sample scores and inferred TP values (short core). $r^2 = 0.27$, $p > 0.05$, $n = 12$.

b) The correlation between DCA axis one sample scores and inferred square-root MZ values (short core). $r^2 = 0.43$, $p < 0.05$, $n = 12$.

c) The correlation between DCA axis one sample scores and inferred TP values (piston). $r^2 = 0.89$, $p < 0.01$, $n = 13$.

d) The correlation between DCA axis one sample scores and inferred square-root MZ values (piston) $r^2 = 0.87$, $p < 0.01$, $n = 13$.

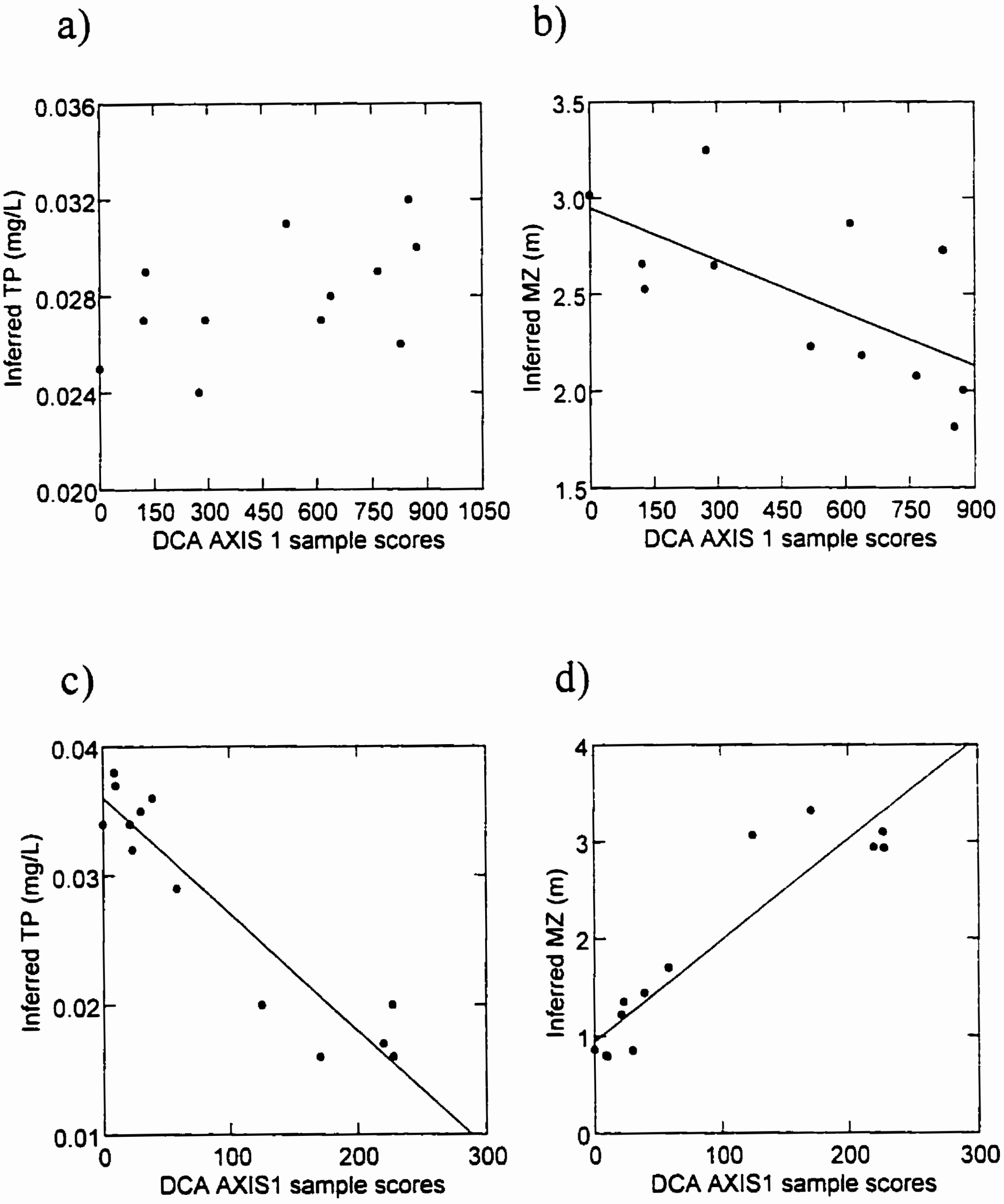
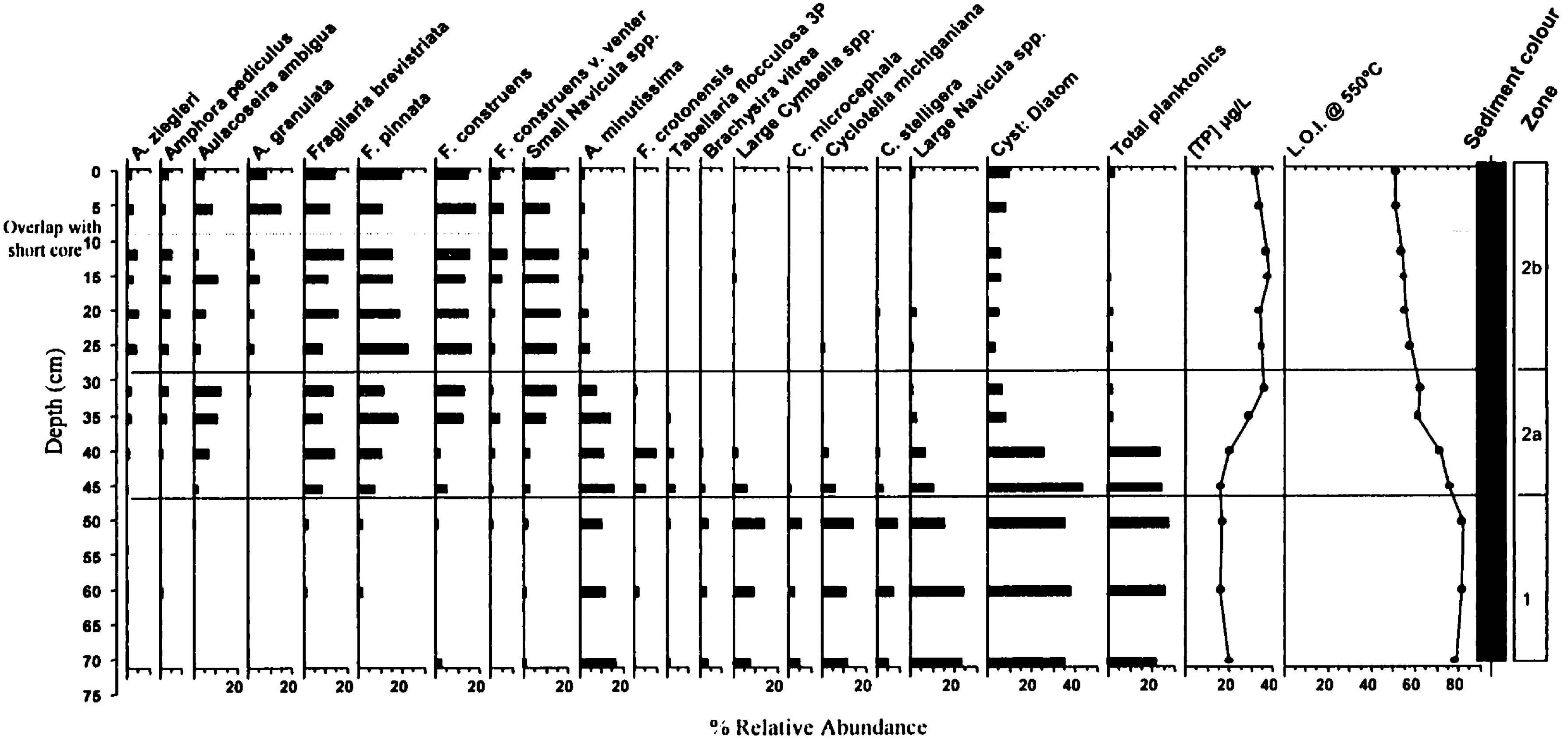

a)
b)
0.036
0.032
0.028
0.024
0.020
Inferred TP (mg/L)
0
150
300
450
600
750
900
1050
DCA AXIS 1 sample scores
3.5
3.0
2.5
2.0
1.5
Inferred MZ (m)
0
150
300
450
600
750
900
DCA AXIS 1 sample scores
c)
d)
0.04
0.03
0.02
0.01
Inferred TP (mg/L)
0
100
200
300
DCA AXIS1 sample scores
4
3
2
1
0
Inferred MZ (m)
0
100
200
300
DCA AXIS1 sample scores

Figure 4.15. Dominant diatom taxa (>3% in at least one interval), L.O.I. and cyst:diatom ratio profiles of Lower Rideau Lake (piston core). (pre-disturbance- Zone 1, historical anthropogenic disturbance - Zone 2a and 2b). Large *Navicula* species include: *N. cari, N. concentrica, N. cryptocephala, N. cryptotenella, N. densilineolata, N. diluviana, N. elginensis, N. laevissima, N. vulpina, N. wildii.* Small *Navicula* species include: *N. ignota v. palustris, N. minima, N. schadei, N. seminulum, N. vitabunda, N. submuralis, N. subrotundata.* * = extrapolated ^{210}Pb date. Dotted line indicates estimated overlap with short core.


A. ziegleri
Amphora pediculus
Aulacoseira ambigua
A. granulata
Fragilaria brevistriata
F. pinnata
F. construens
F. construens v. venter
Small Navicula spp.
A. minutissima
F. crotonensis
Tabellaria flocculosa 3P
Brachysira vitrea
Large Cymbella spp.
C. microcephala
Cyclotella michiganiana
C. stelligera
Large Navicula spp.
Cyst: Diatom
Total planktonics
[TP] µg/L
L.O.I. @ 550°C
Sediment colour
Zone
2b
2a
1
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
Overlap with short core
20
40
60
80
% Relative Abundance

Brachysira vitrea, *Cymbella cesatii*, *Cymbella microcephala* and *Cyclotella michiganiana*, and large *Navicula* species including *N. cryptotenella*, *N. densilineolata*, *N. diluviana*, *N. pupula*, and *N. vulpina* (Figure 4.15). As previously mentioned, many of these species were poorly represented in the southeastern Ontario calibration set. However, the optima of these species suggested that conditions were oliotrophic to mesotrophic [i.e., *A. minutissima* (TP opt. 16 µg/L), *Cymbella microcephala* (TP opt. 16 µg/L), *Cyclotella michiganiana* (TP opt. 14 µg/L), *Cyclotella stelligera* (TP opt. 11 µg/L), *Brachysira vitrea* (TP opt. 22 µg/L) and *N. cryptotenella* (TP opt. 16 µg/L) (Reavie and Smol, 2001)]. Van Dam et al. (1994) also described the other dominant species as oligotrophic to mesotrophic indicators. The high cyst to diatom ratio further indicated relatively unproductive conditions (Smol, 1985). According to pre-canal surveys, conditions were also known to be relatively shallow and likely unproductive at this time (pre-canal depth near Olivers Ferry ~5 m and lake is described as 'beautiful': Welch, 1979). Macrophytes were likely abundant at this time, as epiphytic taxa, such as *Cymbella microcephala* (Reavie and Smol, 1996), are in moderate abundances (Figure 4.15). Therefore, despite poor fossil representation in the southeastern Ontario model, the pre-disturbance assemblage likely represents a shallow, macrophyte-dominated, oligotrophic to mesotrophic lake.

Zone 2: Canal construction and land clearance (~1830 - 1970)

Sediment colour and microfossil changes were further subdivided into two zones: one of change 2a (~1830 - ~1860) and one of stability 2b (~1860 - ~1970). Both sediment colour and microfossil changes were observed following the estimated time of canal construction (~1830). From ~1830 to ~1860 (Zone 2a), the sediment composition decreased in estimates of organic matter (~80 - 55%), and increased in clastic content (~20 - 35%). These trends can be interpreted as increased catchment erosion (Rowan et al., 1992).

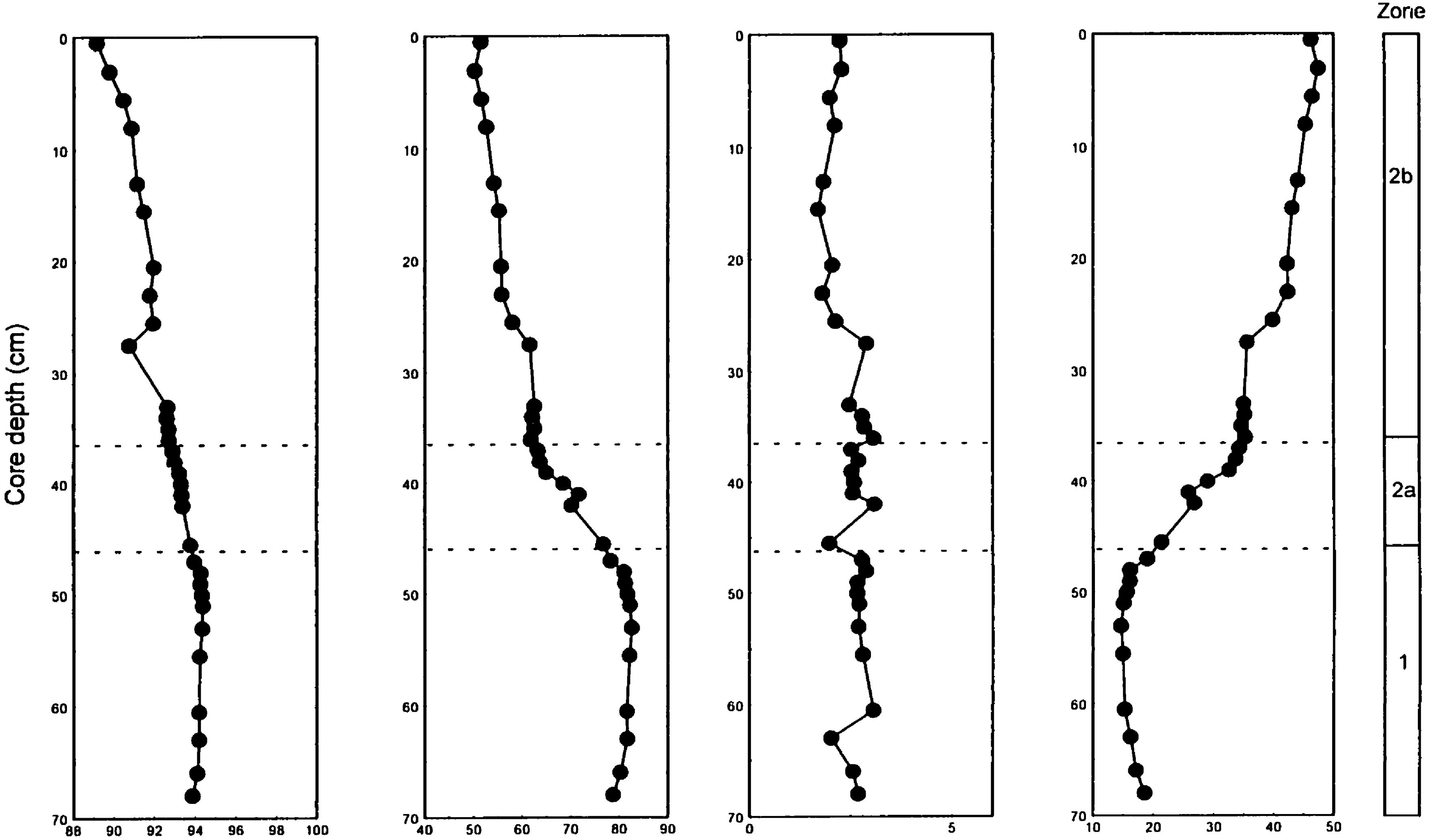
Microfossil assemblage shifts coincided with lithological changes in Zone 2a: ~1830 - ~1860. At the proposed time of canal construction (Zone 2a), there is a shift in the diatom assemblage from large benthic *Cymbella* and *Navicula* species to small benthic *Fragilaria* species and productive planktonic and tychoplanktonic species (e.g. *Aulacoseira ambigua, F. crotonensis and Tabellaria flocculosa* strain *IIIP).* As previously mentioned, *F. crotonensis* is a good indicator of eutrophication (Bradbury, 1975; Reavie et al., 1995) and low light environments (Hartig and Wallen, 1986). *Aulacoseira ambigua* and *T. flocculosa* strain *IIIP* also indicate some nutrient enrichment, with TP optima of 13 µg/L and 16 µg/L, respectively (Reavie and Smol, 2001). The presence of *A. ambigua* may also indicate high silica concentrations and increased water turbulence. This heavy planktonic genus has a high demand for silica (Round et al., 1990). Its occurrence has been suggested to be closely associated with catchment erosion (Kilham et al., 1986) or increased turbulence (Round et al., 1990), which both contribute silica to the water column. A concurrent decrease in the cyst to diatom ratio and an increase in reliable TP inferences (good fit and analogue matches) from 20 µg/L to 36 µg/L also indicate an increase in nutrients during this period. In summary, the changes in sediment composition and microfossil assemblage suggest an increase in productivity, turbidity and turbulence of the lake water.

With eutrophication, phytoplankton abundance generally increases and water clarity decreases, limiting light necessary to maintain submerged aquatic plant growth (Balls et al., 1989). In shallow lakes, increased nutrients can lead to a turbid state that is dominated by phytoplakton (Scheffer and Jeppesen, 1998). For these reasons, Lower Rideau Lake is thought to be in a turbid state at this time (further discussed in Chapter 5).

The increase in inferred productivity, turbidity and turbulent conditions coincides with canal construction and settlement activities. As part of Big Rideau Lake, Lower Rideau Lake was also flooded approximately 3 ft (0.9 m) with the initial construction of the canal in 1830 (Parks Canada, undated). Flooding of lowland areas likely increased nutrient inputs to the lake, in addition increased erosion from logging, quarrying, and settlement activities also likely contributed to the lake's eutrophication. Trees cut for canal construction were located on the edge of Lower Rideau Lake and a quarry operated on its banks (Kennedy, 1984). In terms of settlement, there were between 20 and 30 people per square mile by the time canal construction was completed (Kennedy, 1984). The population of South Elmsley also increased in size four-fold from 1830 to 1845, and wheat farming and livestock husbandry became important farming activities (Kennedy, 1984). Additionally, the water-level change also increased the surface area of the lake and therefore the fetch. These changes may have increased the wind-induced turbulence, required to maintain heavy *Aulacoseira* species in the photic zone.

The sediment colour and microfossil data were generally stable from ~ 1860 until the end of this zone (Zone 2b). The sediment changed little in colour (medium brown),

Figure 4.16. Physical characteristics of Lower Rideau Lake recent sediments (~200 years) (piston core). (pre-disturbance- Zone 1, historical anthropogenic disturbance - Zone 2).



a) % Water

b) L.O.I. @ 550ºC estimating % organic matter

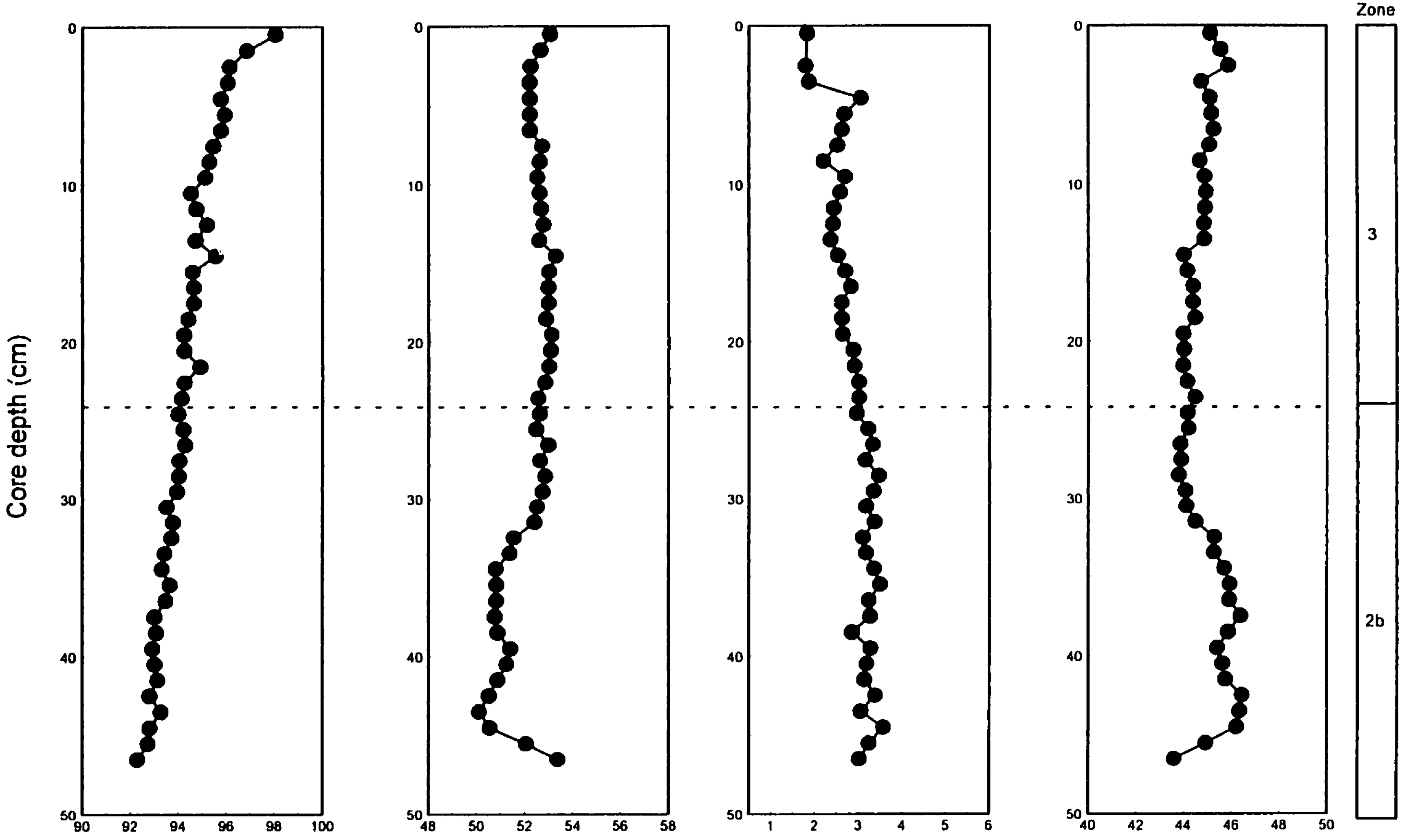
c) Weight loss after heating @ 925ºC estimating % carbonate content

d) % Clastics (remaining material)

and estimates of organic content (~50 to 55%), carbonate content (~3%) and clastic content (~40 to 45%) (Figures 4.16 and 4.17). The diatom assemblages in this zone were dominated by small benthic *Fragilaria* species (*F. brevistriata, F. pinnata, F. construens, F. construens* f. *venter*), and small productive *Navicula* species (*N. minima, N. pseudoventralis, N. schadei, N. seminulum, N. subumuralis, N. vitabunda*), and tychoplanktonic taxa, *A. ambigua* and *A. granulata* (Figures 4.18). *Aulacoseira granulata* is a well-known indicator of nutrient-rich and turbulent conditions (e.g. Kilham et al., 1986; Bennion, 1994). This zone shows little change until the ~1970s, as it remains dominated by these heavy productive *Aulacoseira* species and small benthic taxa. The decrease in abundance of planktonic taxa reflects an increase in littoral habitat or water clarity. Both of these options are possible as there was additional flooding of lowland areas in 1865 (2 ft increase in dam height; Parks Canada, undated) and the presence of benthic taxa, specifically periphyton (e.g. *A. pediculus*; Reavie and Smol, 1997) during this time indicates the water was clear enough to support benthic assemblages and macrophyte growth. However, the cyst to diatom ratio remains low during this period, also indicating productive conditions. Despite the poor fit to TP during this period, the microfossil evidence suggests that the conditions are shallow, macrophyte-dominated and meso-eutrophic.

Further flooding, mining, agriculture and early cottage development activities coincide with this period (~1860 - 1970) of increased productivity. As previously mentioned, further water-level changes likely flooded lowland areas, increasing nutrients to the lake and extended the fetch of the lake, possibly creating more turbulent conditions, ideal for *Aulacoseira* growth. Erosion from local graphite and mica mining activities

Figure 4.17. Physical characteristics of Lower Rideau Lake over the last ~200 years (short core). Historical anthropogenic disturbance - Zone 2b and recent - Zone 3 delineated.



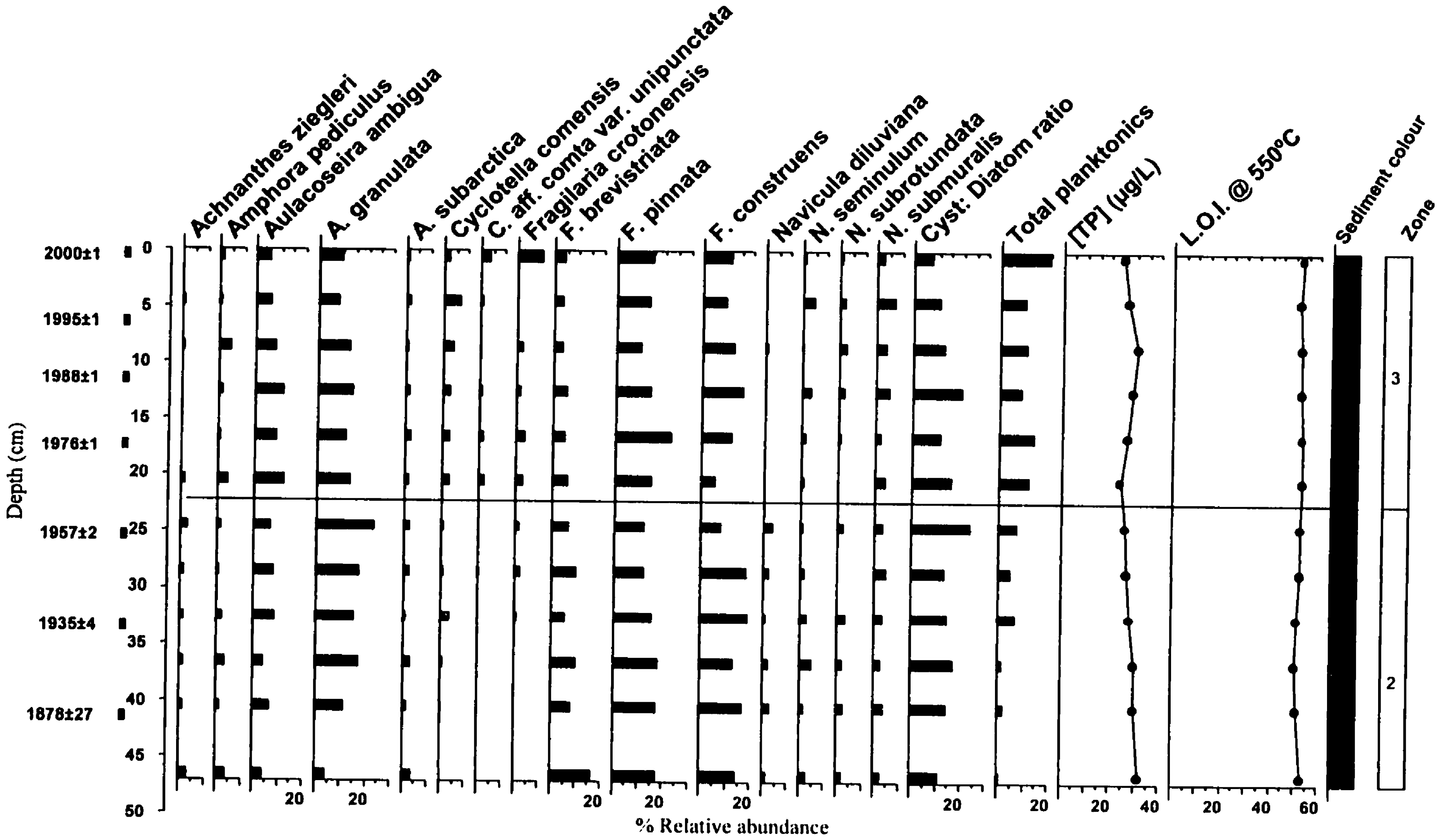
a) % Water

b) L.O.I. @ 550°C estimating % organic matter

c) Weight loss after heating @ 925°C estimating % carbonate content

d) % Clastics (remaining material)

Figure 4.18. Dominant diatom taxa (≥ 3% in at least one interval), L.O.I. @ 550°C and cyst:diatom ratio profiles of Lower Rideau Lake (short core). Maximum depth is strongly related to sum of planktonics. (historical anthropogenic disturbance - Zone 2b and recent - Zone 3 delineated).


Achnanthes ziegleri
Amphora pediculus
Aulacoseira ambigua
A. granulata
A. subarctica
Cyclotella comensis
C. aff. comta var. unipunctata
Fragilaria crotonensis
F. brevistriata
F. pinnata
F. construens
Navicula diluviana
N. seminulum
N. subrotundata
N. submuralis
Cyst: Diatom ratio
Total planktonics
[TP] (μg/L)
L.O.I. @ 550°C
Sediment colour
Zone
3
2
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
2000±1
1995±1
1988±1
1976±1
1957±2
1935±4
1878±27
20
40
60
% Relative abundance

may have also contributed nutrients from the catchment during their operation of 1870 to 1893 (Kennedy, 1984). Nutrient addition from pasture lands were also likely substantial, as dairying was an important industry in the township during these years (Chapter 2). Shoreline development increased in the early-1900s and in 1924, Lower Rideau Lake was described as having moderate cottage development along its shores (Kennedy, 1984). Therefore, despite these continued nutrient additions, the diatom assemblages remain relatively stable during this period. These stable responses are thought to reflect the clear-water state of the alternative equilibrium theory (further discussed in Chapter 5).

Zone 3: Recent era (~1970s to the present)

In the recent zone, the diatom profile continues to be dominated by taxa known to favour mesotrophic conditions, such as *A. granulata*, *A. ambigua*, *F. brevistriata*, *F. pinnata*, and *F. construens* (Figure 4.18). However, as observed in the canal lakes, *Cyclotella comensis* and *C.* aff. *comta* var. *unipunctata* become abundant ~1970. Despite their lower relative abundances, to those of the other deep study lake assemblages, their occurrence coincides with a slight decrease in TP inferences. The inferred spring TP value of 25 µg/L, however, is slightly higher than the measured spring TP value of 19 µg/L (Canadian Museum of Nature, 1999).

As previously mentioned, this recent recovery, is thought to be associated with nutrient reductions related to: 1) the decrease in use of phosphorus detergents, 2) better absorption of soils from redeveloping forests and 3) climate warming (further discussed in Chapter 5).

Otter Lake (control lake):

Chronology:

The ^{210}Pb activity profile records a typical exponential decrease in activity. suggesting that the sediment core was relatively undisturbed (Figure 4.19). Background activity (3.72 dpm/g) was reached after 25 cm in the 38.5 cm long sediment core. Using the CRS model and assuming a constant flux of ^{210}Pb activity to the sediment. the 25 - 26 cm interval was estimated as ~1830.

Ambrosia and grass pollen profiles also provide chronological information of local historical disturbances at ca. 1830. as they increase in abundance after the 24 - 24.5 cm interval (Smol. unpublished: Figure 4.19b). The rise coincides with the historical records of settlement activity surrounding Otter Lake and area in ca. 1830 (Chapter 2) (Kennedy. 1984).

Unlike the canal lakes, there were three lithological changes in the sediment core from Otter Lake, and these colour changes were different from those of the canal lakes around the time of canal construction (Figure 4.19c). Sediments changed in colour at 23 cm from dark-brown bottom sediments to pale-brown upper sediments. The second colour change occured at 10 cm. where the sediments changed from pale-brown to dark greenish-brown colour.

Microfossil and sediment analysis:

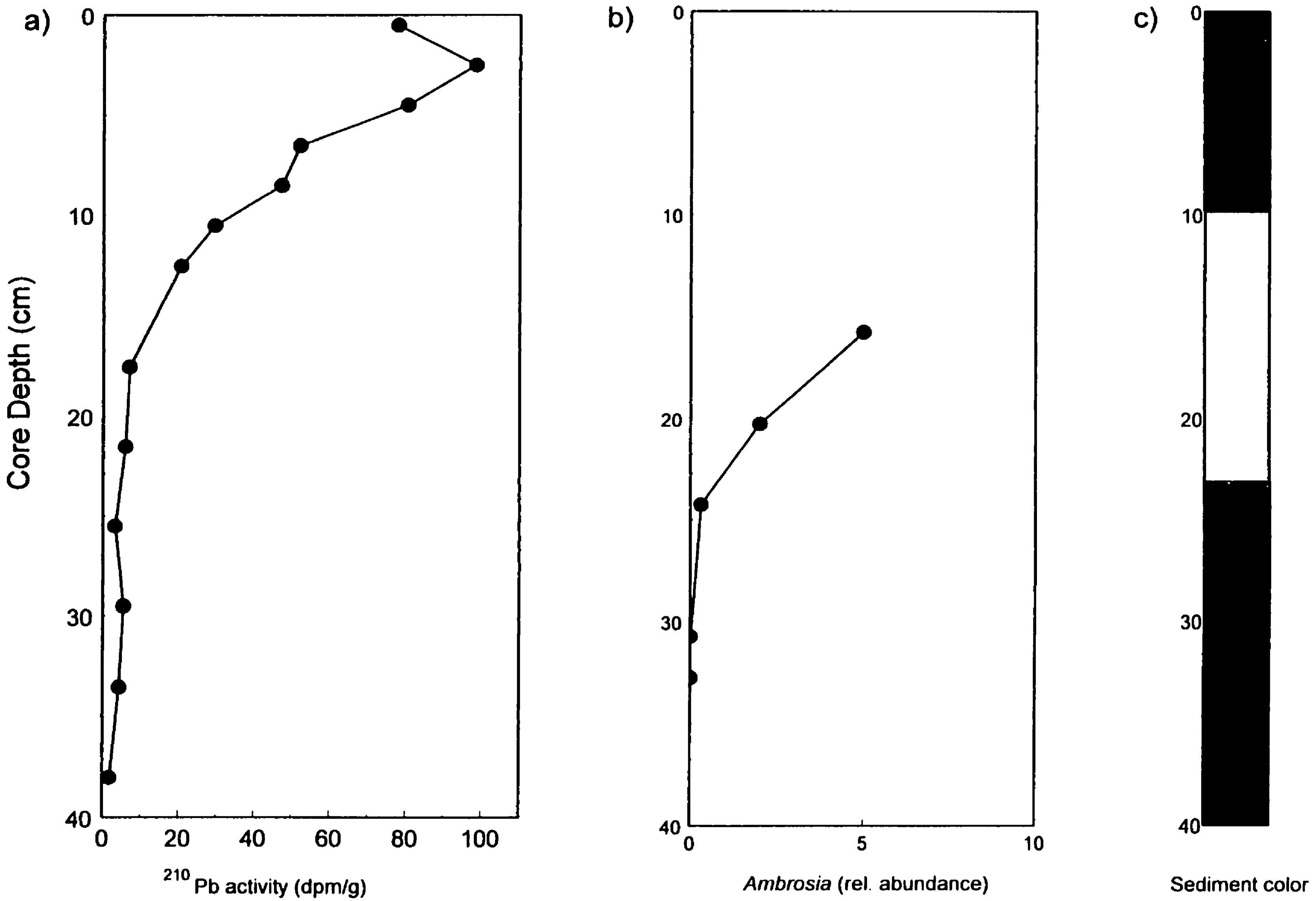
Cluster analysis, ^{210}Pb dating and *Ambrosia* pollen delineated the 38.5 cm long

Figure 4.19. Otter Lake chronology.

a) Profile of ^{210}Pb activity vs. sediment core depth.

b) Profile of *Ambrosia* pollen rise (relative abundance). Analyst: J.P. Smol.

c) Profile of sediment colour changes (from bottom to top: dark-brown to pale-brown to dark-greenish brown organic sediments).


a)
b)
c)
Core Depth (cm)
0
10
20
30
40
0
20
40
60
80
100
210 Pb activity (dpm/g)
0
5
10
Ambrosia (rel. abundance)
Sediment color

sediment core into three zones: Zone 1 is the pre-disturbance era (before ~1830) (38.5 - 25.5 cm); Zone 2 is the canal construction time period and settlement era ~1830 - 1970 (25.5 - 7.5 cm); and Zone 3 is the recent past until the present (~1970 - present) (7.5 - 0 cm). The microfossil, physical sediment characteristics and model inferences are discussed in the context of the known history of the Rideau catchment area, and specifically Otter Lake (Chapter 2).

Paleoenvironmental Reconstructions:

Despite good representation of fossil samples in the southeastern Ontario calibration model (>95%), the model performed poorly for MZ and particularly TP reconstructions. Firstly, DCA axis one sample scores were weakly related to inferred TP values and were not significant ($r^2 = 0.12$, $p = 0.27$, $n = 12$) (Figure 4.20a). Additionally, three samples (15.5 - 16, 23.5 - 24, 35.5 - 36 cm) had poor fit to TP in a constrained CCA of the SE Ontario calibration set. However, a strong relationship was found between inferred MZ values and DCA axis one sample scores ($r^2 = 0.83$, $p<0.001$, $n = 12$) (Figure 4.20b). Samples were deemed to have a good fit to MZ in a constrained CCA of the calibration set, but some samples' (15.5 - 16, 23.5 - 24, 35.5 - 36 cm) squared residual lengths were just within the 90% confidence limits (Figure 4.21d). Additionally, more than half of the fossil diatom assemblages (8 of 12 assemblages) had poor to very poor modern analogues (>95% CLs) within the calibration lake-set (Figure 4.21e). Recent diatom samples (~1965 to present; Figure 4.22) demonstrated both good fit to TP and MZ (in a constrained CCA of the SE Ontario calibration set) and had good modern

Figure 4.20. Otter Lake correlations between DCA axis one sample scores a) TP and b) square-root maximum depth (MZ) inferences.

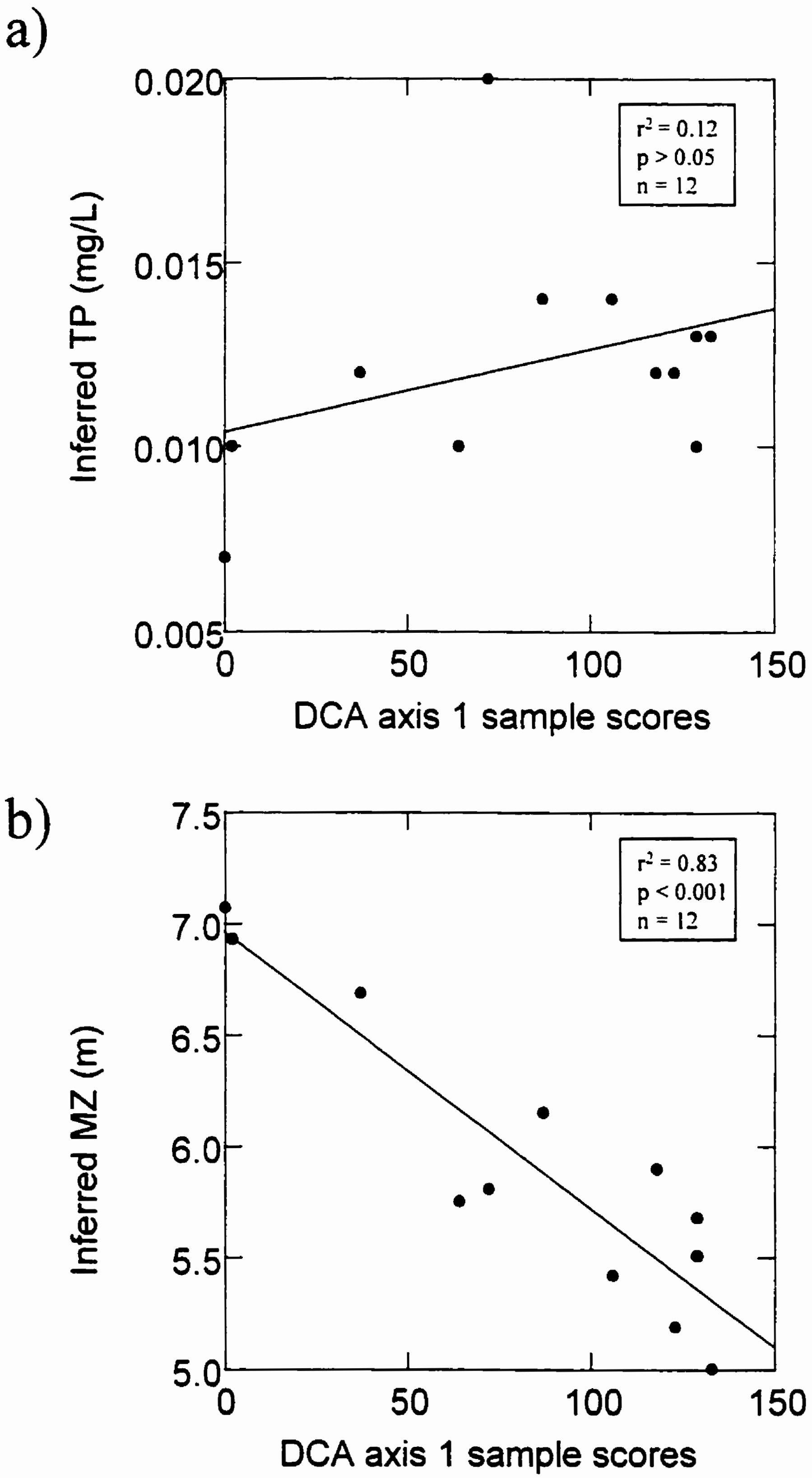

a)
0.020
0.015
0.010
0.005
Inferred TP (mg/L)
0
50
100
150
DCA axis 1 sample scores
r² = 0.12
p > 0.05
n = 12
b)
7.5
7.0
6.5
6.0
5.5
5.0
Inferred MZ (m)
0
50
100
150
DCA axis 1 sample scores
r² = 0.83
p < 0.001
n = 12

Figure 4.21. Diatom reconstructions and evaluations for Otter Lake (pre-disturbance-Zone 1, historical anthropogenic disturbance - Zone 2 and recent - Zone 3 delineated).

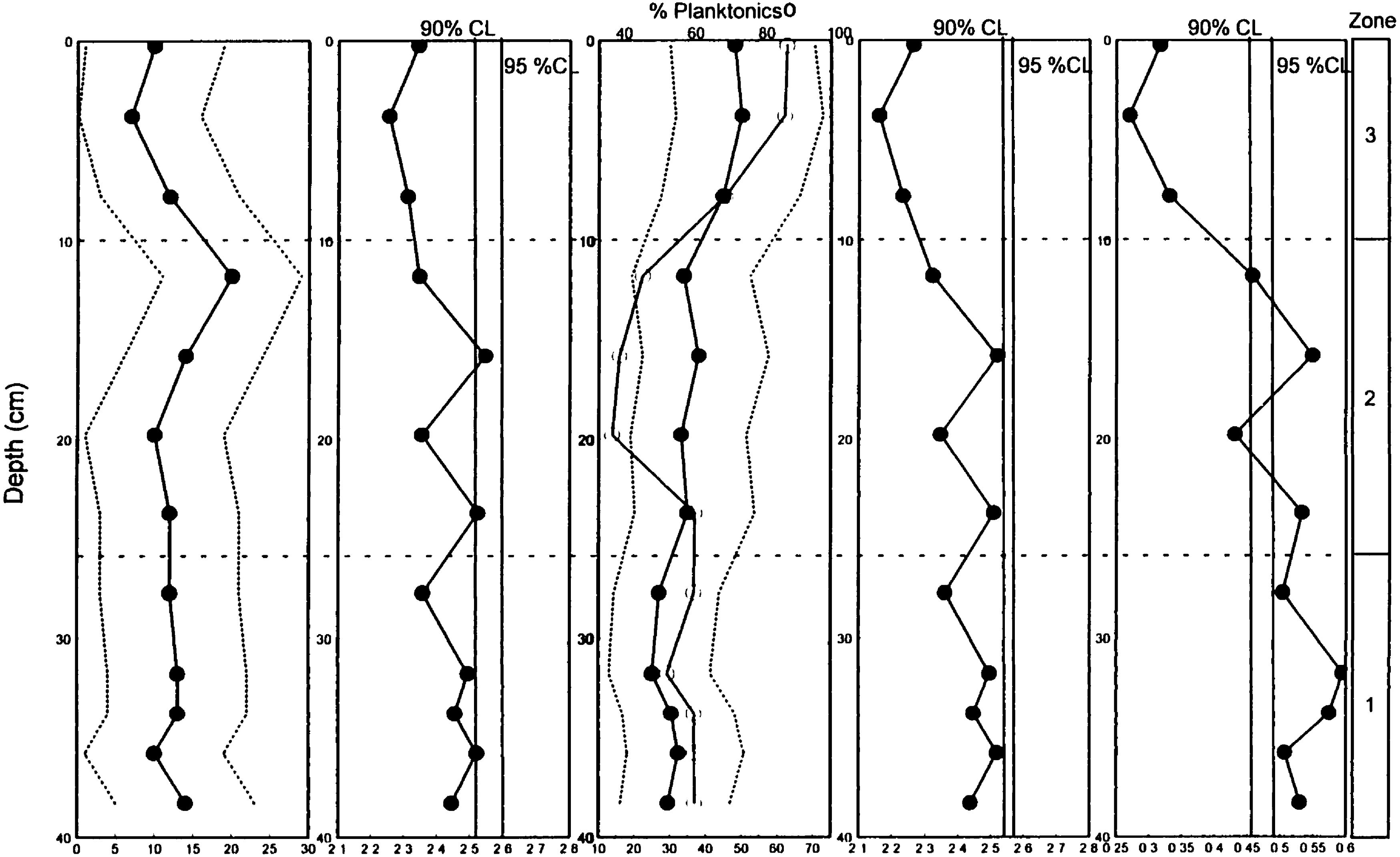
a) Diatom inferred TP reconstruction (dotted lines indicate error estimates).

b) The fit of Otter Lake fossil samples to the TP axis of calibration samples, determined through canonical correspondence analysis (CCA) constrained to TP, with passive analysis of Otter Lake samples. Lines indicate the upper and lower 90 and 95% confidence limits. Otter Lake samples with poor and very poor fit fall beyond the 90% and 95% confidence limits (CL). (diatom zones indicated).

c) Diatom inferred MZ reconstruction (dotted lines indicate error estimates).

d) The fit of Otter Lake fossil samples to the MZ axis of calibration samples, determined through canonical correspondence analysis (CCA) constrained to TP, with passive analysis of Otter Lake samples. Lines indicate the upper and lower 90 and 95% confidence limits. Otter Lake samples with poor and very poor fit fall beyond the 90% and 95% confidence limits.

e) The analogue profile indicating the strength of the match between the Otter Lake fossil samples and the S.E. Ontario calibration set samples (Reavie and Smol, 2001), using the Bray-Curtis dissimilarity coefficient. Solid lines indicate upper 90 and 95% confidence limits. Otter Lake samples falling outside of the 90 and 95% confidence limits are deemed as having poor and very poor analogues.



a) Inferred TP (µg/L) b) Fit to TP log (SRL) c) Inferred MZ (m) ● d) Fit to Max.Z log (SRL) e) ANALOG min. DC analogues with the calibration lake-set. With the exception of these more recent assemblage inferences, TP and MZ inferences were considered unreliable for most of the sediment core. For these reasons, the core will be discussed qualitatively using autoecological information available for the dominant diatom species.

Zone 1: Pre-settlement era (before ~1830)

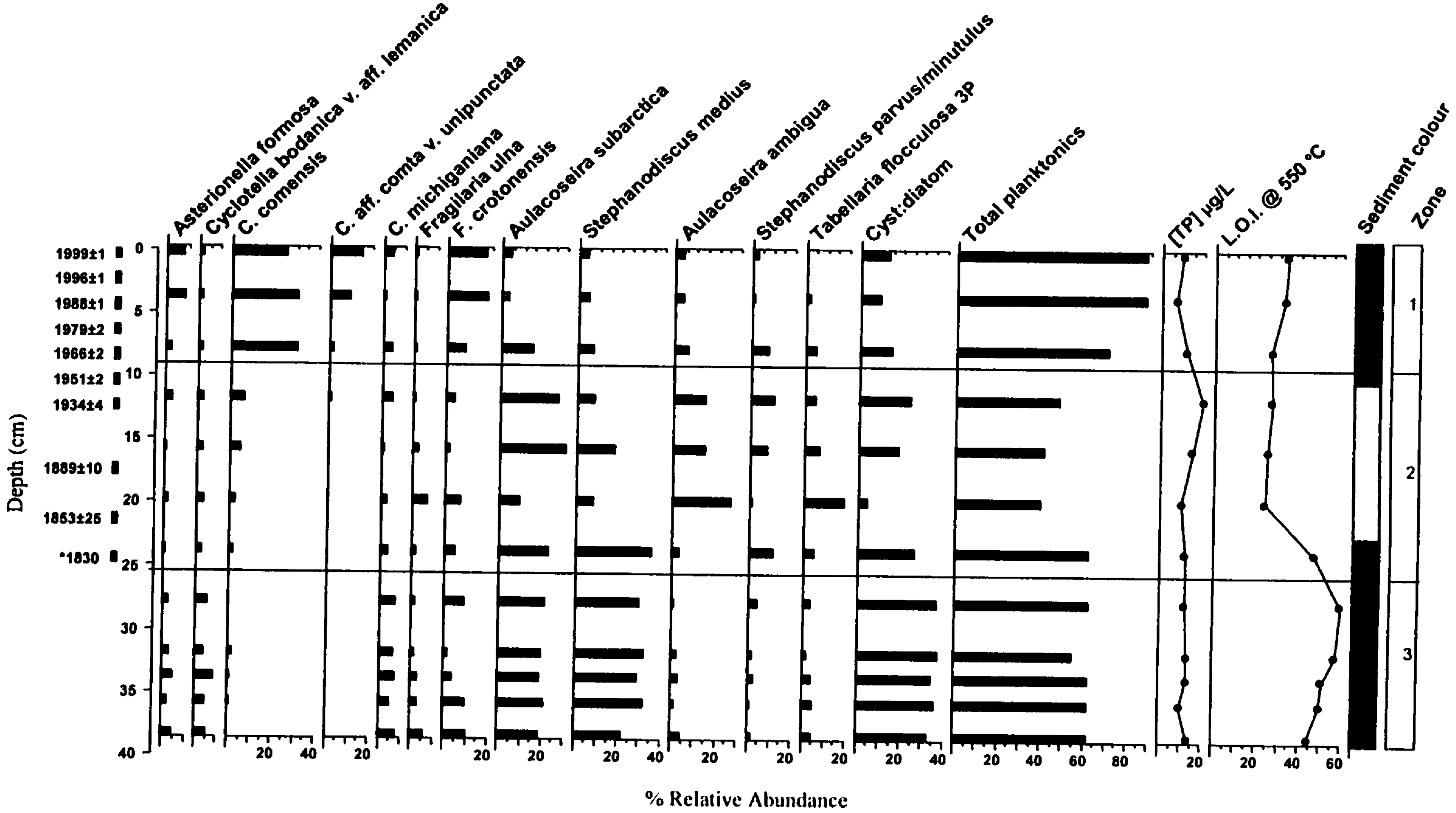
The diatom assemblages in this zone were mainly dominated by *Aulacoseira subarctica*, *Fragilaria crotonensis*, *Stephanodiscus medius*, *Cyclotella bodanica* var. *lemanica* and *C. michiganina* (Figure 4.22). The TP optima of these predominantly planktonic species suggest that the conditions were oligotrophic to mesotrophic [i.e., *Aulacoseira subarctica* (TP opt. 14 µg/L), *F. crotonensis* (TP opt. 14 µg/L), *S. medius* (TP opt. 16 µg/L), *C. bodanica* var. *lemanica* (TP opt. 11 µg/L) and *C. michiganina* (TP opt. 14 µg/L) (Reavie and Smol, 2001)]. The cyst to diatom ratio is relatively high at this time, also suggesting relatively unproductive conditions (Smol, 1985).

Zone 2: Settlement and land clearance (~1830-1970)

Sediments changed in colour from dark brown in Zone 1 to pale brown in Zone 2. From ~1840 to ~1880, there was a dramatic decrease in percent organics (~45 - 20%) and a compensatory increase in carbonate content (~5 - 25%) (Figure 4.23). These changes likely reflect increased erosion of clastics at this time due to settlement, logging and agricultural activities (Chapter 2).

The microfossil assemblage also changed around ~1830. At this time, there was

Figure 4.22. Dominant diatom taxa (≥ 5% in at least one interval), L.O.I. @ 550°C and cyst:diatom ratio profiles of Otter Lake (pre-disturbance- Zone 1, historical anthropogenic disturbance - Zone 2 and recent - Zone 3 delineated). * = extrapolated ^{210}Pb date.

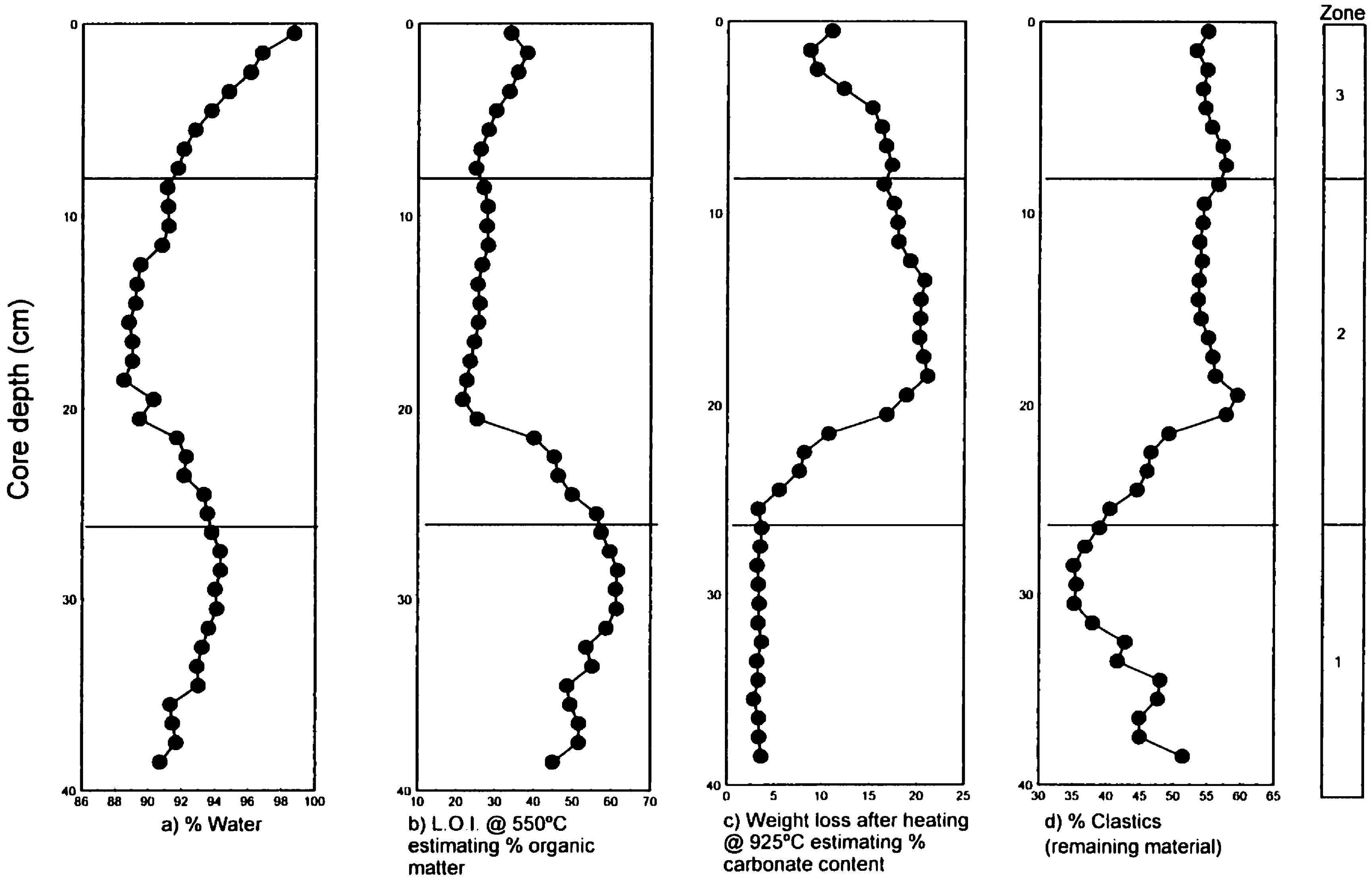

Asterionella formosa
Cyclotella bodanica v. aff. lemanica
C. comensis
C. aff. comta v. unipunctata
C. michiganiana
Fragilaria ulna
F. crotonensis
Aulacoseira subarctica
Stephanodiscus medius
Aulacoseira ambigua
Stephanodiscus parvus/minutulus
Tabellaria flocculosa 3P
Cyst:diatom
Total planktonics
[TP] µg/L
L.O.I. @ 550 °C
Sediment colour
Zone
1
2
3
Depth (cm)
0
5
10
15
20
25
30
35
40
1999±1
1996±1
1988±1
1979±2
1966±2
1951±2
1934±4
1889±10
1853±25
*1830
20
40
60
80
% Relative Abundance

an increase in *S. minutulus* and slight decrease in the cyst to diatom ratio. *Stephanodiscus minutulus* has a high requirement for phosphorus and is therefore a good indicator of eutrophication (Kilham et al., 1986). Around 1870, the heavy mesotrophic species, *A. ambigua* (TP opt. 16 µg/L), also increases in abundance. At this time, there is a compensatory decrease in less productive species, such as *A. subarctica* and *S. medius*. A further decrease in the cyst to diatom ratio provides additional evidence of nutrient enrichment (Smol, 1985).

This 19th century eutrophication coincides with settlement, agriculture and logging activities occurring in the watershed throughout this time period. There are historical reports of settlers on the north banks of Otter Lake in 1829 (Kennedy, 1984). Wheat and later dairying activities were also important in the local area in the mid-1800s (Kennedy, 1984). Logging is also known to have occurred, as there are reports of a sawmill and its intermittent operation from 1840 to 1910 on Otter Creek (Kennedy, 1984).

From the ~1880s to the 1970s, the sediment composition remains generally constant and diatom profile indicates relatively productive conditions. These sediments contained relatively low organic material (25%), and relatively high carbonate (27%) and clastic (50%) content (Figure 4.23). The eutrophic species *A. ambigua, A. subarctica, S. parvus* and *S. minutulus* continue to dominate the diatom assemblages. Nutrient inputs were likely still high at this time, as dairying, mica mining (south end of Otter Lake 1900s), railway (1912) and road construction (1921 and 1927), and lakefront development (after 1930s) are known to have been important activities in the watershed during these years (Kennedy, 1984).

Figure 4.23. Physical characteristics of Otter Lake recent sediments (~200 years). (pre-disturbance- Zone 1, historical anthropogenic disturbance - Zone 2 and recent - Zone 3 delineated).


Core depth (cm)
0
10
20
30
40
86
88
90
92
94
96
98
100
a) % Water
10
20
30
40
50
60
70
b) L.O.I. @ 550°C estimating % organic matter
0
5
10
15
20
25
c) Weight loss after heating @ 925°C estimating % carbonate content
30
35
40
45
50
55
60
65
d) % Clastics (remaining material)
Zone
3
2
1

Zone 3: Recent era (~1970s to the present)

As found in the other study lakes, there was an increase in *Cyclotella* species (i.e. *C. comensis* and *C.* aff. *comta* var. *unipunctata)* around the 1970s. There is a compensatory decrease in the eutrophic *Stephanodiscus* species, *S. parvus* and *S. minutulus*. However, the moderately productive species *Fragilaria crotonensis* and *S. medius* were also more abundant during this time. The combination of these dominant species suggests that the conditions were likely oligo-mesotrophic, and the inferred spring TP value of 10 µg/L closely matches the actual measured value of 8 µg/L (O.M.O.E., 1999, Lake Partner Program, unpublished).

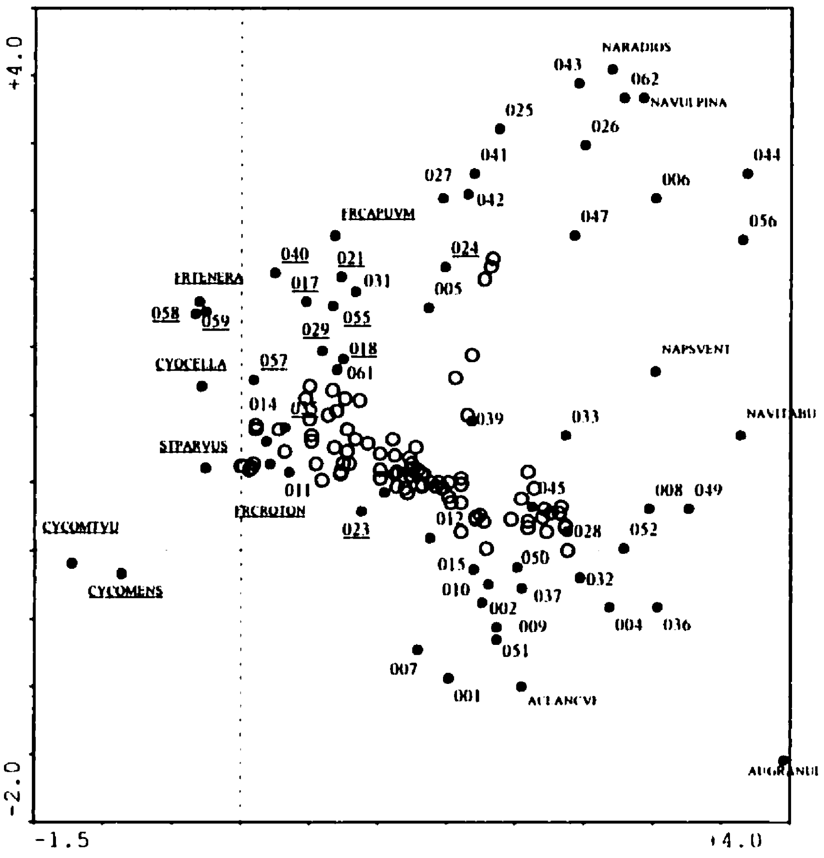
This recent recovery, as previously mentioned, is thought to be associated with nutrient reductions from 1) the decrease in use of phosphorus detergents, 2) higher absorption of soils from redeveloping forests, and 3) climate warming (Chapter 5).

ORDINATIONS OF ALL FOUR STUDY LAKES

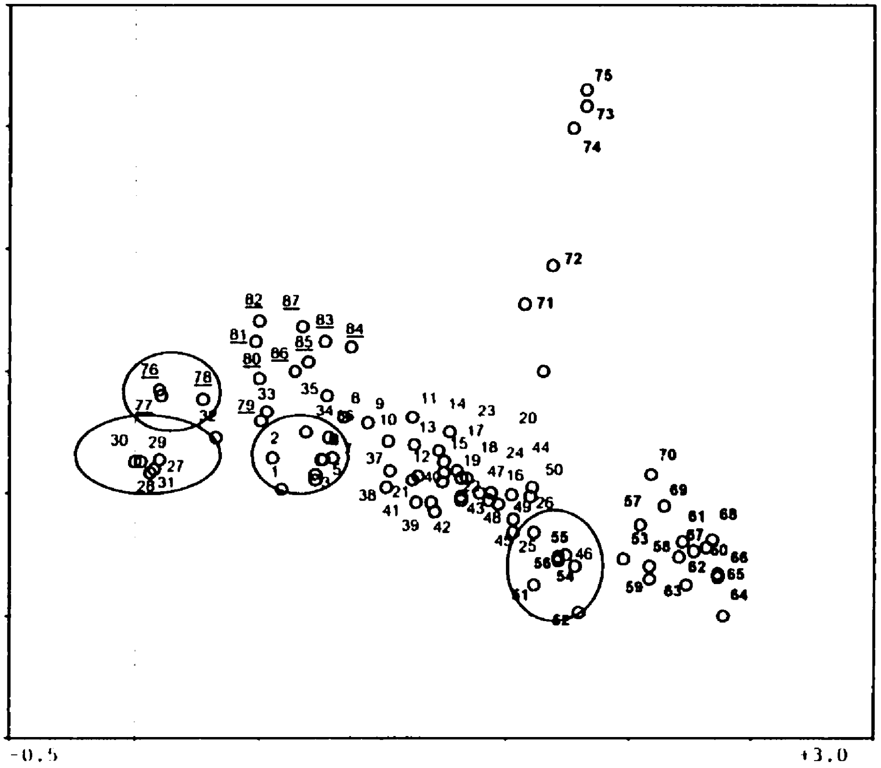
A DCA of diatom assemblage data for the four study lakes was conducted to illustrate trends in species assemblage changes over time. The variation of study lakes' fossil species scores, demonstrated in the DCA, is similar in strength along the first axis ($\lambda_1 = 2.32$) and second axis ($\lambda_2 = 2.28$), representing good separation of the species along these axis (Figure 4.24). Sample scores reflecting the study lakes' species assemblages are generally similar, clustered together in lake groups, but also along the X axis, with the exception of the older pre-disturbance assemblages (before ~1830; Zone 1) from Lower Rideau Lake (73 - 75) (Figure 4.24b). The pre-disturbance benthic assemblage is

Figure 4.24. DCA of the study lakes'
a) fossil diatom species (≥ 2% relative abundance - see Appendix B for species names) planktonic species are underlined and
b) sample intervals. Numbers correspond to lake sample intervals and increase with increasing core depth: Indian (1-26), Big Rideau (27-50), Lower Rideau (51-75 in bold), and Otter control (76-87 underlined) lakes (Recent sediment intervals (~1970 until present) are circled. Gradient length of gradient of Axis 1 = 2.32 SD and Axis 2 = 2.28 SD.

a)


+4.0
-2.0
-1.5
+4.0
NARADIOS
NAVULPINA
NAPSVENT
NAVITABU
AUGRANUL
ACLANCVI
FRCAPUVM
FRTENERA
CYOCELLA
STPARVUS
FRCROTON
CYCOMTYU
CYCOMENS
043
062
025
026
027
041
042
006
044
047
056
024
005
040
021
031
017
055
058
059
029
018
061
057
014
039
033
011
045
008
049
023
012
028
052
015
050
032
010
037
002
004
036
009
051
007
001

b)


+1.5
-0.5
-0.5
+3.0
75
73
74
72
71
82
87
83
84
81
85
80
86
76
78
79
77
30
29
27
28
31
32
33
35
34
2
1
5
3
8
9
10
11
14
23
20
13
17
15
18
24
44
37
12
19
16
50
47
38
21
40
43
48
49
26
41
39
42
45
25
55
56
46
54
51
52
70
69
67
61
68
53
58
57
62
60
66
65
59
63
64

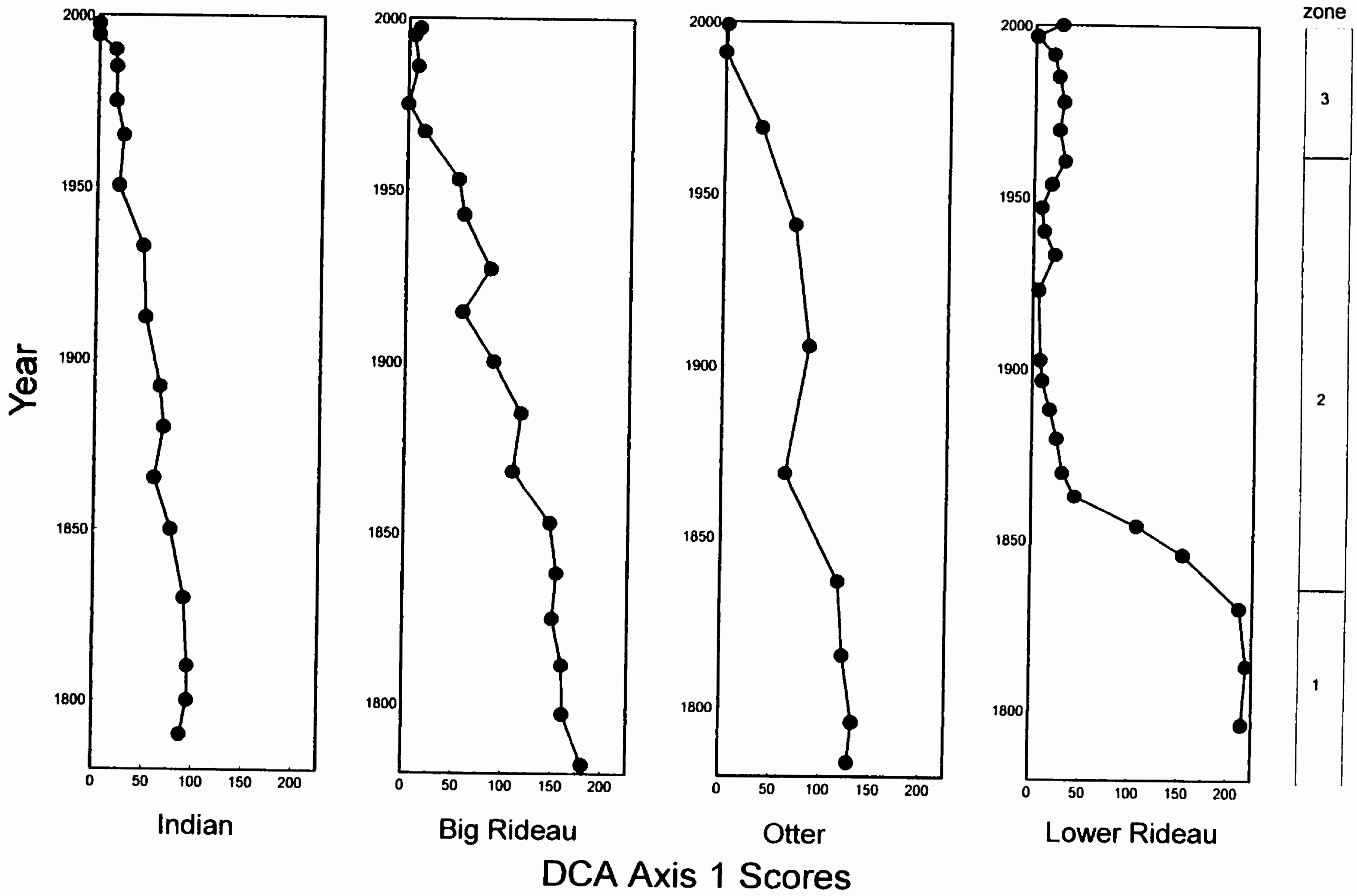
generally larger than the benthic assemblage following canal construction. This latter benthic assemblage is likely related to different water clarity and nutrient conditions created with the canal.

The ordination diagram also highlights the similarity of species assemblages across all lakes. For example, recent species assemblages (1970 to present; zone 3), with similar planktonic taxa, are generally grouped together on the left of the diagram, whereas pre-disturbance benthic taxa are generally plotted to the right of the diagram (Figure 4.24b). This shift to a more planktonic assemblage suggests that the study lakes have experienced an increase in depth, which could be initially attributed to flooding with canal construction. However, the gradual trend towards a similar planktonic oligo-mesotrophic assemblage illustrated in all the study lakes suggests that the assemblages may be tracking a variable related to depth such as water clarity.

Individual DCA axis one sample scores of all lakes over the same time period provided further insight on species assemblage changes (Figure 4.25). All of the deep lakes demonstrated a similar gradual trend in species turnover with time, suggesting a gradual change in taxon composition. However, these lakes varied in their degree of change as demonstrated by their gradient lengths: Indian 1.27, Otter 1.33, Big Rideau 1.96 SD-units (≥2% square-root transformed). All of the deep lakes, however, have experienced at least a 50% change in composition with SD-units greater than 1 (Birks, 1995).

Lower Rideau Lake, the shallow lake, demonstrated stable and abrupt changes in diatom composition and had the greatest diatom assemblage change with a gradient

Figure 4.25. Individual DCA axis one sample scores from the four study lakes over the past ~200 years.


Year
2000
1950
1900
1850
1800
0
50
100
150
200
Indian
Big Rideau
Otter
Lower Rideau
DCA Axis 1 Scores
zone
3
2
1

length of 2.19 SD-units. The stable and abrupt changes are thought to reflect the stable states and alternation of equilibrium characterized for shallow lakes (Scheffer et al., 1993). This lake is believed to have switched from the clear-water state to the turbid state at the time of canal construction and then returned back to the clear-water state (discussed in Chapter 5). Despite the return to a clear-water state, the diatom assemblage is different in composition, reflecting deeper and or more productive conditions created with canal construction. Therefore, in summary, these lakes all experienced at least a 50% change in taxon composition; however, the change in the deep lakes was more gradual and less pronounced than that of the shallow, Lower Rideau Lake. These stable and abrupt shifts in the shallow lake diatom assemblages reflect the alternative equilibria for shallow lakes.

CHAPTER 5: GENERAL DISCUSSION & CONCLUSIONS

LAKE COMPARISONS

Despite independent errors associated with ^{210}Pb dating techniques (estimating older ^{210}Pb dates; Binford, 1990) and *Ambrosia* (Long distance wind transport; Bassett and Terasmae, 1962), the combination of dating evidence (^{210}Pb dating, *Ambrosia*, and sediment colour, microfossil and physical sediment content changes) provided a defendable chronology on which to determine three zones in all the sediment cores: the pre-disturbance zone (before 1800s), an anthropogenic disturbance zone (~1830 to ~1970), and a recent recovery zone (~1970 to present). Establishment of these zones made it possible to compare trophic state responses of the four study lakes, as well as the other lakes previously studied in the Rideau Canal: Lake Opinicon (Karst and Smol, 2000), Upper Rideau Lake (Christie and Smol, 1996) and Sand Lake (Reavie et al., unpublished). The paleolimnological data of pre-disturbance conditions and historical susceptibility of these lakes to eutrophication should help lake managers set realistic targets to maintain present day oligo-mesotrophic conditions.

Pre-disturbance conditions

Prior to European settlement, all the study lakes were considered oligo-mesotrophic based on autoecological data available for the dominant diatoms. Slightly productive conditions were also observed in the pre-disturbance assemblages of other Rideau Canal paleolimnological studies (Karst and Smol, 2000; Christie and Smol, 1996; Reavie and Smol, unpublished) and some other, nearby southeastern Ontario lakes (Neill and Smol, unpublished: Christie. 1993). These findings reflect the relatively rich soils in the region. Knowledge of these background trophic conditions is important to lake managers as it can help set future, realistic mitigation targets.

Historical anthropogenic disturbance zone (~1830 to the ~1970s)

Microfossil evidence from all the study lakes recorded increased productivity around the time of European settlement and canal construction (~1830) in the area. However, the trophic state responses varied in magnitude. These differences were thought to be related to a number of variables, such as surface area-to-catchment ratio (SA:C), watershed topography (e.g. slope of catchment), and magnitude of catchment disturbances. The lakes are discussed in order of increasing SA:C: Indian 1%, Lower Rideau 4% and Big Rideau 36%. My SA:C ratios are likely underestimates for the canal lakes, as surface areas generally increased with flooding during canal construction, particularly that of Lower Rideau Lake (~2x). Nevertheless, this ratio should provide a general estimate of phosphorus export relative to catchment area (Prairie and Kalff. 1986) given similar watershed disturbances. Otter Lake had the second highest SA:C ratio of 13% but it is discussed last because it was considered the control.

Generally, the study lakes with small surface-area-to-catchment ratios experienced more pronounced changes in trophic state at the time of canal construction. Trophic responses were compared between lakes quantitatively through analysis of DCA axis one sample scores and TP inferences, and qualitatively through microfossil changes around the time of canal construction. As previously mentioned (Chapter 4), a high correlation between TP and DCA axis one sample scores suggests that TP explained some 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. Additionally, Indian Lake had a significant and moderately high correlation between inferred TP and DCA axis one sample scores ($r^2 = 0.41$, $p < 0.001$, $n = 26$). This trophic response was not surprising, as Indian Lake has a relatively small SA:C ratio (1%) and its steep-sided granite slopes likely facilitated nutrient transport to the lake. A dramatic trophic response to canal construction was previously observed in the paleolimnological study of Upper Rideau Lake, another deep canal lake within the Rideau system with a relatively low SA:C (9%) (Christie and Smol, 1996).

Lower Rideau Lake, the shallow lake, also experienced a dramatic increase in trophic state at the time of canal construction. The trophic response was illustrated by an abrupt increase in the productive planktonic species, *Fragilaria crotonensis* and *Aulacoseira ambigua*, around the time of canal construction (Figure 4.15) and the strong and significant correlation between DCA axis one sample scores and inferred TP ($r^2 = 0.89$, $p < 0.001$, $n = 13$). This lake also had a low SA:C (4%), however its catchment area was gently sloped.

The pronounced trophic response in Lower Rideau Lake was surprising as the earlier paleolimnological studies of shallow Rideau canal lakes, Sand Lake and Lake Opinicon, demonstrated only modest shifts in their diatom assemblages during this time period (Reavie and Smol, unpublished; Karst and Smol, 2000). Furthermore, Lake Opinicon had an even lower SA:C (1%), suggesting a potentially greater nutrient contribution from its watershed given similar watershed activities (Prairie and Kalff, 1986). These differences in trophic state response are, therefore, possibly related to greater nutrient contributions associated with geology and the magnitude of watershed disturbance. Lower Rideau Lake possibly received higher nutrient loads from its predominantly sedimentary catchment than the other shallow lakes with predominantly igneous bedrock catchments. Additionally, this lake potentially received greater nutrients from local and upstream watershed disturbances, as Perth (upstream) was a thriving settlement at the time of canal construction (Chapter 2).

The deep, Big Rideau Lake recorded a dampened trophic state response at the time of canal construction. The cyst to diatom ratio decreased indicating an increase in nutrients; however, productive planktonic species (i.e. *F. crotonensis* and *S. parvus/minutulus)* only slightly increased in abundance (Figure 4.9). This lake had a significant but small correlation between DCA axis one samples scores and inferred TP ($r^2 = 0.29$, $p < 0.05$, $n = 15$) around the time of canal construction. This minor trophic response was likely related to its relatively large SA:C ratio (36%) and gentle sloping catchment area. Despite major watershed disturbances (Chapter 2), 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). However, this lake could not be compared quantitatively, as there were generally poor analogue matches between the calibration model and this lake's diatom assemblages (Figure 4.22). Qualitatively, there was an increase in productivity demonstrated by a decrease in the cyst to diatom ratio and an increase in the eutrophic indicators, *Aulacoseira ambigua* and *Stephanodiscus parvus/minutulus*. This lake has a moderate SA:C (13%), a gentle to steeply sloping catchment, and experienced moderate disturbances during this period (~1830) (Chapter 2). 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 seemed to be mostly related to their surface area-to-catchment ratios.

Anthropogenic impact in the early 1900s

The abundance of productive diatom taxa and increased inferred TP values (except for Otter Lake which has uncertain TP inferences because of poor analogues) generally peaked or stabilized in all of the deep lakes in the early-1900s (~1930s). This eutrophication coincided with early cottage development, dairy farming and mica mining activities (Chapter 2). However, the diatom assemblages in the shallow Lower Rideau Lake remained dominated by small benthic *Fragilaria* and *Navicula* species during this time, suggesting little change in productivity. The stable response of Lower Rideau Lake during this period likely reflects the clear-water, macrophyte-dominated state of the alternative equilibrium theory for shallow lakes (discussed later).

Recent trophic state inferences (~1970s until present)

The recent recovery zones (~1970 - present) in the three deep lakes were dominated by taxa representing oligo-mesotrophic conditions. These trophic conditions are surprisingly similar to those found 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) appears to be improving the lakes' trophic state conditions.

The distribution of the two planktonic species, *Cyclotella comensis* and *C.* aff. *comta* var. *unipunctata*, 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 (Neill et al., unpublished; Christie, 1993; Hall, 1993), Lake Erie (Stoermer et al., 1996), in a N.W.T. lake, Canada (Rühland, unpublished) and in a subarctic lake in Finnish Lapland (Sorvari and 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 phophorus loading controls in the early 1970s (Stoermer et al., 1996). Zebra mussels were first noticed in the downstream section of the Rideau River near Ottawa in 1990 (Martel, 1995) and have been identified in Lower Rideau Lake 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 (Chaisson et al., unpublished). The decrease in use of phosphate detergents is probably, at least in part, 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* sp. were first observed ~1950). Additionally, other paleolimnological studies of lakes within the immediate area with no cottage development have experienced a similar shift to these less productive conditions (Neill et al., unpublished). Improvement of nutrient retention in soils of 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 have been abandoned since the 1950s (Warren, 1997). 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).

Sorvari and Korhola (1998) attributed a rise in abundance of *Cyclotella comensis* to climate change, as it coincided with increases in mean annual temperatures in the area since the Little Ice Age (~1860-1880 until present). Local anthropogenic disturbances were ruled out, as the lake is remotely located and there were no disturbances in its catchment. Additionally, atmospheric pollution was not considered to be directly related to the shift, as the diatom change pre-dates any potential sources.

Using similar reasoning, the increase in these *Cyclotella* species in my lakes may be related to longer periods of stratification associated with climate warming. Schindler et al. (1996) observed recent (last 30 years) increases in thermocline depths (1 - 1.5 m) and argued that these occurrences were related to climate warming. An increase in depth of the epilimnion may promote the growth of these planktonic *Cyclotella* species. Recent increases in temperature might also cause shallower lakes to stratify and develop a more suitable epilimnion habitat for *C. comensis*. This reasoning may explain the recent occurrence of *C. comensis* in Lower Rideau Lake and other shallow lakes in Ontario (Chaisson, unpublished). However, despite the uncertainty associated with *Cyclotella* increases, these recent diatom assemblages are indicating oligo-mesotrophic conditions.

ALTERNATIVE EQUILIBRIUM THEORY AND LOWER RIDEAU LAKE

The alternative equilibrium theory describes an equilibrium between two stable states in shallow lakes: a turbid state and a clear state (Scheffer et al., 1993). In the turbid state, light conditions are insufficient to support macrophyte growth and planktonic algae dominate, whereas in the clear-water state, macrophytes dominate. Both states are believed to have natural buffers maintaining their conditions, however macrophyte growth and turbidity appear to play a pivotal role in the equilibria (Scheffer, 1998).

Prior to canal construction, the diatom assemblages in Lower Rideau Lake suggest that conditions were oligo-mesotrophic (Chapter 4) and that the lake supported macrophytes, as benthic diatoms and epiphytic taxa dominate (e.g. *Cymbella microcephala;* Reavie and Smol, 1997). Therefore, the lake is thought to have been in a clear-water, macrophyte-dominated state. Around the estimated time of canal construction, there is an increase in the more productive and planktonic species, *Fragilaria crotonensis* and *Tabellaria flocculosa* strain *IIIp*. This inferred increase in nutrient concentrations coincides with increased erosion from watershed disturbance and increased water levels (~1 m), retention time, and wind-induced mixing (increased surface area with flooding) associated with canal construction (Chapter 4). The combination of these disturbances are thought to have shifted the lake to a turbid state. In support, a Swedish shallow lake, Lake Tamaren, also demonstrated a switch from a clear to a turbid state following 0.5-m increase in water-level associated with dam construction (Wallstein and Forsgren, 1989).

Following the ~1860s, Lower Rideau Lake is thought to have returned to the clear-water state (similar to pre-canal conditions) once again supporting macrophyte growth. The productive and planktonic diatom species disappeared from the diatom record, and the assemblages became dominated by a benthic community with some species known to colonize macrophytes (e.g. *Amphora pediculus*; Reavie and Smol, 1997). This increase in periphyton indicates an increase in water clarity necessary to support macrophyte growth and an increase in macrophyte abundance. The decrease in the sum of planktonic taxa, or relative increase in benthic taxa in this period, compared to that of the pre-disturbance conditions, likely reflects the increased littoral habitat 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). This periphytic assemblage remains dominant until present-day clear-water, macrophyte-dominated conditions. The mechanism for this second switch between states is, however, uncertain. A reversion back to the clear-water, macrophyte-dominated state is perhaps related to decreased erosion from the catchment (% organic matter stabilizes; Figure 4.16), once again creating favorable light conditions for benthic diatoms and macrophyte growth.

Unlike the deep lakes' diatom assemblages that demonstrated increases in productive taxa in the 1930s, the diatom assemblages in the shallow lake remained relatively stable during this time. A similarly, 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 and Smol, 2000; Little and Smol, 2000). As argued by Karst and 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. However, the abundance of macrophyte growth throughout the turbid state is uncertain and the continued presence of the small *Fragilaria* species throughout both the turbid and recent clear water state is interesting. Schelske et al. (1999) previously recorded these small *Fragilaria* species in the turbid, unvegetated state of a shallow lake in Florida. The turbid state in the Florida lake was further illustrated in lake sediment by low total carbon to total nitrogen ratios (TC:TN), as this TC:TN ratio is generally smaller in phytoplankton-dominated versus macrophyte-dominated lakes. Further analysis of the TC:TN ratio in the sediment throughout this time period would better characterize macrophyte versus phytoplankton abundance during the turbid state in Lower Rideau Lake. In summary, Lower Rideau Lake is believed to have experienced both a clear-water macrophyte-dominated state and a turbid-productive state over the past ~200 years. Macrophytes have likely played an important role in maintaining present day water clarity and nutrient conditions.

MODEL EVALUATIONS

TP Model Evaluation

Generally, direct comparisons between diatom-inferred TP values and recent lakewater TP measurements were similar in all the deep lakes (Indian, Big Rideau, Otter lakes). This illustrates the general strength of the diatom inference technique. However, analogue matching and fit to TP were poor in the pre-disturbance assemblages of all the study lakes, and most of the assemblages from Otter Lake. Further expansion of the calibration set for southeastern Ontario would perhaps improve analogue matching and strengthen the reliability of the TP inferences.

The TP model did not perform as well in reconstructing TP for the shallow, Lower Rideau Lake. The recent inferred value for TP was slightly overestimated (inferred TP = 25 µg/L, actual TP = 19 µg/L in 1999; Canadian Museum of Nature, unpublished). Overestimations have previously been related to high relative abundances of *F. 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 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). Changes in these taxa are likely more related to habitat availability and structure than open water nutrient concentrations (Bennion et al., 2001). Sampling more lakes and thereby including more taxa in the transfer functions may overcome these inference problems.

Maximum Depth Reconstruction

Despite the moderate strength of the maximum depth model ($r^2 = 0.55$; RMSE = 1.05 m; $r^2_{boot} = 0.38$; $RMSE_{boot} = 1.49$ m) (Reavie and Smol. 2001). maximum depth inferences were highly correlated to the main direction of variation (DCA axis one sample scores) for the fossil species in all the study lakes. Maximum depth values were also strongly related to the abundance of planktonic taxa (Appendix D). Therefore. gradual increases in productive planktonic taxa were thought to reflect a decrease in water clarity and littoral habitat, as water levels have generally been maintained since canal construction (Chapter 2). Many investigators have previously implicated light as an important variable influencing the composition of the periphyton community with depth gradients (Lowe. 1996). therefore maximum depth inferences in relation to water clarity should be further investigated.

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 appeared to be oligo-mesotrophic prior to European settlement. Nutrient loading increased with human activities; however, the magnitude of the trophic state response varied and seemed to be related to a number of variables. but especially the SA:C ratios and the magnitude of catchment disturbance. Otter Lake, the 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. Regional recovery from eutrophication in the last ~30 years is evident in all of the study lakes. This recovery was thought to be related to the mitigation of phosphate detergents, improved soil nutrient retention of secondary growth forests, and possibly climate warming.

The trophic responses of Lower Rideau Lake, support the alternative equilibrium theory. The lake is thought to have maintained a clear-water state despite past anthropogenic disturbances with the exception of canal construction. During the canal construction period, the lake demonstrates a dramatic increase in productivity, likely switching the lake to the turbid state. As conditions are believed to be unvegetated in this state, further sedimentary analysis (e.g. TC:TN ratio) would confirm this speculation. Nevertheless, macrophytes have likely played an important role in maintaining water clarity and nutrient uptake in Lower Rideau Lake.

The work presented in this thesis also raises a number of questions that warrant further investigation. Despite the apparent negligible limnological effects from the canal proper, the indirect impact of dramatic water-level draw-downs in reservoir lakes for the canal could be assessed. The ecology of *Cyclotella comensis* and *C. comta* v. *unipunctata* need to be further characterized to determine their possible roles in climate warming. Additionally, maximum depth inferences were thought to be related to water clarity and littoral habitat; this interpretation deserves further exploration. Nevertheless, this paleolimnological study provided past (~200 years) trophic patterns of the four study lakes, which will help lake managers set realistic mitigation targets to sustain the health of these lakes and the future of the Rideau Canal system.

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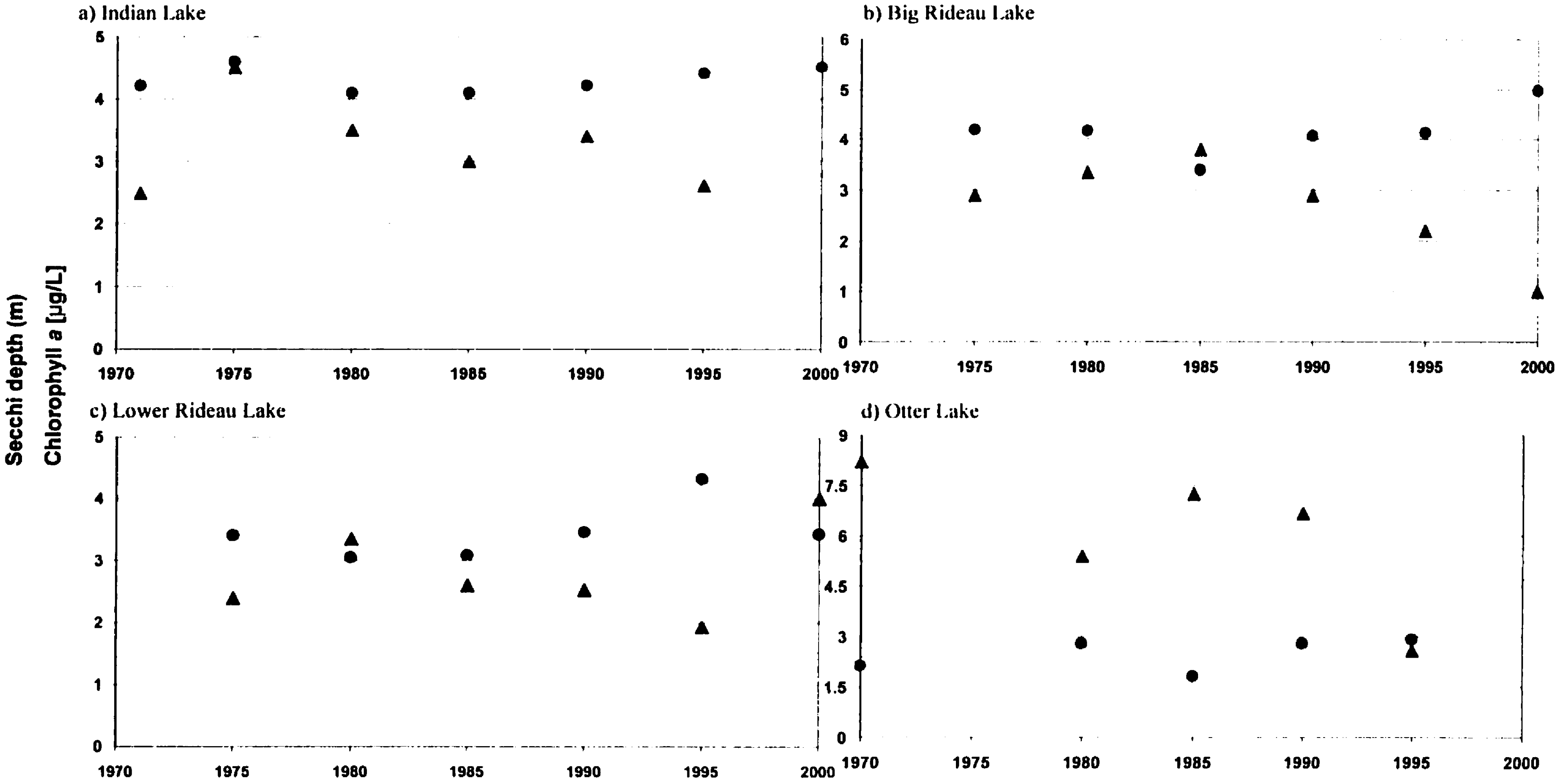
Appendix A. Historical Secchi● and Chl. *a*▲ for study lakes (1970 - 2000) (averaged over 5 year periods).

(Data compiled from the Ontario Ministry of the Environment, unpublished data; Canadian Museum of Nature, unpublished data).



Appendix B. Species code list for tilia and ordination diagrams (p = planktonic species).

#	Code	Species		#	Code	Species	
1	ACCLEVEI	*Achnanthes clevei*		32	FRCONSTR	*Fragilaria construens*	
2	ACCONSPI	*Achnanthes conspicua*		33	FRCONSVV	*Fragilaria construens* f *venter*	
3	ACLANCVF	*Achnanthes lanceolata* var *frequentissima*		34	FRCROTON	*Fragilaria crotonensis*	p
4	ACLANCVR	*Achnanthes lanceolata* var *rostrata*		35	FRNANANA	*Fragilaria nanana*	p
5	ACMINUTI	*Achnanthes minutissima*		36	FRPARASI	*Fragilaria parasitica*	p
6	ACROSENS	*Achnanthes rosenstockii*		37	FRPINNAT	*Fragilaria pinnata*	
7	ACSUCHLA	*Achnanthes suchlandtii*		38	FRTENERA	*Fragilaria tenera*	p
8	ACZIEGLE	*Achnanthes ziegleri*		39	FRTINY	*Fragilaria brevistriata* var #1 SLR	
9	AMINARIE	*Amphora inariensis*		40	FRULNA	*Fragilaria ulna*	p
10	AMPEDICU	*Amphora pediculus*		41	NACEPHLA	*Navicula cryptocephala*	
11	ASFORMOS	*Asterionella formosa*	p	42	NACRELLA	*Navicula cryptotenella*	
12	AUAMBIGU	*Aulacoseira ambigua*		43	NADENSI	*Navicula densilineolata*	
13	AUGRANUL	*Aulacoseira granulata*		44	NADILUVI	*Navicula diluviana*	
14	AUSUBARC	*Aulacoseira subarctica*		45	NAMINIMA	*Navicula minima*	
15	CONEOTHU	*Cocconeis neothumensis*		46	NAPSVENT	*Navicula pseudoventralis*	
16	COPLACVE	*Cocconeis placentula* var. *euglypta*		47	NAPUPULA	*Navicula pupula*	
17	CSTTHOLI	*Cyclostephanos tholiformis*	p	48	NARADIOS	*Navicula radiosa*	
18	CYBODAVL	*Cyclotella bodanica* var aff *lemanica*	p	49	NASCHADE	*Navicula schadei*	
19	CYCOMENS	*Cyclotella comensis*	p	50	NASEMINU	*Navicula seminulum*	
20	CYCOMTVU	*Cyclotella* aff *comta* var. *unipunctata*	p	51	NASUBMUR	*Navicula submuralis*	
21	CYMICHIG	*Cyclotella michiganiana*	p	52	NASUBROT	*Navicula subrotundata*	
22	CYOCELLA	*Cyclotella ocellata*	p	53	NAVITABU	*Navicula vitabunda*	
23	CYPSSTEL	*Cyclotella pseudostelligera*	p	54	NAVULPIN	*Navicula vulpina*	
24	CYSTELLI	*Cyclotella stelligera*	p	55	STALPINU	*Stephanodiscus alpinus*	p
25	CYCESATI	*Cymbella cesatii*		56	STBINDVO	*Stephanodiscus binderanus*	p
26	CYMFALAI	*Cymbella falaisensis*		57	STHANTZS	*Stephanodiscus hantzschii*	p
27	CMMICROC	*Cymbella microcephala*		58	STMEDIUS	*Stephanodiscus medius*	p
28	FRBREVIS	*Fragilaria brevistriata*		59	STMINUTU	*Stephanodiscus minutulus*	p
29	FRCAPUVG	*Fragilaria capucina* var *gracilis*	p	60	STPARVUS	*Stephanodiscus parvus*	p
30	FRCAPUVM	*Fragilaria capucina* var *mesolepta*	p	61	TAFLOC3P	*Tabellaria flocculosa* IIIP	p
31	FRCAPUVV	*Fragilaria capucina* var *vaucheriae*	p	62	ANVITREA	*Brachysira vitrea*	p

Appendix C. Indian Lake ≥ 2% relative abundance of diatom taxa.

Taxa	Mid point of 1 cm interval												
	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5
ACCONSPI	0.26	0.78	1.08	0.59	0.87	0.86	1.30	0.46	0.00	1.60	1.37	1.39	0.87
ACLANCVF	3.38	0.00	0.22	0.00	0.29	0.58	0.00	0.46	0.00	0.00	0.68	0.83	2.02
ACMINUTI	0.00	2.07	4.97	5.57	2.03	3.75	4.87	7.36	3.83	2.93	2.74	3.89	2.89
ACSUCHLA	0.27	0.26	0.00	0.00	0.29	0.00	0.97	0.00	0.26	0.53	1.03	0.56	0.87
AMPEDICU	0.27	0.00	0.86	0.00	1.74	0.29	0.00	0.92	1.79	1.60	0.00	0.83	0.00
ASFORMOS	4.16	2.84	3.67	7.33	1.74	6.92	2.60	5.06	4.08	5.33	2.74	5.28	4.91
AUAMBIGU	3.64	7.75	4.97	3.52	3.78	4.03	5.52	5.75	6.12	8.00	14.38	5.00	2.89
AUSUBARC	10.62	16.54	12.10	7.92	7.56	11.82	10.39	10.34	10.46	6.93	5.82	8.61	7.23
CONEOTHU	0.00	0.00	0.65	1.76	0.29	1.44	0.65	0.23	0.26	0.53	1.71	0.83	0.58
CYCBODVL	0.53	2.33	1.73	2.35	1.16	0.86	0.65	2.30	1.28	0.80	2.40	2.50	3.47
CYCOMENS	26.68	26.10	18.57	17.01	11.34	8.93	6.82	2.76	0.51	0.53	0.00	0.28	0.29
CYCOMTVU	7.77	8.27	14.25	2.35	8.14	3.17	2.92	0.23	0.77	0.00	0.00	0.00	0.00
CYMICHIG	3.37	2.58	4.32	2.64	3.78	4.03	3.25	3.45	4.34	1.87	2.74	0.56	0.58
CYOCELLA	2.59	0.52	0.65	0.59	0.87	2.02	0.00	0.23	0.26	0.53	0.00	0.00	0.00
CYPSSTEL	8.55	2.58	3.02	3.52	2.03	1.73	2.92	2.30	0.77	1.07	1.37	1.39	3.76
FRBREVIS	0.50	0.00	0.86	0.29	1.74	1.44	0.65	2.07	0.51	4.53	2.05	0.00	0.29
FRTINY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.00	0.00	0.00
FRCAPUVV	0.00	0.78	0.86	1.47	1.74	0.58	1.95	0.00	3.06	1.87	1.37	0.00	0.58
FRCAPUVG	0.00	0.26	0.00	0.88	0.00	1.44	2.92	0.69	2.04	2.93	4.11	1.11	1.73
FRCROTON	8.29	7.24	2.59	12.32	20.35	10.37	16.56	14.71	14.03	19.73	17.12	14.44	20.81
FRNANANA	1.55	0.78	0.00	0.88	0.87	2.31	0.00	1.84	0.26	0.53	0.00	0.56	0.87
FRPINNAT	1.25	0.78	2.81	3.52	3.78	1.73	3.25	3.91	3.83	3.20	1.71	8.33	16.47
FRCONSTR	4.00	1.03	6.26	2.05	2.91	2.31	0.00	1.15	0.51	2.13	0.68	11.39	2.89
FRCONSVV	0.75	0.00	0.00	0.00	0.00	0.00	0.32	0.92	4.34	1.60	3.08	0.00	0.58
FRTENERA	0.26	1.03	0.00	3.23	0.00	0.58	0.00	1.38	0.26	0.53	0.00	0.83	0.00
NAMINIMA	0.00	0.00	0.43	0.00	0.00	0.86	0.00	0.23	0.51	1.60	1.37	0.00	1.73
NAPSEUDO	0.00	0.26	0.00	0.59	0.00	0.58	0.65	0.00	0.51	0.27	1.03	0.00	1.16
NASCHADE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.46	0.00	0.00	0.00	0.00	0.29
NASEMINU	0.00	0.43	0.22	1.47	1.16	0.29	0.32	0.92	1.79	1.60	2.74	1.94	1.45
NASUBROT	0.00	0.86	0.00	0.00	0.00	0.00	0.00	0.00	0.26	1.60	0.00	0.56	0.00
NASUBMUR	0.00	0.26	0.86	0.88	0.00	1.44	0.32	1.38	2.81	1.60	3.42	0.56	2.89
STPARVUS	0.79	1.03	1.81	1.47	3.71	8.65	4.87	9.20	5.61	5.60	2.40	3.06	1.45
STMINUTU	0.26	0.52	0.78	0.59	1.24	0.58	1.95	0.46	1.28	1.07	1.71	0.83	2.02
STHANTZS	0.26	0.52	0.86	1.17	3.78	1.15	4.55	1.61	3.57	1.07	1.71	1.94	0.58
STMEDIUS	0.26	1.29	0.65	1.47	1.74	0.86	1.62	1.15	3.06	2.40	0.68	0.83	0.58
TAFLOC3	1.04	0.78	0.65	1.17	1.16	3.17	2.27	4.60	3.57	1.87	3.08	1.94	1.16
Cyst:diatom	8.96	10.62	23.47	12.34	9.95	10.80	11.49	16.18	16.95	22.68	21.08	24.37	24.45
Total	91.30	90.44	90.71	88.56	90.12	88.76	85.06	88.51	86.48	88.53	85.27	80.28	87.86
LOI @ 550C	53.5	48.8	46.4	45.2	44.6	44	42.4	41.2	40.6	40.4	39.5	39.1	37.7
[TP] ug/L	12	13	16	15	17	21	21	21	22	22	21	20	21

Appendix C (cont'd). Indian Lake ≥ 2% relative abundance of diatom taxa.

Taxa	Mid point of 1 cm interval												
	13.5	14.5	15.5	16.5	17.5	18.5	20.5	22.5	26.5	30.5	34.5	38.5	42.5
ACCONSPI	0.87	0.63	3.18	1.35	0.00	1.89	0.71	0.56	2.27	1.60	0.53	1.59	2.59
ACLANCVF	0.00	0.32	0.58	0.34	0.00	0.32	1.43	0.00	1.70	0.32	0.26	2.12	1.81
ACMINUTI	2.90	3.48	4.62	2.36	1.16	0.95	1.43	2.54	4.25	4.49	3.69	1.06	2.85
ACSUCHLA	0.29	0.32	1.16	1.01	0.00	0.32	0.48	0.28	1.13	0.00	2.11	0.79	0.00
AMPEDICU	1.16	0.95	0.87	0.67	1.54	1.26	2.85	0.85	0.57	0.32	1.85	0.53	1.30
ASFORMOS	5.80	3.48	3.18	3.03	1.93	5.05	4.51	3.67	5.10	5.13	3.69	3.70	4.15
AUAMBIGU	4.35	0.63	2.60	1.68	2.32	1.26	4.51	0.28	4.25	3.53	0.79	2.12	1.81
AUSUBARC	7.25	8.86	7.80	14.14	16.99	12.30	10.45	12.71	12.75	7.05	8.97	5.29	8.81
CONEOTHU	1.16	0.95	1.16	0.00	1.16	0.63	1.43	1.69	2.27	0.32	1.06	1.06	2.07
CYCBODVL	3.48	7.91	6.36	8.75	6.18	3.47	4.75	8.19	3.40	3.21	3.69	3.70	5.18
CYCOMENS	0.00	1.27	0.00	1.01	0.39	0.32	1.19	1.41	1.98	0.96	0.00	0.26	0.00
CYCOMTVU	0.00	0.00	0.29	0.67	0.39	0.63	0.71	1.69	0.57	0.00	1.06	0.00	0.00
CYMICHIG	1.74	0.95	0.58	1.68	2.70	0.00	0.48	0.56	0.00	0.64	1.06	0.00	0.52
CYOCELLA	0.29	0.00	0.29	0.67	0.00	0.63	0.00	0.28	0.00	0.64	0.79	0.00	0.00
CYPSSTEL	2.61	1.27	1.45	0.67	0.00	0.95	1.66	1.69	0.85	2.88	2.37	1.06	1.04
FRBREVIS	1.16	3.16	8.09	2.02	5.02	7.57	1.43	3.95	5.67	0.64	2.11	6.08	5.70
FRTINY	0.58	1.27	0.00	0.34	0.00	0.00	0.00	0.00	0.00	2.24	0.79	0.00	0.78
FRCAPUVV	0.00	0.00	1.73	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.52
FRCAPUVG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.00	0.00	0.00	0.00
FRCROTON	18.84	18.67	3.18	7.74	3.09	6.62	9.26	4.52	6.23	13.78	4.49	5.56	4.15
FRNANANA	0.58	0.32	0.58	1.01	0.00	0.00	0.24	0.56	0.00	0.00	0.53	0.00	0.00
FRPINNAT	6.96	5.06	10.69	7.74	8.88	10.41	4.75	12.99	9.35	11.86	16.36	20.11	15.80
FRCONSTR	4.35	2.85	5.49	1.68	9.65	2.21	4.99	5.93	4.53	1.60	5.01	4.76	8.29
FRCONSVV	0.00	0.00	0.00	0.34	0.00	2.21	0.95	2.82	3.97	0.32	1.85	2.38	0.00
FRTENERA	0.00	0.00	0.00	1.01	0.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NAMINIMA	0.29	2.53	0.87	3.03	5.02	3.47	3.09	0.85	3.12	2.56	2.11	2.65	1.30
NAPSEUDO	0.29	0.63	0.58	0.67	0.39	1.26	2.14	1.13	1.42	0.64	1.32	1.32	0.52
NASCHADE	0.87	0.00	0.58	1.01	0.00	2.52	3.33	0.00	0.57	1.92	2.37	1.06	1.04
NASEMINU	4.06	3.16	5.72	3.70	5.41	1.89	3.80	1.69	0.28	2.56	4.49	4.85	2.33
NASUBROT	1.45	0.63	0.64	4.04	1.93	0.00	0.00	0.56	0.28	0.00	0.53	0.44	0.52
NASUBMUR	2.32	4.75	4.05	3.70	7.34	5.05	5.46	5.65	4.53	5.13	3.17	5.56	4.66
STPARVUS	0.87	0.63	0.87	0.67	0.00	0.95	0.00	1.41	0.85	0.32	0.26	0.00	0.26
STMINUTU	1.45	0.63	0.58	0.00	0.39	0.00	0.24	0.56	0.57	0.00	0.00	0.00	0.26
STHANTZS	0.29	1.58	0.87	2.69	0.00	1.26	0.71	1.98	0.28	1.28	1.06	0.00	0.78
STMEDIUS	0.87	0.32	0.87	1.01	1.54	2.21	1.66	0.00	0.28	1.60	0.53	0.53	0.78
TAFLOC3	2.61	4.11	1.16	2.36	2.70	1.26	3.80	4.52	1.13	1.60	2.11	1.59	1.81
Cyst:diatom	26.12	36.55	38.21	33.56	34.43	32.70	32.21	29.48	32.76	29.73	30.97	34.15	30.32
Total	79.71	81.33	80.64	83.16	86.87	78.86	82.42	85.59	84.42	79.17	81.00	80.16	81.61
LOI @ 550C	38.2	38.7	38.6	38.5	39.2	39.2	39.69	38.96	38.44	38.24	37.56	37.5	37.22
[TP] ug/L	18	18	21	19	16	23	19	22	22	20	19	23	23

Appendix C (cont'd). Big Rideau Lake ≥ 2% relative abundance.

Taxa	Mid point of 1 cm interval											
	0.5	**2.5**	**4.5**	**6.5**	**8.5**	**10.5**	**12.5**	**14.5**	**16.5**	**18.5**	**20.5**	**22.5**
ACCLEVEI	0.00	0.23	0.00	0.00	0.00	0.30	0.00	0.69	0.00	0.00	1.71	1.40
ACCONSPI	0.00	0.00	0.24	0.00	0.53	0.00	0.40	0.92	0.30	0.00	1.22	0.56
ACGRANA	0.00	0.46	0.00	0.00	0.53	0.00	0.00	0.46	0.59	0.00	0.00	0.00
ACMINUTI	0.49	2.52	0.71	0.35	2.12	1.05	1.60	0.92	0.59	0.28	2.93	3.36
ACSUCHLA	0.25	0.23	0.47	0.00	0.27	0.15	0.00	0.00	0.59	0.00	0.49	2.52
ACZEGLER	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.46	0.30	0.57	0.98	1.96
AMPEDICU	0.00	0.00	0.47	0.00	0.27	0.45	1.40	0.69	0.59	2.56	2.68	3.08
AMINARIE	0.00	0.00	0.00	0.00	0.27	0.00	0.00	0.00	0.00	0.28	0.49	1.68
ASFORMOS	6.14	5.96	6.37	3.47	2.65	4.51	3.00	2.77	1.48	8.26	2.93	5.88
AUAMBIGU	0.00	0.00	0.00	0.00	0.00	0.30	1.00	1.39	3.86	2.28	3.90	3.92
AUSUBARC	12.29	5.50	8.96	11.11	13.00	12.03	12.40	13.86	8.61	5.70	3.66	1.68
CONEOTHU	0.00	0.00	0.00	0.35	0.00	0.00	0.00	0.46	0.00	1.14	0.98	0.00
CYSTHOLI	0.25	0.00	0.47	0.00	0.00	0.75	0.00	2.54	0.00	0.28	0.24	0.56
CYCBODVL	0.98	2.75	1.42	1.39	0.53	1.50	1.80	1.62	0.59	1.42	2.68	1.40
CYCOMENS	21.87	23.62	21.93	28.82	35.54	17.14	2.40	0.46	0.89	0.85	0.98	0.56
CYCOMTVU	18.18	34.86	33.96	26.04	14.59	4.36	1.00	1.85	0.89	2.56	1.22	2.24
CYMICHIG	0.00	0.23	1.42	0.69	0.80	1.50	1.00	0.69	1.19	0.28	0.73	0.00
CYPSSTEL	0.00	0.00	0.00	0.00	0.80	4.96	1.80	3.00	0.00	5.13	6.83	7.56
CYSTELLI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.98	0.00
FRBREVIS	0.25	0.69	0.47	0.35	0.00	0.15	0.00	1.62	2.08	6.84	2.68	5.60
FRCAPUVV	1.97	0.00	0.94	0.00	0.00	0.60	0.20	4.62	6.23	3.42	0.00	2.24
FRCAPUVM	0.00	0.23	0.00	0.00	0.00	0.00	0.00	0.69	4.75	0.00	0.00	0.00
FRCAPVMG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.34	0.85	0.00	0.00
FRCROTON	20.64	5.50	7.31	11.81	10.08	23.91	25.80	19.63	13.06	9.12	7.80	12.04
FRNANANA	1.72	1.38	1.89	1.74	0.80	1.05	1.80	1.39	4.75	4.56	1.46	2.80
FRPINNAT	0.00	1.15	1.18	0.00	0.53	1.35	1.20	0.46	3.56	3.42	8.78	3.64
FRCONSTR	0.00	0.00	0.00	0.35	0.00	0.45	0.80	0.92	0.00	0.57	0.49	1.12
FRCONSVV	0.49	0.00	0.00	0.35	0.00	0.45	0.80	0.92	0.89	0.57	2.44	1.68
FRTENERA	1.72	2.52	0.94	1.04	1.59	0.45	6.60	0.00	8.01	0.57	1.22	1.12
NAMINIMA	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.46	0.59	0.00	0.98	0.00
NASUBMUR	0.00	0.00	0.00	0.00	0.00	0.15	0.40	0.46	0.59	0.57	0.73	0.84
STPARVUS	1.97	2.75	3.07	3.47	4.75	8.72	9.21	16.86	3.42	16.53	5.82	5.64
STMINUTU	0.98	0.00	0.71	0.00	2.67	0.90	6.39	1.15	9.34	3.98	6.37	4.16
STHANTZS	1.47	0.69	0.47	0.69	1.59	1.65	1.80	4.85	1.78	2.56	1.46	3.36
STMEDIUS	0.00	0.23	2.12	0.35	0.53	1.35	2.40	2.31	1.78	0.85	1.22	0.56
TAFLOC3	1.47	0.23	0.24	0.00	0.00	1.35	2.40	2.77	1.48	2.85	5.37	4.76
% planktonic	95.23	89.45	93.16	94.77	89.26	88.97	83.67	84.62	64.99	72.49	56.28	61.47
Cyst:diatom	4.22	8.40	4.50	4.01	3.46	6.76	5.34	6.54	3.99	8.40	11.16	15.35

Appendix C (cont'd). Big Rideau Lake ≥ 2% relative abundance.

Taxa												
	24.5	**26.5**	**28.5**	**30.5**	**32.5**	**34.5**	**36.5**	**38.5**	**40.5**	**42.5**	**44.5**	**46.5**
ACCLEVEI	0.88	1.13	2.65	3.29	2.67	1.70	0.28	2.32	2.79	2.68	1.89	0.30
ACCONSPI	0.66	0.00	1.59	1.64	1.78	1.13	2.28	1.03	2.54	1.79	0.63	0.00
ACGRANA	0.66	0.56	0.00	0.00	0.89	1.42	0.57	0.00	0.25	0.60	0.63	2.71
ACMINUTI	1.75	1.69	0.80	1.92	0.45	0.85	3.13	0.00	1.78	0.60	1.26	1.51
ACSUCHLA	0.88	1.13	3.18	1.64	3.34	3.12	2.56	2.06	0.25	3.57	4.09	3.01
ACZEGLER	0.00	0.56	0.27	0.00	0.45	1.42	1.42	2.32	1.02	1.19	0.00	0.30
AMPEDICU	3.72	2.82	1.86	3.84	3.56	2.27	4.27	3.35	3.55	4.46	3.46	4.52
AMINARIE	0.66	0.85	0.00	0.82	0.22	0.00	1.71	1.03	1.02	2.08	2.83	0.00
ASFORMOS	3.06	3.38	2.92	3.29	1.78	1.70	2.56	1.29	1.78	2.08	1.89	0.30
AUAMBIGU	3.72	3.10	0.80	2.19	0.67	1.70	2.28	2.06	0.76	0.00	1.89	0.90
AUSUBARC	1.31	1.13	1.59	1.64	1.11	1.42	1.42	0.77	0.51	0.00	0.31	0.00
CONEOTHU	0.00	0.85	0.53	2.19	1.34	0.28	1.99	1.80	2.03	2.08	2.20	0.60
CYSTHOLI	0.22	0.28	0.80	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CYCBODVL	0.22	3.10	0.00	0.82	1.34	0.85	0.00	0.00	1.02	1.79	1.26	3.01
CYCOMENS	1.53	0.28	1.86	0.27	2.67	0.28	1.42	0.77	0.00	0.30	1.26	0.90
CYCOMTVU	0.44	0.28	1.33	2.47	0.45	0.00	0.28	0.00	1.02	0.00	0.00	0.60
CYMICHIG	1.75	2.25	2.39	4.11	2.23	2.83	1.14	1.03	2.54	2.38	4.09	2.71
CYPSSTEL	6.78	6.76	10.08	14.52	10.69	10.20	9.97	2.84	7.11	10.12	15.09	9.34
CYSTELLI	1.97	0.56	7.96	1.92	4.90	2.27	3.70	1.29	1.78	1.49	7.23	0.00
FRBREVIS	4.81	8.45	12.20	5.48	14.70	16.71	19.09	14.69	12.18	11.61	13.21	6.33
FRCAPUVV	0.00	0.00	0.00	0.00	0.00	1.13	0.00	0.00	0.51	0.00	0.00	1.20
FRCAPUVM	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FRCAPVMG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FRCROTON	6.78	9.30	5.04	6.03	4.68	3.40	1.42	1.80	6.85	2.08	5.03	3.92
FRNANANA	2.84	3.10	1.59	0.55	0.89	0.28	0.28	0.00	0.51	0.30	0.63	0.60
FRPINNAT	7.88	7.61	6.37	8.77	7.35	4.25	5.98	6.96	12.69	5.36	8.18	9.04
FRCONSTR	7.66	4.23	4.24	1.64	2.90	7.65	0.28	10.82	0.00	5.36	0.94	9.64
FRCONSVV	8.97	4.23	4.24	2.19	3.56	8.50	1.42	11.08	11.42	5.65	1.26	12.05
FRTENERA	0.22	0.56	1.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NAMINIMA	0.88	1.13	1.33	1.37	0.45	1.13	1.99	4.64	0.00	0.60	0.94	0.00
NASUBMUR	2.63	2.82	3.98	4.38	3.12	4.82	6.27	6.70	4.57	5.36	2.52	5.42
STPARVUS	1.61	2.25	0.93	1.32	1.43	0.28	0.00	0.26	0.25	0.00	0.31	0.30
STMINUTU	2.99	1.41	0.93	0.33	0.57	0.00	0.00	0.00	0.25	0.00	0.00	0.00
STHANTZS	0.22	0.00	0.00	0.00	0.67	0.28	0.00	0.00	0.25	0.30	0.00	0.00
STMEDIUS	0.88	0.56	1.06	0.27	0.22	0.28	0.28	0.26	0.00	0.30	0.00	0.00
TAFLOC3	4.16	3.10	2.12	0.55	1.11	0.28	0.85	0.52	1.02	1.19	0.31	0.90
% planktonic	44.84	45.29	45.71	41.78	37.39	29.75	26.06	14.74	28.39	23.90	40.95	30.19
Cyst:diatom	15.48	26.41	17.39	25.98	21.58	17.26	21.73	19.91	14.59	27.40	20.65	24.93

Appendix C (cont'd). Lower Rideau Lake (super glew) ≥2% relative abundance of diatom taxa.

Taxa	Mid point of 1 cm interval											
	0.5	**4.5**	**8.5**	**12.5**	**16.5**	**20.5**	**24.5**	**28.5**	**32.5**	**36.5**	**40.5**	**46.5**
ACLANCVF	1.30	1.82	0.87	0.00	1.80	2.79	0.93	0.84	1.53	0.00	2.62	1.33
ACLANCVR	1.30	0.61	0.87	0.00	1.29	1.24	1.86	0.84	0.00	2.27	0.29	1.33
ACZIEGLE	0.00	0.30	0.29	0.00	0.00	1.24	2.17	1.12	1.02	1.01	1.46	3.33
AMPEDICU	1.09	0.61	4.62	1.34	0.77	3.72	0.93	0.56	2.05	3.27	0.87	3.78
AUAMBIGU	5.00	5.78	7.80	10.70	7.99	11.46	6.21	7.26	8.44	3.78	6.41	3.78
AUGRANUL	9.13	8.21	12.14	13.71	11.08	13.00	22.98	17.04	15.35	16.88	11.37	3.78
AUSUBARC	0.65	1.22	0.58	1.34	2.06	1.55	2.17	1.96	0.77	2.52	1.17	3.33
COPLACVE	2.17	0.91	0.29	0.00	0.52	0.00	0.62	0.00	0.00	0.00	0.29	0.00
CYCOMENS	2.17	6.38	4.34	3.01	2.84	2.48	0.93	0.56	3.32	0.50	0.29	0.00
CYCOMTVU	3.26	0.61	0.00	0.67	1.29	1.86	0.00	0.28	0.00	0.00	0.00	0.00
FRBREVIS	4.13	3.04	3.18	5.35	4.64	5.88	6.52	9.50	5.12	9.57	7.87	16.44
FRCAPUVV	0.00	0.00	0.00	2.01	0.52	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FRCROTON	9.78	0.00	2.02	1.00	3.09	2.48	1.55	1.68	0.77	0.00	0.00	0.00
FRPARASI	1.74	2.74	0.58	0.33	1.03	1.86	0.00	0.00	0.77	0.00	0.29	0.00
FRPINNAT	14.57	13.37	9.83	13.71	22.42	14.55	12.11	12.29	15.09	17.88	16.91	17.33
FRCONSTR	10.87	8.81	12.14	16.05	11.08	4.64	7.76	17.60	18.41	12.59	16.62	14.00
FRCONSVV	0.00	0.30	1.73	0.00	0.00	0.31	2.48	0.00	1.02	2.52	0.29	0.22
NADILUVI	0.00	0.00	0.87	0.00	0.00	0.00	3.11	1.68	0.51	2.02	2.33	1.11
NAMINIMA	2.61	2.43	1.73	1.00	1.55	1.86	0.00	1.12	0.00	0.25	0.29	1.11
NAPSEUDO	0.87	0.00	0.87	1.34	1.80	0.62	0.62	0.00	0.51	2.02	1.17	0.22
NAPUPULA	0.43	0.00	0.29	0.00	0.77	0.31	2.17	0.00	0.77	0.25	0.87	0.00
NASCHADE	0.87	1.22	2.60	0.67	1.55	0.31	0.00	0.00	0.51	0.50	0.58	1.78
NASEMINU	0.87	4.56	0.29	3.34	1.29	0.62	0.62	1.40	2.30	4.79	1.46	2.67
NASUBROT	0.43	1.82	2.60	1.67	0.52	0.00	1.55	0.00	3.32	2.02	2.33	2.00
NASUBMUR	2.61	7.29	3.47	5.35	2.06	3.72	2.80	4.19	3.07	2.77	3.50	2.22
NAVITABU	0.43	1.22	0.87	0.00	0.52	0.31	0.31	2.23	1.53	1.26	2.62	2.67
STALPINU	0.00	0.30	0.30	0.00	0.00	1.20	2.20	1.10	1.00	1.00	1.50	3.30
Total	76.30	73.25	74.86	82.61	82.47	76.78	80.43	82.12	86.19	88.66	81.92	82.44
Cyst:Diatom	6.88	10.35	12.18	19.41	10.60	15.67	23.33	12.68	14.07	16.77	14.04	11.07
L.O.I. @ 550C	52.00	52.21	52.62	52.78	52.99	53.08	52.61	52.85	51.54	50.82	51.24	53.37
%planktonics	30.00	22.19	26.88	30.43	28.35	32.82	33.85	28.77	28.64	23.68	19.24	10.89

Appendix C (cont'd). Lower Rideau Lake >2% relative abundance of diatom taxa (piston core).

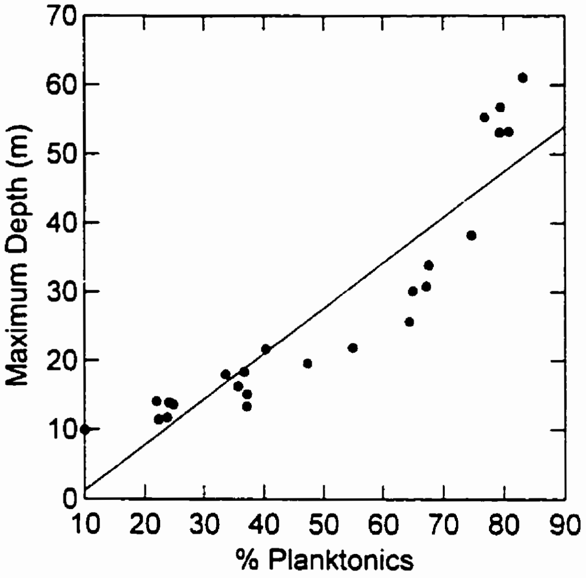
Taxa	Mid point of 1 cm interval												
	0.5	5.5	12	15.5	20.5	25.5	31.5	35.5	40.5	45.5	50.5	60.5	70.5
ACCONSPI	2.20	0.91	0.92	2.30	1.35	1.27	1.36	1.00	0.54	0.51	0.00	0.00	0.00
ACLANCVR	0.66	0.23	0.00	0.77	0.00	2.34	0.00	1.74	0.82	0.00	0.00	0.00	0.00
ACMINUTI	1.98	1.81	3.46	1.28	3.51	4.46	7.24	13.68	10.35	15.78	9.60	11.83	16.43
ACROSENS	0.00	0.00	0.69	0.26	0.54	1.27	1.36	1.49	2.18	1.78	0.53	1.03	2.51
ACZIEGLE	1.76	2.72	3.92	2.30	5.14	4.03	1.58	1.24	0.54	0.25	0.00	0.26	0.28
AMPEDICU	3.30	2.04	4.61	4.08	4.32	3.40	3.39	2.49	0.82	0.00	0.00	0.51	0.00
ASFORMOS	0.44	0.00	0.00	0.00	0.00	0.42	0.00	0.00	2.72	0.25	0.27	0.77	0.28
AUAMBIGU	3.96	8.16	2.07	10.20	4.86	2.76	12.44	10.95	6.27	1.53	0.53	0.00	0.00
AUGRANUL	7.91	14.51	2.53	4.59	2.43	2.12	0.45	0.00	0.27	0.00	0.00	0.00	0.00
AUSUBARC	0.88	0.00	0.00	0.00	1.35	0.00	2.49	1.99	1.09	0.51	0.53	0.00	0.00
ANVITREA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.82	1.78	3.20	2.83	3.06
CYCESATI	0.00	0.00	0.23	0.00	0.00	0.00	0.23	0.00	0.82	1.27	2.67	1.54	0.56
CYMFALAI	0.00	0.00	0.00	0.26	0.00	0.00	0.00	0.00	0.00	2.54	4.53	2.57	0.84
CMMICROC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.02	5.60	2.06	5.01
CYBODAVL	0.44	0.00	0.00	0.00	0.00	0.21	0.23	0.25	1.91	2.04	0.80	2.57	1.39
CYMICHIG	0.00	0.00	0.00	0.00	0.00	0.64	0.00	0.50	2.18	6.11	13.87	10.80	11.14
CYPSSTEL	0.22	0.00	0.00	0.00	0.00	0.00	0.23	0.00	0.27	0.00	0.00	2.06	0.28
CYSTELLI	0.22	0.23	0.00	0.00	0.81	0.00	0.00	0.00	0.54	2.54	8.27	6.68	4.74
FRBREVIS	14.07	11.11	18.20	10.97	15.41	8.07	13.35	7.96	14.17	8.40	1.60	0.77	0.00
FRCROTON	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.25	9.54	4.83	0.00	1.29	0.28
FRPINNAT	19.34	10.66	14.97	15.31	18.65	22.29	11.54	17.16	10.63	7.38	1.33	1.29	0.00
FRCONSTR	14.07	17.46	14.98	12.76	14.05	15.71	12.67	11.69	1.63	4.58	0.53	0.00	2.51
FRCONSVV	3.52	4.99	6.91	4.59	1.62	1.49	0.90	3.98	1.63	0.51	0.27	0.00	0.00
NACCEPHA	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.54	0.25	0.80	2.31	0.56
NACRELLA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	3.54	3.56	5.07	10.80	11.14
NADENSIL	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.04	2.67	1.29	1.95
NADILUVI	0.44	0.00	0.00	0.26	0.00	0.00	0.90	1.24	0.82	1.53	2.67	3.08	4.46
NAMINIMA	0.88	0.91	1.38	4.34	2.70	2.12	4.30	5.22	0.54	1.53	1.07	0.00	0.00
NAPSVENT	3.30	1.36	4.15	4.08	4.05	4.67	3.85	1.99	0.00	0.00	0.53	0.00	0.56
NAPUPULA	0.00	0.23	0.00	0.00	0.27	0.21	0.00	0.50	1.91	2.54	2.13	4.63	3.62
NARADIOS	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	1.02	2.67	2.06	0.56
NASCHADE	0.88	0.91	1.61	0.51	0.54	2.12	0.90	1.00	0.00	0.00	0.00	0.00	0.00
NASEMINU	3.74	4.76	1.84	1.53	2.16	3.58	0.55	0.49	0.27	0.51	0.00	0.00	0.00
NASUBMUR	3.08	0.91	1.38	0.77	0.54	0.42	0.90	0.50	1.09	0.00	0.00	0.00	0.00
NASUBROT	0.44	1.36	1.38	1.53	2.97	1.30	3.52	2.00	0.00	0.00	0.00	0.00	0.00
NAVITABU	1.10	0.68	1.84	2.30	1.89	1.06	2.04	0.50	0.27	0.00	0.00	0.26	0.00
NAVULPIN	0.22	0.00	0.00	0.00	0.00	0.42	0.00	0.25	0.54	0.51	1.33	3.08	2.79
TAFLOC3P	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.75	2.18	3.31	0.80	0.00	1.11
Total	89.23	85.94	87.09	84.95	89.19	86.62	87.10	91.30	81.47	80.41	73.87	76.35	76.04
Cyst: Diatom	9.18	7.93	5.24	5.31	4.64	3.29	6.36	7.80	25.56	42.96	35.01	37.56	34.85
L.O.I. @ 550C	51.50	51.42	54.12	55.20	55.65	57.99	62.50	61.68	71.67	76.09	81.90	81.63	78.76
% Planktonic	14.73	22.90	5.99	15.82	10.54	6.16	17.42	15.42	32.15	25.95	27.73	25.96	22.28

Appendix C. Otter Lake > 2% relative abundance of diatom taxa.

Taxa	Mid point of 0.5 cm intervals											
	0.25	3.75	7.75	11.75	15.75	19.75	23.75	27.75	31.75	33.75	35.75	38.25
ACMINUTI	1.22	2.43	0.71	0.00	0.52	1.94	0.84	1.09	1.85	1.09	1.44	0.81
AMPEDICU	0.00	0.00	0.24	0.59	2.60	0.00	0.56	0.54	0.26	1.09	0.29	0.00
ASFORMOS	7.13	8.41	2.12	3.14	0.52	1.29	0.84	2.17	2.65	3.94	2.30	4.57
AUAMBIGU	3.26	3.54	5.88	13.95	14.06	25.89	2.52	0.82	1.85	2.63	1.15	4.57
AUSUBARC	3.67	2.88	14.35	26.33	29.69	9.06	22.69	20.92	19.05	18.82	20.69	18.55
CYBODAVL	1.63	1.55	1.65	2.16	1.82	2.59	1.96	4.89	3.97	8.10	4.02	4.84
CYCOMENS	25.05	30.31	30.24	5.70	4.43	2.27	1.12	0.27	1.59	0.66	0.57	0.00
CYCOMTVU	14.46	9.29	1.53	1.18	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CYMICHIG	4.07	0.66	3.88	4.91	1.30	2.27	3.08	6.79	6.35	7.00	4.89	8.06
CYOCELLA	3.67	4.42	3.29	1.38	0.52	1.29	0.00	0.27	0.26	0.00	0.00	0.00
CYPSSTEL	0.00	0.00	0.00	1.18	0.26	0.65	1.12	1.09	0.53	1.53	2.01	1.08
FRBREVIS	0.00	0.00	0.47	0.39	0.00	0.00	0.56	2.17	1.32	0.22	4.02	0.00
FRCAPUVV	1.02	4.20	0.47	0.00	0.00	2.59	0.00	0.82	0.00	0.00	0.00	0.81
FRCROTON	17.31	17.92	8.00	3.54	1.56	6.80	3.92	8.70	1.59	3.50	9.77	10.48
FRPINNAT	0.00	0.00	0.12	0.79	0.00	0.00	0.56	0.82	1.59	2.63	0.57	0.00
FRCONSTR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.90	3.70	1.75	0.57	0.81
FRTENERA	0.00	0.44	0.00	0.00	0.00	2.27	0.56	0.54	0.00	0.00	0.00	0.00
FRULNA	0.61	0.44	0.24	0.59	1.56	6.15	1.40	0.82	1.06	2.63	2.30	5.38
STMEDIUS	4.28	5.09	7.06	7.66	17.45	7.77	35.01	29.35	32.01	29.10	31.90	22.31
STMINUTU	1.22	0.22	2.35	5.30	7.29	0.97	10.64	3.80	1.59	2.41	0.86	1.61
STPARVUS	1.63	0.66	5.65	5.70	0.26	0.32	0.00	0.00	0.00	0.22	0.00	0.00
TAFLOC3P	0.41	1.99	4.94	4.52	6.77	18.77	4.48	2.99	1.85	3.72	4.60	4.84
TOTAL	82.28	83.63	90.12	85.27	87.24	89.64	89.64	86.96	78.31	84.90	87.93	83.33
cyst:diatom	13.40	9.60	14.49	23.69	18.30	4.33	26.09	36.55	37.00	34.43	36.03	32.61

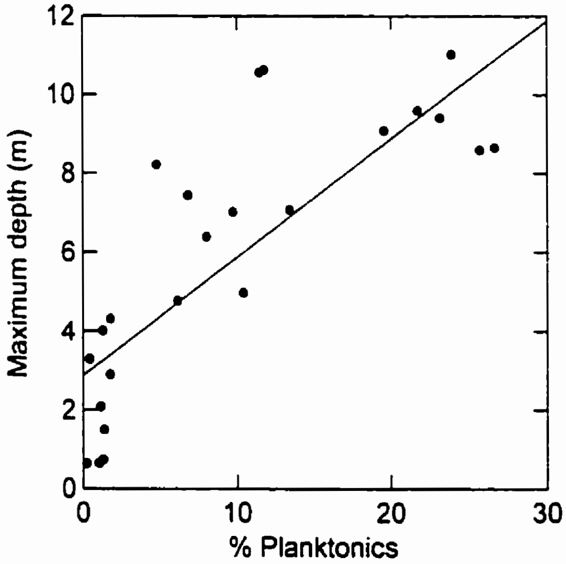
Appendix D. Relationship between % planktonics and inferred maximum depth for a) Big Rideau (BR), b) Lower Rideau (LR), and c) Indian (IN).

a)



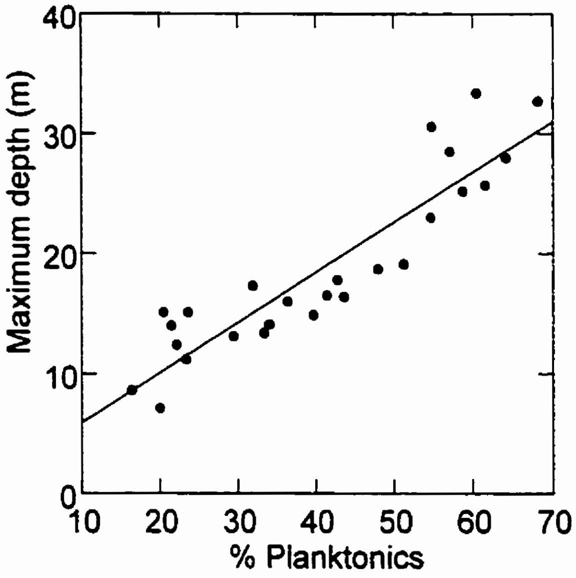
r^2=0.844
n = 24
$P < 0.001$
BR

b)



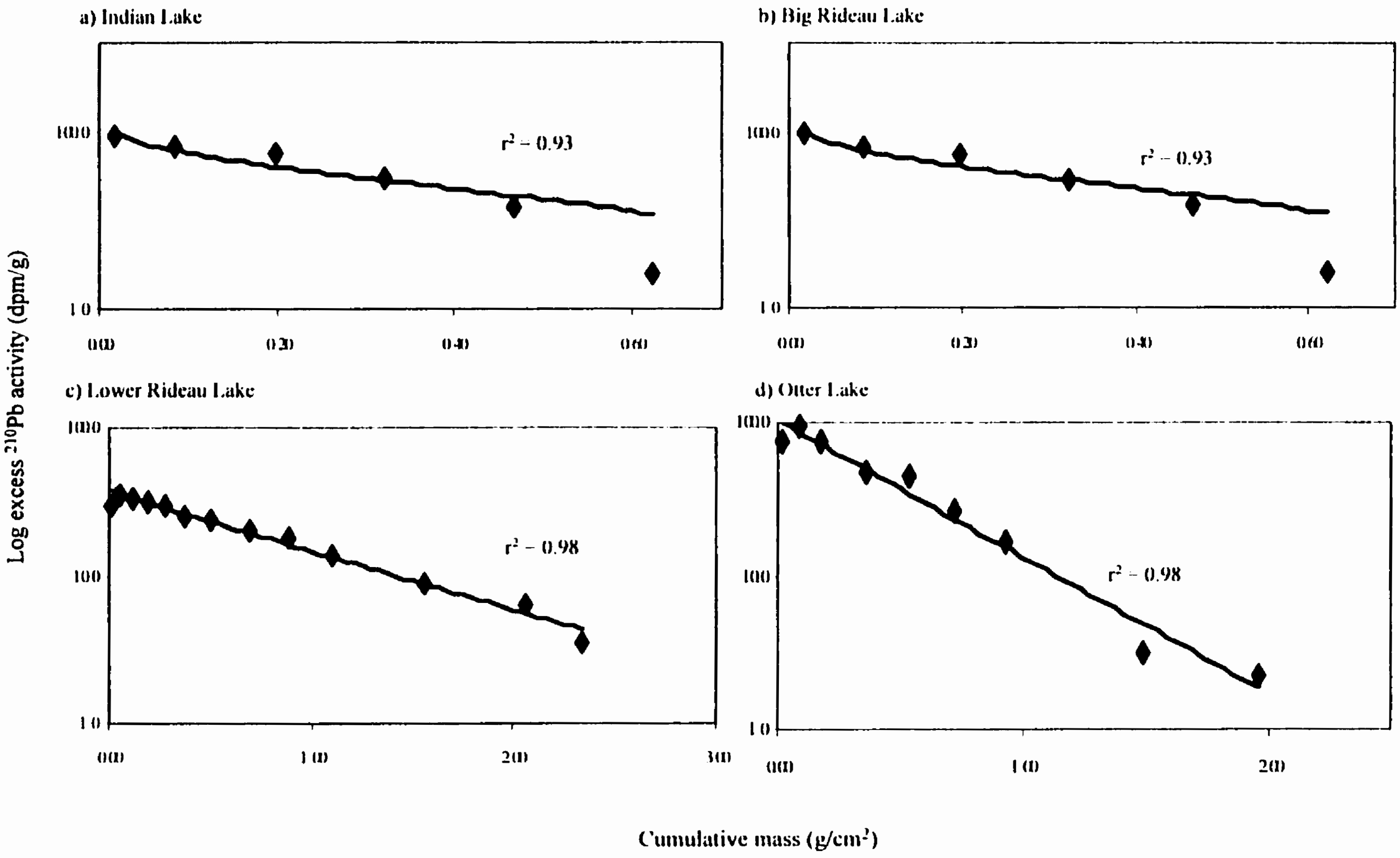
r^2 = 0.687
n = 23
$P < 0.001$
LR

c)



r^2= 0.828
N= 26
$P < 0.001$
IN

Appendix E. Relationship between log excess ^{210}Pb activity and cumulative mass.


a) Indian Lake
b) Big Rideau Lake
c) Lower Rideau Lake
d) Otter Lake
Log excess ^{210}Pb activity (dpm/g)
Cumulative mass (g/cm^2)
$r^2 = 0.93$
$r^2 = 0.93$
$r^2 = 0.98$
$r^2 = 0.98$
1000
100
10
0.00
0.20
0.40
0.60
1.00
2.00
3.00