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Diatom-based interpretation of sediment banding in an urbanized lake

Brian K. Hammer & Eugene F. Stoermer
Center for Great Lakes and Aquatic Sciences, University of Michigan, 2200 Bonisteel Blvd, Ann Arbor, MI 48109–2099, USA (email:bhammer@umich.edu)

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Abstract

Sediment stratigraphy and diatom succession were studied in an 80.5-cm core taken from the deepest part of Third Sister Lake, a small kettle hole in a recently urbanized landscape of southeastern Michigan. Alternating light clay and dark organic bands documented sporadic inputs of clay from outside the basin during rain events, rather than annual laminations. Urban construction activity also disrupted the inflow stream bed and facilitated transport of clay into the lake to generate non-rhythmic banding in the lake's deep hole. Diatom analysis revealed dramatic changes in predominant taxa with sediment depth verifying the non-annual nature of the sediment bands. Observation of halophilic diatom taxa also documented effects of human activity such as road salting on this small, urban lake.

Introduction

Previous descriptions by Eggleton (1931) and Potzger & Wilson (1941) indicated that Third Sister Lake sediments possessed distinct sediment banding of alternating light and dark material. Ludlam (1969) later stated that Third Sister Lake possessed annual laminations or varves, as described for several other lakes (Tippett, 1964; Ludlam, 1969; Saarnisto et al., 1977; Sandman et al., 1990). Coring of Third Sister Lake in 1993 and 1994 revealed that recent sediment bands were not annual, rhythmic varve couplets, but rather laminae of varying thickness. Potzger & Wilson (1941) also reported a maximum depth of 18.5 m at the lake's deepest point, whereas recent measurements indicated a depth of 17.0 m at the deepest part of the lake (Figure 1).

Physical and chemical conditions of lakes may promote deposition of an annual couplet of a dark and light band in sediment. Transport of allochthonous organic material during spring thaws into Cayuga Lake, New York produces varves approximately 1 to 3 cm thick (Ludlam, 1967). During summer in McKay Lake, Ontario, when pH and temperature increase, annual precipitation of calcium carbonate generates varves 0.2 to 1 mm thick (Tippett, 1964). Ludlam (1969) also detailed calcite precipitation in varve formation at Fayetteville Green Lake, New York. Rhythmically laminated sediments in Lake of the Clouds, Minnesota, form by precipitation of iron oxides during spring and fall overturn (Anthony, 1977; Swain, 1978).

Varve formation in eutrophic lakes is often facilitated by biological mechanisms. Lake Lovojärvi, Finland, possesses 2 to 4 mm varves, formed by annual diatom deposits from summer blooms along with seasonal changes in mineral deposits (Saarnisto et al., 1977). Similar varves are found in Lake Heinälampi, Finland, with 1 to 2 mm thick couplets composed of a diatom-rich 'summer' band and a diatom-poor 'autumn-winter-spring' band (Sandman et al., 1990).

Not all sediment laminations are annual in nature. Sediment banding patterns of varying thickness indicate that the time between depositional events is variable, resulting in non-annual laminations. Unpredictable events like climate (Perkins & Sims, 1983; Page et al., 1994), floods (Ludlam, 1967; Lambert & Hsü, 1979), landslides (Nipkow, 1928), and volcanic eruptions (Anderson et al., 1985) may cause sporadic deposits of clay or sand into a lake bottom. Similarly, human activities that expose soil to erosion, such as removal of forest vegetation (Davis, 1976) and construction activities (Wolman & Schick, 1967; Fredrick-

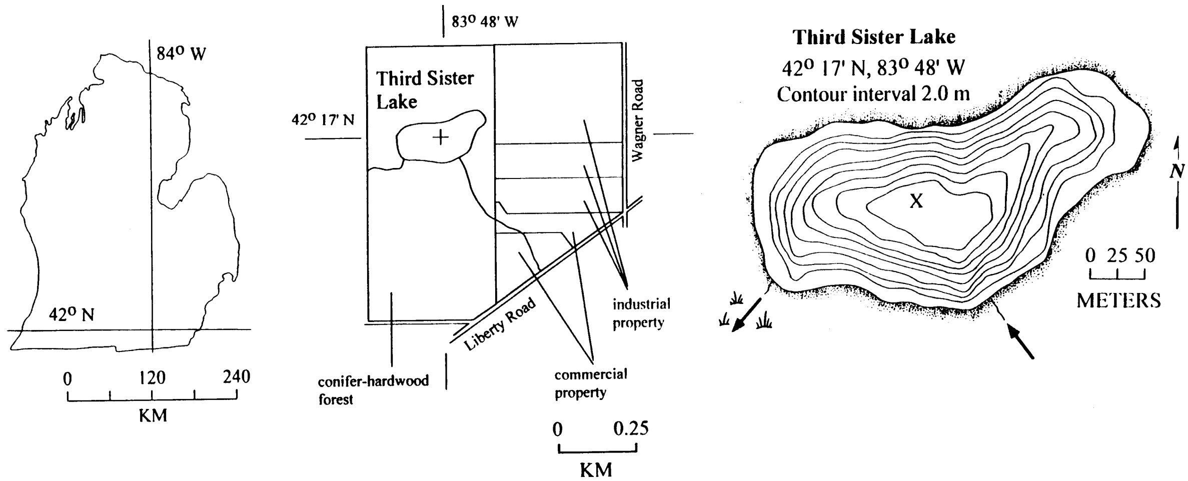

Figure 1. Index map of Third Sister Lake and surroundings showing bathymetry and location of the cores (X) in the deepest part of the lake (17.0 m).

sen, 1965) also contribute to deposition of thick clay bands in lake sediment.

Detailed documentation of band stratigraphy is lacking for Third Sister Lake sediments. Such analysis is essential for ascertaining the current nature of banding in this kettle hole lake. Diatom microfossils have proven useful in previous studies to determine the nature of lake sediment banding patterns (Simola, 1977; Sandman et al., 1990). Annual bands of productive lakes often contain annual composites of the diatom community; similarly, seasonal couplets display seasonal diatom communities.

Since 1963, urbanization has transformed the landscape surrounding Saginaw Forest from one dominated by agriculture to a region with industrial and commercial uses. (Figure 1). Urbanization often has profound effects on diatom communities through cultural eutrophication (Nipkow, 1928; Stockner & Benson, 1967; Engstrom et al., 1985). As a result, diatom succession in recent sediments of Third Sister Lake should provide evidence for evaluating both the origin of sediment deposition as well as the impacts of urbanization on species composition. The objectives of this study were: 1) to elucidate the nature of modern sediment bands in Third Sister Lake; 2) to analyze diatom microfossils from the recent sediments and water column of Third Sister Lake to clarify the nature of sediment banding patterns; and 3) to document recent changes in the diatom community of this small, urban lake.

Study site

Third Sister Lake (42 °17′ N., 83 °48′ W.) is located approximately three miles west of Ann Arbor in the Saginaw Forest of Scio Township, Michigan (Figure 1). This small kettle lake likely formed during the retreat of the Wisconsin glacier, which created a terminal moraine in southern Michigan (Reed, 1902). Mature conifer plantations and hardwood stands of Saginaw Forest shelter Third Sister Lake. Although the lake stratifies in the summer, spring mixing does not occur every year (Lehman & Naumoski, 1986). The present maximum depth is 17.0 m, and the surface area about 3.8 ha. A small intermittent stream enters the lake on the south shore and a single outflow on the southwest shore drains through a small marsh (Figure 1) to the Huron River.

Although Saginaw Forest surrounds Third Sister Lake on a 32 ha tract, significant construction has occurred in the watershed since the 1960s. Agricultural activities originally occupied the entire area east of Saginaw Forest. Currently, this adjacent property is subdivided into several small plots (Wojcik, 1993, personal communication) where industrial and commercial construction has occurred from 1963 to the present (Figure 1). Contamination of Third Sister Lake and local groundwater with 1,4-dioxane was revealed in the 1980s following leakage from an unlined, oxidation lagoon on Gelman Sciences, Inc. property bordering the lake (Brode & Minning, 1988). The most recent project in the adjacent lot, initiated in 1987, included retention pond construction with an outflow that transports stormwater from this nearby property into the inflow stream bed in Saginaw Forest. Ultimately this stormwater reaches Third Sister Lake 300 m downstream. Although erosion barriers were erected in the stream bed on university property, these barriers have since been undercut and subverted by stream flow, creating a gully with steep banks of unconsolidated soil.

Table 1. Diatom taxa used in Principal Components Analysis and Discriminant Analysis. Taxa chosen were present in three or more bands at > 5% relative abundance

Achnanthes minutissima Kütz.
Asterionella formosa Hass.
Cyclotella michiganiana Skv.
Cyclotella stelligera (Cl. & Grun.) V.H.
Cymbella microcephala Grun.
Fragilaria capucina Desm.
Hantzschia amphioxys (Ehrenb.) Grun.
Luticola mutica (Kütz.) Mann
Stephanodiscus hantzschii Grun.
Stephanodiscus minutus Grun.
Stephanodiscus parvus Stoermer & Håkansson
Synedra tenera W. Sm.

Methods

On 16 February 1993, an 80.5-cm sediment core (core #1) was taken from Third Sister Lake's 17.0-m deep hole (Figure 1) using a square rod piston corer (Livingstone, 1955). Core #1 was frozen and cut lengthwise into three slices. The inner, rectangular slice was polished on both sides at 4 °C with a knife in preparation for analysis and photographic documentation (Figure 2). In this study, only the top 33 cm of the 80.5-cm core were photographed and sampled for analysis. The lake was cored again on 18 August 1994, using a modified benthos corer to ascertain the annual nature of sediment deposition. This 36-cm core was similarly prepared for analysis and photographic documentation (core #2, Figure 2). Although the entire 36-cm core was photographed, only a single surficial sample of the 36-cm core was analyzed. Frozen core slices were placed on dry ice, sprayed with water on the surface to enhance contrast, and photographed to document sediment stratigraphy. Representative samples of each band were obtained by dissection with a razor blade and forceps, and stored at −20 °C in plastic scintillation vials.

Plankton samples were collected and preserved *in situ* from Third Sister Lake at biweekly intervals from 7 April 1993 to 5 February 1994. A small aliquot of each sample was prepared as a wet mount and examined for qualitative analysis of preserved phytoplankton. Following examination of wet mounts, each sample was concentrated to a volume of 10 ml by settling for 48 hours, and then cleaned and prepared for qualitative analysis of diatom frustules.

Approximately 0.5 g of each sediment sample (or 10 ml of each concentrated water sample) was cleaned with 30% hydrogen peroxide and the addition of potassium dichromate as an oxidation catalyst (Van der Werff, 1955). For several thin bands, approximately 0.25 g of sediment was cleaned. Following washing to eliminate oxidation byproducts, an ∼200 μl aliquot of each cleaned sample (∼100 μl aliquot of a 0.25 g sample) was placed onto a 22 × 22 mm coverslip. The 200 μl aliquot served as a 'standard aliquot' for comparison between samples. Coverslips were dried overnight at room temperature and permanently mounted on glass microscope slides with Hyrax^{TM} mounting medium (refractive index, 1.63), according to Patrick & Reimer (1966).

Diatom analysis

For core #1, all diatom valves along three random transects were enumerated under oil immersion using a Leitz Wetzlar Ortholux microscope (950X, N.A. ≥ 1.3). When greater than 500 intact valves were counted prior to completion of three transects, the transect being enumerated was discontinued under the assumption that sufficient counts had been made. Counts from multiple transects of each slide were pooled. All identifiable valves and fragments were enumerated with valve fragments categorized according to size and reconstituted to whole diatom units (Glover, 1982). Species identification was primarily based on Patrick & Reimer (1966, 1975) and Krammer & Lange- Bertalot (1986, 1988, 1991a, 1991b). For qualitative analysis of the surficial sample from the top of core #2, diatom valves along random transects were viewed under oil immersion (950X, N.A. ≥ 1.3). Observed taxa were recorded and predominant taxa noted.

Quantitative counts of samples from core #1 were used for statistical analysis. Raw numbers were recorded and relative abundance data generated for each taxon in each band. Statistical analyses were performed

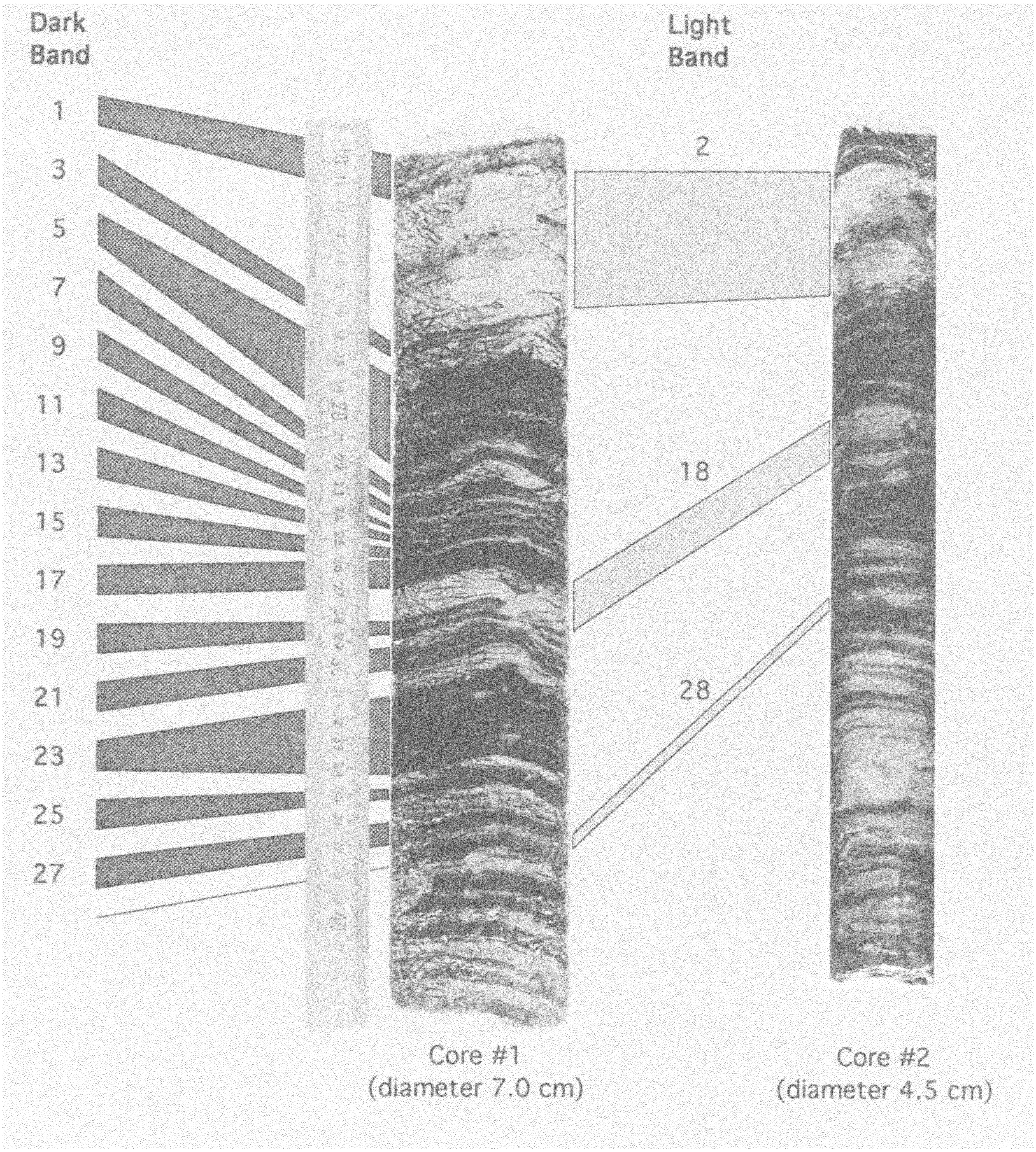

Figure 2. Comparison of core #1 from 16 February 1993 and core #2 from 18 August 1994. Although the scale is identical for both cores, note differences in corer diameter. Dark bands were numbered on core #1, and several light bands were identified between both cores.

on relative abundance of the twelve predominant taxa with greater than 5% relative abundance in at least three bands (Table 1). Plotting and statistical analyses were performed using the SYSTAT statistical package (Wilkinson, 1989). Discriminant Analysis was performed to test whether diatoms in visually discerned bands were classified together. Principal Components Analysis was also employed to categorize all bands into major groupings regardless of visual distinction.

Precipitation and construction data

Precipitation data were obtained from the National Weather Service with assistance from Dennis Kalbaum, weather observer for The University of Michigan and the city of Ann Arbor. These data were published in the National Atmospheric and Oceanographic Administration data for Michigan. Dennis Wojcik, Scio Township engineer, provided information regarding construction permits and zoning.

Results

Sediment stratigraphy

Examination of sediment core #1 revealed a conspicuous pattern of alternating light and dark bands that continued for the entire length of the 80.5-cm core. Band thickness varied from 0.2 cm to 5 cm (Figure 2), similar to Eggleton's (1931) descriptions of 0.5 cm to 2 cm bands from the same lake. Our diatom preparation verified Eggleton's observations (1931) that light bands were primarily clay and devoid of organic material, whereas dark bands had substantial organic material and less mineral debris. The first twenty-eight alternating light and dark bands were numbered sequentially (band 1 was the first dark band at the sediment-water interface, band 2 the first light band).

Core #2 (Figure 2) verified the non-rhythmic banding pattern observed in core #1. Comparison of both cores revealed that relative positions of major bands were similar, and each displayed a conspicuous 5 cm clay band near the top of the core. Although consistent relative band thickness was observed, absolute thickness of a particular band varied between cores #1 and #2, suggesting core foreshortening or minor differences in sampling location.

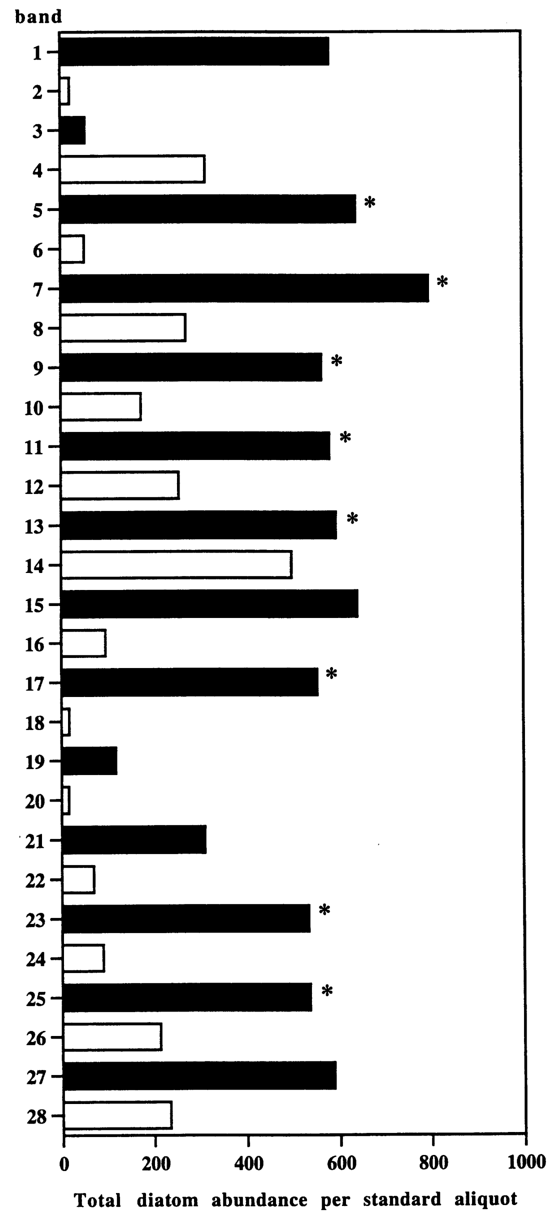

Figure 3. Total abundance of diatom valves per standard aliquot for bands 1 to 28 of sediment core #1 from Third Sister Lake. * Indicates that the third transect was terminated prior to completion.

Diatoms stratigraphy of core #1

A total of 188 diatom taxa were encountered in analysis of bands 1 through 28 from core #1. Dark organic bands showed greater total microfossil abundance than the light clay bands, with the exception of low counts

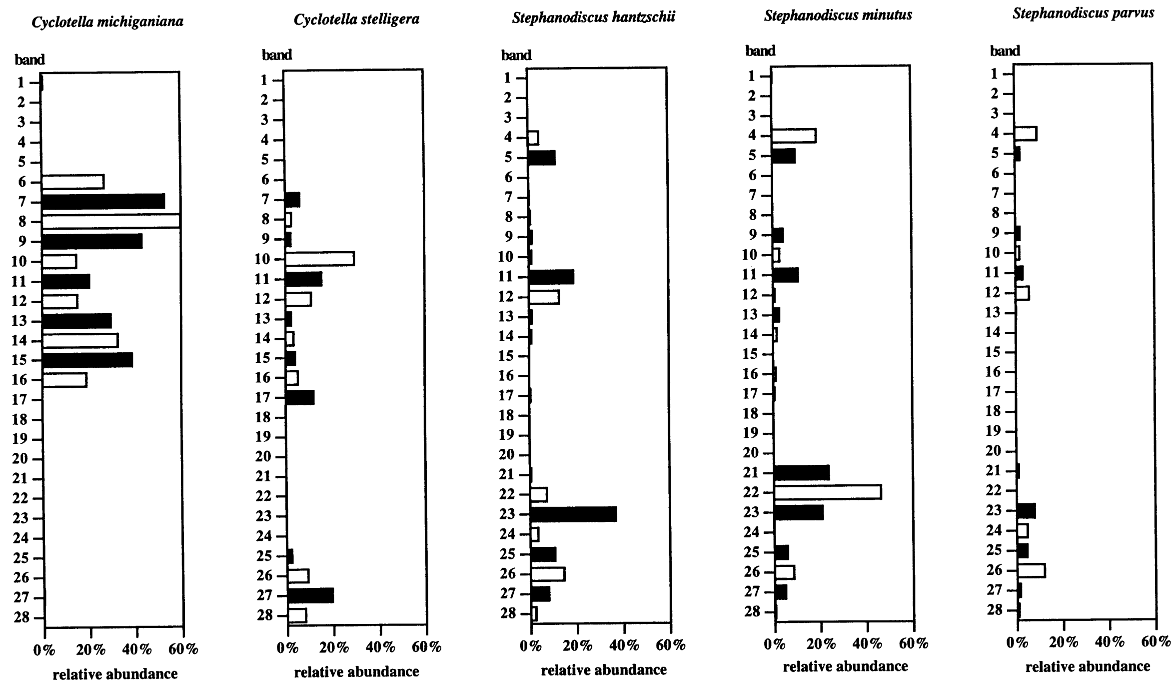

Figure 4. Stratigraphic profile for predominant *Cyclotella* and *Stephanodiscus* species counted in bands 1 to 28 of sediment core #1 from Third Sister Lake.

in dark bands 3 and 19, and a rather high count in light band 14 (Figure 3).

Planktonic forms dominated the sediment assemblage of Third Sister Lake. *Cyclotella michiganiana*, although absent from the core below band 16, was the dominant planktonic taxon present in bands 6 through 16, achieving a maximum relative abundance of 59.6% in band 8 (Figure 4). This centric diatom was dominant throughout a series of light and dark bands, yet remained absent from the core above band 6 (with the exception of a relative abundance of less than 1% in band 1). Consistent with its absence from the top of core #1, *Cyclotella michiganiana* was also lacking from all plankton and whole water samples collected between 17 April 1993 and 5 February 1994, and was not recorded in the surficial sample from core #2. *Cyclotella stelligera*, another predominant planktonic form in Third Sister Lake, was present deep in core #1 in bands 25–28 (Figure 4). Like *C. michiganiana, C. stelligera* appeared in the middle bands (7 through 17) of core #1 (Figure 4) and was absent from core #1 above band 6. This planktonic diatom was also absent from live collections and undetected in the surficial sample from core #2.

With the exception of *Cyclotella stelligera* in bands 25 through 28, the lower portion of the core had a planktonic assemblage dominated by *Stephanodiscus* species, particularly *S. minutus*, *S. hantzschii*, and *S. parvus*. These centric diatoms represented the predominant planktonic flora found throughout bands 21 through 28 and reached maximum relative abundances in bands 22, 23, and 26 respectively (Figure 4). All three displayed a lone peak across bands 11 and 12; and another peak in bands 4 and 5 that declined above and below.

Asterionella formosa, a common planktonic pennate diatom, displayed low abundance in band 18 and remained absent from much of the core (Figure 5). Reappearing in band 5 with a relative abundance of 16.0%, this eurytopic diatom dominated band 1 with a relative abundance of 37.5%. In contrast to the predominant centrics that were absent from the surficial band of core #2 and live collections, *A. formosa* was present in the surficial band of core #2 and was also a major component of both whole water and vertical plankton samples. Commonly described as a summer taxon, this planktonic diatom was present throughout most of year in the water column of Third Sister Lake. The greatest abundance of *A. formosa* in whole water

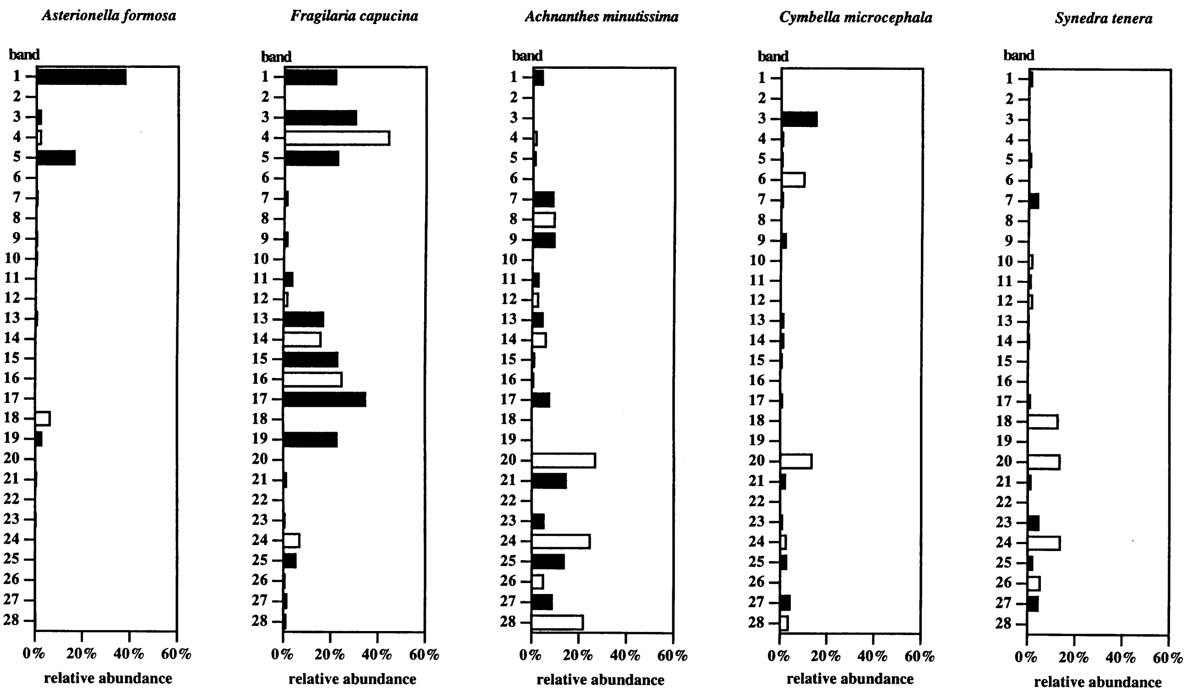

Figure 5. Stratigraphic profile for additional predominant taxa counted in bands 1 to 28 of sediment core #1 from Third Sister Lake.

and plankton samples was observed from mid-winter to early summer. *A. formosa* was a predominant taxon in several bands and absent from other bands, similar to the successions observed for the other predominant taxa. However, dissolution (Parker & Edgington, 1976), or fragmentation of its fragile frustules due to zooplankton grazing (Ferrante & Parker, 1977; Glover, 1982) may account for the distribution of *A. formosa* in core #1.

Fragilaria capucina, although a predominant planktonic pennate in the top of core #1 (bands 1, 3, 4, and 5), displayed very low abundance in bands 6 through 12 (Figure 5). It appeared again in high abundance in bands 13 through 17, and 19, and was of minor importance in the remaining bands. Its spotty distribution was difficult to interpret due to its wide seasonal, nutrient and pH tolerances.

Relative abundance of *Achnanthes minutissima*, a common warm water diatom, varied considerably throughout the core as did the abundance of the periphytic diatom *Cymbella microcephala* (Figure 5). Likewise, *Synedra tenera*, which is found in a variety of habitats, appeared occasionally throughout the core and its sedimentary distribution was difficult to interpret (Figure 5).

Hantzschia amphioxys, a ubiquitous soil diatom (Lund, 1945), occurred in substantial relative abundance in light clay bands and in low relative abundance in dark organic bands (Figure 6). This aerophilic diatom prefers moist rather than submerged habitats. Similarly, *Luticola mutica*, another common soil diatom (Lund, 1945) displayed a stratigraphic distribution of alternating dominance in light bands and absence in dark bands (Figure 6).

Visual classification into light and dark bands suggested that if clay bands were created by inputs from outside the basin, diatom assemblages in light clay bands should be different than assemblages in dark organic bands. Discriminant Analysis using the relative abundances of the twelve predominant taxa, and classification of bands as light or dark prior to analysis, correctly classified bands into the two band types (light and dark) with an error rate of 10.71% or 3/28 (Figure 7).

Principal Components Analysis based on relative abundances of the twelve predominant taxa was utilized for grouping of bands without classification of bands as light or dark prior to analysis (Figure 8). The first two principal components (PC1 and PC2) explained 61.02% of the total variance and divided

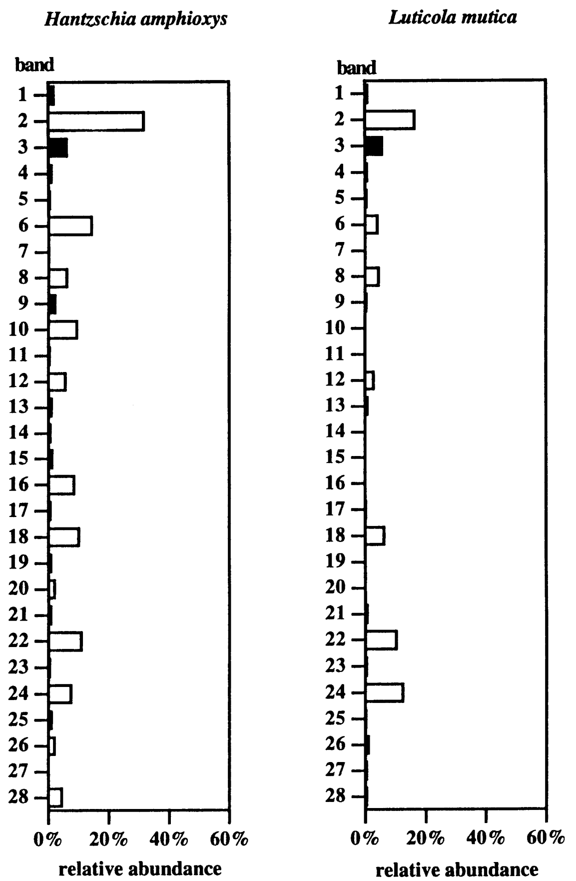

Figure 6. Stratigraphic profile for predominant soil diatoms counted in bands 1 to 28 of sediment core #1 from Third Sister Lake.

bands into four groups (A, B, C, and D). Groups A and B had relatively large numbers of *Cyclotella* and *Stephanodiscus* species. Group A included bands 6 through 12, bands dominated by both *C. michiganiana* and *C. stelligera*. Group B included the sequence of bands 20 through 28, dominated by *Stephanodiscus* taxa. Contrary to the predominance of centric flora in Groups A and B, pennate diatoms were more plentiful in Groups C and D. Bands 13 through 16 comprised Group C, bands dominated by *Fragilaria capucina* and *Cyclotella michiganiana*, as well as a minor contribution by *C. stelligera*. The remaining bands in Group D consisted of bands 1, 3, 4, 5, 17 and 19 dominated by *F. capucina* and *Asterionella formosa*. Principal Components Analysis showed groupings unrelated to our visual classification, and suggested that the low relative abundances of soil diatoms were less important than the high relative abundances of other taxa.

Diatoms of core #2

The single surficial sample dissected from core #2 contained sediment deposited approximately between 16 February 1993 and 18 August 1994, encompassing the biweekly collection dates for whole water and plankton samples. Since core #2 was collected one and one-half years after core #1, the surficial sediment of core #2 likely contained diatoms deposited after those observed at the top of core #1. Most of the predominant taxa observed in core #1 sediment were absent from both the surficial band of core #2 and water column, or only observed as subdominants. Predominant, planktonic diatoms in core #1, such as *Stephanodiscus* and *Cyclotella* taxa, were absent from the surficial sediment of core #2 as well as from plankton and whole water samples. *Cymbella microcephala*, a predominant epipelic form from core #1, was not recorded in core #2 surficial sediments or any water or plankton samples. *Achnanthes minutissima*, predominant in core #1, was a subdominant in three plankton samples and observed in surficial sediments. *Hantzschia amphioxys* and *Luticola mutica* were present in surficial sediment of core #2, yet absent from biweekly water samples.

Several predominant diatoms counted in core #1 were also observed in biweekly plankton samples and in the surficial sediments of core #2. *Asterionella formosa* was one of the predominant planktonic diatoms recorded in the surficial sediment and in whole water and plankton samples collected from mid-winter through early summer, consistent with its appearance at the top of core #1. *Fragilaria capucina* was a prominent member of the planktonic community both in water and plankton samples, and was also present in the surficial sediment of core #2, along with *F. capucina* var. *mesolepta* Rabh. and *F. crotonensis* Kitton.

In addition to diatoms previously recorded in core #1, several taxa were observed in surficial sediment of core #2 and live samples, previously unrecorded in core #1. *Cyclotella bodanica* Grun. was the dominant planktonic form in the surficial sediment band of core #2. Appearance of *C. bodanica* in recent sediment was supported by observations of this taxon in a majority of plankton and whole water samples, commonly as the dominant diatom recorded. *Stephanodiscus niagarae* Ehrenb. was also present in numerous water and plankton samples and on one occasion was the dominant planktonic diatom observed. The epizoic diatom *Synedra cyclopum* Brutschy (Gaiser & Bachmann, 1993) was also present in plankton and whole water samples, yet absent from core #1. *S. cyclopum*,

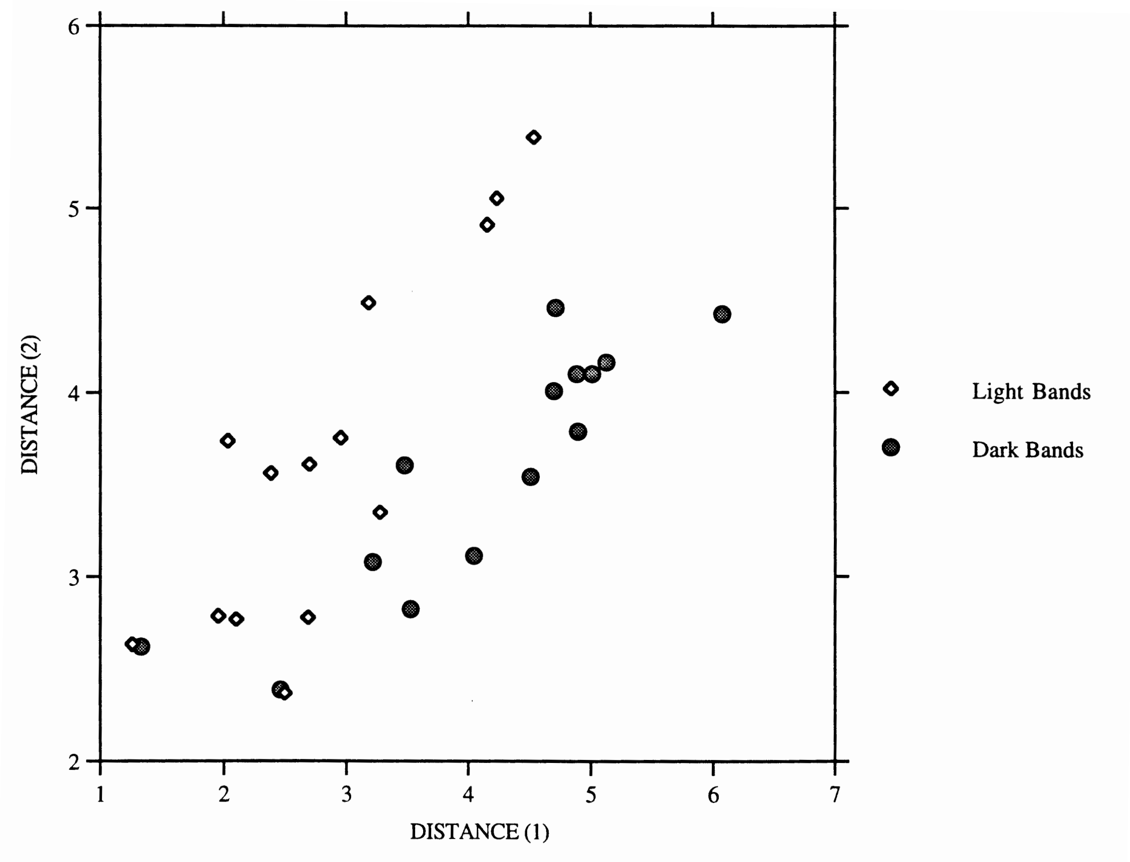

Figure 7. Discriminant analysis of alternating light and dark bands (1 to 28) based on relative abundance of twelve predominant taxa in core #1 from Third Sister Lake.

like *Stephanodiscus niagarae*, was a subdominant in water samples collected, but not observed during qualitative analysis of surficial sediment from core #2.

Unusual diatoms

Several brackish water diatoms were observed in sediment bands and water samples from Third Sister Lake. *Ctenophora pulchella* (Ralfs ex Kütz.) Williams & Round, a mesohalobous diatom (Foged, 1953; Patrick & Reimer, 1966; Lowe, 1974), occurred in several bands (1, 3, 4, 5, and 12) and was also recorded qualitatively in observations of the surficial band of core #2, plankton samples, and whole water samples. *Gyrosigma obscurum* (W. Sm.) Griff. & Henfr., described by Patrick & Reimer (1966) as preferring slightly to highly brackish water, was counted in bands 1 and 4 of core #1, observed in numerous plankton and whole water samples, and recorded in surficial sediment from core #2. Krammer & Lange-Bertalot (1986) also characterized this benthic diatom as a brackish water form. In addition, *Plagiotropis lepidoptera* var. *proboscidea* (Cl.) Reim., characteristic of brackish or marine waters (Patrick & Reimer, 1975), was observed in cursory analysis of surficial sediment from core #2 and in several vertical plankton samples.

Discussion

Third Sister Lake possessed banded sediments as described by Eggleton (1931), however, the banding pattern of the recent sediments was not annual as previously described (Eggleton, 1931; Potzger & Wilson, 1941; Ludlam, 1969), but event-driven. Variations in band thickness from 0.2 to 5 cm suggested that the time between depositional events was variable. The mechanism of band formation was one of allochthonous min-

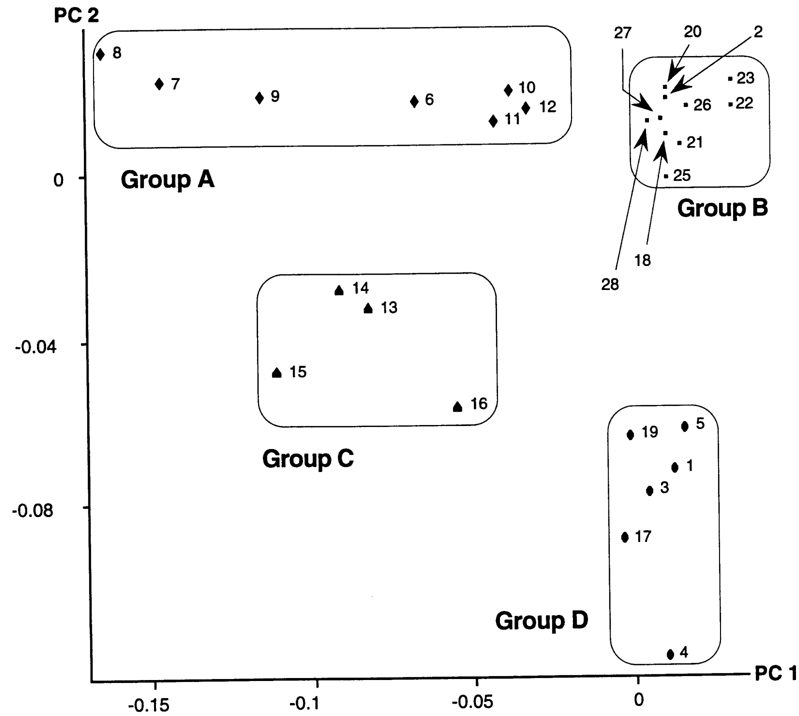

Figure 8. Principal Components Analysis of bands 1 to 28 of sediment core #1 from Third Sister Lake, based on relative abundance of twelve predominant taxa. Numbers refer to bands, and groups were designated with letters following inspection of analysis.

eral inputs from the intermittent stream feeding the lake. Since stream inputs are instrumental in formation of sediment laminations in certain lakes (Ludlam, 1967), factors affecting stream flow have profound effects on band thickness and frequency. Unusually thick clay bands found in two cores from the deep hole of the lake correlated with disturbances to the stream bed of the inflow. Construction of an office park and retention pond on property adjacent to Saginaw Forest in approximately 1988, resulted in scouring of the stream bed on university property and ultimate deposition of a large pulse of clay into the lake (Charles Olson, 1995, personal communication). This surge of clay material was sufficient to create a delta at the stream mouth and a 5-cm thick clay band in the deep hole.

Precipitation records since 1972 highlighted 1990 as an unusually wet year with total annual precipitation of 47.19 inches, the highest recorded in 22 years examined (Figure 9). There were ten days during 1990 that experienced major storm events with precipitation accumulations of $\geq$1.00 inches (Figure 10). For the years studied, only 1985 possessed more major storm events with eleven. The frequency and intensity of storm events during 1990 supported development of storm-induced laminations observed in the recent Third Sister Lake sediments.

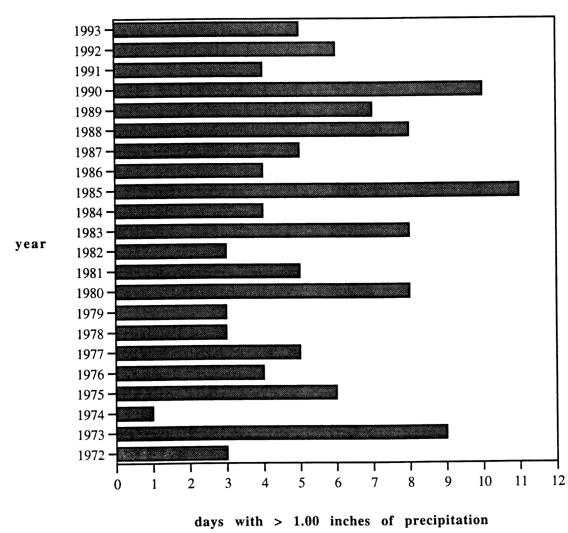

Figure 9. Total annual precipitation for Ann Arbor, Michigan from 1972 to 1993 (National Weather Service data).

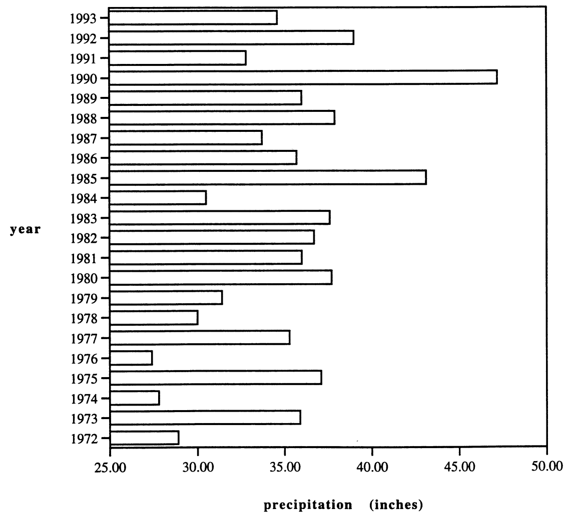

Figure 10. Major storm events for Ann Arbor, Michigan from 1972 to 1993. Days with greater than 0.99 inches of precipitation were classified as days with major storm events (National Weather Service data).

Lake sediments were not dated using radioisotope techniques for a variety of reasons. ^{210}Pb dating models assume constant flux of sediment into the lake, and require estimation of the 'supported' lead component derived from ^{226}Ra levels in eroded material deposited into the lake (Häkanson & Jansson, 1983). Massive variations in storm-induced sediment deposition made this method inappropriate. The other commonly used radioisotope for dating recent sediments is ^{137}Cs. As with ^{210}Pb dating, ^{137}Cs is most successful in lakes with primarily autochthonous sedimentation. This method also requires a core of sufficient depth to use the 1963 peak in ^{137}Cs activity for calibration of sediment isotope levels (Häkanson & Jansson, 1983). It was unlikely that our 80.5-cm core was long enough to include the 1963 peak, due to the large clay inputs punctuating the profile. As a result, the absolute age of the sediment cores collected remained unclear.

Due to the sporadic effects of precipitation on sediment deposition, the 80.5-cm core may have represented accumulations of only a few years to as much as several decades. Previous descriptions of sediment banding in Third Sister Lake (Eggleton, 1931; Potzger & Wilson, 1941) implied that earlier sedimentation was annual, whereas our findings indicated that the recent sedimentation was storm-induced. A longer core of sediment may permit both accurate dating of sediments, as well as provide clarification that arrhythmic sedimentation was solely a recent phenomenon visually distinct from observations noted in 1941 (Potzger & Wilson, 1941).

Clay bands possessed fewer diatoms than organic bands due to dilution of diatoms by large clay inputs in this lake. It is possible that a clay band, formed during a storm event, only contained both diatoms transported from outside the basin (such as *Hantzschia amphioxys* and *Luticola mutica*) and those present in the lake during the storm. A clay band may have been produced in only a few days, and exceed 1 cm in thickness, depending on the severity of the storm. An organic band likely formed during the time period between major storm events and contained diatoms that settled into the organic sediment over that entire period. A long interval between major storm events may have produced a thin dark band containing numerous diatoms from that extended period of time. Hence, clay bands contained fewer diatoms diluted in large quantities of clay, and thin organic bands contained numerous diatoms concentrated in a thin organic layer (Figure 3). Since frequency of storm events is unpredictable, intervals between storm events also vary. This accounted for varying thickness of dark bands, which typically contained a more diverse diatom assemblage and a greater total number of diatom valves.

Third Sister Lake was dominated by planktonic *Stephanodiscus* species at the bottom of core #1. These taxa were replaced by another planktonic taxon, *Fragilaria capucina*. As this diatom's abundance waned, *Cyclotella* species became the predominant planktonic diatoms in the middle of core #1. These centrics were followed by *F. capucina* which reappeared along with *Asterionella formosa* in the lake sediments most recently. The unusual diatom stratigraphy observed indicated that this urban lake is dynamic, with rapid changes in predominant diatom taxa. Depending on the intensity and frequency of allochthonous deposition, variations in common diatom taxa may have described changes over the course of many years, or may have detailed the succession of taxa during a period of only a few years.

If Third Sister Lake sediment laminations were generated by annual deposition of couplets, then the diatom assemblage would have reflected this annual pattern as observed in several varved lakes (Tippett, 1964; Simola, 1977; Sandman et al., 1990) The only predominant taxa in Third Sister Lake that displayed a rhythmic appearance and disappearance synchronized with the banding patterns were *Hantzschia amphioxys* and *Luticola mutica*. The stratigraphy of these taxa was determined by habitat preference, not seasonal preference, thereby supporting the hypothesis of storm-induced sedimentation.

Principal Components Analysis separated bands into four groups (Figure 8) which may relate to storm frequency. A sequence of several storms may have generated a series of numerous thin bands all with similar diatom assemblages. Infrequent storms, that permitted greater deposition of organic material from a longer period of time, allowed accumulation of a more diverse assemblage of diatoms. Numerous storm events during one summer may have created a sequence of thin bands all dominated by summer taxa like *Cyclotella stelligera* and *C. michiganiana*. Frequent spring storms may have generated runoff laden with clay sufficient to produce a series of bands dominated by spring taxa such as *Stephanodiscus* species. Stormwater inputs likely transported fertilizers and other nutrients which may have contributed to rapid changes in predominant taxa.

Although Principal Component 1 (PC1) and Principal Component 2 (PC2) together explained 61.02% of the total variance, these components are arbitrary linear functions of the original variables (relative abundances). PC1 possibly separated bands based on season preference, with Groups B and D toward the right, containing spring *Stephanodiscus* and *Asterionella* species. Toward the left of the graph, Group A contained summer *Cyclotella*, but Group C contained spring *Fragilaria capucina*. However, PC1's representation of seasonal preference did not explain placement of Group C. PC2 appeared to separate taxa into pennates (on top) and centrics (on bottom). Principal Components Analysis confirmed that sequences of bands contained similar taxa, contrary to an alternating annual succession. Discriminant Analysis (Figure 7), on the other hand, verified visual observations by classifying light clay bands as distinct from dark organic bands based solely on the relative abundance of the twelve predominant diatoms.

Biweekly water samples of Third Sister Lake documented the absence of planktonic taxa that were predominant in core #1, as well as the appearance of several taxa not observed in core #1. Such observations indicated that this small urban lake has undergone major changes in the diatom community. Predominant taxa continually changed with others disappearing altogether from the sediments or water column. Deniseger et al. (1986) recorded similar observations of changing diatom flora in Buttle Lake, British Columbia following heavy metal contamination of the lake from acid seepage. Although metal levels decreased, previous predominant taxa did not rebound, but were replaced by one dominant taxon, *Rhizosolenia eriensis*.

Appearance of halophilic diatoms, like *Plagiotropis lepidoptera* var. *proboscidea* and *Ctenophora pulchella*, suggested that salinity may be an additional factor influencing diatom distribution in Third Sister Lake. Between 1980 and 1988, conductivity at Third Sister Lake rose from approximately 200 μs cm^{-1} to 1200 μs cm^{-11} (S. McNaught, unpublished data). In 1994 the range in conductivity was from approximately 600 μs cm^{-1} at the surface to 900 μs cm^{-1} at 16 m. Judd (1969) recorded meromixis and changes in benthic species composition at nearby First Sister Lake due to inputs of salt from road deicing. Our observations of halophilic diatoms suggested that similar anthropogenic effects may have affected both chemical and biological characteristics of Third Sister Lake. Parking lot construction upstream of the lake likely facilitated transport of stormwater runoff high in salt during the winter. It is also possible that temporary pools of saline water on the parking lots in winter may have supported growth of halophilic diatoms, such as *P. lepidoptera* var. *proboscidea*, ultimately transported with water into Third Sister Lake.

Salt water inputs further facilitate formation of strong density gradients, prevent mixing of the lake, and aid in sediment lamination formation through exclusion of burrowing insects from anoxic benthic sediments. It is important to note that Third Sister Lake developed anoxia prior to road deicing techniques in the area (Eggleton, 1931) which is not uncommon for a sheltered lake that is deep relative to its surface area.

Urbanization surrounding Saginaw Forest had dramatic effects on the chemistry, and both the predominant and subdominant diatom flora of Third Sister Lake. The primary repercussion of this recent urbanization was massive sedimentation of the lake basin which had profound effects on the benthic habitats and diatom assemblages of this small, urban lake.

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References

Anderson, R. Y., E. B. Nuhfer & W. E. Dean, 1985. Sedimentation in a blast-zone lake at Mount St. Helens, Washington-implications for varve formation. Geology 13: 348–352.

Anthony, R. S., 1977. Iron-rich rhythmically laminated sediments in Lake of the Clouds, northeastern Minnesota. Limnol. Oceanogr. 22: 45–54.

Brode, J. W., Jr. & R. C. Minning, 1988. Report of phase III hydrogeologic investigation, as cited in R. Hartung. 1989. Health and environmental effects assessment for 1,4-dioxane. Gelman Sciences, Inc. 124 pp.

Davis, M. B., 1976. Erosion rates and land-use history in southern Michigan. Environmental Conservation 3: 139–148.

Deniseger, J., A. Austin, M. Roch & M. J. R. Clark, 1986. A persistent bloom of the diatom *Rhizosolenia eriensis* (Smith) and other changes associated with decreases in heavy metal contamination in an oligotrophic lake, Vancouver Island. Environmental and Experimental Botany 26: 217–226.

Eggleton, F. E., 1931. A limnological study of the profundal bottom fauna of certain fresh-water lakes. Ecological Monographs 1: 231–332.

Engstrom, D. R., E. B. Swain & J. C. Kingston, 1985. A palaeolimnological record of human disturbance from Harvey's Lake, Vermont: geochemistry, pigments and diatoms. Freshwater Biology 15: 261–288.

Ferrante, J. G. & J. I. Parker, 1977. Transport of diatom frustules by copepod fecal pellets to the sediments of Lake Michigan. Limnol. Oceanogr. 22: 92–98.

Foged, N., 1953. Diatoms from West Greenland. Medd. Om Grønl. 147: 1–86.

Fredricksen, R. L., 1965. Sedimentation after logging-road construction in a small western Oregon watershed. Proceedings of the Federal Inter-Agency Sedimentation Conference 1963: U.S. Department of Agriculture Misc. Pub. 970: 56–59.

Gaiser, E. E. & R. W. Bachmann, 1993. The ecology and taxonomy of epizoic diatoms on Cladocera. Limnol. Oceanogr. 38: 628–637.

Glover, R. M., 1982. Diatom fragmentation in Grand Traverse Bay, Lake Michigan and its implication for silica cycling. Ph.D. thesis. The University of Michigan.

Häkanson, L. & M. Jansson, 1983. Sediment dynamics and sediment age. In L. Häkanson and M. Jansson (eds) Principles of lake sedimentology. Springer-Verlag, Berlin: 213–243.

Judd, J. H., 1969. Effects of salt runoff from street deicing on a small lake. Ph.D. thesis. The University of Michigan: 145 pp.

Krammer, K. & H. Lange-Bertalot, 1986. Bacillariophyceae 1. Teil: Naviculaceae. In H. Ettl, J. Gerloff, H. Heynig, D. Mollenhauer (eds), Süsswasserflora von Mitteleuropa, Band 2/1. Stuttgart: Gustav Fischer, Verlag: 1–876.

Krammer, K. & H. Lange-Bertalot, 1988. Bacillariophyceae 2. Teil: Bacillariaceae, Epithemiaceae, Surirellaceae. In H. Ettl, J. Gerloff, H. Heynig, D. Mollenhauer (eds), Süsswasserflora von Mitteleuropa, Band 2/2, Stuttgart: Gustav Fischer, Verlag: 1–596.

Krammer, K. & H. Lange-Bertalot, 1991a. Bacillariophyceae 3. Teil: Centrales, Fragilariaceae, Eunotiaceae. In H. Ettl, J. Gerloff, H. Heynig, D. Mollenhauer (eds), Süsswasserflora von Mitteleuropa, Band 2/3. Stuttgart: Gustav Fischer, Verlag: 1–576.

Krammer, K. & H. Lange-Bertalot, 1991b. Bacillariophyceae 4. Teil: Achnanthaceae, Kritische Erganzungen zu *Navicula* (Lineolatae) und *Gomphonema* Gesamtliteraturverzeichnis Teil 1–4. In H. Ettl, G. Gärtner, J. Gerloff, H. Heynig, D. Mollenhauer, (eds), Süsswasserflora von Mitteleuropa, Band 2/4. Stuttgart: Gustav Fischer, Verlag: 1–437.

Lambert, A. & K. J. Hsü, 1979. Non-annual cycles of varve-like sedimentation in Walensee, Switzerland. Sedimentology 26: 453–461.

Lehman, J. T. & T. Naumoski, 1986. Net community production and hypolimnetic nutrient regeneration in a Michigan lake. Limnol. Oceanogr. 31: 788–797.

Livingstone, D. A., 1955. A lightweight piston sampler for lake deposits. Ecology 36: 137–139.

Lowe, R. L., 1974. Environmental requirements and pollution tolerance of freshwater diatoms. EPA-670/4-74-955. Cincinnati, Ohio.

Ludlam, S. D., 1967. Sedimentation in Cayuga Lake, New York. Limnol. Oceanogr. 12: 618–632.

Ludlam, S. D., 1969. Fayetteville Green Lake, New York. III. The laminated sediments. Limnol. Oceanogr. 14: 848–857.

Lund, J. W. G., 1945. Observations on soil algae. The ecology, size and taxonomy of British soil diatoms. New Phytologist 45: 56–110.

Nipkow, F., 1928. Über das Verhalten der Skelette planktischer Kieselalgen im geschichteten Tiefenschlamm des Zürich-und Baldeggersees. Revue d'Hydrol. 4: 71–120.

Page, M. J., N. A. Trustnum & R. C. DeRose, 1994. A high resolution record of storm-induced erosion from lake sediments, New Zealand. J. Paleolimnol. 11: 333–348.

Parker, J. I. & D. N. Edgington, 1976. Concentration of diatom frustules in Lake Michigan sediment cores. Limnol. Oceanogr. 21: 887–893.

Patrick, R. & C. W. Reimer, 1966. The diatoms of the United States. Vol. 1. Acad. Nat. Sci. of Phil., Monograph No. 13, 688 pp.

Patrick, R. & C. W. Reimer, 1975. The diatoms of the United States. Vol. 2, pt. 1. Acad. Nat. Sci. of Phil., Monograph No. 13, 213 pp.

Perkins, J. A. & J. D. Sims, 1983. Correlation of Alaskan varve thickness with climatic parameters, and use in paleoclimatic reconstruction. Quat. Res. 20: 308–321.

Potzger, G. E. & I. T. Wilson, 1941. Post-pleistocene forest migration as indicated by sediments from three deep inland lakes. The American Midland Naturalist 25: 270–281.

Reed, H. S., 1902. A survey of the Huron River Valley. The Botanical Gazette 34: 125–139.

Saarnisto, M., P. Huttunen & K. Tolonen, 1977. Annual lamination of sediments in Lake Lovojärvi, southern Finland, during the past 600 years. Ann. bot. fenn. 14: 35–45.

Sandman, O., A. Lichu & H. Simola, 1990. Drainage ditch erosion history as recorded in the varved sediment of a small lake in East Finland. J. Paleolimnol. 3: 161–169.

Simola, H., 1977. Diatom succession in the formation of annually laminated sediment in Lovojärvi, a small eutrophied lake. Ann. bot. fenn. 14: 143–148.

Stockner, J. G. & W. W. Benson, 1967. The succession of diatom assemblages in the recent sediments of Lake Washington. Limnol. Oceanogr. 12: 513–532.

Swain, A. M., 1978. A history of fire and vegetation in northern Minnesota as recorded in lake sediments. Quat. Res. 3: 383–396.

Tippett, R., 1964. An investigation into the nature of the layering of deep-water sediments in two eastern Ontario lakes. Can. J. Bot. 42: 1693–1709.

Van der Werff, A., 1955. A new method of concentrating and cleaning diatoms and other organisms. Verh. Int. Ver. Limnol. 12: 276–277.

Wilkinson, L., 1989. SYSTAT: the system for statistics. Evanston, IL, SYSTAT, Inc. 638 pp.

Wolman, M. G. & A. P. Schick, 1967. Effects of construction on fluvial sediment, urban and suburban areas of Maryland. Water Resources Research 3: 451–464.