DIATOM-INFERRED TP IN MCWD LAKES. PHASE II.
(Work Order #107-06)

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EXECUTIVE SUMMARY

In 2005, contemporary water quality and sediment cores were analyzed from ten lakes and bays in the Minnehaha Creek Watershed District (MCWD) to compare modern water quality to historical (pre-European settlement) water quality inferred from diatom remains in the sediment cores. Results showed that both modern water quality and historical water quality were variable across the watershed. Bays with direct connection to the main body of Lake Minnetonka were shown to have mesotrophic water quality in historical and modern times, whereas upgradient bays and lakes tended to have eutrophic to hypertrophic modern conditions and meso- to eutrophic historical water quality.

As followup to the initial project, an additional eight MCWD lakes were identified as lakes of concern by state and MCWD officials, and slated for water quality monitoring and sediment core analysis in 2007 (Phase II). The 2007 study lakes and their location (county) included: Long Lake (Hennepin), Dutch Lake (Hennepin), Schutz Lake (Carver), Virginia Lake (Carver), Auburn Lake (Carver), Piersons Lake (Carver), Minnewashta Lake (Carver), and Luntsen Lake (Carver). Parley Lake (Carver) was also resampled for more detailed sediment core analysis. Water quality monitoring took place on at least five sampling dates in 2007 and showed that annual mean total phosphorus varied widely across the watershed from mesotrophic Minnewashta, Schutz, and Piersons lakes (10-40 μg/L TP), to eutrophic Long, Dutch, Virginia, Auburn, and Luntsen lakes (40-100 μg/L TP), to hypereutrophic Parley Lake (TP > 100 μg/L). Top-bottom analysis of sediment cores collected in summer 2007 showed that diatom-inferred total phosphorus (DI-TP) concentrations in pre-European times were generally mesotrophic (Schutz, Virginia, Auburn, Minnwashta) to eutrophic (Long, Parley). Comparison of pre-European nutrient levels with modern nutrient levels (monitored and DI-TP) showed that Lake Minnewashta has remained mesotrophic, whereas Auburn, Schutz, and Virginia lakes have increased in nutrient concentrations and are now considered eutrophic. Lakes that were eutrophic in pre-European times have remained eutrophic (Long) or had become hypereutrophic (Parley Lake).

Several lakes deserve special comment. First, the current configuration of Luntsen Lake was formed in the early 1960s when the King Marsh complex was dammed. Rather than analyzing sediments from the pre-damming wetland peats, we compared DI-TP from immediate post-damming to modern times. Modern Luntsen Lake is currently macrophyte-dominated and eutrophic, which contrasts the nearly hypereutrophic condition (>90 ppb TP) immediately post-damming. Second, fifteen levels from a ^{210}Pb-dated sediment core from Parley Lake were analyzed and showed that Parley Lake has long been a eutrophic lake with highly variable nutrient levels. Damming of Luntsen Lake clearly affected sedimentation and nutrient dynamics in Parley Lake. Discrepancies between modern DI-TP and water quality monitoring in Parley Lake likely reflect problems associated with first, decoupling of algal productivity and phosphorus in shallow lakes, and second, the propensity of shallow lakes to harbor generalist diatom species that are ecologically adapted to thrive in polymictic, nutrient-rich conditions. Third, diatom preservation was an issue in two MCWD lakes. In Dutch Lake, we could not estimate pre-European DI-TP because diatoms were not preserved at depth in the core. In Piersons Lake, the downcore diatom assemblage appeared to be biased toward more heavily silicified forms, which provided two very different and potentially spurious pre-European DI-TP values.

INTRODUCTION

Federal regulations require that states identify impaired waters and develop plans to protect and remediate water quality. A critical component of developing sound management plans to improve impaired waters requires that we 1) know the modern sources of nutrients to a receiving water, and 2) have an understanding of the natural or background nutrient conditions of a lake or river. The former is normally determined through monitoring and experimental limnology, whereas the latter information is available from either modeling or paleoecology.

Paleoecology offers a unique tool to determine natural or background nutrient conditions in lakes. Lake sediments faithfully record changes that have occurred both within a lake and within its watershed. Broadscale application of sediment analysis to basic and applied research questions followed major advances in core dating in the 1970s and development of statistical tools in the 1980s and 1990s for historical and quantitative environmental reconstruction using biological proxies.

Diatoms are microscopic, single-celled or colonial algae that are characterized by an ornamented two-part siliceous (glass) cell wall. They are often referred to as the "golden-brown" algae, a testament to their pigment complement. Diatoms are seasonally common to abundant in lakes, rivers, streams, and water bodies that experience even emphemeral moisture. Because of their siliceous cell walls, diatoms are usually well preserved in lake sediments and their presence, absence, abundance and community makeup provide a snapshot of historical environmental conditions and change. Diatom calibration and training sets have become powerful tools for paleoecological reconstruction and monitoring of surface water quality using standardized methods to reconstruct specific environmental parameters from modern or fossil diatom assemblages. Whereas earlier diatom-based methods provide qualitative measures of historical water chemistry or productivity using categorical indicator values (ter Braak and van Dam 1989, Agbeti 1992), the development of weighted averaging regression and calibration introduced a method of quantitative reconstruction of historical environmental variables (Birks *et al.* 1990a,b). The method develops a transfer function based on a training set of diatom assemblages from modern lakes and their relationship to select environmental gradients that independently explain variation in species distribution. The transfer function is next applied to historical diatom assemblages in sediment cores to mathematically reconstruct specific environmental variables. The weighted averaging method is statistically robust and based on ecologically sound organismal responses (ter Braak and Prentice 1988, Birks *et al.* 1990b). This approach has been used successfully in reconstructing a wide variety of environmental parameters including pH, total phosphorus (TP), dissolved organic carbon (DOC), and salinity (e.g. Anderson 1989, Fritz *et al.*, 1991, 1999, Dixit *et al.* 1992; Hall and Smol 1992).

For inferring historical total phosphorus (TP), diatom-based reconstructions have been adopted as the most powerful tool at hand (Fritz *et al.* 1993, Anderson and Rippey 1994, Reavie *et al.* 1995, Rippey and Anderson 1996). In the Minnesota region, the most readily applied training set was initially developed by Ramstack et al. (2003) from surface-sediment diatom assemblages from 55 Minnesota lakes of varying trophic status that were earlier cored for a regional mercury study (Engstrom *et al.* 1999). The application of Ramstack's training set has targeted "top-bottom" or modern vs pre-European reconstructions of environmental parameters (Heiskary and Swain 2002, Ramstack *et al.* 2004) and other Minnesota lake sediment records for post-European environmental change (Edlund and Engstrom 2001, Kingston *et al.* 2004, Edlund and Ramstack 2006). The 55 Minnesota Lakes training set has been further supplemented with additional lakes from the west metro (MCWD; Edlund and Ramstack 2006), southwest, westcentral and northern Minnesota to increase its utility and representation of other Minnesota lake types (Edlund and Kingston 2004, Edlund 2005, Edlund and Ramstack 2006) and it has been used for the development of nutrient criteria in Minnesota lakes (Heiskary et al. 2004, Heiskary and Wilson 2008). For the Lake Minnetonka watershed, the total phosphorus (TP) criteria set by the state are 40 μg/L TP for deep lakes and 60 μg/L TP for shallow lakes (<5 m Z_{max}).

The location of the Lake Minnetonka watershed on an ecotone creates natural variability in lake type and water quality. Although the watershed falls into the north-central hardwoods forest ecoregion, lakes in the western part of the watershed are more similar to prairie lakes, lakes and bays in the northern and westcentral part of the basin are similar to lakes in the central hardwood forest region of Minnesota, and the main lake body bears resemblance to more northerly Minnesota lakes (Murchie 1985). Overlying this background and geologic variability are impacts on water quality resulting from 150 years of post-European settlement including water-level management, agriculture, diffuse and point source loadings, cottage and residential development, heavy recreational use, and exotic species introductions (Megard 1970, 1972). As such, the modern Lake Minnetonka watershed has lakes and bays ranging in water quality from hypereutrophic to nearly oligotrophic (Heiskary et al. 2006).

This study examines sediment cores from nine lakes in the Lake Minnetonka watershed to reconstruct historical or pre-European total phosphorus concentrations and compares those to modern water quality conditions in the Lake Minnetonka watershed. Additionally, the sediment core from Parley Lake was examined in greater detail to determine the timing and magnitude of historical change.

METHODS – SEDIMENT CORING

Nine upgradient lakes in the Lake Minnetonka watershed were identified by MCWD personnel for inclusion in this study (Table 1); most were deemed impaired under current nutrient criteria established for this ecoregion in Minnesota (Heiskary and Wilson 2008). The lakes range from Long Lake in the northern part of the watershed to Parley and Luntsen Lakes in the western portion of the watershed, to Piersen, Minnewashta, and Virginia in the southwest portion of the watershed. The study lakes included: Long Lake (Hennepin), Dutch Lake (Hennepin), Schutz Lake (Carver), Virginia Lake (Carver), Auburn Lake (Carver), Parley Lake (Carver), Piersons Lake (Carver), Minnewashta Lake

(Carver), and Luntsen Lake (Carver).

Piston cores and Livingston cores were collected from nine lakes near Lake Minnetonka from June 5-21, 2007. Cores were taken using a drive-rod piston corer equipped with a 2.4 m long, 7 cm diameter polycarbonate barrel (Wright 1991) or a Livingston core equipped with a stainless steel barrel. Target lakes and core recovery are provided in Table 1. Cores were transported vertically to shore, and the top 42-70 cm of unconsolidated sediment removed in 2-cm increments by vertical extrusion. The remaining core material was capped, sealed, and transported to 4°C storage.

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.

Cores were subdivided into 1.55-m long sections (typically the remaining core after field sectioning) for magnetic susceptibility logging on a Geotek Standard MSCL with an automated trackfeed. Susceptibility measures were taken at 1-cm intervals, which integrated a signal over a 5-10-cm length of core. Data were spliced at core breaks for plotting. 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.

All piston cores were logged for magnetic susceptibility, and were split, imaged, and described. Note that these analyses were performed on the intact portion of each core; therefore these data do not exist for the portions of the core that were field-sectioned. Magnetic susceptibility was plotted against downcore depth for each sediment core. Features in the magnetics profile were correlated with core descriptions and core images (see attached Appendix Figs A1-A10). Based on the magnetics and physical features, samples were selected for diatom analysis and unsupported ^{210}Pb gamma analysis.

METHODS – LEAD-210 DATING

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

In the eight remaining cores, select downcore samples were analyzed using gamma lead-210 dating to identify sediments that pre-date European settlement. Two to three downcore samples from each core were selected for quantification of unsupported ^{210}Pb using a high-resolution germanium well gamma detector and multichannel analyzer (Table 2); subsamples were freeze-dried and allowed to ingrow for 30 days before gamma analysis. The presence of any unsupported ^{210}Pb in a core subsample is an indication that the sample is dated at less than seven half-lives of ^{210}Pb, or approximately 150 years. From this analysis we determined whether downcore sediment levels were deposited before European settlement. As a further check of core dates, ^{137}Cs was also quantified in the core samples. Cesium-137 is an isotopic product of atmospheric nuclear bomb testing and its presence indicates sediments deposited after 1950.

METHODS – BIOGEOCHEMISTRY

Weighed subsamples were taken from regular intervals throughout the Parley Lake core 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).

METHODS – DIATOM AND NUMERICAL ANALYSES

Sediments were analyzed for diatom microfossils at four depths in eight of the nine cores: 0-2 cm depth, 2-4 cm depth, and two downcore depths determined to have been deposited before European settlement. These latter depths were initially selected based on magnetic susceptibility and physical properties of the core and were confirmed using ^{210}Pb gamma counting (Table 2). In Parley Lake, fifteen samples throughout the core were analyzed for diatoms (Table 3). Surface and downcore samples were prepared by placing approximately 0.25 cm^3 of homogenized sediment in a 50 cm^3 polycarbonate centrifuge tube, and adding 2-5 drops of 10% v/v HCl solution to dissolve carbonates. Organic material was subsequently oxidized by adding 10 ml of 30% hydrogen peroxide and heating for 3 hours in an 85°C water bath. After cooling, the samples were rinsed with distilled deionized water to remove oxidation biproducts. Aliquots of the remaining material, which contains the diatoms, were dried onto 22x22 mm #1 coverglasses, which were then permanently attached to microscope slides using Zrax mounting medium. Diatoms were identified along random transects to the lowest taxonomic level under 1250X magnification (full immersion optics of NA 1.4). A minimum of 400 valves was counted in each sample. Our analysis used the same enumeration criteria as Ramstack et al. (2003), i.e. diatoms were counted when over 50% of the valve was present or when a distinct valve fragment was present (e.g., central area of *Amphora libyca* or valve end in *Asterionella formosa*). Raw counts were converted to percent abundance relative to all diatom microfossils counted.

Diatoms were identified using primary literature and floras and monographs by Hustedt 1927-1966, 1930, Patrick and Reimer 1966, 1975, Collins and Kalinsky 1977, Camburn *et al.* 1978, 1984-1986, Krammer and Lange-Bertalot 1986, 1988, 1991a, b, Cumming *et al.* 1995, Reavie and Smol 1998, Camburn and Charles 2000, and Fallu et. al. 2000.

In the Parley Lake core, stratigraphies of predominant diatoms (species greater than or equal to 5% relative abundance) were plotted against core date. Relationships among diatom communities within the Parley Lake core were explored using 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 is that samples that plot closer to one another have more similar assemblages.

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

Samples from Parley Lake, as well as top/bottom samples from the other cores, were passively plotted on the 89 MN lakes diatom calibration set to see which modern MN lakes the core sections are most similar to, and to see where they plot along the environmental axes. From this it can be determined if changes in a given core through time are correlated with one or more environmental axes.

RESULTS AND DISCUSSION – CORING, MAGNETIC SUSCEPTIBILITY, CORE IMAGING, AND DATING OF TOP/BOTTOM CORES

Magnetic susceptibility profiles were examined from cores selected for top/bottom analysis (Long Lake, Dutch Lake, Schutz Lake, Virginia Lake, Auburn Lake, Piersons Lake, Minnewashta Lake, and Luntsen Lake). Increases in magnetic susceptibility may be correlated with land use changes including land clearance, increases in terrestrial-derived sediments, and paleosols, and decreases in magnetic susceptibility can result from increased autochthonous productivity, for example from lake eutrophication. In each of these cores, intervals were chosen for gamma lead-210, and cesium-137 analysis based on changes in magnetic susceptibility which may be representative of European settlement and initial land clearance.

Four sections from each of these lakes were selected for diatom analysis. In each lake the two uppermost samples (0-2 cm and 2-4 cm) were selected for analysis; the two downcore sections were determined by first selecting the uppermost core sample found with no unsupported lead-210, and then selecting a second sample taken from sediments deposited approximately 50 years earlier. The estimate of downcore sedimentation rates followed the same method used in a previous report on lakes in the MCWD (Edlund and Ramstack, 2006). Mean linear and bulk sedimentation rates calculated from the Northern Great Plains and Western Corn Belt Plains lakes in the Ramstack et al. (2003) lake set were used to calculate a pre-1850 southwest MN linear sedimentation rate (2.17 +/- 0.32 mm/yr), which guided our downcore sampling. Without detailed analysis on each core, we can only be certain that the two presettlement samples are dated from greater than 150 years before present and were deposited approximately 50 years apart; we cannot assign a specific calendar date to those samples based on gamma analysis and magnetic susceptibility logging.

Long Lake: A 1.95 m piston core was recovered from Long Lake and 50 cm were extruded from the top of the core in the field (Table 1). An overlapping Livingston core was also collected from the lake, representing a maximum sediment depth of 2.66 m. There are two distinct changes in magnetic susceptibility in the Long Lake cores, one is a high spike in magnetics in the Livingston core (Figure 1), beginning at approximately 250 cm and increasing until about 228 cm. There is a distinct decrease in magnetics in the piston core, beginning at about 98 cm and continuing through to 84 cm (Appendix A1).

Based on the lead-210 and cesium-137 results from Long Lake (Table 2), sediments from 140 and 145 cm depth were selected for diatom analysis (Table 3).

Dutch Lake: A 1.93 m piston core was recovered from Dutch Lake and 42 cm were extruded from the top of the core in the field (Table 1). There is a gradual color change in the Dutch Lake core, with dark sediments below 82 cm and sediments becoming gradually lighter above this interval (Appendix A2). There is a slow rise in magnetic susceptibility in this core, beginning at approximately 140 cm and rising through 94 cm (Appendix A2).

In Dutch Lake, sediments from 142, 147, 182, and 187 cm depths were examined for diatom analysis (Table 3), based on the results of the lead-210 and cesium-137 dating (Table 2). As noted later, diatoms were not preserved in the deeper sediments of Dutch Lake thus preventing diatom analysis on all but the near surface sediments of this core.

Schutz Lake: A 1.90 m piston core was recovered from Schutz Lake, with the top 50 cm of the core extruded in the field (Table 1). There is a rise in magnetics, beginning at approximately 160 cm and continuing upcore until about 140 cm; this rise coincides with a color change in the sediments, with darker sediments below 154 cm and lighter sediments above (Appendix A3). There is a rise in magnetics in this core beginning at approximately 100 cm through 90 cm.

Based on the lead-210 and cesium-137 results from the Schutz core (Table 2), downcore samples from 120 and 125 cm were chosen for diatom analysis (Table 3).

Virginia Lake: A 1.97 m piston core was recovered from Virginia Lake and 46 cm were extruded from the top of the core in the field (Table 1). The magnetic susceptibility profile from this core shows a rise in magnetics beginning at approximately 120 cm (Appendix A4).

In Virginia Lake, sediments from 131 and 136 cm depth were selected for diatom analysis (Table 3) based on the results of the lead-210 and cesium-137 analyses (Table 2).

Auburn Lake: A 1.90 m piston core was recovered from Auburn Lake, with the top 42 cm of the core extruded in the field (Table 1). There is a rise in magnetics that begins at the bottom of the piston core, and a gradual decrease farther upcore (from approximately 160 cm to 120 cm) (Appendix A5).

Based on the lead-210 and cesium-137 results from the Auburn Lake core (Table 2), sediments from 132 and 137 cm were selected for diatom analysis (Table 3).

Piersons Lake: A 1.94 m piston core was recovered from Piersons Lake, with 52 cm extruded from the top of the core in the field (Table 1). There is a very gradual increase in magnetic susceptibility in this core from approximately160 cm to 95 cm, followed by a more marked decrease from approximately 90 cm to 82 cm (Appendix A6).

Sediments from 127 and 132 cm were chosen for diatom analysis (Table 3) based on the results of the lead-210 and cesium-137 analyses (Table 2).

Minnewashta Lake: A 2.09 m piston core was recovered from Minnewashta Lake, with 68 cm extruded from the top of the core in the field (Table 1). The core from this lake has numerous color changes and many gradual changes in magnetic susceptibility; the most notable change in magnetics is a decrease beginning at approximately 90 cm (Appendix A7).

Based on the lead-210 and cesium-137 results from Minnewashta Lake (Table 2), sediments from 203 and 208 cm were chosen for diatom analysis (Table 3).

Luntsen Lake: A 1.74 m piston core was recovered from Luntsen Lake and 70 cm were extruded off the top of the core in the field (Table 1). An overlapping Livingston core was also collected from this lake, representing a maximum sediment depth of 2.52 m. Beginning at approximately 30 cm core depth, and throughout the remaining length of the piston core, the sediments from Luntsen Lake are primarily composed of a fibrous plant material, and there are no distinct changes in magnetic susceptibility (Appendix A8). Based on historical aerial photos and information provided by Larry Gillette (LGillette@threeriversparkdistrict.org; email dated 21 March 2008) it was determined that Luntsen Lake had previously been primarily a wetland area and was dammed in the early 1960s (see also Appendix A10).

> From Larry Gillette, 21 March 2008:
>
> "Lunsten Lake was a small lake in what is now the southwest bay of the King Marsh. The entire north bay, leading up to the dike, was a sedge meadow with a stream flowing through it. The dike was built by a land development company before the property was acquired by the Park District. I don't know for sure, but I would guess it was in the early to mid 1960s. It was intended to be a recreational lake. The original control structure was (and still is) in the middle of the dike. The Park District decided to manage newly created lake as a deep marsh instead, but the original control structure was a fixed weir. The Park District installed a new stop-log control structure in the north end of the dike around 1980.
>
> In answer to the question, the north bay has been flooded since about 1965. However, I would caution Mark from jumping to the conclusion that the fibrous peat mat he encountered was the sedge mat that was growing there prior to 1960. Much of that mat floated as the water in the lake increased, and the mats were either deposited along the shore or disintegrated and sank back to the bottom."

Because the lower part of the Luntsen core clearly did not represent lacustrine sedimentation and because management options do not include removal of the water control structure, our analyses targeted only the lacustrine sedimentation in the top 30 cm of core. We focused on sediments from 24 and 28 cm for downcore diatom analysis in Luntsen Lake (Table 3); these depths represent conditions present in Luntsen Lake soon after damming in the early 1960s. The presence of cesium-137 in these core sections corroborates that the sediments in these intervals were deposited after 1950.

RESULTS AND DISCUSSION – CORING, MAGNETIC SUSCEPTIBILITY, CORE IMAGING, BIOGEOCHEMISTRY, SEDIMENTATION, AND DATING OF PARLEY LAKE

A 1.94 m piston core was collected from Parley Lake, with 46 cm extruded off the top of the core in the field (Table 1). There are some subtle decreases in the magnetic susceptibility profile from this core, one beginning at approximately 120 cm and another at approximately 100 cm depth (Appendix A9). There is also a gradual decline in magnetics beginning at approximately 75 cm.

From 75 cm through the bottom of the core, the sediments of Parley Lake are composed of approximately 70 percent inorganic material (Figure 2). There is a large shift in the sediment composition at about 75 cm, with the relative amount of organic material decreasing toward the core top (down to 53 percent at the core top) and the relative amount of carbonate increasing from 12 percent to 28 percent. This increase in the relative amount of carbonate coincides with the decrease in magnetic susceptibility beginning at 75 cm; both suggest an increase in productivity of the system beginning at this time.

The unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for Parley Lake are shown in Figure 3. Lead-210 activity reached supported levels by 132 cm depth. There are some increases in the sediment accumulation rate, first in the early to mid-1900s, and again in the most recent 10-15 years. The peak in sedimentation rate in 1944 (72 cm) coincides with the decrease in magnetic susceptibility and increase in the relative amount of carbonate in the system. In many Minnesota lakes, increases in lake productivity are common following WWII. 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).

RESULTS AND DISCUSSION – TOTAL PHOSPHORUS RECONSTRUCTIONS

The logTP transfer function was applied to downcore diatom assemblages in each sediment core to calculate diatom-inferred total phosphorus (DI-TP; Table 5). For the eight “top/bottom” cores, two samples representing sediments deposited before regional European settlement (or post-damming in Luntsen Lake) provide a measure of baseline or natural nutrient conditions in these lakes. The two core-top samples from these lakes (0-2 cm and 2-4 cm) represent modern conditions, and the difference between them gives an idea of modern variability in the system. Presettlement conditions can be compared to the average DI-TP from the modern samples, and to monitoring records collected by MCWD in 2007 (Table 4) to estimate the amount of change since European settlement (Figure 4). In Parley Lake, 15 core intervals were analyzed for diatoms to obtain a more complete picture of how this lake has changed over the past 200 years.

Long Lake: This lake is currently eutrophic, with an average measured TP value of 74 µg/L (Table 4), and a DI-TP core-top value of 45 µg/L (Fig. 4). The pre-European DI-TP is estimated to be 89 µg/L (Fig. 4). The diatom species in the core-top intervals from this lake (*Aulacoseira* species, *Stephanodiscus* species (especially small forms), *Fragilaria crotonensis*, and *Asterionella formosa*) are indicators of eutrophic conditions, even though some of the species have slightly lower TP optima in the diatom calibration set. Pre-European sediments preserve a similar diatom assemblage as the top of the core except for notably lower abundances of *Fragilaria crotonensis* and *Asterionella formosa* downcore. The diatom results from this core suggest that this system has always been productive, even prior to European settlement.

Dutch Lake: Dutch Lake is currently eutrophic; average modern measured TP values are 59 µg/L (Table 4) and the modern DI-TP is 52 µg/L (Fig. 4). The modern diatom communties are dominated by typical indicators of eutrophy including small *Stephanodiscus* species (*hantzschii*, *parvus*, *minutulus*, *medius*) and fragilarioid species such as *Fragilaria capucina* v. *mesolepta*, *F. vaucheriae*, and *Pseudostaurosira brevistriata*). Unfortunately, diatoms were poorly preserved downcore; therefore, it was not possible to infer pre-European TP. Although the preservation of diatoms is usually assured in sediment cores, certain regions and lake types do not preserve diatoms well. Saline lakes, lakes with high pH, and high carbonate lakes can often have loss of diatoms in their sediments due to dissolution. Diamond Lake in northwestern Hennepin County similarly did not preserve diatoms downcore (Edlund, unpublished).

Schutz Lake: The modern measured TP (36 µg/L; Table 4)) and the modern DI-TP (42 µg/L; Fig. 4) both classify Schutz Lake as presently a eutrophic system. The downcore reconstructed TP value of 22 µg/L puts Schutz Lake in the mesotrophic category (Fig. 4), suggesting that this lake has undergone a shift to a higher trophic status since European settlement. Although historical diatom communities (dominated by *Fragilaria crotonensis*, *Asterionella formosa*, *Stephanodiscus parvus*, and *S. minutulus*) bear similarity to the modern diatom communities in Schutz Lake, modern sediments have greater abundance of *Stephanodiscus parvus*, *S. niagarae*, and *Pseudostaurosira brevistriata* v. *inflata*.

Virginia Lake: The pre-European (40 µg/L) and modern (44 µg/L) DI-TP values in Virginia Lake suggest that there has been little change in the trophic state of this lake since settlement (Fig. 4). The modern measured TP (60 µg/L; Table 4) is slightly higher than the DI-TP at the core top; however, the two core-top sections show some variability in modern DI-TP (51 µg/L at 0-2 cm and 37 µg/L at 2-4 cm). Overall, the results suggest that there has been little change in the productivity and eutrophic status of Virginia Lake since settlement. Modern diatom communities in Virginia Lake are dominated by *Stephanodiscus parvus*, *S. niagarae*, *S. minutulus*, *Asterionella formosa*, *Fragilaria capucina* v. *mesolepta* and *Cyclotella ocellata*. In contrast, pre-European assemblages are dominated by *Aulacoseira* species (*ambigua*, *granulata*) and benthic and attached species. This large shift in diatom communities indicates that there has been some ecological change in Virginia Lake, most likely related to habitat availability.

Auburn Lake: The results of Auburn Lake are similar to Schutz Lake, in that the modern measured TP (53 µg/L; Table 4) and modern DI-TP (41 µg/L; Fig. 4) put the lake in the eutrophic category. Downcore reconstructed TP values (26 µg/L) suggest that the lake was a more mesotrophic system (Fig. 4) and that Auburn Lake has increased in trophic status since the time of European settlement. There are strong differences between the modern and pre-European diatom communites that support this trophic shift. Pre-European planktonic diatoms are characterized by *Asterionella formosa*, *Fragilaria* *capucina*, *F. crotonensis*, *F. vaucheriae*, *Tabellaria flocculosa*, *Cyclotella radiosa*, and *Aulacoseira ambigua*. In the modern sediments, the prominence of the small *Stephanodiscus* species (*parvus*, *minutulus*, *medius*) reflects the increased trophic status of Auburn Lake.

Piersons Lake: Measured (31 µg/L) and modern DI-TP (34 µg/L) results are in close agreement in Piersons Lake (Table 4, Fig. 4), but pre-European DI-TP averages much higher (62 µg/L; Fig. 4). Two things raise concern with these downcore reconstructions. First, diatom valves were not well preserved in the downcore samples from Piersons Lake (resulting in less than 400 valves being identified), which may have biased the pre-European TP reconstructions. The valves that were preserved in these downcore sections were those that were heavily silicified; many of these diatoms have high TP optima in the calibration set. If lightly silicified diatoms with lower TP optima were lost due to dissolution, it would lead to a high downcore TP reconstruction that may not be an accurate reflection of pre-European conditions. Second, there is great variability between the two pre-European samples in terms of diatom communities and inferred phosphorus values. At 127 cm depth, the TP reconstruction is 44 µg/L and the diatom community is dominated by *Staurosirella pinnata*, *Aulacoseira ambigua*, *Pseudostaurosira brevistriata*, *Synedra ulna*, *Gomphonema parvulum*, *Tabellaria flocculosa*, and *Fragilaria vaucheriae*, i.e., a healthy mix of planktonic and attached species that are indicators of mesotrophic conditions. However, at 132 cm depth, the TP reconstructs at 91 µg/L and the diatom community is dominated by *Aulacoseira ambigua*, *A. granulata*, *Cyclotella radiosa*, *Asterionella formosa*, *Fragilaria capucina*, *Stephanodiscus parvus*, and *Gomphonema pumilum*, i.e., a flora that does have some eutrophic indicators. Given these conditions, we are reluctant to draw hard conclusions on the pre-European condition of Piersons Lake. Other lakes in this southwestern region of the drainage were shown to have meso- to eutrophic pre-European conditions (Schutz, Wasserman, Virginia).

Minnewashta Lake: Diatom-inferred TP values from the core top (32 µg/L) and bottom (30 µg/L) are in close agreement, suggesting that there has been little change in the trophic status of this system since the time of European settlement (Fig. 4). Measured TP in this system (21 µg/L; Table 4) is in the same range as modern DI values. Diatom communities in the modern sediments are dominated by planktonic forms including *Asterionella formosa*, *Fragilaria crotonensis*, *F. vaucheriae*, *F. capucina* v. *mesolepta*, and *Stephanodiscus niagarae*, whereas the pre-European diatom assemblage has a greater proportion of benthic and attached diatoms (*Gomphonema* spp and *Amphora* spp) and a planktonic flora dominated by *Asterionella formosa*, *F. crotonensis*, and *Tabellaria flocculosa*.

Luntsen Lake: Luntsen Lake is currently a macrophyte-dominated eutrophic system; measured TP (56 µg/L; Table 4) and modern DI-TP (50 µg/L; Fig. 4) results are in close agreement. Downcore results from this lake do not reflect pre-European times, but reflect sediments that deposited more recently, when the lake was formed by damming in the early 1960s of what had previously been a wetland area (Appendix A10). The DI-TP results from these downcore samples suggest that the lake was very productive at the time of formation (96 µg/L TP), and although it remains a productive system today, modern TP values are significantly lower than at reservoir formation. Hall et al. (1999) compared the ontogenetic history of two reservoir types—river valley impoundment and lake inundation—and showed the initial responses of the two reservoirs differed. River valley inundation resulted in an initial period of eutrophication, similar to what appears to have happened in Luntsen Lake, whereas lake inundation resulted in a decrease in productivity. The modern diatom community is dominated by attached forms (*Cocconeis placentula* vars., *Navicula* spp., *Gomphonema* spp, *Amphora* spp.) and the planktonic species *Stephanodiscus parvus* and *Fragilaria capucina* v. *mesolepta*. The immediate post-damming community notably had a planktonic flora that included *Aulacoseira ambigua*, *A. granulata*, and *Cyclotella meneghiniana* in addition to *S. parvus*, which are indicative of higher TP concentrations.

Parley Lake: A top-bottom analysis of Parley Lake that was completed in the first phase of this project (Edlund and Ramstack 2006) produced two confounding results. First, results suggested that Parley lake was much more productive in pre-European times compared to modern times, and second, modern diatom-inferred TP values significantly underestimated modern water quality measurements. A more detailed analysis of a Parley Lake sediment core was undertaken to try and determine the timing and magnitude of historical ecological changes in the lake. The full core TP reconstruction from Parley Lake confirmed our earlier results and indicates that this lake has been eutrophic, with highly variable TP levels, over the past two hundred years (Fig. 5; Table 6). One of the notable changes in this profile is a gradual decline in DI-TP levels from 1960 to the present, coincident with the dam being built between Parley Lake and Luntsen Lake in the early 1960s. Our results indicate that the damming of the Luntsen Lake system impacted Parley Lake, likely reducing some of the nutrient and sediment input to Parley Lake. However, the modern measured TP value (annual mean) in Parley Lake is 119 µg/L (Table 4), which differs from the diatom inferred value of 40 µg/L at the core top. This discrepancy was also noted in our earlier top-bottom analysis of Parley Lake (Edlund and Ramstack 2006) and is likely due to a change that occurred in Parley after damming. It's possible that the diatom community responded to some other change in the lake instead of nutrient levels (for example, changes in habitat availability or possibly chloride increases, see below). Lastly, diatom-inferred TP reconstruction in shallow lakes (in Minnesota, defined as Zmax < 15 ft or > 80% littoral zone) present special challenges. One of the problems is that in shallow lakes, such as Parley, there is often a decoupling of nutrient levels with variables that are normally correlated such as chlorophyll a and Secchi depth (Heiskary and Lindon 2005). Therefore, a given TP concentration may support a large range of chlorophyll a levels. Similarly, the relationship between TP and diatoms is not as strong in shallow lakes, which makes diatom-based TP reconstructions less reliable. In addition, we find that some shallow lakes are dominated by generalist species; these species are adapted to living in wind-swept shallow systems, so the species turnover in these lakes is less dependent on nutrient levels.

RESULTS AND DISCUSSION – DIATOM STRATIGRAPHY AND ORDINATIONS

Top/bottom cores: Passively plotting the core top and bottom sections on the 89 MN lakes diatom calibration set shows which Minnesota lakes the core sections are most similar to, and if changes through time are correlated with one or more environmental axes. Figure 6 shows the predominant direction of change from the bottommost core sample to the core top (0-2 cm). In pre-settlement times, many of these lakes had diatom communities similar to lakes in the Central Hardwood Forests ecoregion and in modern times the diatom communities are more similar to lakes currently found in the Twin Cities Metro region. The overall trajectory of change in these cores is more strongly correlated with Axis 2 (represented by pH, Cl, and Color) than Axis 1 (TP and Conductivity; Fig. 6). This suggests that TP may not be the primary driver of change in diatom communities in these lakes. Rather the trajectory toward lakes in the Metro region may indicate that chloride (Cl), as a proxy for road salt, may have driven at least some of the recent ecological changes in the MCWD lakes. Ramstack et al. (2003) showed that diatom-inferred chloride concentration had generally increased in Metro lakes since 1970 and Stefan et al. (2008) showed that chloride levels in streams and rivers in the Twin Cities Metro area are also increasing due to road salt.

Parley Lake: A correspondence analysis (CA) was used to identify stratigraphic zones in the Parley Lake core. The pre-European settlement samples (1785-1845; Zone 1) are grouped together (Fig. 7); these samples are similar to each other based on their diatom species assemblage. The diatom community assemblage shifts in the late 1800s and shows a high amount of variability through the next hundred years (1873-1985; Zone 2). The most recent samples represent a new stratigraphic zone in the core with the samples from 1995-2007 (Zone 3) clustering together. Examination of the downcore stratigraphies (Fig. 8) shows why there is great variability in diatom-inferred phosphorus; abundance profiles show the dominant diatom taxa are highly variable. The older Zone 1 sediments are dominated by *Aulacoseira ambigua* and *A. granulata* and moderate abundances of *Stephanodiscus niagarae* and *S. parvus*. Zone 2 (1873-1985) sediments are sporadically dominated by the *Aulacoseira* species, have higher abundances of *Stephanodiscus* species including *S. minutulus*, *S. hantzschii* and *S. medius*, and increased abundance of *Fragilaria vaucheriae*. The most recent sediments (Zone 3, 1995-2007) show an increased abundance of *Asterionella formosa*, *Fragilaria capucina* v. *mesolepta*, and *Pseudostaurosira brevistriata*, continued abundance of the *Stephanodiscus* flora, but decreased abundance of the *Aulacoseira* species. The upcore increases in *Asterionella* and decrease in the dominant *Aulacoseira* flora are what have driven the diatom TP inference down. When Parley Lake diatom assemblages are passively plotted on the ordination of the 89 Minnesota Lakes calibration set (Fig. 9), the overall core trajectory is similar to other MCWD lakes, and strongly directed along Axis 2 (most strongly correlated with chloride), rather than along a nutrient gradient.

CONCLUSIONS

Sediment cores and modern water quality monitoring from 18 lakes in the MCWD have been used to develop a comprehensive picture of variability in modern and pre-European water quality across this large watershed (Fig. 10). These data are valuable for establishing nutrient reduction targets, prioritizing water bodies for remediation, and supporting site-specific standards. Water quality measures indicate that modern nutrient values are highly variable across the watershed, from the mesotrophic (10-40 µg/L TP) Lake Minnetonka bays (St. Albans, Carsons, Spring Park) and lakes in the southern watershed (Schutz, Piersons, and Minnewashta), to eutrophic (40-100 µg/L TP) lakes throughout the watershed (Gleason, Halsteads, Jennings, Stubbs, Wassermann, Long, Dutch, Virginia, Auburn, and Luntsen), to the hypereutrophic (>100 µg/L) Parley and Langdon lakes. Top-bottom analysis of diatom remains in sediment cores was used to estimate nutrient condition (diatom-inferred total phosphorus or DI-TP) of the MCWD lakes in pre-European settlement times and to compare those values to modern DI-TP and water quality monitoring. Ten water bodies were shown to have been mesotrophic in pre-European times (Spring Park, Carsons, St. Albans, Gleason, Stubbs, Langdon, Minnwashta, Schutz, Virginia, and Auburn). Of those lakes, only four remain mesotrophic (Minnewashta, Spring Park, Carsons, St. Albans) whereas Gleason, Schutz, Virginia, and Stubbs lakes have become eutrophic and Langdon Lake has become hypereutrophic. Many lakes in the watershed were eutrophic in pre-European times (e.g. Long, Jennings, Halsteds, Parley, and Wassermann). For most of the eutrophic lakes, measured total phosphorus and modern DI-TP indicate these lakes are still eutrophic systems; however, most show some increase in nutrient values between pre-European and modern times.

Several lakes deserve additional comment. The current configuration of Luntsen Lake was formed in the early 1960s when the King Marsh complex was dammed. Rather than analyzing sediments from the wetland peats, we compared DI-TP from immediate post-damming to modern times. Modern Luntsen Lake is currently macrophyte-dominated and eutrophic, which contrasts the nearly hypereutrophic condition (>90 ppb TP) immediately post-damming. Fifteen levels from a ^{210}Pb-dated sediment core from Parley Lake were analyzed and showed that Parley Lake has long been a eutrophic lake with highly variable nutrient levels. Damming of Luntsen Lake clearly affected sedimentation and nutrient dynamics in Parley Lake. Discrepancies between modern DI-TP and water quality monitoring in Parley Lake likely reflect problems associated with first, decoupling of algal productivity and phosphorus in shallow lakes, and second, the propensity of shallow lakes to harbor generalist diatom species that are ecologically adapted to thrive in polymictic, nutrient-rich conditions. Finally, diatom preservation was an issue in two MCWD lakes. In Dutch Lake, we could not estimate pre-European DI-TP because diatoms were not preserved at depth in the core. In Piersons Lake, the downcore diatom assemblage seemed biased toward more heavily silicified forms, which provided two very different pre-European DI-TP values.

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

Lake	Lat (N)	Long (W)	County	Z (m)	Core length (m)	Field sectioned (cm)
Long Lake	44°59′13.0″	93°33′38.9″	Hennepin	9.75	1.95	0-50
Long Lake Liv-1	44°59′13.0″	93°33′38.9″	Hennepin	9.75	1.00	whole
Dutch Lake	44°56′40.4″	93°40′30.6″	Hennepin	9.78	1.93	0-42
Schutz Lake	44°52′35.4″	93°38′46.9″	Carver	14.5	1.90	0-50
Virginia Lake	44°53′7.8″	93°38′0.8″	Carver	6.4	1.97	0-46
Auburn Lake	44°52′4.6″	93°41′36.5″	Carver	23.8	1.90	0-42
Parley	44°52.822′	93°43.658′	Carver	5.7	1.94	0-46
Piersons	44°50′3.9″	93°41′46.1″	Carver	12.05	1.94	0-52
Minnewashta	44°52′14.8″	93°36′49.8″	Carver	15.58	2.09	0-68
Luntsen	44°52′25.0″	93°42′46.5″	Carver	2.13	1.74	0-70
Luntsen Liv-1	44°52′25.0″	93°42′46.5″	Carver	2.13	1.02	whole

Table 2. Unsupported and excess lead-210, and cesium-137, quantified from select core depths.

Lake Name	County	Core depths (cm)	Excess lead-210 (by difference with lead-214) (pCi/g)	Cs-137 corrected (pCi/g)
Long	Hennepin	105	3.47	2.21
		140	BDL	0
		252	0.88	0
Dutch	Hennepin	142	BDL	0
		182	BDL	0
Schutz	Carver	120	0.06	0
		170	BDL	0
Virginia	Carver	131	0.74	0
		181	0.3	0
Auburn	Carver	132	BDL	0
		187	BDL	0
Pierson	Carver	127	BDL	0
		162	0.7	0
		192	0.71	0
Minnewashta	Carver	118	2.56	0
		178	0.49	0
		203	0.151	0
Luntsen	Carver	28	--	0.94
		34	--	0.3

BDL = below detection limit

Table 3. Pre-European core intervals selected for diatom analysis.

Lake Name	County	Diatom sample depths (cm)	Unsupported 210-Pb depths (cm)
Long	Hennepin	140, 145	140, 252
Dutch	Hennepin	142, 147, 182, 187*	142, 182
Schutz	Carver	120, 125	120, 170
Virginia	Carver	131, 136	131, 181
Auburn	Carver	132, 137	132, 187
Parley	Carver	15 samples determined by alpha 210Pb dating	alpha 210Pb dated
Pierson	Carver	127, 132	127, 162, 192
Minnewashta	Carver	203, 208	203
Luntsen	Carver	24, 28	--

* Downcore samples from Dutch Lake did not have preserved diatom remains. This happens in lakes with high pH, high carbonate levels, or with silica-poor ground water. These pre-European samples were examined for diatoms and did not contain any siliceous remains.

Table 4. Results of water quality monitoring by MCWD in 2007. Data provided by Jason Carlson, MCWD. Summary measures include: TSIS-Trophic State Index Secchi, TSIP-Trophic State Index Phosphorus, TSIC-Trophic State index Chlorophyll, WQG-Water Quality Grade.

Lake	Avg. Secchi (m)	Avg. TP (ug/L)	Avg. Chla (ug/L)	TSIS	TSIP	TSIC	TSI	WQG
Long	0.77	74.29	42.11	64	66	67	66	C-
Dutch	0.86	59.25	33.65	62	63	65	63	C
Schutz	1.73	35.63	17.67	52	56	59	56	C+
Virginia	1.36	59.63	37.48	56	63	66	62	C
East Auburn	0.88	52.67	33.27	62	61	65	63	C
Parley	0.41	119.00	119.20	73	73	77	74	D-
Pierson	2.37	30.43	6.03	48	53	48	50	B+
Minnewashta	1.90	20.75	7.80	51	48	51	50	B+
Luntsen	1.1	55.5	11.9	60	59	51	55	C

Table 5a. Diatom-inferred total phosphorus (DI-TP) reconstructions from sediment core samples (number following lake name is core depth in cm). The uppermost core samples represent modern lake conditions (ca. 2002-2007 AD); the two deepest samples from each core represent sediments deposited before regional European settlement. The 2007 mean observed epilimnetic TP is listed for all nine sites. The dissimilarity coefficient (DC) is calculated as the chord distance between a fossil sample and its nearest modern analog among the 89 lakes in the logTP calibration set. A minimum dissimilarity coefficient (DC) score of less than 5.55 (the first percentile of distance distributions among the modern samples), 7.15 (the fifth percentile), and 8.15 (the tenth percentile) identified a fossil sample with a very good (VG), good (G), or fair (F) modern analogue, respectively.

Site	Site/core depth	2007 observed mean TP	DI-logTP	DI-TP	DC	Modern Analogue
	cm	µg/L		µg/L		
Auburn	Auburn 0-2	53	1.64	43.30	6.18	G
	Auburn 2-4		1.59	38.67	5.42	VG
	Auburn 132		1.52	32.89	6.67	G
	Auburn 137		1.32	21.13	5.07	VG
	Auburn top avg		1.61	40.92		
	Auburn base avg		1.42	26.36		
Minnewashta	Minnewashta 0-2	21	1.49	30.82	6.71	G
	Minnewashta 2-4		1.53	33.73	6.95	G
	Minnewashta 203		1.33	21.57	6.24	G
	Minnewashta 208		1.61	41.05	8.69	F
	Minne top avg		1.51	32.24		
	Minne base avg		1.47	29.76		
Schutz	Schutz 0-2	36	1.68	47.83	5.88	G
	Schutz 2-4		1.57	37.07	6.82	G
	Schutz 120		1.37	23.46	6.36	G
	Schutz 125		1.30	20.15	5.83	G
	Schutz top avg		1.62	42.11		
	Schutz base avg		1.34	21.75		
Virginia	Virginia 0-2	60	1.71	51.27	7.16	G
	Virginia 2-4		1.57	37.10	8.07	F
	Virginia 131		1.69	49.51	7.44	F
	Virginia 136		1.51	32.13	7.64	F
	Viginia top avg		1.64	43.61		
	Virginia base avg		1.60	39.88		
Dutch	Dutch 0-2	59	1.71	51.74	7.48	F
	Dutch 2-4		1.72	52.32	7.56	F
	Dutch top avg		1.72	52.03		

Table 5b. Diatom-inferred total phosphorus (DI-TP) reconstructions from sediment core samples (number following lake name is core depth in cm). The uppermost core samples represent modern lake conditions (ca. 2002-2007 AD); the two deepest samples from each core represent sediments deposited before regional European settlement. The 2007 mean observed epilimnetic TP is listed for all nine sites. The dissimilarity coefficient (DC) is calculated as the chord distance between a fossil sample and its nearest modern analog among the 89 lakes in the logTP calibration set. A minimum dissimilarity coefficient (DC) score of less than 5.55 (the first percentile of distance distributions among the modern samples), 7.15 (the fifth percentile), and 8.15 (the tenth percentile) identified a fossil sample with a very good (VG), good (G), or fair (F) modern analogue, respectively.

Site	Site/core depth	2007 observed mean TP	DI-logTP	DI-TP	DC	Modern Analogue
	cm	µg/L		µg/L		
Long	Long 0-2	74	1.70	50.56	6.39	G
	Long 2-4		1.61	40.66	6.06	G
	Long140		2.02	103.90	6.8	G
	Long145		1.89	76.89	7.3	F
	Long top avg		1.66	45.34		
	Long base avg		1.95	89.38		
Luntsen	Lunt 0-2	56	1.69	49.32	8.77	F
	Lunt 2-4		1.71	51.51	8.33	F
	Lunt 24		1.98	96.21	8.4	F
	Lunt 28		1.99	96.64	8.31	F
	Luntsen top avg		1.70	50.40		
	Luntsen base avg		1.98	96.42		
Pierson	Piersons 0-2	30	1.58	37.91	5.53	VG
	Piersons 2-4		1.47	29.83	6.42	G
	Piersons 127		1.62	41.69	8.1	F
	Piersons 132		1.96	91.45	6.07	G
	Piersons top avg		1.53	33.62		
	Piersons base avg		1.79	61.75		

Table 6. Diatom-inferred total phosphorus (DI-TP) reconstructions from Parley Lake sediment core samples (number following lake name is core depth in cm). Core dates represent 210Pb calculated dates (A.D.). The dissimilarity coefficient (DC) is calculated as the chord distance between a fossil sample and its nearest modern analog among the 89 lakes in the logTP calibration set. A minimum dissimilarity coefficient (DC) score of less than 5.55 (the first percentile of distance distributions among the modern samples), 7.15 (the fifth percentile), and 8.15 (the tenth percentile) identified a fossil sample with a very good (VG), good (G), or fair (F) modern analogue, respectively.

Site/core depth	**210-Pb date**	**DI-logTP**	**DI-TP**	**DC**	**Modern Analogue**
cm	(A.D.)		μg/L		
Parley0-2	2007	1.60	39.9	7.89	F
Parley14-16	2000	1.71	50.8	7.90	F
Parley20-22	1995	1.64	44.1	7.83	F
Parley30-32	1985	1.73	54.2	7.91	F
Parley40-42	1974	1.79	62.3	8.00	F
Parley50-52	1963	1.89	76.7	7.94	F
Parley60-62	1951	2.12	131.3	8.07	F
Parley70-72	1941	1.76	57.9	8.10	F
Parley80-82	1930	2.00	100.7	8.00	F
Parley90-92	1914	2.16	143.6	8.04	F
Parley98-100	1900	2.02	105.4	8.00	F
Parley110-112	1873	1.90	79.0	8.00	F
Parley120-122	1845	1.88	76.6	7.86	F
Parley130-132	1815	1.87	74.3	7.83	F
Parley140-142	1785	2.04	108.9	7.94	F

Figure 1. Magnetic susceptibility (SI) profile from the Livingston core from Long Lake; the y-axis represents depth in the sediment.

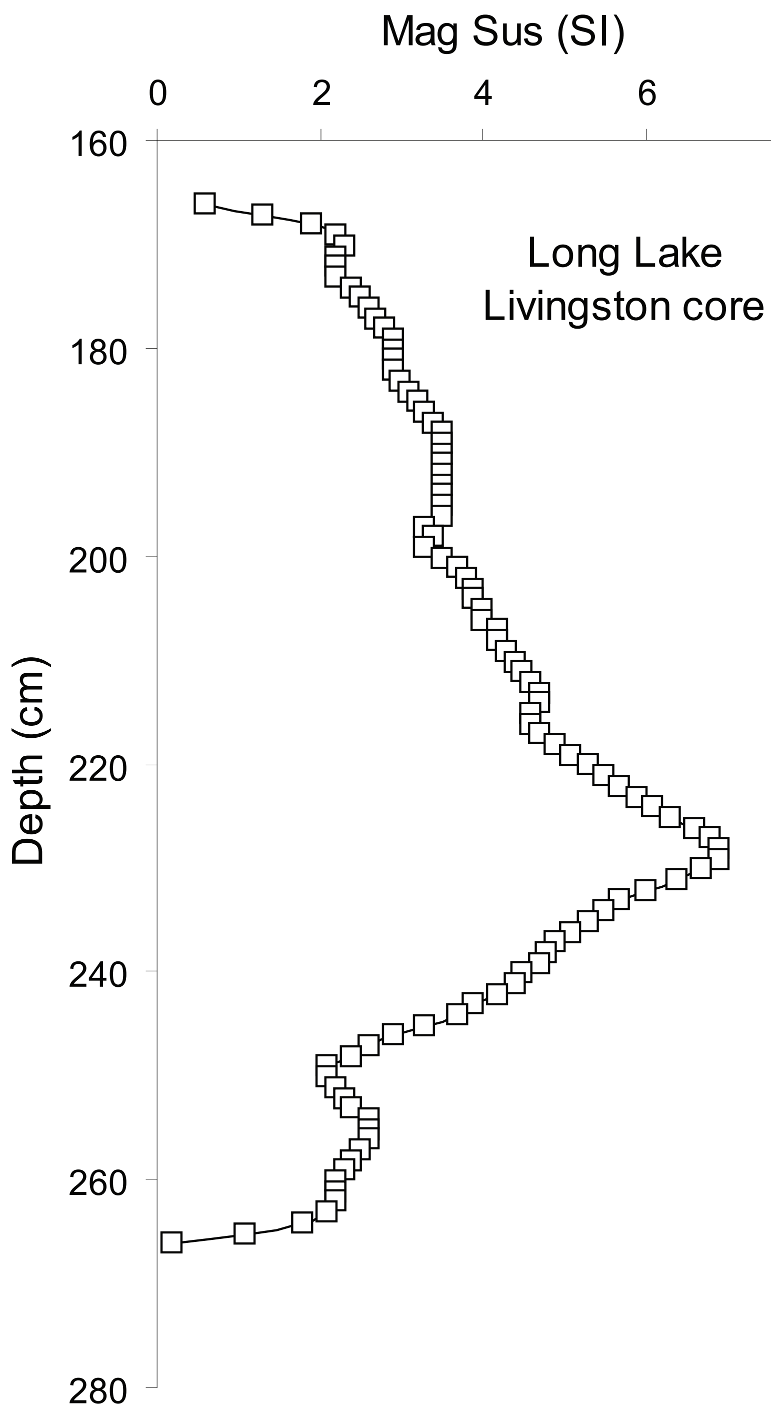


Figure 2. Percent dry weight of organic, CaCO3, and inorganic matter in the Parley Lake core.

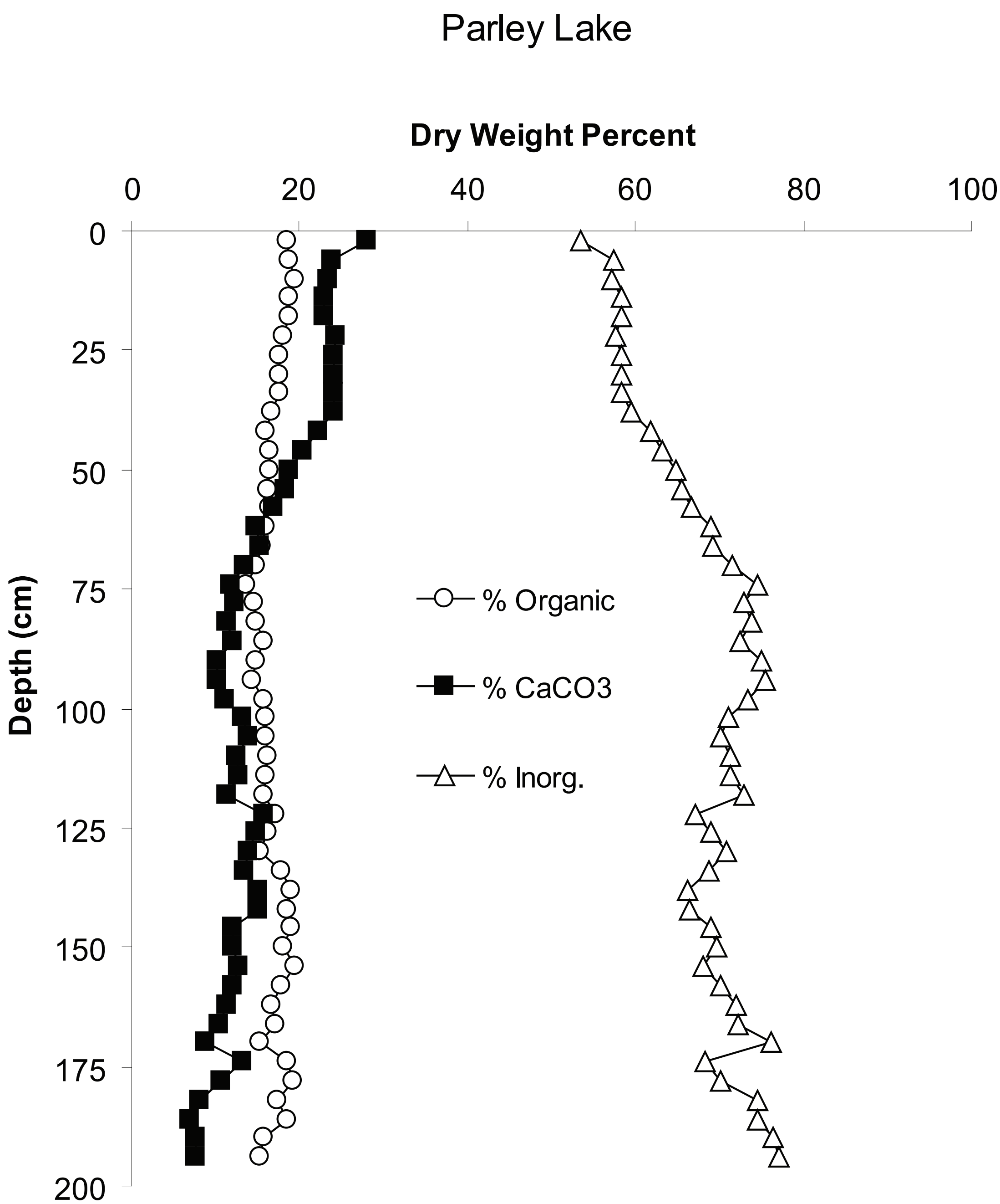


Figure 3. Unsupported lead-210 inventory, lead-210 date-depth model, and sediment accumulation rate for Parley Lake.

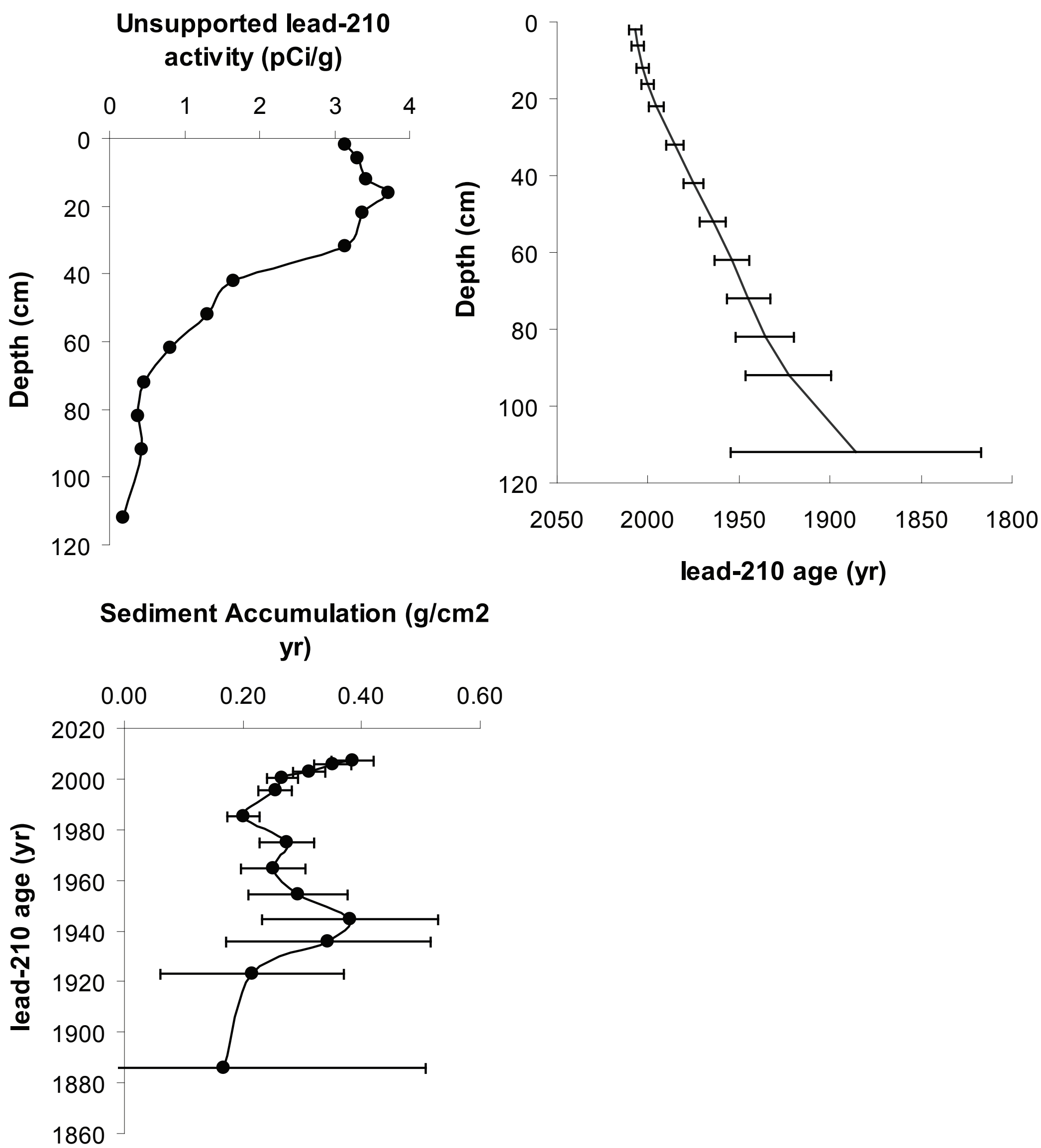


Figure 4. Histogram comparing diatom-inferred (DI) total phosphorus (pre-European and modern), and measured total phosphorus in 2007 for eight lakes in the Minnehaha Watershed District. Note that the "DI Pre-European" sample from Luntsen Lake reflects when the lake was formed by damming in the 1960s instead of pre-European conditions.

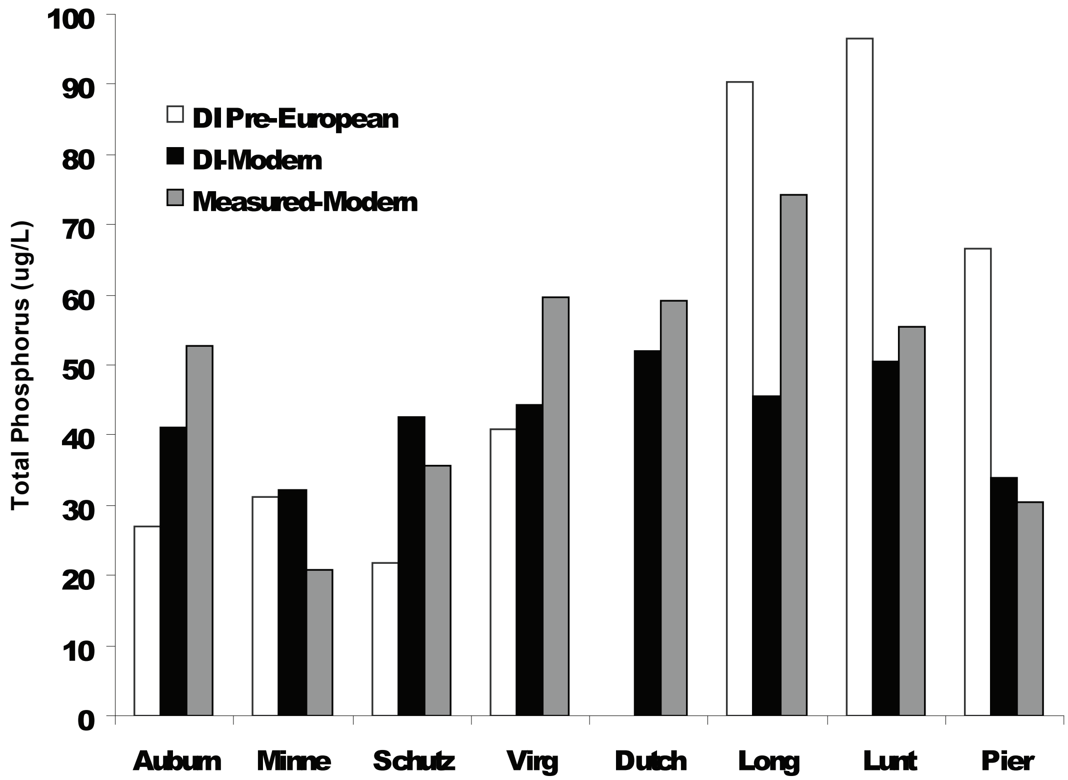


Figure 5. Diatom-inferred total phosphorus (TP) reconstruction for Parley Lake.

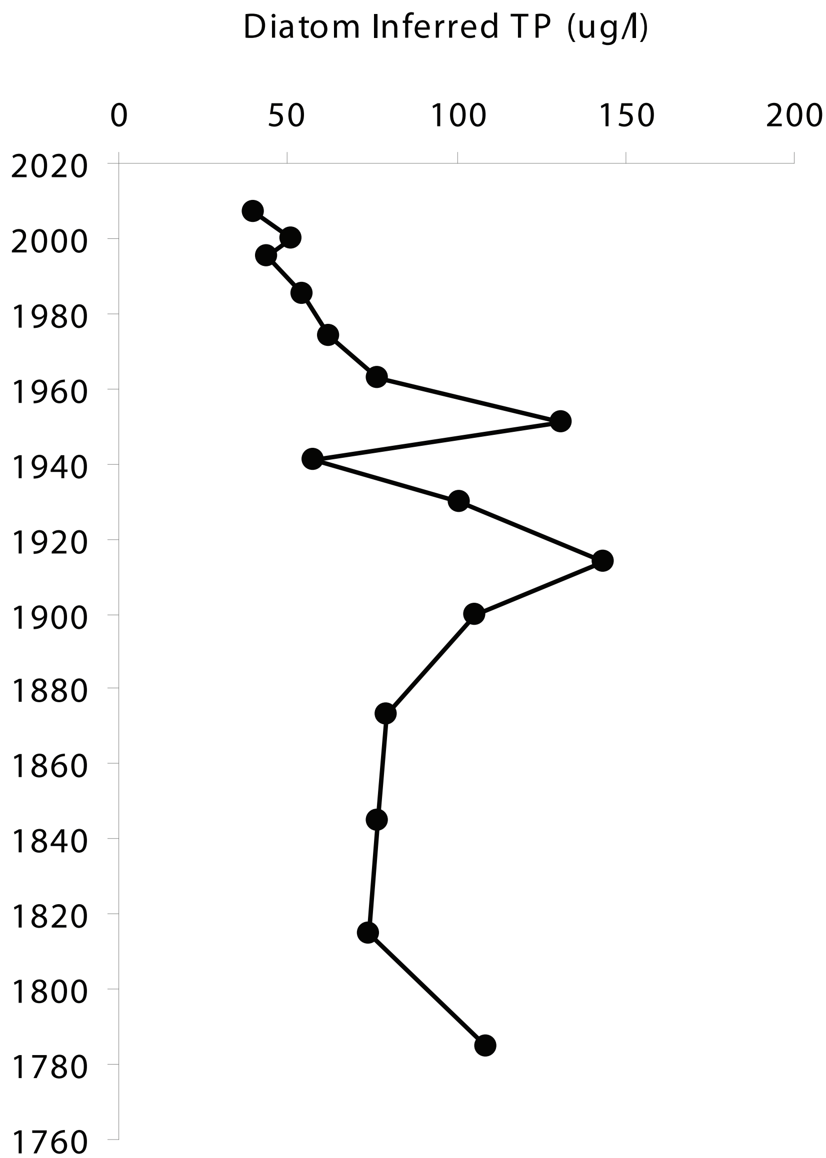


Figure 6. The 89 lakes diatom calibration set with the trajectory of change from the bottommost sample to core top sample of seven of the MCWD lakes passively plotted. The end of each line represents the midpoint of the two downcore samples, the arrowhead represents the midpoint of the two core top samples. The core top of Dutch Lake is represented by the lake name, the downcore samples from this lake were not analyzed due to preservation issues.

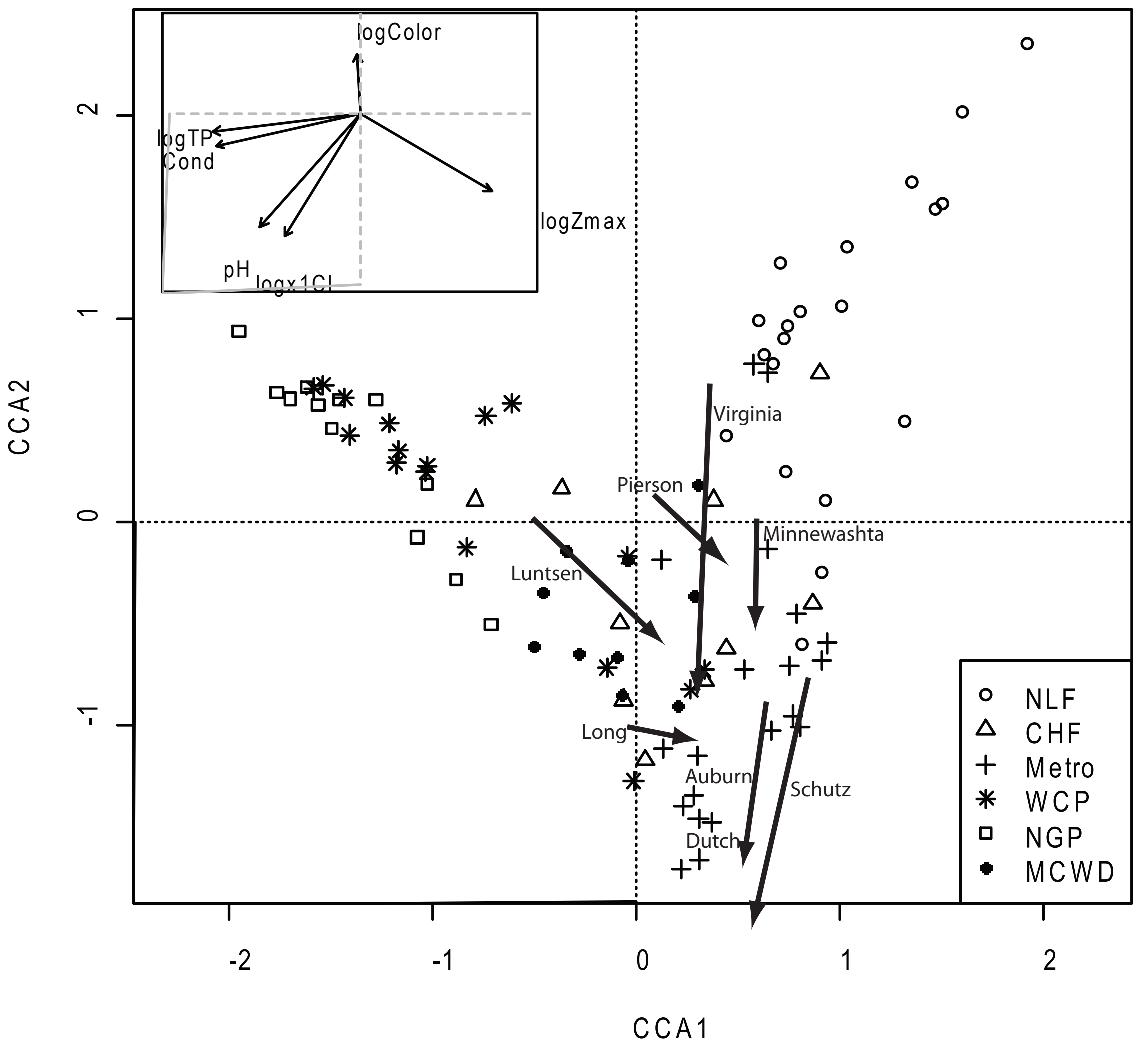


Figure 7. Correspondence analysis (CA) of diatom communities from Parley Lake. Circles and arrows were drawn to illustrate the trajectory through time.

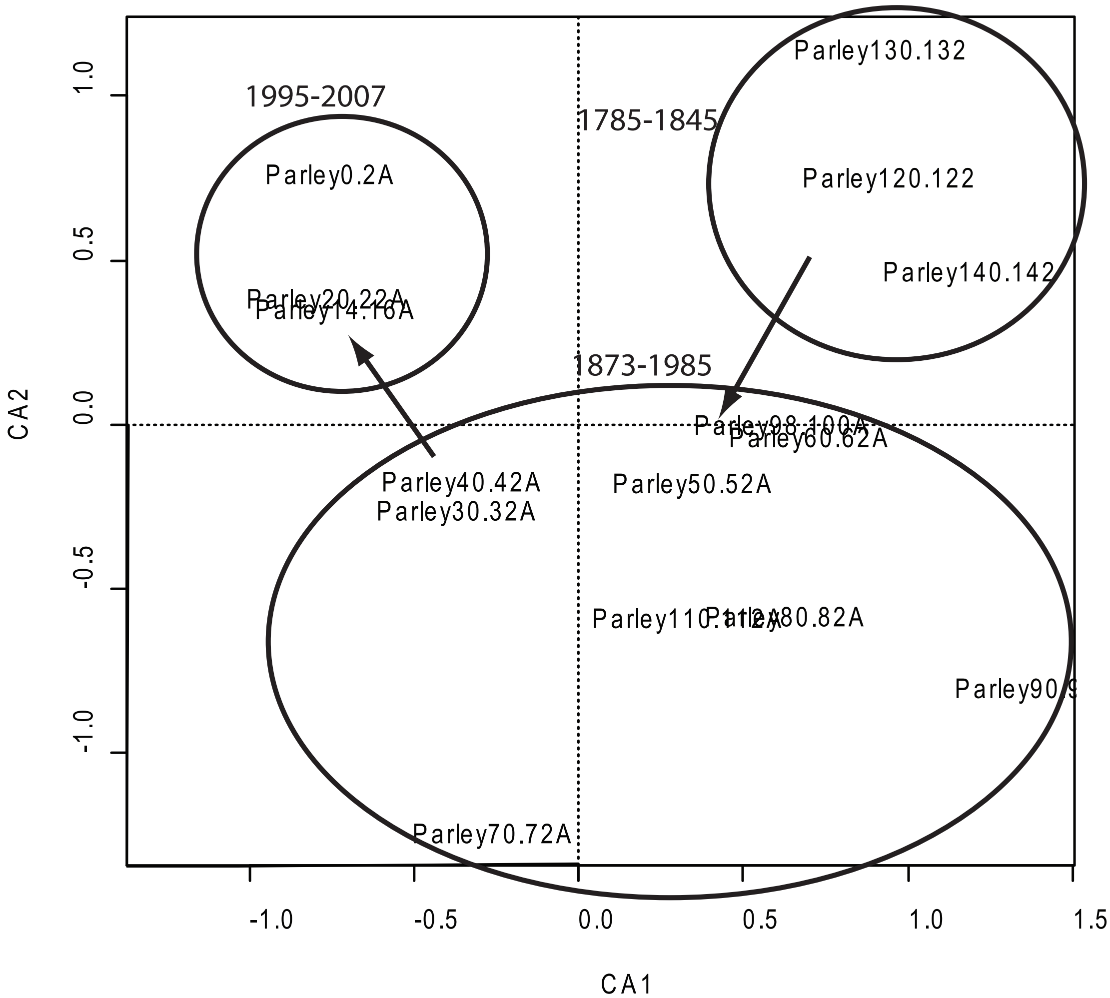


Figure 8. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance) in Parley Lake.

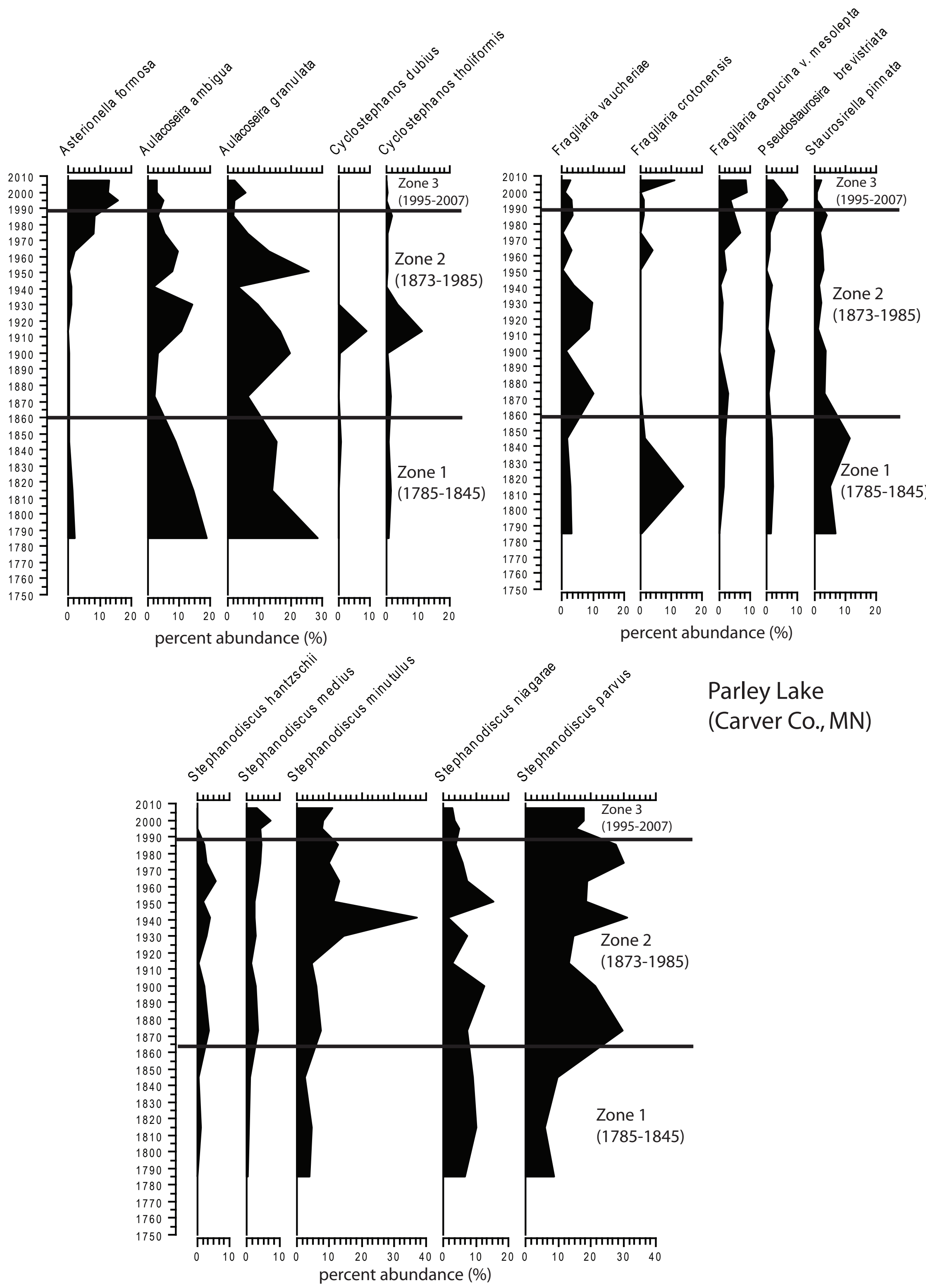


Figure 9. Downcore diatom assemblages from Parley Lake passively plotted on the 89 Minnesota Lakes calibration set.

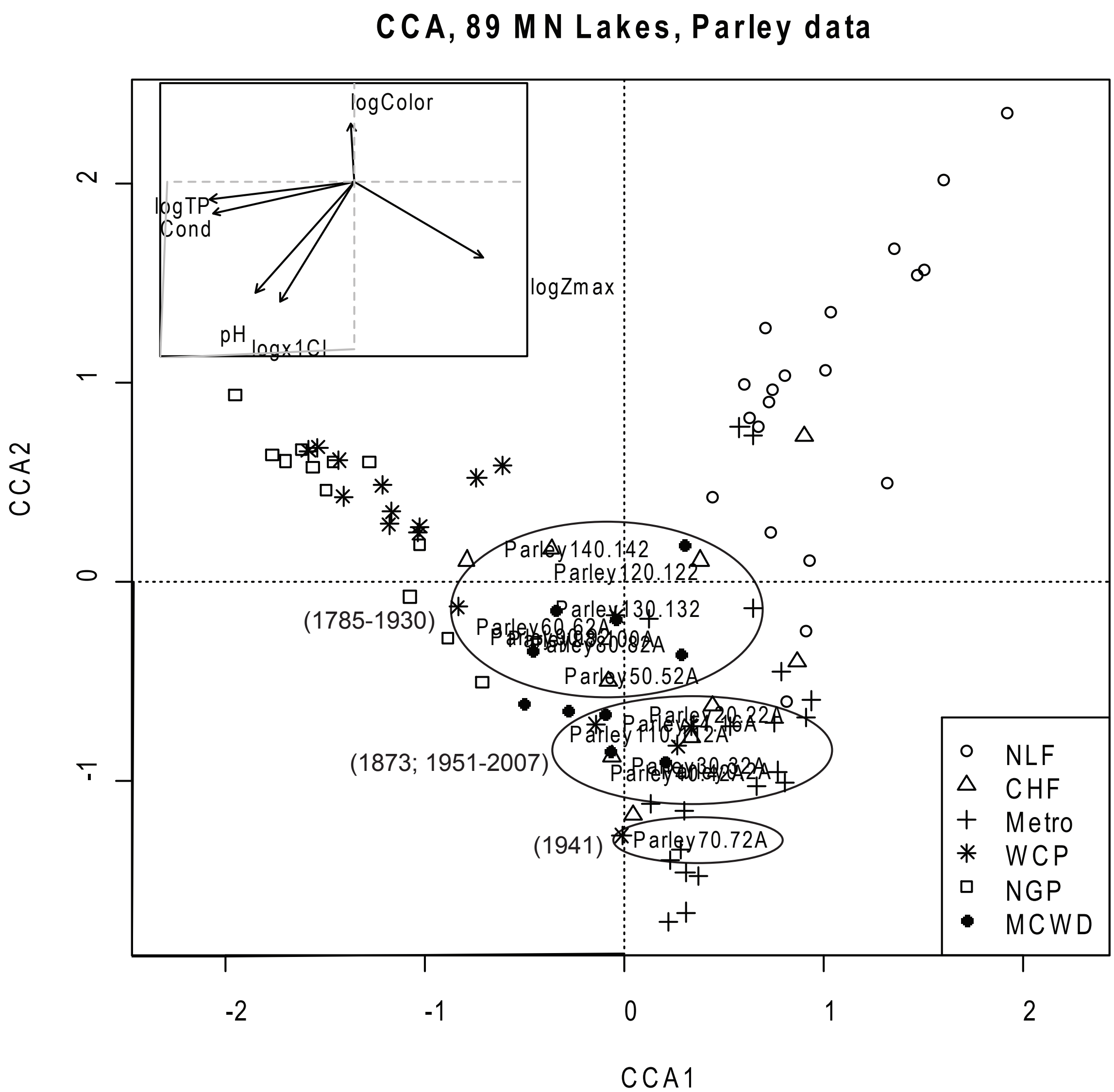
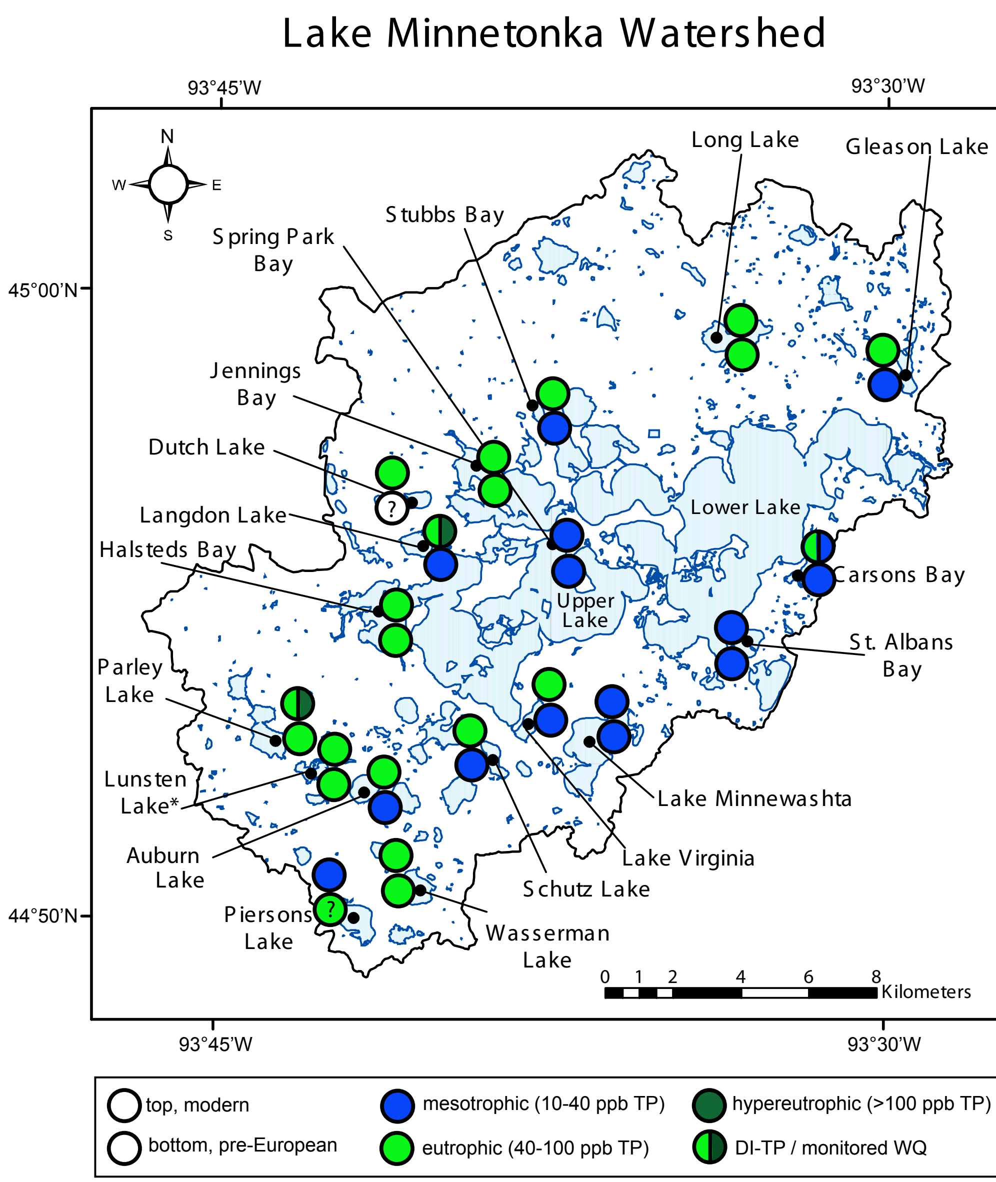
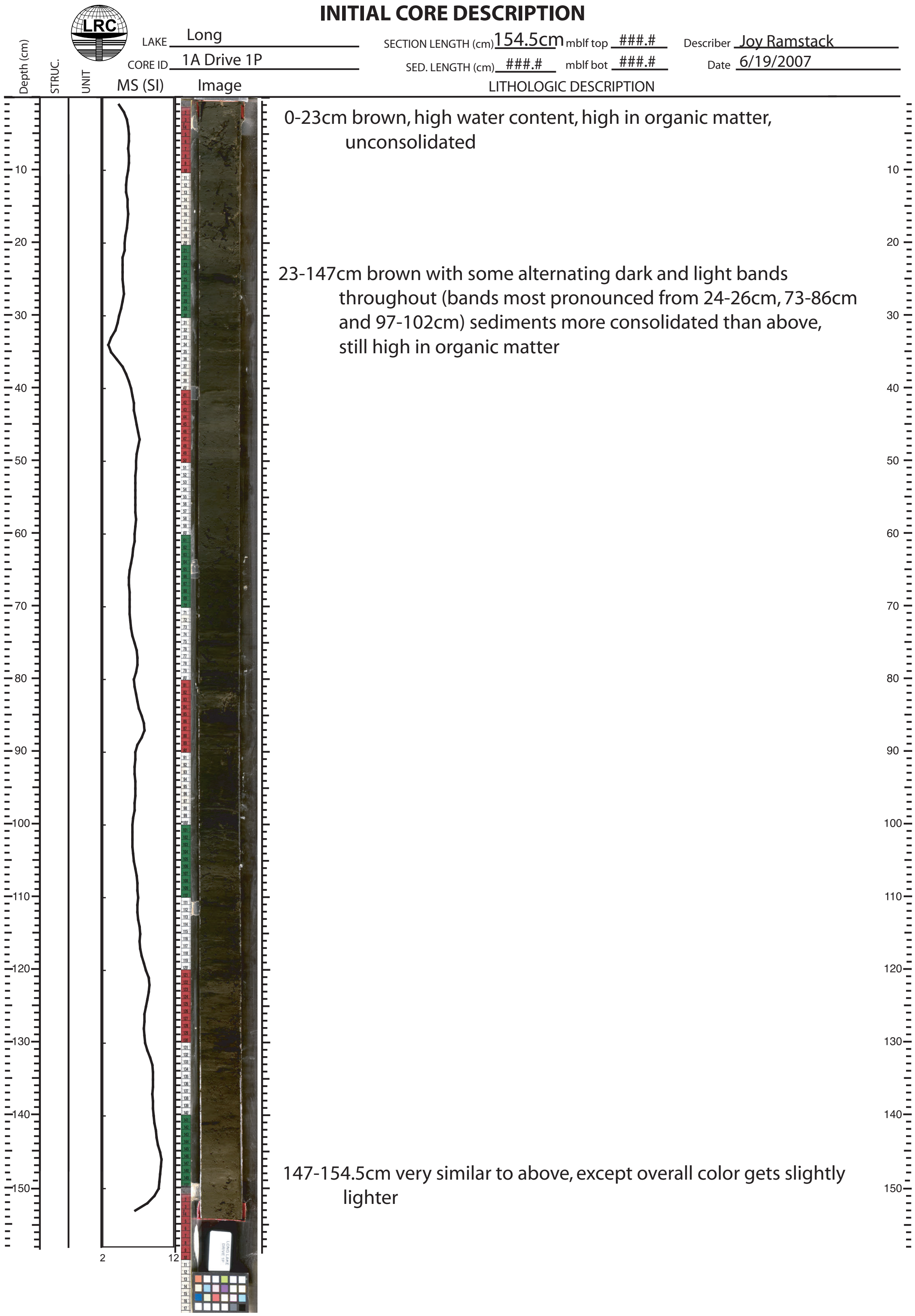


Figure 10. Lake Minnetonka watershed showing lakes cored, 2005-2007. Historical and modern trophic status of each lake is indicated with a pair of colored circles. The bottom circle indicates trophic level based on pre-European diatom-inferred total phosphorus (DI-TP). The top circle reflects modern trophic conditon based on modern DI-TP and water quality monitoring. Split circles are used when modern DI-TP and water quality monitoring results differ, with DI-TP indicated on the left half of split circles. See legend for color key to trophic states.



Appendix A1. Core image, magnetic susceptibility, and physical description of the piston core from Long Lake. Note that 50 cm have been extruded from the top of the core.



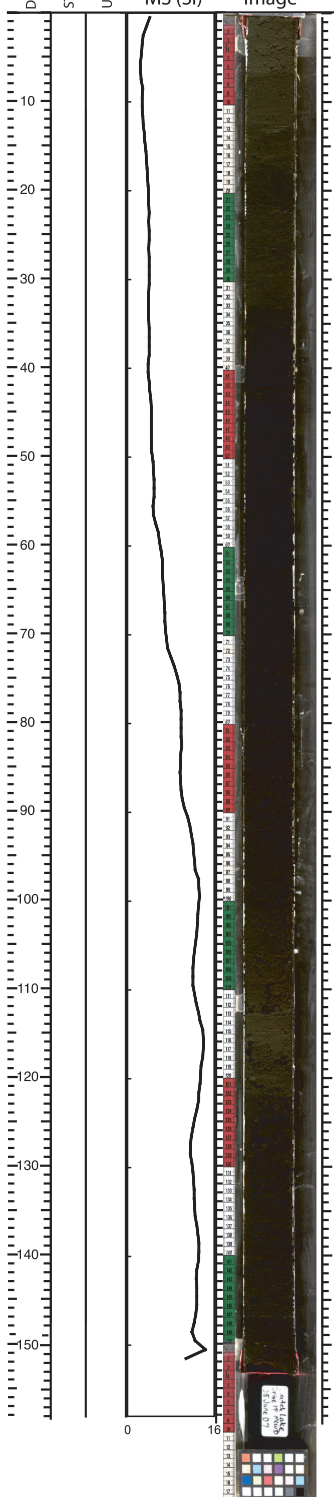
Appendix A2. Core image, magnetic susceptibility, and physical description of the piston core from Dutch Lake. Note that 42 cm have been extruded from the top of the core.

INITIAL CORE DESCRIPTION

LRC

LAKE Dutch — SECTION LENGTH (cm) 153 cm — mblf top ###.# — Describer Joy Ramstack

CORE ID 1A Drive 1P — SED. LENGTH (cm) ###.# — mblf bot ###.# — Date 6/19/2007



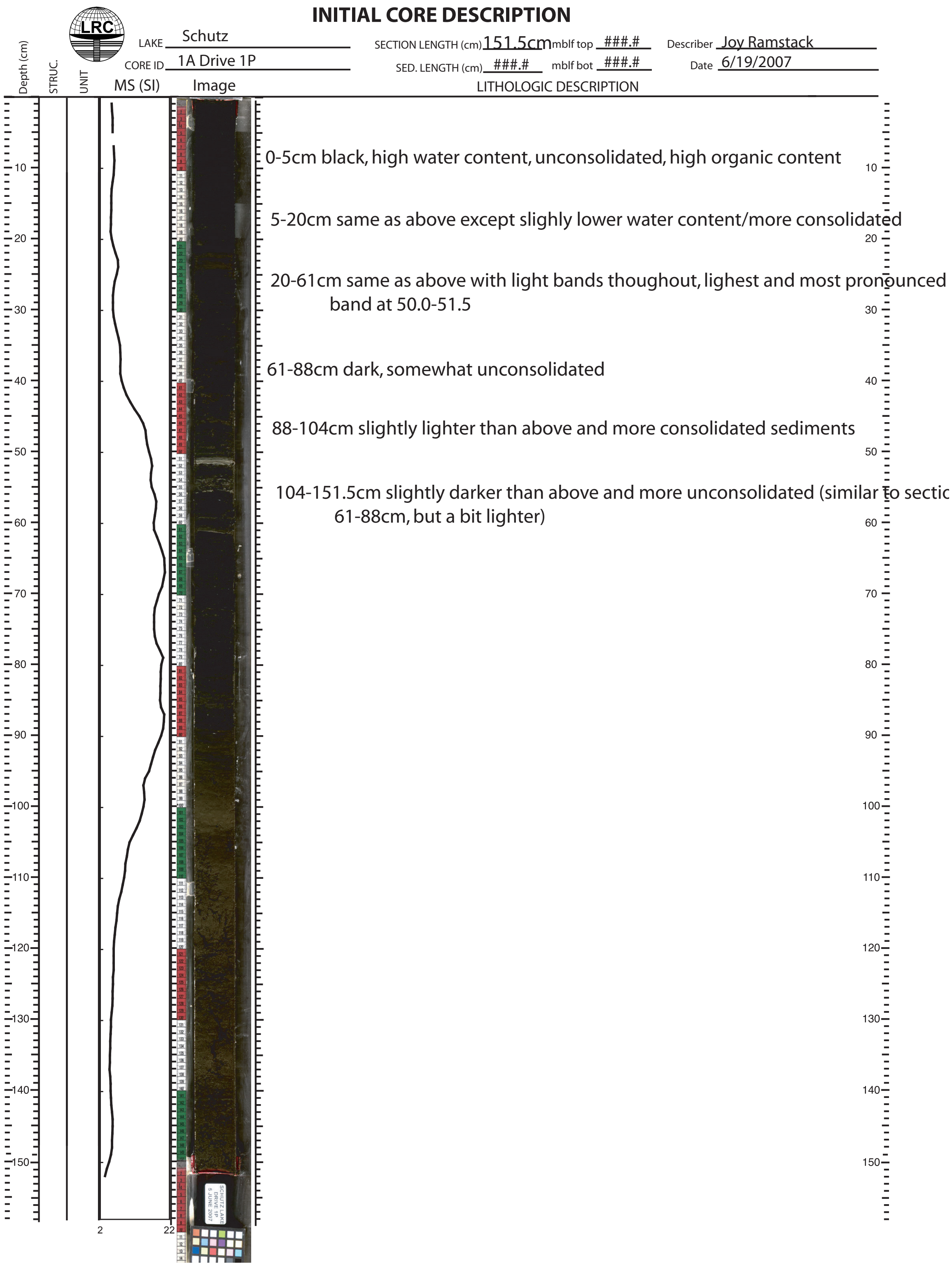
LITHOLOGIC DESCRIPTION

0-6cm brown, slightly lighter in color than the rest of the core
high water content
high organic content/extremely fine grains

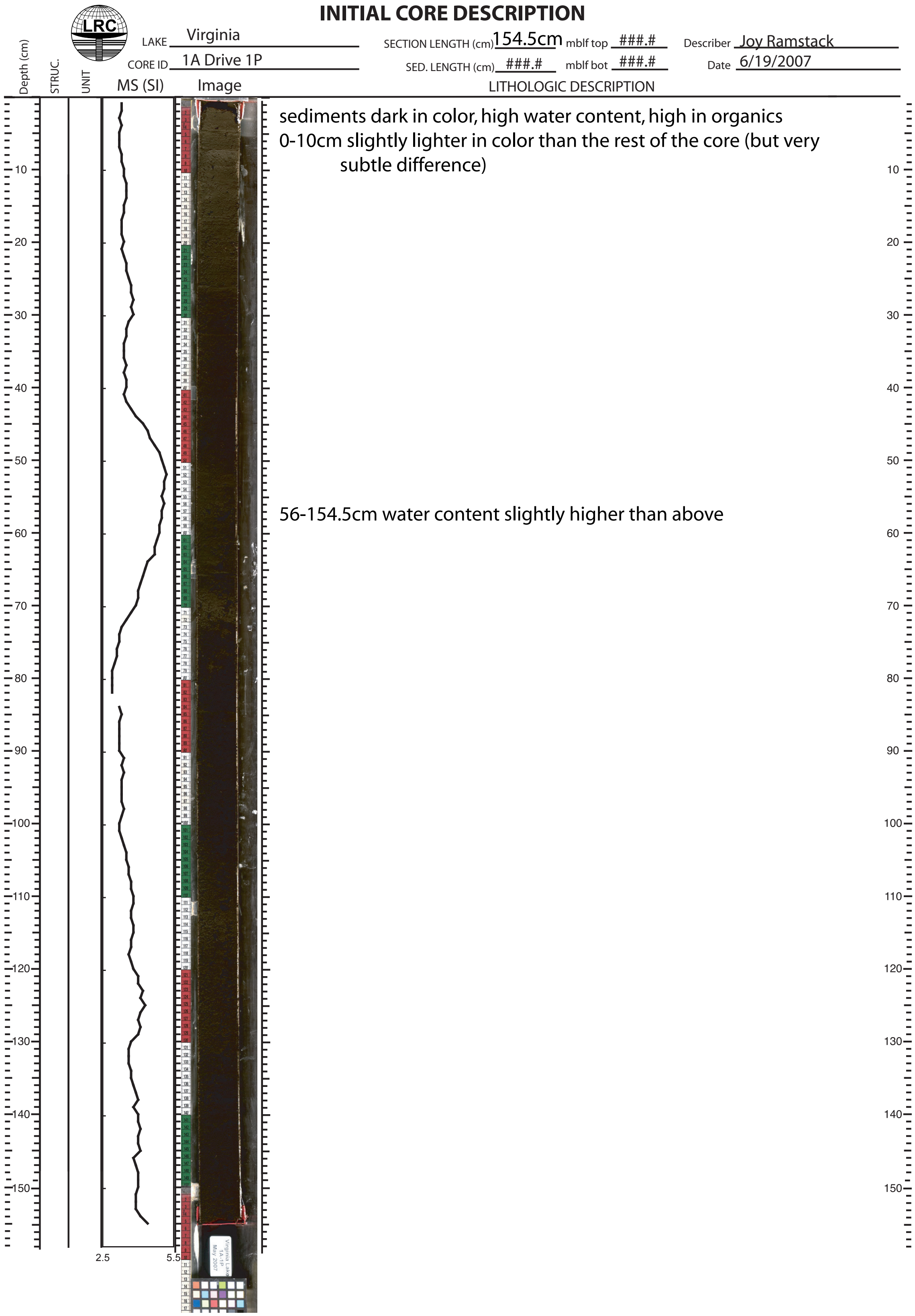
6-12cm color slightly darker than above and water content a little lower, otherwise same as above

12-153cm same as above except color continuing to get slightly darker (by about 40cm the color is uniform throughout the rest of the core)

Appendix A3. Core image, magnetic susceptibility, and physical description of the piston core from Schutz Lake. Note that 50 cm have been extruded from the top of the core.



Appendix A4. Core image, magnetic susceptibility, and physical description of the piston core from Virginia Lake. Note that 46 cm have been extruded from the top of the core.



Appendix A5. Core image, magnetic susceptibility, and physical description of the piston core from Auburn Lake. Note that 42 cm have been extruded from the top of the core.

INITIAL CORE DESCRIPTION

LRC

LAKE: Auburn

CORE ID: 1A Drive 1P

SECTION LENGTH (cm): 152cm

SED. LENGTH (cm): ###.#

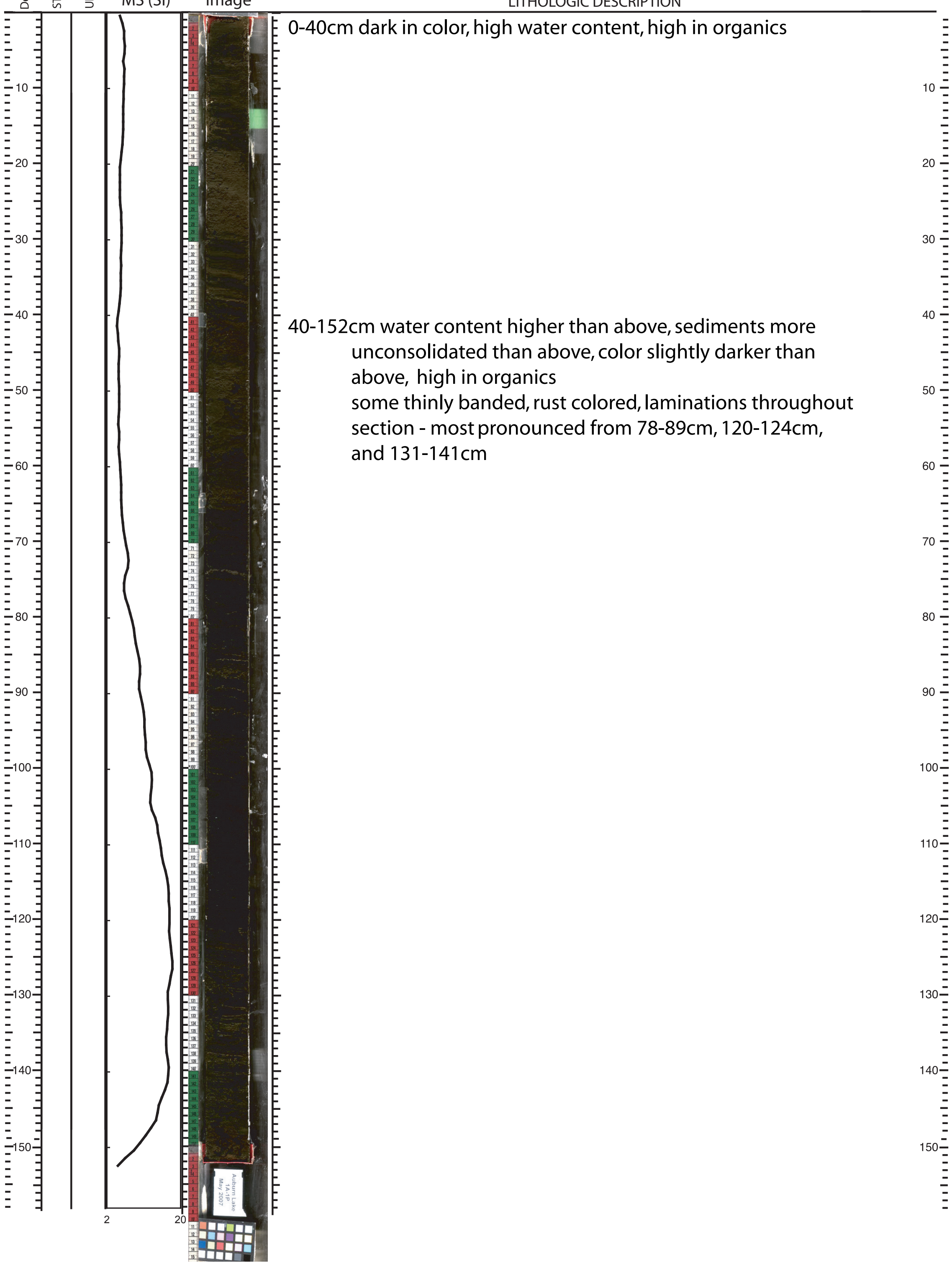
mblf top: ###.#

mblf bot: ###.#

Describer: Joy Ramstack

Date: 6/19/2007

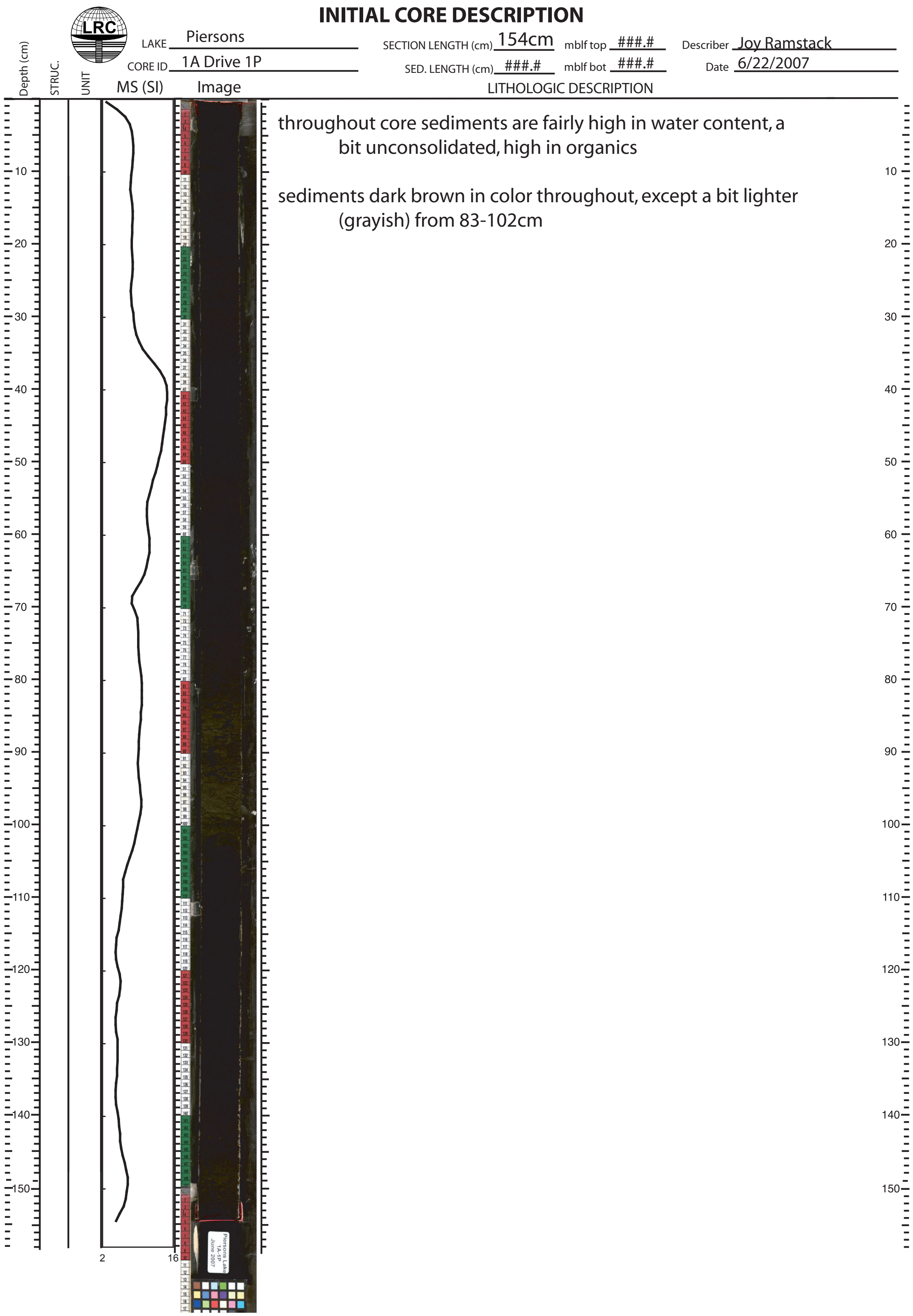
Depth (cm) | STRUC. | UNIT | MS (SI) | Image | LITHOLOGIC DESCRIPTION



0-40cm dark in color, high water content, high in organics

40-152cm water content higher than above, sediments more unconsolidated than above, color slightly darker than above, high in organics
some thinly banded, rust colored, laminations throughout section - most pronounced from 78-89cm, 120-124cm, and 131-141cm

Appendix A6. Core image, magnetic susceptibility, and physical description of the piston core from Piersons Lake. Note that 52 cm have been extruded from the top of the core.



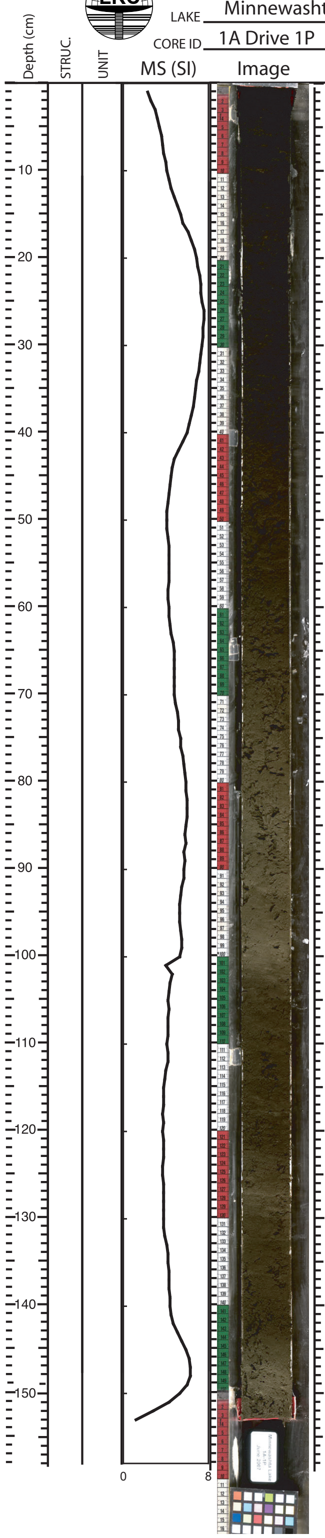
Appendix A7. Core image, magnetic susceptibility, and physical description of the piston core from Minnewashta Lake. Note that 68 cm have been extruded from the top of the core.

INITIAL CORE DESCRIPTION

LRC

LAKE Minnewashta | SECTION LENGTH (cm) 153cm | mblf top ###.# | Describer Joy Ramstack

CORE ID 1A Drive 1P | SED. LENGTH (cm) ###.# | mblf bot ###.# | Date 6/19/2007



LITHOLOGIC DESCRIPTION

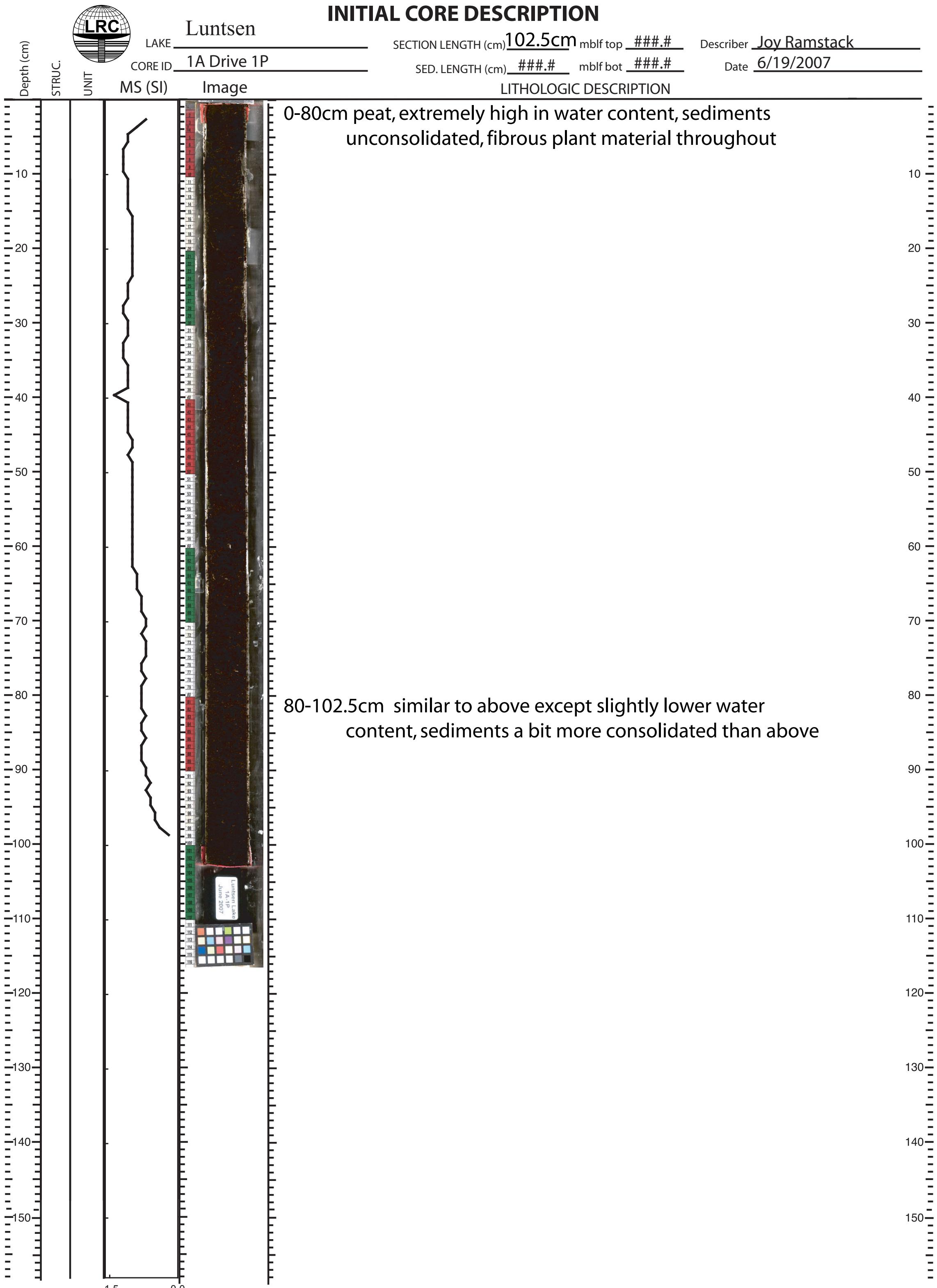
0-68cm dark in color (getting gradually lighter at the bottom) high in water content, somewhat unconsolidated (becoming more consolidated toward the bottom of this section)

68-102cm lighter in color than above, lower water content than above, sediments more consolidated toward the bottom of this section the sediments feel a bit like clay

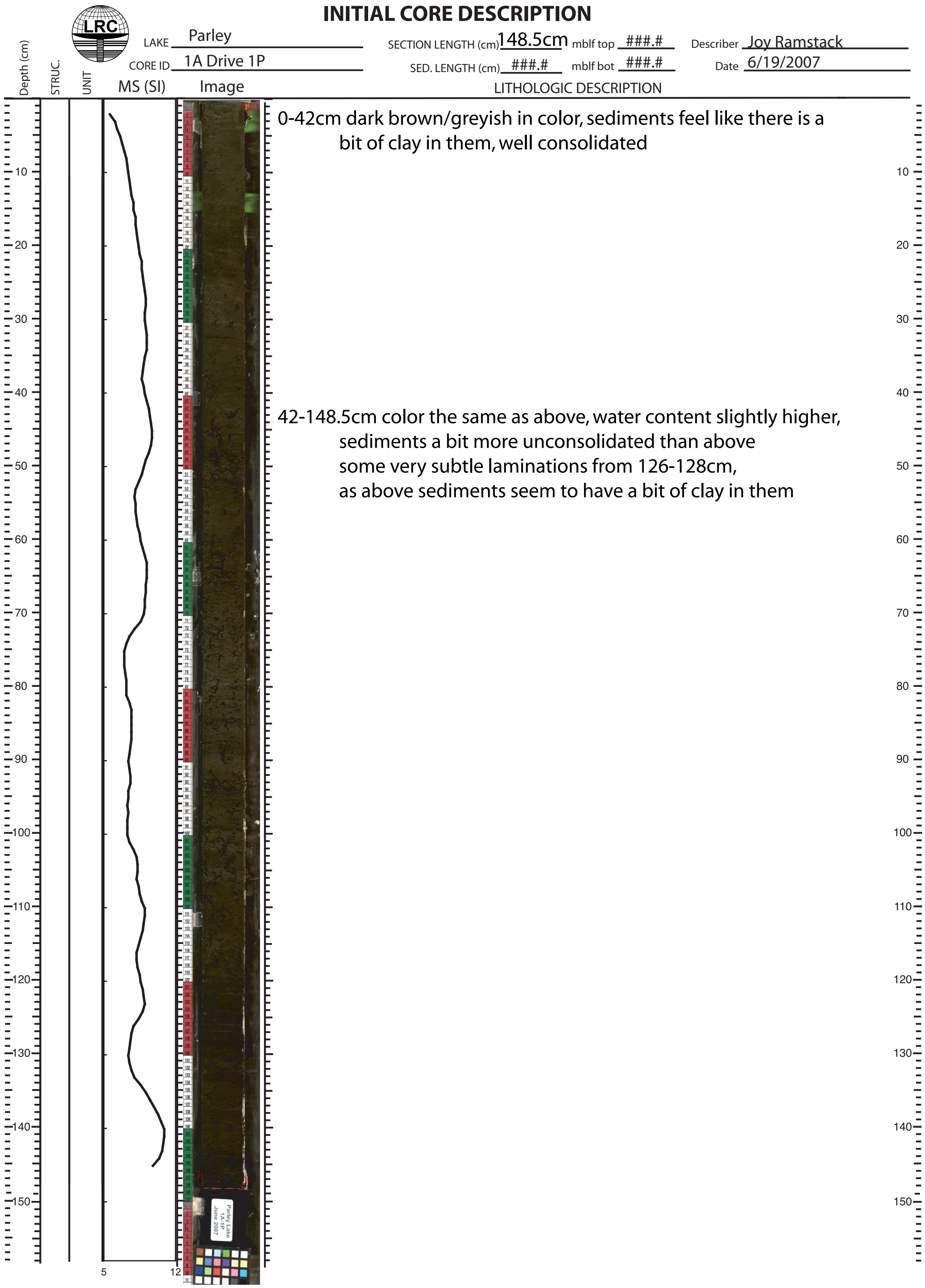
102-146cm color a bit darker than above (with a ligher spot from 123-130cm), very fine grains

146-153cm sediments lighter in color, feels like there is a bit of clay (same as section ending at 102cm)

Appendix A8. Core image, magnetic susceptibility, and physical description of the piston core from Luntsen Lake. Note that 70 cm have been extruded from the top of the core.



Appendix A9. Core image, magnetic susceptibility, and physical description of the piston core from Parley Lake. Note that 46 cm have been extruded from the top of the core.

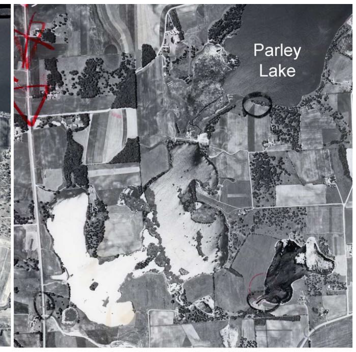


Appendix A10. Aerial photos of the Luntsen Lake area dated 1937, 1951, 1957, 1963, 1984, and 1991. As evident in the 1963 photo, the King Marsh drainage was dammed in the early 1960s to create Luntsen Lake.


Luntsen Wetland 1937

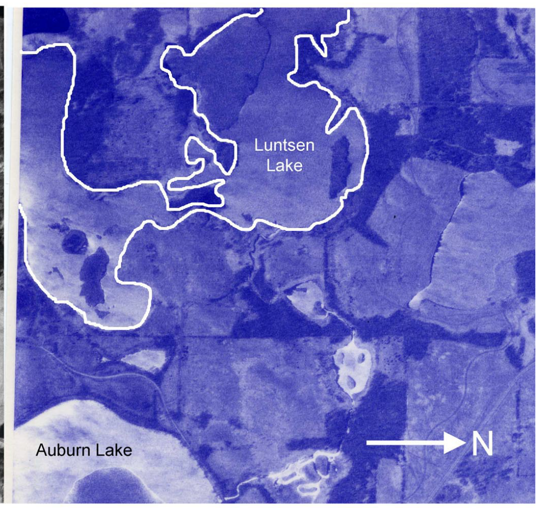

Luntsen Wetland 1951


Luntsen Wetland 1957



Luntsen Lake 1963


Luntsen Lake 1984



Luntsen Lake 1991