HISTORICAL WATER QUALITY AND ECOLOGICAL CHANGE IN RAMSEY AND WASHINGTON COUNTY LAKES

Joy M. Ramstack and Mark B. Edlund

St. Croix Watershed Research Station
Science Museum of Minnesota
16910 152nd Street N
Marine on St. Croix, MN 55047

Final Report submitted to:

Ramsey-Washington Metro Watershed District

April 2010

Recommended citation: Ramstack, J.M. and Edlund, M.B. 2010. Historical Water Quality and Ecological Change in Ramsey and Washington County Lakes. Final Report submitted to Ramsey-Washington Metro Watershed District. St. Croix Watershed Research Station, Science Museum of Minnesota, Marine on St. Croix, Minnesota, 55047.

TABLE OF CONTENTS

SUMMARY

1. In this project, we used paleolimnological techniques to reconstruct the trophic and sedimentation history of Kohlman, Battle Creek, and Wakefield Lakes in Ramsey and Washington Counties, Minnesota.
2. The lakes in this study have been determined to be impaired for nutrients, particularly total phosphorus (TP). Wakefield Lake and Battle Creek Lake also suffer from excessive macrophyte growth, in particular from curly leaf pondweed and Eurasian milfoil.
3. Piston cores were collected from Wakefield and Battle Creek Lakes; an overlapping Livingston core was also collected from Battle Creek Lake. Cores were lead-210 dated, and sediments were analyzed for changes in magnetic susceptibility, loss-on-ignition, and diatom community composition.
4. Diatom community composition was also analyzed on an existing, lead-210 dated core from Kohlman Lake.
5. Results from Kohlman Lake indicate that sedimentation rate has more than doubled since the mid-1800s; there have also been shifts in the diatom community since the time of European settlement. However, the diatom community throughout the core is dominated by planktonic species that are indicative of eutrophic conditions.
6. Wakefield Lake has undergone significant changes in sediment composition, sedimentation rate, and diatom community assemblage since the early 1800s. Diatom community composition and TP reconstructions indicate that this lake has changed from a mesotrophic to eutrophic system since the time of European settlement.
7. The sedimentation rate in Battle Creek Lake is currently more than five times higher than it was prior to European settlement. The shifts in diatom community assemblage, and the associated TP reconstruction, indicate that this lake was mesotrophic in the 1800s and has been eutrophic since the early 1900s.

INTRODUCTION

Within the glaciated regions of the Upper Midwest, lakes feature prominently in the landscape and are a valued resource for tourism, municipalities, home and cabin owners, recreational enthusiasts, and wildlife. Current and historical land and resource uses around the lakes in Ramsey and Washington Counties, including shoreline development, transportation development, sport fisheries, stormwater runoff, water level management, grazing, and agriculture, have raised concerns about the state of the lakes and how to best manage them in a future certain to bring change. To effectively develop management plans, knowledge of the natural state of a lake and an understanding of the timing and magnitude of historical ecological changes become critical components. In this project, we used paleolimnological techniques to reconstruct the trophic and sedimentation history of Kohlman, Battle Creek, and Wakefield Lakes in Ramsey and Washington Counties, Minnesota. Results provide a management foundation by determining the natural or reference condition of these lakes and reconstructing a history of ecological changes that have occurred in the lakes during the last 150-200 years.

With any lake management plan it is important to have a basic understanding of natural fluctuations within the system. Reliable long-term data sets, on the order of 30 - 50 years, are generally not available for most regions of the country. Through the use of paleolimnological techniques and quantitative environmental reconstruction, we can estimate past conditions, natural variability, timing of changes, and determine rates of change and recovery. This type of information allows managers and researchers to put present environmental stresses into perspective with the natural variability of the system. It can also be used to identify response to and recovery from short-term disturbances.

The lakes in this study have been determined to be impaired for nutrients, particularly total phosphorus (TP). Kohlman Lake is located in Maplewood and is part of the Phalen Chain; current total phosphorus values in the lake are near 90 ppb. Wakefield Lake is a very small lake located near Maplewood in Ramsey County. Wakefield has the highest TP of the three lakes at 130 ppb. Battle Creek Lake is located in Washington County near Woodbury and has TP values of approximately 75 ppb. The latter two lakes also suffer from excessive macrophyte growth, in particular from curly leaf pondweed and Eurasian milfoil.

The primary aim of this project was to use paleolimnological analysis of dated sediment cores from the three lakes to reconstruct ecological histories using biogeochemistry, sediment accumulation, diatom-inferred total phosphorus (DI-TP), and diatoms as biological indicators. The lakes currently have marginal to poor water quality and are the subject of local and state concern to develop management plans that include an understanding of presettlement conditions, historical lake response to landuse and past management, and development of management targets through TMDL planning. These goals are well-suited to a paleolimnological study. Analytical tools used include radioisotopic dating of the cores, geochemical analyses to determine local sediment accumulation rates, and analysis of subfossil algal communities. Multivariate analyses, diatom-based transfer functions, and comparison of diatom assemblages with an 89 Minnesota lake data set were also used to relate changes in trophic conditions and diatom communities to human impacts in the local watershed.

Diatoms have been widely used to interpret environmental conditions in lakes (Dixit et al. 1994). Many species are sensitive to specific water conditions and are useful as bioindicators. Over the past 20 years, statistical methods have been developed to estimate quantitative environmental parameters from diatom assemblages. These methods are statistically robust and environmentally sound. They have been used successfully in reconstructing a wide variety of environmental parameters including pH, total phosphorus (TP), salinity, and recently, dissolved organic carbon (DOC). In the state of Minnesota, diatom analysis has been used as one line of evidence for developing nutrient criteria (Heiskary and Wilson 2008) and lake specific nutrient standards (Edlund and Ramstack 2007).

METHODS – SEDIMENT CORING

Piston cores were collected from both Wakefield and Battle Creek Lakes in April of 2009. In addition, an overlapping Livingston core was collected from Battle Creek Lake. Cores were collected from a deep, flat area of each basin; the deep-water sediments of lakes provide a highly integrated sample of diatom community structure from the lake as a whole. Piston cores were taken using a drive-rod piston corer equipped with a 6.5 cm diameter polycarbonate barrel (Wright 1991). A Livingston corer was used to collect a secondary core from Battle Creek Lake from sediment depths below that of the piston core in case the sedimentation rate was too high to capture sediments dating prior to European settlement within the length of the piston core.

Recovered piston cores were transported to the shore and extruded vertically in 1 or 2-cm increments to a depth with cohesive sediment texture. Core sections, material remaining in the core barrels, and Livingston cores (wrapped in aluminum foil), were returned to the laboratory and stored at 4°C. Lakes, coring locations, and core recovery are provided in Table 1.

An existing lead-210 dated sediment core from Kohlman Lake was used for analysis.

METHODS – MAGNETIC SUSCEPTIBILITY LOGGING AND CORE IMAGING

Magnetic susceptibility provides a non-destructive measure of relative quantity and size of ferro-magnetic minerals. Increases in magnetic susceptibility signatures may be correlated with land use changes including land clearance, increased terrestrial-derived sediments, and paleosols. Decreases in magnetic susceptibility often accompany increased carbonate and organic fluxes to the sediments from increased productivity.

A Geotek Standard MSCL with an automated trackfeed was used for magnetic susceptibility logging. Susceptibility measures were taken at 1-cm intervals, which integrate a signal over a 5-10-cm length of core. Following susceptibility logging, cores were split lengthwise, physically described, and digital images taken of each core section using a Geoscan Corescan-V. Following scanning, cores were returned to storage at 4°C. Magnetic susceptibility logging and core imaging were performed at the Limnological Research Center's core lab facility at the University of Minnesota.

Cores from Wakefield and Battle Creek Lakes (piston and Livingston) were logged for magnetic susceptibility; in addition, the piston cores were split, imaged, and described. Appendix A shows the core image, magnetic susceptibility curve, and the physical description of both of the piston cores. Note that these analyses were performed on the intact portion of each core; therefore these data do not exist for the portions of the core that were field-sectioned. For example, in Appendix A1 (piston core from Wakefield Lake), 0 cm actually corresponds to 15 cm depth, because 15 cm were sectioned off the top of the core in the field (refer to Table 1 for the length of core that was field sectioned). In the magnetic susceptibility profiles for the Wakefield and Battle Creek cores (Figures 1 and 2), the depths are actual core depths; note that there is some overlap between the piston and Livingston core from Battle Creek Lake. Magnetic susceptibility is a relative measurement; the overall magnetic susceptibility differs between the piston core and the Livingston core simply because the diameter of the cores is different.

METHODS – LEAD-210 DATING

Sediments from each lake were analyzed for lead-210 activity to determine age and sediment accumulation rates for the past 150-200 years. Lead-210 was measured at numerous depth intervals by lead-210 distillation and alpha spectrometry methods, and dates and sedimentation rates were determined according to the c.r.s. (constant rate of supply) model (Appleby and Oldfield 1978). Dating and sedimentation errors were determined by first-order propagation of counting uncertainty (Binford 1990).

METHODS – BIOGEOCHEMISTRY

Weighed subsamples were taken from regular intervals throughout the cores for loss-on-ignition (LOI) analysis to determine dry density and weight percent of organic, carbonate, and inorganic matter. Sediment subsamples were heated at 105ºC for 24 hr to determine dry density, then sequentially heated at 550°C and 1000°C to determine organic and carbonate content from post-ignition weight loss, respectively.

METHODS – DIATOM AND NUMERICAL ANALYSES

Twelve downcore samples from each lake were analyzed for diatoms. See Table 2 for a list of samples prepared for diatom analysis from each lake.

Diatoms and chrysophyte cysts were prepared by placing approximately 0.25 cm^3 of homogenized sediment in a 50 cm^3 polycarbonate centrifuge tube, and adding 2-5 drops of 10% v/v HCl solution to dissolve carbonates. Organic material was subsequently oxidized by adding 10 ml of 30% hydrogen peroxide and heating for 3 hours in an 85°C water bath. After cooling, the samples were rinsed with distilled deionized water to remove oxidation biproducts. Aliquots of the remaining material, which contains the diatoms, were dried onto 22x22 mm #1 coverglasses, which were then permanently attached to microscope slides using Zrax mounting medium. Diatoms were identified along random transects to the lowest taxonomic level under 1250X magnification (full immersion optics of NA 1.4). A minimum of 400 valves was counted in each sample. Abundances are reported as percentage abundance relative to total diatom counts. Identification of diatoms used regional floras (e.g. Patrick and Reimer 1966, 1975, Edlund 1994, Camburn and Charles 2000) and primary literature to achieve consistent taxonomy.

Stratigraphies of predominant diatoms (species greater than or equal to 5% relative abundance) were plotted against core date. Relationships among diatom communities within a sediment core were explored using the methods of Principal Components Analysis (PCA) or Detrended Correspondence Analysis (DCA), depending on gradient lengths in the core; analyses were performed using the software package R (Ihaka & Gentleman 1996). Core depths/dates were plotted in ordinate space and their relationships and variability used to identify periods of change, sample groups, and ecological variability among core samples. A general rule for interpreting a PCA or DCA is that samples that plot closer to one another have more similar assemblages.

Downcore diatom communties were also used to reconstruct historical epilimnetic total phosphorus (TP) levels. A transfer function for reconstructing historical logTP was earlier developed based on the relationship between modern diatom communities and modern environmental variables in 89 Minnesota lakes (Ramstack et al. 2003, Edlund and Ramstack 2006) using weighted averaging (WA) regression with inverse deshrinking and bootstrap error estimation (C2 software; Juggins 2003). The strength of the transfer function was evaluated by calculating the squared correlation coefficient (r^2=0.83) and the root mean square error (RMSE=0.181) between the observed logTP with the model estimates of logTP for all samples. Bootstrapping is used in model validation to provide a more realistic error estimate (RMSEP, the root mean square error of prediction=0.208) because the same data are used to both generate and test the WA model (Fritz et al. 1999). Reconstructed estimates of logTP (diatom-inferred TP, or DI-TP) for each downcore sample were determined by taking the logTP optimum of each species, weighting it by its abundance in that sample, and determining the average of the combined weighted species optima. Data are presented both as logTP and as backtransformed values, to TP in µg/l.

RESULTS AND DISCUSSION – CORING, MAGNETIC SUSCEPTIBILITY, AND CORE IMAGING

Kohlman Lake: A sediment core from Kohlman Lake was collected and lead-210 dated in 2007. This existing core was used for diatom analysis.

Wakefield Lake: A 0.81 m long piston core was recovered from Wakefield Lake and 15 cm were extruded from the top of the core in the field (Table 1). There were distinct changes in sediment color and composition in the piston core (Appendix A1). The top sediments were fairly homogeneous, these sediments are grey/brown in color with a high water content. Beginning at approximately 43 cm downcore the sediments become drier, with a clay-like texture. From 59 cm to the core bottom the sediments are dry and fibrous, and full of plant remains. There is a distinct rise in magnetic susceptibility in this core between 50 and 60 cm depth corresponding to this change in sediment composition (Figure 1). This increase in magnetic susceptibility may be correlated with land use changes including land clearance, increases in terrestrial-derived sediments, and paleosols.

Battle Creek Lake: A 1.63 m long piston core was recovered from Battle Creek Lake and 38 cm were extruded from the top of the core in the field (Table 1). An overlapping Livingston core was also collected from the lake representing a maximum sediment depth of 2.11 m. The top 151 cm of sediment from the piston core are fairly homogeneous; these sediments are dark brown in color with plant fragments throughout. From 151-163 cm there is a distinct increase in the amount of sand in the sediment (Appendix A2). There is a rise in magnetic susceptibility in both the piston and Livingston cores at approximately 150-160 cm, corresponding to the increase in sand. There is another peak in magnetic susceptibility at approximately 200 cm in the Livingston core (Figure 2). These increases in magnetic susceptibility may be correlated with land use changes including land clearance, increases in terrestrial-derived sediments, and paleosols.

RESULTS AND DISCUSSION – BIOGEOCHEMISTRY

Wakefield Lake: From the core top to approximately 60 cm depth the sediments are primarily composed of inorganic matter (fluctuating between 69 and 87 percent; Figure 3). In the same section, organic matter remains low and relatively constant. At approximately 60 cm there is an abrupt change in the relative amount of organic and inorganic matter in the Wakefield core, with the sediments becoming roughly half organic and half inorganic matter below this depth. The amount of carbonate in the Wakefield Lake core remains low and constant throughout the length of the core.

This abrupt change in sediment composition corresponds with the sharp rise in magnetic susceptibility in the Wakefield core; both suggest that there was a dramatic change in the sediment load or source to the lake at that time.

Battle Creek Lake: As with Wakefield Lake, the amount of carbonate in the Battle Creek core remains low throughout the length of the core (Figure 4). At the top of the Battle Creek core (0-40 cm) the sediment is 50-60% inorganic matter and approximately 30% organic matter. There is a dramatic change in composition from 40 to 52 cm where the relative amount of inorganic material decreases and organic material increases. This pattern holds until 140 cm depth where there is a steep decline in organic matter and rise in inorganics. This peak in inorganics at 140 cm corresponds with a peak in magnetic susceptibility.

RESULTS AND DISCUSSION – DATING AND SEDIMENTATION

Kohlman Lake: The unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for Kohlman Lake are shown in Figure 5 (from the analysis performed in 2007). The sediment accumulation rate showed an increase in the late 1800s, and then another increase in the 1930s (Figure 5). Changes in sedimentation rate in a single core could be due to changes in sediment focusing in the lake; however, the earlier change coincides with the time of initial land clearance (late 1800s/early 1900s), and the later change roughly corresponds with a shift in the diatom community. Current sedimentation rates in the lake are more than double what they were prior to European settlement.

Wakefield Lake: The unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for Wakefield Lake are shown in Figure 6. Lead-210 activity reached supported levels at approximately 61 cm. The sedimentation rate shows large changes throughout the length of the core. Sedimentation rate began to rise in the late 1800s and reached a peak during the 1950s and 1960s; the sedimentation rate during this peak was approximately 10 times greater than it was in the early to mid-1800s. Since the peak in the middle of the 1900s, sedimentation rate has steadily decreased, yet remains two to three times higher than it was in the early to mid-1800s.

These increases in sedimentation rate in Wakefield Lake beginning in the late 1800s and continuing into the early 1900s coincides with the time of European settlement and initial land clearance. This initial increase in sedimentation also corresponds with the sharp rise in inorganic matter and the increase in magnetic susceptibility in the core. All of these suggest that there was a large influx of sediment from the watershed beginning at the time of European settlement and continuing into the mid-1900s. The sedimentation rate has continued to decline since the peak in the 1960s, although present-day rates still exceed pre-settlement levels.

Battle Creek Lake: The unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for Battle Creek Lake are shown in Figure 7. Lead-210 activity steadily declines throughout the core and reaches supported levels at approximately 58 cm. Sedimentation rate remained relatively stable throughout the 1800s and then began to increase in the early 1900s. There was a period of stability from the 1950s to the 1980s, with another increase in sedimentation in recent decades; the sedimentation rate at the core top is more than five times higher than it was prior to European settlement.

The beginning of the rise in inorganic matter at 52 cm dates to 1860 and continues through to 1950, again showing that the timing of European settlement and land use correspond with an increase in sedimentation rate and inorganic matter in the lake.

RESULTS AND DISCUSSION – DIATOM STRATIGRAPHY AND ORDINATIONS

Kohlman Lake: A principal components analysis (PCA) of the Kohlman Lake core shows shifts in the diatom community assemblage (Figure 8). A constrained cluster analysis of this core indicates that the three most significant groupings in the core sections are from 1819-1892, 1922-1966, and 1976-2007 (indicated by circles on Figure 8). The first shift in the community (late 1800s to early 1900s) occurred around the time of European settlement and land clearance, and the second shift (1960/70s) occurred in the past few decades.

The stratigraphic diagram from Kohlman Lake shows the abundant diatoms that are driving the shifts in the community assemblage (Figure 9). Prior to European settlement (1819-1892) the diatom community was dominated by small *Stephanodiscus* and *Cyclostephanos* species, as well as *Aulacoseira ambigua* and *A. granulata*. The section from 1922-1966 is marked by a decrease in small *Stephanodiscus* and *Cyclostephanos* species, and an increase in *A. ambigua*, *Asterionella formosa,* and *Fragilaria crotonensis*. The most recent decades (1976-2007) show a decrease in *Asterionella formosa*, and a rise in *Cyclostephanos tholiformis* and *Fragilaria capucina* var. *mesolepta*. Overall, the abundant species throughout this core are planktonic diatoms that are indicative of eutrophic conditions, although some can be found in mesotrophic systems (e.g. *A. ambigua, A. formosa*, and *F. crotonensis*). This indicates that although there have been some shifts in the diatom community assemblage, Kohlman Lake has been a productive system since the early 1800s.

Wakefield Lake: Detrended correspondence analysis (DCA) was used to examine the shifts in the diatom community assemblage in the Wakefield Lake core (Figure 10). DCA was chosen for analysis due to the long gradients in the diatom data. The three most significant groupings in the diatom community data were identified using a constrained cluster analysis, and found to be from 1829-1904, 1925-1976, and 1988-2009 (indicated by circles on Figure 10). The first shift in the early 1900s is later than the initial rise in sedimentation rate and change in sediment composition, but does occur during the time of rapid increase in sedimentation rate. The shift in the 1970s/80s occurs during a rapid decline in sedimentation rate.

The stratigraphic diagram from Wakefield Lake shows the abundant diatoms that are driving the shifts in the community assemblage (Figure 11). The bottommost samples (1829 and 1856) are dominated by small *Fragilaria* species, which are commonly found in shallow lakes and can live attached to substrates. In the late 1800s and into the 1900s, as the sedimentation rate increases and there is a sharp rise in inorganic material, the diatom community also changes; at this time the benthic *Fragilaria* species begin to decline and there is a large increase in planktonic taxa such as *Aulacoseira ambigua* and small *Stephanodiscus* and *Cyclostephanos* species. The 1940 sample is the only one in which there is a significant benthic diatom assemblage (dominated by *Navicula minima*) after the decline of the benthic taxa in the late 1800s.

Battle Creek Lake: To examine the shifts in the diatom community assemblage in the Battle Creek Lake core, detrended correspondence analysis (DCA) was used (Figure 12); DCA was chosen over PCA due to the long gradients in the diatom species data. A constrained cluster analysis showed that the three most significant groupings in the diatom community data are from 1824-1897, 1923-1975, and 1987-2008. The first shift in the late 1800s/early 1900s corresponds to the increase in the relative amount of inorganic matter in the sediments.

The stratigraphic diagram from Battle Creek Lake shows the abundant diatoms that are driving the shifts in the diatom community assemblage (Figure 13). In the 1800s the diatom community in Battle Creek Lake was a mix of benthic *Fragilaria* species and tychoplanktonic *Fragilaria* species, which can live either attached to the benthos or suspended in the plankton. In the 1900s, the benthic *Fragilaria* species such as *F. construens* v. *venter* and *F. pinnata* decrease in abundance with a concurrent increase in planktonic taxa such as *Aulacoseira ambigua* and *Fragilaria capucina* v. *mesolepta*.

RESULTS AND DISCUSSION – PHOSPHORUS RECONSTRUCTIONS

Kohlman Lake: The total phosphorus (TP) reconstruction from Kohlman Lake shows some small fluctuations in TP values, but overall indicates that this has been a productive lake since the early 1800s (Figure 14; Table 3). The diatom-inferred TP at the top of the core (56 µg/l) is lower than the modern measured value of close to 90 µg/l, although both indicate eutrophic conditions.

Wakefield Lake: The TP reconstruction indicates that Wakefield Lake was a mesotrophic system in the early to mid-1800s (Figure 15; Table 3). By the late 1800s, TP levels began to rise and the reconstruction indicates that conditions in the lake would have been characterized as eutrophic or hypereutrophic since that time.

Battle Creek Lake: The diatom-inferred TP values for Battle Creek Lake indicate that in the 1800s the lake would have been classified as mesotrophic (Figure 16; Table 3). Since the early 1900s there has been a rise in TP values with the lake now classified as eutrophic.

Diatom-based weighted averaging reconstructions have worked well to infer past TP concentrations in deep lakes; however, shallow lakes can challenge these traditional methods (Sayer 2001; SCWRS unpublished data). One of the problems with diatom-inferred nutrient reconstructions in shallow lakes is that in these systems there is often a decoupling of nutrient levels with variables that are normally correlated, such as chlorophyll a and Secchi depth (Heiskary and Lindon 2005). Therefore, a given TP concentration may support a large range of chlorophyll a levels. Similarly, the relationship between TP and diatoms is not as strong in shallow lakes, which can make diatom-based TP reconstructions less reliable (Ramstack and Edlund, unpublished data). In addition, we find that some shallow lakes are dominated by generalist species; these species are adapted to living in wind-swept shallow systems, so the species turnover in these lakes is less dependent on nutrient levels (Bennion et al. 2001; Sayer 2001). The diatom community changes in shallow lakes are quite informative as to changes in habitat and overall ecology of the lake. Therefore, it is important to interpret the TP reconstruction in conjunction with diatom species changes and changes in the physical and geochemical properties of the sediments.

CONCLUSIONS

Based on the diatom analysis, Kohlman Lake has shown some changes from its pre-European condition. Shifts in the diatom community occurred around the time of European settlement (late 1800s to early 1900s) and again in more recent decades (1960/70s). However, the diatom community throughout the core indicates that Kohlman Lake has been a productive system since the early 1800s. The sedimentation rate in Kohlman Lake has increased since the mid-1800s; current sedimentation rates have more than doubled since that time.

Wakefield Lake has undergone dramatic changes in sediment composition, sediment accumulation rate and diatom community assemblage since the early 1800s. The sediment accumulation rate increased tenfold from pre-European settlement to its peak in the 1950s and 60s; the current sedimentation rate in the lake has decreased since the peak but remains two to three times higher than the early to mid-1800s. Diatom community assemblage has also changed from a pre-European benthic community to a modern day assemblage that is predominantly planktonic. This is reflected in the TP reconstruction, which indicates that the lake has shifted from mesotrophic conditions prior to European settlement to eutrophic or hypereutrophic conditions since that time.

Battle Creek Lake has also undergone significant increases in sedimentation rate beginning in the early to mid-1900s; the current sedimentation rate in the lake is more than five times higher than it was prior to European settlement. The changes in the diatom community reflect a switch from a benthic and tychoplanktonic community to a planktonic and tychoplanktonic community. As in Wakefield Lake, the TP reconstruction indicates a change from pre-settlement mesotrophic conditions to current eutrophic conditions in the lake.

ACKNOWLEDGEMENTS

Jessica Wong, William Daniels, Erin Mortenson and Dan Engstrom (SCWRS) performed loss-on-ignition and 210-Pb analysis. Alaina Fedie (SCWRS) prepared samples for diatom analysis. LacCore (National Lacustrine Core Repository), Department of Geology and Geophysics, University of Minnesota-Twin Cities (http://lrc.geo.umn.edu/corefac.htm) and Amy Myrbo, Kristina Brady, and Anders Noren are acknowledged for

coordinating magnetics logging and core scanning.

REFERENCES

Appleby, P.G., and F. Oldfield. 1978. The calculation of lead-210 dates assuming a constant rate of supply of the unsupported lead-210 to the sediment. Catena 5:1-8.

Bennion, H., P.G. Appleby, and G.L. Phillips. 2001 Reconstructing nutrient histories in the Norfolk Broads, UK: implications for the role of diatom-total phosphorus transfer functions in shallow lake management. Journal of Paleolimnology 26:181-204.

Binford, M.W. 1990. Calculation and uncertainty analysis of 210-Pb dates for PIRLA project lake sediment cores. J. Paleolimnol. 3:253-267.

Camburn, K.E., and D.F. Charles. 2000. Diatoms of low-Alkalinity Lakes in the Northeastern United States. Academy of Natural Sciences of Philadelphia Special Publication 18:152pp.

Dixit, S. S. and J.P. Smol. 1994. Diatoms as indicators in the Environmental Monitoring and Assessment Program-Surface Waters (EMAP-SW). Environ. Monit. Assessm. 31:275-306.

Edlund, M.B. 1994. Additions and confirmations to the algal flora of Itasca State Park. II. Diatoms of Chambers Creek. J. Minn. Acad. Sci. 59:10-21.

Edlund, M.B. and J.M. Ramstack. 2006. Diatom-Inferred TP in MCWD Lakes. Final Report to Minnehaha Creek Watershed District, Work Order #116-04, 33 pp.

Edlund, M.B., and J.M. Ramstack. 2007 Historical water quality and biological change in Peltier Lake, Anoka Co., MN. Final report submitted to Emmons and Olivier Resources, Inc. and the Rice Creek Watershed District, 19 pp.

Fritz, S.C., B.F. Cumming, F. Gasse, and K. Laird. 1999. Diatoms as indicators of hydrologic and climatic change in saline lakes. In Stoermer, E.F. and J.P. Smol, (eds.), The Diatoms: Applications for the Environmental and Earth Sciences. Cambridge University Press, Cambridge & New York, pp 41-72.

Heiskary, S. and M. Lindon. 2005. Interrelationships among water quality, lake morphometry, rooted plants and related factors for selected shallow lakes of West-Central Minnesota. Minnesota Pollution Control Agency, St. Paul, Minnesota, 133 pp.

Heiskary, S.A., and C.B. Wilson. 2008. Minnesota's approach to lake nutrient criteria development. Lake and Reservoir Management 24:282-297.

Ihaka, R. and R. Gentleman. 1996. R: a language for data analysis and graphics. J. Comput. Graph. Stat. 5:299-314.

Juggins, S. 2003. C2 version 1.3, Software for ecological and palaeoecological data analysis and visualization. University of Newcastle, Newcastle upon Tyne, NE17RU, United Kingdom.

Patrick, R. and C.W. Reimer. 1966. The diatoms of the United States, exclusive of Alaska and Hawaii, Volume 1-Fragilariaceae, Eunotiaceae, Achnanthaceae, Naviculaceae. Academy of Natural Sciences of Philadelphia Monograph No. 13, 699 pp.

Patrick, R. and C.W. Reimer. 1975. The diatoms of the United States, exclusive of Alaska and Hawaii, Volume 2, Part 1-Entomoneidaceae, Cymbellaceae, Gomphonemaceae, Epithemaceae. Academy of Natural Sciences of Philadelphia Monograph No. 13,

213 pp.
Ramstack, J.M., S.C. Fritz, D.R. Engstrom, and S.A. Heiskary. 2003. The application of a diatom-based transfer function to evaluate regional water-quality trends in Minnesota since 1970. J. Paleolimnol. 29:79-94.
Sayer, C.D. 2001. Problems with the application of diatom-total phosphorus transfer functions: examples from a shallow English lake. Freshwater Biol. 46:743-757.
Wright, H.E., Jr. 1991. Coring tips. J. Paleolimnol. 6:37-49.

Table 1. Lakes cored, length of core recovered, and results of field sectioning.

Lake Name	Coring Date	Coring Location	Type of Core	Water Depth (m)	Core length (m)	Field sectioned (cm)
Wakefield	4/21/2009	44°59.718' N 93°02.107' W	Piston	2.40	0.81	0-15*
Battle Creek	4/21/2009	44°56.691' N 92°58.439' W	Piston	2.67	1.63	0-38*
Battle Creek	4/21/2009	44°56.691' N 92°58.439' W	Livingston	2.67	0.77	--

*The Wakefield core was sectioned in 1-cm increments, the Battle Creek core in 2-cm increments.

Table 2. Samples prepped for diatom analysis from each lake.

Core	Sample Depth (cm)	Lead-210 Date
Kohlman Lake	0-2	2007
Kohlman Lake	16-18	1994
Kohlman Lake	24-26	1986
Kohlman Lake	32-34	1976
Kohlman Lake	40-42	1966
Kohlman Lake	48-50	1956
Kohlman Lake	56-58	1946
Kohlman Lake	72-74	1922
Kohlman Lake	88-90	1892
Kohlman Lake	96-98	1870
Kohlman Lake	100-102	1848
Kohlman Lake	104-106	1819
Wakefield Lake	0-1	2009
Wakefield Lake	7-8	1999
Wakefield Lake	13-14	1988
Wakefield Lake	21-22	1976
Wakefield Lake	28-29	1966
Wakefield Lake	35-36	1957
Wakefield Lake	43-44	1940
Wakefield Lake	48-49	1925
Wakefield Lake	53-54	1904
Wakefield Lake	57-58	1883
Wakefield Lake	60-61	1856
Wakefield Lake	63-64	1829
Battle Creek Lake	0-2	2008
Battle Creek Lake	12-14	1999
Battle Creek Lake	20-22	1987
Battle Creek Lake	26-28	1975
Battle Creek Lake	30-32	1967
Battle Creek Lake	34-36	1957
Battle Creek Lake	38-40	1940
Battle Creek Lake	40-42	1923
Battle Creek Lake	44-46	1897
Battle Creek Lake	48-50	1873
Battle Creek Lake	50-54	1850
Battle Creek Lake	56-58	1824

Table 3. Diatom-inferred total phosphorus values for each lake.

Lake/Date	Diatom-inferred Total Phosphorus (ug/l)
Kohlman Lake	
2007	57
1994	71
1986	88
1976	61
1966	63
1956	72
1946	67
1922	60
1892	71
1870	78
1848	77
1819	80
Wakefield Lake	
2009	55
1999	59
1988	70
1976	112
1966	67
1957	73
1940	39
1925	62
1904	48
1883	38
1856	22
1829	19
Battle Creek Lake	
2008	60
1999	50
1987	61
1975	42
1967	41
1957	40
1940	41
1923	47
1897	29
1873	28
1850	23
1824	21

Figure 1. Magnetic susceptibility (SI) profile from the piston core from Wakefield Lake.

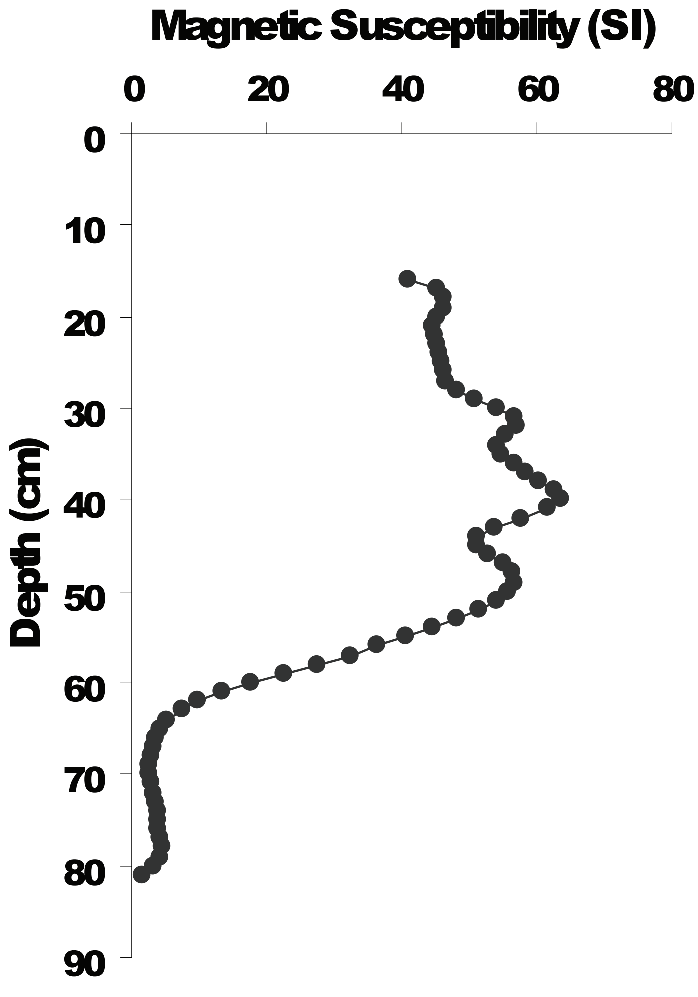


Figure 2. Magnetic susceptibility (SI) profiles from the overlapping piston and Livingston cores from Battle Creek Lake.

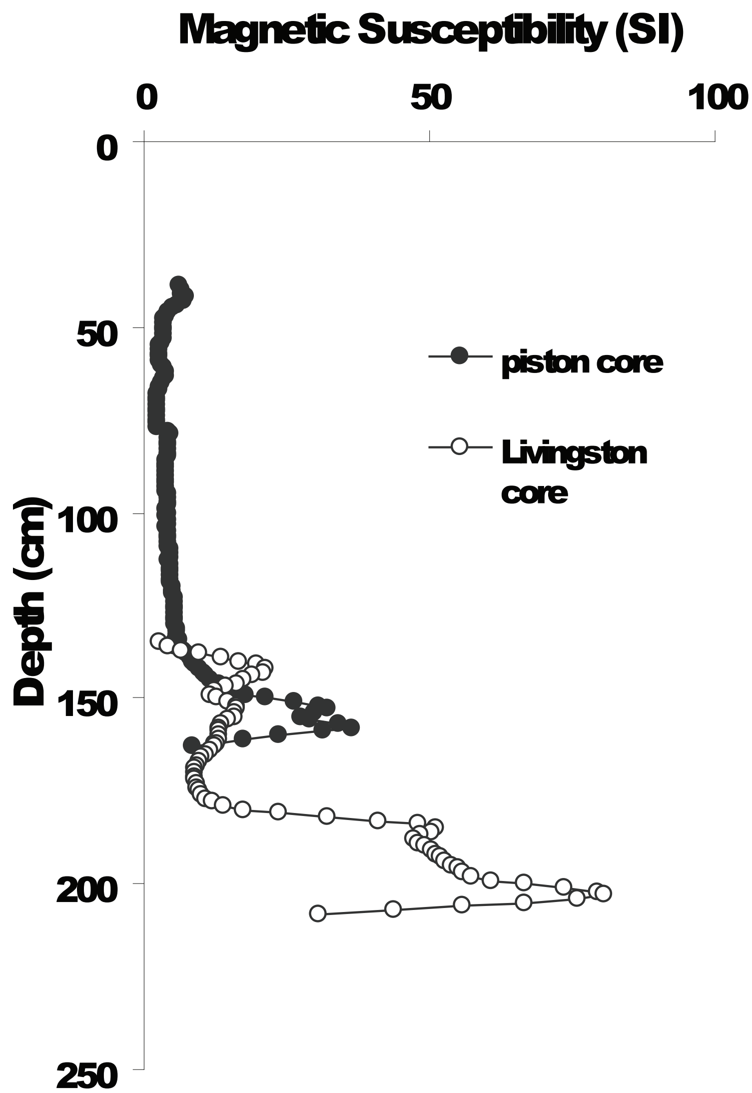


Figure 3. Percent dry weight of organic, CaCO3, and inorganic matter in the Wakefield Lake core.

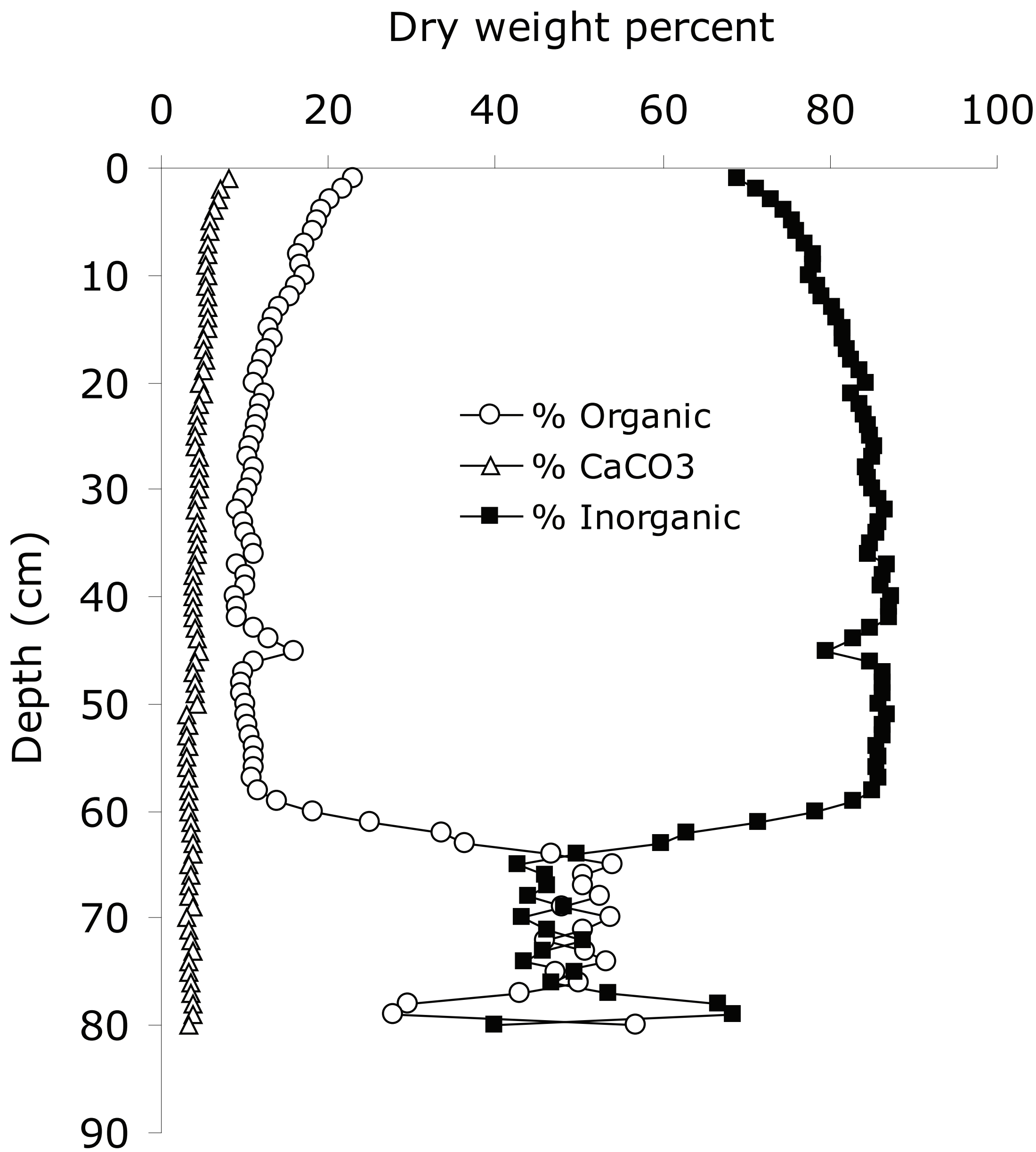


Figure 4. Percent dry weight of organic, CaCO3, and inorganic matter in the Battle Creek Lake core.

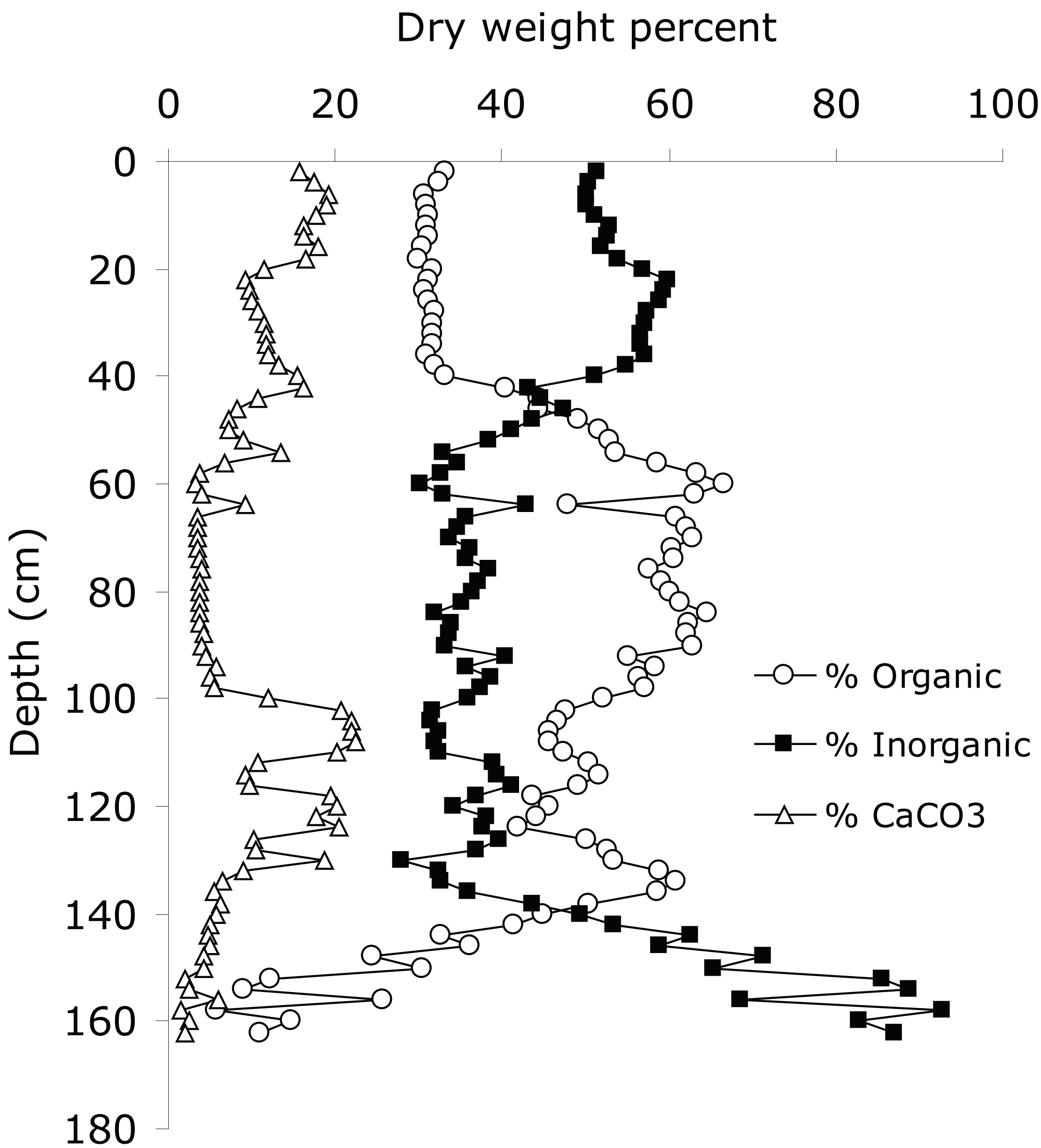


Figure 5. Lead-210 dating model and sediment accumulation rate for Kohlman Lake.

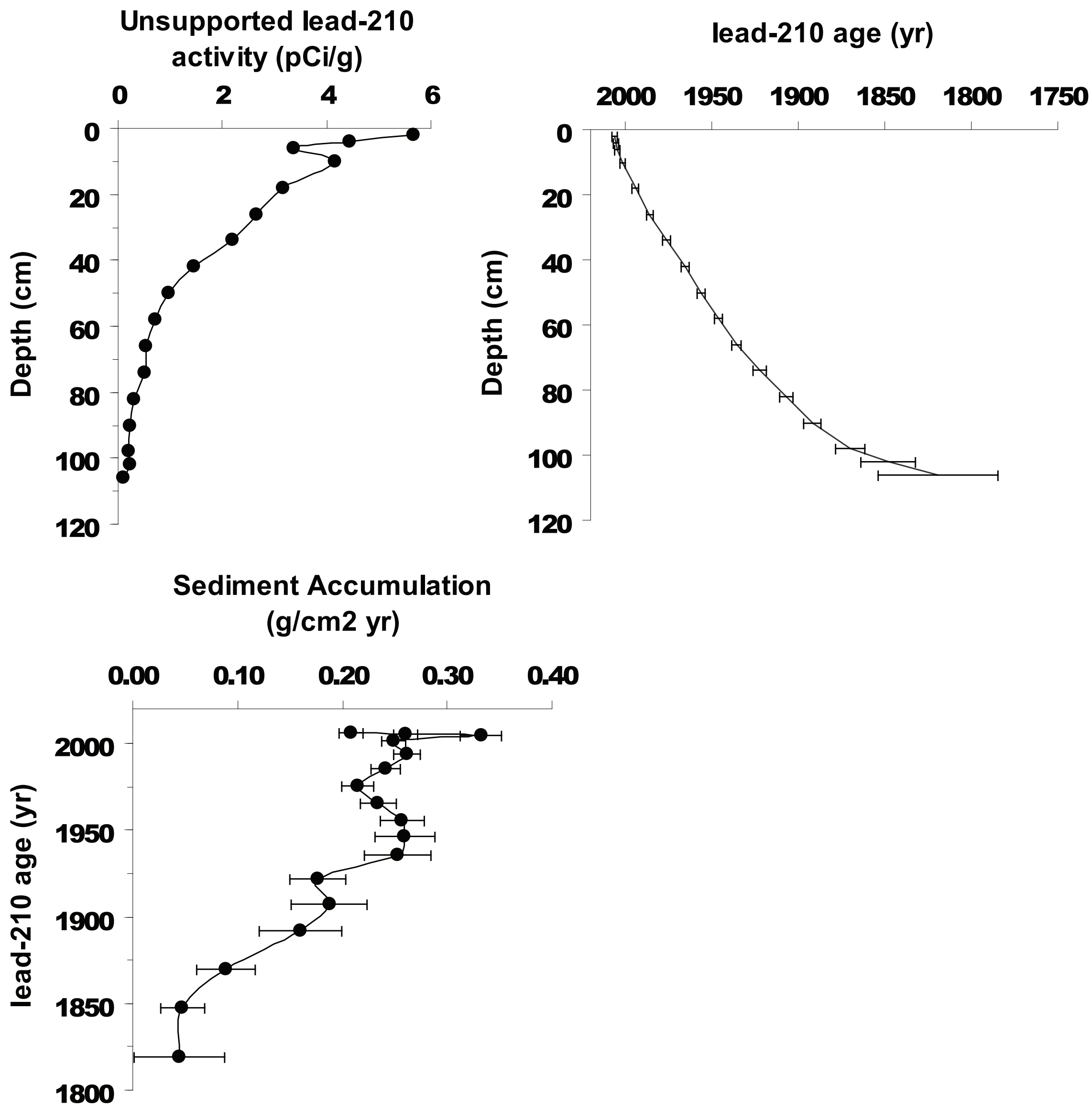


Figure 6. Lead-210 dating model and sediment accumulation rate for Wakefield Lake.

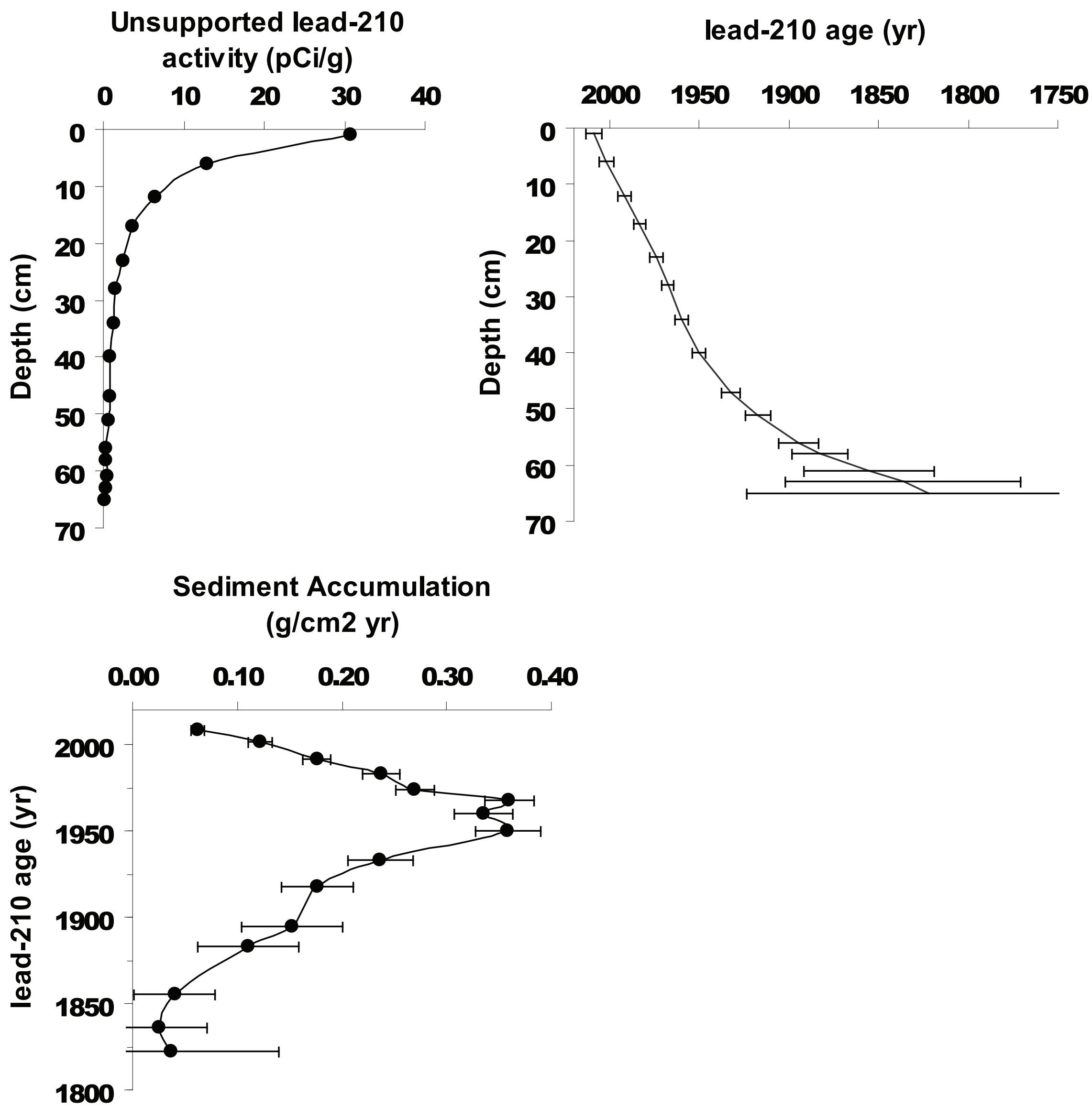


Figure 7. Lead-210 dating model and sediment accumulation rate for Battle Creek Lake.

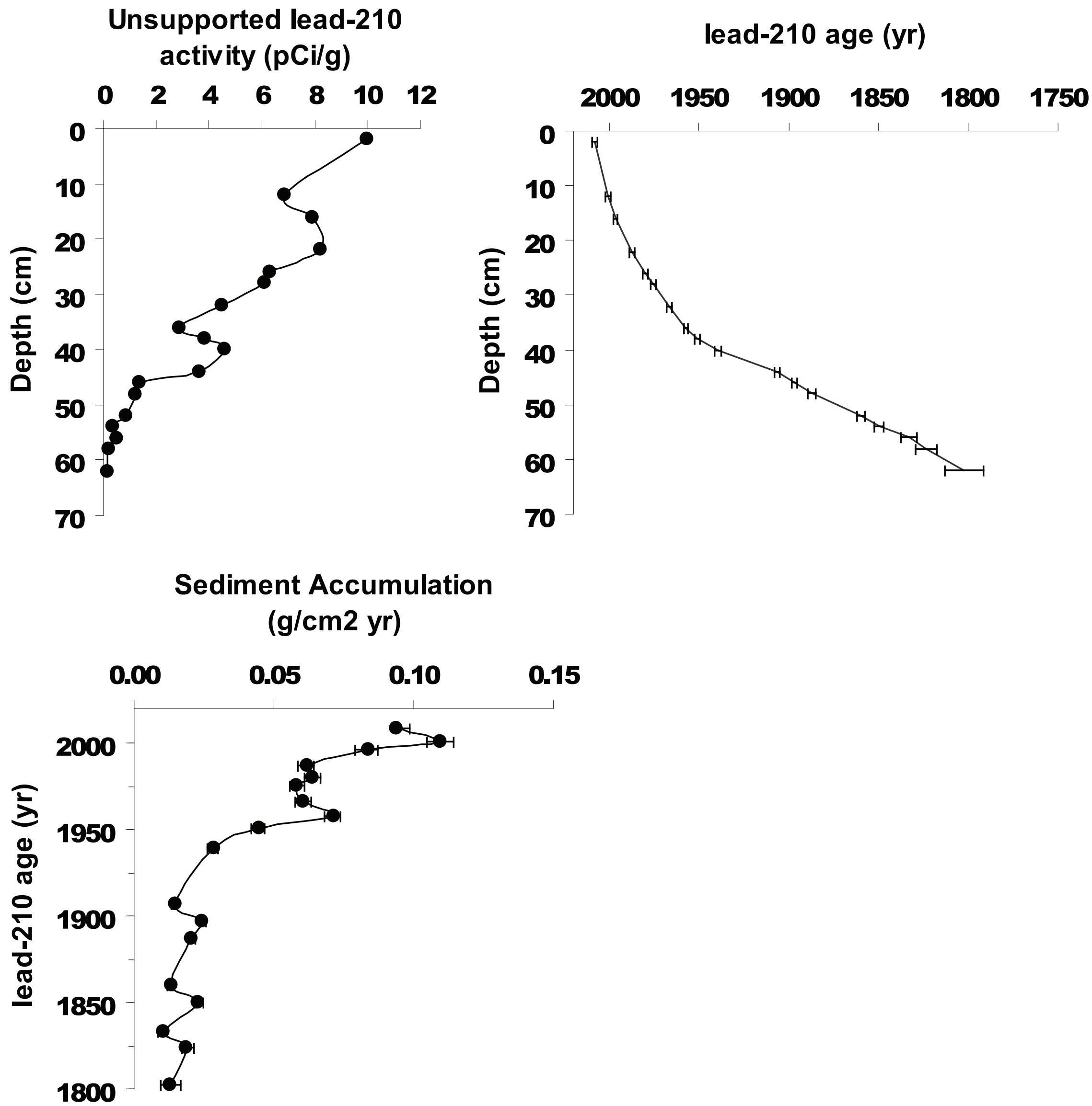


Figure 8. Principal components analysis (PCA) of diatom communities from Kohlman Lake. Circles indicate the grouping of samples based on a constrained cluster analysis, arrows were drawn to illustrate the trajectory through time.

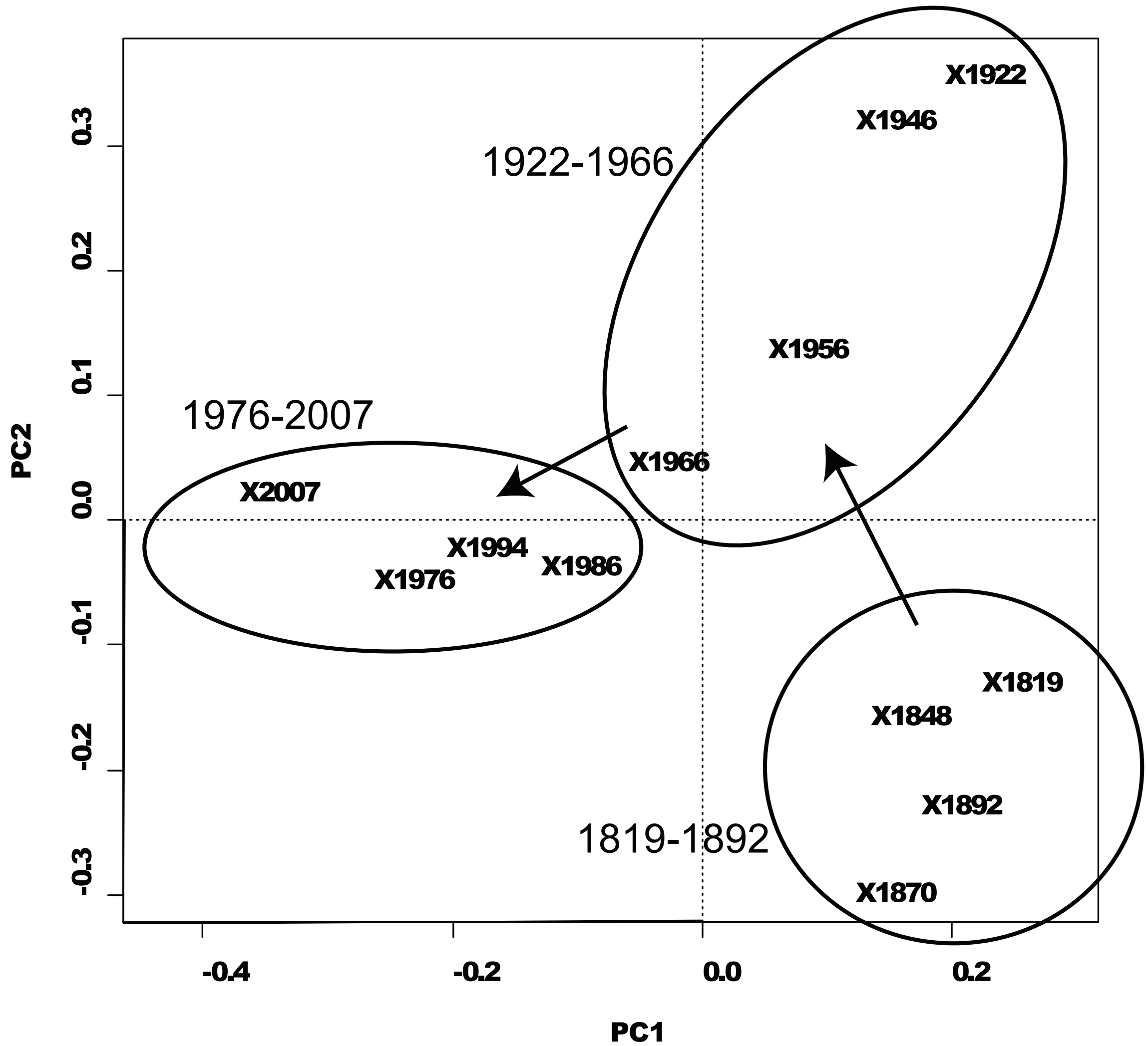


Figure 9. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance) in Kohlman Lake (1819-2007). Lines indicate the grouping of samples based on a constrained cluster analysis.

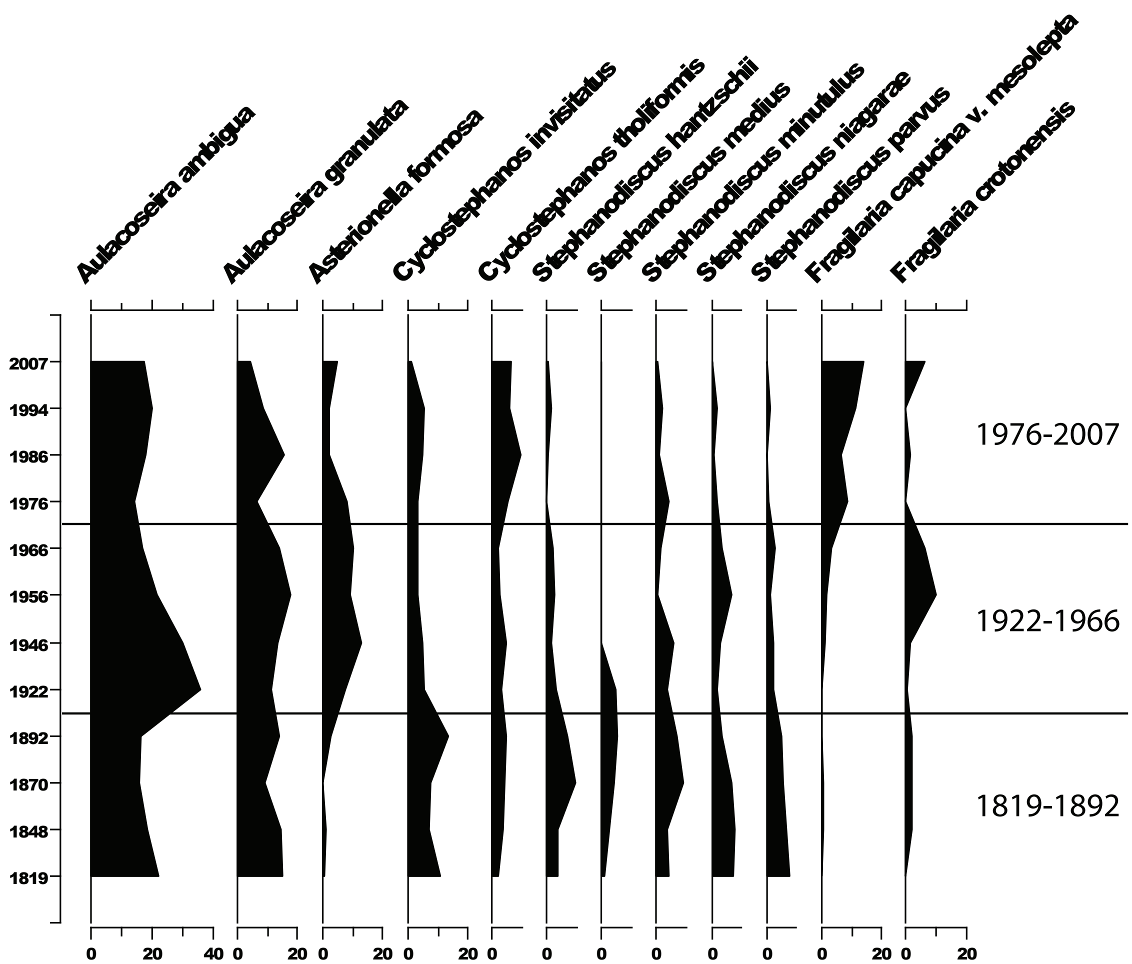


Figure 10. Detrended correspondence analysis (DCA) of diatom communities from Wakefield Lake. Circles indicate the grouping of samples based on a constrained cluster analysis, arrows were drawn to illustrate the trajectory through time.

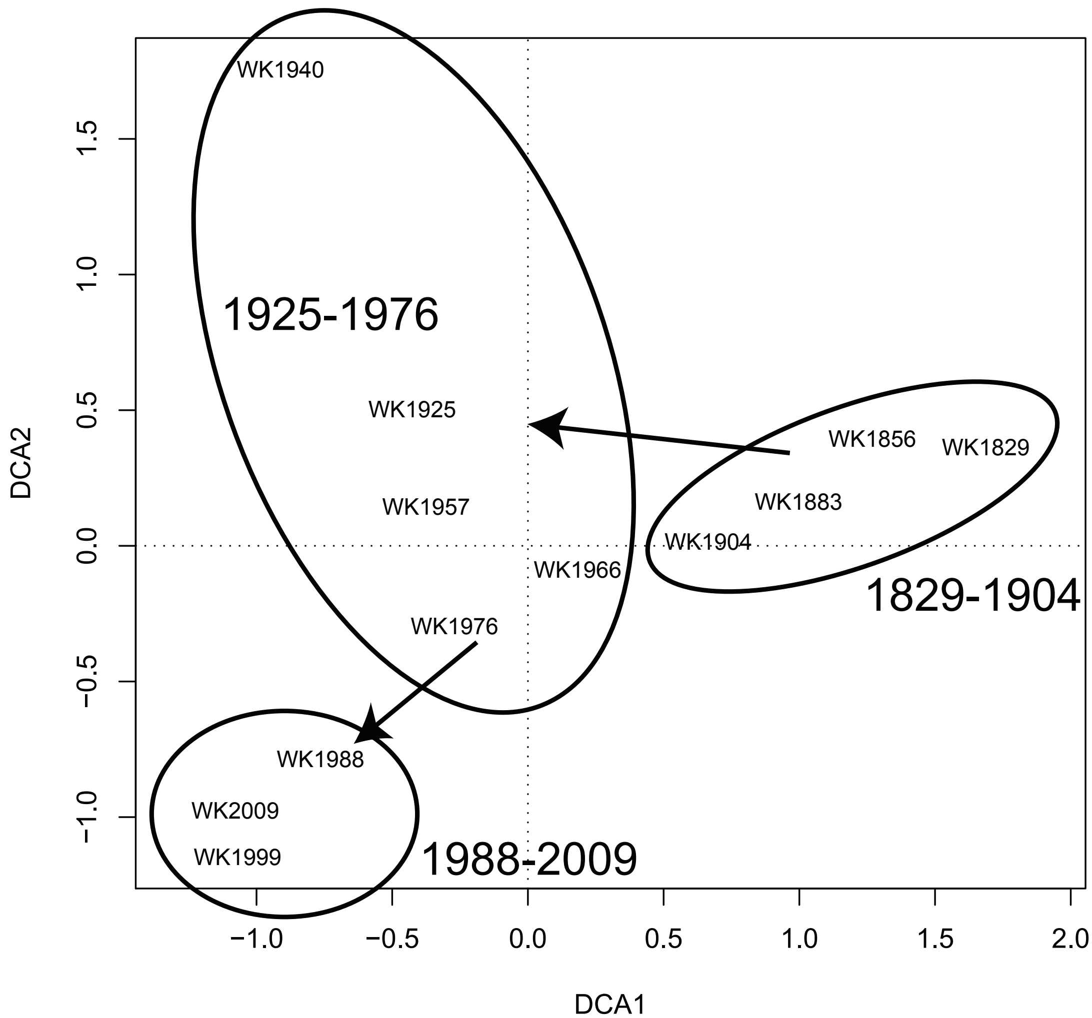


Figure 11. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance) in Wakefield Lake (1829-2009). Lines indicate the grouping of samples based on a constrained cluster analysis.

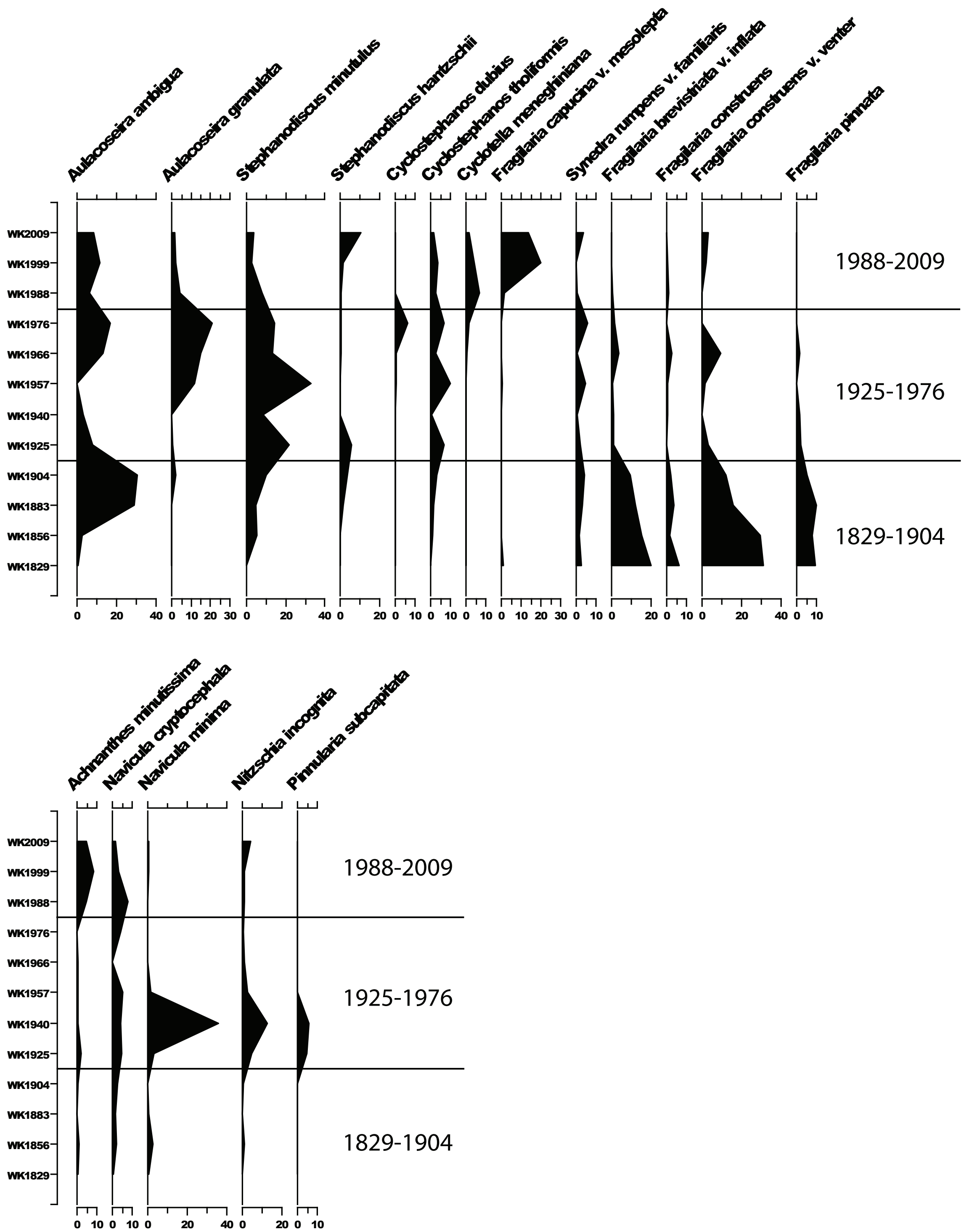


Figure 12. Detrended correspondence analysis (DCA) of diatom communities from Battle Creek Lake. Circles indicate the grouping of samples based on a constrained cluster analysis, arrows were drawn to illustrate the trajectory through time.

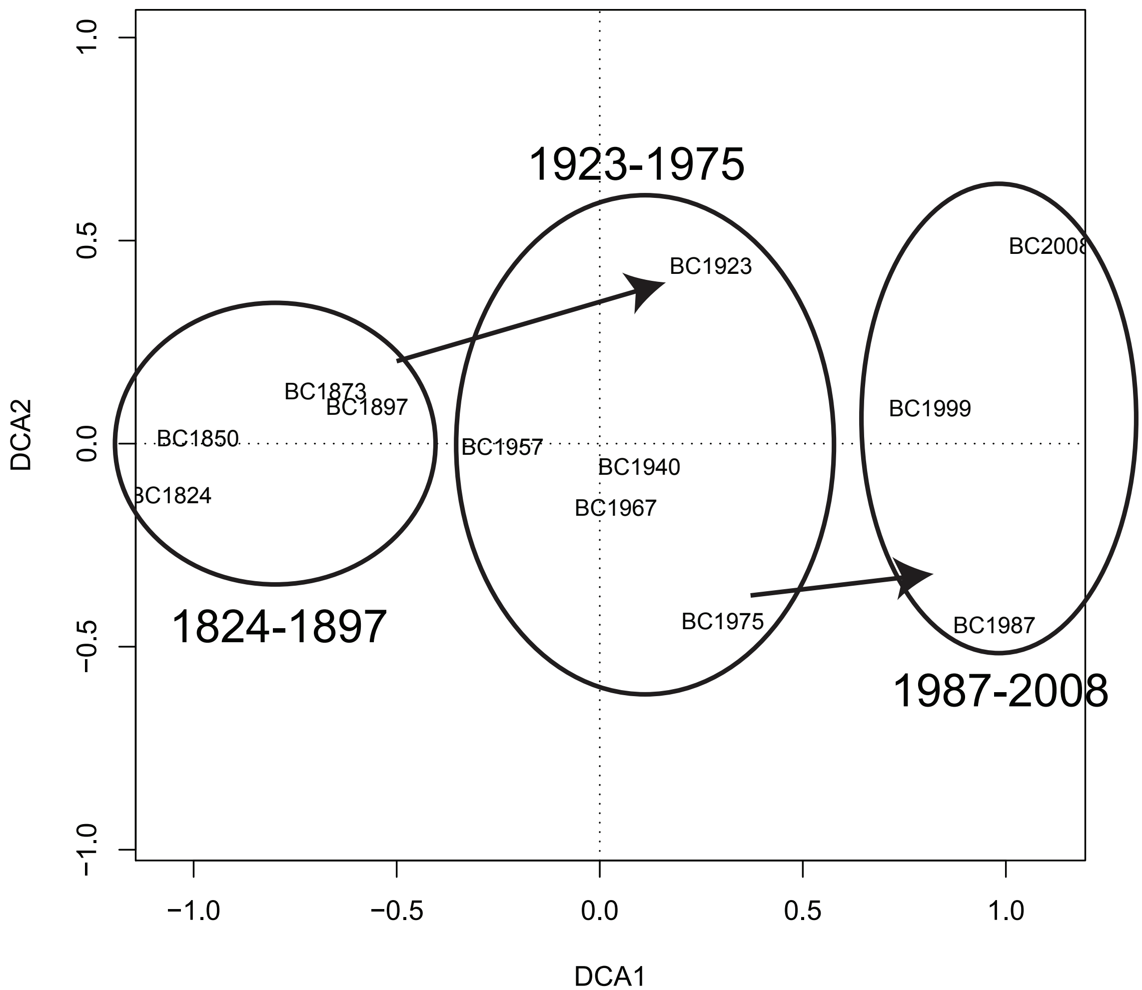


Figure 13. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance) in Battle Creek Lake (1824-2008). Lines indicate the grouping of samples based on a constrained cluster analysis.

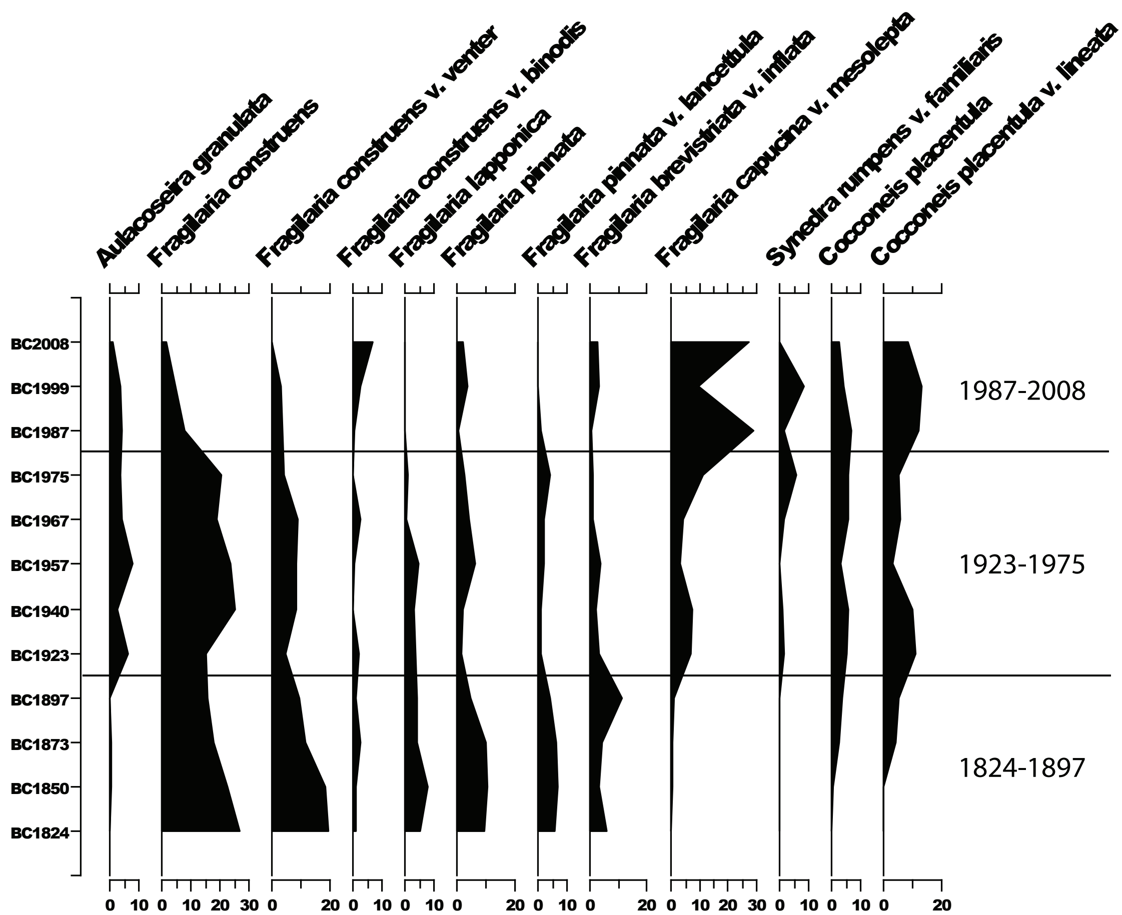


Figure 14. Diatom-inferred total phosphorus (TP) reconstruction for Kohlman Lake.

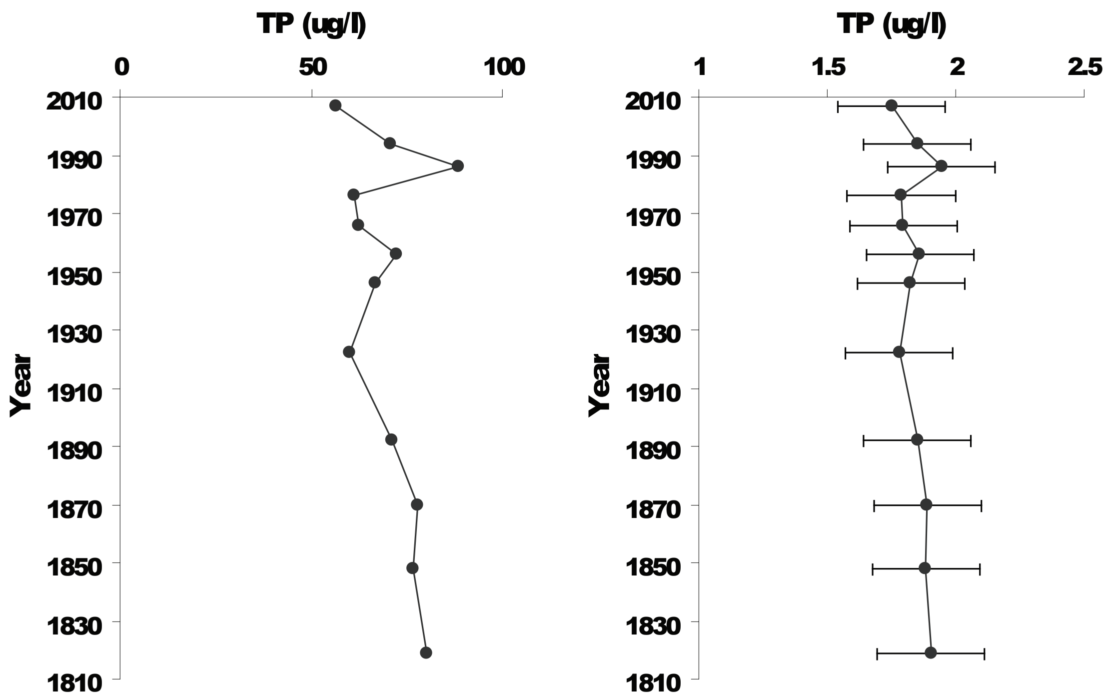


Figure 15. Diatom-inferred total phosphorus (TP) reconstruction for Wakefield Lake.

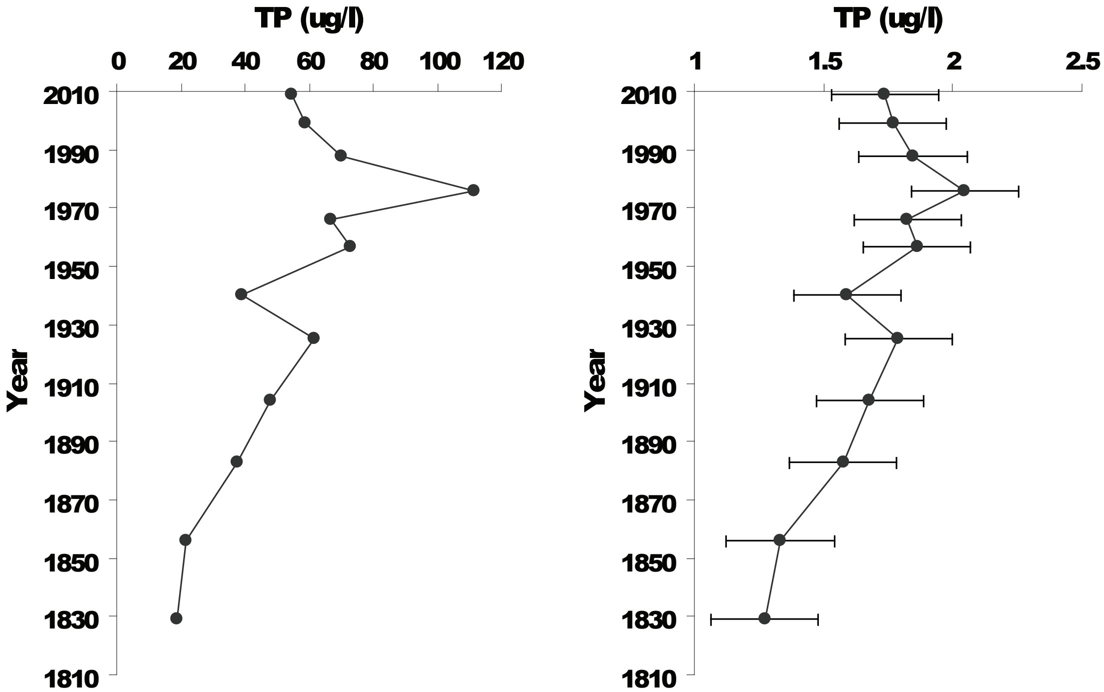
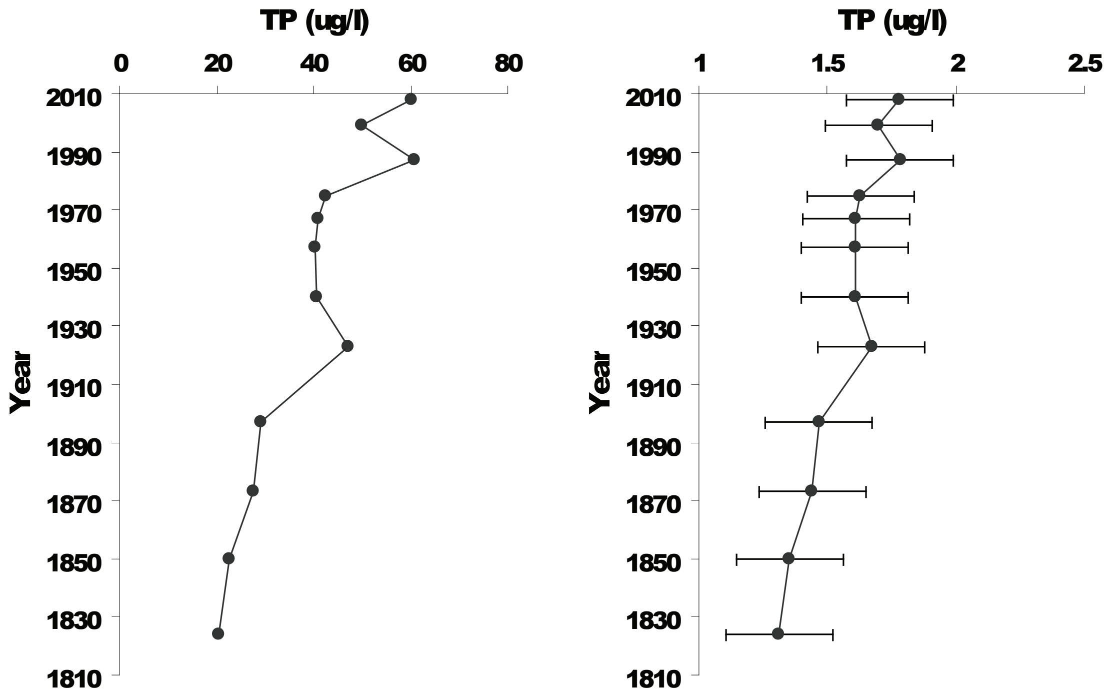
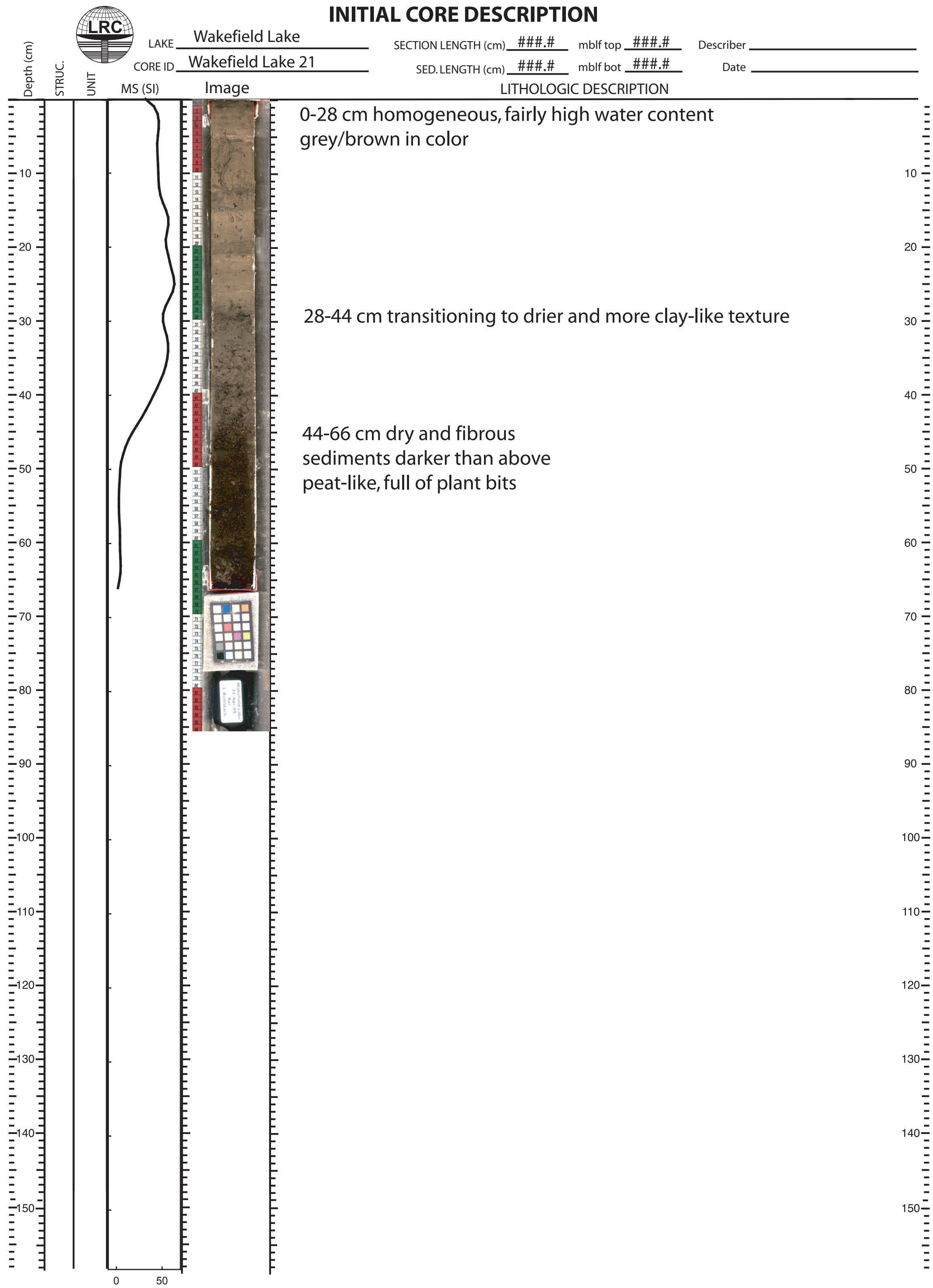


Figure 16. Diatom-inferred total phosphorus (TP) reconstruction for Battle Creek Lake.



Appendix A1. Core image, magnetic susceptibility, and physical description of the piston core from Wakefield Lake. Note that 15 cm have been extruded from the top of the core.



Appendix A2. Core image, magnetic susceptibility, and physical description of the piston core from Battle Creek Lake. Note that 38 cm have been extruded from the top of the core.