Reconstruction of Holocene lake level from diatoms, chrysophytes and organic matter in a drainage lake from the Experimental Lakes Area (northwestern Ontario, Canada)

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Abstract

A paleolimnological study of lake-level changes in Lake 239 (Rawson Lake), a headwater lake in the Experimental Lakes Area in northwestern Ontario, indicates large fluctuations have occurred over the Holocene. Analyses are based on diatoms, the proportion of chrysophyte scales to diatoms and organic matter content from near-shore sediment cores. Quantitative estimates of lake level are based on a diatom-inferred depth model that was developed from surficial sediments collected along several transects in Lake 239. Declines of ∼1–3 m occurred during the late Holocene, whereas declines of at least 8 m occurred during the more arid mid-Holocene. These results provide the first substantive evidence of large declines in lake level in northwestern Ontario during the mid-Holocene. Conditions during the mid-Holocene may provide a partial view of future conditions under increasing global temperatures.
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Introduction

Numerous studies indicate that the droughts of the 20th century in western North America and the northern Great Plains were shorter and less extreme than those that occurred during the past several thousand years (e.g., Laird et al., 2003; Woodhouse, 2004; Cook et al., 2007) and represent only a small subset of the range in natural climatic variability, even in comparison to the last few centuries (St. George and Nielsen, 2002; Case and MacDonald, 2003; Sauchyn et al., 2003). In arid and semi-arid regions, many studies have used sediment records from topographically closed-basin lakes to infer past climatic conditions (e.g., Fritz, 1996; Fritz et al., 1999). Whereas, in

more humid regions, the response of drainage lakes (i.e., lakes that have a surface outflow) to climatic conditions is more complex and the extent to which they respond can be difficult to estimate from sediment records (Smol and Cumming, 2000).

Studies from the Experimental Lakes Area (ELA) in northwestern Ontario indicate that many drainage lakes in this region showed marked climate-induced changes during an extended period of drier and warmer conditions during the 1970s and 1980s (Schindler et al., 1996; Schindler, 1997; Findlay et al., 2001). Impacts on lake ecosystems included warmer temperatures, clearer waters due to reduced inputs of DOC from the catchments, deeper thermoclines, increased water renewal time and declines in lake level, although small. The responsiveness of Rawson Lake (ELA Lake 239) to these recent drought conditions suggests that a longer-term history of climatic conditions may be archived in the sedimentary record.

ELA lies within the Winnipeg River Drainage Basin, which provides a major component of the hydroelectric power generation system of Manitoba Hydro (St. George, 2007). Long-term planning for future extremes is currently only based on ∼80–100 yr instrumental records. Little is known about the

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past climate of this region. A few Holocene pollen records exist within the basin (McAndrews, 1982; Kronberg et al., 1998) and to the east (Björck, 1985), along with studies of the history of deglaciation and Lake Agassiz (e.g., Bajc et al., 2000). Recently, a network of tree rings was developed to provide a 200- to 300-yr perspective on drought conditions throughout the basin (St. George, 2007).

Here we present a multi-proxy study of lake-level changes in ELA Lake 239 over the Holocene based on analyses of diatoms, the proportion of scaled chrysophytes to diatom valves and organic matter content from near-shore sediment cores based on a modified Digerfeldt (1986) method. Quantitative estimates of lake level are based on a diatom-inferred depth model that we developed specifically for Lake 239 from surface samples collected along several littoral to pelagic depth transects. The aim of this paper is to provide substantive evidence for large declines in effective moisture (the balance between precipitation and evaporation) in northwestern Ontario during the mid-Holocene, as well as lower declines over the past ~3000 yr. Inferred conditions during the late and/or mid-Holocene may provide a partial analogue of potential future conditions as the estimated increases in temperature during the mid-Holocene are often what is projected for Ontario under increasing CO_2 conditions (1–2°C) (IPCC, 2007).

Study site

Lake 239 (Rawson Lake) is a headwater lake located within the Experimental Lakes Area (ELA) (49°40′N, 93°44′W) in northwestern Ontario (Fig. 1a) and has been one of the primary reference lakes at ELA since its inception in 1968 (Johnson and Vallentyne, 1971). It is a relatively small lake (surface area ~56 ha), with a catchment of ~240 ha and a maximum depth of ~32 m (Fig. 1b). Limnological monitoring data from Lake 239 are extensive and have formed the basis of numerous studies of climatic effects on lake ecosystems (e.g., Schindler et al., 1996; Findlay et al., 2001). The drainage system of Lake 239 flows into Lake of the Woods, which flows into Lake Winnipeg via the Winnipeg River and eventually into the Hudson Bay drainage system (Schindler et al., 1996). The region is dominated by boreal tree species such as jack pine (*Pinus banksiana*) and black spruce (*Picea mariana*). Precambrian shield underlies the area with bedrock dominated by pink granodiorite (granite). Soils are categorized as thin and mostly moss covered (Schindler et al., 1996).

Surface-sample analyses along littoral to pelagic depth transects

Two main approaches using diatom assemblages have been used in an attempt to reconstruct lake level in drainage lakes: (1) analysis of the distribution of diatoms across a suite of lakes along a depth gradient and (2) analysis of the distribution of diatoms from the shallow littoral zone to the deeper pelagic zone within the study lake. Calibration sets of diatom assemblages from surface samples across a suite of lakes have been used to qualitatively assess lake-level changes and quantitatively using

inference models based on statistical methods, such as weighted averaging (e.g., Yang and Duthie, 1995; Brugam et al., 1998). However, there can be complex interactions between the distribution of diatoms with depth and the distribution of aquatic macrophytes, water clarity, as well as other variables (e.g., Brugam et al., 1998; Moser et al., 2000). As a consequence, some predictive models for depth reconstruction based on a suite of lakes may not be that strong and are not always applicable to the lake under investigation. A number of studies have used the relationship between the distribution of diatom species assemblages and water depth within the study lake as a basis for reconstruction of changes in past lake levels (e.g., Yang and Duthie, 1995; Brugam et al., 1998; Nguetsop et al., 2004). These studies, along with this study and our recent analysis of samples along a depth gradient in ELA Lake 239 (Moos et al., 2005), clearly indicate that the distribution of diatom species within a lake basin are related to changes in water depth and can be used to infer past fluctuations in lake level.

As lake level declines, the sediment limit or depositional boundary depth (i.e., the lower edge of the littoral zone) will move towards the center of the lake (Dearing, 1997). Analysis of near-shore cores can provide a means of tracking the changes in the position of the sediment limit and thus infer periods of lower lake level. The amount of organic matter (OM) in sediments can vary tremendously between lakes; however, within a lake, the profundal sediments (deep sediments) vary little (2–5%), whereas large changes in OM occur at the boundary of the near-shore littoral zone (Shuman, 2003). Thus, a series of surface samples across the depth gradient within the study lake can determine where the present-day sediment limit is and the percent of OM in the profundal zone.

Analysis of near-shore cores and multiple lines of evidence of lake-level changes

One of the most common methods used for tracking changes in shoreline location has been the Digerfeldt (1986) method, a technique used to track sedimentary units across a transect of cores sampled from the shore towards the center of the lake. Multiple lines of evidence are needed to have confidence in inferred lake-level changes using marginal sediments (Digerfeldt, 1986; Digerfeldt et al., 1992; Dearing, 1997). In our analyses of sediment cores from ELA Lake 239, we used diatom composition, the proportion of scaled chrysophytes to diatom valves and percent OM analyses from near-shore cores to infer changes in past lake levels. This combination of proxies, along with the modern surface-sample analyses of diatoms and OM, has proved to be a robust means of inferring past lake levels in Lake 239.

Many of the characteristics of Lake 239 fall within the general characteristics of lakes that seem to be the best candidates for using the Digerfeldt method. Lakes that tend to preserve Digerfeldt's lines of evidence for lake-level change typically are small (<50 ha), relatively shallow (<10 m max depth) and have a catchment area to lake area ratio of <5:1 (Dearing, 1997). Lake 239 is ~56 ha and has a catchment: lake ratio of 4.3. However, its maximum depth falls much outside of the typical
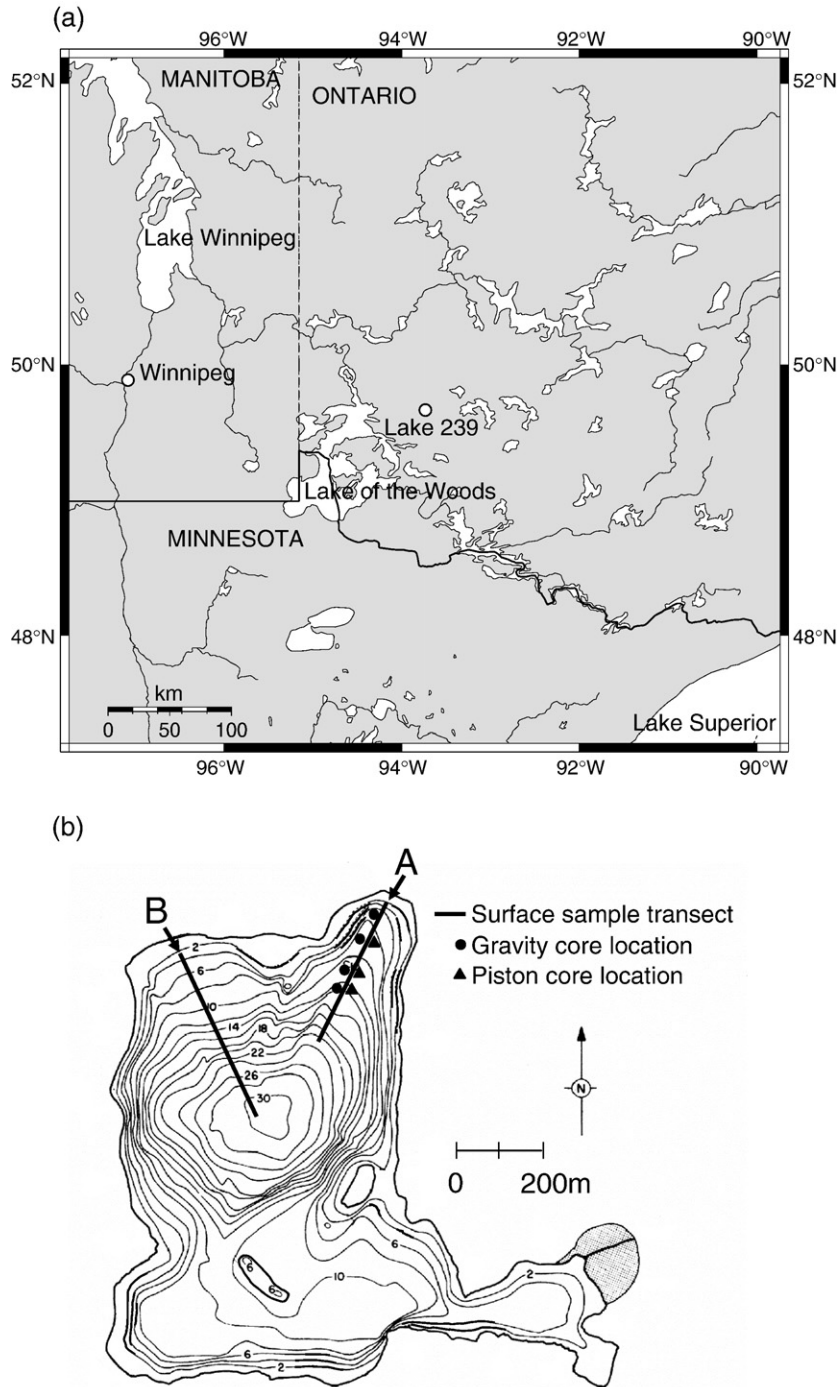
Figure 1. Location of Lake 239 (a) and bathymetric map indicating transect and core locations (b).

'Digerfeldt lake' at ~ 32 m. This suggests, that at least in the case of Lake 239, it is the clearly defined sedimentation limits, which we base on our analysis of surface samples along a depth transect of OM and diatoms, and the location of our near-shore cores along a relatively shallow underwater slope that proved successful. In addition, direct groundwater flow to Lake 239 is negligible (Schindler et al., 1996), and thus groundwater interactions likely did not complicate the lake-level reconstructions (e.g., Digerfeldt et al., 1992).

Methods

Sampling

A series of surface samples, gravity cores and piston cores were collected in July 2004 from the near-shore sediments of the northeast basin (Fig. 1b, Transect A). The location of the near-shore cores was based on high-resolution seismic reflection data (e.g., Lewis et al., 2001), enabling us to choose an area

that had the greatest near-shore sediment deposition along a relatively gentle slope. The surface samples (∼0.5-cm interval) consisted of two replicate samples collected approximately every 2 m with a modified K-B corer (Glew, 1989) between ∼1 and 20 m. Replicate gravity cores were collected approximately every 2 m between 7 and 13 m using a modified K-B corer (Glew, 1989) and 3 overlapping piston core series were retrieved from ∼9 to 13 m using a 1-m Livingstone square-rod corer (Glew et al., 2001). The gravity cores were sectioned in the field at 0.25-cm intervals for the entire length of the cores. The piston cores were collected in 1-m sections and wrapped on site.

Preliminary diatom and chrysophyte scale analyses of the top 10–12 cm from the series of gravity cores, covering the past ∼130–150 yr, indicated that the largest changes occurred in the cores collected from ∼11 to 13 m. The longest gravity and piston cores were collected from ∼13 m, and thus we deemed this location would provide the best record of declines in lake level through time. Three gravity cores were collected at ∼13 m (13A, B, C) that were ∼25, 19 and 47 cm in length, respectively. Detailed analyses were completed on the longest core, 13C. Two piston cores were collected at 12.6 m that were ∼3.5 and 4.3 m in length. The longest core, piston core 2, was split, described and sectioned into 0.5-cm intervals. Only the top two sections of the piston core 2 (158 cm) were analyzed since the focus of this study was the mid-Holocene to the present.

Chronology

The chronologies of the gravity and piston cores are based on ²¹⁰Pb for the top 10 cm of the gravity core and on radiocarbon dates determined by accelerator mass spectrometry (AMS) from 9 samples (Table 1). The ²¹⁰Pb analysis is based on counts from a low-background gamma counter (Schelske et al., 1994) and chronology is calculated with the constant rate of supply model (Oldfield and Appleby, 1985). The apparent higher rate of sedimentation in the upper sediments is primarily the result of the more watery unconsolidated top sediments (Fig. 2a). The ¹⁴C AMS dates were calibrated to years AD and calendar years BP using OxCal version 3.1 (Stuiver et al., 1998). The resulting age model indicates that sedimentation rates have changed little over the last ∼8000 yr; before this period, sedimentation rates were substantially lower in the near-shore environment (Fig. 2b).

Table 1
AMS radiocarbon dates (Lawrence Livermore National Laboratory) for the gravity core (GC) and piston core (PC)

Sample depth (cm)	Material dated	¹⁴C age (±1 SD)	Cal yr BP (±2 sigma)	No. of CAMS
GC 15.25–15.5	Isolated pollen	565±35	615±35	131909
GC 26.75–27.0	Isolated pollen	1590±35	1470±80	131910
GC 39.75–40.0	Isolated pollen	2535±35	2565±85	131911
PC 79.0–80.0	Isolated pollen	4825±35	5520±45	130308
PC 79.0–80.0	Plant material	5035±35	5780±120	130559
PC 128.5–129.5	Isolated pollen	7385±30	8245±85	130384
PC 184.0–185.0	Isolated pollen	8375±40	9390±100	130386
PC 234.0–235.0	Isolated pollen	8715±40	9680±140	130385
PC 282.0–283.0	Isolated pollen	10,070±100	11,625±375	130387

SD=Standard Deviation.
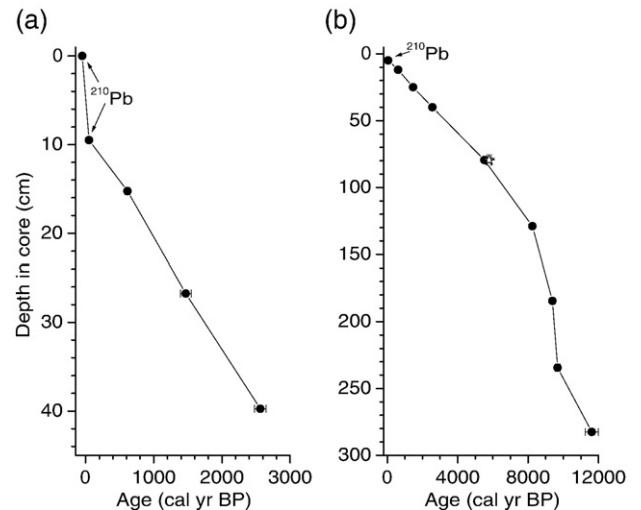

Figure 2. Age model for the gravity core (a) and piston core (b) based on ²¹⁰Pb for the upper sediments and AMS ¹⁴C analysis of isolated pollen (solid circles) in deeper sediments. The star represents AMS ¹⁴C analysis of plant material (Table 1). Error bars represent ±2 sigma.

Approximately 12,000 yr is contained within the top 3 m of the piston core (Table 1, Fig. 2b). The bottom meter of the 4.3-m-long piston core consisted of glacial clays and there was no dateable material. These clays are derived from Lake Agassiz, as in the adjacent Hayes Lake (ELA Lake 240; McAndrews, 1982), which covered much of this area after deglaciation at ∼12,000–11,000 ¹⁴C yr BP until ∼10,000 ¹⁴C yr BP (McAndrews, 1982; Bajc et al., 2000; Dyke, 2005). A radiocarbon date based on macrofossil material was consistent with the pollen-dated sample from the same interval (Table 1, Fig. 2b). A similar result was found from a pollen sample (8210±40 ¹⁴C yr BP) and macrofossil sample (8170±70 cal yr BP) dated from the same interval of a deep central core. The 3 radiocarbon dates from the gravity core were stratigraphically related to the piston core based on the diatom assemblages and organic matter content.

Diatom analysis

Each of the surface samples from Transect A (Fig. 3a, 22 samples in total) was prepared for diatom analysis. All of the 0.25-cm intervals of gravity core 13C (186 samples in total, with an average resolution of 21 yr/0.25 cm), and all of the 0.5-cm intervals for the top 82 cm of piston core 13A and then every 2 cm to 158 cm (200 samples in total, with an average resolution of 35 yr/0.5 cm) were prepared for diatom analysis. Approximately 0.2–0.3 g of wet sediment were sub-sampled from each of the core samples and placed in 20-ml glass vials for acid digestion, while ∼1 g of wet sediment was sampled for the surface samples. The procedure then followed Moos et al. (2005). Diatoms were identified and counted along transects on the prepared slide using a Leica DMRB microscope fitted with a 100× fluotar objective (NA=1.3) and using differential interference contrast optics at 1000× magnification. Approximately 300 diatom frustules were enumerated per slide. For the surface samples and every 2 cm of the piston core samples, diatoms were identified down to the species level, whereas only the
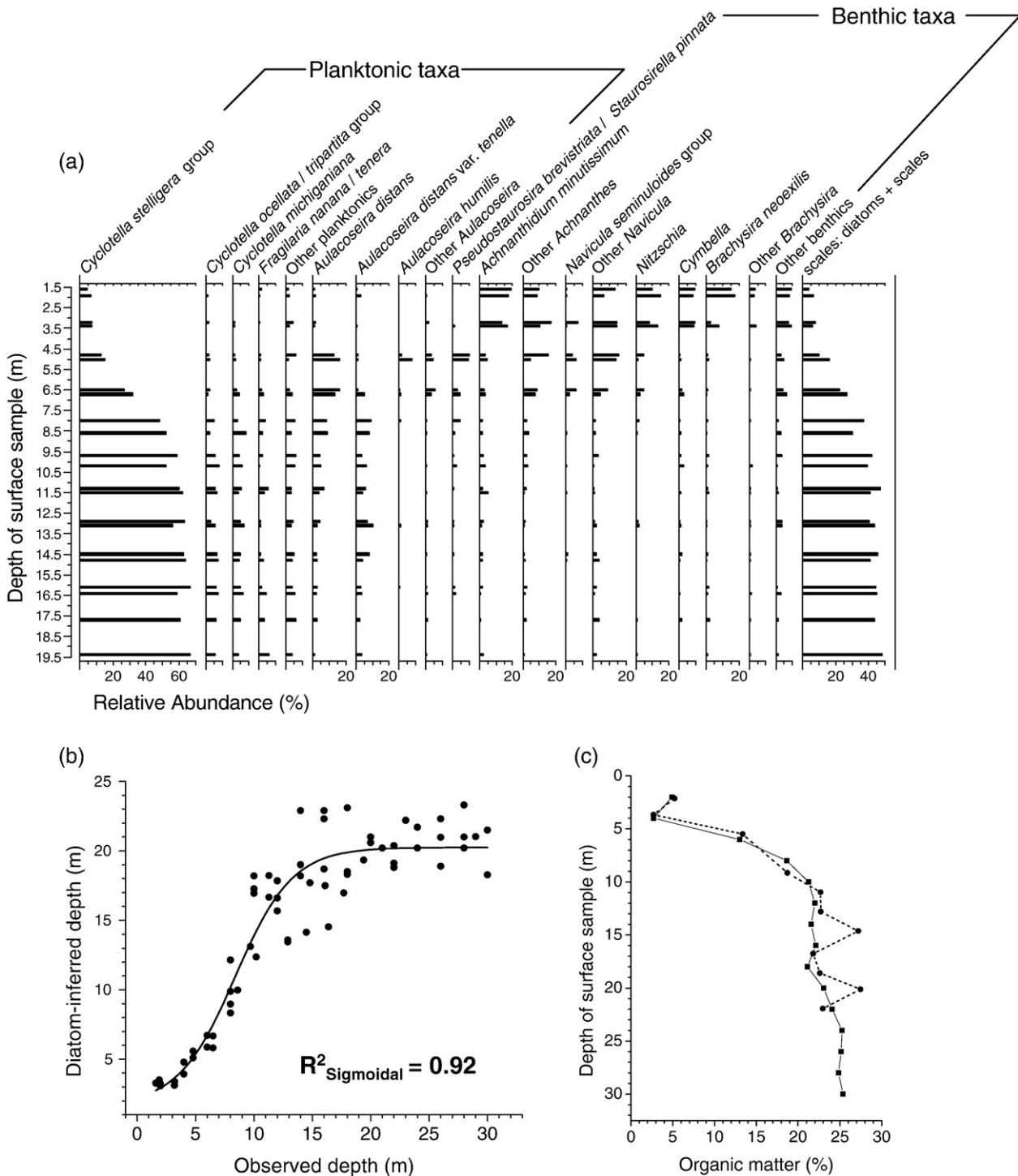
Figure 3. Dominant diatom taxa (>5%) found in the surface samples of Transect A (a), diatom-inferred depth based on the average depth of ten most similar diatom assemblages (modern analogue technique) along a depth transect versus measured depth (b) and organic matter content of surface samples from 1 Transect A series (dashed line) and 1 Transect B series (solid line) (c). The planktonic taxa designation includes tychoplanktonic taxa (e.g., *Aulacoseira distans*).

dominant taxa (>∼ 5%), based on the previous counts, for the rest of the samples were identified to species and the rare taxa were counted in appropriate groups (e.g., genera, species with similar life forms and habitats). The main taxonomic references were Krammer and Lange-Bertalot (1986, 1988, 1991a,b), Cumming et al. (1995) and Camburn and Charles (2000).

Chrysophyte scales were enumerated but not identified to the species level. Major stratigraphic zones were identified from fossil diatom assemblages using a constrained cluster analysis (CONISS), a squared-chord distance to estimate dissimilarity, and were performed with the program TILIA v. 2.02 (Grimm, 1987).

Organic matter analysis

Organic matter (OM) content in the surface samples, gravity cores and piston core samples were estimated through the method of Loss-on-Ignition (LOI) (Dean, 1974). One series of surface samples from Transect A in the northeast basin and one series from Transect B in the northwest basin (Fig. 1b) were analyzed for OM (26 samples in total). Gravity core 13C was analyzed for OM approximately every 0.5 cm (93 samples) and the top two sections of the piston core were analyzed approximately every 1 cm (159 samples).

Diatom-inferred depth model

A quantitative depth model was developed using the diatom species data from 5 series of surface-sample transects; Transect A consisted of 2 replicates (22 samples in total) and Transect B consisted of 3 replicates (45 samples in total, Moos et al., 2005) (Fig. 1b), using the computer program C2 (Juggins, 2003). The model is based on a modern analogue technique (MAT) on square-root-transformed species data using a Bray–Curtis dissimilarity index and matched to the 10 most similar surface samples. The MAT approach was used since the relationship of the distribution of diatoms to depth was not linear. The model was run with the dominant 5% taxa and appropriate taxonomic groupings, as well as with the full species counts. The results of these two models (based on dominant taxa versus full species counts) for samples with full species counts (every 2-cm interval of the piston core) were highly correlated ($r = 0.95$). Thus, the results based on the dominant taxa and grouped rarer taxa provide a good summary of full species counts with the advantage of much reduced enumeration time.

Results

Surface samples

The series of surface samples analyzed for diatoms from the northeast basin (Transect A) showed similar results to those found from the diatom analyses in the northwest basin (Transect B) (Moos et al., 2005). From the deeper areas of the lake to the shallower, the diatom assemblage changes from a predominantly planktonic one, composed largely of *Cyclotella stelligera* Cleve and Grunow (in Van Heurck), to the one dominated by benthic taxa at depths shallower than 8 m (Fig. 3a). The diatom-inferred depth model provides a good estimate of observed depth, particularly when less than ~10–12 m, with a strong sigmoidal relationship (Fig. 3b). At depths shallower than ~8–10 m, there is also a large decrease in the proportion of chrysophyte scales to diatoms (Fig. 3a; Moos et al., 2005), which is consistent with the planktonic nature of scaled chrysophytes. LOI analysis of OM in surface samples of one of the replicates from each of the transects showed a sharp decline in percent OM at depths less than 10 m (Fig. 3c).

These three lines of evidence clearly show that there is a major change in the diatom assemblage, proportion of scaled chrysophytes to diatoms and sediment type starting at ~8–

10 m. The increase in the tychoplanktonic diatom taxon *Aulacoseira distans* (Ehrenberg) Simonsen between ~8 and 5 m and sharp increases in benthic taxa (e.g., *Achnanthes*, *Navicula*, *Nitzschia*, *Cymbella*, *Brachysira*) at ~5 m and shallower indicate the location of the littoral zone being from approximately 2–8 m, with the dominant benthic habitat ≤5 m. Large decreases in OM also occur in this zone, from ~20% to 25% in the profundal samples, decreasing to ~10% by 6 m and 5% or less at 4 m or shallower. As in Shuman (2003), the decreases in LOI occur at the transition into the littoral zone.

Because the changes in the diatom surface samples occur at depths less than ~10–12 m (Fig. 3a; Moos et al., 2005), the quantitative depth model developed from these samples is most sensitive in estimating depths below this interval (Fig. 3b). As a consequence, our model when applied on diatom assemblages from a core taken at 13 m is able to estimate declines in lake level more accurately than increases in lake level. This is largely due to the dominance of a single taxon (*C. stelligera*) in the deeper planktonic zone starting at ~10–12 m. The average difference between observed depth and the diatom-inferred depth model is 2.3 m for depths shallower than 12 m and 3.7 m for depths deeper than 12 m.

Late Holocene lake history (Gravity core analyses)

The dominant taxon in the gravity core was the planktonic taxon *C. stelligera* (Fig. 4). However, there are distinct changes in the percent abundance of this taxon, along with the other subdominant taxa found in the diatom assemblages. A stratigraphically constrained cluster analysis indicates three clear zones of distinct diatom assemblages in this record (Fig. 4).

The largest change over the last ~120 yr (top 12 cm, Zone A; Fig. 4) occurs between 7 and 12 cm (Zone A2), with a large decrease in *C. stelligera* and an increase in the tychoplanktonic taxon *A. distans*, suggesting a lowering of lake level at this time. The largest decrease in *C. stelligera* occurs at ~10 cm (approximately mid-1890s). The diatom evidence alone suggests a substantial lowering of lake level. However, the percent OM and the scaled chrysophytes-to-diatom ratio (Fig. 5) suggests that the sediments are still within the profundal zone (> ~10 m) (Fig. 3). Thus, the distinct decrease in *C. stelligera* and the rise in the tychoplanktonic taxon *A. distans* (which occurred at its highest percentages in the more near-shore environments, Fig. 3a) may be largely due to an increased euphotic zone as the result of increased percent light transmission during more arid conditions (Schindler et al., 1996; Findlay et al., 2001; Moos et al., 2005) with only a modest decline in lake level (<1 m). This qualitative assessment is corroborated by our diatom-inferred depth reconstruction that suggests an average decline of ~0.8 m, relative to the core depth of 13 m, during Zone A2 (Fig. 5).

The diatom flora in Zone B (Fig. 4) suggests that lake levels were higher than today as indicated by the increase in *C. stelligera*, which reached its highest percent abundance during the past ~3000 yr. The quantitative estimate of lake level suggests that this period does correspond to the period of highest lake level during the late Holocene (Fig. 5). However, the amount of increase is difficult to estimate since our model is most sensitive at estimating
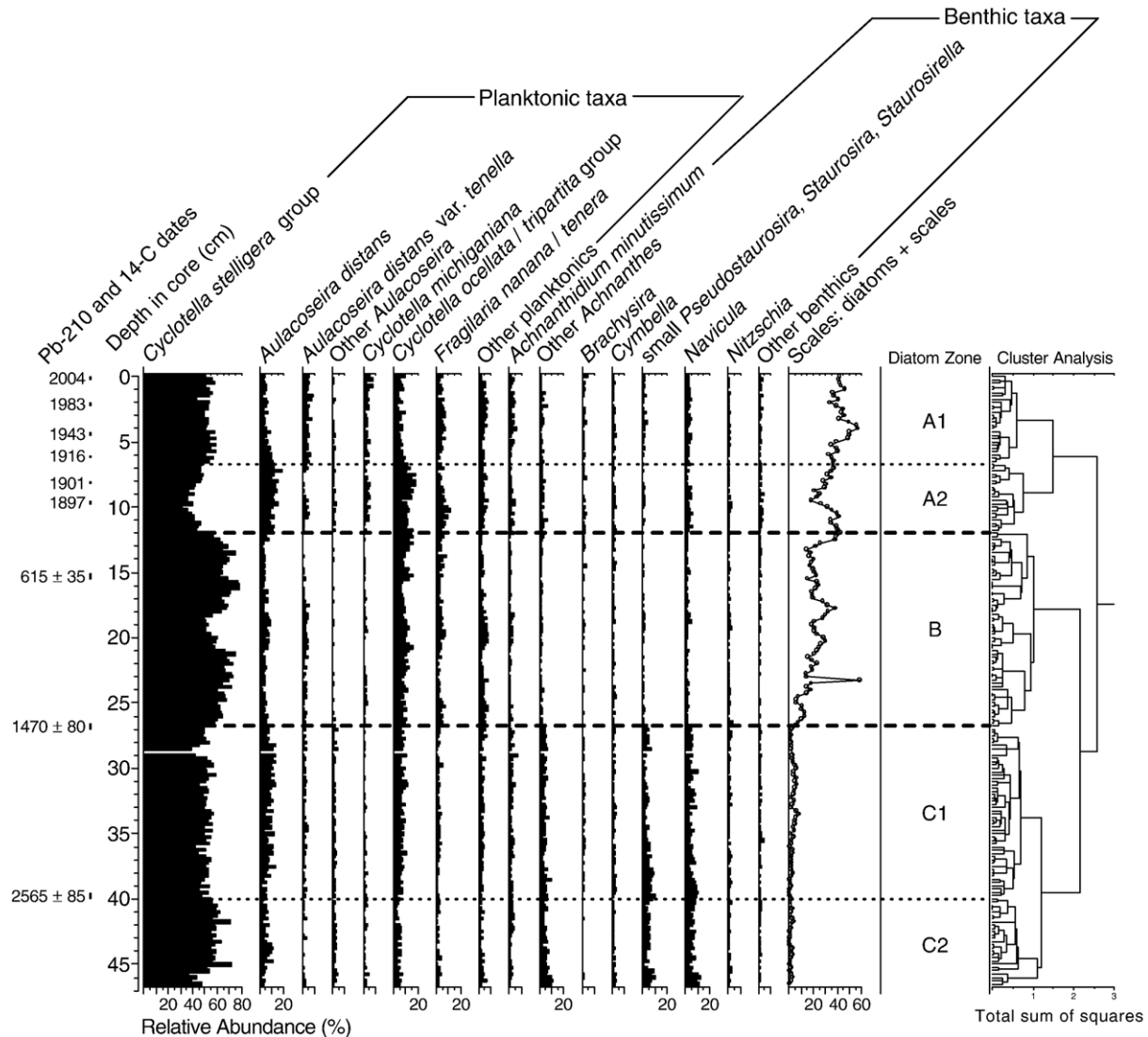
Figure 4. Dominant diatom taxa (>5%) found in the gravity core. ^{210}Pb and calibrated AMS ^{14}C dates (cal yr BP ±2 sigma) are indicated. The proportion of chrysophyte scales to diatom valves is shown (No. of scales/(No. of diatoms+No. of scales)×100). Diatom zones are based on the indicated constrained cluster analysis. The planktonic taxa designation include tychoplanktonic taxa (e.g., *Aulacoseira distans*).

lake levels shallower than ∼10–12 m. As a consequence, we can reliably state that lake levels were higher during this period, but we cannot accurately estimate how much higher based on this core alone.

Prior to ∼1500 yr ago, the diatom flora was quite different (Fig. 4, Zone C) with higher abundances of benthic taxa (e.g., *Achnanthes*, small *Pseudostaurosira, Staurosira, Staurosirella* and *Navicula*), which is coincident with the near disappearance of chrysophyte scales and a sharp decrease in percent OM (Fig. 5). Prior to ∼2500 yr ago, further declines in OM suggest even lower lake levels corresponding to the diatom Zone C2 (Figs. 4 and 5). All of these lines of evidence suggest that Lake 239 was at its lowest lake level of the past ∼3000 yr in Zone C (∼1500 to 3000 cal yr BP).

The diatom evidence on its own suggests that lake level at the 13-m coring site during Zone C was similar to the surface-sample assemblages between 9 and 10 m. However, given that

percent light transmission may have been higher at this time, due to reduced DOC inputs during more arid conditions (Schindler et al., 1996), the increase in benthic diatoms in Zone C may be in part due to an increased euphotic zone (Findlay et al., 2001; Moos et al., 2005). Percent OM content in Zone C1 is around 20% (Fig. 5), which is still within the profundal zone of the surface-sample transects (Fig. 3), in comparison to 16% in Zone C2. The OM content from the surface samples suggest that ∼16% content would occur at the outer edge of the littoral zone at ∼8–10 m. Given that the percent OM is not influenced by the euphotic zone, then the increased benthic diatoms are likely primarily due to lake lowering and an inward shift of the littoral zone. Furthermore, the sharp decline in the scaled chrysophytes-to-diatom ratio suggests that lake level was ∼4 m below the 13-m depth of the coring site. Our diatom-based depth model indicates that the average lake level in Zone C was ∼10.5–11.0 m (Fig. 5a), which would indicate an average decline of ∼2.0–2.5 m at the
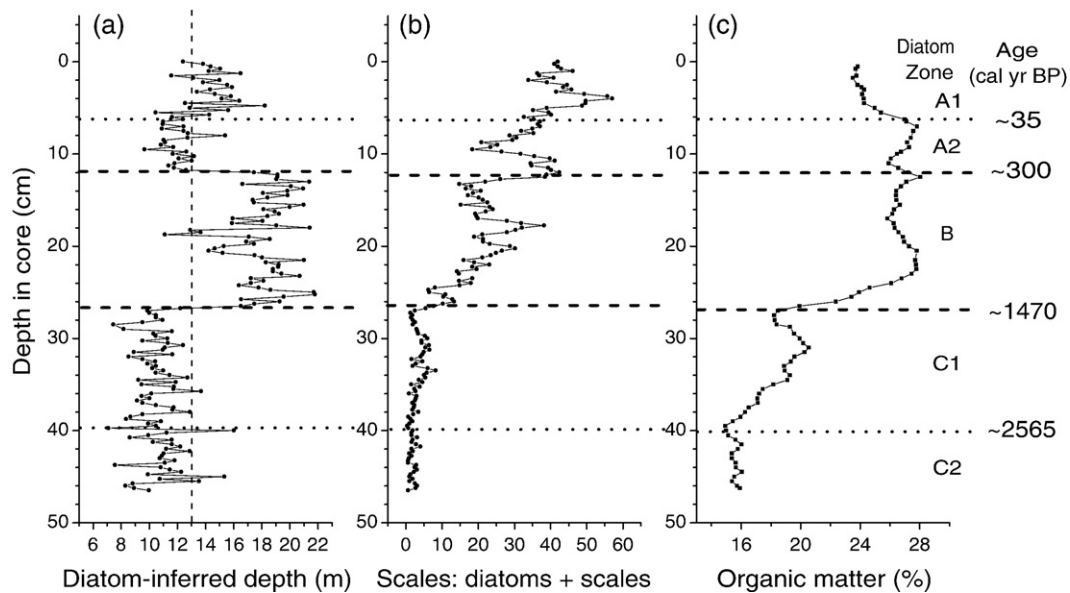
Figure 5. Gravity core analyses: diatom-inferred depth (a), proportion of chrysophyte scales to diatom valves (No. of scales/(No. of diatoms+No. of scales)×100) (b) and percent organic matter content (c). Vertical line in panel a indicates the present-day depth at the coring site. Zones are based on the constrained cluster analysis of the diatom assemblages. Approximate ages (cal yr BP) are provided for the zone boundaries.

13-m coring site. The lowest inferred levels in Zone C were ~7–8 m, thus indicating short-duration declines of 5 to 6 m. An estimate of the decrease in lake surface area and volume for a 2-m decline in lake level, based on area and volume estimates of 2-m intervals of today's lake (Table 2), would result in an ~14% decrease in lake surface area and an ~18% decrease in lake volume.

Holocene lake history (piston core analyses)

Analyses of the top 50 cm of the piston core indicates that there is a high degree of reproducibility with the gravity core

Table 2
Area (hectares) and volume calculations for 2-m intervals for Lake 239

Depth, Z (m)	Area, A_i ($10^4 m^2$)	Interval (m)	Volume, V_{i-j} (10^5 m³)
0	56.1		
2	48.3	0–2	10.4
4	43.0	2–4	9.12
6	37.4	4–6	8.03
8	32.5	6–8	6.98
10	23.1	8–10	5.53
12	16.2	10–12	3.92
14	14.3	12–14	3.06
16	12.5	14–16	2.68
18	10.8	16–18	2.33
20	9.24	18–20	2.00
22	7.67	20–22	1.69
24	5.76	22–24	1.34
26	4.10	24–26	0.981
28	2.61	26–28	0.665
30	0.65	28–30	0.304
30.4	0	30–30.4	0.008

From Experimental Lakes Area database.

results in the diatom composition (Figs. 4 and 6), diatom-inferred depth (Figs. 7a, b) and OM (Figs. 7c, d). These comparisons also indicate that the top ~6–7 cm of the piston core (corresponding to Zone A1 of the gravity core) was not retrieved. Zones P-A1 and P-A2 of the piston core (Fig. 6) correspond to the time frame represented by the gravity core. Zones P-B and P-C extend the record back to ~8900 cal yr BP (Figs. 2 and 6). In Zone P-B, *C. stelligera* was at its lowest percent abundances than any time after this (Fig. 6). In addition, the percentage of benthic taxa increase (e.g., *Achnanthes*, *Staurosirella*, *Pseudostaurosira* and *Navicula*) and were dominant throughout Zone P-B2. Prior to ~5500 cal yr BP (Zone P-C), the diatom assemblage is composed of benthic taxa and very small percentages of the tychoplanktonics *A. distans* and *Aulacoseira humilis* (Cl-Eul.) Simonson. Percent OM is on average ~10% in Zone B and even lower (~6–8%) in Zone P-C (Fig. 8). There were virtually no chrysophyte scales, relative to the number of diatoms in Zone P-B and P-C (Fig. 8).

Both the diatom and the OM results indicate that lake level in Lake 239 was very much lower prior to ~3000 yr ago. The diatom surface-sample data (Fig. 3a) indicate that dominance of the assemblage by benthic taxa occurs at depths less than 5 m. Both surface-sample transects of OM (Fig. 3c) indicate that 10% OM occurs around 5 to 6 m, and percentages lower than this clearly occur shallower than 5 m. Thus, both lines of evidence indicate that the lake level at the present-day 13 m coring site was less than 5 meters depth. Because OM is consistently low during Zone P-C, it is unlikely that the benthic diatom assemblage of this zone is due to large increases in percent light transmission. Rather, these lines of evidence indicate that the littoral zone shifted inwards due to a large decline in lake level.
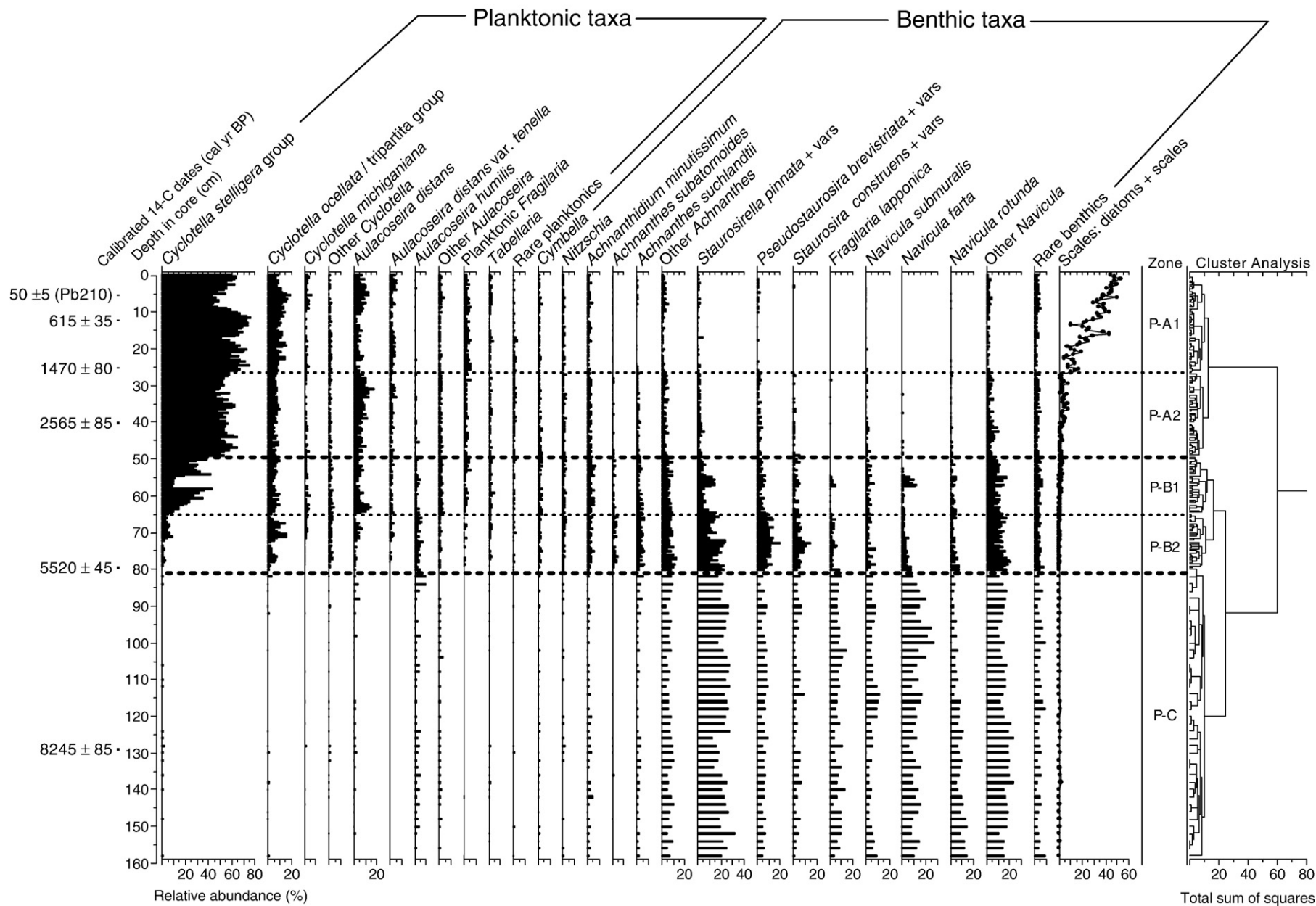
Figure 6. Dominant diatom taxa (> 5%) found in the piston core. [210]Pb and calibrated AMS ^{14}C dates (cal yr BP ±2 sigma) are indicated. The proportion of chrysophyte scales to diatom valves is shown (No. of scales/ (No. of diatoms + No. of scales) × 100). Diatom zones are based on the indicated constrained cluster analysis. The planktonic taxa designation include tychoplanktonic taxa (e.g., *Aulacoseira distans*).
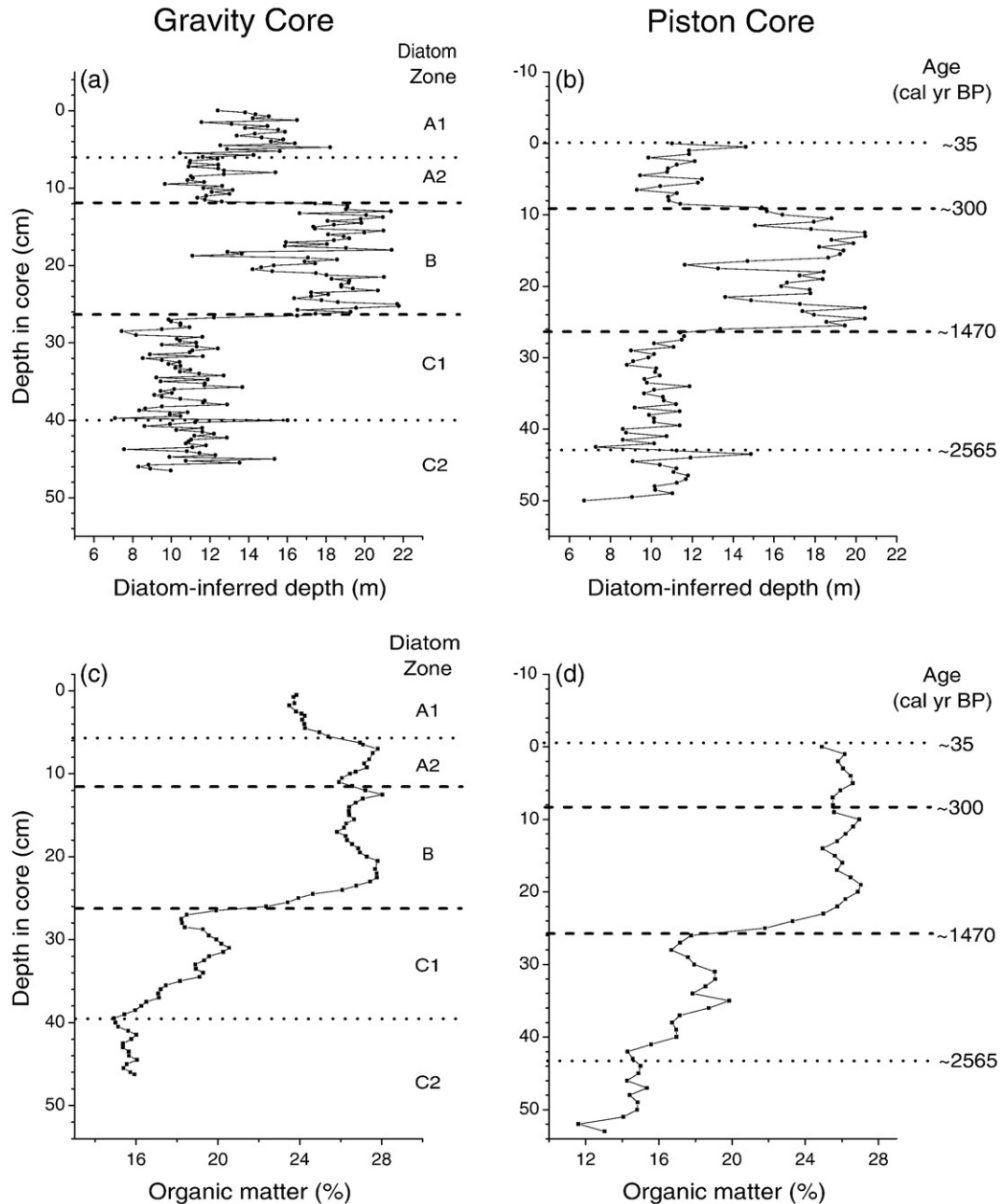
Figure 7. Comparison of diatom-inferred depth for the gravity core (a) and the top of the piston core (b). Comparison of organic matter content for the gravity core (c) and the top of the piston core (d). The diatom zones for the gravity core (a, c) are based on the constrained cluster analysis in Fig. 4. Zones for the piston core (b, d) are based on stratigraphic correspondence to the gravity core.

From these lines of evidence, the lake level of Lake 239 was at least 8 m shallower in Zone P-C (~5500 to 8900 cal yr BP), in comparison to the lake level today. This estimate is supported by our diatom-based depth model (Fig. 8). An estimate of the decrease in lake surface area and volume, based on area and volume estimates of 2-m intervals of today's lake (Table 2), suggests that an 8-m decline in lake level would result in a 42% decline in surface area and a 58% decline in volume. Our surface-sample analyses of the diatom assemblages indicate that the flora is very similar at or less than a depth of ~4–5 m (Fig. 3); thus, it is possible that the lake may have dropped more than 8 m.

Discussion

Historical and late-Holocene aridity

Historical lake level data have been recorded at Lake 239 from 1969 to present. During the 1980s, conditions at ELA were warmer and drier (Schindler et al., 1996) and lake levels at Lake 239 were distinctly lower (see Fig. 4 in Moos et al., 2005), although the declines were only 0.2–0.3 m. Our record does not distinguish the 1980s, likely due to the small measured changes in lake level, but it does indicate that ca. 1890s (Zone A2) was substantially drier with inferred lake-level declines of approximately 0.8 m (Fig. 5). Tree-
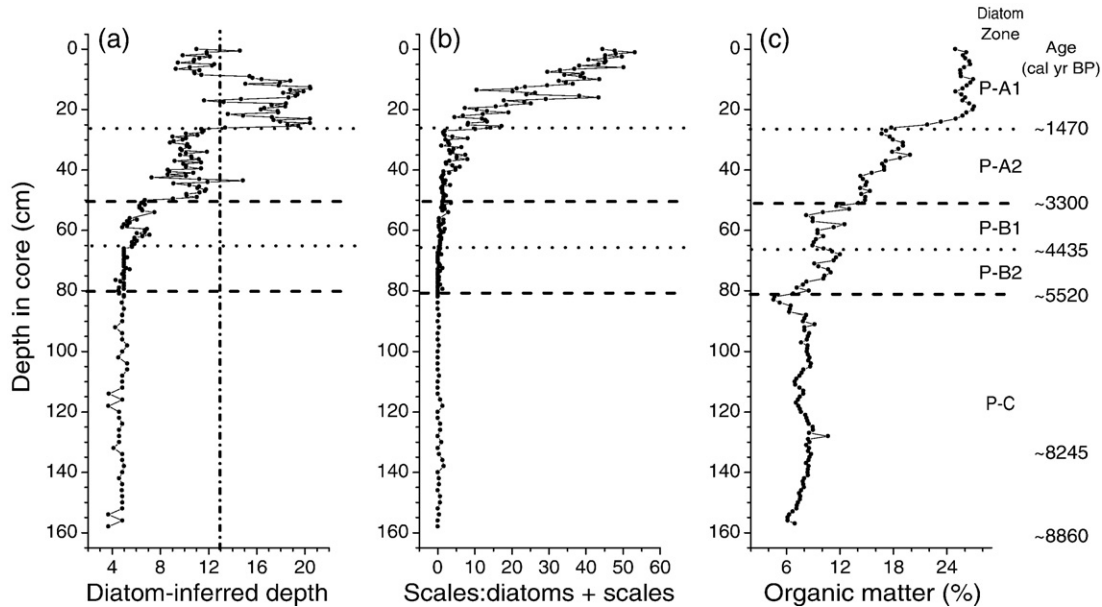
Figure 8. Piston core analyses: diatom-inferred depth (a), proportion of chrysophyte scales to diatom valves (No. of scales/(No. of diatoms + No. of scales)) × 100) (b), percent organic matter content (c). Vertical line in panel a indicates the present-day depth at the coring site. Zones are based on the constrained cluster analysis of the diatom assemblages. Approximate ages (cal yr BP) are provided for the zone boundaries, dated interval in Zone P-C and approximate bottom age.

ring records within the Winnipeg River Drainage Basin (WRDB) suggest intermittent lower growth years during much of the 1880s and 1890s, but these were not as extreme as in the 1860s and 1910s (St. George, 2007). Tree-ring records further to the west have indicated that the 1890s was a period of drier conditions in many parts of the North American prairies (e.g., Sauchyn et al., 2003; Herweijer et al., 2007). However, these recent droughts are small in comparison to late Holocene multi-decadal and century-scale arid periods documented in proxy records from western North America (Laird et al., 1996a; St. George and Nielsen, 2002; Woodhouse, 2004; Cook et al., 2007).

The lake-level record of Lake 239 indicates generally high lake levels between ∼300 cal yr BP and 1470 cal yr BP (Zone B) and generally lower lake levels from ∼1470 cal yr BP to ∼3300 cal yr BP (Zone C). Our resolution of ∼20 yr/sample provides inferences of average conditions over this time frame, whereas higher frequency fluctuations are not distinguished in these analyses. To our knowledge, no other decadal-scale records of lake level reconstructions during the late Holocene exist within the WRDB or adjacent areas and only a few high-resolution records exist within the western Great Lakes basin. An exception to this is the high-resolution record of water-table depth from a Michigan raised bog (Booth and Jackson, 2003). A period of higher water-table levels from ∼1000 cal yr BP to ∼1900 cal yr BP overlaps with our high stand, and water-table levels were generally low from ∼1900 cal yr BP to ∼3500 cal yr BP (Booth and Jackson, 2003).

Aridity in the mid-Holocene in northwestern Ontario and adjacent regions

During the mid-Holocene, the sedimentary evidence from Lake 239 suggests that the lake declined by at least 8 m, which

would have resulted in a 42% decline in surface area and a 58% decline in volume. Presumably, the climate of the region during this period was extremely arid in order to result in lake-level declines of this magnitude, which is similar to what has been documented in the Canadian and U.S. northern prairies but has not been documented for northwestern Ontario.

In northwestern Ontario, there are some indications that conditions were warmer and more arid during the mid-Holocene. Yang and Teller (2005) surmise from modeling that lake level in Lake of the Woods likely fell below the outlets at Kenora during the mid-Holocene. Pollen data from northwestern Ontario suggest that the composition of the boreal forest changed during the mid-Holocene to one that indicated a drier and warmer climate during the time of the prairie expansion further west (McAndrews, 1982; Björck, 1985). The record from Hayes Lake (ELA Lake 240, into which Lake 239 flows) suggests the vegetation was similar to an open, grassy jack pine–poplar woodland with juniper on arid, windswept hilltops (McAndrews, 1982). At Rattle Lake, just to the east of Hayes Lake, the composition of the boreal forest only changed slightly during the mid-Holocene, with prairie pollen (Ambrosia + Chenopodiaceae) more common between ∼7000 and 8000 yr BP (Björck, 1985). Based on the substantial decline in lake level and the corresponding reduction of lake area and volume in Lake 239 during the mid-Holocene, our data indicate that even with the apparently small vegetational changes, a large change in effective moisture occurred during this period.

Farther to the west, although isostatic rebound is a complicating factor in the interpretation of records from Lake Manitoba and Lake Winnipeg, there is convincing evidence that lake levels were significantly lower during the mid-Holocene (Teller and Last, 1981; Lewis et al., 2001). In lake sediment cores from Lake Manitoba, there are indications of very low water stages

scattered throughout the early to mid-Holocene (~9000 to 4500 ^{14}C yr BP) (Teller and Last, 1981). Analysis of lake sediment cores and high-resolution seismic reflection data from Lake Winnipeg revealed similar dry zones with extreme periods of arid conditions between ~7500 and 4000 ^{14}C yr BP (Lewis et al., 2001). The lake area was substantially reduced during this period, with the southern basin having completely dried out (Lewis et al., 2001).

From a variety of sites in the Canadian prairies and the U.S. northern prairies, increased aridity is inferred for the mid-Holocene between ~8300 and 4500 cal yr BP (e.g., Vance et al., 1995; Dean et al., 1996; Laird et al., 1996b). Lake levels in the Canadian prairies were lower in much of the region and the grassland and boreal forest ecozones were extended north of their present conditions (Vance et al., 1995). The eastward expansion of the prairie in the northern U.S. during the arid mid-Holocene is well documented (e.g., Baker et al., 1992; Dean et al., 1996). However, in the central Canadian provinces, the extent of the eastward expansion is not well constrained (Ritchie, 1976).

In eastern Ontario and the Great Lakes regions of the United States, there are indications that the mid-Holocene was a period of warmer and drier conditions. The boreal forest–Great Lakes forest ecotone advanced ~140 km northward of its present position (Liu, 1990). Lower lake levels were recorded in many regions, although the period of maximum warmth, and aridity was variable across the Great Lakes basin (Winkler et al., 1986; Brugam et al., 1998; Booth et al., 2002). In Minnesota, Elk Lake, Grant County, lake level declined by ~15 m during the mid-Holocene (Smith et al., 2002). Similarly in the Crow Wing watershed, an upland lake (Mina Lake) declined by ~15 m, while the lowland lake (Moody Lake) declined by as much as 4 m (Cohen et al., 2006).

Conclusions

Lake levels in ELA Lake 239 appear to have been relatively stable during the past ~3000 yr in comparison to the previous ~6000 yr. The late Holocene was dominated by the planktonic *C. stelligera*, with fluctuations of this taxon and others indicating declines in lake level of between 1 and 3 m. During the mid-Holocene, the sedimentary evidence from Lake 239 suggests that lake level declined by at least 8 m, which would have resulted in a 42% decline in surface area and a 58% decline in volume.

The evidence presented here from Lake 239 provides the first substantive evidence of a large decline in lake level, presumably as the result of declines in effective moisture in northwestern Ontario during the mid-Holocene. Estimated temperature increases of ~0.5 to 3°C are inferred in the prairie during this time, with decreases in inferred mean annual precipitation (Vance et al., 1995). The increases in temperature during the mid-Holocene are similar to what is projected for Ontario under increasing CO_2 conditions (1–2°C) (IPCC, 2007). As a consequence, inferred conditions of the mid-Holocene may provide a partial analogue of potential future conditions.

The lakes within the ELA have had similar chemical responses to recent droughts as they are located within a surface-water dominated region (Webster et al., 2000). The drainage system of Lake 239 (Rawson Lake) is within the Lake of the Woods watershed, which is part of the Winnipeg River Drainage Basin (WRDB). As a result, our detailed paleolimnological analyses of the past ~3000 yr, and the extended view to ~9,000 yr ago from Lake 239 may provide a view of what conditions were like in other parts of the WRDB. However, given the large difference in spatial scale, our findings need to be corroborated by other lake level studies within ELA and other regions of the WRDB.

Although many regions of Canada are projected to have increased precipitation under increasing CO_2 conditions, there is great uncertainty in both the temporal and spatial distribution of future precipitation based on GCMs (Schindler, 1997; IPCC, 2007). Even with an increase in precipitation, there will likely be less water availability due to higher air temperatures and associated periods of extended evaporation and transpiration (Schindler, 1997). At ELA, during the warm 1970s and 1980s, average evaporation increased by ~35 mm per 1°C increase in annual temperature and nearly double this rate (~68 mm per 1°C increase) during the summer months (Schindler, 1997). As a consequence, without a substantial increase in precipitation, it is projected from the empirical data from ELA that lake levels, stream flows and groundwater levels will all decline under a warmer climate (Schindler et al., 1996; Schindler, 1997).

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