Reports

Early Eutrophication in the Lower Great Lakes: New Evidence from Biogenic Silica in Sediments

Abstract. *New evidence from studies of biogenic silica and diatoms in sediment cores indicates that eutrophication in the lower Great Lakes resulted from nutrient enrichment associated with early settlement and forest clearance. Diatom production peaked from 1820 to 1850 in Lake Ontario, at about 1880 in Lake Erie, but not until 1970 in Lake Michigan. This is the first reported sediment record of the silica-depletion sequence for the Great Lakes.*

Silica depletion can be an effect of eutrophication because phosphorus enrichment of phosphorus-limited waters causes increased silica demand for diatom production (*1*). Increased diatom production can reduce silica supplies to limiting levels, eventually causing a shift in phytoplankton from diatoms to other algae that have no silica requirement. This effect of increased phosphorus inputs, shown for Lake Michigan from water mass data (*2*), is referred to here as the silica-depletion sequence. In this report we relate variations in diatom production recorded in sediment cores to known or inferred trends in phosphorus enrichment and silica depletion in the water mass.

The expected pattern of biogenic silica (BSI) storage in sediments based on the silica-depletion sequence is shown in Fig. 1. Under pristine conditions, diatom production is controlled by phosphorus supplies with a relatively small seasonal demand for silica (*3*). With increased phosphorus loads, diatom production and silica demand increase until diatom production becomes silica-limited as BSI storage increases in the sediments, that is, silica inputs and recycling are less than the demand for silica (*4*). A complete eutrophication sequence of increased diatom production caused by increased phosphorus loading and reduced diatom production caused by silica limitation, therefore, should produce a pulse of BSI in the permanent sediments below the mixed layer (*5, 6*).

Sediment cores from Lake Ontario and Lake Erie show pulses of BSI storage in the 1800's (*7*). Storage peaked from 1820 to 1850 in Lake Ontario (Fig. 2A) and at about 1880 in Lake Erie where resolution is not precise because the 5-cm sampling intervals are ~ 25 years apart (Fig. 2B). Although we know of no long-term historical data, we believe that silica-limited diatom growth after 1850 in Lake Ontario and after 1880 in Lake Erie is responsible for decreased rates of BSI storage.

The BSI storage in a Lake Michigan core (Fig. 2C) also conforms to the hypothetical pattern. In this core BSI storage was not affected greatly during early settlement in the 1800's, as in the Lake Ontario and Lake Erie cores, but increased tenfold from 1940 to 1970 when loading from phosphate-based detergents increased (*8*) and then decreased after 1970 when silica became limiting for diatom production (*2*). Data on soluble silica indicate that the near-surface BSI rise is in the dissolution front (*5, 9*).

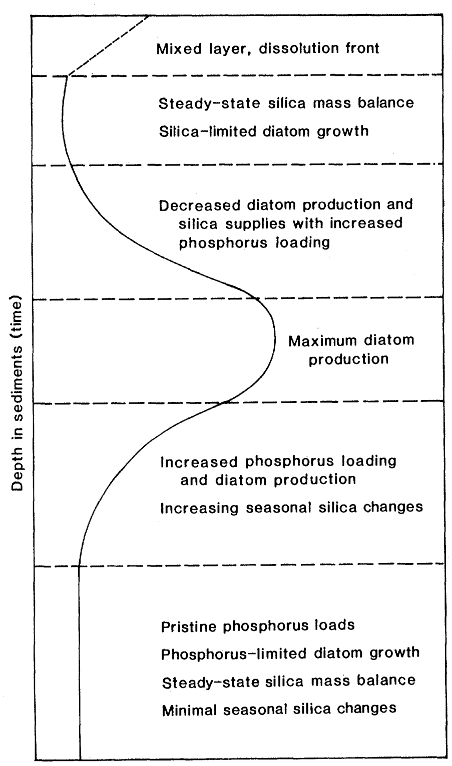

Fig. 1. Hypothetical pattern of BSI storage in Great Lakes sediments based on phosphorus loading and the silica-depletion sequence (*2, 8*).

Lake Huron and Lake Superior should have a different pattern of BSI storage in sediments than the lower Great Lakes, according to the model in Fig. 1, because diatom production is not silica-limited (Table 1). The BSI storage in Lake Huron cores increased about 50 percent in the last 30 to 40 years when loadings from phosphate-based detergents increased (*8*) with no apparent decrease in recent sediments (*10*). Diatom concentrations in Lake Superior are greater in the upper 1.0 cm of sediments than at depth (*11, 12*), but these data are not adequate to test our hypothesis. This increase may represent an early effect of eutrophication or may only reflect a dissolution front.

Diatom dissolution (*13, 14*) and mineralogical arguments have been advanced to explain the profiles of BSI in sediments (*12, 15*). Our results indicate that the BSI we have reported is diatom silica because there was excellent agreement between diatom counts and BSI in Lake Erie (Fig. 2B) and Lake Michigan cores (*9*). A logarithmic decrease in diatoms with depth was reported from 1973–1974 Lake Michigan samples (*14*). Since silica depletion occurred in Lake Michigan at about 1970 (*2*), the resulting reduced BSI storage was probably masked in earlier studies by the dissolution front. In the core collected in 1980 (Fig. 2C), only a few 0.5-cm sampling intervals show decreased BSI storage and diatom counts that can be considered part of the permanent sedimentary record. These intervals, according to ^{210}Pb dates, were deposited from 1974 to 1978 and represent at most only 4 to 5 years of sedimentation (*9*). This recent change in system silica dynamics undoubtedly accounts for the absence of the expected BSI pulse in 1973–1974 samples.

In Lake Michigan and Lake Huron, increases in BSI storage after 1940 (Fig. 2C) are well correlated with increased phosphorus loadings from human wastes and detergents (*8*). However, in Lake Ontario and Lake Erie, peak BSI storage occurred in the 1800's (Fig. 2, A and B), before human wastes contributed large loads (*8, 16*), and therefore probably resulted mainly from increased phosphorus inputs during early settlement and forest clearance. Decreases in water-column silica concentrations during the 1960's and 1970's indicate that increased BSI storage should have occurred in the recent sediments of Lake Michigan and Lake Huron and that there should have been little change in Lake Ontario BSI storage during that time (Table 1).

We believe that diatom production peaked sooner in Lake Ontario than in Lake Erie because the Lake Ontario basin was settled earlier (*16*). The sharp decrease in BSI storage in Lake Ontario after 1850 must have resulted partly from decreased silica concentrations in the outflow from Lake Erie where increased diatom production was robbing part of the former silica input to Lake Ontario. In Lake Erie the silica-depletion sequence was protracted because the supply from Lake Huron with its relatively large silica concentrations was unchanged (Table 1).

Increased nutrient loading associated with early settlement is the most probable cause of increased diatom production in Lake Ontario and Lake Erie during the 1800's. Why comparable changes did not occur in Lake Michigan until the mid-1900's can be explained from data on total phosphorus (TP) (Table 1). The TP concentrations are three times as great in Lake Ontario and Lake Erie as in Lake Michigan because of greater phosphorus loadings in the lower lakes (*8*). A TP concentration of 8 μg liter^{-1} was associated with rapid silica depletion in Lake Michigan, whereas the silica-depletion sequence has not occurred in Lake Superior and Lake Huron (present TP averages 4 to 5 μg liter^{-1}). These data indicate that relatively small TP concentrations could have induced the silica-depletion sequence in the lower lakes soon after early settlement and corroborate the recent conclusion that diatom assemblages in Lake Erie were altered by small increases in phosphorus loading as early as 1850 (*17*), during the period of increased BSI storage we found in Lake Erie and Lake Ontario cores.

Morphometric and hydraulic differences are also important in understanding the eutrophication–silica-depletion sequence. Lake Michigan has a 100-year flushing time, much longer than the 8- to 16-year response time to changes in phosphorus loading (*18*); flushing times for Lake Ontario and Lake Erie are only 8 and 3 years, respectively (*19*). Most of the hydraulic load (83 percent) to Lake Ontario is supplied from Lake Erie (*16*), whose waters have large TP and reduced silica concentrations (Table 1). In contrast, Lake Michigan has no upstream lakes, and Green Bay and eastern-shore marginal lakes may act as nutrient sinks for tributaries that supply more than half the lake's phosphorus load (*3*).

The validity of the silica-depletion hypothesis rests on the discovery of an adequate inventory of BSI in depositional basins of the lakes. Although no adequate inventory yet exists, increased BSI storage rates in a few cores support the hypothesis. Increases in BSI storage with time can be calculated from data on mass sedimentation rates and the percentage (by weight) of BSI (Fig. 2). In the Lake Michigan core, BSI storage increased 93 mg cm^{-2} from 1940 to 1970, equivalent to the removal of 4.4 mg of silica per liter from the water mass (*20*). In the Lake Ontario core, increased BSI storage from 1820 to 1850 is equivalent to a silica depletion of 1.3 mg liter^{-1} (*20*). These necessarily crude calculations support earlier reports that historical silica decreases were several milligrams per liter in Lake Michigan (*2*).

Table 1. Comparison of water-column data; E.B. and C.B. denote, respectively, the eastern and central basins of Lake Erie; N.D., no data; TP, total phosphorus. The silica data from the early 1960's are based on average chemical characteristics (*24*).

Lake	Silica (mg liter^{-1})			Average chlorophyll *a* (μg liter^{-1})	Average winter TP (μg liter^{-1})
	Late 1970's		Early 1960's average		
	Summer minimum	Winter maximum			
Ontario (*19, 25*)	0.1	0.4	0.3	4.8	25
Erie, E.B. (*19, 25*)	< 0.1	0.3	N.D.	4.3	25
Erie, C.B. (*19, 25*)	< 0.1	0.4	N.D.	5.5	29
Erie			1.5		
Michigan (*26*)	0.1	1.5	3.1	2.2	8
Huron (*19, 25*)	1.1	1.9	2.3	1.8	5
Superior (*19, 25*)	2.3	2.4	2.1	0.9	4

The results presented here offer new insights into silica dynamics in the Great Lakes. (i) The BSI data from Lake Michigan and Lake Ontario cores indicate that the silica-depletion sequence occurred over a relatively short period of time, possibly as little as 20 to 40 years. (ii) This short time course shows that silica dynamics and mass-balance relations can be affected significantly and

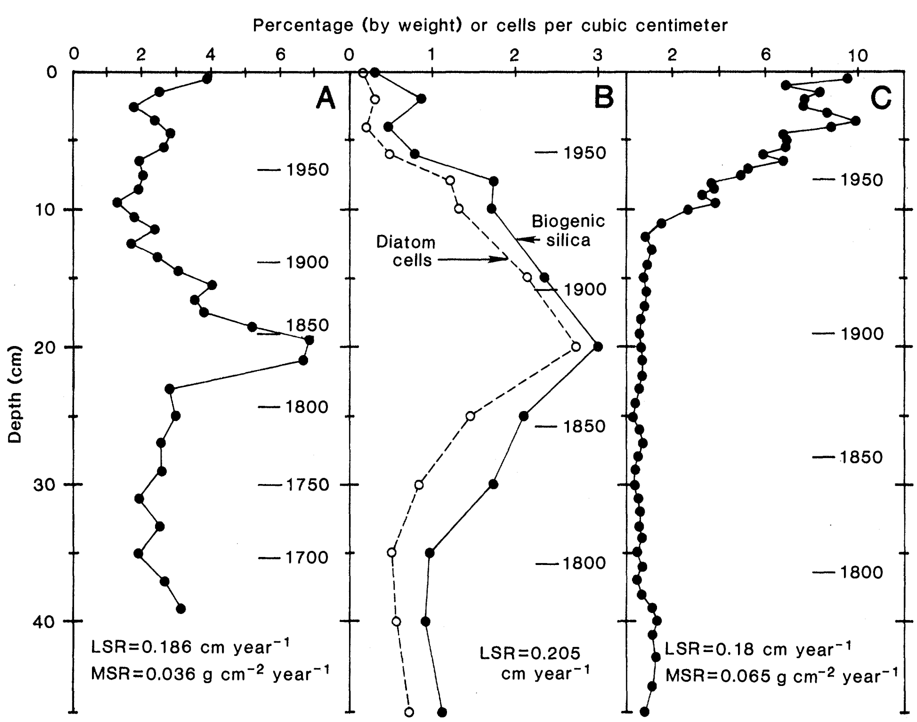

Fig. 2. Depth distribution of BSI (percentage by weight) and diatoms ($\times 10^6$ cells per cubic centimeter) in sediment cores from three of the Great Lakes. (A) The BSI in Lake Ontario core E30, taken in 1981; the upper 20 cm was sectioned at 1-cm intervals, and the lower 20 cm at 2-cm intervals. (B) Diatom counts from Frederick (*13*) and the BSI in a core from the eastern basin of Lake Erie. (C) The BSI in core SRP02, collected in 1980 from Grand Traverse Bay, Lake Michigan (*9*); the upper 10 cm was sectioned at 0.5-cm intervals, and deeper depths at 1- or 2-cm intervals. Mass sedimentation rates (*MSR*) and linear sedimentation rates (*LSR*) for Lake Ontario and Lake Michigan cores were obtained from ^{210}Pb dating (*27*); the linear sedimentation rate for Lake Erie was obtained from the *Ambrosia* horizon (*13*).

rapidly by biological effects of nutrient enrichment. (iii) Silica-limited steady states have developed in Lake Ontario and Lake Erie and possibly since 1970 in Lake Michigan. (iv) Lake Huron with recent increases in BSI storage may be in a transition between steady states (*3, 10*), whereas silica dynamics have been affected least in Lake Superior where phosphorus enrichment has been least (Table 1).

Initial and subsequent silica steady states differ greatly in relation to associated phytoplankton dynamics. During the early state associated with presettlement phosphorus loadings (Fig. 1), there is surplus silica throughout the year for the predominant oligotrophic diatom assemblages (*3, 21*), whereas during subsequent states diatom growth is limited, at least during part of the year, by supplies of silica and is dependent mainly on recycled silica (*4, 22*).

Noted added in proof: A recent report concluded that the Schelske-Stoermer silica-depletion hypothesis is clearly "undemonstrable in Lake Michigan" (*23*, p. 459) [a similar argument was used in litigation between Milwaukee and Illinois (*23*)]. These results (*23*) were based on data from the Chicago water filtration plant and completely ignored the water-column data from the open lake, which were the main basis for our conclusion that the silica concentrations of Lake Michigan had decreased (*2*). These water-column data indicate that the summer hypolimnetic and winter maximum silica concentrations decreased as much as 3.0 mg $liter^{-1}$ between 1954 and 1969 (*2, 22*). The silica-depletion hypothesis is supported strongly by open lake water-column data (*2*) and by the sedimentary evidence presented here.

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References and Notes

1. P. Kilham, *Limnol. Oceanogr.* **16**, 10 (1971); C. L. Schelske, E. D. Rothman, E. F. Stoermer, M. A. Santiago, *ibid.* **19**, 409 (1974).
2. C. L. Schelske and E. F. Stoermer, *Science* **173**, 423 (1971); in *Nutrients and Eutrophication*, G. E. Likens, Ed. (Allen, Lawrence, Kans., 1972), pp. 157–171.
3. C. L. Schelske, in *Coupling of Land and Water Systems*, A. D. Hasler, Ed. (Springer, New York, 1975), pp. 277–299.
4. J. I. Parker, H. L. Conway, and E. M. Yaguchi [*J. Fish. Res. Board Can.* **34**, 545 (1977)] have shown that most of the BSI produced by diatoms is recycled; however, some small fraction is permanently buried in the sediments.
5. J. A. Robbins, J. Krezoski, and S. C. Mozley [*Earth Planet. Sci. Lett.* **36**, 325 (1977)] reported a mixed layer 3 to 4 cm deep produced by benthic organisms. Rates of sediment redistribution apparently are smaller than rates of BSI dissolution, and so a sharp gradient and dissolution front of BSI develops (Fig. 1). Permanent burial and preservation of diatoms occur only below this layer, where reducing sediments and high interstitial silica concentrations minimize dissolution (*6*).
6. D. J. DeMaster, *Geochim. Cosmochim. Acta* **45**, 1715 (1981).
7. We measured BSI or amorphous silica by leaching samples at 85°C with 1.0 percent Na_2CO_3 for 2, 3.5, and 5 hours to correct for mineral interference (*6*).
8. S. C. Chapra, *J. Environ. Eng. Div. Am. Soc. Civ. Eng.* **103**, 147 (1977).
9. R. M. Glover, thesis, University of Michigan, Ann Arbor (1982).
10. J. A. Robbins, "Sediments of southern Lake Huron: Elemental composition and accumulation rates" (Report EPA-600/3-80-080, Environmental Protection Agency, Duluth, 1980).
11. V. L. Thayer, thesis, University of Minnesota, Minneapolis (1981).
12. T. C. Johnson and S. J. Eisenreich, *Geochim. Cosmochim. Acta* **43**, 77 (1979).
13. V. R. Frederick, *J. Great Lakes Res.* **7**, 404 (1981).
14. J. I. Parker and D. N. Edgington, *Limnol. Oceanogr.* **21**, 887 (1976).
15. J. O. Nriagu, *ibid.* **23**, 53 (1978).
16. A. M. Beeton, in *Eutrophication: Causes, Consequences, Correctives* (National Academy of Sciences, Washington, D.C., 1969), pp. 150–187.
17. G. P. Harris and R. A. Vollenweider, *Can. J. Fish. Aquat. Sci.* **39**, 618 (1982); E. C. Theriot and E. F. Stoermer, *Nova Hedwigia Z. Kryptogamenkd.*, in press.
18. P. W. Rodgers and D. K. Salisbury, *J. Great Lakes Res.* **7**, 467 (1981).
19. R. Weiler, *Verh. Int. Verein. theoret. Angew. Limnol.* **21**, 1681 (1981).
20. It is assumed that increase occurred over 40 percent of the lake bottom, which is equal to the area of depositional basins in Lake Michigan reported by R. A. Cahill [*Ill. State Geol. Surv. Circ. 517* (1981)].
21. E. F. Stoermer, *Trans. Am. Microsc. Soc.* **97**, 2 (1978).
22. The biological residence time of silica is 1 to 2 years in Lake Michigan and an order of magnitude larger in Lake Superior (C. L. Schelske, in preparation).
23. J. Shapiro and E. B. Swain, *Science* **221**, 457 (1983).
24. A. M. Beeton and D. C. Chandler, in *Limnology in North America*, D. G. Frey, Ed. (Univ. of Wisconsin Press, Madison, 1966), pp. 535–558.
25. H. F. H. Dobson, M. Gilbertson, P. G. Sly, *J. Fish. Res. Board Can.* **31**, 731 (1974).
26. D. C. Rousar, *Water Air Soil Pollut.* **2**, 497 (1973); C. L. Schelske, L. E. Feldt, M. S. Simmons, "Phytoplankton and physical-chemical conditions in selected rivers and the coastal zone of Lake Michigan, 1972" (Publication 19, University of Michigan, Great Lakes Research Division, Ann Arbor, 1980).
27. J. A. Robbins, D. N. Edgington, A. L. W. Kemp, *Quat. Res.* (*N.Y.*) **10**, 256 (1978).

28. We thank R. A. Bourbonniere and V. R. Frederick for providing the Lake Ontario and Lake Erie cores, and P. Kilham, S. S. Kilham, and J. T. Lehman for reviewing the manuscript. This report is Contribution No. 361 of the Great Lakes Research Division, University of Michigan, and was supported in part by grants from the Environmental Protection Agency (R806294 and R810396) and the National Science Foundation (OCE-8216588).

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Tilt and Seismicity Changes in the Shumagin Seismic Gap

Abstract. *Changes in the ground surface tilt and in the rate of seismicity indicate that an aseismic deformation event may have occurred between 1978 and 1980 along the plate boundary in the eastern Aleutians, Alaska, within the Shumagin seismic gap. Pavlof Volcano was unusually quiescent during this period. The proposed event would cause an increase of stress on the shallow locked portion of the plate boundary, bringing it closer to rupture in a great earthquake.*

The portion of the Pacific–North American plate boundary in the Shumagin Islands region of the eastern Aleutians has been identified as a seismic gap where a great earthquake (moment magnitude $M_w \approx 8.4$) is expected to occur within the next two decades (*1*). Great earthquakes occurred within the gap in 1788, 1847, and possibly in 1903. The elapsed time (80 to 140 years) since the last great shock is of the same order as estimates of average recurrence times at this plate boundary (60 to 80 years) (*2*). A 10-year record of seismic and geodetic data indicates that an episodic strain release occurred during 1978 and 1979 between the overriding and the subducting plate at depths below 20 km, accompanied by increased regional seismicity and a quiescence of the eruptive activity of Pavlof Volcano.

The Shumagin Islands extend halfway between the volcanic arc and the trench axis (Fig. 1). Hence, leveling lines on the islands are well suited to detect possible tilt changes resulting from deformation along the plate boundary. Data from one line (SQH) releveled nine times since 1972 and another line (SDP) releveled annually since 1977 (*3*) indicate that surface deformation in the Shumagin Islands shows a steady tilt downward toward the trench through 1982, interrupted by a rapid tilt reversal in 1978 to 1980 (Fig. 2a) that is significant at the 99 percent confidence level. Data from a line (SIM) releveled annually since 1978 in the outer Shumagins show a similar reversal, although of smaller magnitude. Even though each data set shows considerable scatter, the fact that all have similar temporal character suggests that the