

Multiproxy record of prairie lake response to climatic change and human activity, Clearwater Lake, Saskatchewan

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Abstract: Multiple paleolimnological indicators (mineralogy, diatoms, pigments, and macrofossils) were used to quantify the relative impacts of recent climatic change and terrestrial disturbance on Clearwater Lake, a closed-basin lake in southern Saskatchewan. Four periods were identified: 1) initial conditions (ca. AD 1600–1920), characterized by low salinity, planktonic algal taxa, and variable primary production; 2) ca. 1920–1940, characterized by declining water levels, slightly elevated salinity, predominantly benthic diatoms, and increased primary production; 3) ca. 1940–1970, characterized by slightly increased water levels and declining concentrations of indicator algal pigments; and 4) 1970–1993, characterized by a unique combination of abundant Chara, historical maxima of pigments from chlorophytes and siliceous algae, and highly variable water levels, ionic composition, and diatom species composition. The timing of these changes was more similar to patterns of land use than to those of climatic change, suggesting that paleoclimatic reconstructions of recent events (e.g. global warming) must also consider the influence of land-use practices and local hydrology on lake characteristics.

Résumé : De nombreux indicateurs paléolimnologiques (minéralogie, diatomées, pigments, macrofossiles) ont été utilisés afin de quantifier les incidences relatives des changements climatiques et des perturbations terrestres récents sur le lac Clearwater, lac de bassin fermé du sud de la Saskatchewan. Quatre périodes ont été identifiées : (1) conditions initiales (environ 1600–1920), période caractérisée par une faible salinité, des algues planctoniques et une productivité primaire variable; (2) environ 1920–1940, période caractérisée par une diminution du niveau de l'eau, une légère augmentation de la salinité, des diatomées principalement benthiques et une productivité primaire accrue; (3) environ 1940–1970, période caractérisée par une légère hausse du niveau de l'eau et une diminution de la concentration de pigments d'algues indicateurs; et (4) 1970–1993, période caractérisée par une combinaison unique de l'abondance de charas, de maxima historiques des pigments de chlorophytes et d'algues siliceuses, et de la forte variabilité du niveau de l'eau, de la composition ionique et de la composition des espèces de diatomées. La chronologie de ces changements ressemble plus aux configurations d'utilisation des sols qu'à celle des changements climatiques, ce qui donne à penser que les reconstitutions paléoclimatiques des événements récents (p. ex. le réchauffement global) doivent également prendre en considération l'influence des pratiques relatives à l'utilisation des sols et de l'hydrologie locale sur les caractéristiques des lacs.

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INTRODUCTION

The continued anthropogenic production of greenhouse gases is expected to promote global warming and severely increase the aridity of central continental regions, including the Palliser Triangle (El-Ashry and Gibbons, 1988; Gleick, 1989). The Palliser Triangle occupies much of the Great Plains of western Canada (Fig. 1), an important agricultural area whose high moisture deficit ($>400 \text{ mm}\cdot\text{a}^{-1}$) makes it sensitive to climatic change (Lemmen et al., 1993; Last, 1994). Long-term meteorological records show a distinct warming trend in the Canadian Prairies during the past century, particularly during the 1980s (Gullet and Skinner, 1992; Evans and Prepas, 1996). As a consequence, water levels have declined more than 3 m in some prairie lakes since 1970 (Vance and Last, 1994).

Lakes in the Palliser Triangle can provide sensitive long-term records of past climatic conditions that may prove important for determining the effects of future climate change (Vance, 1997). In particular, the balance between precipitation and evaporation can regulate water levels, salinity, and brine composition of closed-basin lakes (Wiche, 1986; Vance and Last, 1994; Lent et al., 1995; Fritz, 1996), which in turn affects lake production, community composition, and water quality (Hammer, 1990; Evans and Prepas, 1996). For example, periods of increased salinity can cause taxonomic shifts that favour chlorophytes and diatoms over filamentous

cyanobacteria (Marino et al., 1990; Evans and Prepas, 1996; but see Hammer et al., 1983). In addition, climate-related salinity fluctuations alter the species composition of diatom assemblages in a predictable and quantifiable manner (Fritz et al., 1991, 1993; Laird et al., 1996a, b). Because the sediments at the bottom of prairie lakes preserve a mineralogical record of lake chemistry and the physical remains of aquatic communities, it should be possible to obtain detailed records of biotic responses to past climate change from an analysis of sediments (e.g. Vance and Last, 1994; Fritz, 1996).

Standard methods for paleoclimatological research can be problematic for use in dry prairie regions. Trees suitable for tree-ring analyses are rare on agricultural plains (Fritz et al., 1994); consequently, most tree-ring records come from the eastern foothills of the Rocky Mountains (e.g. Case and MacDonald, 1995) or from river valleys (e.g. Will, 1946; Meko, 1992) that are under different climatic and hydrological controls than upland prairies (Fritz et al., 1994). Furthermore, pollen studies have proven difficult because climatic interpretations are obscured by the low taxonomic resolution (family level only, e.g. 'grasses') of fossil records from grasslands (Vance and Mathewes, 1994; Fritz et al., 1994; Laird et al., 1996a). Finally, little is known of how the response of individual lakes to climatic change may vary with hydrological setting and human land-use history (Adams et al., 1990; Wilson et al., 1997).

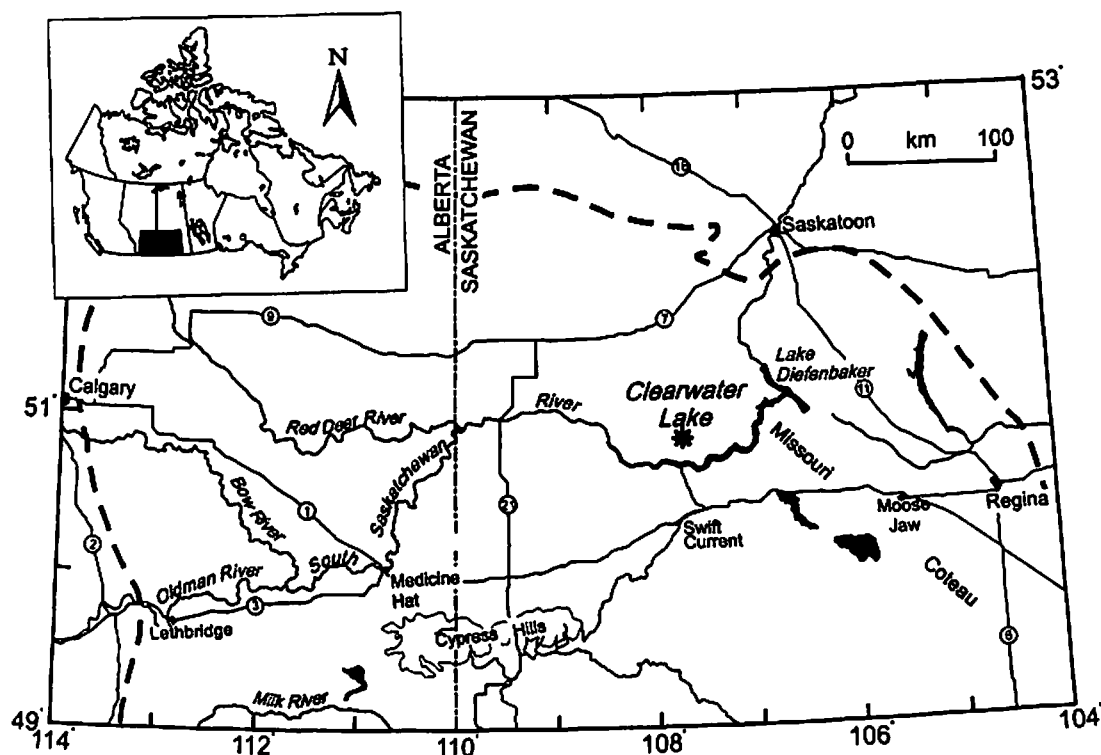


Figure 1. Map of the northern Great Plains showing the location of Clearwater Lake within the Palliser Triangle. Dashed line marks limit of the Palliser Triangle; shaded area represents the Brown Chernozemic Soil Zone.

In this study, we used stratigraphic changes in the abundance of diatom valves, algal pigments, plant macrofossils, and the physical and mineralogical properties of lake sediments to assess the effects of climate change and human land-use on Clearwater Lake, Saskatchewan, during the past 400 years. Diatoms are abundant members of the algal flora of inland saline lakes whose distribution is strongly related to lake-water salinity (Fritz et al., 1993; Cumming et al., 1995; Gasse et al., 1995) and whose species composition allows quantitative reconstruction of past lake salinity (Fritz et al., 1993; Laird et al., 1996a, b). Similarly, carotenoids and chlorophylls include compounds that allow quantification of past changes in algal abundance and gross composition (Leavitt, 1993; Leavitt and Findlay, 1994), whereas remains of aquatic plants provide information on water depth, littoral zone development, and gross floral community composition (Vance et al., 1992, 1997). Changes in sediment texture, bedding characteristics, mineralogy, and geochemical composition further facilitate inferences of past lake levels, watershed weathering, and lake chemistry (Torgersen et al., 1986; Teller and Last, 1990).

Study site

Clearwater Lake (lat. 50° 53' N, long. 107° 54' W, elev. 680 m a.s.l.) is centrally located within the Palliser Triangle, a dry subhumid region of the Great Plains of western Canada (Fig. 1). Annual precipitation averages 380 mm, whereas about twice this amount is lost through evaporation (Canadian National Committee for the International Hydrologic Decade, 1978). The region experiences long winters with mean annual temperatures of 1.5°C and average January temperatures of -15°C. Lakes are normally ice covered from November to April. Summers are short and warm with average daily July temperatures of 19°C. Aerial photographs show that the level of Clearwater Lake has fluctuated over the last few decades (Fig. 2). Changes in the presence of numerous ponds and the lake's northeastern bay indicate that water levels were relatively high in 1956 and during the 1970s, and low following droughts of the late 1930s and the 1980s.

The basin occupies a small catchment situated on The Missouri Coteau, a relatively stony and infertile region of hummocky moraine and poorly integrated drainage.

Table 1. Water chemistry of Clearwater Lake, 1938–1995. Ion concentrations in mmol·L⁻¹ (with mg·L⁻¹ in parentheses).

Parameter	Average	Range
Ca ²⁺	0.32 (8)	0.09–0.27 (4–11)
Mg ²⁺	6.13 (149)	4.73–8.69 (115–211)
Na ⁺	3.45 (79)	2.35–5.32 (54–122)
K ⁺	0.51 (20)	0.07–0.71 (3–28)
HCO ₃ ⁻ +CO ₃ ²⁻	10.34 (626)	8.81–13.94 (537–847)
SO ₄ ²⁻	2.00 (192)	1.39–3.25 (134–312)
Cl ⁻	0.76 (27)	0.54–1.16 (19–41)
TDS	1109	923–1565
pH	8.9	8.40–9.25

TDS – total dissolved solids (in mg·L⁻¹).

Clearwater Lake is small (0.5 km²), relatively shallow (maximum depth approx. 9 m), and has uncharacteristically low salinity (approx. 1 g·L⁻¹ total dissolved solids (TDS); Table 1) given the high regional precipitation deficit (approx. 400 mm·a⁻¹). Vance and Last (1994) suggested that Clearwater Lake is influenced by fresh groundwater inputs, although hydrological budgets are not available. The lake lacks permanent stream inflow, but drains from a northeastern outlet and intermittent streams during periods of exceptionally high water. Lake water is alkaline (pH approx. 9) and dominated by Mg²⁺, Na⁺, and HCO₃⁻ ions. The lake is always supersaturated with respect to most carbonate minerals and, because of high Mg/Ca ratios (>20), aragonite is precipitated as the stable carbonate phase. Consequently, present-day sediments contain mainly endogenic aragonite, detrital carbonates, detrital siliciclastics, and organic matter (Table 2). Small quantities of endogenic or authigenic protodolomite (disordered, nonstoichiometric CaMg(CO₃)₂) and magnesian calcite also occur in modern sediments, and are probably generated in response to short episodes of elevated (>30) or reduced (<10) Mg/Ca ratios (Müller et al., 1972).

A small regional park and seasonal-use cottages occupy more than two-thirds of the perimeter of the lake (Fig. 2). Cottage construction increased after 1940 and the lake remains a popular recreation locale despite declining lake levels since the 1970s. Other land-use features include a golf course to the west and a refuse dump immediately south of the lake. Sparse

Table 2. Summary of average mineralogical and grain size characteristics of modern and late Holocene sediment in Clearwater Lake. Ranges shown in parentheses.

Parameter	Modern	1800–1990
Organic matter (%)	15.0	15.1 (10–20)
Mean particle size (µm)	39.7	26.5 (6–60)
Standard deviation of mean size	32.9	24.8 (4–36)
Median particle size (µm)	32.4	21.9 (4–55)
Sand (%)	13.6	7.8 (0–32)
Silt (%)	80.8	80.5 (48–92)
Clay (%)	5.6	11.1 (1–42)
Detrital fraction (%)	79.4	83.9 (37–89)
(Endogenic+authigenic) fraction (%)	20.6	16.1 (11–63)
Detrital components:		
Total clay minerals (%)	51.9	49.4 (23–69)
Quartz (%)	12.0	10.4 (4–34)
Plagioclase (%)	6.1	7.8 (0–20)
K-feldspars (%)	n.p.	2.6 (0–34)
Amphibole minerals (%)	n.p.	<0.1 (0–2)
Calcite (%)	4.2	5.5 (0–14)
Dolomite (%)	6.5	8.0 (3–27)
Endogenic and authigenic components:		
Mg-calcite (%)	2.0	0.5 (0–5)
Mol% MgCO ₃ in Mg-calcite	5.3	10.3 (4–16)
Nonstoichiometric dolomite (%)	0.8	1.2 (0–8)
Mol% CaCO ₃ in protodolomite	63.5	67.4 (58–70)
Magnesite (%)	n.p.	<0.1 (0–3)
Aragonite (%)	15.8	12.9 (0–29)
Gypsum (%)	n.p.	1.6 (0–22)
Na-sulphate salts (%)	n.p.	<0.1 (0–7)
Pyrite (%)	n.p.	<0.1 (0–3)

n.p. – not present

historical data suggest that the lake has recently undergone episodic deoxygenation, leading to occasional fish kills and poor water quality (Vance and Last, 1996).

MATERIALS AND METHODS

Core collection and chronology (R.E. Vance)

Three short cores (57–88 cm) were collected from the southern basin of Clearwater Lake in February 1994 using a modified gravity corer (Turner, 1994). Sites were within 3 m of each other. All cores were extruded from the 10 cm diameter

plexiglass coring tube at the lakeside. During extrusion, the outer 1 cm layer of the core was removed to reduce sample contamination from core smearing. One core (CWS1) was sectioned into 1 cm intervals and dated using ^{210}Pb analyses and the constant rate of supply model (CRS; Appleby and Oldfield (1978)). A second core (CWS2) was subsampled at 1 cm intervals for sediment mineralogy, particle-size distribution, fossil pigments, siliceous microfossils, and plant macrofossils. The shortest of the cores (CWS3) was sectioned into 2 cm increments and used for additional macrofossil analyses. Sediment accumulation rates were assumed to be similar among cores.

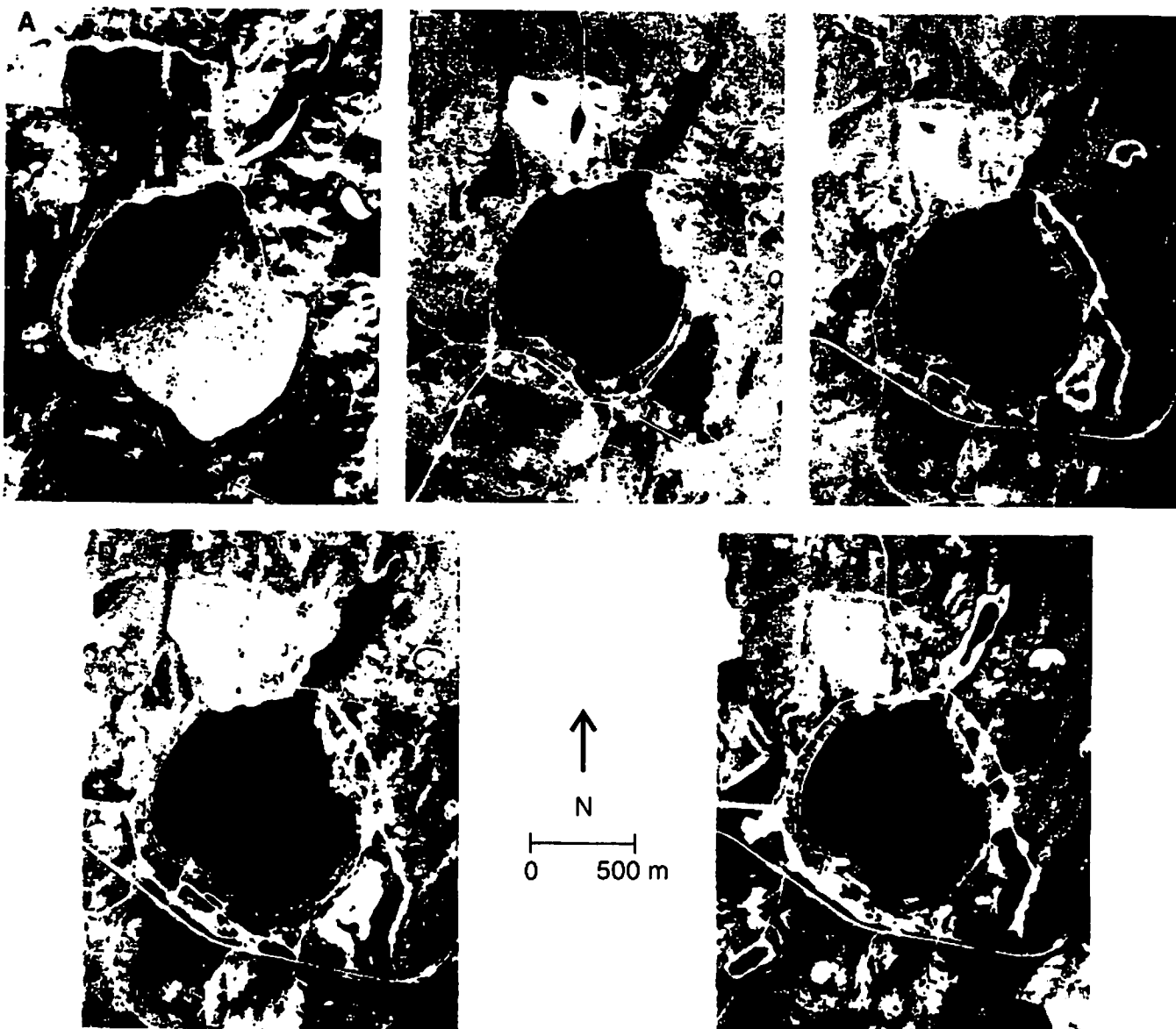


Figure 2. Aerial photographs of Clearwater Lake showing fluctuations in water levels, 1939–1990. Photographs were taken: A) November 11, 1939 (NAPLA6752-15); B) September 24, 1956 (NAPLA15504-14); C) May 20, 1972 (NAPLA22663-196); D) May 26, 1979 (NAPLA25126-59); and, E) June 19, 1990 (NAPLA27580-166). Scale bar represents 0.5 km in the 1979 photograph, but is only approximate in other photographs.

Lithostratigraphy (W.M. Last)

All mineralogical analyses were performed using standard X-ray diffraction techniques (Klug and Alexander, 1974; Hardy and Tucker, 1988) and a Philips PW1710 Automated Powder Diffraction System. Mineral identification was aided by the use of an automated peak-match computer program (Marquart, 1986). Percentages of the various minerals were estimated from diffractograms using a weighted peak-intensity method modified after Schultz (1964). Nonstoichiometry of the dolomite and calcite was determined by examining the displacement of the d_{104} peak on a detailed (slow) X-ray diffractogram, and was calculated according to Goldsmith and Graf (1958). Organic matter and total carbonate mineral content of the sediment were determined by weight loss on heating to 500°C and 1000°C, respectively (Dean, 1974). Particle-size spectra for each sample were determined using an automated laser-optical particle-size analyzer (GALAI™ CIS-1; Aharonson et al., 1986) after removal of organic matter. Particle-size statistics were calculated according to Allen (1981). Mineralogy, organic matter content, and texture of sediments from CWS1 were determined at 1 cm intervals.

Diatoms (S.E. Wilson)

Diatom sample preparation followed standard procedures detailed in Wilson et al. (1994, 1996). Once isolated, diatom frustules were mounted on glass slides with Naphrax™ medium. Diatoms were identified and enumerated under oil immersion using a Leitz DMRB microscope at 1000x magnification with differential interference contrast optics (numerical aperture = 1.30). Over 350 diatom valves were enumerated from each sample. Diatoms were analyzed at 2 cm intervals, except in the upper 20 cm where analyses were at 1 cm intervals. Taxonomic identifications were based on published descriptions of flora from saline and freshwater lakes of British Columbia (Cumming et al., 1995), as well as Krammer and Lange-Bertalot (1986, 1988). Past salinity levels were reconstructed from relative abundances of fossil diatoms using a salinity transfer function developed from 219 lakes in southern British Columbia and the Prairies (Wilson et al., 1996) and the program WACALIB v. 3.3 (Line et al., 1994). Bootstrapping was used to estimate the standard error of prediction for each diatom-inferred salinity value. Diatom-inferred salinities were expressed as the sum of major ion concentrations in $\text{mg}\cdot\text{L}^{-1}$ (Wilson et al., 1996), and are slightly lower than salinities measured as $\text{g}\cdot\text{L}^{-1}$ TDS. The ratio of chrysophycean stomatocysts to diatom frustules was also used as a qualitative indicator of past salinities (Smol, 1985).

Sedimentary algal pigments (R.D. Vinebrooke)

Sediments for pigment analysis were immediately frozen and stored in the dark until pigment extraction and analysis. High-performance liquid chromatography (HPLC) was used to quantify fossil pigment concentrations (Leavitt et al., 1989; Leavitt and Findlay, 1994). Carotenoids, chlorophylls, and their derivatives were extracted using a standard mixture of

acetone:methanol:water (80:15:5, by volume) from sediments that had been freeze-dried for 24 h in the dark at a pressure of 0.1 Pa (Leavitt et al., 1989). Pigment concentrations were quantified using a Hewlett-Packard (HP) Model 1050 HPLC system coupled with a HP Model 1050 photodiode array detector and a HP Model 1046A scanning fluorescence detector. Pigments were identified based on spectrophotometric characteristics and by co-chromatography with authentic standards from the United States Environmental Protection Agency (Leavitt et al., 1989; Leavitt and Findlay, 1994).

Pigment concentrations were expressed as nmoles pigment·g⁻¹ organic matter (Leavitt, 1993) following determination of organic content by weight-loss-on-ignition at 500°C (Dean, 1974). Recent calibration of annual fossil pigment records against 20 years of phytoplankton data indicates that organic matter-specific concentrations are significantly correlated with the abundance of most major algal groups, and thus permit high-resolution reconstructions of algal abundance (Leavitt and Findlay, 1994; Leavitt et al., 1994).

Sediments contained more than 50 pigments, many of which were at low concentration or exhibited infrequent occurrence. We restricted our analysis to major taxonomically diagnostic pigments that identified cryptophytes (alloxanthin), siliceous algae and dinoflagellates (fucoxanthin), diatoms (diatoxanthin), total cyanobacteria (echinenone), colonial cyanobacteria (myxoxanthophyll), chlorophytes and cyanobacteria (lutein-zeaxanthin), and total algal abundance (β -carotene). Chlorophyll *b* and pheopigment derivatives (mainly pheophytin *b*) were used to distinguish green algae from cyanobacteria, whose carotenoid, zeaxanthin, was not separated from the chlorophyte pigment, lutein. Pheophytin and pheophorbide derivatives of chlorophyll *a* and chlorophyll *b* were prepared from pure pigments following the procedures of Leavitt et al. (1989). The distribution of carotenoids among algae was detailed in Goodwin (1980).

Plant macrofossils (R.E. Vance)

Samples were prepared for analysis of plant macrofossils by gently washing the sediment with tap water through nested sieves (No. 16, 60, and 80 mesh). Macrofossils were removed from organic residue and identified at 40x magnification using a stereoscopic microscope. Identifications were made using Martin and Barkley (1961), Beijerinck (1976), and Montgomery (1977), and were verified using the Geological Survey of Canada (GSC) Calgary macrofossil reference collection or vouchered specimens from the University of Calgary herbarium. Plant macrofossil abundance was expressed as remains per 100 mL whole sediment.

RESULTS AND DISCUSSION

Chronology and sedimentation rate

The rate of sediment accumulation was not constant in Clearwater Lake cores (Fig. 3), indicating that CRS dating models were most appropriate for estimation of sediment

chronology (Appleby and Oldfield, 1983; Turner, 1994; Blais et al., 1995). Replicate determinations of ^{210}Pb activity at 9.4 cm ($0.115 \pm 0.004 \text{ Bq}\cdot\text{g}^{-1}$) and 28.5 cm depth ($0.053 \pm 0.002 \text{ Bq}\cdot\text{g}^{-1}$) exhibited only small errors, suggesting that estimates of sediment age were reliable (e.g. AD 1983.3 ± 0.6 , 1949.5 ± 1.0 , respectively). Ages for sediments deposited before AD 1885 ± 5 (below 42.5 cm) were estimated from regressions of sediment depth and ^{210}Pb -derived age, and yielded an approximate basal date of AD 1570 for core CWS2 at 87 cm. Complete details of the ^{210}Pb results have been presented by Turner (1994).

Baseline sediment accumulation rates were relatively low ($0.05 \text{ g}\cdot\text{cm}^{-2}\cdot\text{a}^{-1}$) but increased four-fold during the period 1920–1975, coincident with intensification of European-style land use (Fig. 3). The most rapid dry mass accumulation occurred during the period 1960–1973. Since 1975, dry mass accumulation rates have declined, but have remained two-fold greater than background values. The average linear sedimentation rate ($\pm\text{SD}$) was relatively high ($0.65 \pm 0.27 \text{ cm}\cdot\text{a}^{-1}$) but comparable to rates reported for other northern Great Plains lakes ($0.14\text{--}0.95 \text{ cm}\cdot\text{a}^{-1}$; Lent et al. (1995), Laird et al. (1996a), Vinebrooke et al. (1998)).

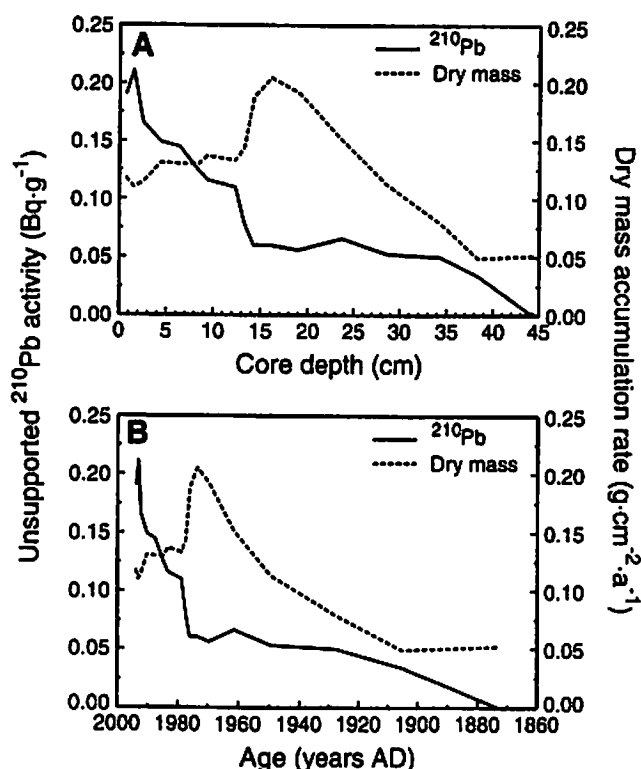


Figure 3. Unsupported ^{210}Pb activities in sediments and dry mass sediment accumulation rates in Clearwater Lake (core CWS1) as a function of A) burial depth and B) estimated age.

Lithostratigraphy

Remarkably few stratigraphic variations were observed in the major mineralogical components, particle-size attributes, and organic matter content (Fig. 4). In general, the composition of late Holocene sediments was similar to that of present-day offshore deposits (Table 2). Sediments consisted of subequal proportions of detrital siliciclastic minerals (mainly clay minerals, quartz, plagioclase), detrital carbonate minerals (dolomite, calcite), endogenic and authigenic carbonates (mainly aragonite), and organic matter. In addition, minor and trace amounts of pyrite, amphiboles, magnesite, gypsum, and Na-sulphates occurred sporadically. Sediments were consistently dominated by relatively fine-grained siliciclastics and detrital carbonates, with some endogenic or authigenic carbonate precipitates. Overall, these patterns provided little mineralogical or geochemical evidence of greatly altered salinity during the past approximately 400 years (Fig. 4).

Small stratigraphic changes in the proportion of magnesian calcite and protodolomite in endogenic and authigenic mineral fractions suggest that Mg/Ca ratios and water sources have fluctuated in the recent past, despite comparatively stable total salinity (Fig. 5). For example, the carbonate mineral assemblage of aragonite, protodolomite, and magnesite below 35 cm indicates high (>20) but variable Mg/Ca ratios and high carbonate alkalinities, with perhaps low sulphate concentrations, in the lake prior to 1930 (Folk and Land, 1975; Baker and Kastner, 1981; Last, 1990). In contrast, magnesian calcite, whose precipitation is encouraged by Mg/Ca ratios less than 10 (Eugster and Hardie, 1978), was restricted to depths of 5–25 cm (ca. 1960–1990). The occurrence of magnesian calcite only in these sediments indicates that the Mg/Ca ratio of Clearwater Lake has been variable but lower during the past three decades than earlier in the lake's history. Variation in Mg/Ca ratios most often arises from changes in relative proportion of water sources (e.g. surface vs. aquifer; Müller et al. (1972)) and signals alteration in the hydrological budget of Clearwater Lake during the period ca. 1960–1990. Finally, the increased abundance of protodolomite since 1990 indicates a recent return to present-day Mg/Ca ratios of approximately 20 (Fig. 4, Table 2). Overall, sediment mineralogy indicates a shift from higher Mg/Ca ratios before 1930 (>20), to lower ratios after 1960 (<10), and a recent return to pre-1930s values (Fig. 5), each reflecting changes in water inputs to the lake. Comparison of these results with an analysis of the previous 3500 years suggests that the recent Mg/Ca composition of Clearwater Lake has been unusually variable (W.M. Last, unpub. data, 1994).

The appearance of low levels of gypsum at depths of 45–60 cm may indicate a period of increased erosion or sediment redistribution prior to the arrival of ancestral Europeans (Fig. 5, Evaporites). Gypsum can precipitate in brines rich in Ca-sulphate, but only at salinities greater (i.e. $>10 \text{ g}\cdot\text{L}^{-1}$ TDS; Last (1994)) than those in Clearwater Lake at present (approx. $1 \text{ g}\cdot\text{L}^{-1}$ TDS) or since ca. 1600 ($0.3\text{--}0.6 \text{ g}\cdot\text{L}^{-1}$; see diatoms below). However, because gypsum is common in the glacial drift of The Missouri Coteau (Freeze, 1969; Wallick and Krouse, 1977), we infer that sedimentary deposits

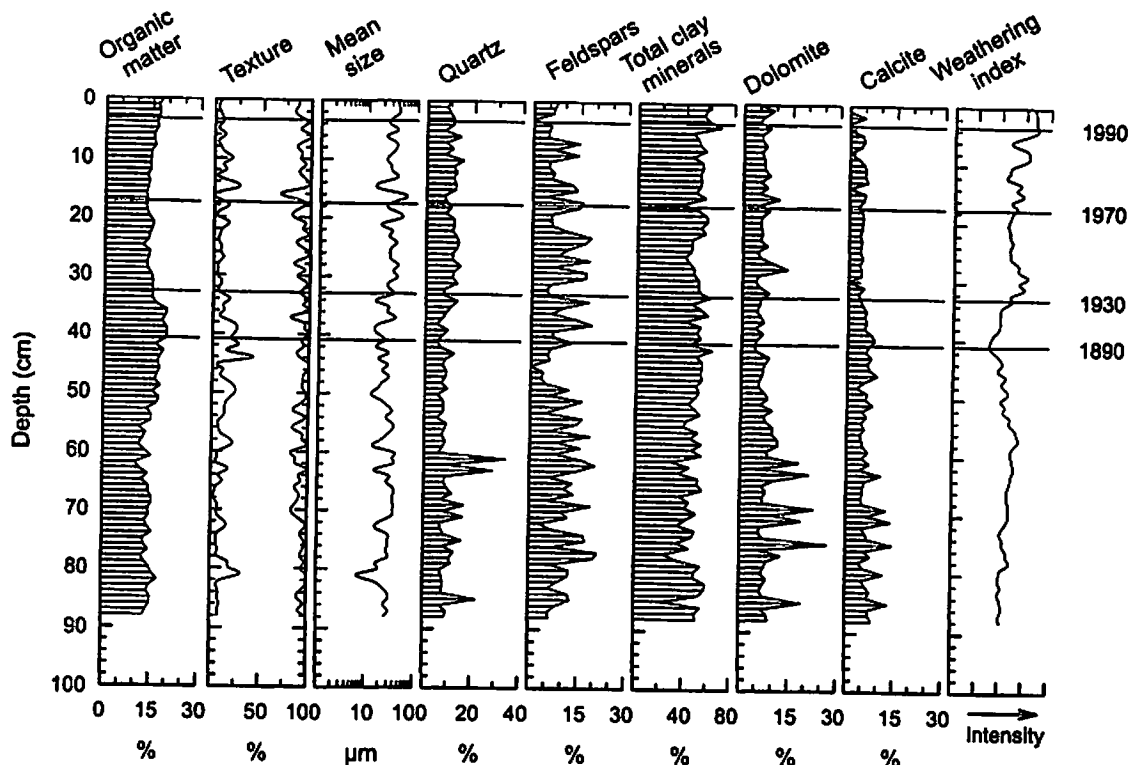


Figure 4. Stratigraphic variation in general physical properties and mineralogy of Clearwater Lake sediments (core CWS2). ^{210}Pb chronology is shown on right side of graphs.

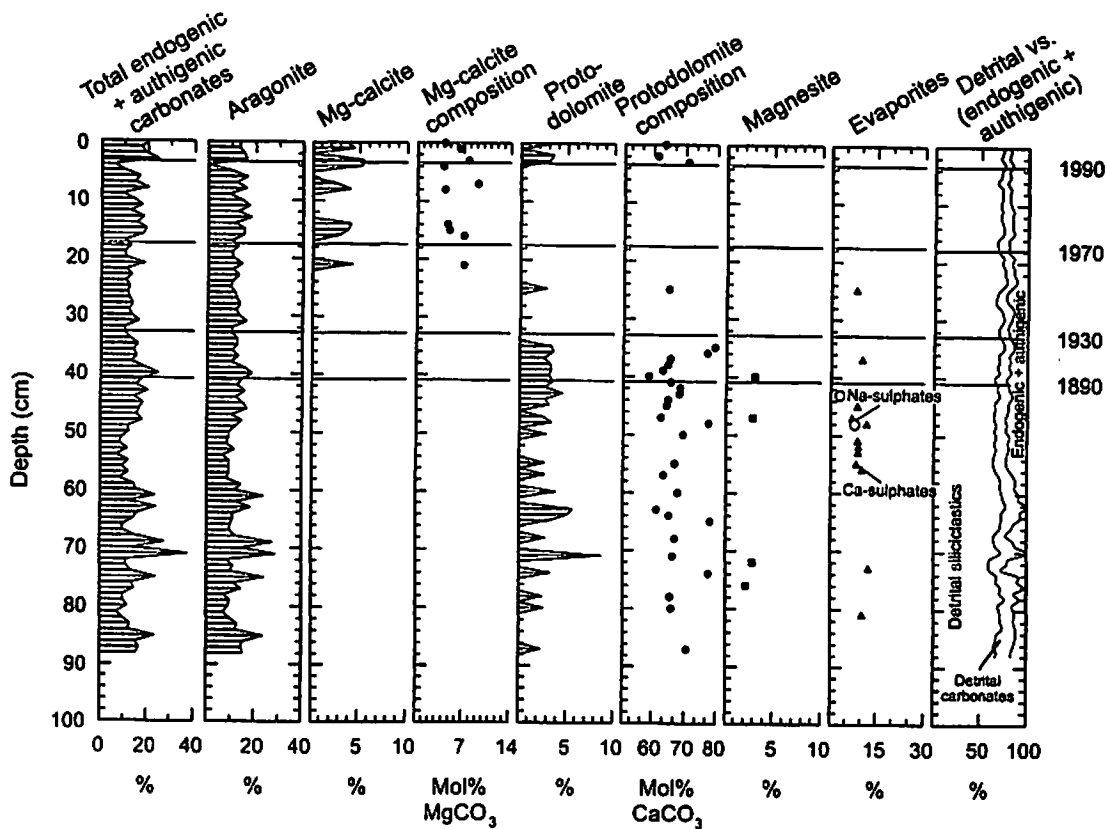


Figure 5. Stratigraphic variation in carbonate mineralogy of Clearwater Lake sediments (core CWS2). ^{210}Pb chronology as in Figure 4.

originated from catchment tills or from reworked shallow-water deposits, and not from endogenic precipitation during periods of high salinity.

The uniformity of the late Holocene lithostratigraphy in Clearwater Lake contrasts with the dramatic mineralogical and geochemical fluctuations that have occurred in other closed-basin lakes in the region (Last and Schweyen, 1985; Vance et al., 1992; van Stempvoort et al., 1993; Sack and Last, 1994; Vance et al., 1997). We attribute the stability of endogenic and authigenic mineralogy in Clearwater Lake to its hydrological setting. Because of an absence of surface-water flow at present (Fig. 2), we assume that the hydrological budget of the lake is dominated by groundwater discharge and recharge, factors that are known to control the major ion composition, salinity, and chemical sedimentology processes in other closed-basin lakes (Vance and Last, 1994). Such a groundwater influence might also moderate the effects of short-term variations in evaporation and precipitation that would otherwise regulate lake-water chemistry.

Diatoms

Diatom communities were composed predominantly of benthic taxa, reflecting the shallow nature of Clearwater Lake during the past 400 years (Fig. 6). Additionally, sedimentary assemblages consisted almost entirely of diatoms that are common in fresh ($<0.5 \text{ g} \cdot \text{L}^{-1} \text{ TDS}$) to subsaline ($0.5\text{--}3 \text{ g} \cdot \text{L}^{-1} \text{ TDS}$) waters (Wilson et al., 1994, 1996; Cumming et al., 1995). Consequently, overall diatom composition inferred that Clearwater Lake fluctuated within a narrow range of salinity despite periods of drought and documented water-level change (Fig. 2; Maybank et al., 1995).

Diatom analyses identified three periods of distinctly different species assemblages. Between ca. 1600 and 1920 (zone 1), diatoms consisted mainly of benthic taxa such as *Epithemia argus* (Ehrenb.) Kütz., *Amphora* cf. *pediculus* (Kütz.) Grun. ex A. Schmidt, *Gomphonema angustum* Agardh, *Cocconeis placentula* var. *euglypta* (Ehrenb.) Grun., *Cocconeis placentula* var. *lineata* (Ehrenb.) V.H., *Achnanthes minutissima* Kütz., *Fragilaria brevistriata* Grun.

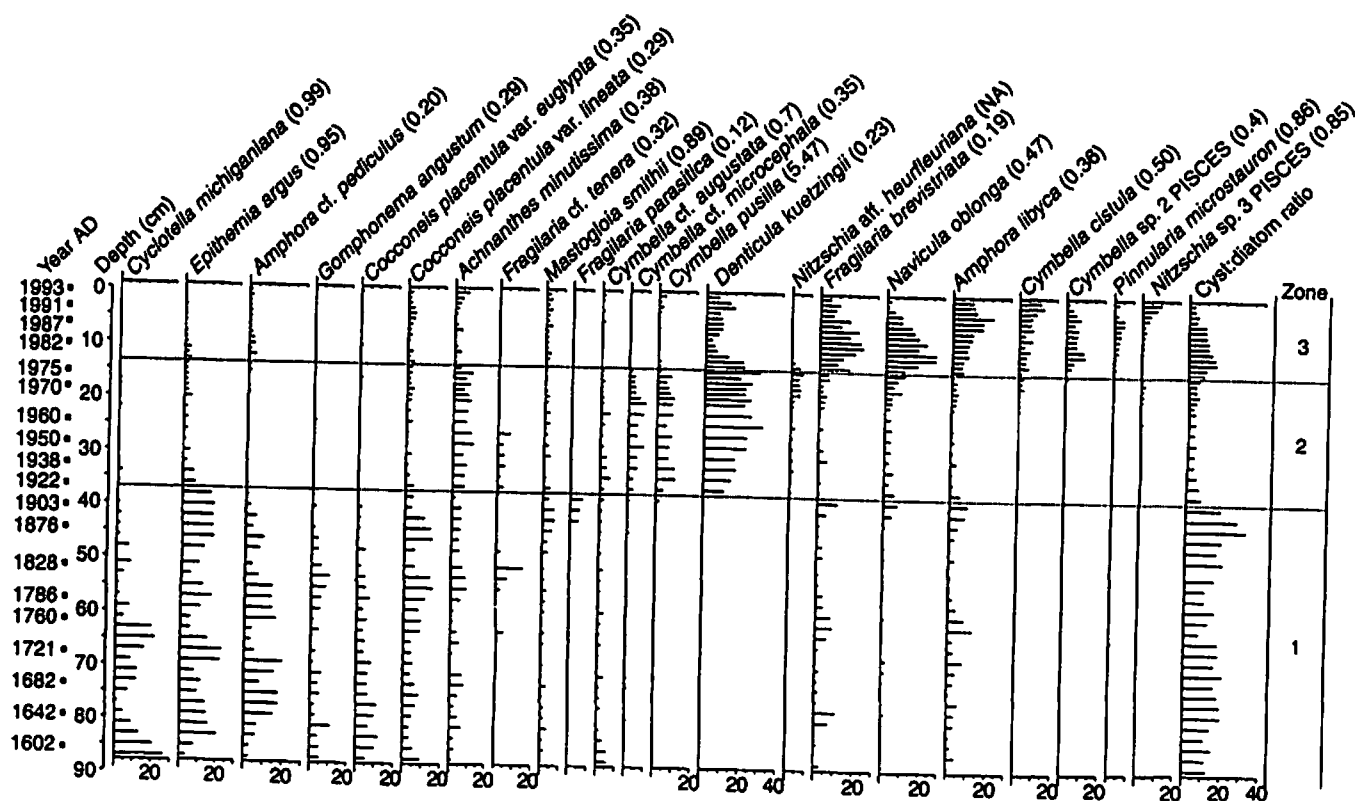


Figure 6. Stratigraphic variation in diatom taxa in Clearwater Lake sediments (core CWS2), showing taxa with greater than 5% relative abundance in at least two samples. Salinity optima ($\text{g (major ions)} \cdot \text{L}^{-1}$) for each taxon from Wilson et al. (1996). Taxa with the PISCES designation were documented from lakes sampled as part of the Paleolimnological Investigations of Salinity, Climatic, and Environmental Shifts (PISCES) project (Wilson et al., 1994; Cumming et al., 1995). Diatom zones determined by subjective analysis.

in V.H., and *Amphora libyca* Ehrenb. (Fig. 6, zone 1). The only common planktonic species, *Cyclotella michiganiana* Skvort., also reached its maximum abundance during zone 1, suggesting that the water column was deep enough to allow for a simple suspended community. Similarly, chrysophyte cyst abundance was high relative to that of diatom frustules (Fig. 6). Chrysophyte assemblages in temperate freshwater lakes consist primarily of planktonic species (Smol, 1995). Consequently, high cyst/frustule ratios, combined with some development of planktonic diatom populations, suggest that water levels were relatively high.

Striking changes in diatom community composition occurred shortly after 1920 and persisted until ca. 1977 (Fig. 6, zone 2). The abundances of most common taxa from zone 1 were reduced ca. 1922 as other species increased for the first time in this record, including *Denticula kuetzingii* Grun., *Cymbella pusilla* Grun. ex A. Schmidt, *Cymbella* cf. *microcephala* Grun. in V.H., *Cymbella* cf. *angustata* (W.Sm.) Cleve, and *Nitzschia* aff. *heurfleuriana*. While some of these changes suggest a rapid shift towards shallow saline conditions, the overall pattern is not consistent with major changes in salinity or climatic conditions. For example, both the appearance of hyposaline *Cymbella pusilla* (optimum = 5.5 g·L⁻¹ TDS; Wilson et al. (1996)) and a pronounced drop in the cyst:diatom ratio (Cumming et al., 1993) suggest that salinities were elevated during zone 2. Similarly, the loss of planktonic *Cyclotella michiganiana* and the decline in the cyst:diatom ratio possibly resulted from loss of pelagic habitats as the water level declined. However, the majority of taxa have salinity optima similar to those of species from zone 1 (Wilson et al., 1996), suggesting that community shifts did not arise from changes in lake-water salinity. Instead, we infer that these changes in species composition reflect alterations in ionic composition (Fritz et al., 1993; Cumming and Smol, 1993), such as that inferred from the mineralogical analysis of Clearwater Lake sediments (Fig. 5). Further, because diatom community change coincided with increased activities of ancestral European colonists on the Prairies (Hall et al., 1999), we infer that human land-use practices are the main agents of environmental change.

The third distinct diatom community occurred ca. 1977 to the present (Fig. 6). This period was marked by declines in *Denticula kuetzingii*, *Cymbella* cf. *microcephala*, *Cymbella* cf. *angustata*, and *Cymbella pusilla*, and increases in the relative abundances of *Fragilaria brevistriata*, *Navicula oblonga* (Kütz.) Kütz., *Amphora libyca*, *Cymbella cistula* (Ehrenb. in Hemp. and Ehrenb.) Kirchn., *Cymbella* sp. 2 PISCES, *Pinnularia microstauron* (Ehrenb.) Cleve, and *Nitzschia* sp. 3 PISCES. Although this assemblage has continued to the present, *Navicula oblonga* and *Fragilaria brevistriata* percentages have declined since the mid-1980s. These taxonomic changes coincided with multi-year drought (1987–1989; Jones (1991), Wheaton et al. (1992)) and lake-level decline (Fig. 2).

The diatom data suggest that Clearwater Lake has been relatively unresponsive to regional droughts during the past 150 years (Fig. 7). For example, severe droughts in western Canada during 1860 (Bark, 1978; Stockton and Meko, 1983; Case and MacDonald, 1995) and the early 1890s (Borchert,

1971; Bark, 1978; Jones, 1987) were not recorded by diatom-inferred salinity. Even the well documented droughts of the 1930s and 1980s (Evans and Prepas, 1996) resulted in few changes in diatom-inferred salinity. The observation that lake levels have recently declined (Fig. 2), yet diatom-inferred salinity has remained constant (Fig. 7) and similar to present-day values (approx. 1 g·L⁻¹ TDS), indicates that Clearwater Lake is not as sensitive to climatic fluctuations as are other prairie lakes (e.g. Fritz, 1990; Laird et al., 1996a, b). Overall, quantitative reconstruction of salinity from diatoms suggests that concentrations of major ions have been comparatively stable (0.3–0.6 g·L⁻¹ TDS), with only slightly elevated values during 1920–1940, 1700–1760, and 1580–1630.

Diatoms may have responded more strongly to changes in land-use practices and groundwater hydrology than to climate. The most dramatic shifts in diatom community composition coincided with inferred shifts in Mg/Ca ratios, elevated sediment accumulation rates, and the major influx of European settlers during the period 1906–1921 (Jones, 1987; Hall et al., 1999). Similarly, the shift in assemblages after ca. 1977 may reflect the end of the main phase of cottage development,

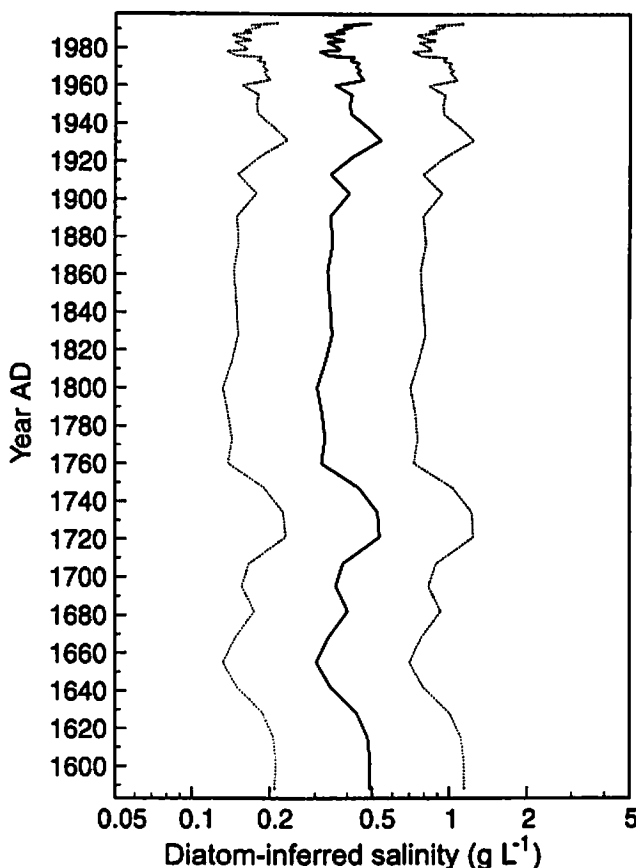


Figure 7. Diatom-inferred salinity for the period ca. AD 1600–present at Clearwater Lake (core CWS2). Salinity inferences were derived from a salinity transfer function developed from lakes in southern British Columbia and the northern Great Plains (Wilson et al., 1996). Inferred salinity values are mean bootstrap estimates and the errors (dotted lines) are estimated standard errors of prediction.

lake-level decline, or increased landscape development at the southeast park boundary (Fig. 2). Disturbance of terrestrial vegetation is known to increase erosional inputs of silicates and nutrients (Likens et al., 1970), and may have fertilized benthic diatom assemblages (Fritz, 1989; Håkansson and Regnéll, 1993; Anderson et al., 1995).

Algal pigments

Concentrations of ubiquitous pigments (e.g. β -carotene) in Clearwater Lake sediments have been variable during the last approximately 400 years (Fig. 8). The pigment β -carotene is a reliable marker of total phototroph abundance (Leavitt, 1993; Leavitt and Findlay, 1994) and its analysis suggested few directional changes in algal abundance. Instead, striking shifts in algal composition occurred since ca. 1920, based on changes in fossil concentrations of taxonomically diagnostic carotenoids and chlorophylls (Fig. 8). Specifically, pigments from chrysophytes, diatoms, and dinoflagellates (fucoxanthin, diatoxanthin) increased five-fold during the main period of European colonization ca. 1920 (Jones, 1987; Potyondi, 1995), whereas concentrations doubled for pigments from chlorophytes (chlorophyll *b*, lutein-zeaxanthin), cyanobacteria (echinenone, myxoxanthophyll, lutein-zeaxanthin), and cryptophytes (alloxanthin). These changes were likely unrelated to the modest inferred shifts in salinity (approx. 0.2 g-L^{-1} TDS; Fig. 7). Instead, pigment-inferred algal production may have been stimulated by transient increases in nutrients associated with initial changes in land-use.

Inferred eutrophication of Clearwater Lake was not sustained, and abundance of total algae, cyanobacteria, chlorophytes, and cryptophytes apparently declined to

pre-European settlement levels by 1970 (Fig. 8). Similar transient responses of algae to terrestrial disturbances have been recorded following deforestation (Smol et al., 1983; Sanger, 1988), fires (Schindler et al., 1990), and agriculture (Hurley et al., 1992; Hall et al., 1999). Unexpectedly, the abundance of diatoms, chrysophytes, and dinoflagellates are inferred to have remained two-fold greater than predisturbance levels, based on continued high concentrations of fucoxanthin and diatoxanthin. Overall, analysis of fossil pigments suggests that recent lake conditions have continued to stimulate production of benthic diatoms (Fig. 6, 8).

The recent water quality of Clearwater Lake has remained variable, with elevated concentrations of most pigments following 1970 (Fig. 8). While these data suggest that recreational or climatic changes since 1970 may have adversely affected water quality, the fossil patterns are also similar to artifacts produced by rapid postdepositional pigment degradation (Leavitt, 1993). In particular, the observation that most pigments show similar patterns of increase in uppermost sediments is consistent with rapid postdepositional losses, and argues for a cautious interpretation of recent stratigraphic variations in fossil pigments.

Plant macrofossils

Macrofossils consisted primarily of stonewort reproductive structures (oogonia) of the genus *Chara* (Fig. 9). Concentrations of oogonia began to increase at 20 cm (ca. 1970), peaked at 13 cm (ca. 1980), and then declined to values two-fold greater than baseline in the most recent sediments (1985–present). Charophytes are common in the littoral zones of a wide variety of lakes (Hutchinson, 1975) and are considered to be sensitive to environmental change, although

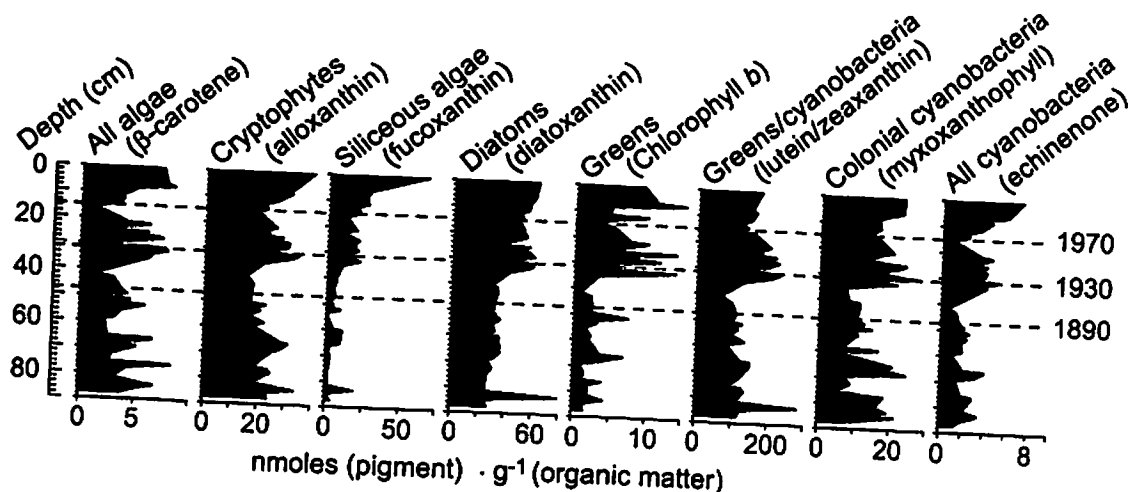


Figure 8. Stratigraphic variation in fossil pigment concentrations of Clearwater Lake sediments (core CWS2). Dashed lines indicate sediment age estimated from ^{210}Pb analysis. Indicator pigments include β -carotene (all algae), alloxanthin (cryptophytes), fucoxanthin (siliceous algae, some cyanobacteria), diatoxanthin (diatoms), chlorophyll *b* (green algae), lutein-zeaxanthin (green algae, cyanobacteria), myxoxanthophyll (colonial cyanobacteria), and echinenone (all cyanobacteria).

factors controlling their distribution are poorly understood (Garcia, 1994). A narrow band of thick *Chara* growth was observed in relatively shallow water (depth <2 m) near the northern shoreline of Clearwater Lake (R.E. Vance, unpub. data, 1993), suggesting that their distribution is limited to comparatively shallow waters. Unfortunately, it is difficult to interpret whether elevated charophyte remains signal a decline in lake level that allowed *Chara* closer to the coring site, or transient increases in water during the 1970s (Fig. 2)

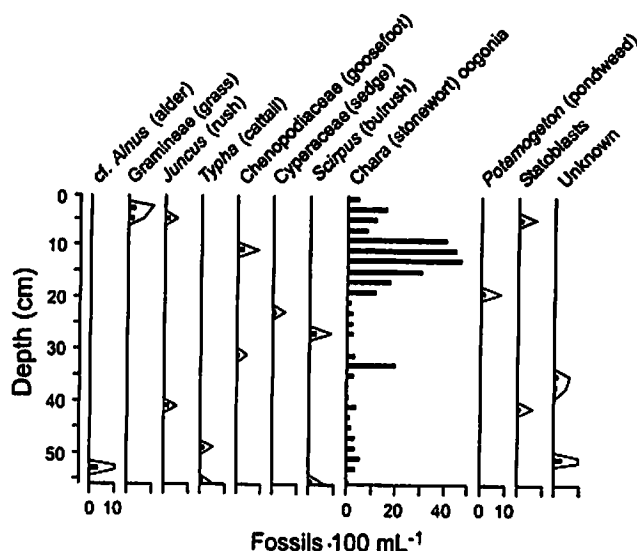


Figure 9. Stratigraphic variation in plant macrofossils of Clearwater Lake sediments (core CWS3). Grey shading represents five-fold exaggeration of concentration scale.

that increased the extent of the shallow water habitat. Further research is required to refine paleoecological interpretations based on remains of *Chara*.

CONCLUSIONS

Analysis of multiple proxy data (mineralogy, diatoms, pigments, and plant macrofossils) identified four main periods within the past 400 years and documented a transition from stable freshwater conditions (ca. AD 1600–1920) to shallow conditions of variable ionic composition (Table 3). The most recent period (1970–present) was characterized by rapid variations between magnesian calcite (1970–1990) and protodolomite (1990–present; Fig. 5), in lake level (Fig. 2), and in diatom composition (Fig. 6), although both diatoms and overall mineralogy infer little change in total salinity (Fig. 4, 7). During this period, the abundances of *Chara* (Fig. 9), siliceous algae (as fucoxanthin; Fig. 8), and chlorophytes (chlorophyll *b*) were comparatively great, particularly during the relatively high-water stands of the mid-1970s (Fig. 2). In contrast, the period 1940–1970 was marked by constant intermediate lake levels, relatively low inferred Mg/Ca ratios (<10), and declining concentrations of pigments from algae other than siliceous taxa or dinoflagellates (diatoxanthin, fucoxanthin; Fig. 8). These conditions may represent a slight increase in water level and declines in pigments when compared to the period 1920–1940. During that latter era, rural populations in Saskatchewan reached an historical maximum (Jones, 1987; Hall et al., 1999). Coincident with these changes, diatom abundance and species composition were fundamentally altered (Fig. 6) and pigment-inferred water quality declined (Fig. 8). Overall, the post-1920 fossil record suggests a distinctly different history than during the period

Table 3. Summary of the paleolimnological evidence of changing lake conditions in Clearwater Lake, Saskatchewan, ca. AD 1600–1993.

Time	Lake conditions	Lithology, mineralogy	Diatoms	Algal pigments	Plant macrofossils
1970s– present	Variable lake level (high in 1970s, low in 1980s)	Mg-calcite (1970–1990), protodolomite (1990); variable Mg:Ca ratio	Variable benthic diatom assemblages	High inferred biomass (chlorophytes, siliceous algae)	Increased <i>Chara</i> abundance (1970–1985)
1940–1970	Intermediate lake level	Little protodolomite or Mg-calcite; Mg:Ca ratio <10	No planktonic diatoms	Declining algal biomass; high diatom abundance	Few
1920–1940	Low lake level (late 1930s)	Protodolomite; Mg:Ca ratio >20	No planktonic species; shifts in benthic taxa with land use	Enhanced abundance of siliceous algae, chlorophytes, cyanobacteria	Few
pre-1920	Stable freshwater conditions; high water level	Protodolomite; Mg:Ca ratio >20	Freshwater taxa; planktonic <i>Cyclotella</i>	Variable algal abundance; low diatoms, chrysophytes, greens	Few

1600–1920, during which water levels and Mg/Ca ratios appeared to have been greater, but diatom and chlorophyte abundance was reduced (Table 3).

Although closed-basin prairie lakes are regarded as sensitive indicators of climatic change (Fritz, 1996), our findings suggest that basin-specific factors such as hydrological setting and human land-use history can moderate the effects of climate on lake chemistry and communities. For example, Clearwater Lake is uncharacteristically fresh (approx. $1 \text{ g} \cdot \text{L}^{-1}$ TDS) given the high precipitation deficit ($>400 \text{ mm} \cdot \text{a}^{-1}$) and continued climatic warming (Evans and Prepas, 1996). Vance and Last (1994) speculated that Clearwater Lake may be buffered against drought because of groundwater inputs similar to those reported for Harris Lake, Saskatchewan (Wilson et al., 1997). In addition, catchment disturbances arising from modern land-use and recreational activities appear to have influenced several fossil groups and may have obscured responses to recent climatic change. Consequently, we hypothesize that natural environmental perturbations which influence terrestrial characteristics (e.g. fire) may also alter lake conditions independent of direct climatic effects. Fortunately, the use of multiple paleolimnological indicators can help safeguard against erroneous paleoclimatic interpretations by distinguishing between climatic events and human activities as controls on lake ecosystem characteristics.

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REFERENCES

- Adams, R.H., Rosenwieg, C., Peart, R.M., Ritchie, J.T., McCarl, B.A., Glycer, J.D., Curry, R.B., Jones, J.W., Boote, K.J., and Allen, L.H.
1990: Global climate change and US agriculture; *Nature*, v. 345, p. 219–221.
- Aharonson, E.F., Karasikov, N., Rolter, M., and Shamir, J.
1986: GALAI-CIS-1 – a novel approach to aerosol particle size analysis; *Journal of Aerosol Science*, v. 17, p. 530–536.
- Allen, T.
1981: Particle Size Measurement; Chapman and Hall, Toronto, Ontario, 486 p. (third edition).
- Anderson, N.J., Renberg, I., and Segerström, U.
1995: Diatom production responses to the development of early agriculture in a boreal forest lake-catchment (Kassjön, northern Sweden); *Journal of Ecology*, v. 83, p. 809–822.
- Appleby, P.G. and Oldfield, F.
1978: The calculation of lead-210 dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment; *Catena*, v. 5, p. 1–8.
- 1983: The assessment of ^{210}Pb data from sites with varying sediment accumulation rates; *Hydrobiologia*, v. 103, p. 29–35.
- Baker, P.A. and Kastner, M.
1981: Constraints on the formation of sedimentary dolomite; *Science*, v. 213, p. 214–216.
- Bark, L.D.
1978: History of American droughts; in *North American Droughts*, (ed.) N.J. Rosenberg; American Association for the Advancement of Science, Selected Symposium 15, Westview Press Inc., Boulder, Colorado, p. 9–23.
- Beljers, W.
1976: Zadenatlas der Nederlandsche Flora: Ten Behoeve van de Botanische, Palaeontologie, Bodemcultuur en Warenkennis; Backhuys and Meesters, Amsterdam, The Netherlands, 316 p.
- Blais, J.M., Kalff, J., Cornett, R.J., and Evans, R.D.
1995: Evaluation of ^{210}Pb dating in lake sediments using stable Pb, *Ambrosia* pollen, and ^{137}Cs ; *Journal of Paleolimnology*, v. 13, p. 169–178.
- Borchert, J.R.
1971: The dust bowl in the 1970s; *Annals of the Association of American Geographers*, v. 61, p. 1–22.
- Canadian National Committee for the International Hydrologic Decade
1978: Hydrologic Atlas of Canada; Fisheries and Environment Canada, Ottawa, Ontario, 75 p.
- Case, R.A. and MacDonald, G.M.
1995: A dendroclimatic reconstruction of annual precipitation on the western Canadian Prairies since A.D. 1505 from *Pinus flexilis* James; *Quaternary Research*, v. 44, p. 267–275.
- Cumming, B.F. and Smol, J.P.
1993: Development of diatom-based salinity models for paleoclimatic research from lakes in British Columbia (Canada); *Hydrobiologia*, v. 269/270, p. 179–196.
- Cumming, B.F., Wilson, S.E., Hall, R.I., and Smol, J.P.
1995: Diatoms from British Columbia (Canada) and their relationship to salinity, nutrients, and other limnological variables; *Bibliotheca Diatomologica Band 31*; Gebrüder Borntraeger, Berlin/Stuttgart, Germany, 207 p.
- Cumming, B.F., Wilson, S.E., and Smol, J.P.
1993: Paleolimnological potential of chrysophyte cysts and scales and of sponge spicules as indicators of lake salinity; *International Journal of Salt Lake Research*, v. 2, p. 87–92.
- Dean, W.E.
1974: Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods; *Journal of Sedimentary Petrology*, v. 44, p. 242–248.
- El-Ashry, M. and Gibbons, D.C.
1988: Water and Arid Lands of the Western United States; Cambridge University Press, Cambridge, Massachusetts, 415 p.
- Eugster, H.P. and Hardie, L.A.
1978: Saline lakes; in *Lakes – Chemistry, Geology, Physics*, (ed.) A. Lerman; Springer-Verlag, New York, p. 237–293.
- Evans, J.C. and Prepas, E.E.
1996: Potential effects of climate change on ion chemistry and phytoplankton communities in prairie saline lakes; *Limnology and Oceanography*, v. 41, p. 1063–1076.
- Folk, R.L. and Land, L.S.
1975: Mg/Ca ratio and salinity: two controls over crystallization of dolomite; *American Association of Petroleum Geologists Bulletin*, v. 59, p. 60–68.
- Freeze, R.A.
1969: Regional groundwater flow — Old Wives Lake drainage basin, Saskatchewan; Department of Energy, Mines and Resources, Canada, Inland Waters Branch, Scientific Series, v. 5, 245 p.
- Fritz, S.C.
1989: Lake development and limnological response to prehistoric and historic land-use in Diss, Norfolk, U.K.; *Journal of Ecology*, v. 77, p. 182–202.
- 1990: Twentieth-century salinity and water-level fluctuations in Devils Lake, North Dakota: test of a diatom-based transfer function; *Limnology and Oceanography*, v. 35, p. 1771–1781.
- 1996: Paleolimnological records of climatic change in North America; *Limnology and Oceanography*, v. 41, p. 882–889.
- Fritz, S.C., Engstrom, D.R., and Haskell, B.J.
1994: 'Little Ice Age' aridity in the North American Great Plains: a high resolution reconstruction of salinity fluctuations from Devils Lake, North Dakota, USA; *The Holocene*, v. 4, p. 69–73.

- Fritz, S.C., Juggins, S., and Battarbee, R.W.
1993: Diatom assemblages and ionic characterization of lakes of the northern Great Plains, North America: a tool for reconstructing past salinity and climate fluctuations; *Canadian Journal of Fisheries and Aquatic Sciences*, v. 50, p. 1844-1856.
- Fritz, S.C., Juggins, S., Battarbee, R.W., and Engstrom, D.R.
1991: Reconstruction of past changes in salinity and climate using a diatom-based transfer function; *Nature*, v. 352, p. 706-708.
- Garcia, A.
1994: Charophyta: their use in paleolimnology; *Journal of Paleolimnology*, v. 10, p. 43-52.
- Gasse, F., Juggins, S., and Ben Khellifa, L.
1995: Diatom-based transfer functions for inferring past hydrochemical characteristics of African lakes; *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 117, p. 31-57.
- Gleick, P.H.
1989: Climate change, hydrology, and water resources; *Reviews in Geophysics*, v. 27, p. 329-344.
- Goldsmith, J.R. and Graf, D.L.
1958: Relation between lattice constants and composition of the Ca-Mg carbonates; *American Mineralogist*, v. 43, p. 84-101.
- Goodwin, T.W. (ed).
1980: *The Biochemistry of the Carotenoids, Volume 1. Plants*; Chapman and Hall, London, United Kingdom, 377 p.
- Gullett, D.W. and Skinner, W.R.
1992: The state of Canada's climate: temperature change in Canada 1985-1991; Environment Canada, Atmospheric Environment Service, State of the Environment Report No. 92-2, 36 p.
- Håkansson, H. and Regnéll, J.
1993: Diatom succession related to land use during the last 600 years: a study of a small eutrophic lake in southern Sweden; *Journal of Paleolimnology*, v. 8, p. 49-69.
- Hall, R.L., Leavitt, P.R., Quinlan, R., Dixit, A.S., and Smol, J.P.
1999: Effects of agriculture, urbanization and climate on water quality in the northern Great Plains; *Limnology and Oceanography*, v. 43, p. 739-756.
- Hammer, U.T.
1990: The effects of climate change on the salinity, water levels and biota of Canadian prairie saline lakes; *Verhandlungen der Internationale Vereinigung für Angewandte und Theoretische Limnologie*, v. 24, p. 321-326.
- Hammer, U.T., Shames, J., and Haynes, R.C.
1983: The distribution and abundance of algae in saline lakes of Saskatchewan; *Hydrobiologia*, v. 105, p. 1-26.
- Hardy, R. and Tucker, M.
1988: X-ray diffraction of sediments; in *Techniques in Sedimentology*, (ed.) M. Tucker; Blackwell Scientific Publishers, Boston, Massachusetts, p. 191-228.
- Hurley, J.P., Armstrong, D.E., and DuVall, A.L.
1992: Historical interpretation of pigment stratigraphy in Lake Mendota sediments; in *Food Web Management*, (ed.) J.F. Kitchell; Springer-Verlag, New York, p. 49-68.
- Hutchinson, G.E.
1975: *A Treatise on Limnology, Volume III, Limnological Botany*; John Wiley and Sons, New York, 660 p.
- Jones, D.C.
1987: *Empire of Dust*; University of Alberta Press, Edmonton, Alberta, 316 p.
- Jones, K.H.
1991: Drought on the Prairies; in *Symposium on the Impacts of Climatic Change and Variability on the Great Plains (1990: Calgary, Alberta)*, (ed.) G. Wall; Department of Geography, University of Waterloo, Waterloo, Ontario, p. 125-129.
- Klug, H.P. and Alexander, L.E.
1974: X-ray Diffraction Procedures for Polycrystalline and Amorphous Materials; John Wiley and Sons, New York, 346 p.
- Krammer, K. and Lange-Bertalot, H.
1986: Bacillariophyceae. 1. Teil: Naviculaceae; in *Süßwasserflora von Mitteleuropa, Band 2/1*, (ed.) H. Ettl, J. Gerloff, H. Heynig, and D. Mollenhauer; Gustav Fischer Verlag, Stuttgart, Germany, 876 p.
- 1988: Bacillariophyceae. 2. Teil: Bacillariaceae, Epithemiaceae, Surirellaceae; in *Süßwasserflora von Mitteleuropa, Band 2/2*, (ed.) H. Ettl, J. Gerloff, H. Heynig, and D. Mollenhauer; Gustav Fischer Verlag, Stuttgart, Germany, 611 p.
- Laird, K.R., Fritz, S.C., Grimm, E.C., and Mueller, P.O.
1996a: Century-scale paleoclimatic reconstruction from Moon Lake, a closed-basin lake in the northern Great Plains; *Limnology and Oceanography*, v. 41, p. 890-902.
- Laird, K.R., Fritz, S.C., Maasch, K.A., and Cumming, B.F.
1996b: Greater drought intensity before AD 1200 in the northern Great Plains, USA; *Nature*, v. 384, p. 552-554.
- Last, W.M.
1990: Lacustrine dolomite - an overview of modern, Holocene, and Pleistocene occurrences; *Earth Science Reviews*, v. 27, p. 221-263.
- 1994: Paleohydrology of playas in the northern Great Plains: perspectives from Palliser's Triangle; in *Paleoclimate and Basin Evolution of Playa Systems*, (ed.) M.R. Rosen; Geological Society of America, Special Paper 289, p. 69-80.
- Last, W.M. and Schwenen, T.H.
1985: Late Holocene history of Waldsea Lake, Saskatchewan, Canada; *Quaternary Research*, v. 24, p. 219-234.
- Leavitt, P.R.
1993: A review of factors that regulate carotenoid and chlorophyll deposition and fossil pigment abundance; *Journal of Paleolimnology*, v. 9, p. 109-127.
- Leavitt, P.R. and Flindlay, D.L.
1994: Comparison of fossil pigments with 20 years of phytoplankton data from eutrophic Lake 227, Experimental Lakes Area, Ontario; *Canadian Journal of Fisheries and Aquatic Sciences*, v. 51, p. 2286-2299.
- Leavitt, P.R., Carpenter, S.R., and Kitchell, J.F.
1989: Whole-lake experiments: the annual record of fossil pigments and zooplankton; *Limnology and Oceanography*, v. 34, p. 700-717.
- Leavitt, P.R., Hann, B.J., Smol, J.P., Zeeb, B.A., Christie, C.E., Wolfe, B., and Kling, H.J.
1994: Paleolimnological analysis of whole-lake experiments: an overview of results from Experimental Lakes Area Lake 227; *Canadian Journal of Fisheries and Aquatic Sciences*, v. 51, p. 2322-2332.
- Lemmen, D.S., Dyke, L.D., and Edlund, S.A.
1993: The Geological Survey of Canada's Integrated Research and Monitoring Area (IRMA) projects: a contribution to Canadian global change research; *Journal of Paleolimnology*, v. 9, p. 77-83.
- Lent, R., Lyons, W.B., Showers, W.J., and Johannesson, K.H.
1995: Late Holocene paleoclimatic and paleobiologic records from sediments of Devil's Lake, North Dakota; *Journal of Paleolimnology*, v. 13, p. 193-207.
- Likens, G.E., Bormann, F.H., Johnson, N.M., Fisher, D.W., and Pierce, R.S.
1970: Effects of forest cutting and herbicide treatment on nutrient budgets in Hubbard Brook watershed-ecosystem; *Ecological Monographs*, v. 40, p. 23-47.
- Line, J.M., ter Braak, C.J.F., and Birks, H.J.B.
1994: WACALIB version 3.3 - a computer program to reconstruct environmental variables from fossil assemblages by weighted averaging and to derive sample-specific errors of prediction; *Journal of Paleolimnology*, v. 10, p. 147-152.
- Marino, R., Howarth, R.W., Shames, J., and Prepas, E.E.
1990: Molybdenum and sulfate as controls of the abundance of nitrogen-fixing cyanobacteria in saline lakes in Alberta; *Limnology and Oceanography*, v. 35, p. 245-259.
- Marquart, R.G.
1986: μ PDSM: mainframe search/match on an IBM PC; *Powder Diffraction*, v. 1, p. 34-36.
- Martin, A.C. and Barkley, W.D.
1961: *Seed Identification Manual*; University of California Press, Berkeley, California, 220 p.
- Maybank, J., Bonsal, B., Jones, K., Lawford, R., O'Brien, E.G., Ripley, E.A., and Wheaton, E.
1995: Drought as a natural disaster; *Atmospheric-Ocean*, v. 33, p. 195-222.
- Meko, D.M.
1992: Dendroclimatic evidence from the Great Plains of the United States; in *Climate Since AD 1500*, (ed.) R.S. Bradley and P.D. Jones; Routledge, New York, p. 312-330.
- Montgomery, F.H.
1977: *Seeds and Fruits of Plants of Eastern Canada and Northeastern United States*; University of Toronto Press, Toronto, Ontario, 232 p.
- Müller, G., Irion, G., and Förstner, U.
1972: Formation and diagenesis of inorganic Ca-Mg carbonates in the lacustrine environment; *Naturwissenschaften*, v. 59, p. 159-164.

- Potyondl, B.
1995: In *Palliser's Triangle: Living in the Grasslands 1850-1930*; Purich Publishing, Saskatoon, Saskatchewan, 143 p.
- Sack, L.A. and Last, W.M.
1994: Lithostratigraphy and recent sedimentation history of Little Manitou Lake, Saskatchewan, Canada; *Journal of Paleolimnology*, v. 10, p. 199-212.
- Sanger, J.E.
1988: Fossil pigments in paleoecology and paleolimnology; *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 62, p. 343-359.
- Schindler, D.W., Beatty, K.G., Fee, E.J., Cruikshank, D.R., DeBruyn, E.R., Findlay, D.L., Lindsay, G.A., Shearer, J.A., Stainton, M.P., and Turner, M.A.
1990: Effects of climatic warming on lakes of the central boreal forest; *Science*, v. 250, p. 967-970.
- Schultz, L.G.
1964: Quantitative interpretation of mineralogical composition from X-ray and chemical data for the Pierre Shale; United States Geological Survey, Professional Paper 391-C, 31 p.
- Smol, J.P.
1985: The ratio of diatom frustules to chrysophyte statospores: a useful paleolimnological index; *Hydrobiologia*, v. 123, p. 199-208.
1995: Application of chrysophytes to problems in paleoecology; in *Chrysophyte Algae: Ecology, Phylogeny and Development*, (ed.) C.D. Sandgren, J.P. Smol, and J. Kristiansen; Cambridge University Press, Cambridge, United Kingdom, p. 303-330.
- Smol, J.P., Brown, S.R., and McNeely, R.N.
1983: Cultural disturbances and trophic history of a small meromictic lake from central Canada; *Hydrobiologia*, v. 103, p. 125-130.
- Stockton, C.W. and Meko, D.W.
1983: Drought recurrence in the Great Plains as reconstructed from long-term tree-ring records; *Journal of Climate and Applied Meteorology*, v. 22, p. 17-29.
- Teller, J.T. and Last, W.M.
1990: Paleohydrological indicators in playas and salt lakes, with examples from Canada, Australia, and Africa; *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 76, p. 215-240.
- Torgersen, T., DeDekker, P., Chivas, A.R., and Bowler, J.M.
1986: Salt lakes: a discussion of processes influencing paleoenvironmental interpretation and recommendations; *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 54, p. 7-19.
- Turner, L.J.
1994: ^{210}Pb dating of lacustrine sediments from Clearwater Lake (Core 064, Station CWS1), Saskatchewan; National Water Research Institute, Burlington, Ontario, Contribution 94-141, 27 p.
- Vance, R.E.
1997: The Geological Survey of Canada's Palliser Triangle Global Change Project: a multidisciplinary geolimnological approach to predicting potential global change impacts on the northern Great Plains; *Journal of Paleolimnology*, v. 17, p. 3-8.
- Vance, R.E. and Last, W.M.
1994: Paleolimnology and global change on the southern Canadian Prairies; in *Current Research 1994-B: Geological Survey of Canada*, p. 49-58.
- Vance, R.E. and Last, W.M. (cont.)
1996: Stop 31: Clearwater Lake; in *Landscapes of the Palliser Triangle. Guidebook for the Canadian Geomorphology Research Group Field Trip*, (ed.) D.S. Lemmen; Canadian Association of Geographers, 1996 Annual Meeting, Saskatoon, Saskatchewan, p. 78-79.
- Vance, R.E. and Mathewes, R.W.
1994: Deposition of modern pollen and plant macroremains in a hypersaline prairie lake basin; *Canadian Journal of Botany*, v. 72, p. 539-548.
- Vance, R.E., Last, W.M., and Smith, A.J.
1997: Hydrologic and climatic implications of a multidisciplinary study of Holocene sediment from Kenosee Lake, southeastern Saskatchewan, Canada; *Journal of Paleolimnology*, v. 18, p. 365-393.
- Vance, R.E., Mathewes, R.W., and Clague, J.J.
1992: 7000 year record of lake-level change on the northern Great Plains: a high-resolution proxy of past climate; *Geology*, v. 20, p. 879-882.
- van Stempvoort, D.R., Edwards, T.W.D., Evans, M.S., and Last, W.M.
1993: Paleohydrology and paleoclimate records in a saline prairie lake core: mineral, isotope and organic indicators; *Journal of Paleolimnology*, v. 8, p. 135-147.
- Vinebrooke, R.D., Hall, R.I., Leavitt, P.R., and Cumming, B.F.
1998: Fossil pigments as indicators of phototrophic response to salinity and climatic change in lakes of western Canada; *Canadian Journal of Fisheries and Aquatic Sciences*, v. 55, p. 668-681.
- Wallick, E.I. and Krouse, H.R.
1977: Sulfur isotope geochemistry of a groundwater-generated $\text{Na}_2\text{SO}_4/\text{Na}_2\text{CO}_3$ deposit and the associated drainage basin of Horseshoe Lake, Metiskow, east-central Alberta, Canada; in *The Second International Symposium on Water-Rock Interaction*, Strasbourg, France, p. 1156-1164.
- Wheaton, E.E., Arthur, L.M., Chorney, B., Shewchuk, S., Thorpe, J., Whiting, J., and Wittrock, V.
1992: The Prairie drought of 1988; *Climatological Bulletin*, v. 26, p. 188-205.
- Wiche, G.J.
1986: Hydrologic and climatologic factors affecting water levels in Devil's Lake, North Dakota; United States Geological Survey, Water Research Investigations Report 86-4320, 86 p.
- Will, G.F.
1946: Tree ring studies in North Dakota; North Dakota Agricultural Experiment Station, Bulletin 338, p. 1-24.
- Wilson, S.E., Cumming, B.F., and Smol, J.P.
1994: Diatom-salinity relationships in 111 lakes from the Interior Plateau of British Columbia, Canada: the development of diatom-based models for paleosalinity reconstructions; *Journal of Paleolimnology*, v. 12, p. 197-221.
- 1996: Assessing the reliability of salinity inference models from diatom assemblages: an examination of a 219 lake data set from western North America; *Canadian Journal of Fisheries and Aquatic Sciences*, v. 53, p. 1580-1594.
- Wilson, S.E., Smol, J.P., and Sauchyn, D.J.
1997: A Holocene paleosalinity diatom record from southwestern Saskatchewan, Canada: Harris Lake revisited; *Journal of Paleolimnology*, v. 17, p. 23-31.