Historical Water Quality and Biological Change in Northcentral Minnesota Lakes

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CONTENTS

Executive Summary

1. In this project, we used paleolimnological techniques to reconstruct the trophic and sedimentation history of five lakes (Winona, Big Sandy, 1st Crow Wing, Dixon, Margaret) in northcentral Minnesota that are impaired or considered at risk for impairment by excess nutrients.

2. Three additional lakes (Decker, Portage, 8th Crow Wing) were unsuitable for paleoecological reconstructions because their sediment cores did not contain well-preserved diatom assemblages.

3. An approximately 2.0 m long core was recovered from each lake to capture a complete sediment sequence including pre-Euroamerican settlement (sediments dated earlier than 1860-1880 A.D) through post-settlement changes that variously included logging, lakeshore development, damming, WWTP installation, and residential development.

4. Each core was dated using 210-Pb inventories and analyzed for geochemical and biological indicators of ecological change including inorganics, organics, carbonates, total phosphorus, biogenic silica and siliceous microfossils (diatoms and chrysophytes). The diatom assemblages were further used to estimate historical total phosphorus levels by applying a weighted averaging phosphorus model based on species-environment relationships in 89 Minnesota lakes.

5. All lakes showed some ecological change in the last 200 years. Most lakes showed an increase in sedimentation rates and a shift in diatom communities in the late 1800s likely in response to wide scale logging in the region. Secondary shifts occurred in most lakes in the 1960s-1980s during times of landuse change such as develoment around the lakes.

6. Winona Lake showed the greatest change among the lakes. Sedimentation rates in Winona Lake increased following Euroamerican settlement, were relatively stable from 1930-1980, and have increased since 1980. Modern sedimentation rates are at least seven-fold greater that pre-settlement rates. The first major biological change in the core occurs around the time of WWII. Other indices of eutrophication also record this event including a sharp increase in the plankton to benthic diatom ratio and a decrease in the abundance of chrysophyte cysts. Further evidence of increased eutrophication was found in the upper three core levels that were investigated (1984-2007). Diatom-inferred phosphorus reconstructions show that Winona Lake is currently hypereutrophic (>100 ppb TP). This increase in TP has been stepwise with the first increase occurring around WWII. The pre-war and pre-settlement TP reconstructions (1802-1933) ranged from 24-40 ppb TP. From 1947-1976, diatom-inferred TP in Winona Lake increased to 54-60 ppb TP before rapidly increasing in the last three decades to hypereutrophic levels of ca 120 ppb TP in the two most recent samples analyzed (1994, 2007).

7. The greatest change in Big Sandy occurred following settlement and damming of the lake. Sedimentation rates and accumulation of inorganics increased, the largest biological shift occurred, and nutrient levels increased slightly. Diatoms suggest that nutrient levels increased after damming, peaked in the 1930s at ca. 77 ppb TP, and have declined since the 1980s to ca 53 ppb.

8. In 1st Crow Wing Lake, two periods of ecological change are evident. Initial Euroamerican settlement and logging in the region resulted in increased sedimentation rates due primarily to overall increased flux of carbonates and secondarily organics and inorganics. Diatom communities shifted in the late 1800s to a more benthic-dominated flora, which apparently also reflected lower nutrient values in the lake. The second large shift occurred in the late 1970s as sedimentation rates returned to near pre-settlement condition and diatom communities became more plankton-dominated. Diatom inferred TP reconstructions suggest that nutrient levels in 1st Crow Wing Lake were at one time higher (including during pre-Euroamerican settlement times) but that nutrient levels have remained nearly constant since the 1930s at mesotrophic levels.

9. There has been very small changes in Dixon Lake in the last 200 years. Biological indicators, diatom communities, and diatom-inferred total phosphorus all suggest very little historical change in Dixon Lake. Among the geochemical indicators, a suggestion of increased sedimentation rates since the 1930s remains the only indication of environmental change in Dixon Lake. It is unclear what might have driven these late changes given that the major landuse changes of logging would have occurred several decades earlier than the 1930s.

10. Notable in Margaret Lake was an increase in sedimentation rates between 1880 and 1940 likely as a result of logging activities and development of the area. Diatom communities have shifted several times in the past 200 years, but shifts primarily reflect changes in abundances of a core set of planktonic taxa that are common in meso- to eutrophic Minnesota lakes. Modern diatom-inferred TP values (40 ppb TP) are similar to monitored values in Margaret Lake (49 ppb TP).

11. Although Portage Lake did not have diatoms preserved downcore, the core that was recovered was radiometrically dated and analyzed for geochemistry including carbonates, organics, inorganics, biogenic silica, and total phosphorus. Pre European and pre-damming sedimentation rates were variable in Portage Lake. The impact of damming was reflected in a rapid decline in sedimentation rates to 0.025 g/cm^2/yr which lasted until about 1960. This likely does not reflect a true decline in sedimentation but a reorganization and likely enlargement of the depositional basin of Portage Lake. After 1960, sedimentation in Portage Lake increased upcore to pre-damming rates. The pattern of carbonate and organic flux reflects the overall sedimentation pattern with a rapid two-fold decline in flux following damming. Accumulation of carbonates and organics then increases to the core top, especially after the 1960s. Inorganic accumulation shows a general increase upcore. Weight percent TP increased following damming from 0.06% to modern levels of nearly 0.1%. Accumulation of phosphorus in Portage Lake sediments has a similar pattern and increases from 0.015 mg/cm^2/yr to modern rates of 0.06 mg/cm^2/yr. The pattern of biogenic silica content and accumulation in the Portage Lake sediment core confirms microscopic evidence of diatom dissolution.

INTRODUCTION

To effectively develop TMDL and management plans for Minnesota lakes, knowledge of the natural state of a lake and an understanding of the timing and magnitude of historical ecological changes become critical components especially for determining ecological and nutrient targets. Similarly, with environmental monitoring it is important to have a basic understanding of natural fluctuations within the system. Reliable long-term water quality 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 and natural variability, identify timing and magnitude of ecological changes, and determine rates of change and recovery (Anderson and Rippey 1994, Dixit and Smol 1994, Smol 2002). These techniques have been widely used in Minnesota to develop ecoregional nutrient criteria (Heiskary and Wilson 2008), assess historical watershed variability (Edlund and Ramstack 2006), and propose site-specific variances for TMDLs (Edlund and Ramstack 2007).

As one of the principal indicators used in sediment cores, diatoms have been widely used to interpret environmental conditions in lakes (Dixit *et al.*, 1992). Many species are sensitive to specific water conditions and are useful as bioindicators. Over the past 15-20 years, statistical methods have been developed to reconstruct specific environmental parameters from diatom assemblages (Birks et al. 1990). These methods are statistically robust and environmentally sound although results must be used with caution and are best when supported by multiple lines of evidence. Diatoms have been used successfully in reconstructing a wide variety of environmental parameters including pH, total phosphorus (TP), salinity, and recently, dissolved organic carbon (DOC).

The primary aim of this project is to use paleolimnological analysis of dated sediment cores to quantitatively reconstruct environmental histories using biogeochemistry, sediment accumulation, diatom-inferred total phosphorus (DI-TP), diatoms as biological indicators, and other sediment geochemical (inorganic, carbonates, organics, biogenic silica, and phosphorus) and biological proxies in eight northcentral MN lakes. This project will provide data to develop management plans that include an understanding of pre-settlement conditions, post-settlement conditions, historical lake response to landuse and past management, and development of nutrient targets necessary for TMDL planning. Results will provide a management foundation by determining the natural or reference condition of these lakes and by reconstructing a history of ecological changes that have occurred in the lakes during the last 150 years.

METHODS-SEDIMENT CORING

On May 12-15, 2008, sediment cores were collected from eight northcentral Minnesota Lakes (Winona, 8th Crow Wing, 1st Crow Wing, Portage, Dixon, Decker, Margaret, Big Sandy; Table 1). A single drive piston core was collected from a central depositional basin in each lake using an anchored rowboat, pontoon boat, or barge. The piston core was taken using a drive-rod piston corer equipped with a 6.5-cm diameter polycarbonate barrel (Wright 1991). The piston core was transported to the shore and extruded vertically in 2-cm increments to a depth with cohesive sediment texture (~40 cm). Core sections and material remaining in the core barrel were returned to the laboratory and stored at 4°C.

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 integrated 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.

METHODS-LEAD-210 DATING

Sediments 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 piston cores for loss-on-ignition (LOI) analysis to determine dry density and weight percent 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 (Dean 1974).

Thirteen weighed freeze-dried subsamples (30 mg) of sediment were digested for biogenic silica (BSi) analysis using 40 mL of 1% (w/v) Na_2CO_3 solution heated at 85°C in a reciprocating water bath for five hours (DeMaster 1979, Conley and Schelske 2001). A 0.5 g aliquot of supernatant was removed from each sample at 3, 4, and 5 h. After cooling and neutralization with 4.5 g of 0.021N HCl solution, dissolved silica was measured colorimetrically on a Lachat QuikChem 8000 flow injection autoanalyzer as molybdate reactive silica (McKnight 1991). BSi content and accumulation in a core is a proxy for historical diatom productivity.

Thirteen core increments were analyzed for sediment total P (Sed TP) following the procedures in Engstrom (2005) and Engstrom and Wright (1984). Total P was measured as the ortho-P extracted by sequential digestion with 30% hydrogen peroxide, followed by 0.5 M HCl. The extract was analyzed colorimetrically on a Lachat QuikChem 8000 flow injection autoanalyzer.

Sedimentation rates as determined by 210-Pb dating (as g/cm^2/yr) were then be used to convert the measured SedP concentration (in mg/g dry sediment) in the core to areal TP flux or accumulation rates in the sediments (as mg/cm^2/yr). Comparing modern P flux rates to flux rates from before European settlement, or before ecological state change, can provide managers with a first estimate of the percent P load reduction necessary to return the lake to conditions present before European settlement or present at a particular time period. This approach does not allow us to determine if phosphorus loading was the main driver of ecological change in the system, and there may be other management actions that are necessary in conjunction with P load reduction to return the lake to the pre-impact ecological state.

METHODS-DIATOM AND NUMERICAL ANALYSES

Thirteen core sections were prepared for diatom analysis. Samples noted as pre-settlement have approximate dates based on extrapolation of the Pb-210 model below the 1880s by assuming a constant sediment accumulation rate prior to settlement.

Diatoms and chrysophyte cysts were prepared by placing approximately 0.25 cm^3 of homogenized sediment in a 50 cm^3 polycarbonate centrifuge tube, 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 a 85°C water bath (Renberg 1990). 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 siliceous microfossils 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, Krammer and Lange-Bertalot 1986-1991, Edlund 1994, Camburn and Charles 2000) and primary literature to achieve consistent taxonomy.

Species present at greater than 1% relative abundance in two or more samples or at greater than 5% relative abundance in one sample were included in further analyses; the same selection criteria were used by Ramstack et al. (2003). Stratigraphies of subdominant diatoms were plotted against core date. Relationships among diatom communities within the sediment core were explored using Principal Components Analysis (PCA) or Correspondence Analysis (CA), which is available in 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 CA or PCA is that samples that plot closer to one another have more similar assemblages. Constrained cluster analysis, also available in the software package R, was also used to identify biostratigraphic zones in sediment cores based on historical diatom assemblages

Downcore diatom communities were used to reconstruct historical epilimnetic phosphorus levels in each lake. A transfer function for reconstructing historical logTP was earlier developed based on the relationship between modern diatom communities and modern environmental variable in 89 Minnesota lakes (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. Reconstructed logTP values are plotted downcore and also backtransformed to TP in ppb. The error bars represent the root mean squared error of prediction (RMSEP, bootstrapped), i.e. the error of the model. In interpreting change in a reconstruction, we assign significance to changes that are greater than the RMSEP (Ramstack et al. 2003).

RESULTS & DISCUSSION

WINONA LAKE-BACKGROUND, CORING, MAGNETIC SUSCEPTIBILITY AND CORE IMAGING

Winona Lake is located in Douglas County within the city of Alexandria, Minnesota. The lake is approximately two miles long (NE-SW) and less than a quarter mile wide. Although initially surrounded by farmland following Euroamerican settlement, the area around Winona Lake has been largely surrounded by residential development since the 1970s. The lake has also been the receiving water body for treated waste from treatment plants including the Alexandria WWTP (began operation 1967) and the ALASD Plant (replaced Alexandria WWTP in 1978). Efforts to reduce nutrient loading from the ALASD Plant have included increased tertiary treatment efforts using chemical dosage since 1994. Current water quality is hypereutrophic with total phosphorus and chlorophyll levels at 194 ppb and 85 ppb, respectively (Table 1)

A 1.93 m long piston core was recovered from the central basin of Winona Lake on May 12, 2008 (Table 2). The piston core was logged for magnetic susceptibility (Fig. 1), split, imaged, and described. There was some color change and stratigraphy in the core, notably an alternation of brown and dark gray banding. The magnetic susceptibility analysis and imaging are performed on the intact portion of the core; therefore these data do not exist for the portions of the core that were field sectioned (top 40 cm of the piston core). The core from Winona Lake is light brown-gray with variable dark banding along its length. There is a rise in magnetic susceptibility at 70 cm core depth (Fig. 2). An increase in magnetic susceptibility is often seen at the time of European settlement, when initial land clearance increased the amount of terrestrial-derived sediments to the lake, although in Winona Lake this shift in magnetics slightly pre-dates Euroamerican settlement.

WINONA LAKE-DATING AND SEDIMENTATION

Winona Lake showed a nearly monotonic decrease in ^{210}Pb activity and reached supported levels below 66 cm core depth (Fig. 2). Figures 2-4 show the unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for Winona Lake. Sedimentation rates increased in Winona Lake from 1860-the 1920s following Euroamerican settlement. From the 1920s to ca. 1980 sedimentation rates were relatively stable around 0.1 g/cm^{2}yr before increasing dramatically from 1984-2007. Current sedimentation rates are approximately seven times greater than pre-settlement rates.

WINONA LAKE-BIOGEOCHEMISTRY

Sediments from Winona Lake have historically been dominated by carbonates (Fig. 5). Carbonates decrease upcore from 60 to 35 percent dry weight between 70 and 30 cm core depth. Carbonates then increase upcore to relatively constant levels of 50 percent dry weight in the top 20 cm of the core. Changes in carbonate content are mirrored by changes in inorganics; inorganics become the dominant sediment component from 40-25 cm core depth. Organics vary between 17-28 percent dry weight in the Winona Lake core.

When converted to flux, all sediment components increase in accumulation following settlement (Fig. 6). Organic and carbonate accumulation peaked in the 1920s, fell from the 1920s until 1980 and then increased upcore. Inorganic accumulation peaked ca. 1960, dropped slightly from 1960-1980, then increased upcore.

Sediment total phosphorus was extracted from thirteen levels in the Winona Lake core (Table 3). Percent dry weight of phosphorus is fairly constant from pre-settlement to the time of damming at about 0.04% before increasing rapidly upcore to modern weight percent that is 2X greater than pre-damming levels (Fig. 7). Flux of TP to the sediments similarly increases upcore from almost zero in the pre-settlement sediments to increased accumulation of sediment TP after damming to modern levels that are five- to ten-fold higher than pre-damming rates.

The weight percent of biogenic silica has remained relatively constant in Lake Winona sediments for the past 200 years at between 4% and 6% dry weight (Fig. 8). In contrast, biogenic silica accumulation has increased dramatically from pre-settlement levels of about 1.0 mg/cm^2/yr to modern levels that are ten-fold higher. The increase in biogenic silica flux was interrupted by a plateau at about 5.0 mg/cm^2/yr from 1930-1980.

WINONA LAKE-DIATOM STRATIGRAPHY

Based on a correspondence analysis of subfossil diatom communities (and corroborated using constrained cluster analysis), Winona Lake has seen dramatic ecological changes in the last 200 years (Figs 9, 10). The diatom communities can be separated into three stratigraphic zones in the core: Zone 1 (1802-1933), Zone 2 (1943-1976), and Zone 3 (1984-2007). Transitions between these zones represent periods of greatest ecological change in Winona Lake. Zone 1 sediments

(1802-1933) have high abundance of benthic and epiphytic diatom species (*Gomphonema*, *Amphora*, *Cymbella*, *Denticula* spp.) and many chrysophyte cysts. Zone 2 sediments (1943-1976) show the first development of a significant planktonic flora in Winona lake (*Aulacoseira ambigua*, *A. subarctica*, *Stephanodiscus hantzschii*) and lower abundance of benthic and attached diatom species. Zone 3 sediments (1984-2007) are dominated by planktonic diatom species including high abundance of the eutrophic to hypereutrophic species *Aulacoseira granulata*, *Cyclotella meneghiniana*, and *A. ambigua* (Fig. 10).

Although biogeochemical and sedimentation changes occurred following Euroamerican settlement, the first major biological change in the core occurs around the time of WWII. This is a time when we see changes in many Minnesota lakes. Widespread post-WWII changes in agricultural practices that may have contributed to increased nutrient loading included greater mechanization and the increased use and availability of chemical fertilizers (Edlund et al. 2009a, Edlund et al. 2009b). Other indices of eutrophication also record this event and include a sharp increase in the plankton to benthic diatom ratio and a decrease in the abundance of chrysophyte cysts (Table 4). Additional biological evidence of increased eutrophication was found in the upper three core levels that were investigated (1984-2007; Table 4).

WINONA LAKE-PHOSPHORUS RECONSTRUCTION

Downcore total phosphorus reconstructions (Fig. 11) show that Winona Lake is currently hypereutrophic (~120 ppb TP) with TP levels far in excess of pre-Euroamerican TP concentrations. This increase in TP has been stepwise with the first increase occurring around WWII. The pre-war and pre-settlement TP reconstructions (1802-1933) ranged from 24-40 ppb TP. From 1947-1976, diatom-inferred TP in Winona Lake increased to 54-60 ppb TP before rapidly increasing in the last three decades to hypereutrophic levels of ca 120 ppb TP in the two most recent samples analyzed (1994, 2007).

WINONA LAKE-CONCLUSIONS

Based on diatom analysis, Winona Lake has been dramatically altered from its pre-European condition; the most dramatic changes in Winona Lake have occurred since WWII. Sediments deposited from 1802-1933 indicate that Winona Lake was likely a macrophyte-dominated lake with minimal plankton development and total phosphorus levels between 24 and 40 ppb. Following WWII (1943-1976), Winona Lake became a more productive system, likely lost some of its macrophyte coverage, developed its first significant planktonic diatom flora, and its TP concentrations increased to 54-60 ppb TP. Additional enrichment of Winona Lake has occurred from the 1980s-2000s as diatom-inferred TP concentrations rose to hypereutrophic levels of ~120 ppb diatom-inferred TP, diatom communities further shifted to dominance by planktonic indicators of eutrophication, and flux of TP and biogenic silica to the sediments increased rapidly.

BIG SANDY LAKE-BACKGROUND, CORING, MAGNETIC SUSCEPTIBILITY AND CORE IMAGING

Big Sandy Lake is located in Aitkin County, Minnesota. The lake is relatively large (area > 6000 acres) and deep (Zmax 84 ft) and has high development of cottages and homes on its shoreline (Table 1). The lake was dammed in the late 1800s to provide water level management on the Upper Mississippi River and remains dammed today.

A 1.95 m long piston core was recovered from Big Sandy's south central basin on 15 May 2008. The core was sectioned in the field to 48 cm. At the Limnological Research Center, the core was logged for magnetic susceptibility, split, and imaged (Fig. 12). There was minimal color variation in the core, which was an overall dark brown and fine-grained along its length (Fig. 12). There was a general decrease in magnetic susceptibility above 150 cm core depth and no clear evidence of a sharp increase in magnetic susceptibility as seen in many Minnesota lake cores at the time of Euroamerican settlement, which is located at about 80 cm depth (Fig. 12).

BIG SANDY LAKE-DATING AND SEDIMENTATION

Big Sandy Lake showed a monotonic decrease in ^{210}Pb activity and reached supported levels below 80 cm core depth (Fig. 13). A depth-date model for Big Sandy suggests that the Euroamerican settlement horizon is located at approximately 80 cm core depth, which corresponds to an approximate date of 1865 A.D. (Fig. 14). Before Euroamerican settlement, sediment accumulation rates were variable at about 0.07 $g/cm^2/yr$ (Fig. 15). After 1900, sedimentation rates increased to 0.12 $g/cm^2/yr$ and then fell to their modern levels of around 0.08-0.09 $g/cm^2/yr$ by 1940. The peak in sedimentation after 1900 could be the result of damming of Big Sandy or land use. In addition to damming, this time period coincides with major logging around Minnesota. Logging may have also contributed to increased sedimentation rates; however, we would have expected a simultaneous increase in magnetic susceptibility. That is not evident in the Big Sandy core. Since 1940, sedimentation rates have varied little but remained slightly higher than pre-Euroamerican rates (Fig. 15).

BIG SANDY LAKE-BIOGEOCHEMISTRY

The Big Sandy Lake core has been historically dominated by the inorganic fraction, which accounts for over 60% of the sediment weight (Fig. 16). The inorganic fraction increased following Euroamerican settlement and damming to a peak around the turn of the 20^{th} century. Organics have typically accounted for between 20 and 30% of the Big Sandy sediment with slightly higher percentages up core. Carbonates remain low in Big Sandy sediments but generally increase upcore. Although carbonates never reach greater than 10% dry weight, the increase upcore may suggest some increases in algal productivity.

When converted to accumulation rates, carbonates show minor increases upcore whereas organic accumulation rates remain relatively constant over the last 150 years (Fig. 17). In contrast, inorganic accumulation peaked in the early 1900s at rates nearly 2X pre-Euroamerican settlement rates. This peak likely reflects the impact of damming on Big Sandy Lake. Inorganic accumulation dropped between 1920 and 1940, and since the 1940s, accumulation of inorganics in Big Sandy lake has remained constant at around 6 $g/cm^2/yr$.

Sediment total phosphorus was also determined in the Big Sandy core. Phosphorus was less than 0.5% of the dry weight throughout the core and by weight showed little discernable trend (Fig. 18). In contrast, flux of phosphorus to the sediments of Big Sandy Lake in pre-Euroamerican times was 1.5-2X lower than in modern sediments. There was also a peak in accumulation of TP in the 1910s-1920s (Fig. 18).

Biogenic silica is measure of primarily the amount and accumulation of diatom and chrysophyte algae in a sediment core. Pre-Euroamerican quantity and flux of biogenic silica was slightly lower than in modern Big Sandy sediments (Fig. 19). There is also a strong peak in both % dry weight and flux of biogenic silica in the 1910s-1920s when sediment composition and accumulation were 2-4X greater than in pre-European times. Biogenic silica fell to lower levels by the 1930s and has shown a slight decreasing trend in both percent dry weight and flux between the 1930s and 2000s.

BIG SANDY LAKE-DIATOM STRATIGRAPHY

There were 170 different diatom species noted in the thirteen samples analyzed in the Big Sandy Lake core (Table 6). The core is dominated by meso-eutrophic taxa including the planktonic *Aulacoseira ambigua*, *A. subarctica*, *A. granulata*, *Fragilaria crotonensis*, and *F. capucina* and its variety *mesolepta*, as well as the benthic taxa *Staurosira construens* and its variety *venter* (Fig. 21). Based on a principal components analysis of the subfossil diatom communities in the Big Sandy Lake sediment core (and corroborated using constrained cluster analysis), four stratigraphic zones were resolved (Fig. 20): Zone 1 (1858-1878), Zone 2 (1896-1924), Zone 3 (1936-1965), and Zone 4 (1975-2008). The basal Zone 1 sediments have high abundances of benthic forms and the *Aulacoseira* taxa. Zone 2 sediments continue to be dominated by the *Aulacoseira* taxa but show a decrease in the benthic species and in increase in the eutrophic species *Cyclostephanos tholiformis*, *Fragilaria crotonensis*, and *Asterionella formosa*. These responses are likely a result of increased and more stable water levels in Big Sandy following damming. *Aulacoseira ambigua* begins to increase in abundance in Zone 3 sediments whereas *A. subarctica* declines in abundance. The shift from Zone 3 to 4 may be the result of cottage and home development around Big Sandy. Zone 4 sediments have a peak in abundance of *A. ambigua*, *F. crotonensis*, and *F. capucina* v. *mesolepta*.

Biological indicators of eutrophication including percent planktonic diatoms, percent chrysophyte cysts, diatoms to chrysophyte ratio, and planktonic to benthic diatom ratio (P:B) suggest that the greatest ecological changes occurred in Big Sandy Lake in the late 19th century concomitant with damming of the lake (Table 7). These indicators include an increase in planktonic diatoms and an increase in the P:B ratio, which suggest shift to more water column algal productivity (Table 7).

Big Sandy Lake-Phosphorus Reconstruction

The diatom-inferred total phosphorus reconstructions for Big Sandy Lake (Fig. 22) corroborates much of the biological and geochemical information from the sediment core. Pre-Euroamerican settlement TP values were 40-50 ppb. Following the turn of the 20th century, TP levels increased in Big Sandy Lake to a peak in the 1930s around 77 ppb. Since the 1930s TP levels in Big Sandy Lake have decreased slightly to modern diatom-inferred values of 53 ppb. This value compares favorably with recent measured TP in Big Sandy Lake of 51 ppb (Table 1). The changes in historical TP values in Big Sandy Lake have not been as dramatic compared to other Minnesota lakes (compare to Winona Lake); all changes are below the model error estimates (Fig. 22).

Big Sandy Lake-Conclusions

As evidenced from the geochemical and diatom analysis of the Big Sandy Lake sediment core, the greatest change in Big Sandy occurred following settlement and damming of the lake. Sedimentation rates and accumulation of inorganics increased, the largest biological shift occurred, and nutrient levels increased slightly. Diatoms suggest that nutrient levels increased after damming, peaked in the 1930s at ca. 77 ppb TP, and have declined since the 1980s to ca 53 ppb. An improved understanding of the history of Big Sandy Lake (damming, hydromanagement, logging history, and development in basin) would improve our interpretation of the sediment core.

1ST CROW WING LAKE-BACKGROUND, CORING, MAGNETIC SUSCEPTIBILITY AND CORE IMAGING

1st Crow Wing Lake is located in Hubbard County, Minnesota, and is part of the eleven lake Crow Wing chain. The lake is shallow (Zmax 15 ft), medium-sized (526 acres), and has moderate cottage and home development especially on its southeastern and southern sides. Water levels in 1st Crow Wing Lake are passively controlled by the roadbed and riprap at the CR109 bridge at its outlet. Modern nutrient levels are eutrophic with measured TP and chlorophyll values of approximately 56 ppb and 28.2 ppb, respectively (Table 1).

On May 13, 2008, a 2.09 m long piston core was recovered from the central basin of 1st Crow Wing Lake (Table 8). The core was sectioned to 58 cm in the field. The core was overall a medium brown color and graded to more gray below 125 cm (ca 1870). The magnetic susceptibility profile also showed a small decrease in susceptibility above the 125 cm level. In some Minnesota lakes, decreases in susceptibility reflect increased in-lake productivity (Fig. 23) following settlement or changes in nutrient loading.

1ST CROW WING LAKE-DATING AND SEDIMENTATION

The 210-Pb inventory in 1st Crow Wing Lake showed a steady decrease in activity downcore and reached supported levels below 130 cm depth (Fig. 24). The resulting depth-date model for 1st Crow Wing Lake suggests that 120 cm depth is approximately 1875 A.D. (Fig. 25). Sediment accumulation rates in 1st Crow Wing Lake were approximately 0.08 g/cm^2/yr before settlement and logging in the region. At the turn of the 20th century (Fig. 26), sedimentation rates increased to a peak in the 1960s of approximately 0.15 g/cm^2/yr, nearly two-fold pre-settlement rates. Since the 1960s, sedimentation rates in 1st Crow Wing Lake have declined to about 0.10 g/cm^2/yr, only slightly higher than pre-settlement rates.

1ST CROW WING LAKE-BIOGEOCHEMISTRY

The sediments of 1st Crow Wing Lake have been predominately carbonate-based in the last 200 years (Fig. 27). Carbonates account for between 40-65% of the sediment dry weight, and show a pattern of decline at 120 cm, an increase between 105 and 60 cm, followed by a decrease to 40% dry weight upcore. Organics are the second predominant sediment component and makes up between 25 and 35 percent dry weight. Organics generally increase upcore with an initial peak at 115 cm, a local minimum at 60 cm, and highest levels at the core top. Inorganics range from 13-25% dry weight and generally increase upcore, to constant levels of 20-25% above 100 cm core depth.

When sediment constituents are converted to flux or accumulation rates, a clear increase in flux of carbonates, organics and inorganics begins around 1900 AD (Fig. 28). Carbonates show a strong increase in flux to a peak in the 1960s, then decline upcore to pre-settlement levels. Organic flux increases upcore from 1.5 g/cm^2/yr to a steady rate of 4 g/cm^2/yr since the 1940s.

Inorganic flux shows a similar pattern to organic flux; however, inorganic accumulation remains slightly lower than organic accumulation throughout the core.

Sediment total phosphorus levels and accumulation rates in 1st Crow Wing have varied dramatically in the last 200 years (Fig. 29). Basal depths in the core have high quantity and flux rates that drop precipitously to around 0.1% dry weight or 0.1 mg/cm^2/yr by the 1900. This initial drop in sediment TP actually predates settlement. Sediment TP levels and flux show a slight increasing trend upcore between 1900 and the 1990s before spiking to new levels of 0.25-0.3 % dry weight or 0.25-0.3 mg/cm^2/yr during the 2000s (Fig. 29). The two high values at the core top may reflect a diagenetic artifact.

There is little correspondence between sediment TP and biogenic silica burial in the 1st Crow Wing Lake core. The bottom levels in the core have rather low quantity and flux of biogenic silica; these levels both increase by the 1870s, which again predates intense Euroamerican activity in the region (Fig. 30). There is an overall decreasing trend in biogenic silica quantity and flux from 1870 to 1990, but with ample variation over that time period. The top two samples show increased percent dry weight and flux of biogenic silica, which, similar to sediment TP, may be a diagenetic artifact rather than a reflection of recent increases in algal productivity.

1ST CROW WING LAKE-DIATOM STRATIGRAPHY

Analysis of thirteen samples from the 1st Crow Wing core (Table 9) revealed 166 diatom taxa. Historically the core has been dominated by the planktonic forms *Aulacoseira granulata*, *A. ambigua*, *Fragilaria crotonensis*, *Pseudostaurosira brevistriata*, and the benthic form *Staurosira construens* v. *venter*. A principal components analysis and a constrained cluster analysis identified four stratigraphic zones in the 1st Crow Wing Lake core (Figs 31, 32): Zone 1 (1834-1872), Zone 2 (1896-1968), Zone 3 (1978), and Zone 4 (1988-2008). Zone 1 is characterized by high abundance of *A. granulata*, *A. ambigua*, *F. crotonensis*, and *Cyclostephanos tholiformis*—an assemblage of typical indicators of eutrophic conditions. The transition to Zone 2 coincides with Euroamerican settlement and initial logging in the region and has a shift to decreased abundance of *A. granulata*, *A. ambigua*, and *F. crotonensis*, and an increased abundance of benthic forms including *S. construens* v. *venter*, *S. construens* v. *pumila*, and *Martyana martyii* and planktonic forms including *Stephanodiscus hantzschii*, and *P. brevistriata* v. *inflata*. Zone 3 comprises only a single sample dated from 1978 that is characterized by spikes in abundance of the planktonic forms *A. granulata, A. ambigua*. Zone 4 sediments are dated from 1988-2008 and stand out by their high abundance of *F. crotonensis* and *P. brevistriata*. Among the stratigraphic zones, the greatest ecological shift occurred at Euroamerican settlement between Zones 1 and 2 and the most recent shift between Zone 3 (1978) and Zone 4 (1988-2008). The timing of this latter shift corresponds to the timing of the most recent climate warming in Minnesota; other lakes in northern Minnesota show similar timing of recent ecological change that may reflect seasonal changes in ice cover and nutrient dynamics. Other drivers of change in the late 1970s through the 1980s should be explored including landscape and watershed changes around 1st Crow Wing Lake.

Other biological indicators of change that can be used to assess ecological change include percent planktonic diatoms, percent chrysophyte cysts, diatoms to chrysophyte ratio, and planktonic to benthic diatom ratio (P:B). Among these indices, % plankton and the P:B ratio identify the large changes between Zones 1 and 2 and Zones 3 and 4 as being primarily defined by the loss of planktonic diatoms and then the return of planktonic diatoms to 1st Crow Wing Lake (Table 10). The long period of increased abundance of benthic diatoms from 1896-1968 may suggest that macrophyte development was greater, or that water levels fluctuated more or were lower. Again, exploring the history of water management of 1st Crow Wing would may well explain the timing of these changes.

1ST CROW WING LAKE-PHOSPHORUS RECONSTRUCTION

Downcore total phosphorus reconstructions based on subfossil diatom assemblages shows that 1st Crow Wing Lake has shown some significant changes in its nutrient history (Fig. 33). In contrast to many Minnesota lakes that show increases in nutrients following Euroamerican settlement or shifts in agricultural practices, 1st Crow Wing Lake shows an opposite trend. The highest inferred TP levels are during the pre-Euroamerican settlement period and suggest that 1st Crow Wing was strongly eutrophic with levels nutrient levels of ca. 100 ppb TP. The core is dominated in this time period by *Aulacoseira granulata*, *A. ambigua* and *Cyclostephanos tholiformis* suggesting that there was substantial plankton development that was dominated by these eutrophic species. *Aulacoseira granulata* is often the dominant diatom in polymictic and shallow lakes that are in a turbid nutrient rich condition. Although the inferred TP values seem somewhat high for pre-settlement times, the potential for damming by beaver or early logging interests may have resulted in the conditions necessary to produced a highly productive system. After settlement, diatom inferred nutrient levels drop to more mesotrophic values of ca. 30 ppb TP by the 1930s. These values remain relatively constant upcore except for the brief excursion in the Zone 3 sample from 1978. The most recent diatom-inferred TP values are around 30 ppb TP, which compares to slightly higher modern monitored values of 56 ppb.

1ST CROW WING LAKE-CONCLUSIONS

Based on geochemical and diatom analysis of the 1st Crow Wing Lake core, two periods of ecological changes are evident in the lake's history. Initial Euroamerican settlement and logging in the region resulted in increased sedimentation rates due primarily to overall increased flux of carbonates and secondarily organics and inorganics. Diatom communities shifted in the late 1800s to a more benthic dominated flora that apparently also reflected lower nutrient values in the lake. The second large shift occurred in the late 1970s as sedimentation rates returned to near pre-settlement condition and diatom communities became more plankton-dominated. Diatom inferred TP reconstructions suggest that nutrient levels in 1st Crow Wing Lake were at one time higher (including during pre-Euroamerican settlement times) but that nutrient levels have remained nearly constant since the 1930s at mesotrophic levels.

DIXON LAKE-BACKGROUND, CORING, MAGNETIC SUSCEPTIBILITY AND CORE IMAGING

Dixon Lake is located in Itasca County just north of Lake Winnibigoshish. Dixon Lake is a medium-sized lake (600 acres) and has a maximum depth of about 29 ft (Table 1). Recent monitoring suggests the lake is mesotrophic with TP values of 40 ppb and chlorophyll concentrations of 15.9 ppb. The lake has some cottage and home development especially on the western shore but much of the shoreline remains undeveloped.

A 2.05 m long piston core was recovered on May 13, 2008 from the southern basin of Dixon Lake (Table 11). The core was generally a dark brown color with some regions of slightly lighter brown (Fig. 34). Magnetic susceptibility showed a decrease upcore from 150 cm; however most of the post-settlement core was sectioned in the field and not logged for susceptibility.

DIXON LAKE-DATING AND SEDIMENTATION

The Dixon Lake core shows a declining inventory of ^{210}Pb activity downcore that reached supported levels at approximately and reached supported levels below 62 cm depth (Fig. 35). The date-depth model for Dixon Lake indicates that sediments below 50 cm depth were deposited before 1880, which is around the time of initial settlement and logging interest in this region (Fig. 36). Sediment accumulation rates remained constant from before Euroamerican settlement until about 1930 at 0.025-0.030 g/cm^2/yr. After the 1930s, sedimentation rates increased quickly to a local maximum in the 1950s, fell slightly by 1970, and have increased upcore to modern levels of 0.07-.0.08 g/cm^2/yr or nearly three times pre-settlement rates (Fig. 37).

DIXON LAKE-BIOGEOCHEMISTRY

Sediment composition in Dixon Lake has changed very little in the last 200 years (Fig. 38). The inorganic fraction has been the dominant fraction, accounting for between 40 and 50 percent of the dry weight. The organic fraction has been about 30 percent and the carbonate fraction has varied between 20 and 25 percent of the sediment dry weight. Changes in accumulation of sediment components has been driven by the increased overall sediment flux since the 1930s (Fig. 39). All three sediment components show some similar accumulation patterns with increased flux between 1930 and the 1950s, a slight drop in flux from the 1950s until 1970, and then further increased accumulation rates upcore. (Fig. 39).

The amount and accumulation of total phosphorus in Dixon Lake sediments shows high variability in the last 200 years (Fig. 40). Percent dry weight of total phosphorus in the sediments was highest in the presettlment section (pre-1880) at ca 0.35%. Weight percent of phosphorus decreased to ca 0.2% from 1880 through the 1950s and then jumps in the 1960s to modern levels of about 0.3%. When converted to flux, a different pattern of phosphorus accumulation emerges (Fig. 40). There is relatively constant flux of TP from pre-settlement until 1930 and then a rapid and continuous increase in TP flux from 1930 to present day.

Biogenic silica is a major component of Dixon Lake sediments varying from between 10 and 15 percent by dry weight (Fig. 41). Percent biogenic silica was highest in the Dixon Lake core before 1900, when it reached over 15%; however, since 1900 the dry weight percent of biogenic silica has remained approximately 10%. When considered as a flux or burial rate, the accumulation of biogenic silica follows the same pattern as overall sediment flux with increases between 1930 and the 1950s, a slight drop in flux from the 1950s until 1970, and then further increased flux upcore.

DIXON LAKE-DIATOM STRATIGRAPHY

Approximately 153 diatom taxa were identified in the thirteen samples analyzed from the Dixon Lake core (Table 12). The historical diatom assemblages were dominated by meso- and eutrophic planktonic forms including *Aulacoseira ambigua*, *A. granulata*, *A. alpigena*, *Asterionella formosa*, *Cyclostephanos tholiformis*, and *Fragilaria crotonensis*. Based on a principal components analysis and constrained cluster analysis of the subfossil diatom communities from the thirteen sediment depths, three biostratigraphic zones were identified in the Dixon Lake core (Figs 42, 43): Zone 1 (1814-1884), Zone 2 (1910-1955), and Zone 3 (1965-2007). The entire core was dominated by approximately 20% relative abundance of *Aulacoseira ambigua* and 10-15% abundance of *A. granulata*. The oldest sediments in Zone 1 were secondarily characterized by abundance of the benthic species *Staurosira construens* v. *venter*. Zone 2 sediments, dated from 1910-1955, showed an interesting peak in abundance of *Asterionella formosa* and the uncommon species *Aulacoseira alpigena*. The most recent sediments in Zone 3 have a peak in abundance of *Fragilaria crotonensis*. The timing of shifts between these stratigraphic zones seems rather typical for the northern Minnesota lakes. The transition between Zones 1 and 2 coincides with the timing of Euroamerican settlement and logging in this region. The second major shift between core Zones 2 and 3 may be related to the development of cottages and homes around Dixon Lake in the late 1950s and 1960s. Within Zone 3 sediments or since the 1960s the biological communities are very tightly grouped in the principal components analysis, which indicates that there has been little recent change in Dixon Lake.

Other biological indicators in the Dixon Lake core including percent planktonic diatoms, percent chrysophyte cysts, diatoms to chrysophyte ratio, and planktonic to benthic diatom ratio (P:B) corroborate the diatom stratigraphies and suggest that there has been only minor changes in biological communities in Dixon Lake in the last 200 years (Table 13).

DIXON LAKE-PHOSPHORUS RECONSTRUCTION

By applying a model of diatom species-TP relationships based on nearly 90 Minnesota lakes to historical Dixon Lake diatom communities, historical total phosphorus levels can be estimated. Downcore total phosphorus reconstructions for Dixon Lake show (Fig. 44) show little if any significant change in phosphorus levels in Dixon Lake in the last 200 years. Diatom-inferred total phosphorus levels have been at or near 50 ppb TP throughout the length of the core. Modern total phosphorus values in Dixon Lake are approximately 40 ppb TP, just slightly less than predicted by the diatom assemblages.

DIXON LAKE-CONCLUSION AND RECOMMENDATIONS

Analysis of a sediment core from Dixon Lake for geochemical and biological indicators of ecological change has shown that there has been very small changes in Dixon Lake in the last 200 years. Biological indicators, diatom communities, and diatom-inferred total phosphorus all suggest very little historical change in Dixon Lake. Among the geochemical indicators, a suggestion of increased sedimentation rates since the 1930s remains the only indication of environmental change in Dixon Lake. It is unclear what might have driven these changes given that the major landuse changes of logging would have occurred several decades earlier than the 1930s. It would be a worthwhile exercise to develop a timeline of historical landuse around Dixon Lake including logging history and lakeshore development.

MARGARET LAKE-BACKGROUND, CORING, MAGNETIC SUSCEPTIBILITY AND CORE IMAGING

Margaret Lake is located in Cass County, Minnesota, and is a minor embayment connected to the north end of Gull Lake. Margaret Lake is fed by Home Brook, which flows into its southernmost basin. Margaret Lake is relatively small (250 acres) and is of medium depth (Zmax 26 ft). Its shoreline is mostly developed by larger homes. Modern monitoring reports show that total phosphorus levels (49 ppb TP) and chlorophyll levels (27.5 ppb) are typical of meso- to eutrophic levels (Table 1).

On May 15, 2008, a 1.89 m long piston core was recovered from Margaret Lake's southern basin from 7 m of water just N of the mouth of Home Brook. The top 40 cm of the core were sectioned in the field (Table 15). The upper 50 cm (ca 1880) of the core were a dark brownish gray (Fig. 45). Farther downcore there was much more variability in the core including significant banding and sand lenses that may reflect inputs from Home Brook. There was a higher magnetic signature downcore; however in the portion of the core of interest to this project (0-60 cm) there was little change in magnetic susceptibility.

MARGARET LAKE-DATING AND SEDIMENTATION

Activity of ^{210}Pb decreased monotonically downcore in Margaret Lake sediments and reached supported levels by 64 cm core depth (Fig. 46). The date-depth model for Margaret Lake indicates that sediments below 50 cm core depth were deposited before 1880 and represent pre-Euroamerican sedimentation (Fig. 47). Sedimentation rates in Margaret Lake show large historical changes most notably with initial settlement and logging activity in the region between 1880 and 1900 (Fig. 48). Pre-settlement sedimentation rates were approximately 0.04 g/cm^2/yr. Between 1880 and 1900 sedimentation rates began a rapid increase rising to a peak in sedimentation in the early 1940s of 0.10 g/cm^2/yr, over two times pre-settlement rates. Sedimentation rates fell during the 1950s-1980s to 0.07 g/cm^2/yr. The two most recent samples that were analyzed included had sedimentation rates similar to the 1940s but may reflect a diagenetic bias at the core top.

MARGARET LAKE-BIOGEOCHEMISTRY

Sediments from Margaret Lake have historically been dominated by the inorganic component (Fig. 49). Inorganics have accounted for 67-75% dry weight with a general decrease upcore from highest levels in the basal depths to lowest levels at the core top. Organics are the next dominant sediment component and show an upcore increase in abundance from approximately 20% dry weight at 60 cm core depth to 27% dry weight at the core surface. Carbonates have always been a minor component of Margaret Lake sediments accounting for less than 5% of the sediment weight.

The minor changes in sediment components are magnified when converted to accumulation rates (Fig. 50). Flux of inorganics shows a large three-fold increase between 1880 and 1940 likely in response to logging practices and land clearance. Inorganic accumulation decreases between the 1950s and 1980s but increases again in the more recent sediments of Margaret Lake. Organic accumulation follows a similar pattern of change with increased flux from 1880-1940, lower flux during the 1950s-1980s, and some increases in the topmost sediment levels. Carbonate accumulation, the minor component of Margaret Lake sediments, shows only a slight increasing trend in the last 200 years.

Sediment total phosphorus, expressed as either weight percent or accumulation rates, generally increases upcore in Margaret Lake (Fig. 51). Percent dry weight of sediment phosphorus increases from 1820 to 1900, then decreases to a local minimum in the 1930s. From the 1930s to present sediment phosphorus increases from 0.4% to modern values of 0.7%. Flux of TP to the sediments begins to increase in Margaret Lake after the 1870s from presettlement levels of ca 0.15 mg/cm^2/yr to modern levels of over 0.7 mg/cm^2/yr.

Amount and accumulation of biogenic silica in Lake Margaret have varied significantly over time from approximately 6% to 10% of sediment dry weight and accumulation rates from 2-10 mg/cm^2/yr (Fig. 52). Pre-settlement levels were variable between 6-9% dry weight and 2-3 mg/cm^2/yr. Biogenic silica decreased in quantity from 1880-1920, then increased to its highest level of nearly 11% dry weight in 1950. There has been a trend from 1950-2008 of decreasing biogenic silica in the Margaret Lake core. The changes in percent dry weight of biogenic silica may reflect the relative influence of inputs from Home Brook. In contrast to weight percent, flux of biogenic silica followed the pattern of sediment accumulation in Margaret Lake with increases from 1880 to 1940, decreased flux between 1950 and the 1980s, and slight increases at the core top. Flux rates of biogenic silica over the last 50 years have been about two-fold greater than pre-settlement rates.

MARGARET LAKE-DIATOM STRATIGRAPHY

Based on microscopic analysis of thirteen levels in the Margaret Lake core, 168 diatom species were identified (Table 15). Planktonic diatoms dominate the Margaret Lake core, notably *Aulacoseira ambigua*, *A. granulata*, *Asterionella formosa*, *Fragilaria crotonensis*, and *Stephanodiscus parvus*, a suite of taxa that are typical of meso- to eutrophic lakes in Minnesota. The core also has about 10-25% benthic species along its length including many species that are indicative of stream inputs (*Melosira varians*, *Rhoicosphenia abbreviata*). Using multivariate community analysis (principal components) and a constrained cluster analysis, five biostratigraphic zones were identified in the Margaret Lake core (Figs 53, 54): Zone 1 (1820-1873), Zone 2 (1900-1916), and Zone 3 (1935-1944), Zone 4 (1952-1966), and Zone 5 (1976-2007). The basal or pre-Euroamerican sediments in Margaret Lake fell out in Zone 1 (1820-1873) and were characterized by high abundance of *Aulacoseira ambigua*, *A. granulata* and the highest historical abundance of *Stephanodiscus parvus*. Zone 2 sediments (1900-1916) had decreased abundance of *S. parvus* and *A. ambigua*, and the beginning of an increased abundance of *Asterionella formosa*. Sediments from Zone 3 showed the greatest ecological shift in the core with a continued decrease in abundance of *S. parvus*, but an increase in abundance of *Aulacoseira ambigua* and *Asterionella formosa*. Zone 4 sediments (1952-1966) had the greatest abundance of *Asterionella formosa* and decreased abundances of *Aulacoseira ambigua* and *A.*

granulata. The uppermost biostratigraphic zone in Lake Margaret has high abundance of *Asterionella formosa*, lower abundance of *Aulacoseira ambigua*, and an increased abundance of *Fragilaria crotonensis*.

Other methods of looking at biological indicators in sediment cores include several diatom and chrysophyte indices (Table 16). For Margaret Lake, changes in planktonic diatom percentage may reflect periods of relative impact of loading from the Home Brook. Periods of lower plankton percentage include 1880-1920 (Table 16), which may result from logging and clearance. Additionally there is lower percentage of planktonic forms and an increase in chrysophyte cysts in post 1975 sediments. This might be a consequence of changed water chemistry toward more stained conditions or be a consequence of earlier or longer periods of spring mixing to promote increased chrysophyte growth.

MARGARET LAKE-PHOSPHORUS RECONSTRUCTION

The diatom-inferred total phosphorus reconstruction for Margaret Lake is the most confounding among the lakes sampled in this study (Fig. 55). Modern monitored TP levels in Margaret Lake are at 49 ppb TP. Diatom-inferred TP levels suggest a eutrophic to mesotrophic history in Margaret Lake. Pre-1900 sediments have the highest diatom-inferred TP levels of 60-67 ppb TP. After 1900, diatom inferred TP levels decrease slightly to 40 ppb TP by 1950. From 1950 to 2008 diatom-inferred TP levels remain at approximately 40 ppb. Modern chlorophyll values and Secchi depths in Margaret Lake are indicative of a meso- to eutrophic values (Table 1), which is along the lines of what lake condition our diatom-inferred TP would indicate.

MARGARET LAKE-CONCLUSIONS

Analysis of diatom remains and geochemical signals preserved in a sediment core from Margaret Lake indicated that the lake has experienced some change in the last 200 years. Notable was an increase in sedimentation rates between 1880 and 1940 likely as a result of logging activities and development of the area. Diatom communities have shifted several times in the past 200 years, but shifts primarily reflect changes in abundances of a core set of planktonic taxa that are common in meso- to eutrophic Minnesota lakes. Modern diatom-inferred TP values (40 ppb TP) are near current monitored values (49 ppb TP) suggesting that the lake is a meso- to eutrophic system.

Portage Lake-Background, Coring, Magnetic susceptibility and Core imaging

Portage Lake (Hubbard County) is a medium-sized reservoir (400 acres) that was constructed in the late 1930s along the Fish Hook Lake drainage. The lake is relatively shallow (17 ft max depth) and has experienced a wide variety of fish management (stocking, winterkill), hydromanagement, and the introduction of the exotic macrophyte curly-leaf pondweed in the 1990s. The lake has suffered from poor water quality with monitored total phosphorus (55 ppb) and chlorophyll (24.2 ppb) levels exceeding regional standards. The shoreline of Portage Lake is well-developed with cottages and homes especially along the north and south shores of its large eastern basin.

A 2.10 m long piston core was recovered from the eastern basin of Portage Lake on May 13, 2008 from 4.1 m of water (Table 17). The core was returned to shore where it was sectioned to 48 cm depth in 2-cm increments. The core had an overall gray-brown color with some dark banding below 60 cm core depth (pre-Euroamerican settlement). Magnetic susceptibility varied a bit in the portion of the core that remained in the core barrel (Fig. 56); however, most of the core portion of interest (post-damming, post-settlement, logging) was sectioned in the field.

Portage Lake-Dating and Sedimentation

Despite having been dammed in the late 1930s, sediments from Portage Lake sediments showed a monotonic decrease in ^{210}Pb activity and reached supported levels below 58 cm core depth (Fig. 57). There was clearly a permanent body of water present in this basin before damming occurred in 1938. A date-depth model for Portage Lake indicates that pre-Euroamerican sediment (ca 1870) are deposited below 50 cm, and that post-damming sediments (ca 1938) are located above 28 cm (Fig. 58). Sedimentation rates in Portage Lake have varied tremendously over the last two centuries (Fig. 59). Pre European and pre-damming sedimentation rates were variable but around 0.05 g/cm^2/yr. The impact of damming was reflected in a rapid decline in sedimentation rates to 0.025 g/cm^2/yr which lasted until about 1960. This likely does not reflect a true decline in sedimentation but a reorganization and likely enlargement of the depositional basin of Portage Lake. After 1960, sedimentation in Portage Lake increased upcore to pre-damming rates.

Portage Lake-Biogeochemistry

Sediments from Portage Lake have historically been dominated by carbonates (Fig. 60). Basal carbonate content was greater than 80%. Following settlement (ca 40 cm, 1895) and damming (ca 28 cm, 1938) carbonate content began declining. Above 25 cm, carbonate content has remained about 55% dry weight of Portage Lake sediments. Organics are the next most abundant constituent of Portage Lake sediments and mirror the abundance of carbonates. Pre-damming organic content of the core was 15-20% which increased after damming to modern levels of 30% dry weight. Inorganics have historically been the least abundant component of Portage Lake sediments; however, there is an increase in inorganics following damming, from about 5% to 15% organics. Increases in inorganic content are typical following dam construction as trapping efficiency increases with reservoir formation.

If sediment constituents are converted to accumulation rates, the pattern of carbonate and organic flux reflects the overall sedimentation pattern (Fig. 59) with a rapid two-fold decline in flux following damming (Fig. 61). Accumulation of carbonates and organics then increases to the core top, especially after the 1960s. Inorganic accumulation shows a general increase upcore.

Total phosphorus in the sediments of Portage Lake was extracted from thirteen samples (Table 18) to determine weight percent of TP and its accumulation rate (Fig. 62). Pre-damming weight percent and flux rates were variable (Fig. 62). Following damming of Portage Lake in the late 1930s, TP concentration and accumulation has increased. Weight percent TP increased following damming from 0.06% to modern levels of nearly 0.1%. Accumulation of phosphorus in Portage Lake sediments has a similar pattern and increases from 0.015 $mg/cm^2/yr$ to modern rates of 0.06 $mg/cm^2/yr$.

Biogenic silica content is very low in Portage Lake sediments compared to other lakes sampled in this study (Fig. 63). The highest abundance of biogenic silica is in the surface sediments of the core, where weight percent reaches 1.7%. Moving downcore, the amount of biogenic silica declines almost monotonically to 0.2% by weight in sediments deposited in the 1890s. Accumulation of biogenic silica follows a similar pattern. This pattern of biogenic silica in a sediment core is a sure sign of diatom dissolution.

Microscopic analysis of Portage Lake sediments confirmed our fear of diatom dissolution. Diatoms quickly dissapeared in the top 15 cm of sediment core and their condition was indicative of dissolution. Unfortunately, this prevents any meaningful diatom analysis on Portage Lake to determine historical nutrient levels. Dissolution of diatoms in Portage Lake is likely because of the high carbonate content of the sediments; diatoms readily dissolve in high pH water. Other factors that may contribute to dissolution include lake hydrology and groundwater flow. Although we've studied nearly 200 lakes in Minnesota, only a handful have problems with diatom dissolution. Others include 8^{th} Crow Wing (Hubbard Co.), Decker Lake (Itasca Co.), Lake Itasca (Clearwater Co.), and Diamond Lake (Hennepin Co.).

OTHER LAKES (DECKER, 8TH CROW WING)

8TH CROW WING LAKE-BACKGROUND, CORING, MAGNETIC SUSCEPTIBILITY AND CORE IMAGING

Eighth Crow Wing Lake is part of the eleven lake Crow Wing chain in Hubbard County. The lake is mid-sized (~500 acres) and of mid depth with a maximum depth of 30 ft (Table 1). There is development around much of its shoreline including several family resorts that are still in operation. Water quality indicators suggest that 8th Crow Wing lake is mesotrophic with total phosphorus of 36 ppb, chlorophyll of 28.2 ppb, and a mean Secchi depth of 2.5 m. Water level in the lake is controlled by a small dam beneath the bridge of Hwy 33.

On 13 May 2008 we recovered a 1.94 m long core from 7.64 m of water depth from the large southern basin of 8th Crow Wing Lake, 1.94m long, sect to 48 cm (Table 19). The core was transported to shore and the top 48 cm was extruded and sectioned in 2-cm increments. The core was a medium grayish brown color along its length and slightly more gray in the deeper sediments (Fig. 64). Magnetic susceptibility began declining at approximately 75 cm core depth, which may be an indication of environmental change in the lake from increased productivity (Fig. 64). Unfortunately the 8th Crow Wing Lake core did not have good diatom preservation so no dating was completed on the core.

8TH CROW WING LAKE-BIOGEOCHEMISTRY

Loss on ignition was run on the top 48 cm of the 8th Crow Wing Lake core to determine percent composition of inorganics, organics, and carbonates (Fig. 65). Carbonates dominated 8th Crow Wing sediments with >80% dry weight at 48 cm and decreasing upcore to approximately 70% dry weight. Organics and inorganic equally made up the remainder of the sediment weight. Both constituents increased from about 8% dry weight at 48 cm to 13-15% dry weight at the core surface.

As with the carbonate-dominated Portage Lake core, 8th Crow Wing suffered from lack of diatom preservation downcore. Microscopical analysis showed that diatoms disappeared after the top 10-15 cm in the core and that the diatoms showed strong evidence for dissolution. This prevented any additional dating, geochemistry, or biological analyses being done on the core for environmental reconstruction.

DECKER LAKE-BACKGROUND, CORING, MAGNETIC SUSCEPTIBILITY AND CORE IMAGING

Decker Lake is on the western edge of Itasca County. It is a small (300 acres), shallow lake (Zmax 10-12 ft) that has only one lake home on its shoreline. Water quality in Decker Lake places it in the eutrophic category with total phosphorus of 69 ppb and chlorophyll a of 29.7 ppb (Table 1).

A 2.00 m long piston core was recovered from 2.95 m of water from Decker Lake on 14 May 2009 (Table 20). The sediment was very soft and needed to be sectioned in the field to 80 cm before reaching cohesive material. When the remaining core was returned to the laboratory for imaging and susceptibility logging, it was found to be a homogenous dark brown to black color in its entire length with very high water content. (Fig. 66). Of the sediment that remained in the core barrel, there was an increase in magnetic susceptibility above 120 cm core depth. Unfortunately when the sediment was examined under the microscope it was determined that this core suffered from diatom dissolution and no dating model was completed on the core.

DECKER LAKE-BIOGEOCHEMISTRY

Decker Lake stood out among the lakes in this project because it had very high organic content in the core. Organics decreased upcore from around 65% dry weight at 80 cm depth to 55-60% dry weight at the core surface. The major drop in organics happened between 35 and 25 cm core depth. Inorganic content mirrored organic content in Decker Lake. Lower core depths had 25% dry weight of inorganics, whereas upper core depths had 35% inorganic content with the major increase occurring between 35 and 25 cm. Carbonates remained a minor component of the core and remained between 5 and 10% of the sediment dry weight (Fig. 67). Because the core suffered from diatom dissolution, no further analyses were undertaken.

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Bob Toborg	Gull Chain of Lakes Association	Lake Margaret

REFERENCES

Anderson, N. J. and Rippey, B. 1994. Monitoring lake recovery from point-source eutrophication: the use of diatom-inferred epilimnetic total phosphorus and sediment chemistry. Freshwater Biology 32: 625-639.

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.

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

Birks, H.J.B., Line, J.M., Juggins, S., Stevenson, A.C., and ter Braak, C.J.F. 1990. Diatoms and pH reconstruction. Philos Trans R Soc Lond B Biol Sci 327: 263-278

Conley, D.J. and Schelske, C.L. 2001. 14. Biogenic silica. In: Smol, J.P., Birks, H.J.B., Last, W.M. [eds], Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal, Siliceous Indicators. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp 281-293.

DeMaster D.J. 1979. The marine budgets of silica and ^{32}Si. Ph.D. Dissertation, Yale University.

Dixit, S. S., Smol, J. P., Kingston, J. C. and Charles, D. F. 1992. Diatoms: Powerful indicaotrs of environmental change. Environ. Sci. Technol. 26:22-33.

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

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.

Dean, W.E. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition; comparison with other methods. J Sed Res 44: 242-248

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

Edlund, M. B.; Ramstack, J. M. (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.

Edlund, M.B., Triplett, L.D., Tomasek, M. and Bartilson, K. 2009a. From paleo to policy: partitioning of historical point and nonpoint phosphorus loads to the St. Croix River, Minnesota-Wisconsin, USA. Journal of Paleolimnology 41: 679-689. DOI: 10.1007/s10933-008-9288-1

Edlund, M. B., Engstrom, D. R., Triplett, L., Lafrancois, B. M. and Leavitt, P. R. 2009b. Twentieth-century eutrophication of the St. Croix River (Minnesota-Wisconsin, USA) reconstructed from the sediments of its natural impoundment. Journal of Paleolimnology 41: 641-657. DOI:10.1007/s10933-008-9296-1

Engstrom, D. R. 2005. Long-term changes in iron and phosphorus sedimentation in Vadnais Lake, Minnesota, resulting from ferric chloride addition and hypolimnetic aeration. *Lake and Reservoir Management* 21: 95-105.

Engstrom, D. R.; Wright, H. E. Jr. 1984. Chemical stratigraphy of lake sediments as a record of environmental change. Lake sediments and environmental history. E.Y. Haworth, Leicester University Press: 11-67.

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

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

Ihaka, R. and Gentleman, R. 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.

Krammer, K. and Lange-Bertalot, H. 1986-1991. Bacillariophyceae. in Ettl, H., Gerloff, J., Heynig, H. and Mollenhauer, D. (eds) Süsswasser flora von Mitteleuropa, Band 2/1-4. Gustav Fischer Verlag: Stuttgart, New York.

McKnight, R. 1991. QuikChem method 10-114-27-1-A, Determination of Silica in Waters by Flow Injection Analysis, 0.2 to 20.0 mg SiO_2/L. Lachat Instruments, 6645 West Mill Road, Milwaukee, Wisconsin 53218-1239.

Patrick, R. and Reimer, C.W. 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 Reimer, C.W. 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., Fritz, S. C., Engstrom, D. R. and Heiskary, S. A. 2003. The application of a diatom-based transfer function to evaluate regional water-quality trends in Minnesota since 1970. J. Paleolimnol. 29: 79-94.

Renberg, I., 1990. A procedure for preparing large sets of diatom slides from sediment cores. Journal of Paleolimnology 4: 87-90.

Smol, JP, 2002: Pollution of Lakes and Rivers:a Paleoenvironmental Per- spective, Arnold, London: 280 pp.

Wright, H.E., Jr. 1991. Coring tips. J. Paleolimnol. 6:37-49.

TABLES

Table 1. Northcentral Minnesota lakes targeted for this study. Data from Minnesota DNR and Minnesota Pollution Control Agency.

Lake MNDNR	County	Zmax ft	TP ppb	chl a ppb	Secchi m	exotics	dam	analysis
Portage 29-0250-00	Hubbard	15	55	24.2	1.1	curlyleaf	yes	dating/ geochem
1st Crow Wing 29-0086-00	Hubbard	15	56	28.2	1.2	-	no	full
8th Crow Wing 29-0072-00	Hubbard	30	36	15.1	2.5	-	yes	core rejected
Decker 31-0934-00	Itasca	10	69	29.7	0.9	banded mystery snail	no	core rejected
Winona 21-0081-00	Douglas	9	194	84.9	0.6	-	no	full
Margaret 11-0222-00	Cass	49	49	27.5	1.5	-	no	full
Dixon 31-0921-00	Itasca	30	40	15.9	1.7	curlyleaf	no	full
Big Sandy 01-0062-00	Aitkin	84	51	17.2	1.25	-	yes	full

Table 2. Core type, date of collection, location, depth of sampling site, length of core recovered, and results of field sectioning from Winona Lake core.

Type of Core	Coring Date	Coring Location	Water Depth (m)	Core length (m)	Sediment depth (m)	Field sectioned (cm)
Piston	12May2008	45°52.964' N 95°23.370' W	2.16	1.93	0-1.93	40

Table 3. Samples prepared for diatom, biogenic silica and sediment TP analysis from Winona Lake core.

Sample Depth (cm)	Lead-210 Date (Year A.D.)
2	2007.0
14	1995.7
22	1984.2
26	1976.2
30	1968.1
36	1956.0
42	1942.9
46	1933.4
52	1916.3
56	1897.7
62	1835.7
64	1810.1
66	1802.4

Table 4. Biological indicators of eutrophication including percent planktonic diatoms, percent chrysophyte cysts, diatoms to chrysophyte ratio, and planktonic to benthic diatom ratio (P:B) suggest that dramatic ecological changes occurred in Winona Lake began about the time of WWII and worsened in the latter decades of the 20th century. These indicators suggest a biological response to increases in nutrient loading and a shift to more water column algal productivity.

Depth (cm)	Date (A.D.)	% plankton	% cyst	diat:cyst	P:B
2	2007.0	94.77	0.65	153.0	18.13
14	1995.7	85.71	2.43	40.1	6.00
22	1984.2	76.51	0.95	103.3	3.26
26	1976.2	69.81	1.65	59.1	2.31
30	1968.1	71.59	3.75	25.5	2.52
36	1956.0	75.13	4.14	22.9	3.02
42	1942.9	57.71	3.57	26.8	1.36
46	1933.4	18.41	4.06	23.0	0.23
52	1916.3	20.38	9.26	9.6	0.26
56	1897.7	16.92	4.46	20.8	0.20
62	1835.7	16.05	6.16	14.6	0.19
64	1810.1	10.89	7.17	12.3	0.12
66	1802.4	11.59	20.28	3.3	0.13

Table 5. Core type, date of collection, location, depth of sampling site, length of core recovered, and results of field sectioning from Big Sandy Lake core.

Type of Core	Coring Date	Coring Location	Water Depth (m)	Core length (m)	Sediment depth (m)	Field sectioned (cm)
Piston	13May2008	46°44.800' N 93°17.511' W	13.39	1.95	0-1.95	48

Table 6. Samples prepared for diatom, biogenic silica and sediment TP analysis from Big Sandy Lake core.

Sample Depth (cm)	Lead-210 Date (Year A.D.)
2	2007.5
10	1998.8
18	1985.6
24	1975.4
30	1964.8
38	1948.7
44	1936.3
52	1923.8
60	1911.8
68	1896.3
76	1877.8
80	1868.7
84	1857.9

Table 7. Biological indicators of eutrophication including percent planktonic diatoms, percent chrysophyte cysts, diatoms to chrysophyte ratio, and planktonic to benthic diatom ratio (P:B) suggest that the greatest ecological changes occurred in Big Sandy Lake in the late 19th century concomitant with damming of the lake. These indicators include an increase in planktonic diatoms and an increase in the P:B ratio, which suggest shift to more water column algal productivity.

Depth (cm)	Date (A.D.)	% plankton	% cyst	diat:cyst	P:B
2	2007.5	89.78	5.93	14.85	8.78
10	1998.8	90.93	3.80	24.81	10.03
18	1985.6	91.09	4.02	23.76	10.22
24	1975.4	85.61	5.71	16.12	5.95
30	1964.8	89.55	5.10	18.27	8.57
38	1948.7	93.70	4.81	19.67	14.88
44	1936.3	92.11	3.58	26.13	11.67
52	1923.8	93.23	2.68	36.27	13.78
60	1911.8	87.41	2.44	39.70	6.94
68	1896.3	84.20	2.39	40.50	5.33
76	1877.8	65.15	2.91	33.00	1.87
80	1868.7	41.31	6.88	13.23	0.70
84	1857.9	43.13	7.68	11.86	0.76

Table 8. Core type, date of collection, location, depth of sampling site, length of core recovered, and results of field sectioning from 1st Crow Wing Lake core.

Type of Core	Coring Date	Coring Location	Water Depth (m)	Core length (m)	Sediment depth (m)	Field sectioned (cm)
Piston	13May2008	46°49.881' N 94°50.817' W	4.95	2.09	0-1.93	58

Table 9. Samples prepared for diatom, biogenic silica and sediment TP analysis from 1st Crow Wing Lake core.

Sample Depth (cm)	Lead-210 Date (Year A.D.)
2	2007.7
18	1999.5
34	1987.6
46	1978.3
58	1967.7
70	1955.1
76	1947.6
88	1932.9
100	1916.1
112	1896.3
124	1871.6
130	1853.1
136	1833.9

Table 10. Biological indicators of eutrophication in 1st Crow Wing Lake , including percent planktonic diatoms, percent chrysophyte cysts, diatoms to chrysophyte ratio, and planktonic to benthic diatom ratio (P:B).

Depth (cm)	Date (A.D.)	% plankton	% cyst	diat:cyst	P:B
2	2007.7	60.68	3.74	25.75	1.54
18	1999.5	54.00	3.49	27.53	1.17
34	1987.6	62.65	17.65	4.38	1.68
46	1978.3	79.40	3.36	28.79	3.86
58	1967.7	33.91	5.51	17.04	0.51
70	1955.1	37.75	1.47	66.67	0.61
76	1947.6	40.05	4.02	23.65	0.67
88	1932.9	18.64	25.54	2.32	0.23
100	1916.1	50.48	3.42	27.87	1.02
112	1896.3	60.73	4.62	20.50	1.55
124	1871.6	78.22	0.98	101.00	3.59
130	1853.1	77.15	7.47	12.33	3.38
136	1833.9	81.34	23.31	3.24	4.36

Table 11. Core type, date of collection, location, depth of sampling site, length of core recovered, and results of field sectioning from Dixon Lake core.

Type of Core	Coring Date	Coring Location	Water Depth (m)	Core length (m)	Sediment depth (m)	Field sectioned (cm)
Piston	14May2008	47°35.975' N 94°16.989' W	8.10	2.05	0-2.05	52

Table 12. Samples prepared for diatom, biogenic silica and sediment TP analysis from Dixon Lake core.

Sample Depth (cm)	Lead-210 Date (Year A.D.)
2	2007.3
14	1995.1
18	1988.9
22	1981.4
26	1970.9
28	1965.0
32	1954.9
36	1943.6
40	1927.6
44	1909.9
50	1883.5
56	1851.3
62	1813.5

Table 13. Biological indicators of eutrophication including percent planktonic diatoms, percent chrysophyte cysts, diatoms to chrysophyte ratio, and planktonic to benthic diatom ratio (P:B) in Dixon Lake.

Depth (cm)	Date (A.D.)	% plankton	% cyst	diat:cyst	P:B
2	2007.3	74.88	8.55	10.62	2.98
14	1995.1	78.75	4.28	22.22	3.71
18	1988.9	76.56	5.13	18.29	3.27
22	1981.4	84.65	3.78	25.25	5.52
26	1970.9	74.64	3.94	24.35	2.94
28	1965.0	82.60	4.88	19.43	4.75
32	1954.9	79.20	2.75	35.25	3.81
36	1943.6	82.00	2.38	41.10	4.55
40	1927.6	83.62	4.48	21.21	5.11
44	1909.9	82.18	2.85	33.67	4.61
50	1883.5	70.90	5.84	16.08	2.44
56	1851.3	76.67	4.05	23.71	3.29
62	1813.5	60.76	4.58	20.79	1.55

Table 14. Core type, date of collection, location, depth of sampling site, length of core recovered, and results of field sectioning from Margaret Lake core.

Type of Core	Coring Date	Coring Location	Water Depth (m)	Core length (m)	Sediment depth (m)	Field sectioned (cm)
Piston	15May2008	46°29.091' N 94°22.069' W	7.03	1.89	0-1.89	40

Table 15. Samples prepared for diatom, biogenic silica and sediment TP analysis from Margaret Lake core.

Sample Depth (cm)	Lead-210 Date (Year A.D.)
2	2006.6
6	2002.1
14	1988.1
20	1975.5
24	1966.4
30	1951.9
34	1943.5
38	1934.8
44	1916.4
48	1899.8
52	1873.1
56	1848.9
60	1819.5

Table 16. Biological indicators of eutrophication including percent planktonic diatoms, percent chrysophyte cysts, diatoms to chrysophyte ratio, and planktonic to benthic diatom ratio (P:B) In Margaret Lake.

Depth (cm)	Date (A.D.)	% plankton	% cyst	diat:cyst	P:B
2	2006.6	75.25	7.42	12.12	3.04
6	2002.1	80.39	5.64	16.32	4.10
14	1988.1	82.17	5.32	17.29	4.61
20	1975.5	78.02	5.94	15.58	3.55
24	1966.4	82.18	2.82	33.67	4.61
30	1951.9	86.73	1.66	58.14	6.54
34	1943.5	88.36	1.29	75.60	7.59
38	1934.8	83.74	1.85	51.50	5.15
44	1916.4	72.84	1.61	57.86	2.68
48	1899.8	74.39	3.17	29.29	2.90
52	1873.1	88.97	1.87	52.13	8.07
56	1848.9	89.63	1.90	50.63	8.64
60	1819.5	88.89	2.10	46.00	8.00

Table 17. Core type, date of collection, location, depth of sampling site, length of core recovered, and results of field sectioning from Portage Lake core.

Type of Core	Coring Date	Coring Location	Water Depth (m)	Core length (m)	Sediment depth (m)	Field sectioned (cm)
Piston	13May2008	46°57.719' N 95°06.496' W	4.10	2.10	0-2.10	48

Table 18. Samples prepared for diatom, biogenic silica and sediment TP analysis from Portage Lake core. Diatoms were not preserved beyond the first two samples.

Sample Depth (cm)	Lead-210 Date (Year A.D.)
2	2006.3
6	2000.5
10	1995.1
14	1986.7
18	1975.4
20	1968.4
22	1961.4
24	1953.4
26	1944.9
28	1936.1
32	1921.1
42	1893.2
54	1852.4

Table 19. Core type, date of collection, location, depth of sampling site, length of core recovered, and results of field sectioning from 8th Crow Wing Lake core.

Type of Core	Coring Date	Coring Location	Water Depth (m)	Core length (m)	Sediment depth (m)	Field sectioned (cm)
Piston	13May2008	46°57.245' N 94°47.951' W	7.64	1.94	0-19.4	48

Table 20. Core type, date of collection, location, depth of sampling site, length of core recovered, and results of field sectioning from Decker Lake core.

Type of Core	Coring Date	Coring Location	Water Depth (m)	Core length (m)	Sediment depth (m)	Field sectioned (cm)
Piston	14May2008	47°38.742' N 94°24.109' W	2.95	2.00	0-2.00	80

FIGURES

WINONA LAKE

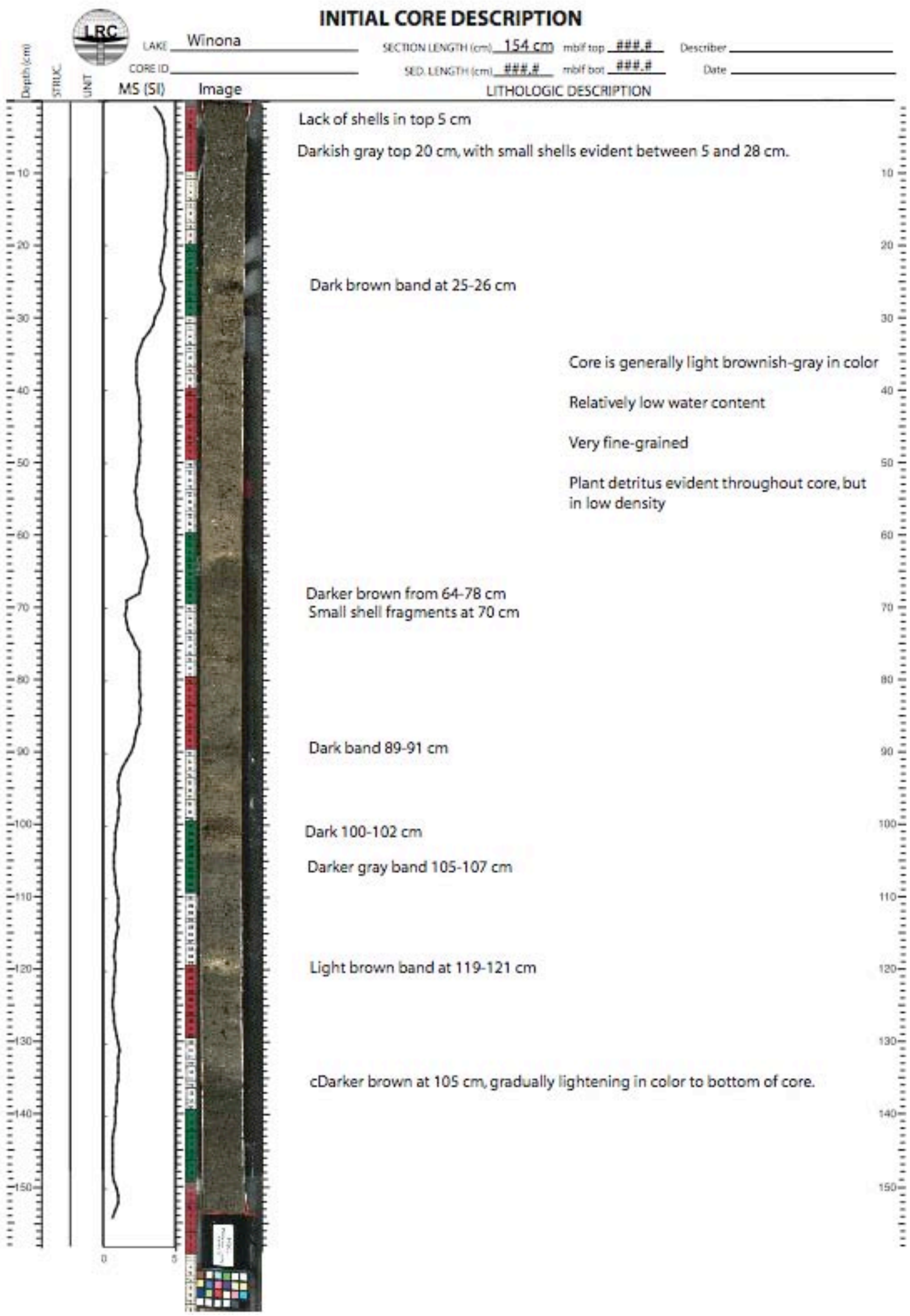

Fig. 1. Image and magnetic susceptibility of the Winona Lake core. The piston core image begins at 40 cm core depth because the top of the core was sectioned in the field.

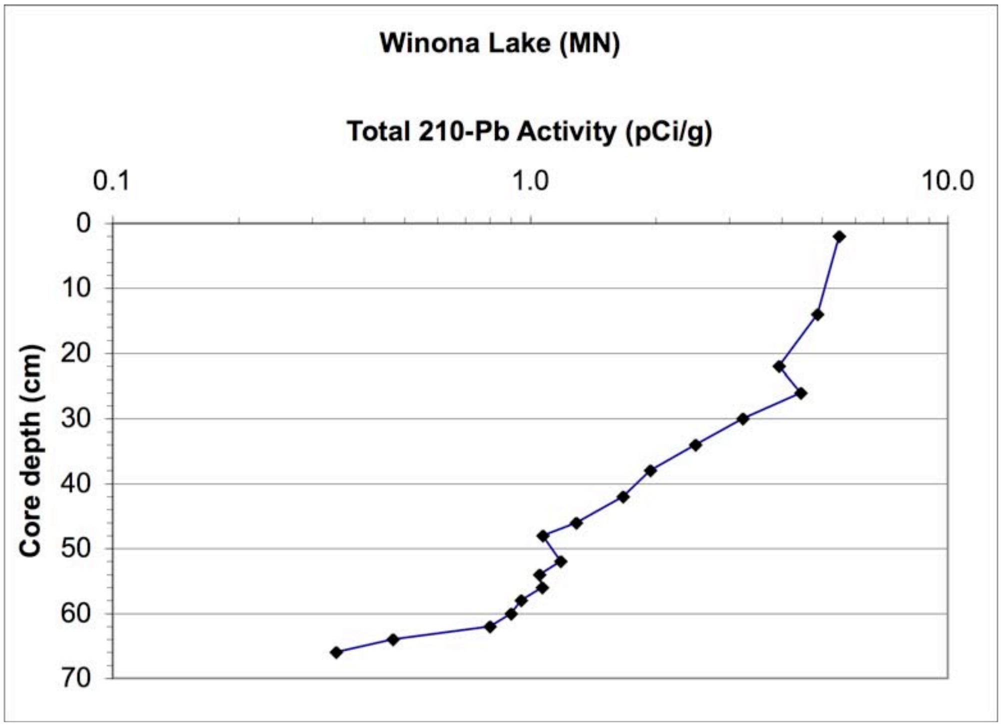

Fig. 2. Total lead-210 activity, Winona Lake core.

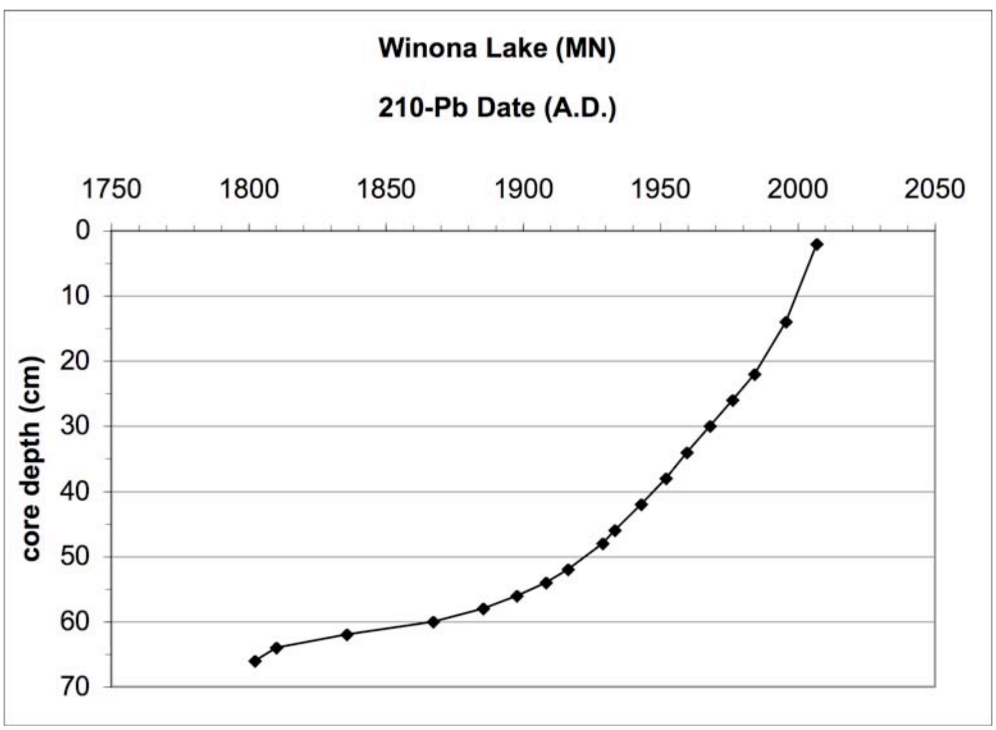

Fig. 3. Resulting 210-Pb dating model for Winona Lake core.

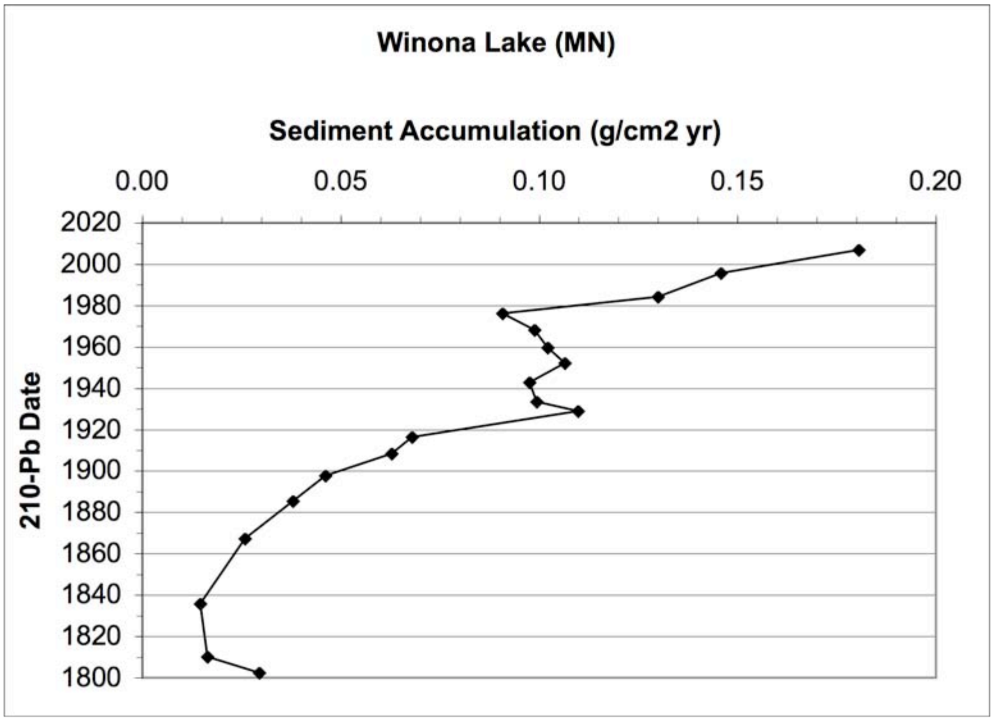

Fig. 4. Sediment accumulation rates (g/cm^{2}yr) for Winona Lake core.

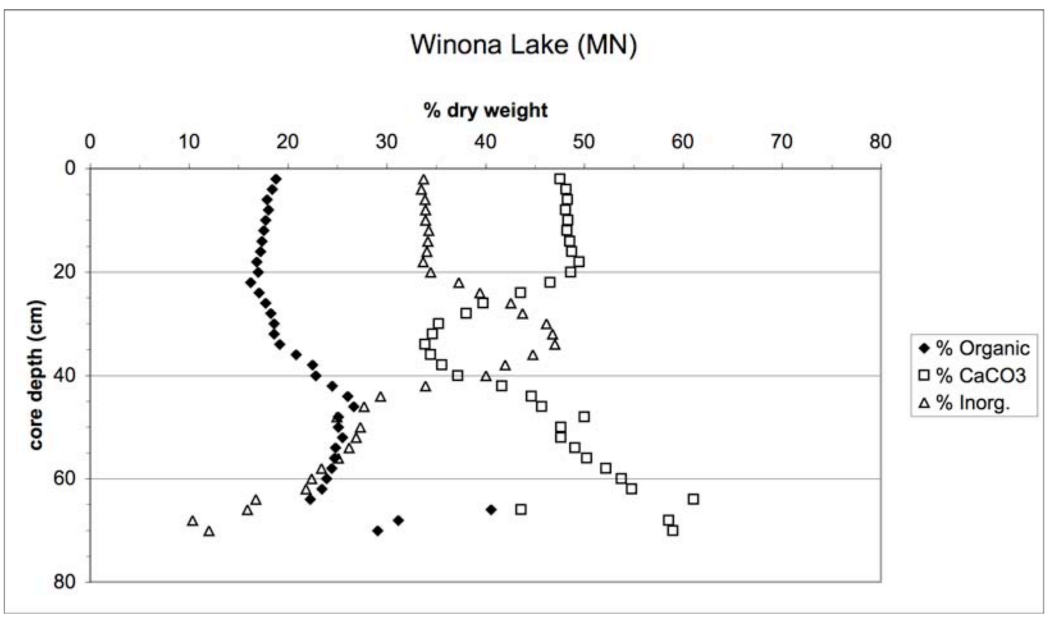

Fig. 5. Percent dry weight composition of organics, carbonates, and inorganics versus core depth based on loss on ignition analysis of Winona Lake core.

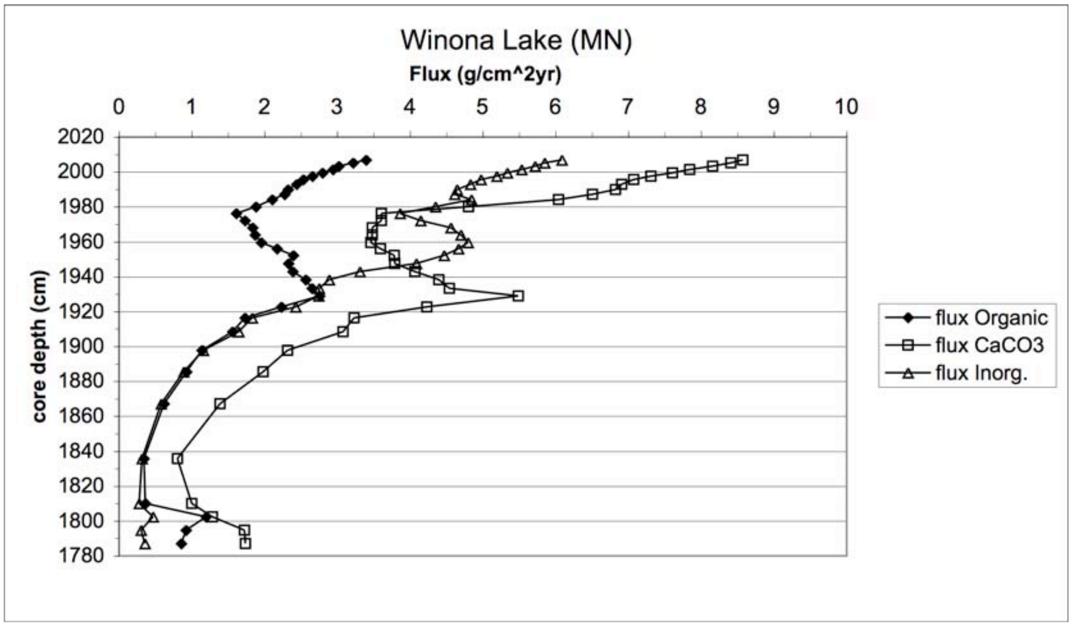

Fig. 6. Flux of sediment components (g/cm^{2}yr) by date in the Winona Lake core.

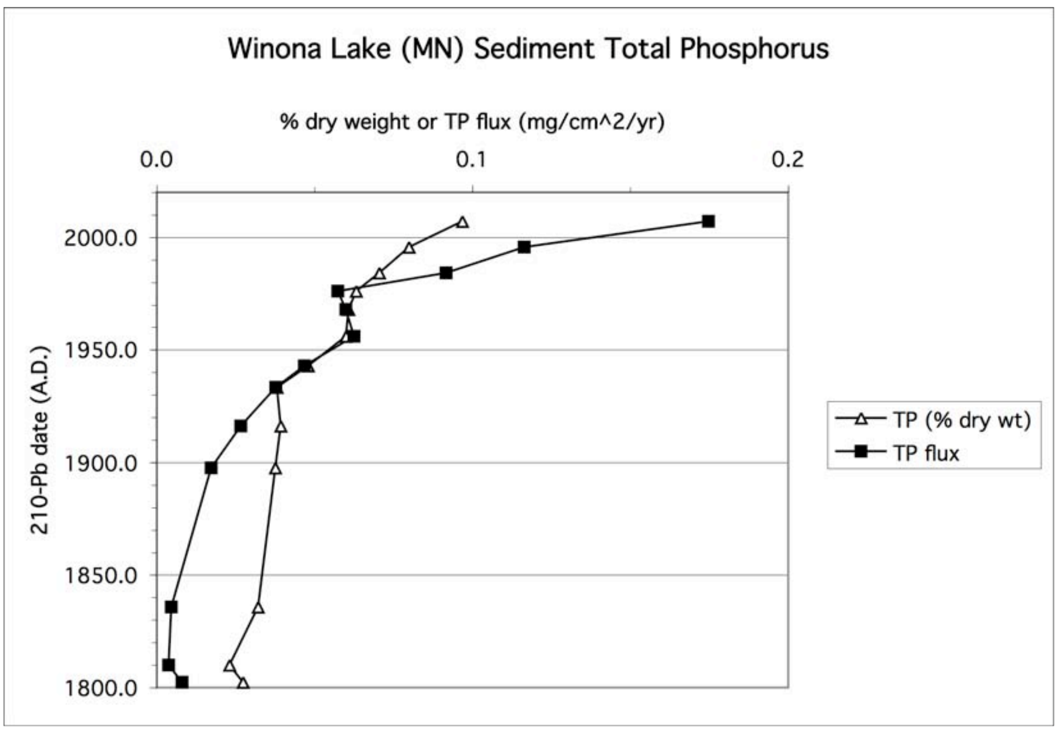

Fig. 7. Sediment total phosphorus, dry weight percent and flux (mg/cm^{2}yr) by date in the Winona Lake core.

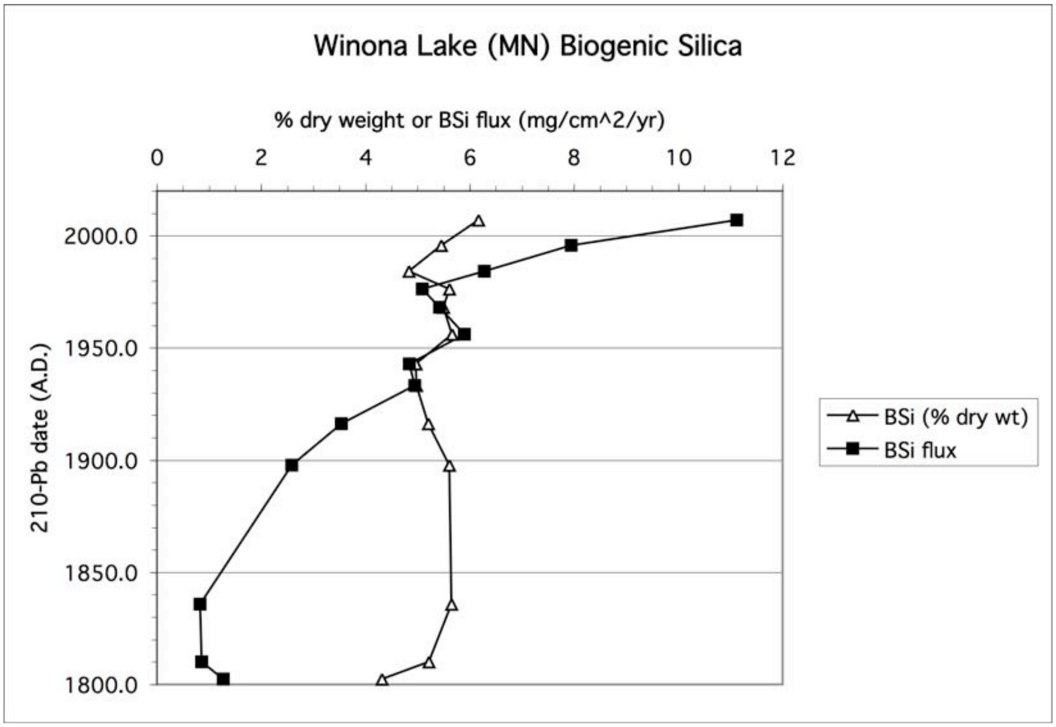

Fig. 8. Sediment biogenic silica, dry weight percent and flux (mg/cm^2yr) by date in the Winona Lake core.

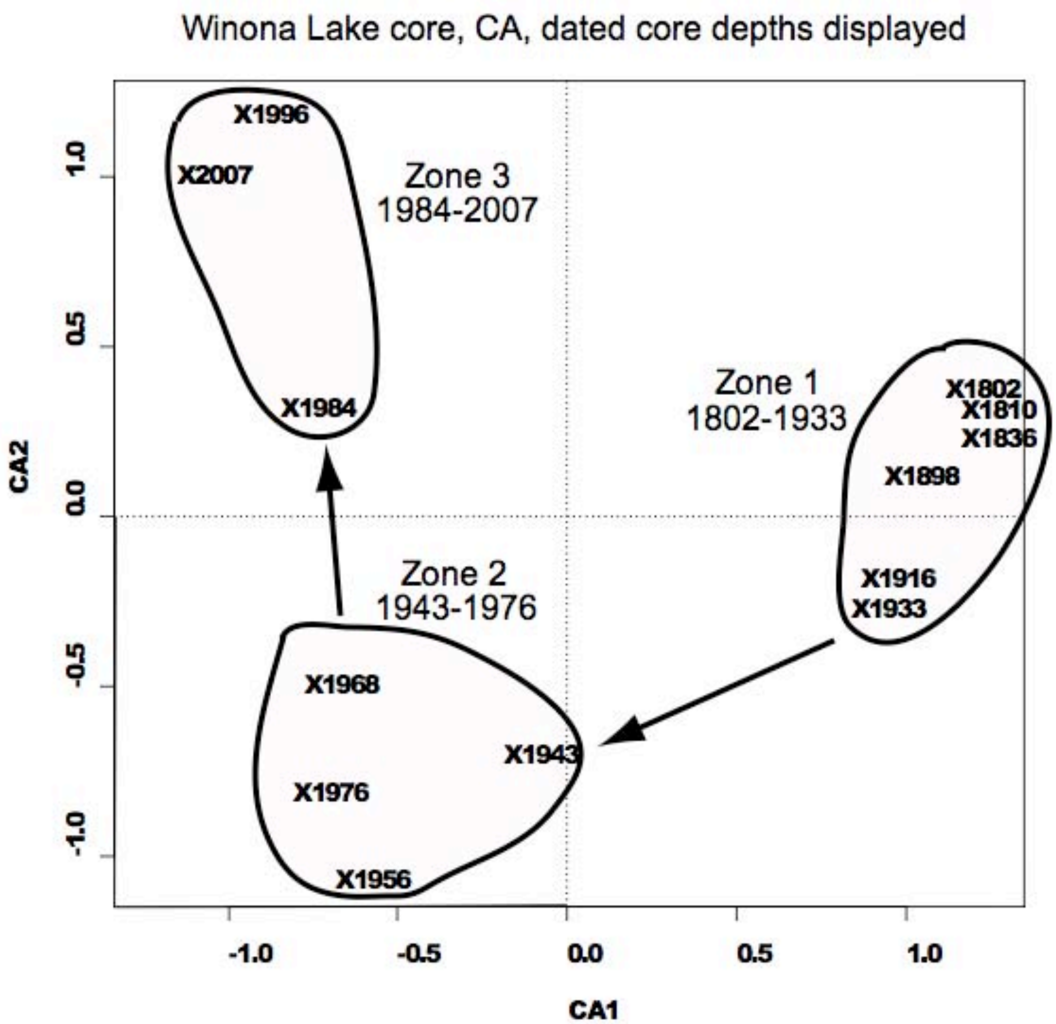

Fig. 9. Correspondence analysis of downcore Winona Lake diatom communities shows three stratigraphic zones: Zone 1 (1802-1933), Zone 2 (1943-1976), and Zone 2 (1984-2007).

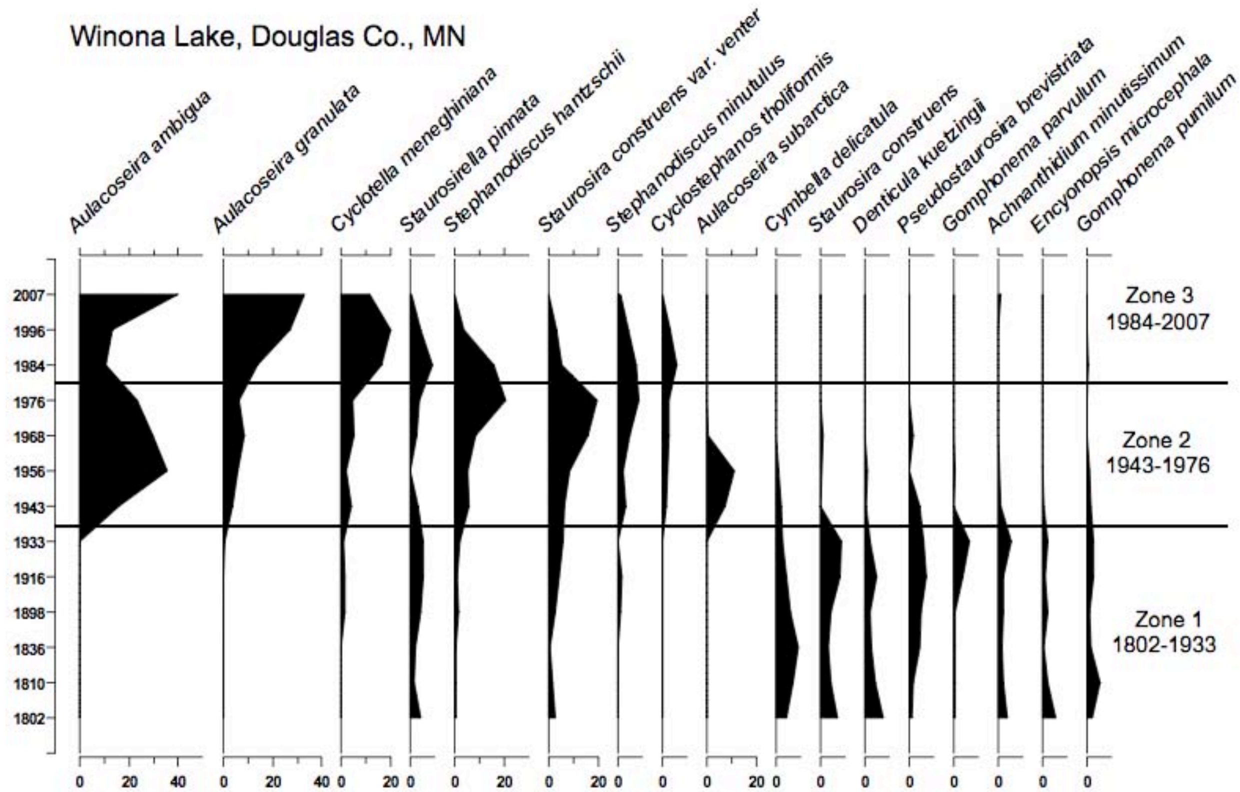

Fig. 10. Diatom stratigraphy of species present at >5% relative abundance in Winona Lake core, 1802-2007. Stratigraphic zones identified by correspondence and cluster analysis indicated by horizontal lines.

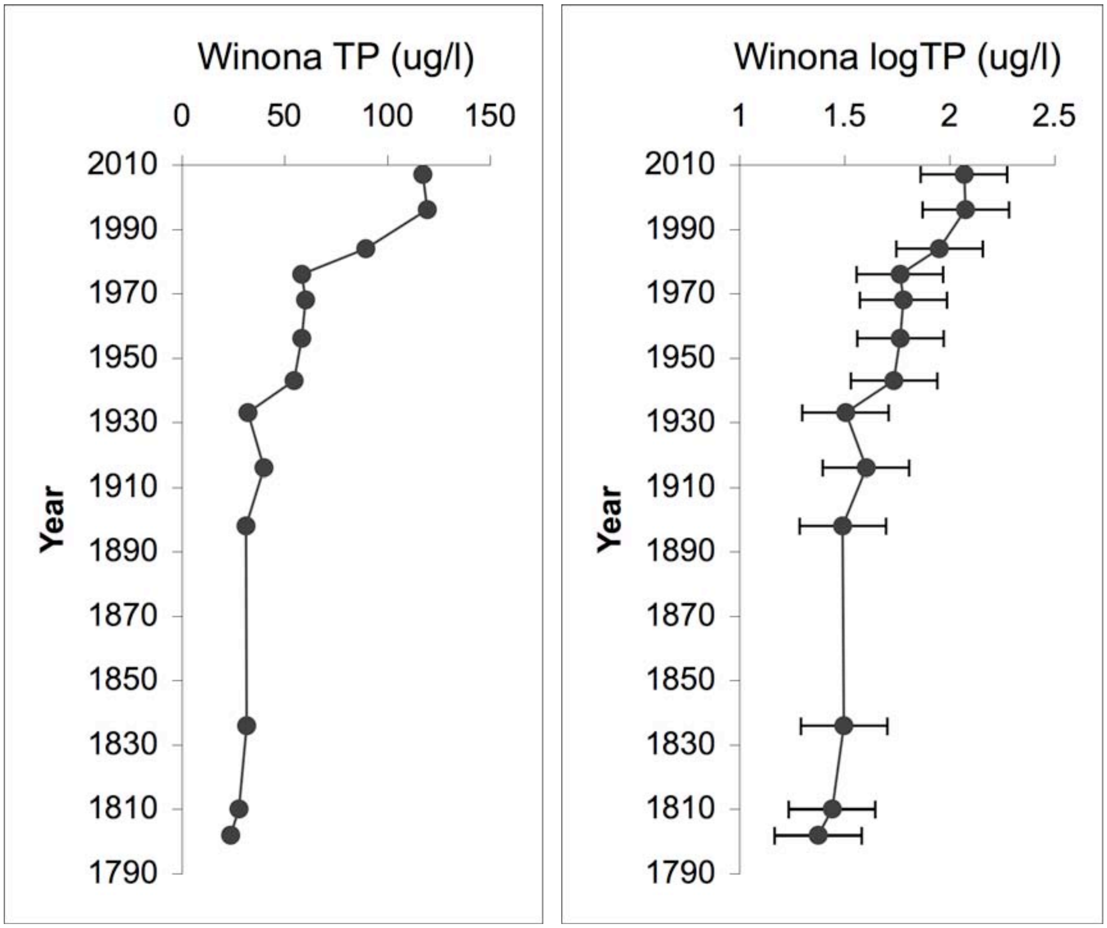

Fig. 11. Diatom-inferred total phosphorus reconstructions for Winona Lake 1802-2007. Total phosphorus is reconstructed as log TP; error bars represent the bootstrapped root mean square error of prediction for the Minnesota lakes diatom calibration model (see text).

BIG SANDY LAKE

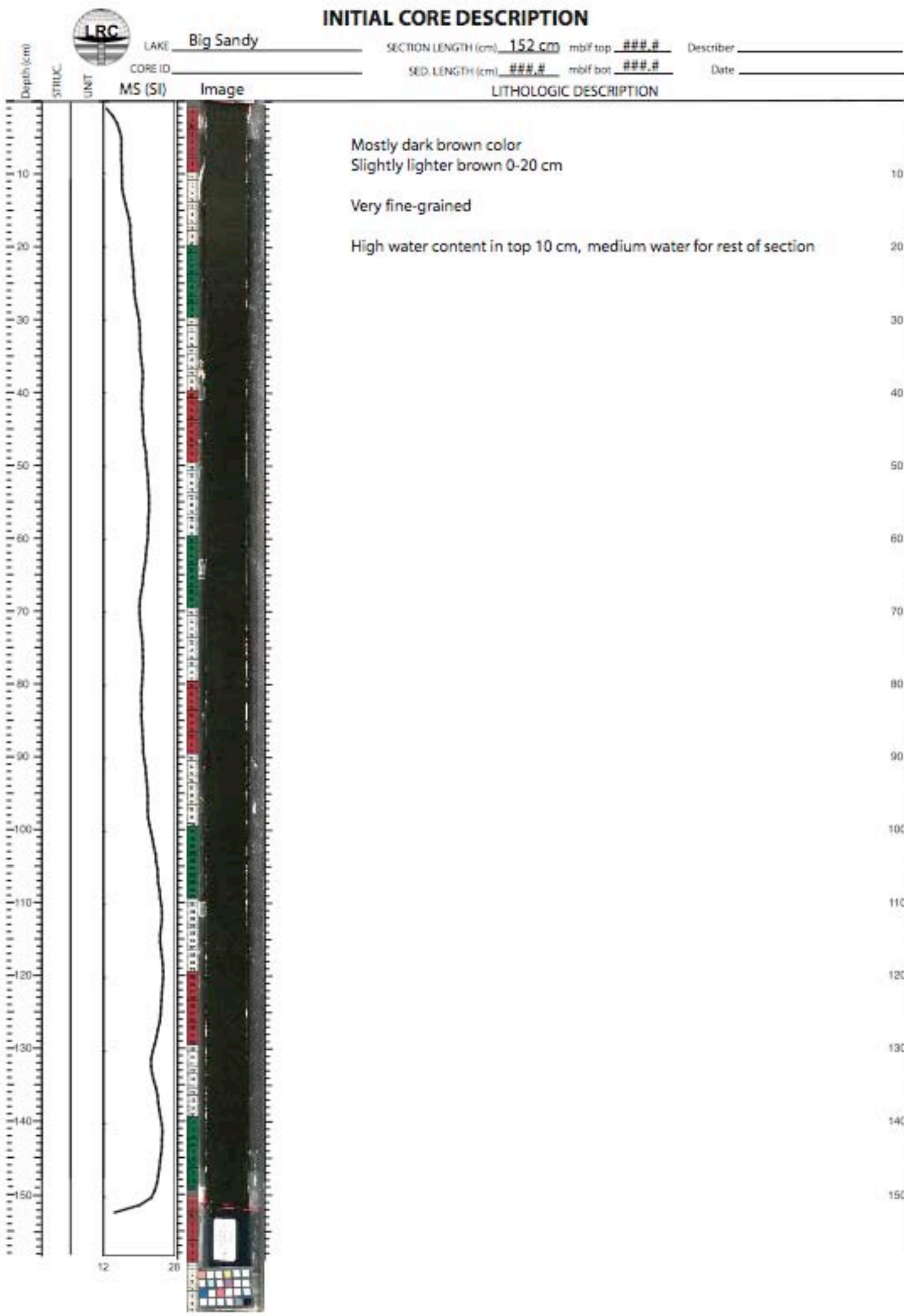

Fig. 12. Image and magnetic susceptibility of the Big Sandy Lake piston core. The piston core image begins at 48 cm core depth because the top of the core was sectioned in the field.

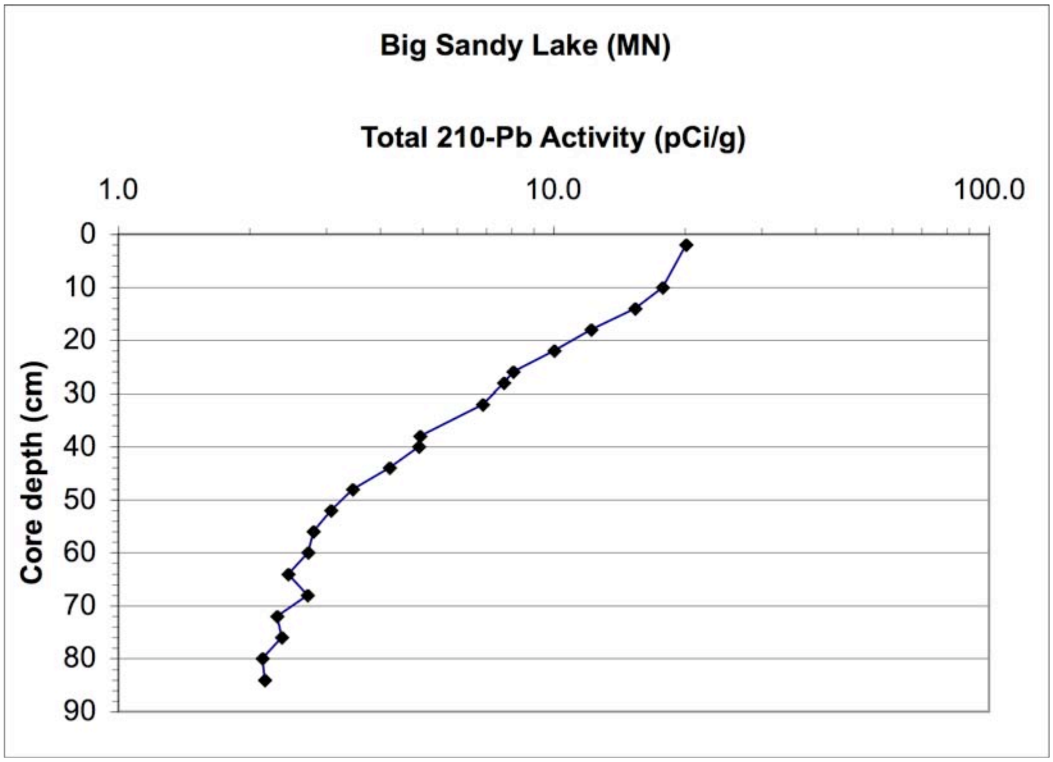

Fig. 13. Total lead-210 activity, Big Sandy Lake core.

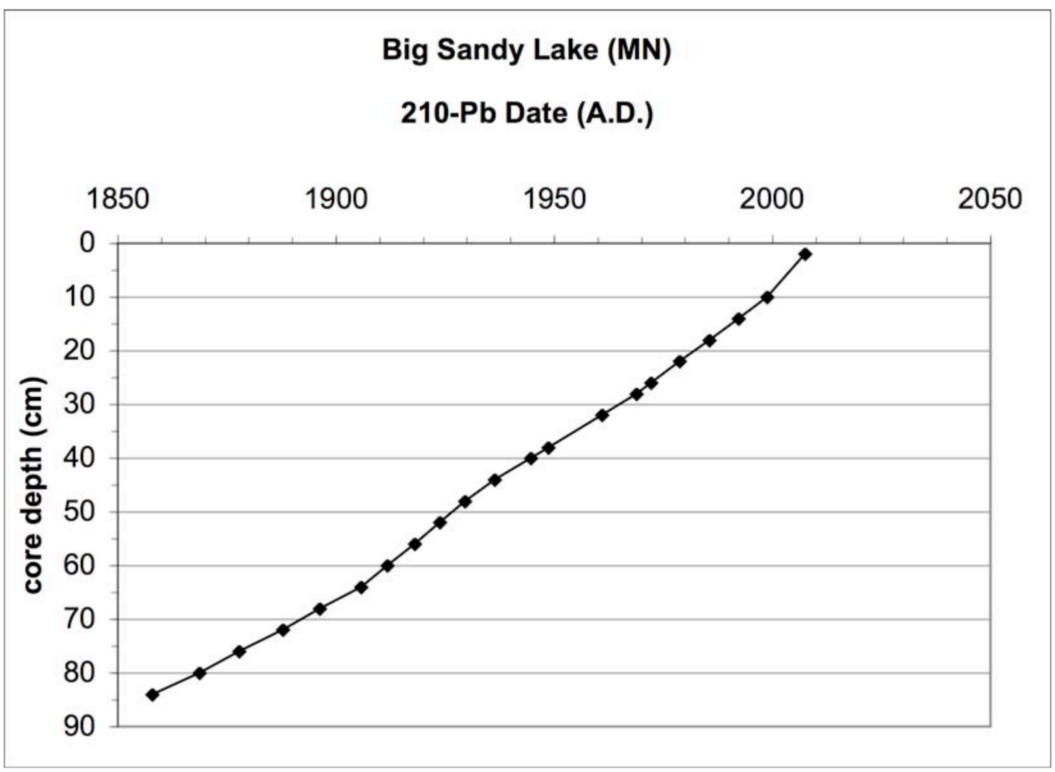

Fig. 14. Resulting 210-Pb dating model for Big Sandy Lake core.

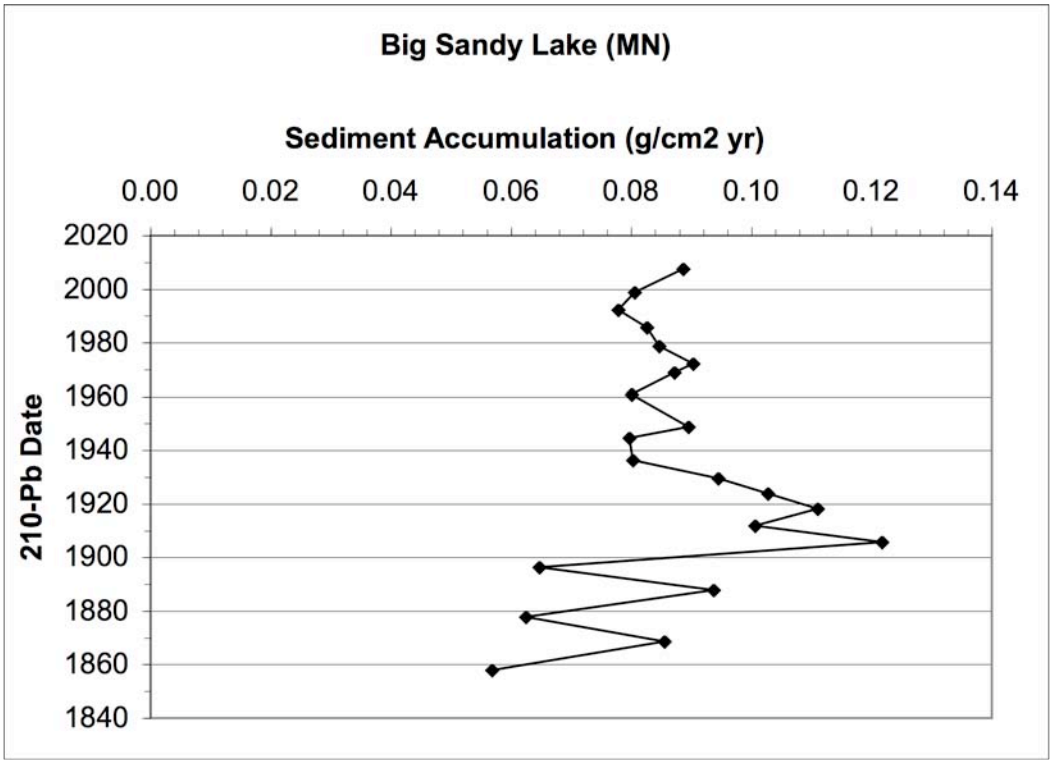

Fig. 15. Sediment accumulation rates (g/cm^{2}yr) for Big Sandy Lake core.

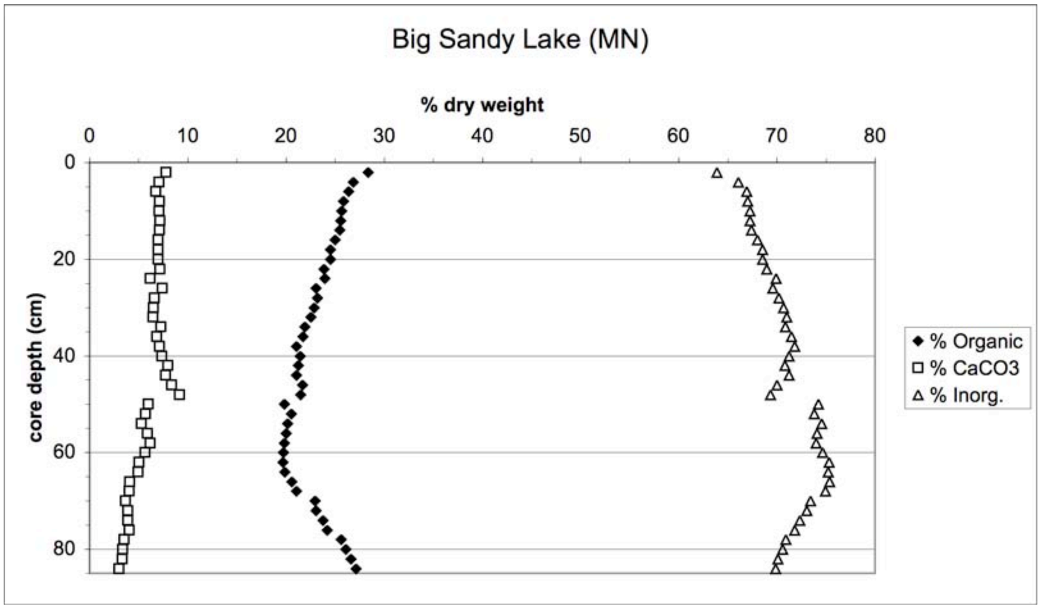

Fig. 16. Percent dry weight composition of organics, carbonates, and inorganics versus core depth based on loss on ignition analysis of Big Sandy Lake core.

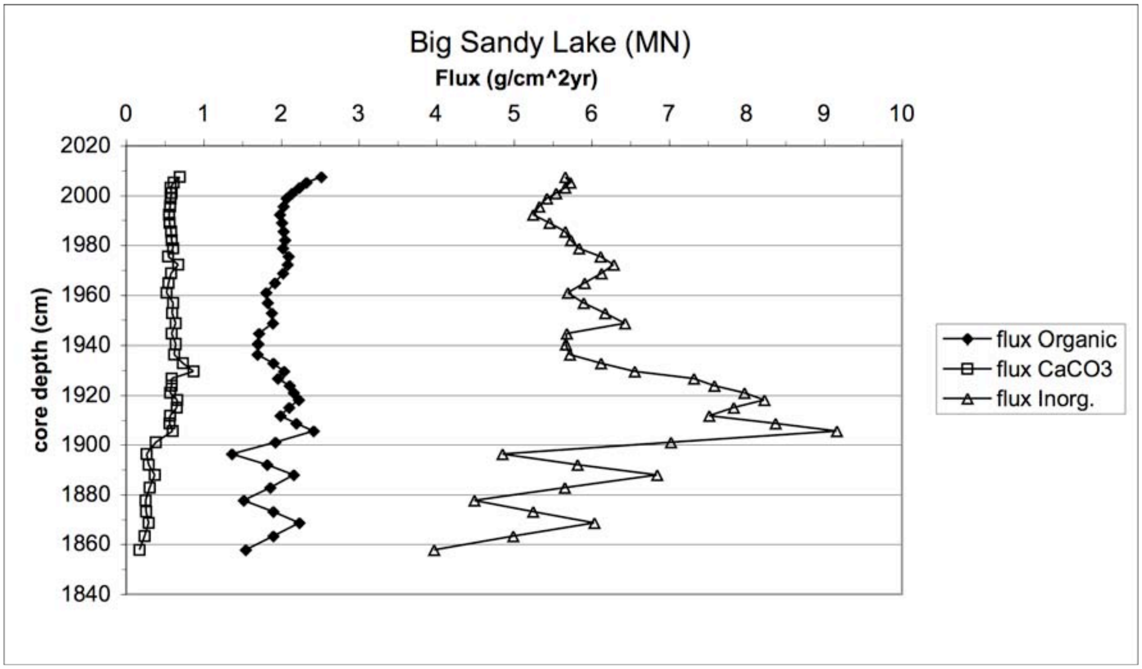

Fig. 17. Flux of sediment components (g/cm^{2}yr) by date in the Big Sandy Lake core.

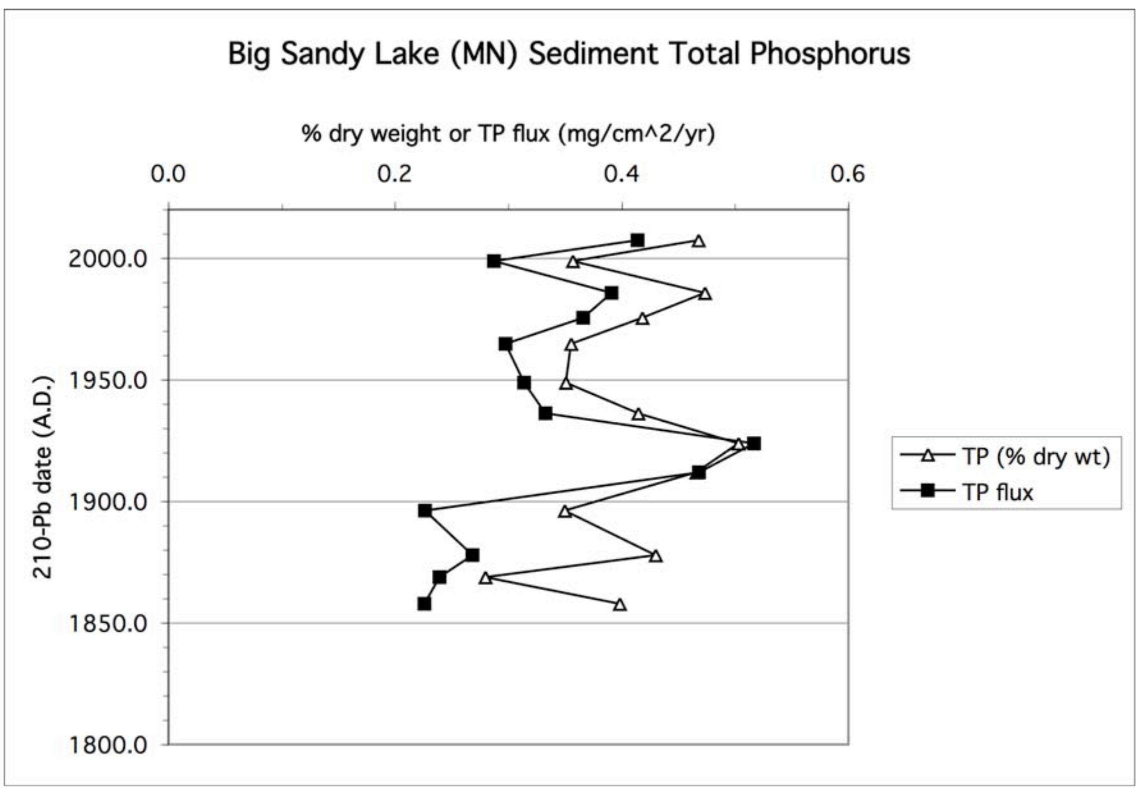

Fig. 18. Sediment total phosphorus, dry weight percent and flux (mg/cm^{2}yr) by date in the Big Sandy Lake core.

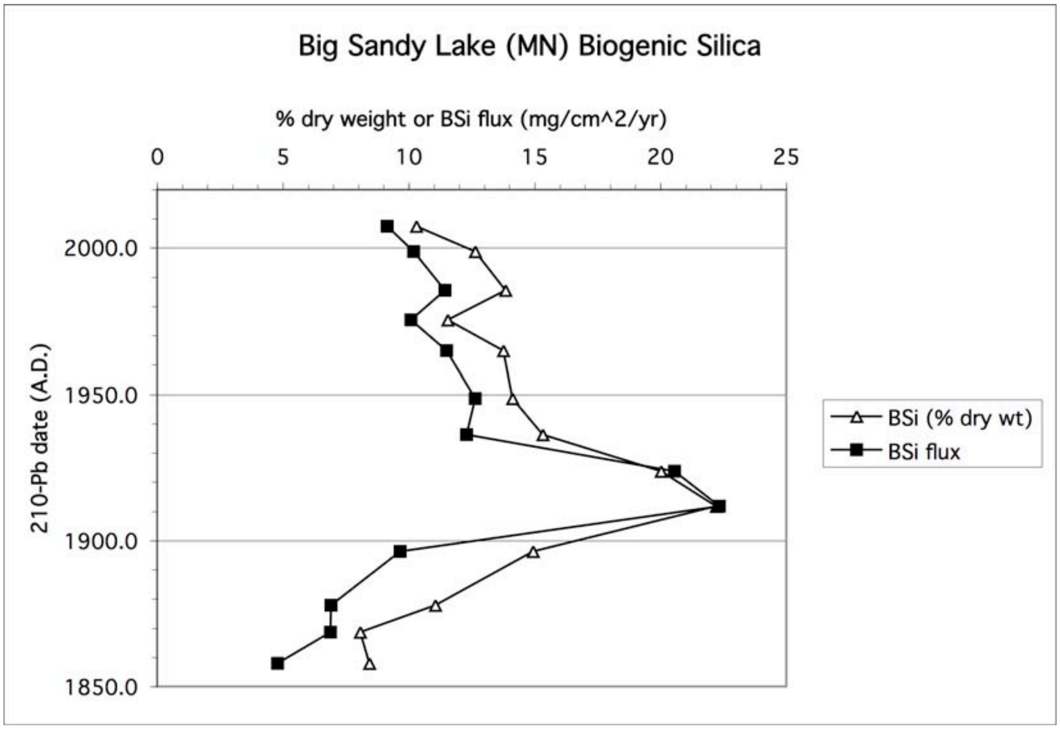

Fig. 19. Sediment biogenic silica, dry weight percent and flux (mg/cm^2yr) by date in the Big Sandy Lake core.

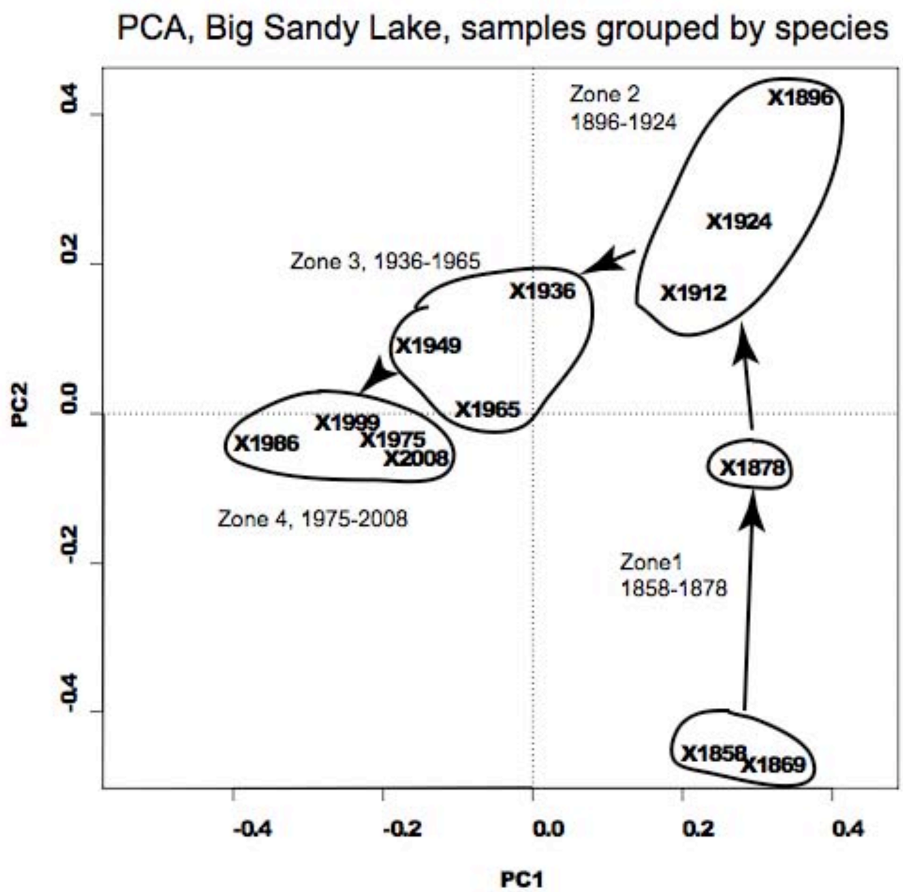

Fig. 20. Principal components analysis of downcore Big Sandy Lake diatom communities shows four stratigraphic zones: Zone 1 (1858-1878), Zone 2 (1896-1924), and Zone 2 (1936-1965), Zone 4 (1975-2008).

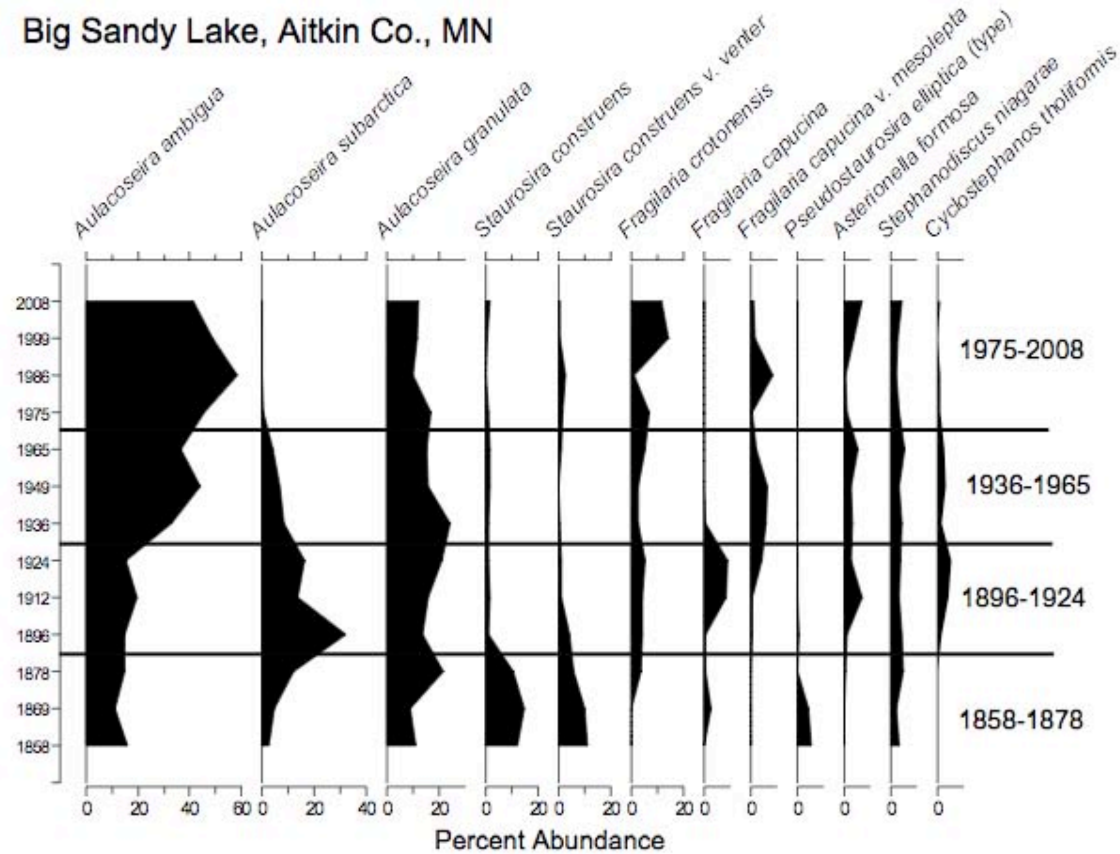

Fig. 21. Diatom stratigraphy of species present at >5% relative abundance in Big Sandy Lake core, 1858-2008. Stratigraphic zones identified by principal components and cluster analysis indicated by horizontal lines.

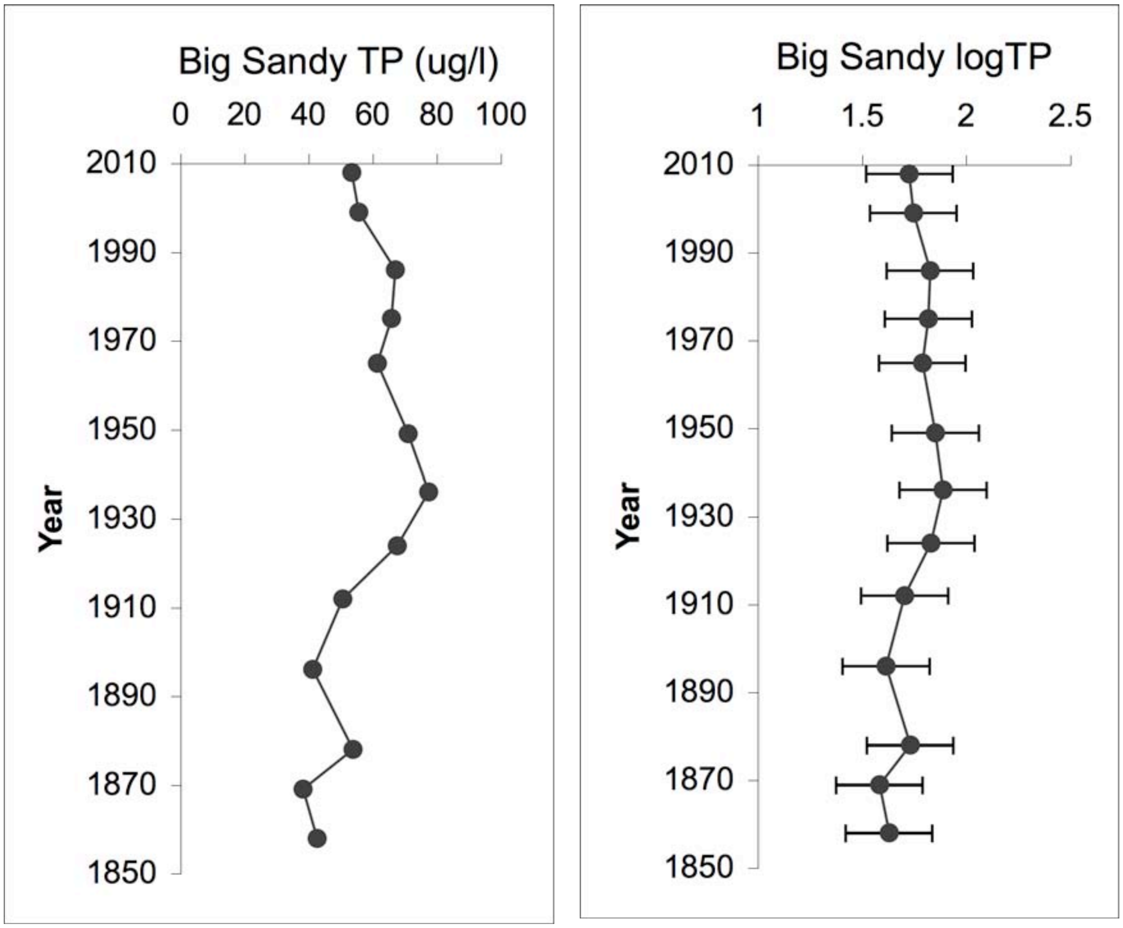

Fig. 22. Diatom-inferred total phosphorus reconstructions for Big Sandy Lake 1802-2007. Total phosphorus is reconstructed as log TP; error bars represent the bootstrapped root mean square error of prediction for the Minnesota lakes diatom calibration model (see text).

1st Crow Wing Lake

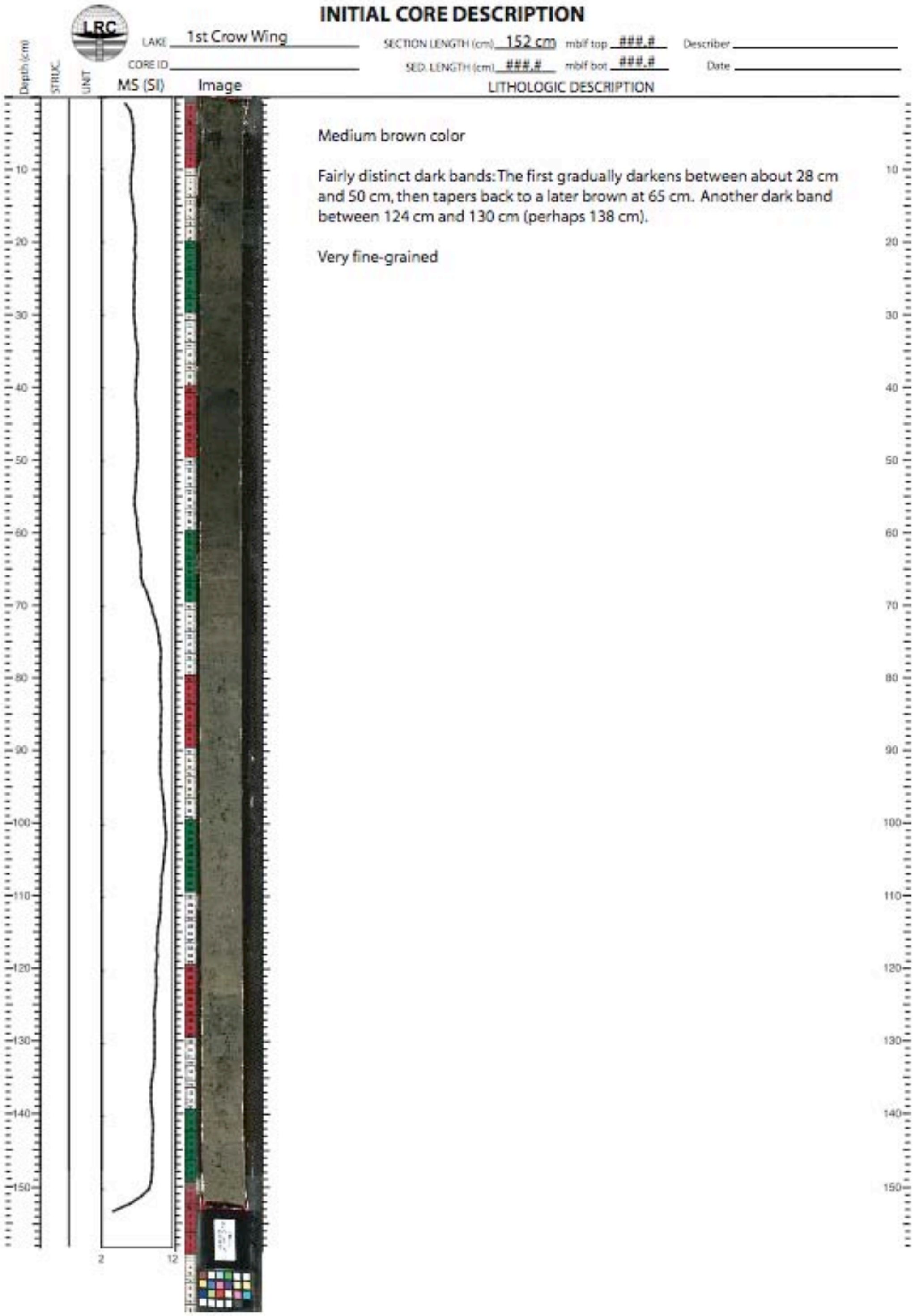

Fig. 23. Image and magnetic susceptibility of the 1st Crow Wing Lake piston core. The piston core image begins at 58 cm core depth because the top of the core was sectioned in the field.

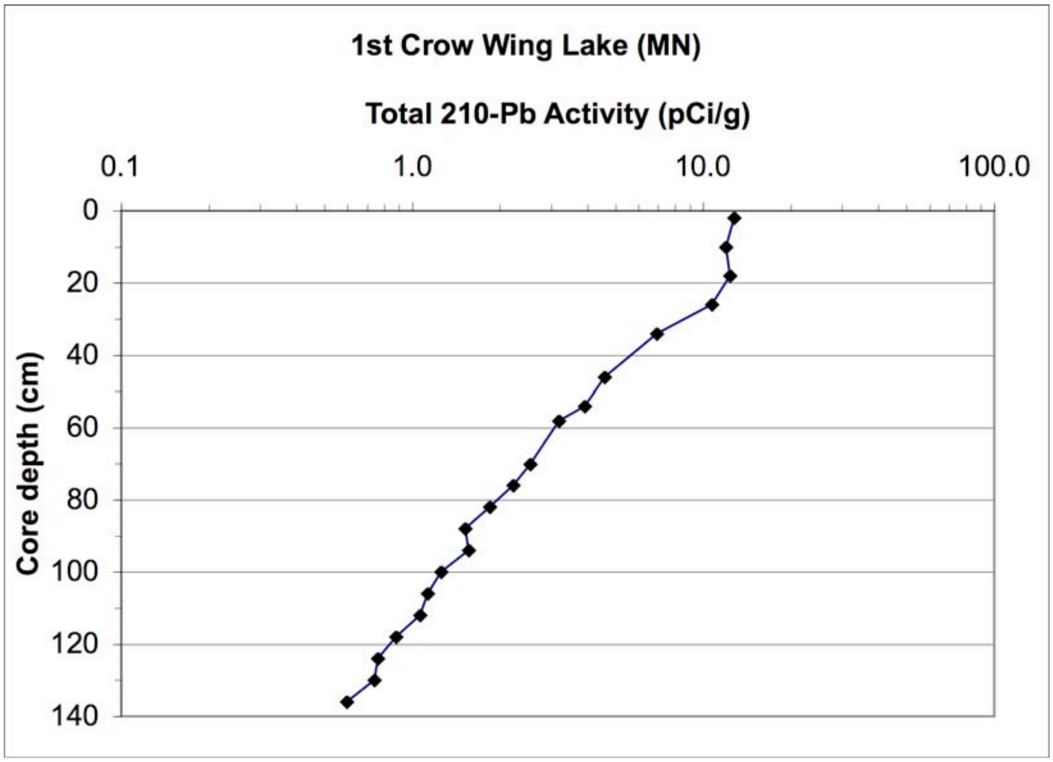

Fig. 24. Total lead-210 activity, 1st Crow Wing Lake core.

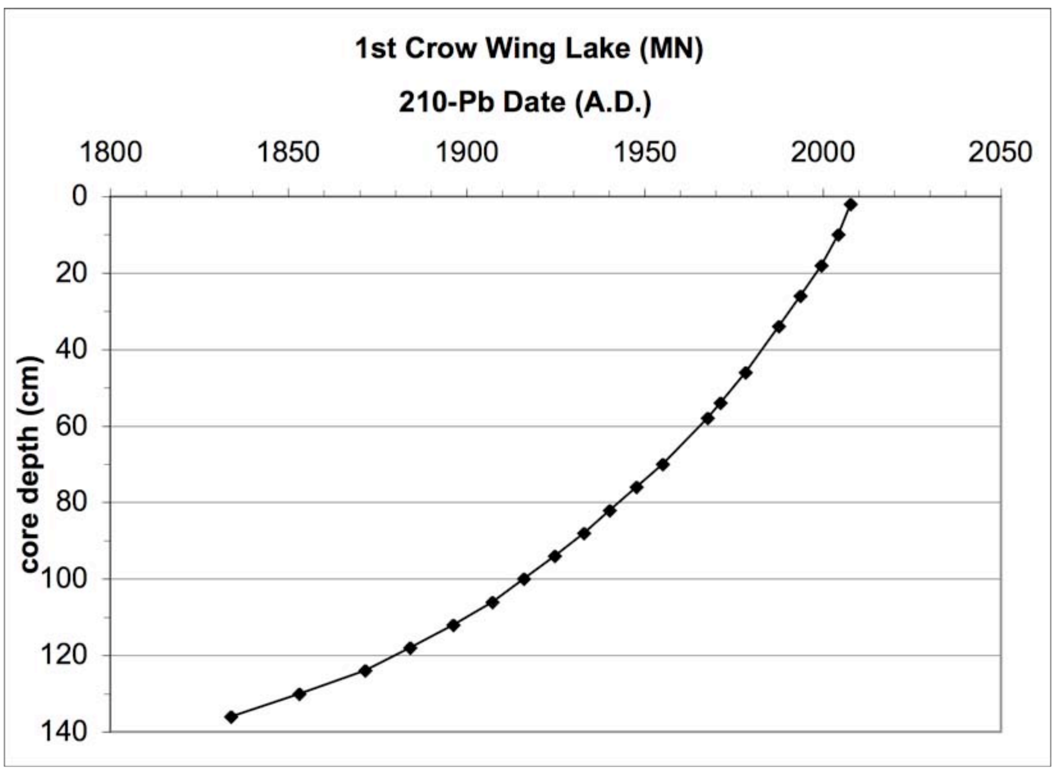

Fig. 25. Resulting 210-Pb dating model for 1st Crow Wing Lake core.

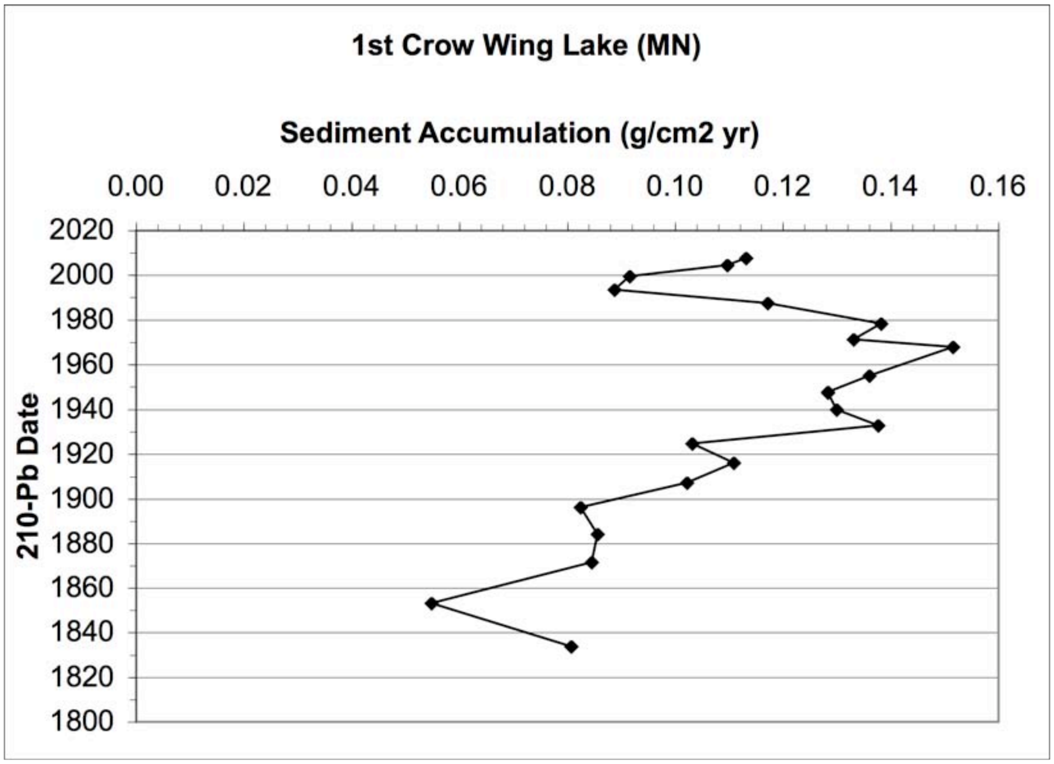

Fig. 26. Sediment accumulation rates (g/cm^{2}yr) for 1st Crow Wing Lake core.

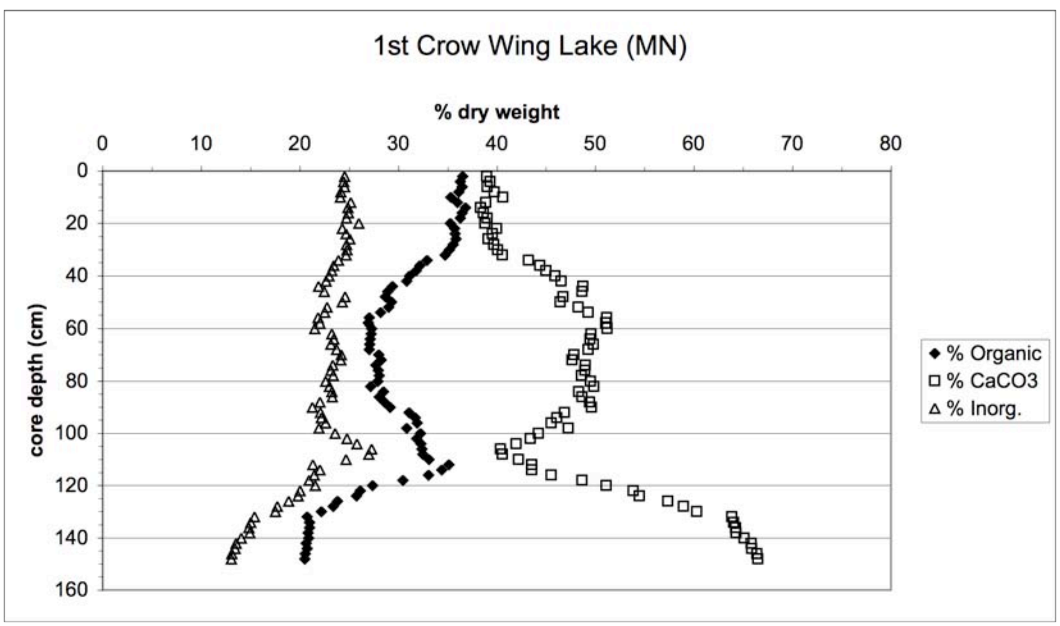

Fig. 27. Percent dry weight composition of organics, carbonates, and inorganics versus core depth based on loss on ignition analysis of the 1st Crow Wing Lake core.

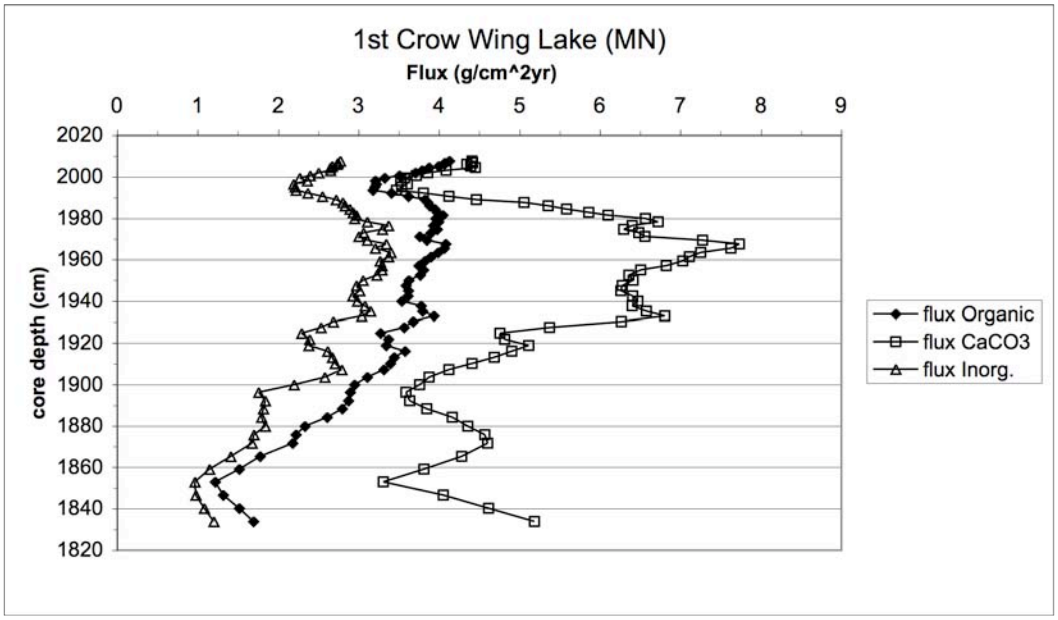

Fig. 28. Flux of sediment components (g/cm^{2}yr) by date in the 1st Crow Wing Lake core.

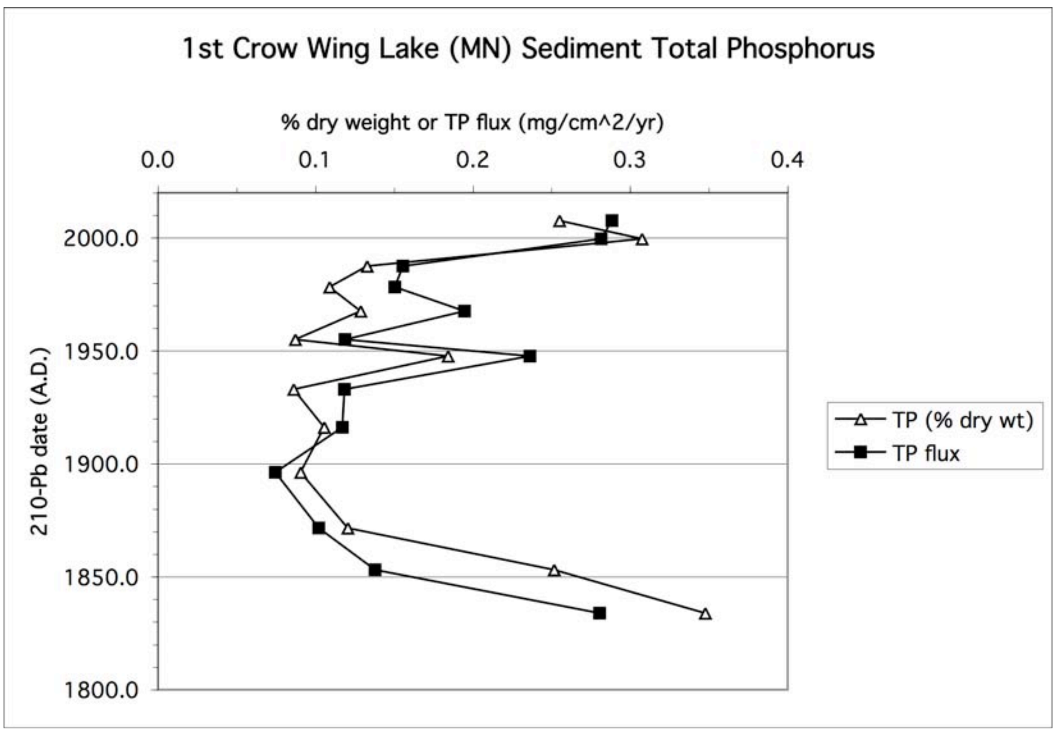

Fig. 29. Sediment total phosphorus, dry weight percent and flux (mg/cm^{2}yr) by date in the 1st Crow Wing Lake core.

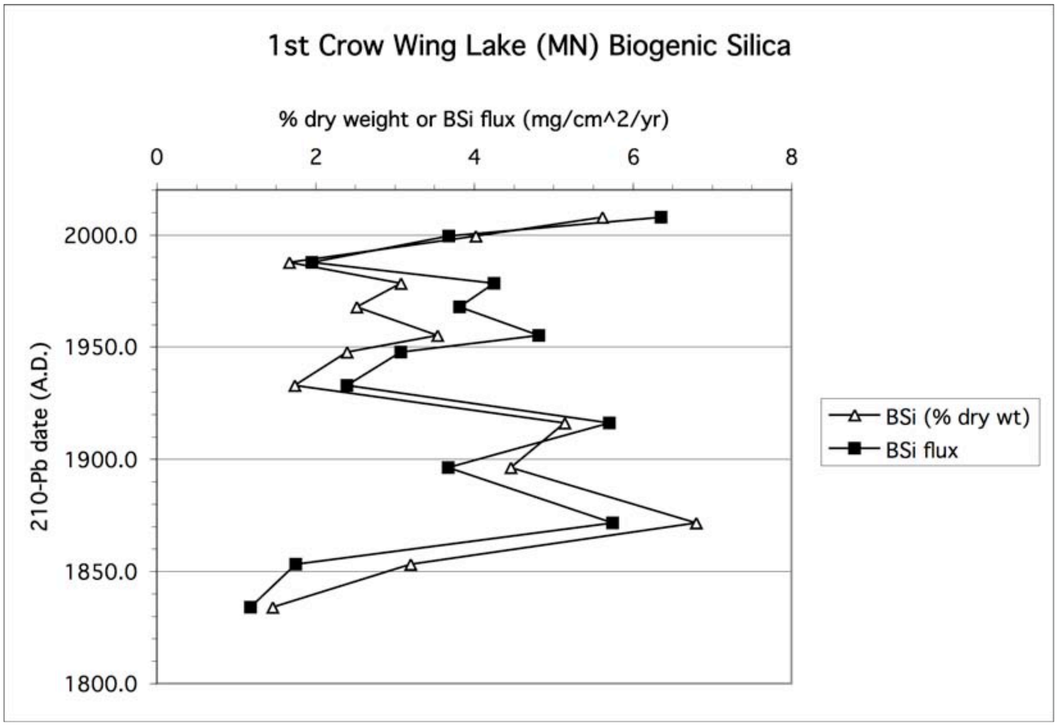

Fig. 30. Sediment biogenic silica, dry weight percent and flux (mg/cm^2yr) by date in the 1st Crow Wing Lake core.

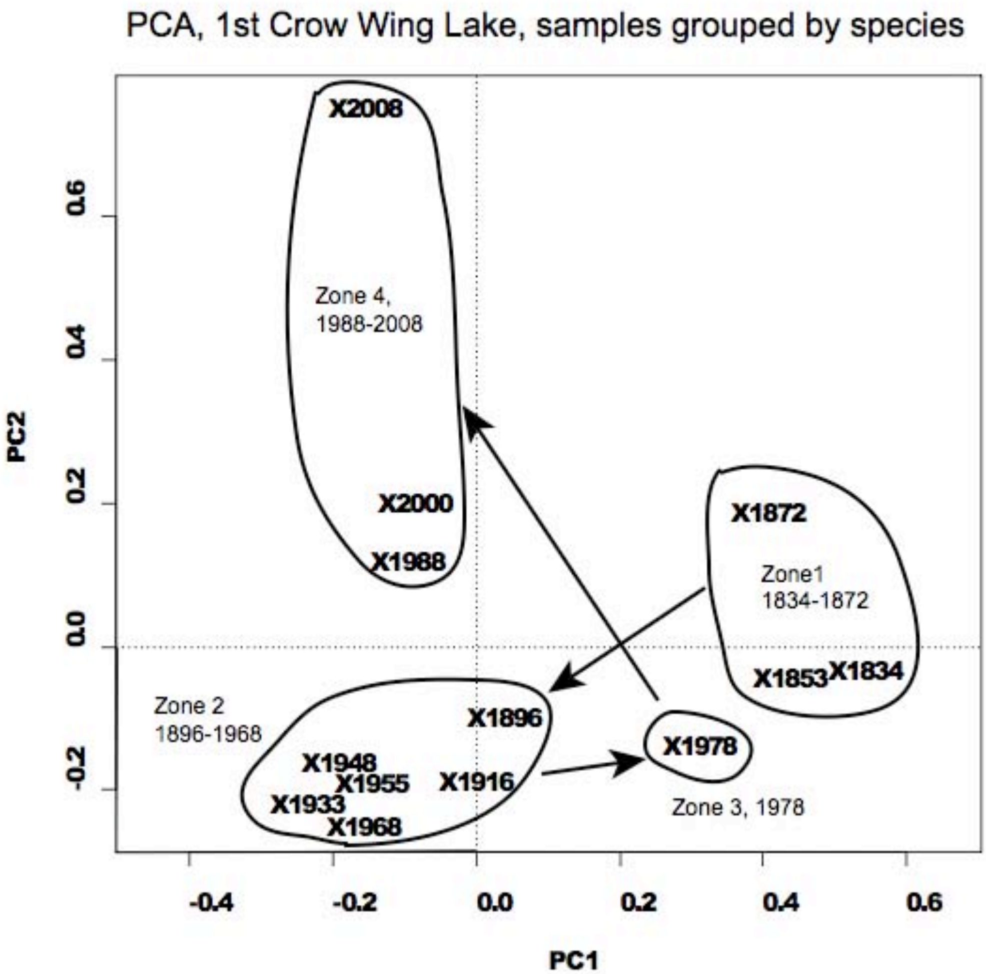

Fig. 31. Principal components analysis of downcore 1st Crow Wing Lake diatom communities shows three stratigraphic zones: Zone 1 (1834-1872), Zone 2 (1896-1968), Zone 3 (1978), and Zone 4 (1988-2008).

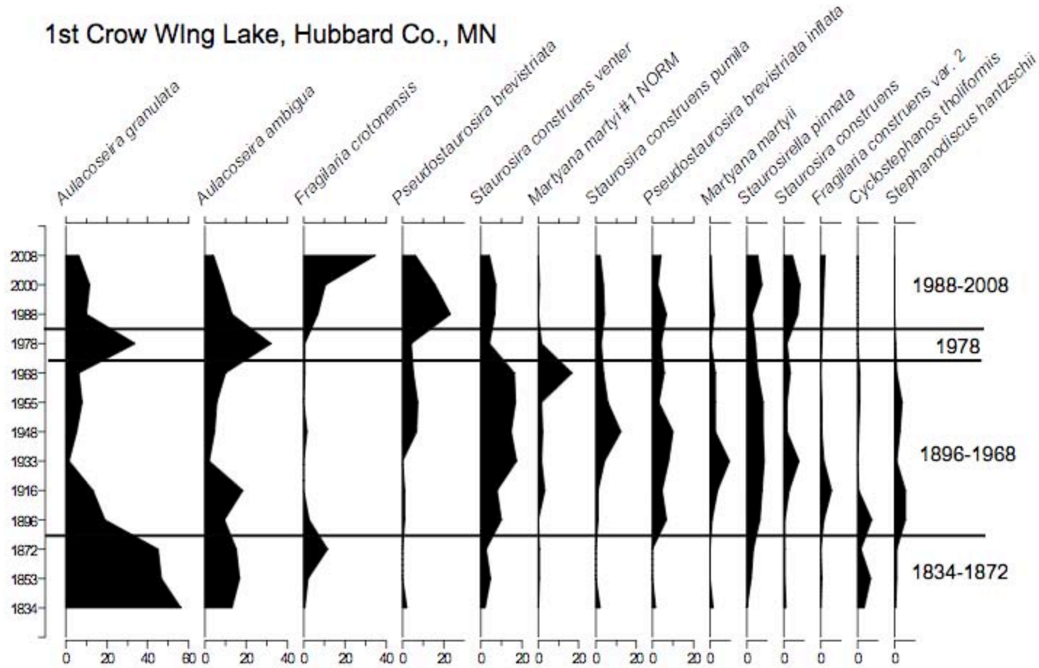

Fig. 32. Diatom stratigraphy of species present at >5% relative abundance in 1st Crow Wing Lake core, 1834-2008. Stratigraphic zones identified by principal components and constrained cluster analysis indicated by horizontal lines.

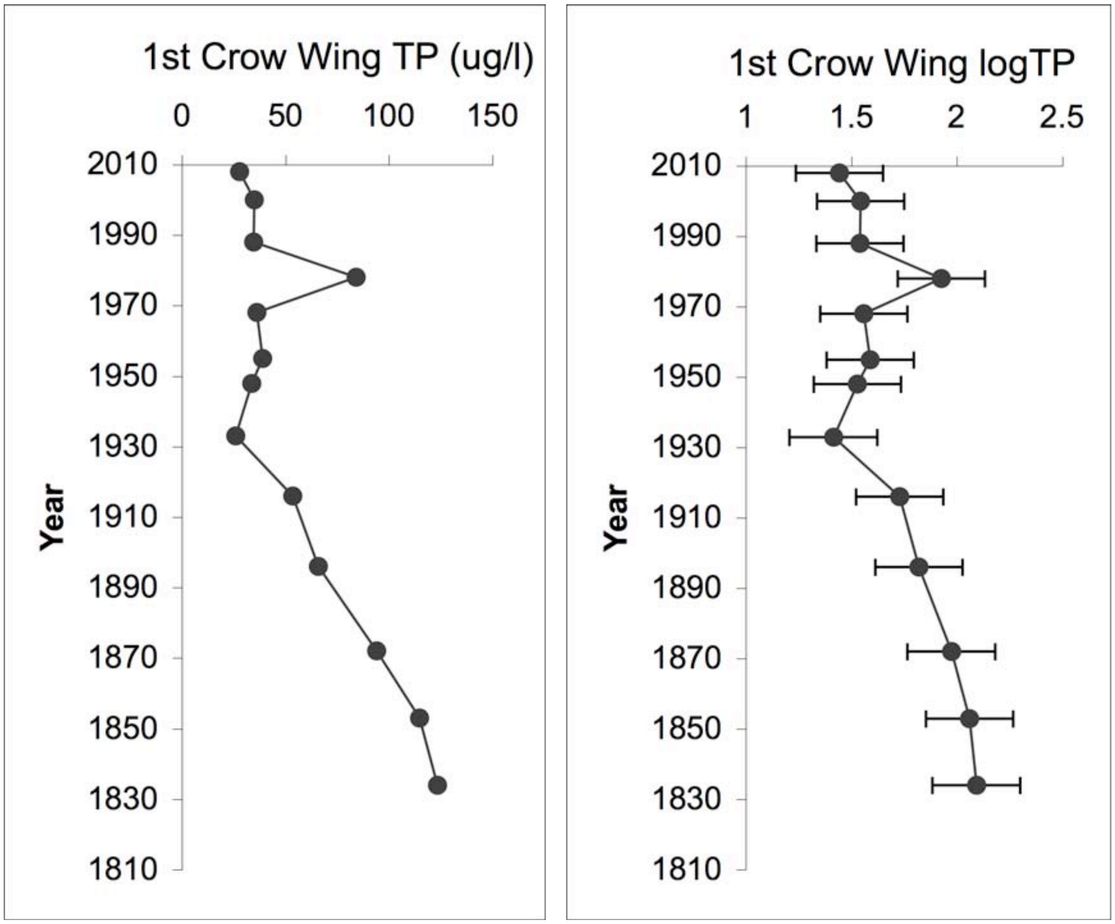

Fig. 33. Diatom-inferred total phosphorus reconstructions for 1st Crow Wing Lake 1802-2007. Total phosphorus is reconstructed as log TP; error bars represent the bootstrapped root mean square error of prediction for the Minnesota lakes diatom calibration model (see text).

DIXON LAKE

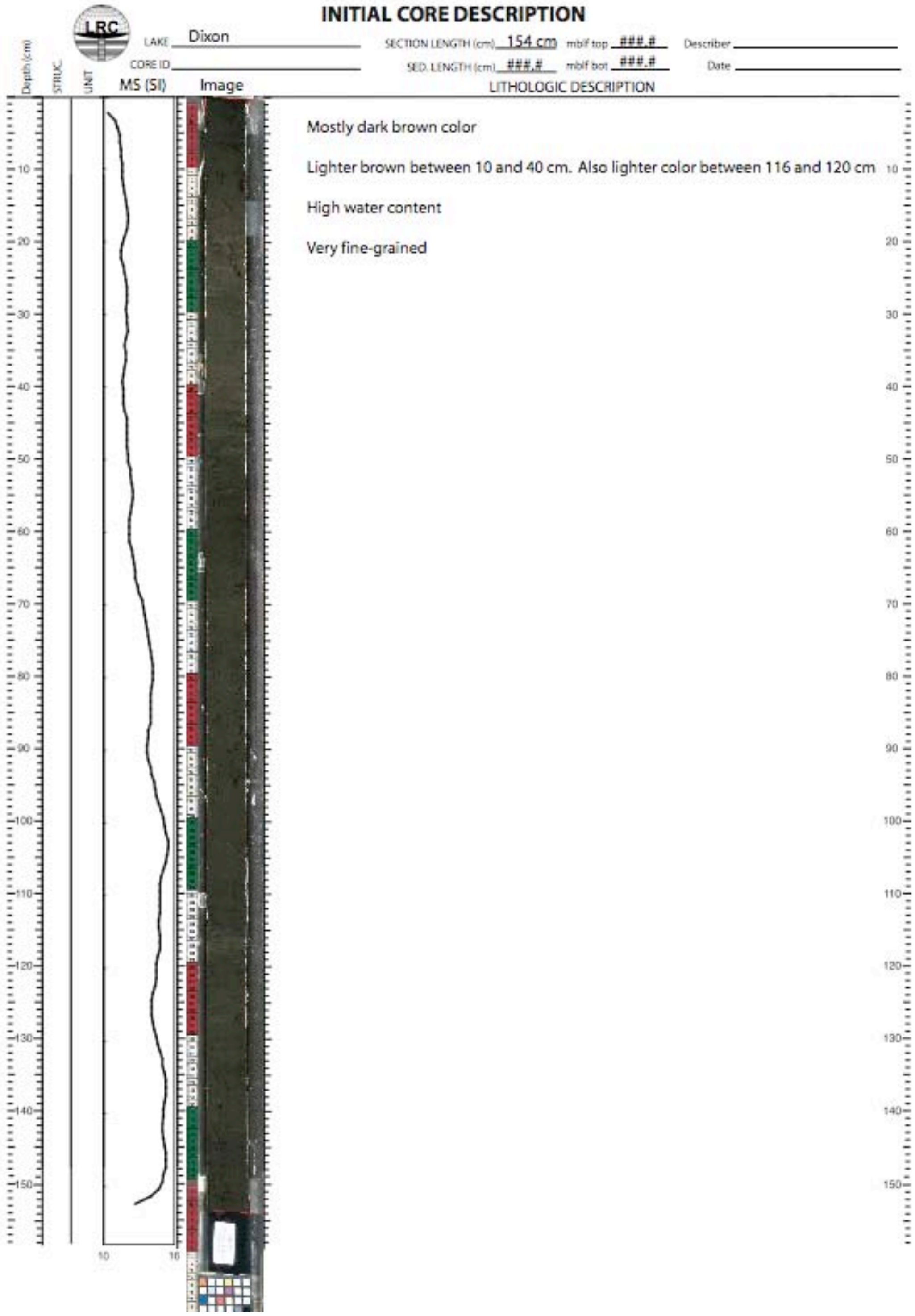

Fig. 34. Image and magnetic susceptibility of the Dixon Lake piston core. The piston core image begins at 52 cm core depth because the top of the core was sectioned in the field.

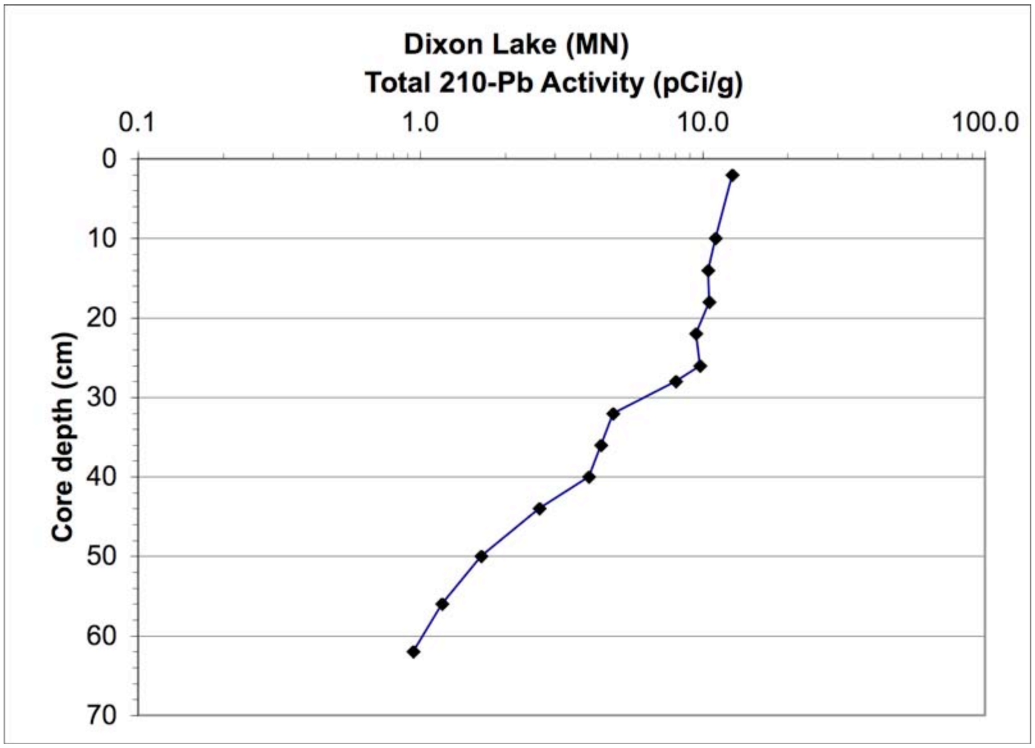

Fig. 35. Total lead-210 activity, Dixon Lake core.

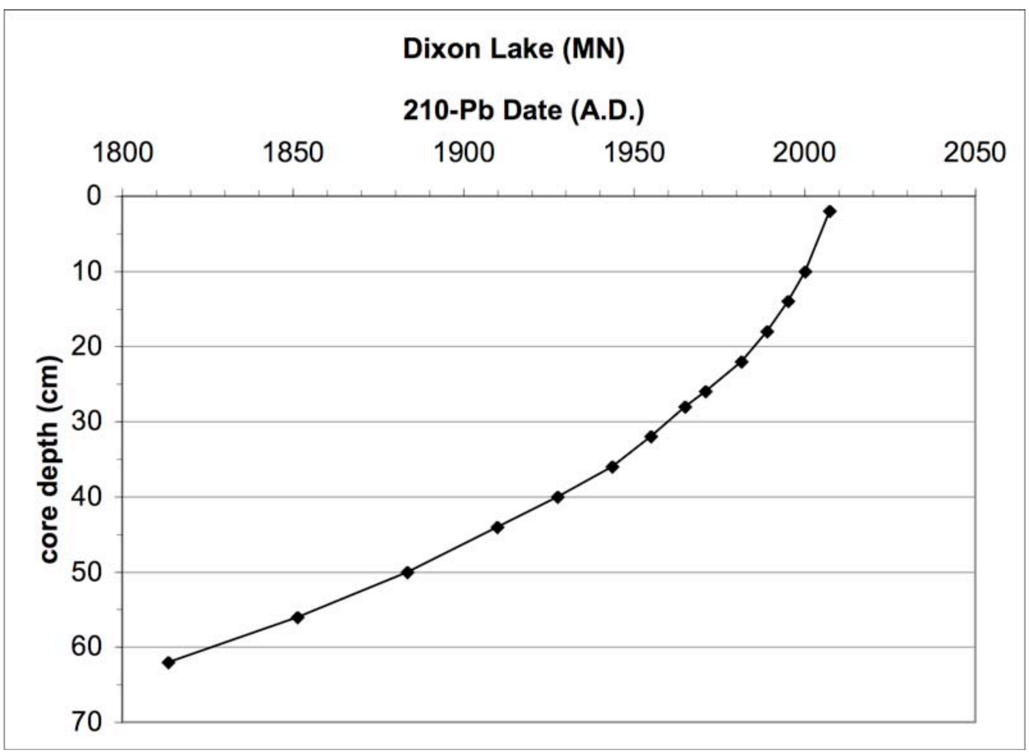

Fig. 36. Resulting 210-Pb dating model for Dixon Lake core.

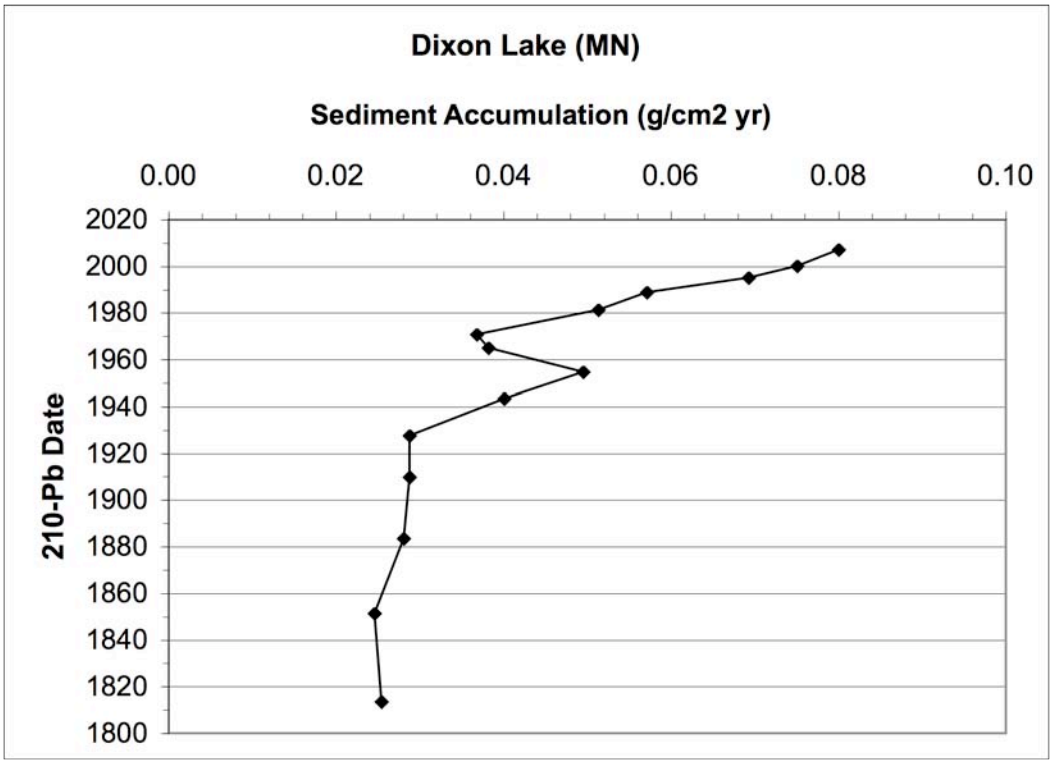

Fig. 37. Sediment accumulation rates (g/cm^{2}yr) for Dixon Lake core.

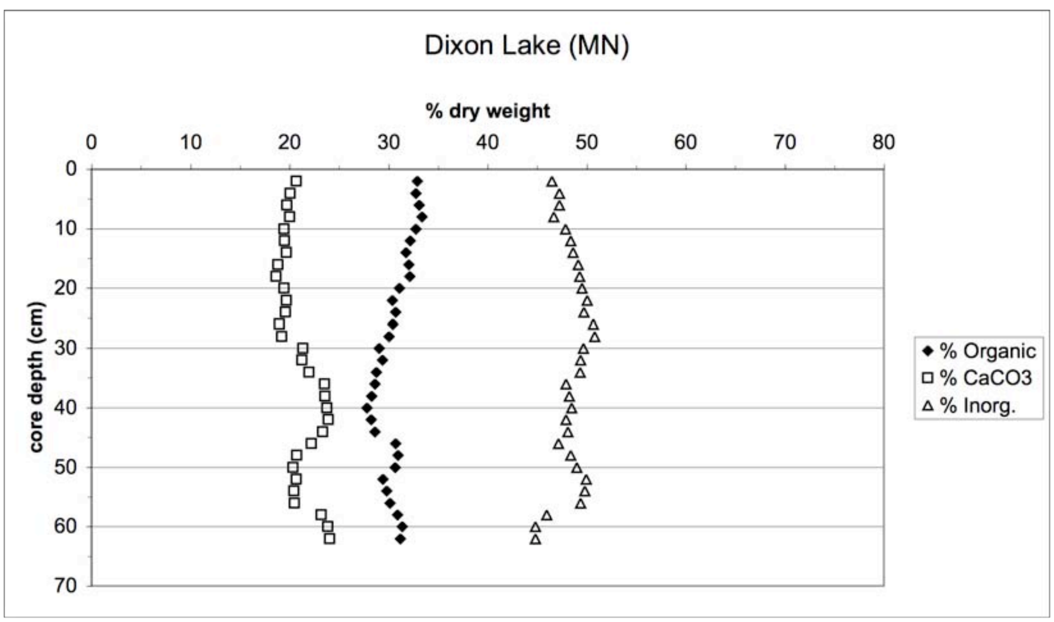

Fig. 38. Percent dry weight composition of organics, carbonates, and inorganics versus core date based on loss on ignition analysis of Dixon Lake core.

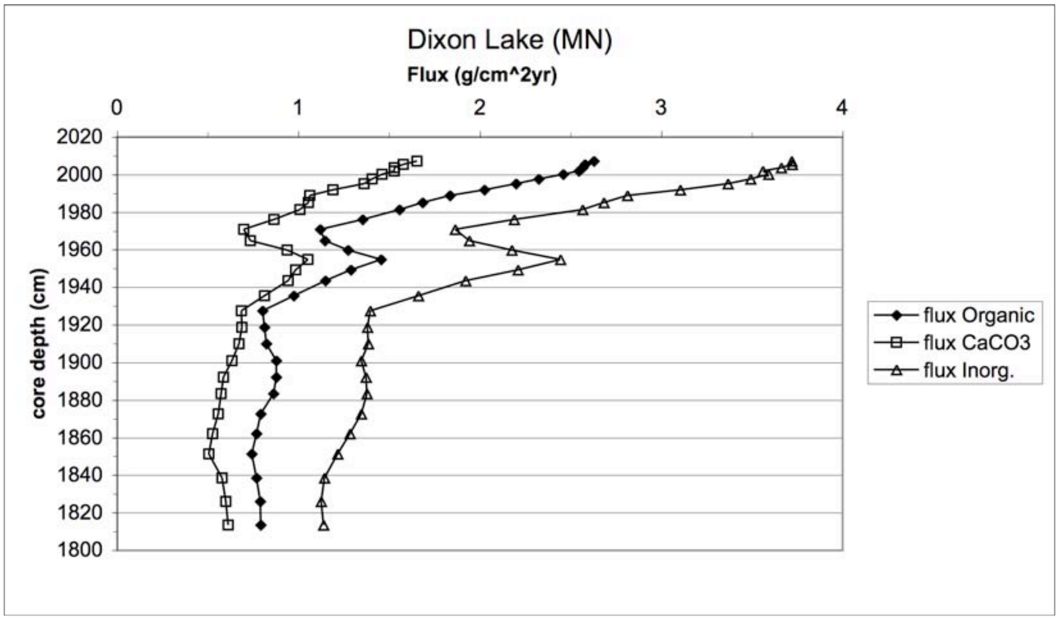

Fig. 39. Flux of sediment components (g/cm^{2}yr) by date in the Dixon Lake core.

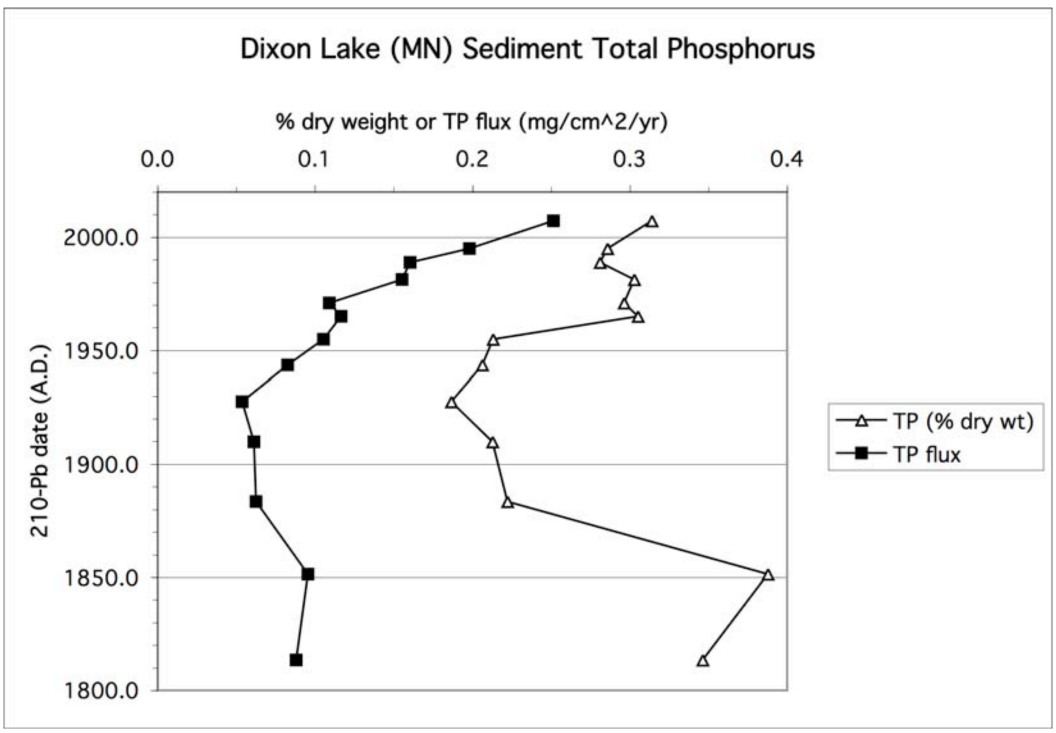

Fig. 40. Sediment total phosphorus, dry weight percent and flux (mg/cm^{2}yr) by date in the Dixon Lake core.

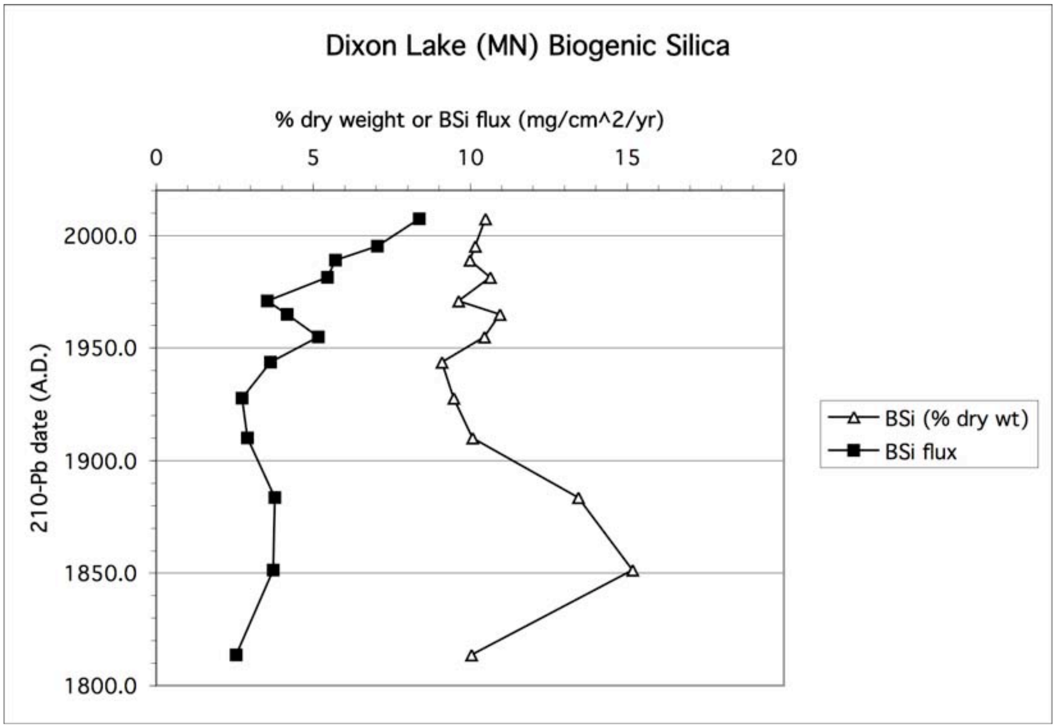

Fig. 41. Sediment biogenic silica, dry weight percent and flux (mg/cm^{2}yr) by date in the Dixon Lake core.

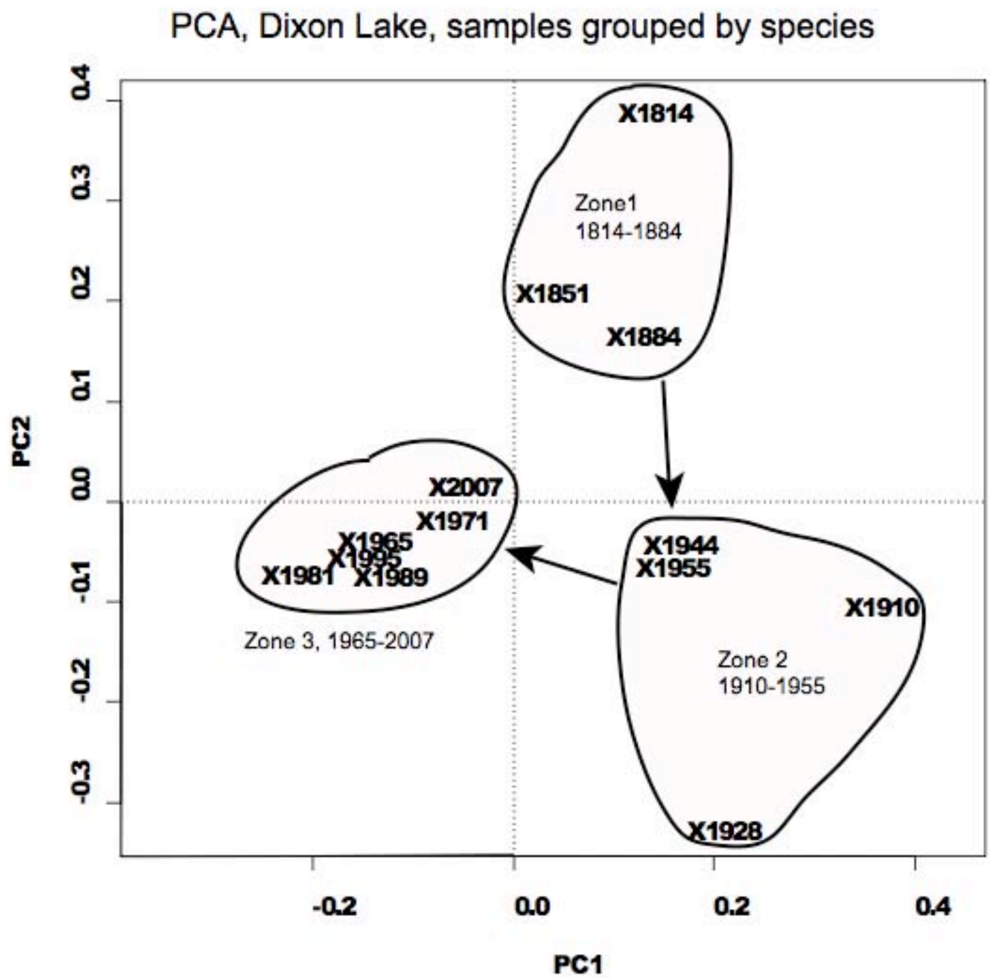

Fig. 42. Principal components analysis of downcore Dixon Lake diatom communities shows three stratigraphic zones: Zone 1 (1814-1884), Zone 2 (1910-1955), and Zone 3 (1965-2007).

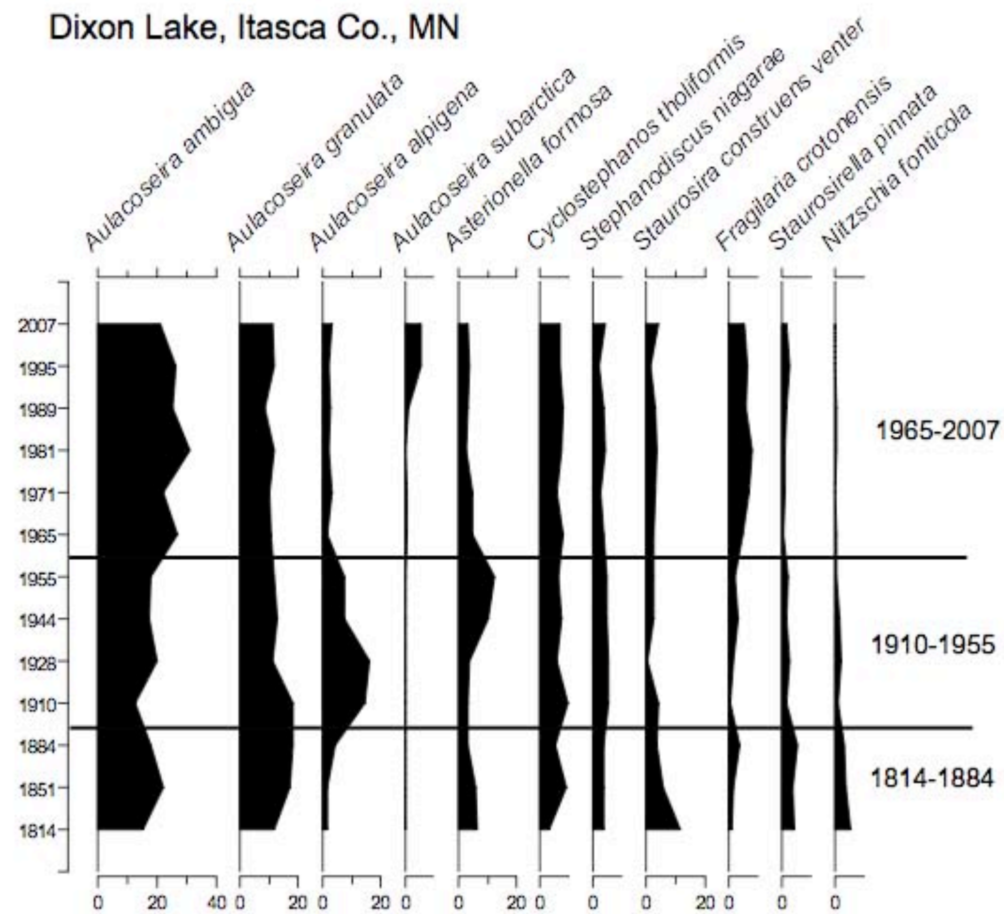
Dixon Lake, Itasca Co., MN
Aulacoseira ambigua
Aulacoseira granulata
Aulacoseira alpigena
Aulacoseira subarctica
Asterionella formosa
Cyclostephanos tholiformis
Stephanodiscus niagarae
Staurosira construens venter
Fragilaria crotonensis
Staurosirella pinnata
Nitzschia fonticola
2007
1995
1989
1981
1971
1965
1955
1944
1928
1910
1884
1851
1814
1965-2007
1910-1955
1814-1884
0 20 40 0 20 0 20 0 0 20 0 0 0 20 0 0 0

Fig. 43. Diatom stratigraphy of species present at >5% relative abundance in Dixon Lake core, 1802-2007. Stratigraphic zones identified by principal components and constrained cluster analysis are indicated by horizontal lines.

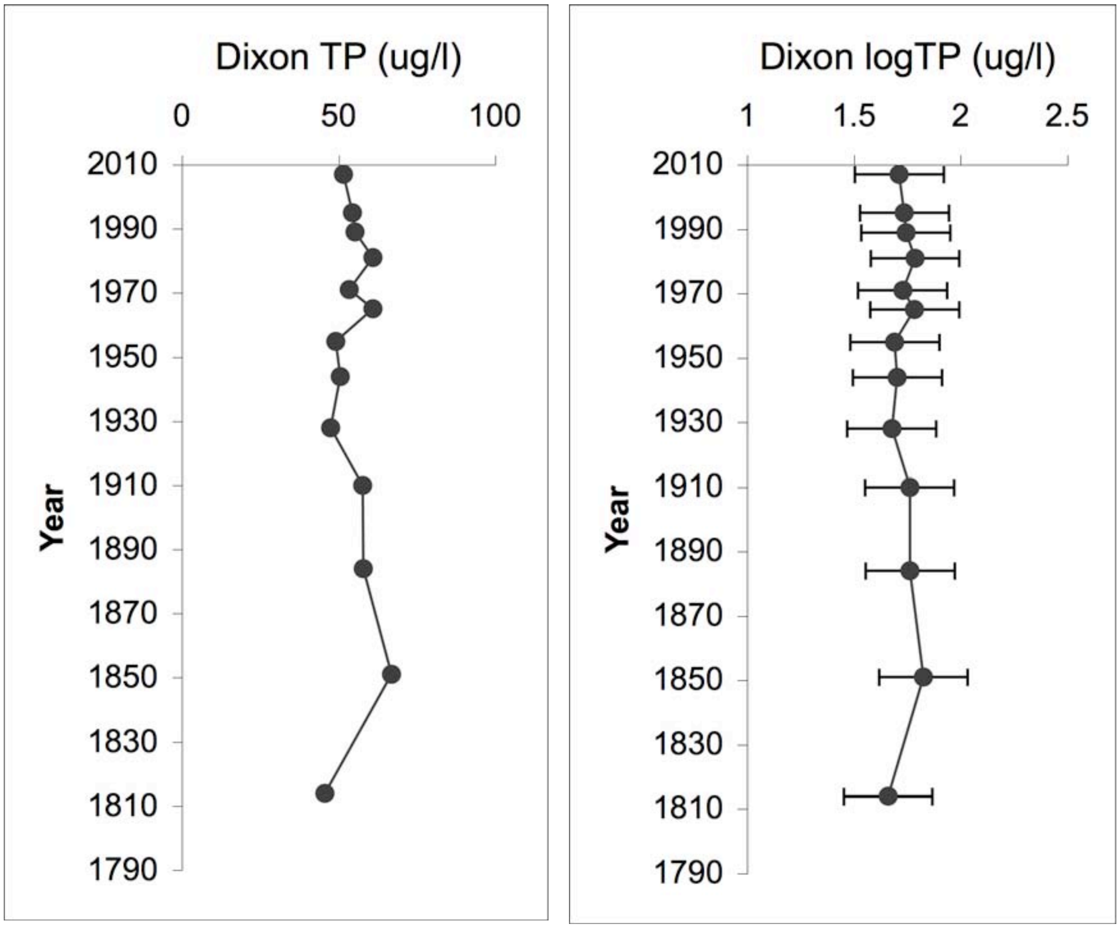

Fig. 44. Diatom-inferred total phosphorus reconstructions for Dixon Lake 1802-2007. Total phosphorus is reconstructed as log TP; error bars represent the bootstrapped root mean square error of prediction for the Minnesota lakes diatom calibration model (see text).

MARGARET LAKE

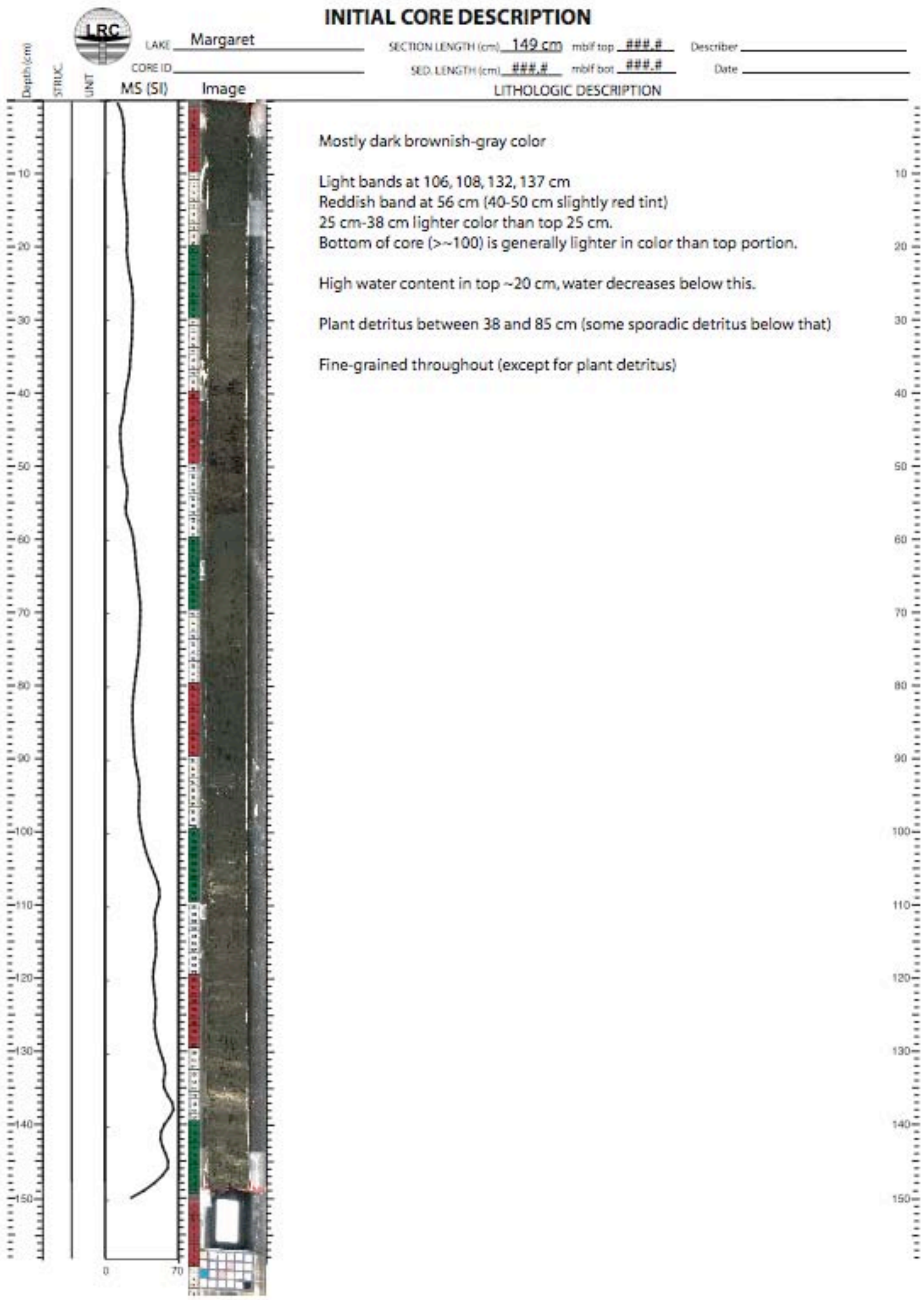

Fig. 45. Image and magnetic susceptibility of the Margaret Lake piston core. The piston core image begins at 40 cm core depth because the top of the core was sectioned in the field.

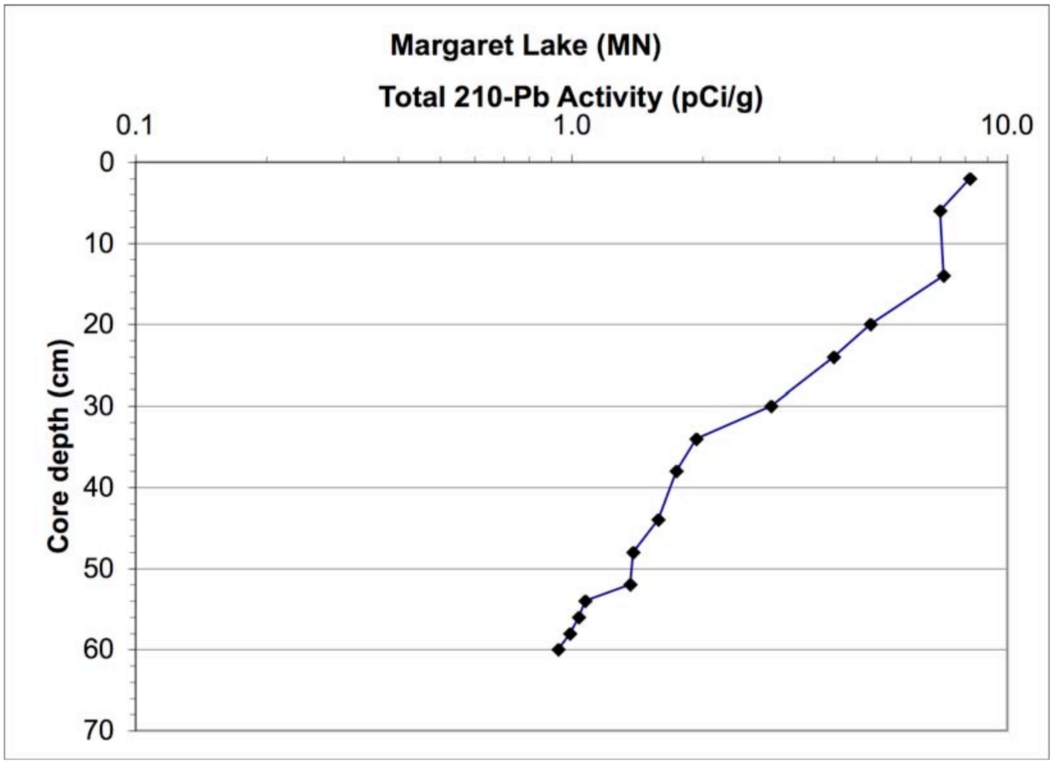

Fig. 46. Total lead-210 activity, Margaret Lake core.

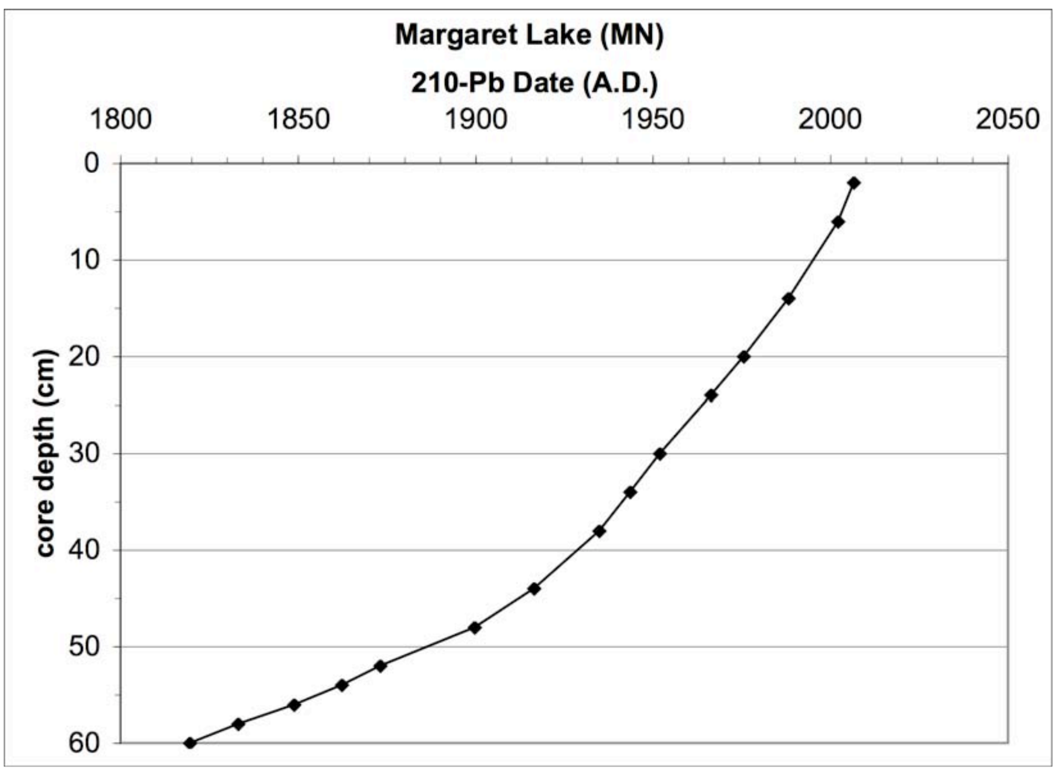

Fig. 47. Resulting 210-Pb dating model for Margaret Lake core.

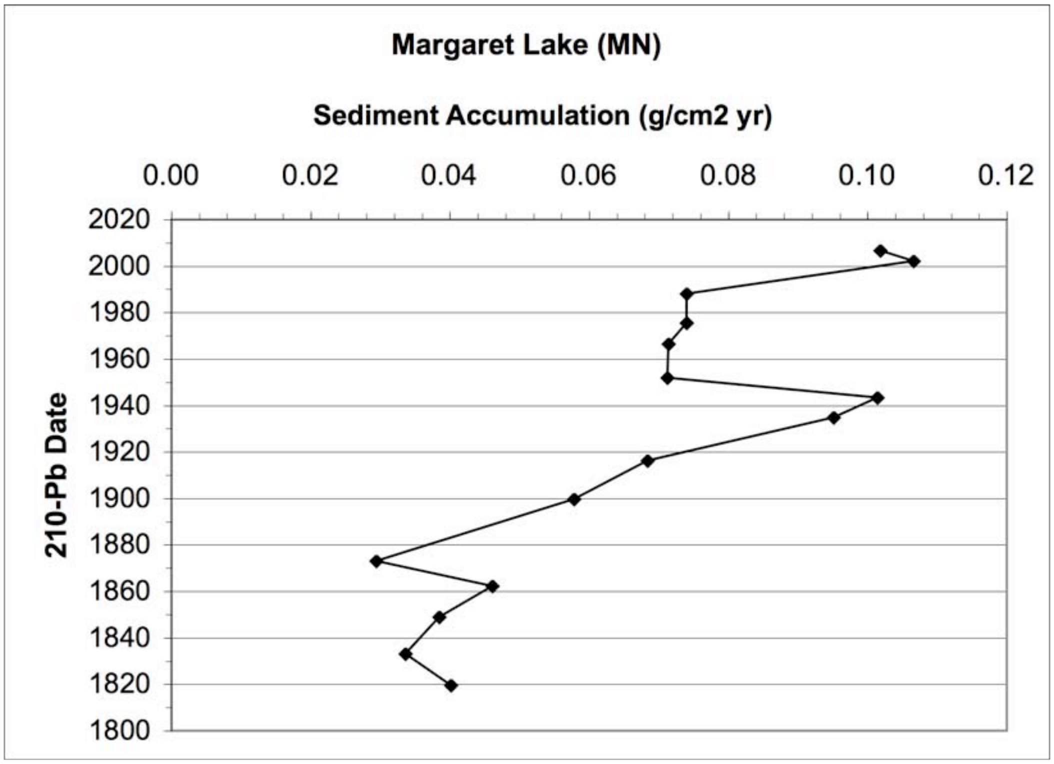

Fig. 48. Sediment accumulation rates (g/cm^{2}yr) for Margaret Lake core.

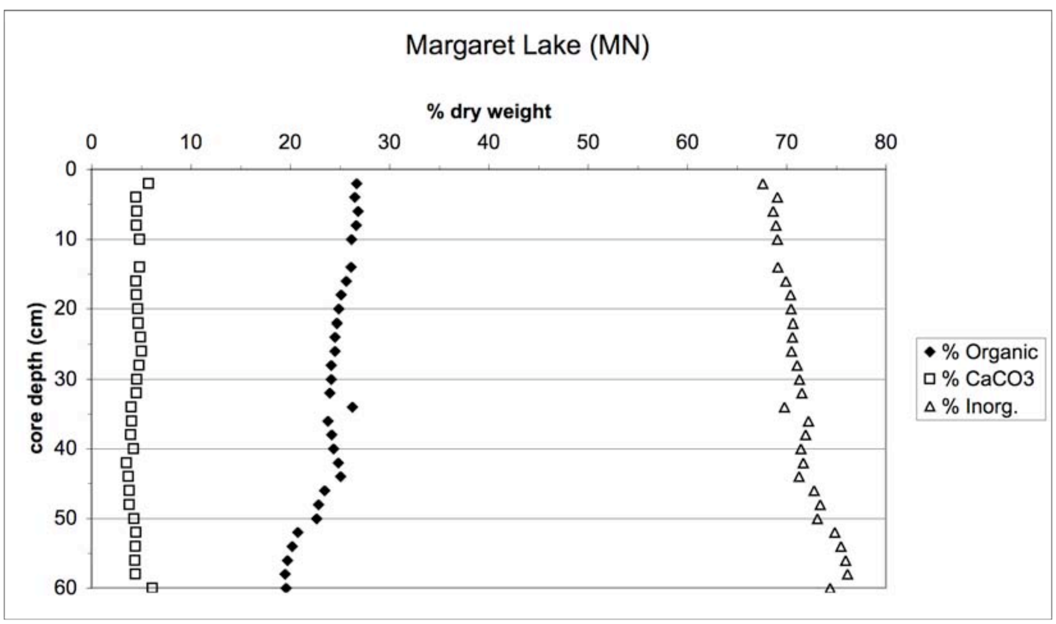

Fig. 49. Percent dry weight composition of organics, carbonates, and inorganics versus core date based on loss on ignition analysis of Margaret Lake core

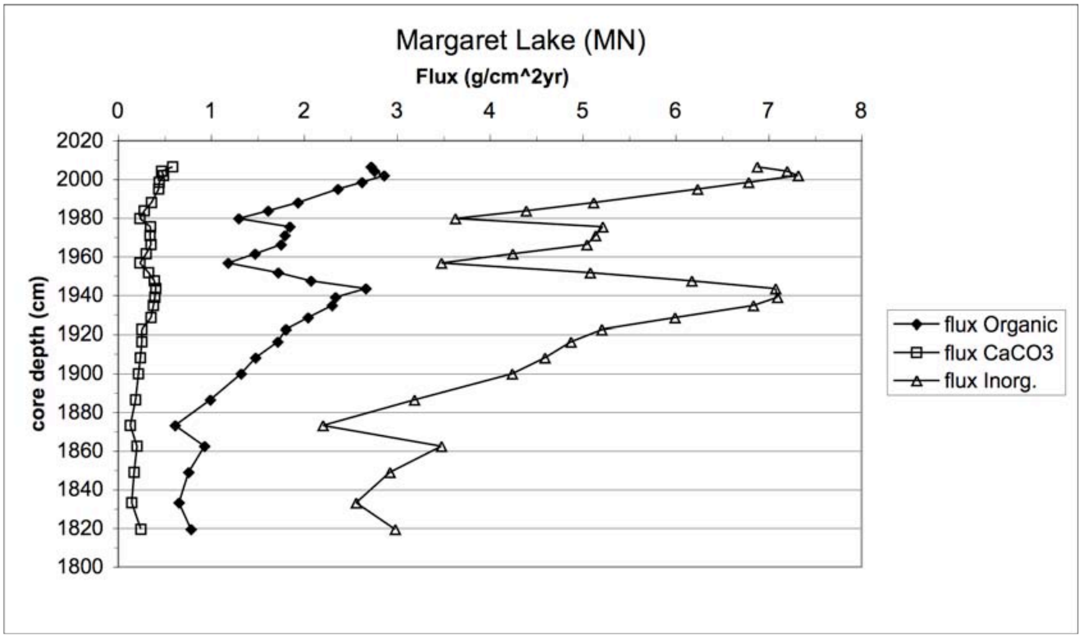

Fig. 50. Flux of sediment components (g/cm^{2}yr) by date in the Margaret Lake core.

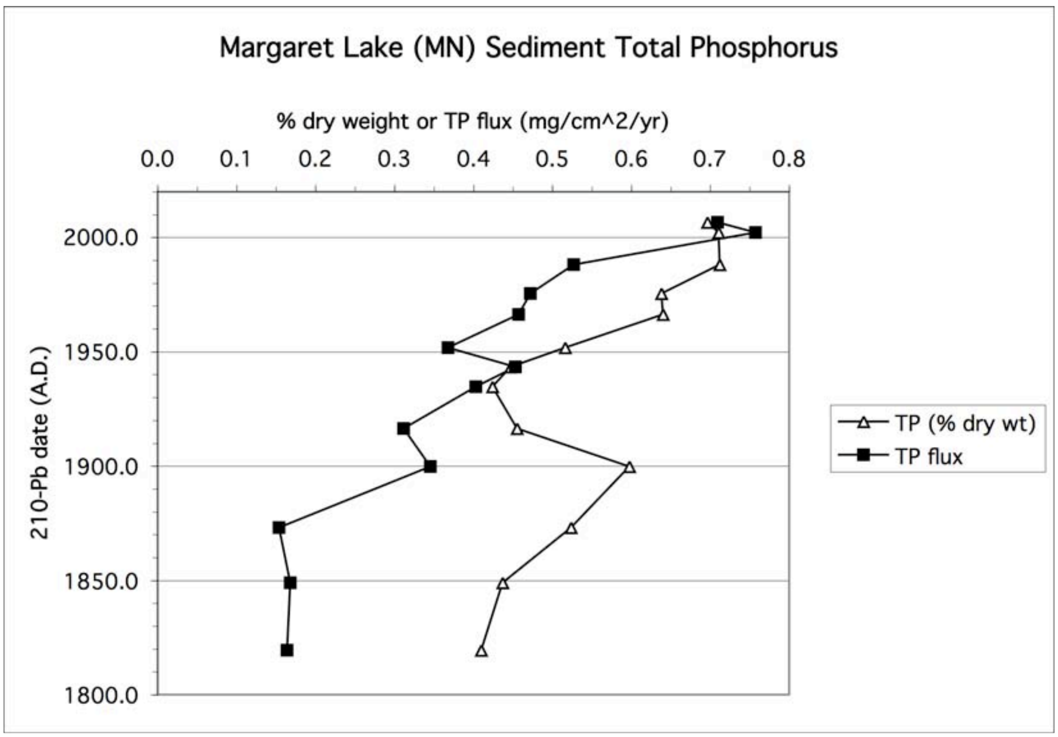

Fig. 51. Sediment total phosphorus, dry weight percent and flux (mg/cm^{2}yr) by date in the Margaret Lake core.

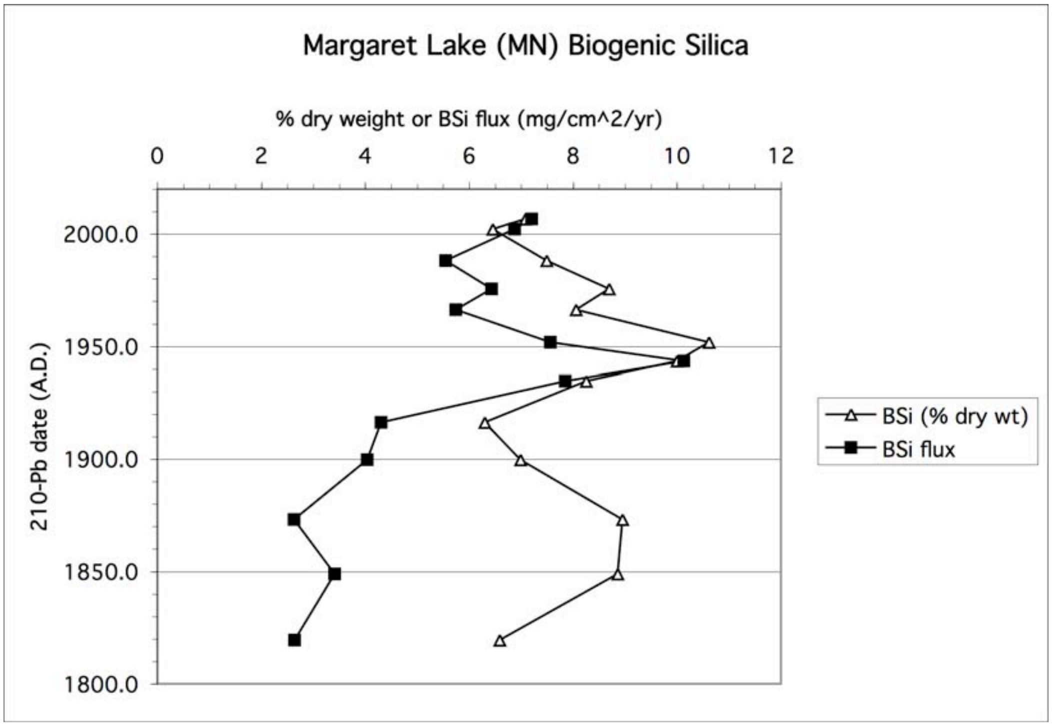

Fig. 52. Sediment biogenic silica, dry weight percent and flux (mg/cm^{2}yr) by date in the Margaret Lake core.

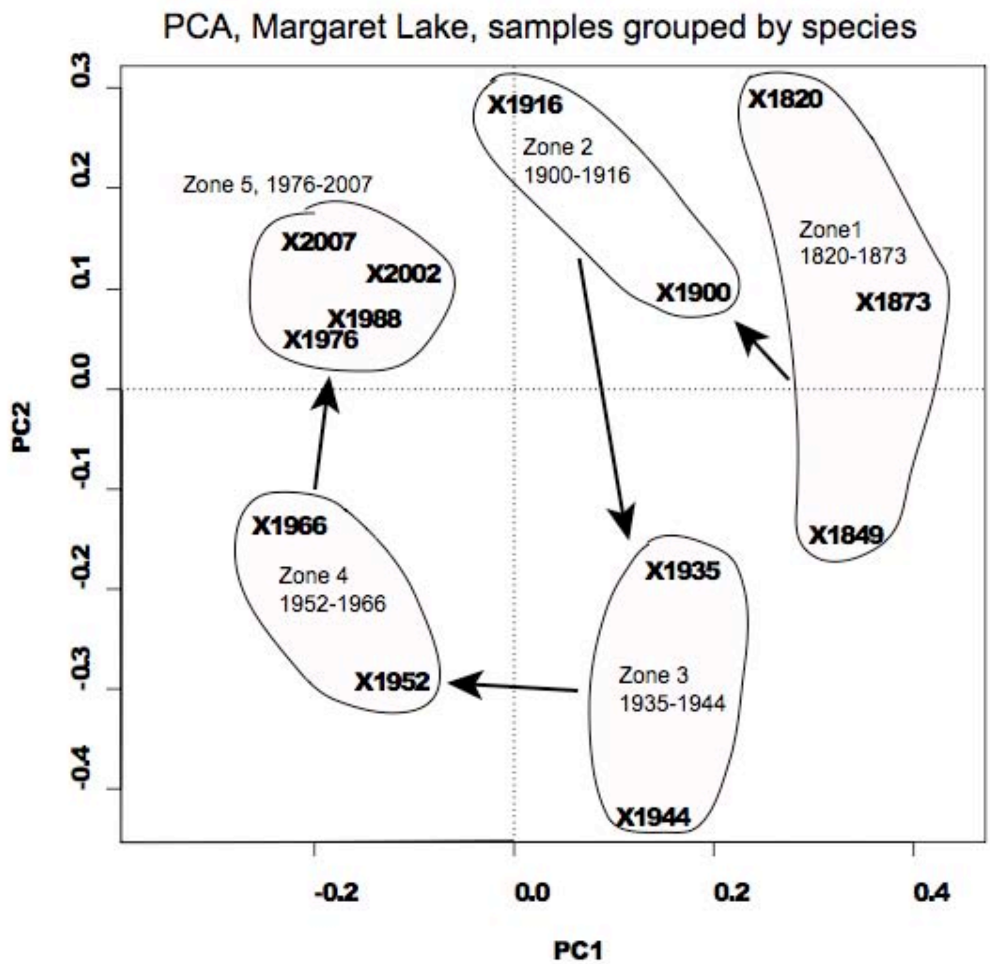

Fig. 53. Principal components analysis of downcore Margaret Lake diatom communities shows five stratigraphic zones: Zone 1 (1820-1873), Zone 2 (1900-1916), and Zone 3 (1935-1944), Zone 4 (1952-1966), and Zone 5 (1976-2007).

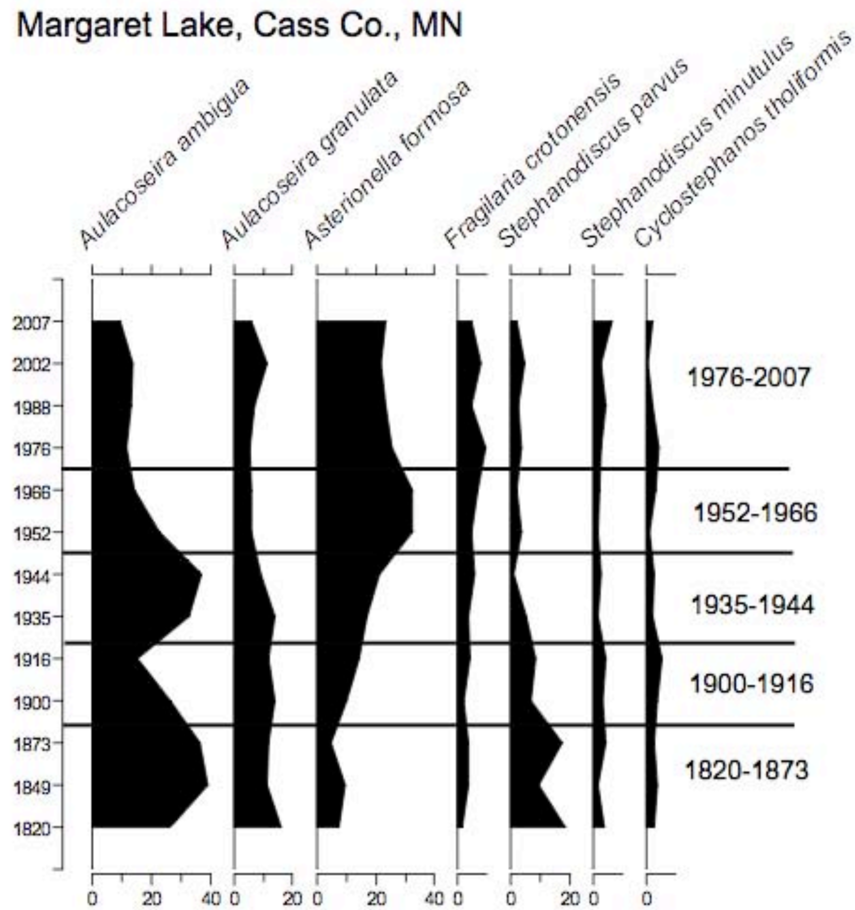

Fig. 54. Diatom stratigraphy of species present at >5% relative abundance in Margaret Lake core, 1820-2007. Stratigraphic zones identified by principal components and constrained cluster analyses are indicated by horizontal lines.

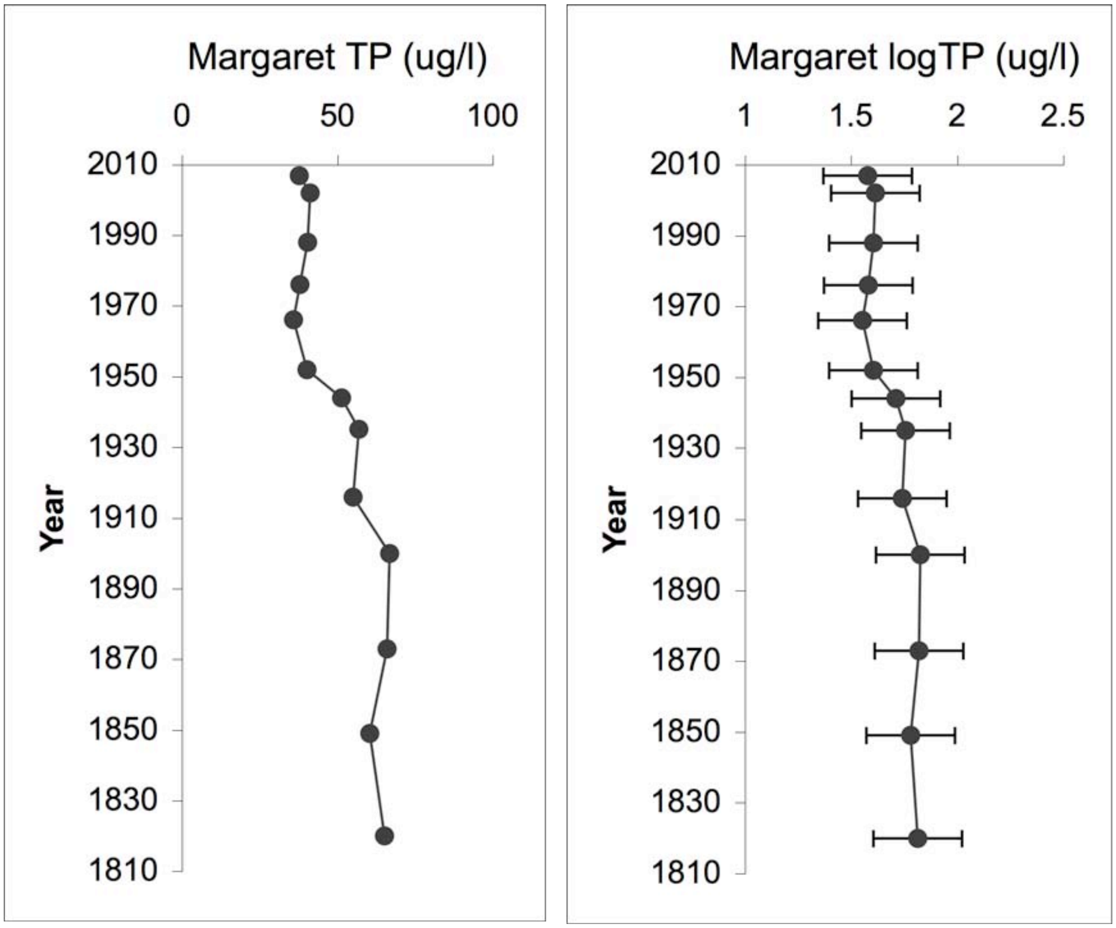

Fig. 55. Diatom-inferred total phosphorus reconstructions for Margaret Lake 1802-2007. Total phosphorus is reconstructed as log TP; error bars represent the bootstrapped root mean square error of prediction for the Minnesota lakes diatom calibration model (see text).

PORTAGE LAKE

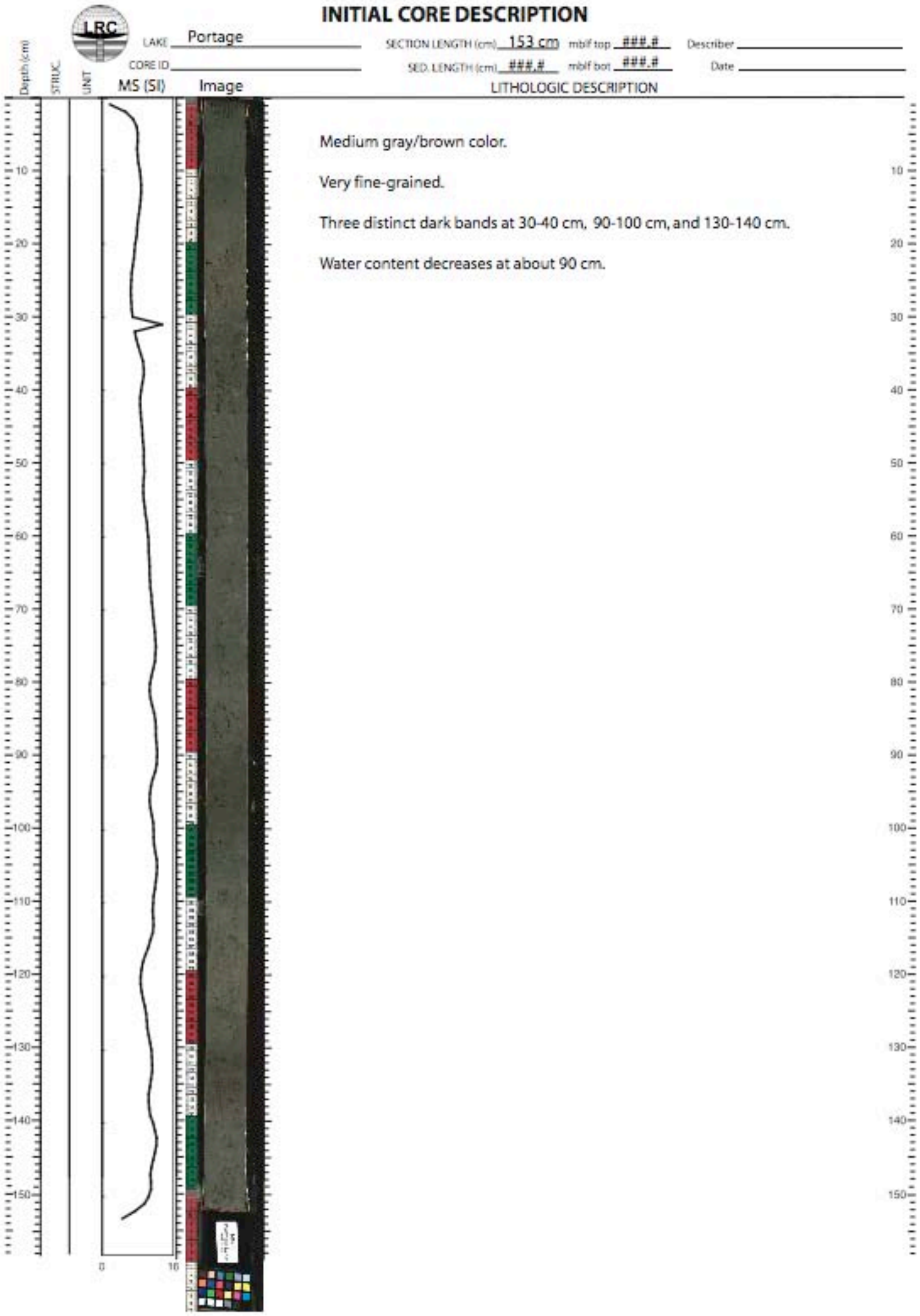

Fig. 56. Image and magnetic susceptibility of the Portage Lake piston core. The piston core image begins at 48 cm core depth because the top of the core was sectioned in the field.

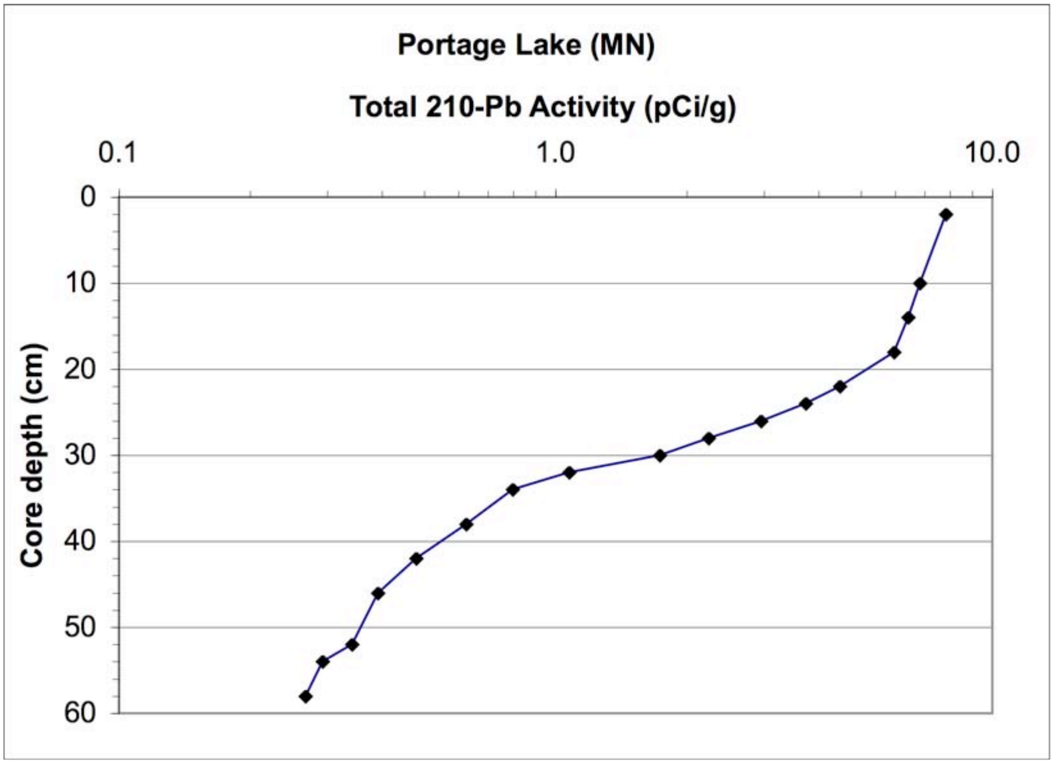

Fig. 57. Total lead-210 activity, Portage Lake core.

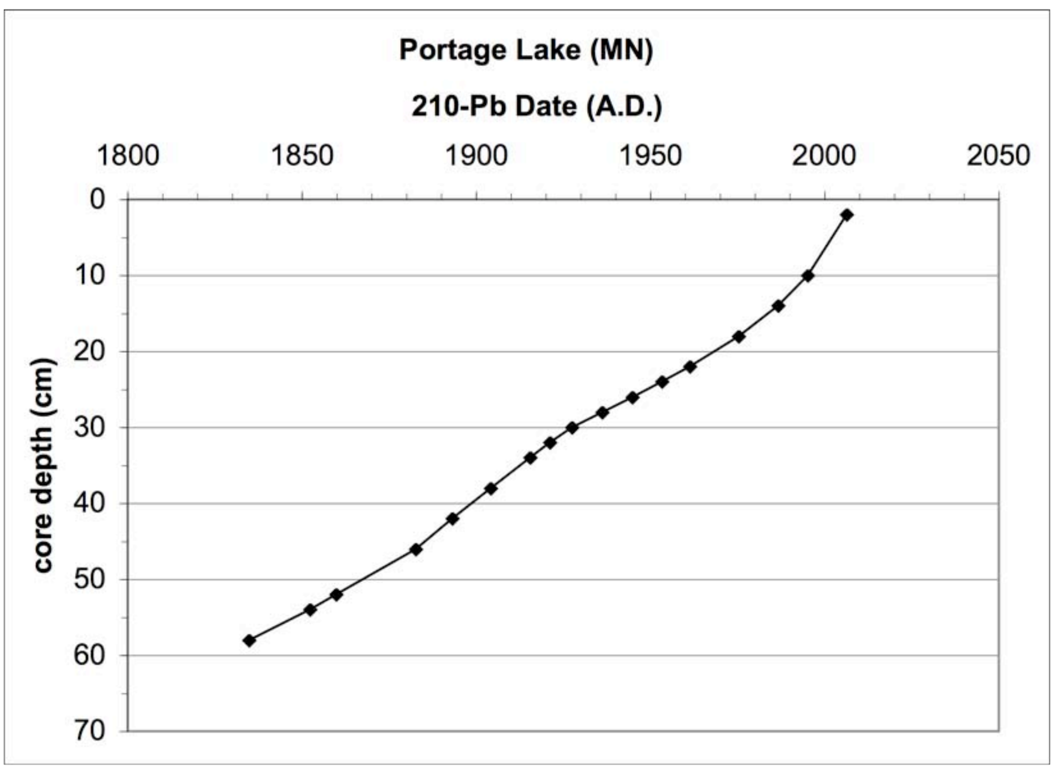

Fig. 58. Resulting 210-Pb dating model for Portage Lake core.

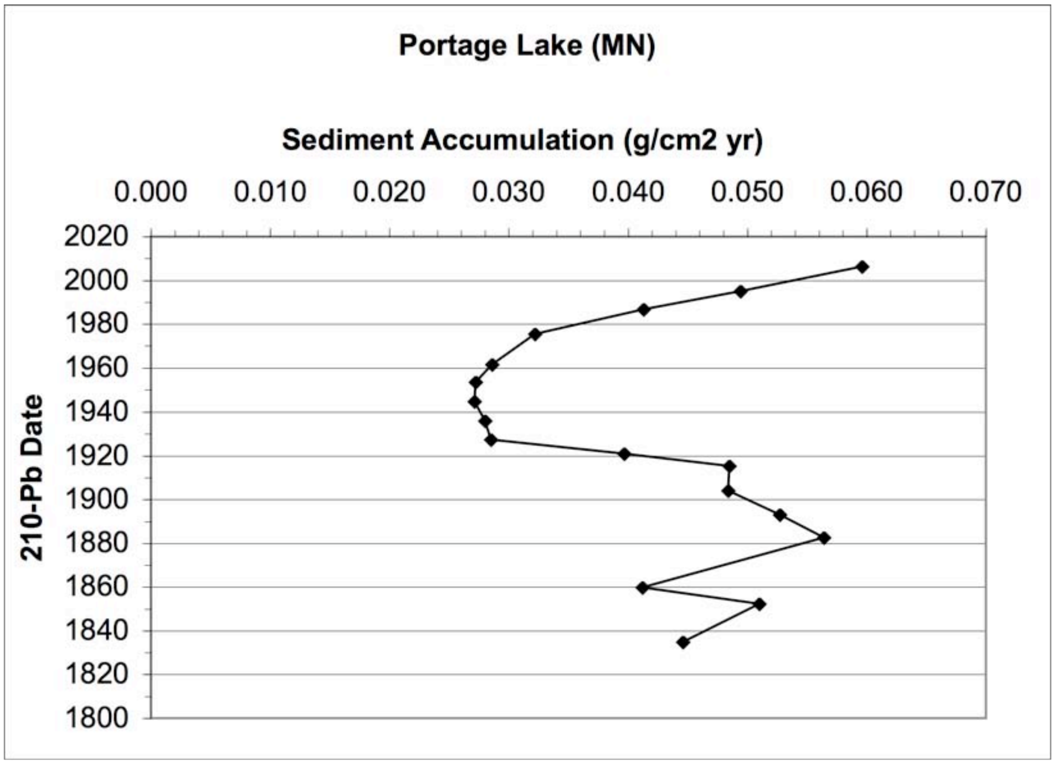

Fig. 59. Sediment accumulation rates (g/cm^2yr) for Portage Lake core.

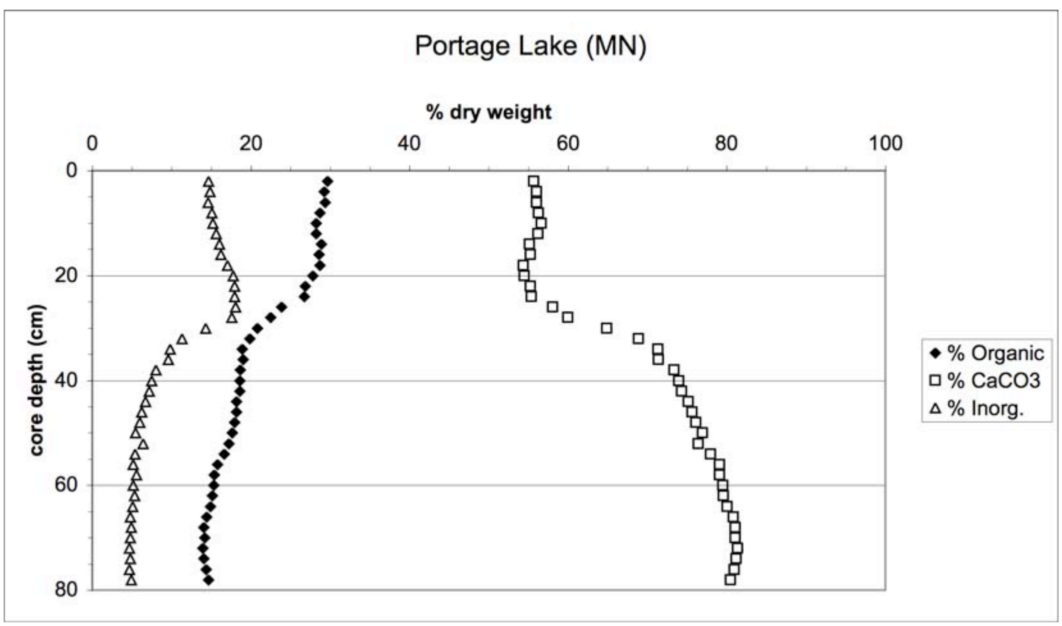

Fig. 60. Percent dry weight composition of organics, carbonates, and inorganics versus core date based on loss on ignition analysis of the Portage Lake core.

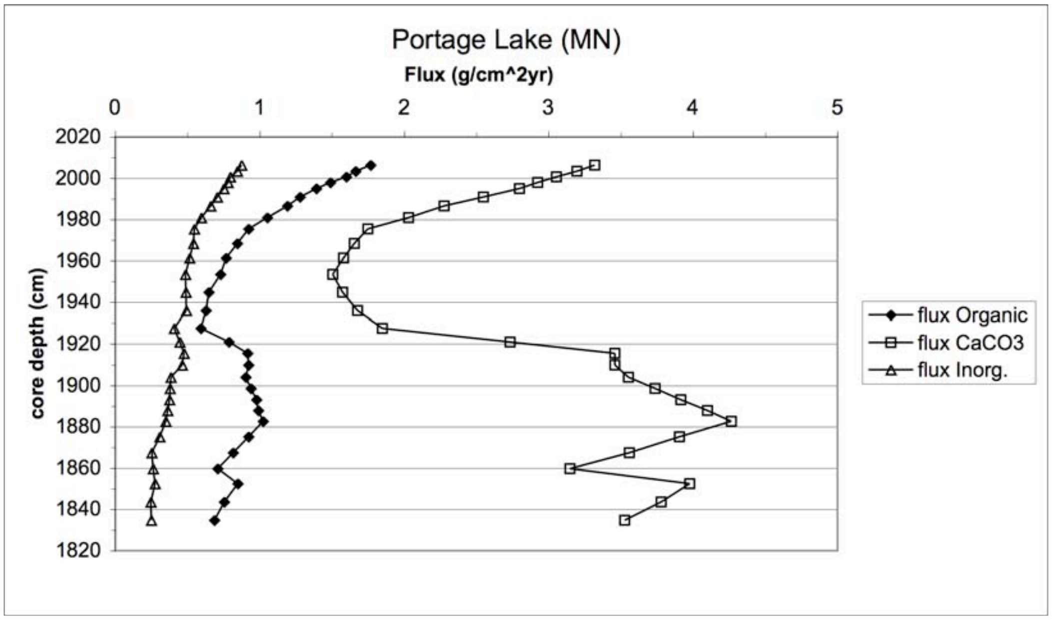

Fig. 61. Flux of sediment components (g/cm^2yr) by date in the Portage Lake core.

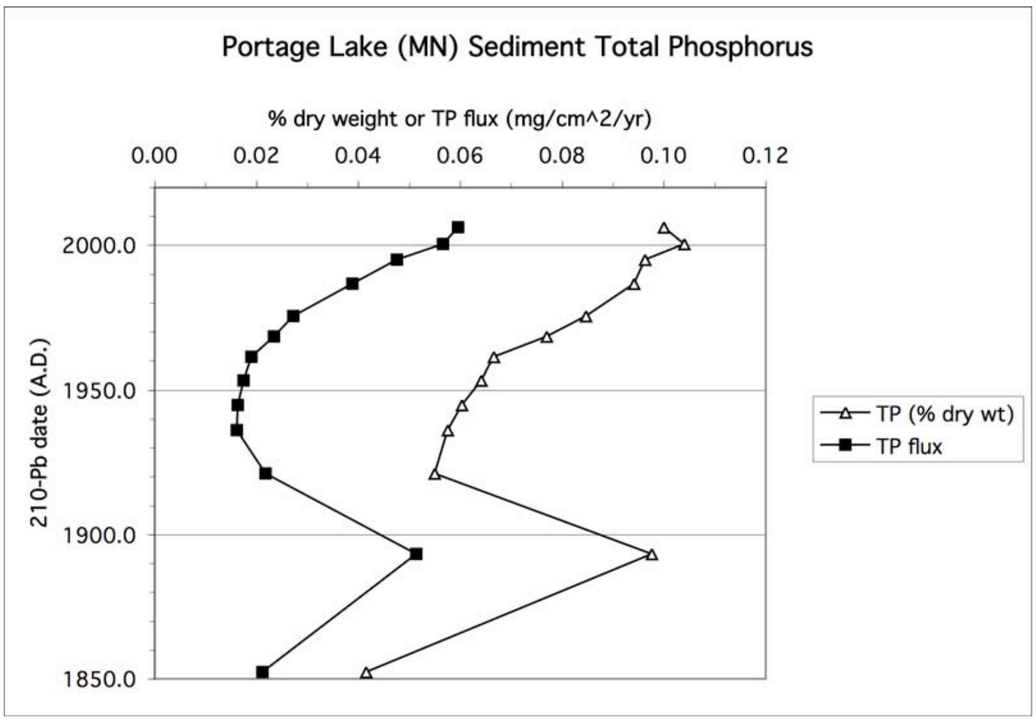

Fig. 62. Sediment total phosphorus, dry weight percent and flux (mg/cm^2yr) by date in the Portage Lake core.

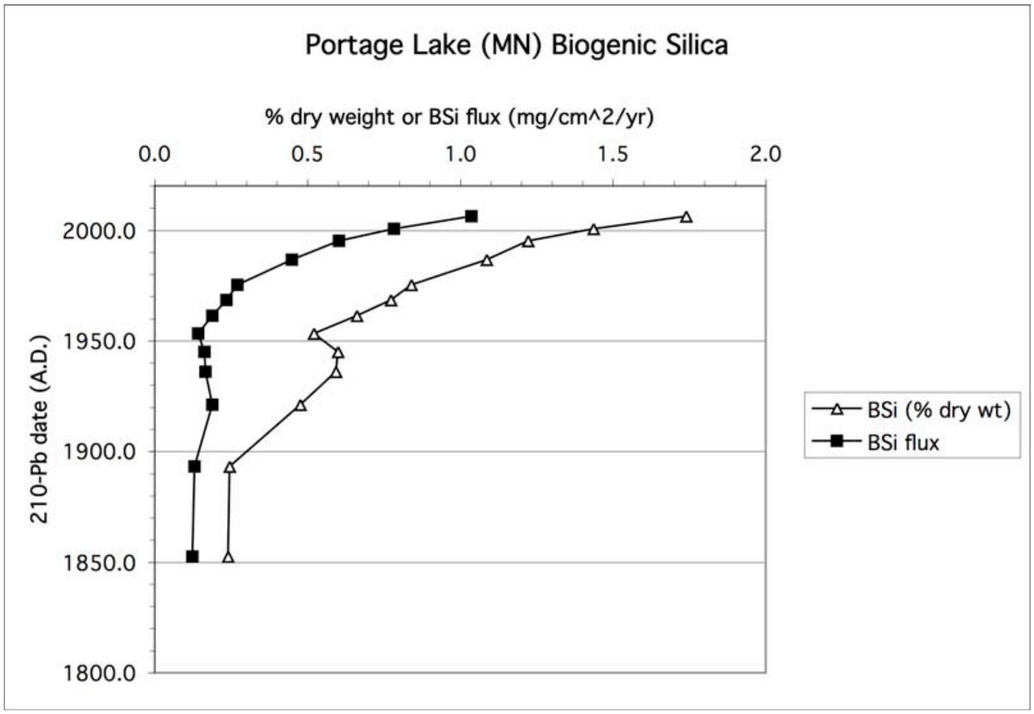

Fig. 63. Sediment biogenic silica, dry weight percent and flux (mg/cm^{2}yr) by date in the Portage Lake core.

OTHER LAKES-8TH CROW WING LAKE, DECKER LAKE

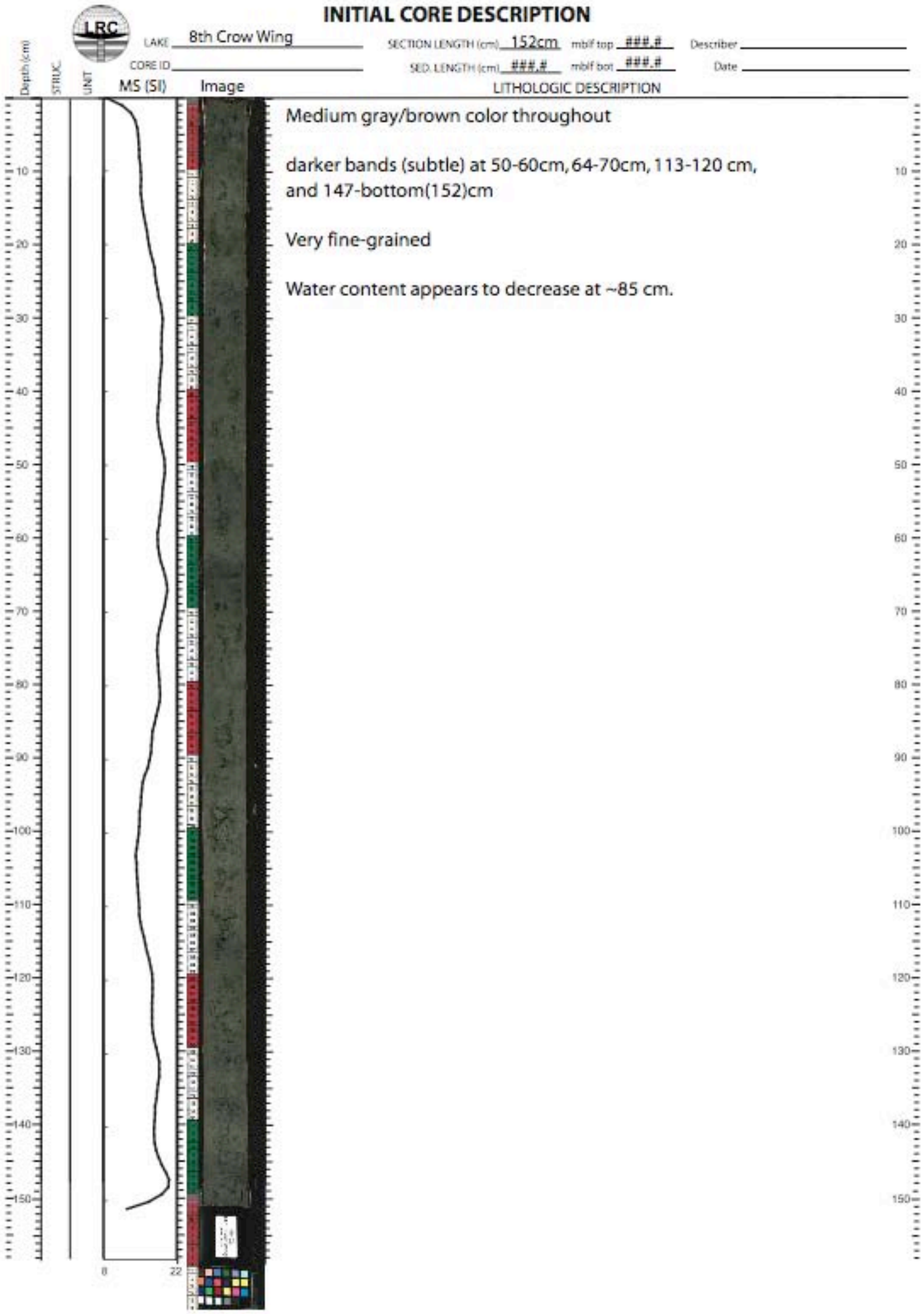

Fig. 64. Image and magnetic susceptibility of the 8th Crow Wing Lake piston core. The piston core image begins at 48 cm core depth because the top of the core was sectioned in the field.

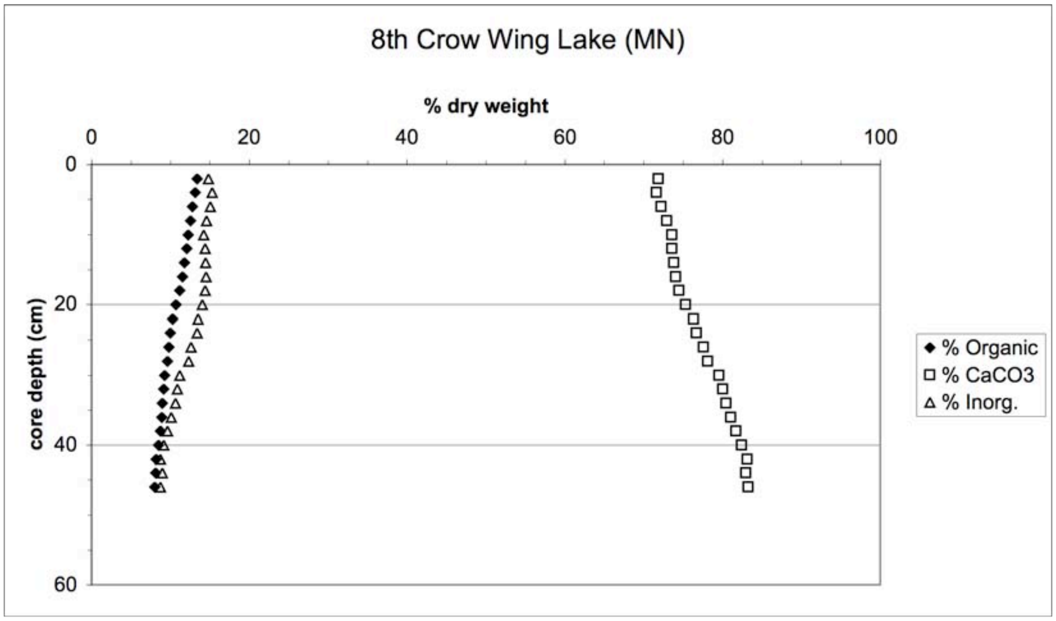

Fig. 65. Percent dry weight composition of organics, carbonates, and inorganics versus core depth (cm) based on loss on ignition analysis of 8th Crow Wing Lake sediment core.

Fig. 66. Image and magnetic susceptibility of the Decker Lake piston core. The piston core image begins at 80 cm core depth because the top of the core was sectioned in the field.

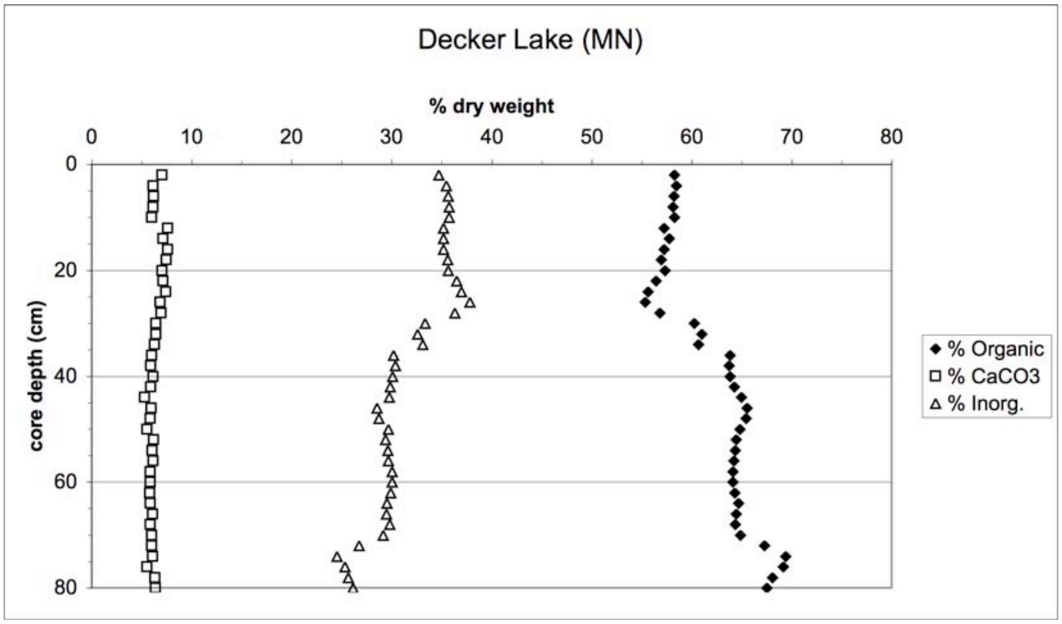

Fig. 67. Percent dry weight composition of organics, carbonates, and inorganics versus core depth (cm) based on loss on ignition analysis of Decker Lake sediment core.