Completion Report Mille Lacs Lake Paleolimnology Project

Prepared by:
John Kingston
Natural Resources Research Institute
University of Minnesota
19 East Camp Street
Ely MN 55731 USA
jkingsto@nrri.umn.edu

Prepared for:
Mille Lacs Soil and Water Conservation District
900 5th Street SW
Milaca MN 56353

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Mille Lacs Lake is a high-priority lake in terms of its size and premier walleye fishery, and it has a relatively small watershed compared to the size of the lake surface. Expected future increases in development of the lakeshore have prompted a desire to know about water quality baselines for this important lake. This paleolimnological study examines a sediment core collected in late winter of 2002 using radioisotope dating, loss-on-ignition analysis of organic and inorganic sediment components, and diatom analysis as a proxy for nutrient loading.

Land use changes in the watershed have caused accelerating soil erosion from 1960 until the present day. Diatom counts show a decline of benthos-dominated assemblages starting by the 1950s, with greater dominance of planktonic species for the last 60 years. This indicates nutrient loading increases and water transparency decreases. The core-top, representing conditions in 2001, shows the highest relative abundance of planktonic diatom species, indicating that nutrient loading is still increasing. Preliminary diatom-based reconstructions of past lakewater total phosphorus concentrations show that nutrient loading in Mille Lacs has increased approximately 30% during the past half century and remains at an historical high level.

Introduction

Mille Lacs Lake is the second largest lake entirely within the state of Minnesota; it is a premier walleye and perch fishery; and a coalition of agencies, an American Indian band, and a lake association has formed to protect the resource (Mille Lacs Lake Watershed Management Group 1999). The Minnesota Pollution Control Agency has submitted a "Clean Lakes Study (314a)" based on fieldwork in 1992 (Heiskary *et al.* 1994), and selected conclusions from that study include:

- Trophic status indicators including chlorophyll *a* and total phosphorus (TP) (summer-mean of 27 μg/L) show that Mille Lacs is mesotrophic and not severely degraded by human activity in the watershed;
- Based on 9 years of Secchi Disk data, the transparency of Mille Lacs lake was improving slightly through 1992; based on a comparison of 3 water quality surveys, lakewater TP may be declining between 1971 and 1992;
- Chlorophyll *a* concentrations were lower than expected considering TP and Secchi data, and offshore waters had slightly better trophic status indicators than some nearshore sampling sites;
- Atmospheric sources were larger TP contributors than groundwater or streams;
- An antidegradation goal for maintaining summer-mean TP at 27 μg/L was suggested as prudent by MPCA.

The present paleolimnology study was commissioned to use consistent methods on a dated sediment core from Mille Lacs Lake to determine past baselines, trends, and magnitude of change in lakewater TP during the period of European settlement and changing land uses in this watershed.

Materials and Methods

We cored through the ice on March 11, 2002, at a comparatively deep (10.72 m) portion of Mille Lacs Lake near existing water quality sampling station ML6 (Fig. 1). Surface sediments (down to 52 cm) were retrieved with a gravity corer (Glew 1989) and sediment intervals were extruded in the field (Glew 1988). We collected deeper sedimentary material (1 m) using a Russian peat sampler (Aquatic Research Instruments), and this sediment was sectioned in the laboratory. The two cores were matched based on measurements of the sediment samples collected from each device and the distance to bottom sediments as measured in the field using a tape measure and coring rods.

We use loss on ignition methods to partition the sedimentary dry mass into organic matter, carbonate (or clay water of hydration in low-carbonate lakes), and inorganic matter (Dean, Jr. 1974).

Cores of Mille Lacs Lake sediments were analyzed for excess ^{210}Pb activity to determine age and sediment accumulation rates for the past ca. 150 years (Engstrom 1996;Appleby

2001). ^{210}Pb was measured at 17 depth intervals in the cores through its grand-daughter product ^{210}Po, with ^{209}Po added as an internal yield tracer. The dating methods are modified from Eakins and Morrison (Eakins and Morrison 1978). Activity was measured for 1-6 x 10^5 s with ion-implanted or Si-depleted surface barrier detectors and an alpha spectroscopy system. Unsupported ^{210}Pb is calculated by subtracting supported activity from the total activity measured at each level; supported ^{210}Pb is estimated from the asymptotic activity at depth (the mean of the lowermost samples in a core). Dates and sedimentation rates are determined according to the c.r.s. (constant rate of supply) model (Appleby and Oldfield 1978) with confidence intervals calculated by first-order error analysis of counting uncertainty (Binford 1990).

Diatoms were prepared from 11 sediment intervals and analyzed using standard paleolimnological methods (Battarbee *et al.* 2001;Kingston 1986). Sediment was cleaned of organic matter using 35% hydrogen peroxide, and cleaned diatoms were prepared on permanent slides using the high-refractive index mountant Pleurax. For the nutrient calibration, portions of randomly selected transects were counted on research grade microscopes with objective N.A. of 1.4 and differential interference contrast optics. Taxonomy used diverse literature sources and was harmonized among analysts; images of taxa were captured and cataloged on computers using a 750-line video camera and 640x480 capture card.

We obtained the 55-lake MN diatom calibration data set from Ramstack (Ramstack 1999;Heiskary and Swain 2002;Ramstack *et al.* 2002), and censored it for our own analyses as follows: all indeterminate categories (such as *Navicula* spp.) were deleted, and only taxa that occurred in at least two lakes at > 1% were used in the total phosphorus calibration in this paper. Sixty common diatom taxa were used. Ramstack (1999) showed that the calibration of lakewater total phosphorus was strong and explained a significant amount of variance in the diatom species data. The data was prepared for analysis using WinTran, and the DI TP analysis was performed using WACALIB3.5.

Results

We noted a color change in the sediment collected with the gravity corer at 38cm (dark gray above to brown below), and hypothesized that this level could represent the settlement horizon and the major logging of pines in the watershed over 100 years ago.

Total ^{210}Pb activity declines from surface values around 31 pCi/g to a near constant background (supported ^{210}Pb) of 0.96 pCi/g below 36 cm (Fig. 2). The down-core decrease is monotonic and below ca. 12 cm it is close to exponential. The section of exponential decline indicates fairly uniform sedimentation rates. The break between sediments containing unsupported ^{210}Pb (36 cm and above) from older sediments with only supported (background) ^{210}Pb is very sharp; supported values are well defined by the two intervals below 36 cm with similar low activities. Dates calculated according to the constant rate of supply (c.r.s.) model (Fig. 3) have an uncertainty (based on counting precision -- a minimum error) of less than ± 6 years for the last 135 years; dating error rises substantially only for the oldest dated interval: ± 15 years at 1825 (36 cm). This is excellent dating precision.

Sediment accumulation rates are relatively uniform throughout the lower core, then increase steadily from about 1970 onward (Fig. 4). The error terms for rates prior to 1900 are fairly large, so the small oscillation that appears around the turn of the last century may not be significant. The inventory of unsupported ^{210}Pb in the core (21.9 pCi/cm2) is equivalent to a ^{210}Pb flux of 0.70 pCi cm-2 yr-1. This value is about 1.4 X the mean atmospheric flux of ^{210}Pb for the region (ca. 0.5 pCi cm-2 yr-1), indicating that the core-site over-represents sedimentation rates to the lake as a whole. Dividing core-specific sedimentation rates by a focusing factor of 1.4 could make an estimate of whole-lake fluxes.

These dating results indicate highly conformable sedimentation over the last few centuries. However, the occurrence of inorganic sand at less than 1.5 m implies a major hiatus in sediment deposition at this site sometime within the last millennium. Assuming an average sedimentation rate of 1.6 mm/yr from the lower part of the 210Pb profile (26-36 cm), the transition to sand (something like 150 cm) would be around 700 years old.

Loss on ignition data vs. age (Fig. 5) show that percent organic matter increases with sediment accumulation after about 1950. Slightly earlier than that, the diatom community began changing (gaining plankton and losing benthos), indicating lower water transparency and increasing nutrient loading. The diatom-inferred total phosphorus (DI TP) follows the pattern of the increasing plankton trend, because these planktonic diatoms are the ones found in higher TP lakes from the Minnesota calibration set.

The common diatoms are typical of those in a shallow mesotrophic lake, and selected taxa are shown on a summary diagram (Fig. 6) – most common taxa were in the lake prior to European settlement and land clearance, but the relative abundances have changed through time. To the left of the core diagram are several benthic organisms that have declined to the present, such as *Fragilaria microstriata*. Other benthic species such as *Pseudostaurosira brevistriata* have maintained their abundance in a more stable manner, though many decline at the top of the core (2002). Many plankton species such as *Fragilaria crotonensis* and *Asterionella formosa*, typical summer and spring plankton bloom organisms, were very rare until the 1950s and are increasing to the present. The high abundances of the heavy *Aulacoseira* species are typical for a lake with this shallow morphometry and large wind fetch. Based on the Minnesota calibration data set (Ramstack *et al.* 2002) most of the centric species at the right of the diagram and *Aulacoseira granulata* have high TP optima. During the past 50 years, increases of the araphid and centric planktonic diatoms indicate increased nutrient loading to the lake. These nutrient increases are subtle because they are added to a background of mesotrophic indicator organisms.

The regression of diatom-inferred log (total phosphorus, µg/L) had an R^2 of 0.59, a root mean square error of prediction based on bootstrapping of 0.255, with N of 55. Mille Lacs Lake diatoms predict lakewater TP concentrations consistent with what has been seen in the 3 water quality surveys, with a slight increasing trend for over 50 years and the highest DI TP of 31 μg/L at the core top.

Discussion

The dating and sediment accumulation data from our cores is impressive (Figs. 2-4), showing very good dating control and small errors, so the core is from a consistently accumulating basin. The loss on ignition profile, changes in diatom community composition, and DI TP reconstruction (Fig. 5) all indicate that soil erosion and nutrient loading have been on an upward trend for 40 to 50 years. The highest reconstructed lakewater TP occurs at the top of the core in 2002.

The key features of the diatom-based assessment of Mille Lacs Lake are a decline in some benthic species that were more abundant pre-European-settlement, and the increasing abundance of many planktonic species that indicate higher nutrient loading during the past 40 to 50 years. The changes in diatom taxa and the resulting DI TP inference of past conditions show that this important lake resource has changed less precipitously and more recently than is the case in some smaller lakes in Minnesota, but the lake is changing in ways that indicate increasing human impacts including nutrient loading.

The paleolimnological results differ from the past comparisons of water quality data in suggesting that the nutrient loading trends in Mille Lacs are not improving over the past many decades, in a temporally broader context than was provided by the water quality surveys.

Multiple stressors may bear upon the evidence in the sediment record of Mille Lacs Lake: logging, regrowth, herbicides used in the forest, farming, building and maintenance of lakeshore dwellings and roads, manure, fertilizer use, beaver activity, atmospheric deposition, global warming.

The diatom calibration that we used here was developed across the state from SW to NE, and its application has not been ideal for this assessment of Mille Lacs for one reason not discussed previously – the taxonomic decisions from the calibration set and the sediment assessment have not been fully harmonized. Nevertheless, we expect the DI TP trend to be valid. We are currently working to expand this Minnesota data set with the addition of 50 more lakes from northern Minnesota, with the idea that expanding the numbers in the "northern lakes and forests" ecoregion will lead to more robust nutrient prediction models for northern Minnesota, where we expect anthropogenic nutrient changes to be subtle.

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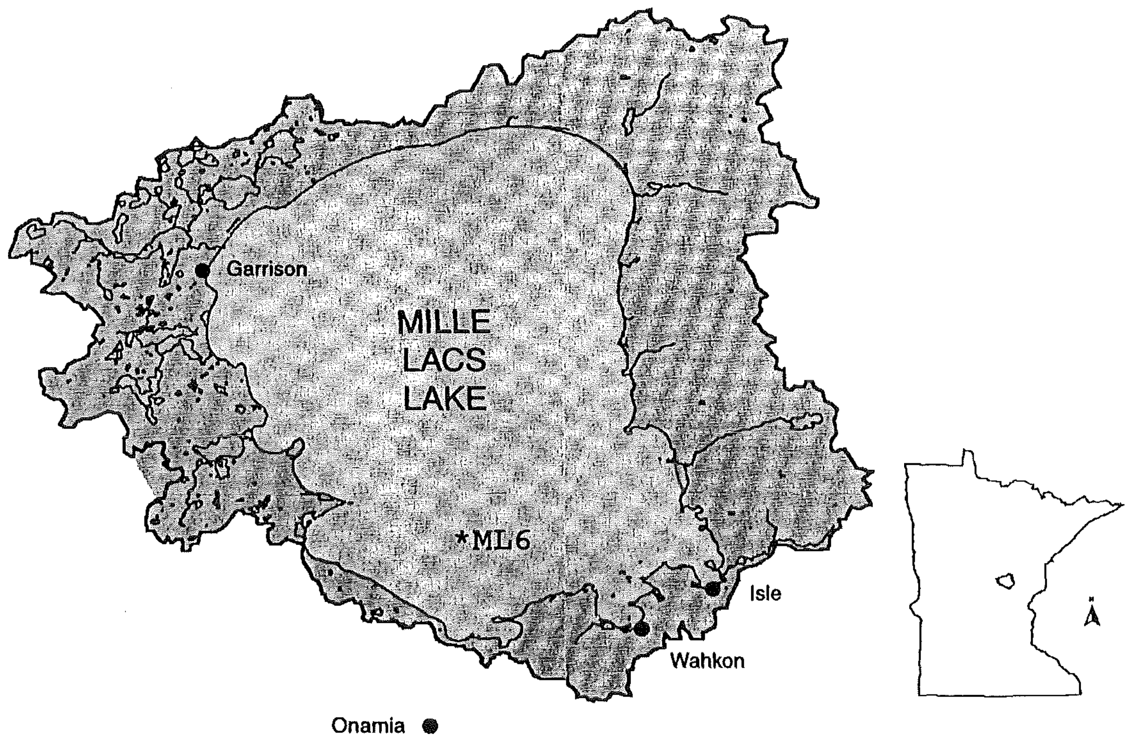
Figure 1. Map showing Mille Lacs Lake and its watershed, the towns near the lake, the position of the watershed in the state of Minnesota, and the location of water quality station ML6 (the coring site). map from (Mille Lacs Lake Watershed Management Group 1999). Location of ML6 in the Lat/Long coordinate system, WGS 84 Datum:
46 09'34.20" N, 93 38'58.20" W



Figures. 2-4. Dating and sediment accumulation graphs. Figure 2. Radioisotope activity versus depth in the lake sediment core. The monotonic decrease of activity and the level nature of the supported 210Pb indicate that we have collected at a good depositional site. Figure 3. Depth versus age graph with the errors represented; errors are small in this core, and they always increase with depth due to the model. Figure 4. Sediment accumulation versus age based on a constant rate of supply model (see text for details).

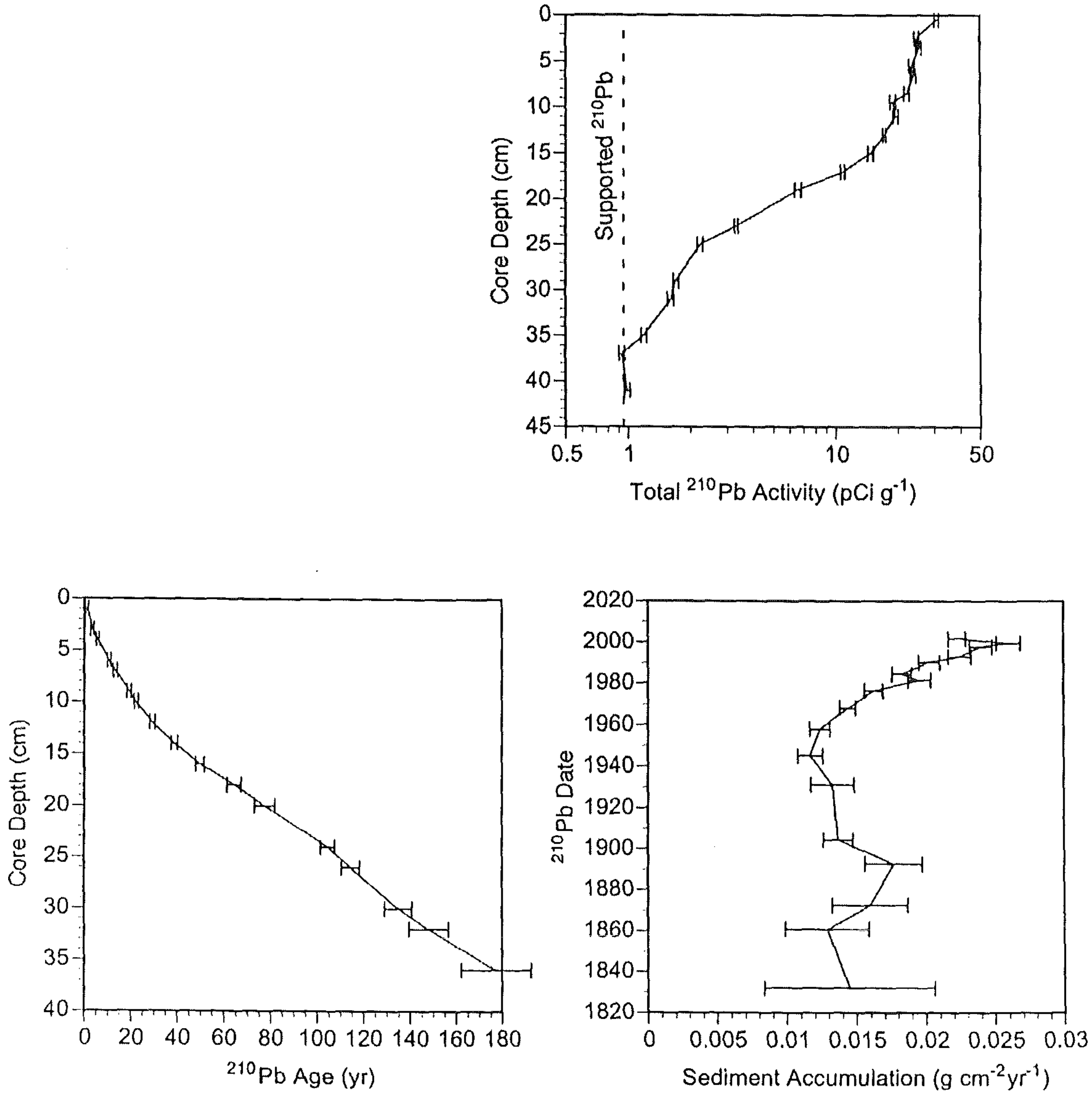


Figure 5. Summary sediment core diagram showing trends in sediment accumulation; water content of the lake sediments (compared to dry mass of sediment intervals); relative abundances of organic content, water of hydration, and inorganic content (as percent of dry matter); relative abundance of benthic and planktonic diatoms (compared to each other); and the diatom inferred past lakewater total phosphorus concentration (based on data from (Ramstack 1999;Heiskary and Swain 2002)). Errors are not plotted on the TP reconstruction; RMSEboot=0.255 logged TP units, which amounts to 10 to14 μg/L below the calculated value and 16 to 25 μg/L above the calculated value. R^2 for the calibration = 0.59.

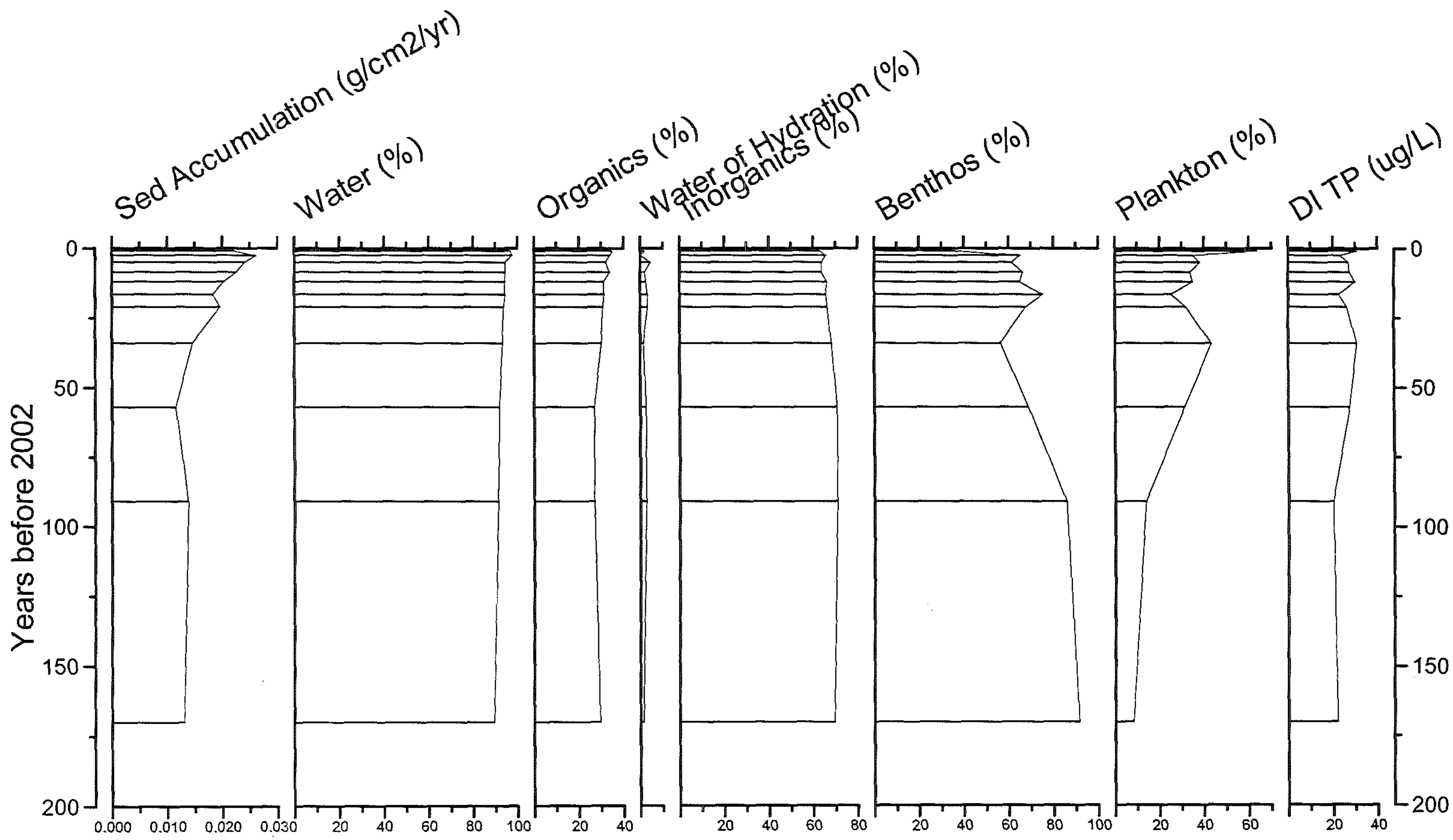
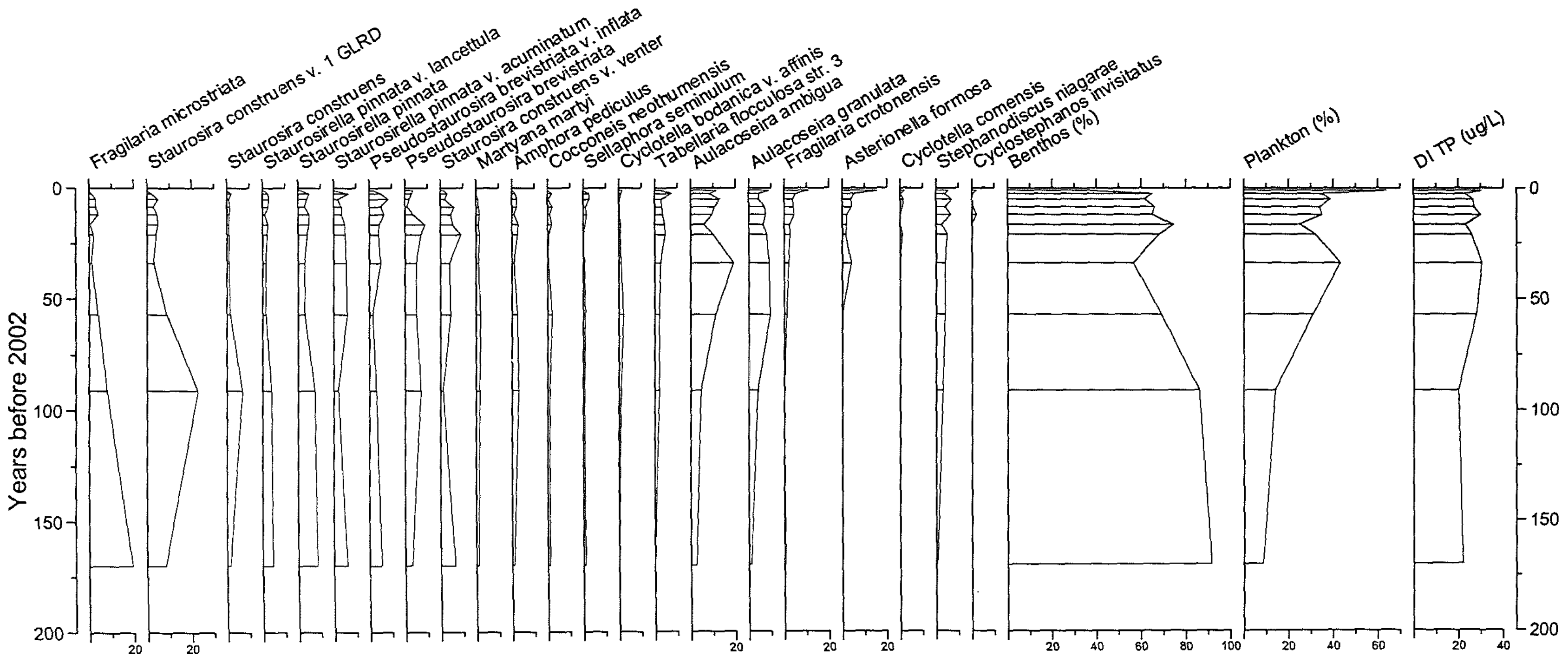


Figure 6. Summary sediment core diagram showing trends in relative abundance of selected common diatom taxa during the period of European settlement of Mille Lacs Lake. Diatoms at the left side of the diagram are benthic, growing on bottom substrates. Diatoms to the right of *Sellaphora seminulum* are planktonic, growing suspended in the water column. Many benthos species have declined during the past six decades, and the relative abundance of plankton species has increased during this period. The diatom-inferred past lakewater total phosphorus (based on data from (Ramstack 1999;Heiskary and Swain 2002)) generally increases during the past 6 decades, in step with this shift from benthic to planktonic community composition. All x-axis scales are percent abundance (with the species in relation to all others and the benthos and plankton in relation to each other), except the inferred total phosphorus which is in μg/L. Errors are not plotted on the TP reconstruction; RMSEboot=0.255 logged TP units, which amounts to 10 to14 μg/L below the calculated value and 16 to 25 μg/L above the calculated value. R^2 for the calibration = 0.59.



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