KECK Geology Consortium
Learning Science Through Research
Published by Keck Geology Consortium

Short Contributions
30th Annual Symposium Volume
29th April, 2017
ISBN: 1528-7491

A DIATOM-BASED, PALEOLIMNOLOGICAL STUDY OF SHADOW LAKE, WAUPACA COUNTY, WISCONSIN

TAYLOR MOONEY, Colgate University
Research Advisors: Jill Leonard-Pingel, Andy Michelson, Amy Leventer and Karen Harpp

ABSTRACT

In 1978, alum (aluminum sulfate) was applied to in Shadow Lake, Waupaca County, Wisconsin, to lower the phosphorus concentration and reduce the effects of cultural eutrophication. In order to understand the effectiveness of this treatment, diatom species abundances and paleolimnological data were interpreted to provide a reconstruction of Shadow Lake's history. Using the alum layer as the sole ground-truthing date in a 1.27 m core, these data revealed that species indicating more eutrophic conditions like *Fragilaria crotonensis,* characterized post-human impact conditions, while *Cyclotella bodanica* appears post-remediation, indicating the lowering of N and P levels. Based on these interpretations, it is clear that the remediation efforts conducted at Shadow Lake have helped to improve the lake's condition, although the effects of human-impact persist.

INTRODUCTION

Because diatom species are highly diverse and susceptible to environmental change, they are useful for determining how freshwater environments have changed over time (Vilmi et al., 2015). Opaline silica cell walls allow for their preservation in lake sediments, and assemblages can reveal a mosaic of environmental disturbances, from eutrophication to land use changes (Dixit et al., 1992). Moreover, diatoms can also reveal changes caused by global phenomena like climate change, so even the most relatively pristine lakes can exhibit changes in diatom assemblages over time (Wigdahl-Perry et al., 2016).

Figure 1. White placemarks indicate the location of the extracted core from Shadow Lake. Orange lines represent inflow and outflow points.a

Wisconsin lakes provide a mostly complete record of environmental changes during the Holocene (Williams et al., 2015). Therefore, diatom assemblages in Wisconsin lakes can offer important and useful information about climatic events and local disturbances throughout the Holocene and are frequently to reconstruct environmental histories (e.g., Garrison, 2013; Garrison, 2014; Edlund et al., 2015).

Focusing on anthropogenic environmental changes since European settlement, we used diatom assemblages as bioindicators to discover how humans have disrupted Shadow Lake, a 44-acre remediated, drainage kettle lake in Waupaca County, Wisconsin (Figure 1). The region's development began in the 1850s with the arrival of European settlements. Storm sewers were introduced to the lakes in the 1930s, resulting in higher sedimentation rates, a greater concentration of pigment degradation products, increased organic matter, and the development of a diatom community that thrived in eutrophic conditions (Garrison & Knauer, 1983). Eutrophication was exacerbated by groundwater infiltration and surface run-off, and residents began to notice unpleasant odors and winter fish kills in the 1960s (Garrison & Knauer, 1983). In an effort to reduce eutrophication, the storm sewers were diverted in 1976 and the lake was treated with alum (aluminum sulfate) in 1978 (Garrison & Knauer, 1983). In Shadow Lake, the alum reduced phosphorus concentrations by approximately 0.02 mg/L, and remained stable through to 1983 when Garrison & Knauer (1983) conducted their assessment. Shadow Lake is now considered mesotrophic, and phosphorus levels remain below the levels measured before storm sewer diversion and alum treatment (Garrison & Knauer, 1983).

The objective of this study is to place the current conditions of Shadow Lake in historical context. Comparing diatom assemblages in a single core in Shadow Lake's basin sheds light on how environmental conditions have changed since European settlement, specifically before and after remediation. My study has the potential to demonstrate whether the remediation efforts successfully return Shadow Lake to a relatively natural condition.

METHODS

Diatom Analysis

Samples were taken from a 1.27 m sediment core extracted using a piston corer at a depth of 9.24 m (Wright et al., 1984). The core was sampled every centimeter for Loss on Ignition (LOI) analysis using the methodology of Heiri, et al., 2001. Slides were subsequently prepared using the methodology of Warnock and Scherer (2014). Samples from one-centimeter intervals in the core were chosen for slide preparation. Slides of the intervals that exhibited magnetic susceptibility anomalies or physical changes were chosen for diatom counts and therefore counts were not made at standard intervals (chosen intervals are indicated as individual points in Figures 3 and 4). Twenty-eight slides were counted under 1000x magnification on an Olympus BX50 or Zeiss Primo Star microscope. Ten measured transects or a minimum of 400 diatom valves were counted on each slide. This study focuses on the diatoms that were abundant or signaled environmental changes (Appendix 1).

RESULTS

Interval Distinctions

The interval between 125 cm and 94 cm (Interval 3b) is characterized by dark brown mud containing little $CaCO_3$ (2-20%) and high organic content (63-77%), and medium brown mud containing increased $CaCO_3$ (30-56%) and reduced organic content (33-50%). Medium brown bands correspond with positive magnetic susceptibility anomalies. The interval between 80 cm and 50 cm (Interval 3a) is characterized by a dark brown mud with a lower $CaCO_3$ (3-27%), and high organic content (63-78%). Between 50 cm to 23 cm (Interval 2b), a lighter brown lower band and medium brown upper band is characterized by high $CaCO_3$ (43-63%) content and low organic content (15-34%). From 23 cm to 17 cm (Interval 2b), the sediment exhibits the largest, positive magnetic susceptibility anomaly (4.5 SI at 21 cm), sharp decreases in carbonate (48 to 21% at 20 cm) and organic content (21 to 8% at 20 cm), and an abrupt increase in inorganic content (34 to 71% at 20 cm). The alum layer at 17 cm provides the only date marker of the core because its deposit was documented to have occurred in 1978 (a Pb-210 based age model for this core is being developed). Finally, distinct dark brown, light brown, and cream-colored lamellae characterize Interval 1 between 17 and 11 cm (Figure 2 & 3).

Pennates

All selected species abundances remain negligibly low throughout Interval 3b except for *F. construens. Fragilaria construens* is a species that resides in the

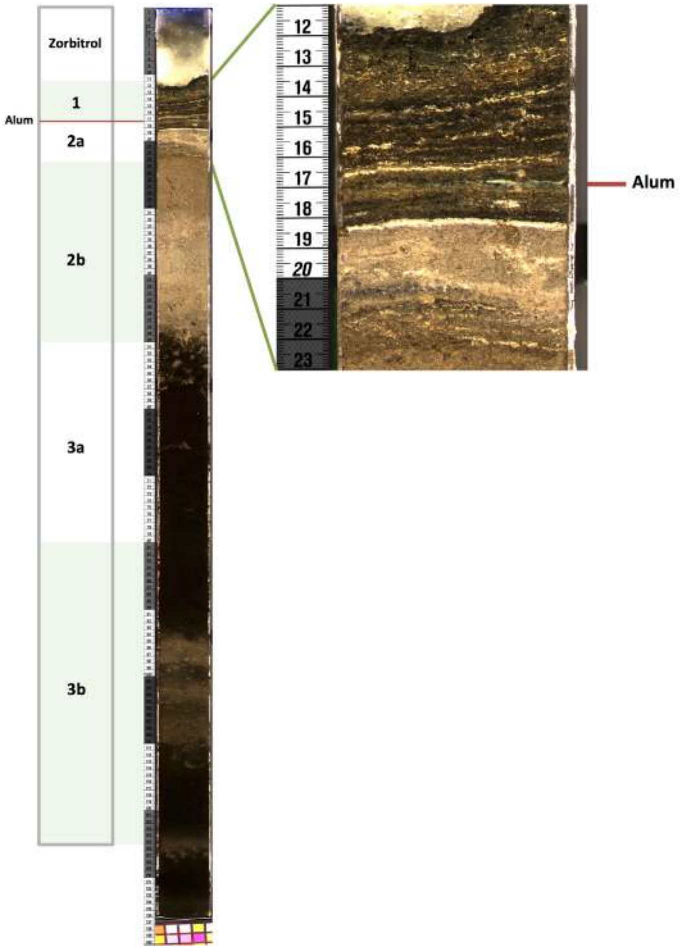


Figure 2. Image of the core divided into intervals. Intervals 1 and 2a are magnified to show the alum layer.

water-sediment interface and is generally found at shallow depths (Brugam et al., 1998). It dominates in Interval 3b, constituting 72-91% of the total number of valves counted (the lower intervals are characterized by the lowest diatom abundances of the core at a range of 2.7×10^4 to 8.4×10^5 valves/gram dry sediment). In Interval 3a, the *F. construens* abundance remains high, but decreases to 42% between 80 cm and 40 cm. It subsequently drops significantly and remains low from 38 cm to 12 cm (Figure 4). (insert Figure 4)

A diatom of the same genus, *F. crotonensis*, a planktonic species associated with eutrophic, light-limited conditions (Reynolds et al., 2002), is negligibly low in abundance from 125 cm to 38 cm. *Fragilaria crotonensis* also displays an abrupt increase from 7% to 29% in Interval 2b. *Fragilaria crotonensis* dominates Interval 1 until 13 cm, when abundances drop to 6%.

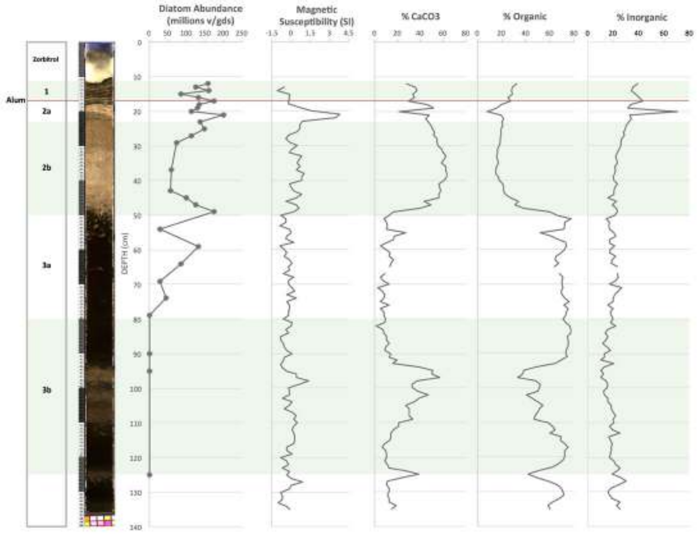


Figure 3. Absolute diatom abundances (millions of valves per gram dry sediment) along with magnetic susceptibility and loss on ignition data. Green-shaded and white regions indicate separate intervals. Magnetic Susceptibility, $\%CaCO_3$, %Organic and %Inorganic data were taken at one centimeter intervals, while the Diatom Abundance data were taken from one centimeter intervals at each specified data point. Intervals 3b and 3a may indicate a period of natural variation in the environment, while Intervals 2a and 2b may indicate the effects of cultural eutrophication. The alum layer terminates Interval 2a and is indicated by the red line. The line provides the only date marker (1978), as we have no dates for the rest of the core. Interval 1 indicates the history of Shadow Lake post-remediation.

Asterionella formosa along with *F. crotonensis* are the only species examined in this study that experiences a distinct increase within Interval 1 (3% to 21%). *Asterionella formosa* is associated with eutrophic and light-limited conditions, similar to *F. crotonensis* and A. *ambigua* (Reynolds et al., 2002).

Centrics

Prior to Interval 2b, the planktonic diatoms A. *ambigua, C. michiganiana,* and S. *niagarae* remain low in abundance, but in Interval 2b at 38 cm, they peak in abundance (16%, 42%, and 5%, respectively). Shear et al. (1976) found that in Ontario Lakes, A. *ambigua* seems to prefer higher temperature and light intensity relative to other *Aulacoseira* species, but in Minnesota lakes, Brugam (1993) found no clear optima for the species.

Cyclotella michiganiana is a planktonic species that is generally found in open water environments. Because they grow in the mid-level of the lake (the metalimnion), they also need good water clarity for photosynthesis (Garrison, 2013).

Discostella stelligera, a planktonic species, peaks to 16% at 19 cm, immediately before the appearance of alum at the end of Interval 2b, but remains low throughout the rest of the core. In Greenland lakes, D. *stelligera* is sensitive to light exposure and nutrient levels (Saros et al., 2016).

The abundance of S. *parvus* peaks abruptly to 33-43% in Interval 2b, *Stephanodiscus parvus* may broadly indicate nutrient enrichment (Edlund et al., 2015). Both S. *niagarae* and S. *parvus* became dominant species during the time of heavy metal pollution into Hamilton Harbour, Lake Ontario, Canada (Yang & Duthi, 1993).

Cyclotella bodanica is one of two species that increases in abundance in Interval 1 (1% to 40%). In Elk Lake, Minnesota, C. *bodanica* coincides when nitrogen and total phosphorus levels are lower (Bradbury et al., 2002).

DISCUSSION

Intervals 3b and 3a

Interval 3b is associated with the lowest diversity total diatom abundance of the entire core. Because *F. construens* dominates this interval and is associated with shallower depths, the lake was possibly shallower at this time (Brugam et al., 1998). The core in this study was taken at a depth of 9.24 m, which may have limited the ability of sunlight to reach the bottom of the lake. This possibility is strengthened by the increase in planktonic diatoms that thrived in Interval 2a and above because planktonic species would require deeper waters.

Interval 2b

Interval 2b may represent the initial effects of human impact as European settlers began to colonize the area. High calcium carbonate content characterizes this interval, suggesting a rise in primary productivity that would allow for the water to become supersaturated with respect to calcium and carbonate. This prolonged period of supersaturation may have resulted from increased sediment input from the construction of surrounding roads, homes and buildings.

Drastic increases occur in abundances of A. *ambigua, C. michiganiana, F. crotonensis, S. niagarae* and S. *parvus*, all of which are planktonic. Their presence may suggest a deepening of the lake, since they require open water to survive. Increasing turbulence resulting from sediment input or increased productivity may also have allowed for heavily silicified species like A. *ambigua* to thrive (Brugam, 1993).

Both A. *ambigua* and S. *niagarae* may indicate mesotrophic to eutrophic conditions in lakes, although generally A. *ambigua* dominate in low to moderate phosphorus concentrations (Garrison, 2013; Hutchinson et al., 1956). Rises in abundances of both *Stephanodiscus* species have coincided with nutrient enrichment and heavy metal pollution in other lakes (Yang & Duthi, 1993; Edlund et al., 2015). Increasing C. *michiganiana* has also coincided with lakeshore development at Moose Lake, Wisconsin (Garrison & Wakeman, 2000). The amplified abundances of these particular species support the assumption that Interval 2b is a product of land development during European settlement.

Interval 2a

Interval 2a characterizes the time period in which Shadow Lake was the most severely impacted prior to alum treatment. Due to its close proximity to the alum layer that was introduced to the lake in 1978, it is assumed that this interval may have accumulated during the early to mid-1900s. The abrupt anomalies in magnetic susceptibility, carbonate, organic and inorganic content that occur at 20 cm may correspond with the dumping of storm sewer drainage into the lake (Figure 2). The positive anomalies in inorganic content and dry bulk density would indicate an increase in the presence of iron oxides or sulfides, which probably came from the urban run-ofF.

F. crotonensis reaches its highest abundances, indicating eutrophic and light-limited conditions. However, D. *stelligera* is shown to grow in the metalimnion and requires good water clarity (Garrison, 2013). The increase in abundances of both

F. crotonensis and D. *stelligera* are contradictory and requires further investigation.

Interval 1

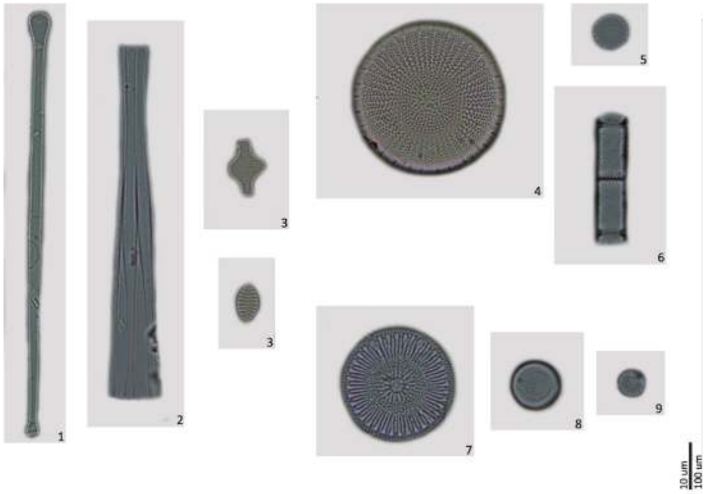
Interval 1 characterizes the time period post-remediation. The organic-rich and carbonate-rich laminations are a result of seasonal variations in thermal stratification. Because there is so little sediment deposited post-remediation, it is difficult to make any clear observations. However, organic content seems to be rising and carbonate content is falling, reflecting the contents of Intervals 3b and 3a (Figure 3). High inorganic content, however, suggests that the lake has not fully recovered from the effects of storm sewer drainage.

In this interval, C. *bodanica* abundances rise quickly, which may indicate low N and lower total P and low nutrient availability (Bradbury et al., 2002; Hixson et al., 2014). *Asterionella formosa* abundances are also correlated with low P levels, but higher N levels (Saros et al., 2005). All of these occurrences suggest that the lake is recovering from eutrophication. However, diatom assemblages indicate that it may not be the case that the lake is reverting to pre-impact conditions, as we see A. *formosa*, a diatom indicative of eutrophic conditions, in Interval 3.

CONCLUSION

Diatom assemblages have changed drastically over the course of Shadow Lake's history as seen in this core. The species abundances paired with the loss on ignition data reveal considerable changes in nutrient loading that resulted in variability in species changes. The species changes indicate a reduction in anthropogenic eutrophic conditions, but not a complete reversal. This study is important as it shows that even without dating the core, one may be able to loosely reconstruct a lake's history using only diatom species abundances and paleolimnological data. It also reveals that interpretations become much more speculative without core dates, as it is difficult to confidently correlate historically documented events with changes in the core without them. However, the assemblages still reveal distinct changes between pre-settlement, early settlement, heavy impact and post-remediation periods. Because the insights provided in this study revealed that Shadow Lake is still experiencing the effects of human-impact prior to remediation, efforts can now be better tailored to remedy the issues unique to Shadow Lake.

APPENDIX



Appendix 1. Selected diatom species used to interpret environmental conditions through time in Shadow Lake.

REFERENCES

Bradbury, P., Cumming, B. & Laird, K. (2002). A 1500-year record of climatic and environmental change in Elk Lake, Minnesota III: measures of past primary productivity. *Journal of Paleolimnology, 27*(3), 321-340.

Brugam, R.B. (1993). Surface sample analogues of Elk Lake fossil diatom assemblages. In Bradbury, J.P. & W.E. Dean (eds), Elk Lake, Minutes nesota: Evidence for Rapid Climate change in the North-Central United States, Boulder Colorado, Geological Special Paper 276: 189–214.

Brugam, R.B., McKeever, K., & Kolesa, L. (1998). A diatom-inferred water depth reconstruction for an Upper Peninsula, Michigan, lake. *Journal of Paleolimnology, 20,* 267-276.

Dixit, S.S., Smo, J.P., & Kingston, J.C. (1992). Diatoms: Powerful indicators of environmental change. *Environmental Science and Technology, 26*(1), 23-33.

Edlund, M. B., Ramstack Hobbs, J. and Williamson, J. (2015). A Paleolimnological Study of Bone Lake, Polk County, Wisconsin. Final Report to Bone Lake Management District. St. Croix Watershed Research Station, Science Museum of Minnesota, Marine on St. Croix, Minnesota.

Garrison, P.J. (2013). A paleoecological study of Waushara County lakes. *Wisconsin Department of Natural Resources, Bureau of Science Services.*

Garrison, P.J. (2014). A paleoecological study of Marathon County lakes. *Wisconsin Department of Natural Resources, Bureau of Science Services.*

Garrison, P.J. & Knauer, D.R. (1983). Lake restoration: A five year evaluation of the Mirror and Shadow Lakes Project Waupaca, Wisconsin. *Environmental Protection Agency.*

Heiri, O., Lotter, A.F. & Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. *Journal of Paleolimnology, 25*, 101–110.

Hixson, J., Stone, J.R., Yeager, K.M., & Schindler, K. (2014, October). Eutrophication Tracking through Interconnected Kettle Lakes in Agricultural Indiana. In 2014 GSA Annual Meeting in Vancouver, British Columbia.

Hutchinson, G.E., Patrick, R., & Deevey, E.S. (1956). Sediments of Lake Patzcuaro, Michoacan, Mexico. *Bulletin of the Geological Society of America, 67,* 1491-1504.

Reynolds, C.S., Huszar, V., Kruk, C., Naselli-Flores, L., & Melo, S. (2002). Towards a functional classification of the freshwater phytoplankton. *J Plankton Res, 24*(5), 417-428.

Saros, J.E., Michel, T.J., Interlandi, S.J, & Wolfe, A.P. (2005). Resource requirements of *Asterionella formosa* and *Fragilaria crotonensis* in oligotrophic alpine lakes: implications for recent phytoplankton community reorganizations. *Canadian Journal of Fisheries and Aquatic Sciences, 62*, 1681-1689.

Shear, H., Nalewajko, C., & Bacchus, H.M. (1976). Some aspects of the ecology of *Melosira spp.* in Ontario lakes. *Hydrobiologia, 50,* 173-176.

Vilmi, A., Karjalainen, S.M., Landeiro, V.L., & Heino, J. (2015). Freshwater diatoms as environmental indicators: evaluating the effects of eutrophication using species morphology and biological indices. *Environmental Monitoring and Assessment 187*, 243.

Wigdahl-Perry, C.R., Saros, J.E., Schmitz, J., Calcote, R., Rusak, J., Anderson, D., & Hotchkiss, S. (2016). Response of temperate lakes to drought: a paleolimnological perspective on the landscape position concept using diatom-based reconstructions. *Journal of Paleolimnology, 55,* 339-356.

Williams, J.J., McLauchlan, K.K., Mueller, J.R., Mellicant, E.M., Myrbo, A.E., Lascu, I., 2015. Ecosystem development following deglaciation: A new sedimentary record from Devils Lake, Wisconsin, USA. *Quaternary Science Reviews 125*, 131-143.

Warnock, J.P. & Scherer, R.P. (2014). A revised method for determining the absolute abundance of diatoms. *Journal of Paleolimnology, 53*(1), 157-163.

Wright, H.E., Jr., Mann, D.H., & Glaser, P.H. (1984). Piston corers for peat and lake sediments. *Ecology, 65*(2), 657-659.

Yang, J., & Duthi, H.C. (1993). Morphology and ultrastructure of teratological forms of the diatoms Stephanodiscus niagarae and S. parvus (Bacillariophyceae) from Hamilton Harbour (Lake Ontario, Canada). Hydrobiologia, 269/270, 57-66.