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Reading the Records Stored in the Lake Sediments: A Method of Examining the History and Extent of Industrial Damage to Lakes

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In this chapter, the effects of air pollutants from the roasting beds and smelters on Sudbury area lakes are examined. A rather novel approach has been used to track the lake water quality changes that occurred in the past century. This approach uses the rapidly expanding science of paleolimnology, the study of the fossil record in the lake sediments. In the absence of long-term data, paleolimnological techniques using biological remains in lake sediment cores are being used extensively to provide quantitative assessments of past water quality in North America (Charles et al. 1990; Dixit et al. 1987, 1992c) and Europe (Battarbee et al. 1990).

A large area around Sudbury is characterized by a geological environment that is highly resistant to chemical weathering (see Chapter 1). As a result, many lakes have low acid-neutralizing (buffering) capacity, making them vulnerable to inputs of strong acids. The widespread acidification and metal contamination of area lakes are major environmental problems resulting from metal mining and smelting activities near Sudbury. Acidification is also a global concern (Fig. 3.1).

The very acidic nature of some lakes in the Sudbury area was observed as early as the late 1950s (Gorham and Gordon 1960). Evidence of fish population disappearance (Beamish and Harvey 1972; Keller 1978; Kelso and Gunn 1984) indicates that the acidification of many Sudbury area lakes was severe by the 1950s and 1960s. However, long-term water quality data are lacking, because the actual monitoring of water chemistry of some Sudbury lakes only began in the 1970s. Recently, it has been estimated that lakes in a 17,000-km^2 area (Fig. 3.2) have been measurably affected by the Sudbury emissions. If pH 6.0 is considered the acidity level at which significant damage begins to occur to the most acid-sensitive components of lake communities (e.g., some aquatic insects, crustaceans, and small fish species; see Fig. 5.2), then more than 7000 lakes within this zone have likely suffered biological damage (Neary et al. 1990).

Paleolimnology and Environmental Assessment

Paleolimnology uses the physical, chemical, and biological information contained in lake sediments to assess past environmental characteristics (Smol and Glew 1992). This multidisciplinary science has made a unique contribution to environmental assessment studies by making data available that would otherwise be unattainable. It has provided answers to questions such as (1) Has there been a change in the lake? (2) If so, what was the magnitude and rate of change? (3) Is the observed change greater than the natural variability? and (4) What caused the change?

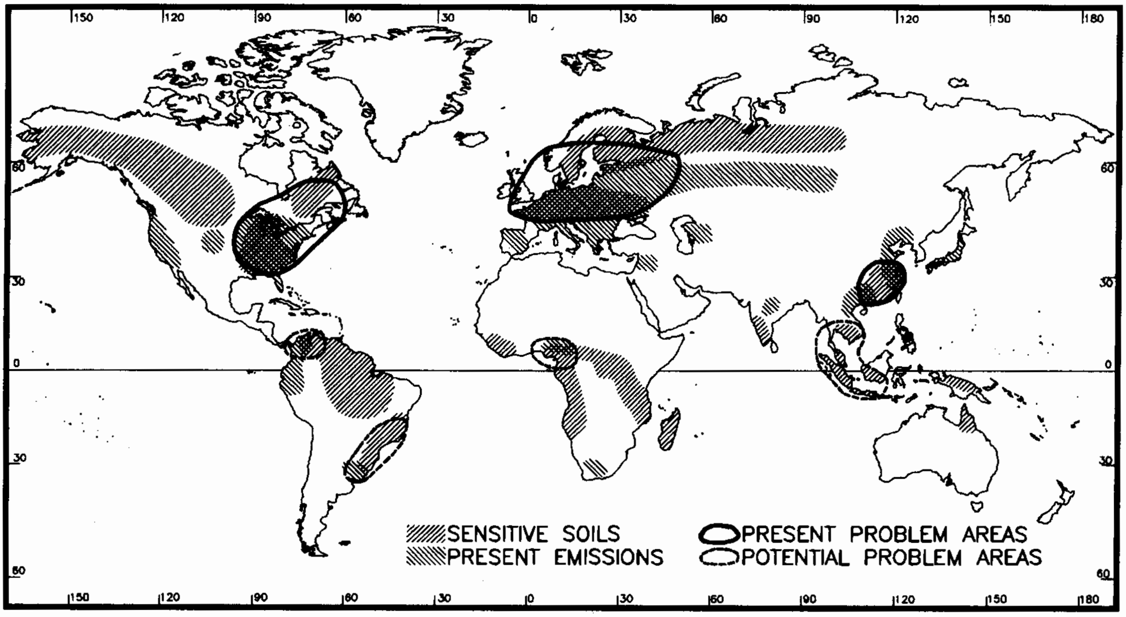

Figure 3.1. The combination of acid-sensitive terrain and high levels of acid deposition has resulted in widespread acidification, with effects documented in areas of North America, Europe, and Asia. Other areas of the world may develop acidification problems in the future if industrialization increases (from Rodhe and Herrera 1988).

Lake sediments contain many indicators of environmental conditions, including geochemical markers, plant pigments, and the fossil remains of aquatic organisms (Smol and Glew 1992). The remains of diatoms (Fig. 3.3) are the most widely used biological indicators of past lake water characteristics (Dixit et al. 1992c), although the fossil remains of other organisms such as *Chaoborus* (Box 3.1) have also provided much useful information. Within Canada, sedimentary diatoms have been used most extensively in Sudbury lakes to assess the impacts of industrial activities (Dixit et al. 1987, 1990, 1991).

Diatoms are single-celled microscopic plants belonging to the algal class Bacillariophyceae. They are made up of a highly ornamented cell wall composed primarily of glass (SiO_2). Each cell wall is made up of two pieces called valves and beltlike elements called girdle bands that hold them together. The size, shape, and sculpturing of the valve are species-specific (Fig. 3.3) and provide the basis for identification. Because diatom valves are made of silica, they are generally well preserved in the lake sediments (see Plate 3, following page 182).

Diatoms are key components of nearly all fresh and saline environments. They are ecologically diverse and colonize virtually every microhabitat in lakes and rivers. Diatom species have narrow optima and tolerances for many environmental variables and respond quickly to changes because of their ability to immigrate and replicate rapidly. Also, changes in diatom assemblages correspond closely to shifts in other biotic communities such as other algae, zooplankton, aquatic macrophytes, and fish. Although paleolimnology and study of sedimentary diatoms have become highly sophisticated in recent years, refinements to paleolimnological approaches are constantly being sought and implemented as techniques and protocols are evaluated.

Field and Laboratory Methods

The approach commonly used for paleolimnological monitoring and assessments is summa-

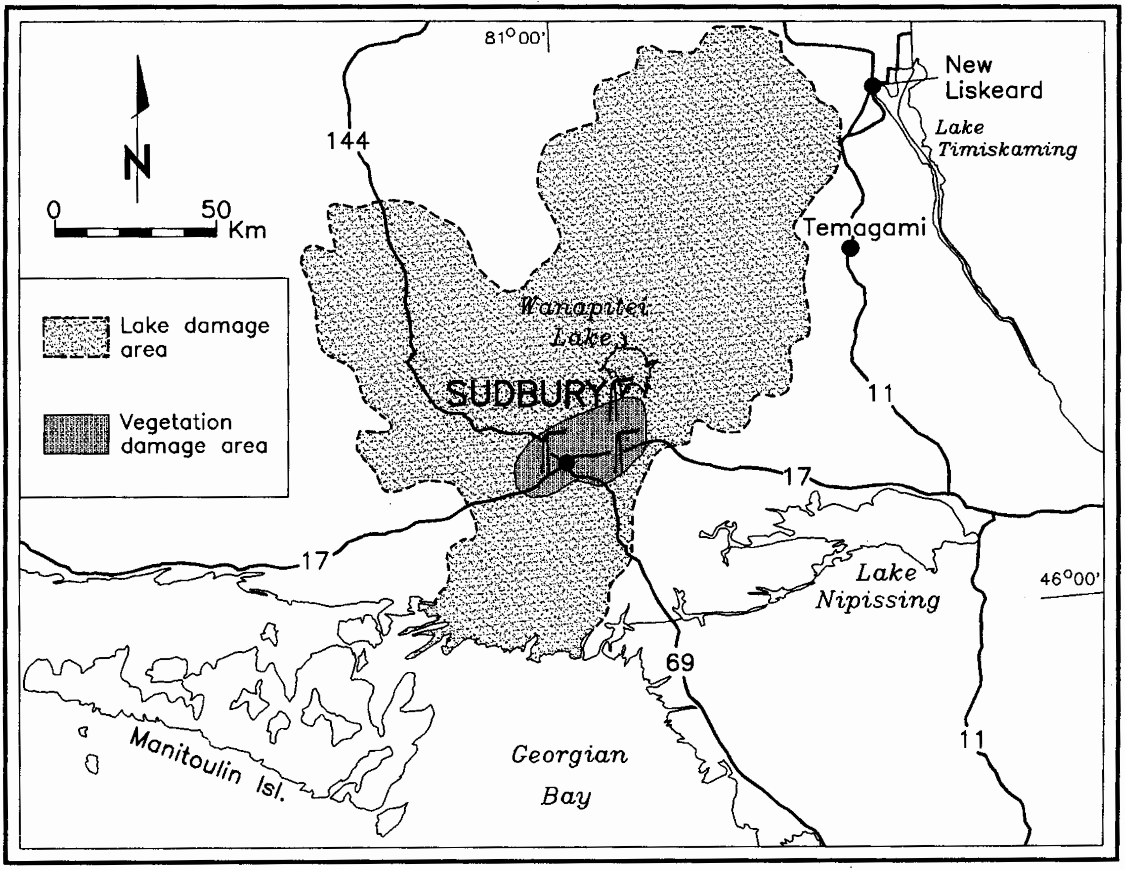

FIGURE 3.2. Approximate zone of influence of the Sudbury smelters on lake chemistry, based on water quality surveys (from Neary et al. 1990).

rized in Figure 3.4. Sediment cores are obtained from the deep basin of the lake using gravity or piston corers. Sediment cores of 30–40 cm generally cover the past two centuries of sediment accumulation in Sudbury and so are of sufficient length to study the post-industrial environmental changes. The cores are slowly pushed out of the top of the core tube and sectioned at specified intervals. The thickness of the sections is set by the investigators to meet the goals of the project (i.e., reconstruct environmental conditions for the past 3 years, 10 years, a century, or thousands of years). The upper portions of the cores from the Sudbury study were sectioned at fine intervals (i.e., 0.25 cm) so that recent (<10 years) as well as long-term environmental trends could be established. Techniques are also available to obtain information at annual or seasonal levels in some lakes (Simola 1977; Renberg 1981).

The sections of the sediment cores are dated to determine the time when the sediment was deposited at any particular depth (a depth–time profile must be established for each sediment core). Although a variety of techniques are available, the lead-210 radioisotope method (Appleby and Oldfield 1978) is the most commonly used dating method for recent (<150 years) lake sediments.

Diatoms are first cleaned and separated from the rest of the sediment by using strong acids, followed by repeated washes in distilled water. The resulting siliceous slurries are then mounted on glass slides for microscopic examination. Identifications are made to the lowest possible level (e.g., variety), because it is not uncommon

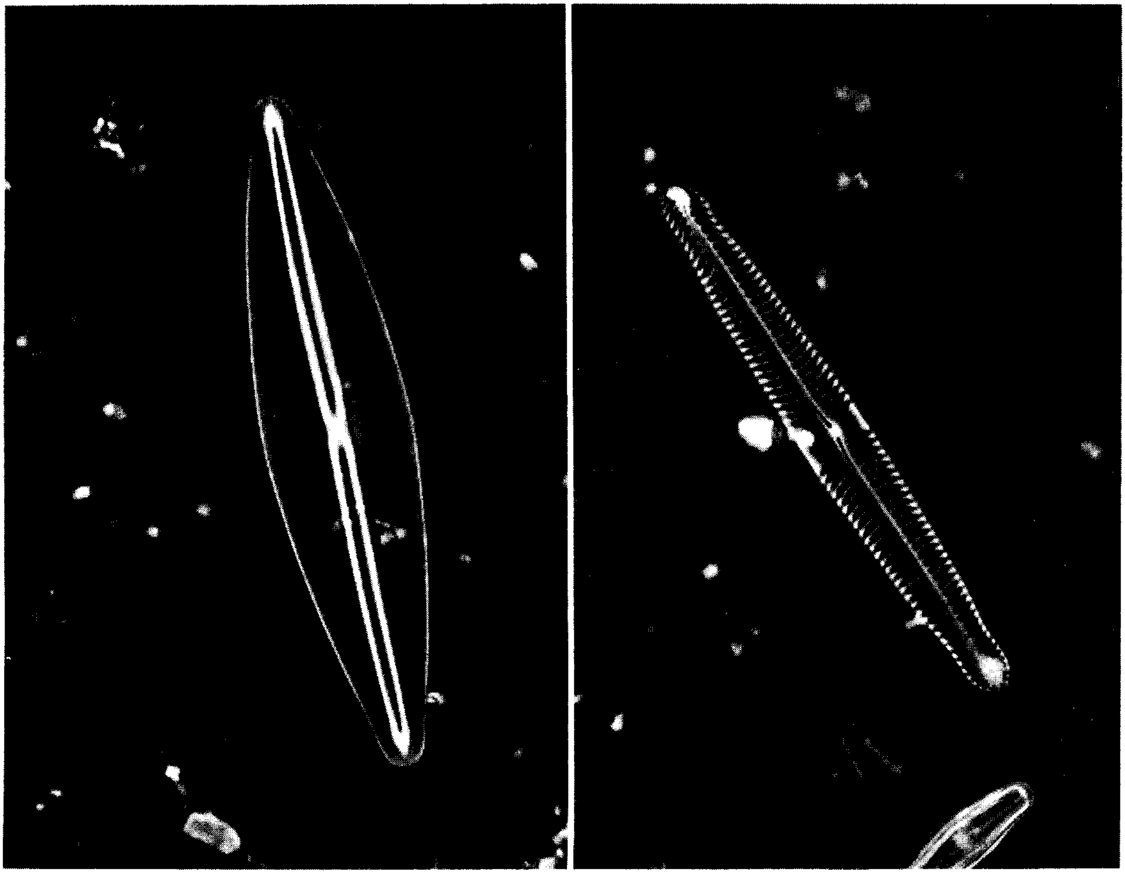

FIGURE 3.3. Light micrograph of microfossils of two diatom species.

for species belonging to the same genus to have different environmental tolerances and optima.

Diatom Calibration for Sudbury Lakes

In many lake regions of North America and Europe, surface (recent) sediment studies (calibration or training sets) have shown that the distribution of most diatoms is significantly correlated with variables such as lake water pH, metals, nutrients, conductivity, and many morphometric (e.g., lake size and depth) characteristics. Using a variety of statistical treatments (Charles et al. 1993), mathematical relationships (transfer functions) can be developed that quantitatively relate species distributions to environmental variables, such as lake water pH. Fortunately, a single sediment sample can provide a realistic picture of conditions in the whole lake because the sediments integrate diatoms both in space and time from different habitats within the lake.

Diatom assemblages present in the top 0.25-cm sediment of 72 lakes located within a 100-km radius of Sudbury have been calibrated (Dixit et al. 1991). Diatom-based models were then developed to infer past lake water pH and conductivity and concentrations of aluminum, nickel, and calcium. These models have been used to reconstruct past lake water characteristics of many Sudbury lakes (Dixit et al. 1991, 1992a,b).

Environmental Shifts in Clearwater Lake: A Case Study

Clearwater Lake is located 13 km southwest of Sudbury. It is a moderate-sized lake (76.5 ha), with maximum and mean depths of 21.5 and

Box 3.1.

Paleolimnological methods can be used to infer historical biological conditions as well as the chemical and physical characteristics of lakes. In particular, the remains of hard mouthparts (mandibles; shown in the photograph) of larvae of the phantom midge, *Chaoborus* (see Plate 4, following page 182), in lake sediments can be used to reconstruct general patterns in historical fish populations (Uutala 1990; Uutala et al. 1994). Some *Chaoborus* species can coexist with fish, whereas others, notably *Chaoborus americanus,* cannot withstand fish predation. Thus, the species of *Chaoborus* found at different levels in the sediments indicate the presence or absence of fish at that time. This technique has been used to show that the current absences of fish from lakes in Ontario and the Adirondack Mountains of New York are not natural conditions but resulted from lake acidification.

8.3 m, respectively. Since 1973, this lake has been monitored as a reference site for lakes manipulated by liming (see Chapter 15) and to study seasonal and long-term changes in water chemistry and biota of an acidic lake (Yan and Miller 1984). Since the monitoring began, the lake has remained fishless, and no records are available to indicate whether the lake supported a viable fish population in the past.

Diatoms deposited over the past 200 years were analyzed from a sediment core retrieved in 1984. The core was dated using the lead-210 chronology method. The distribution of common diatom taxa in the past (Fig. 3.5) indicates that until about 1920, the diatom community remained relatively unchanged; however, since then major shifts have occurred. The relative abundance of acid and metal-tolerant species (e.g., *Tabellaria quadriseptata, Eunotia exigua,* and *Frustulia rhomboides* var. *saxonica*) increased, while *Cyclotella stelligera* (a species characteristic of nonacidic waters) declined sharply. These species shifts provide a strong indication that the lake has experienced marked water quality changes during this century.

Mathematical relationships (Dixit et al. 1991) for estimating past conditions of pH, aluminum, and nickel were then applied to the above diatom data. The resulting diatom-inferred pH profile (Fig. 3.6) indicates that the lake's preindustrial pH ranged between 5.7 and 6.1, whereas since 1920, the lake acidified very rapidly to a pH of 4.7 in 1980.

The acidification of Clearwater Lake appears to be directly related to sulfur dioxide emissions from the smelters in Sudbury. The study also shows that acidification began about 20 years after metal smelting commenced in Sudbury; this delay was likely due to the natural buffering capacity of this lake and its watershed. It is also possible that the open-pit roasting of ore, which started in the 1880s, did not adversely affect the lake and that the acidification only started after tall stacks were installed in the 1920s. Between 1980 and 1984, the inferred pH profile indicates that lake water pH has recovered slightly. Recent pH recoveries have also been observed in many other Sudbury lakes (see Chapter 5).

The Sudbury region is one of the few regions in which fossil diatoms found in lake sediments have been used to establish past trends in lake water metal concentrations. Inferred aluminum and nickel profiles indicate that lake water metal concentrations increased greatly in Clearwater Lake after the smelters

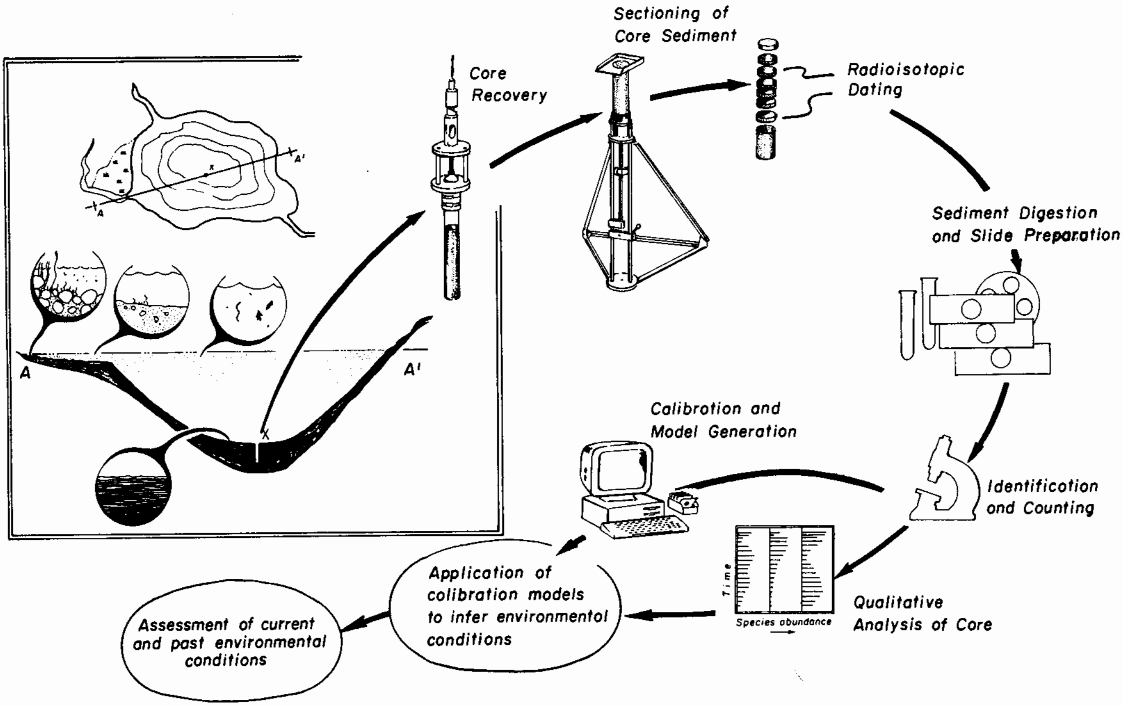

FIGURE 3.4. Microfossil inputs from various habitats to the lake bottom and the steps used in paleolimnological investigation of aquatic ecosystems (from Dixit et al. 1992c).

started operating (Fig. 3.6). Nickel and aluminum increases started about the same time that the lake water began to acidify. In the 1970s, lake water metal concentrations stabilized, and coincident with the pH recovery between 1980 and 1984, nickel and aluminum declines occurred in Clearwater Lake. The recovery is undoubtedly a reflection of the recent decline in smelter emissions. Paleolimnological inferences of the chemical history of Clearwater Lake agree well with actual chemistry monitoring data collected since 1973 (see Chapter 20).

Similar reconstructions of past lake water acidity have also been completed for 13 other Sudbury lakes. From these studies, it is possible to generalize that in acidic lakes located close to the smelters (<15 km), acidity-related changes started early in this century (i.e., 1920s–1940s), whereas in lakes located farther away from the emission sources, acidification began in the late 1950s and 1960s. In some of the study lakes, recent lake water pH increases and declines in metal concentrations have also been identified.

Changes in Lake Water Chemistry since Preindustrial Times

The analysis of complete sediment cores provides continuous assessment (e.g., timing, rate, and magnitude) of postindustrial changes in lake water quality. However, this is very time-consuming work, and it is not logistically feasible to analyze complete sediment cores from a large number of lakes to provide regional assessments of lake water quality change. The most effective approach for such a study is to analyze only the top (recent) and bottom (preindustrial) sediments of cores from a large number of lakes (Charles and Smol 1990). The difference between preindustrial and recent inferences provides an estimate of the change in

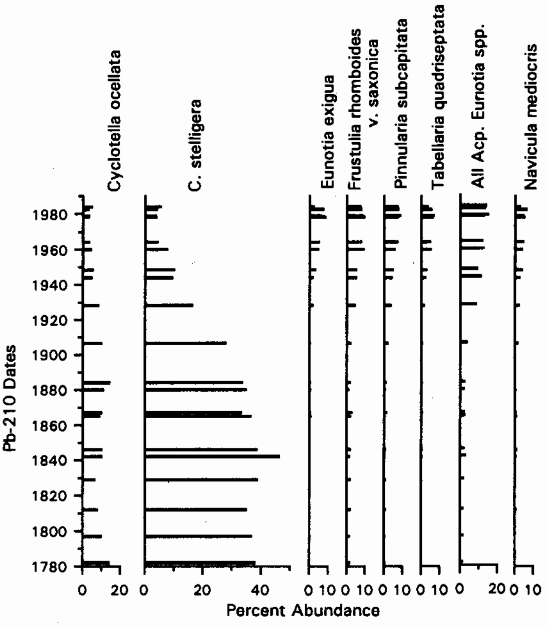

Figure 3.5. Relative percentage abundance of common diatoms in a sediment core from Clearwater Lake (modified from Dixit et al. 1987).

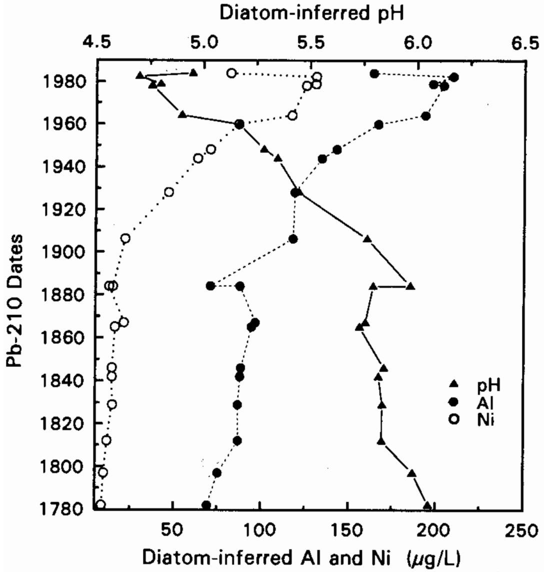

Figure 3.6. Diatom inferences of past changes in lake water pH, aluminum, and nickel in Clearwater Lake.

lake water chemistry as a result of industrial activity. Moreover, inferences for the bottom samples also provide information on background or reference limnological conditions.

The recent and preindustrial diatom-inferred water chemistry for 72 lakes within a 100-km radius of Sudbury (Dixit et al. 1992a) showed that extensive acidification has occurred in presently acidic (pH <6.0) lakes. The region also contains a few naturally acidic lakes; however, these lakes have acidified further as a result of industrial activity. Lakes that have current measured pH between 6.0 and 7.0 have either declined or increased in pH in the past, whereas high pH lakes (pH >7.0) have become more alkaline. Aluminum has increased in acidified lakes, whereas nickel increased in all study lakes. In general, in both acidic and nonacidic lakes, concentrations of dissolved elements (identified through inferred conductivity values, a measure of the total concentration of dissolved materials) have increased (Dixit et al. 1992a) because of direct atmospheric deposition to lakes and watersheds (e.g., sulfate) and high leaching of watershed soils by acid deposition (e.g., calcium). Patterns of elevated concentrations of some dissolved elements in Sudbury lakes have been shown by water chemistry surveys (Jeffries et al. 1984). In lakes close to the smelters, the loss of vegetation cover and resulting erosion of soils (see Chapter 2) no doubt contributed to the high loadings of some elements to lakes.

In addition to preindustrial and recent diatom assemblages, sediments deposited during about 1900, 1930, 1950, and 1970 were also studied for 22 Sudbury lakes to assess the rate of change in lake water chemistry since preindustrial time. Diatom-inferred pH, aluminum, and nickel were computed for these six sediment levels of lead-210 dated cores. Differences (increases or decreases) between preindustrial conditions (pre-1880) and the above time periods are plotted in Figure 3.7.

The inferred pH differences show that between pre-1880 and 1900, lake water pH remained relatively unchanged (Fig. 3.7). The small declines or increases that occurred in some lakes likely reflect natural variation, especially because there was no pattern of change with respect to current measured pH. By 1930, the lakes had started to show some pH decline, and in five of the 22 lakes, pH had declined 0.3 of a pH unit or more since pre-1880. In three lakes, pH increased 0.3 of a pH unit or more. Lakes continued to acidify during 1950 and 1970. Although further acidification occurred in some lakes between 1970 and recent time, a distinct pH recovery occurred in others. Marked pH recovery in Hannah and Middle lakes is a response to the liming of these lakes in the 1970s (see Chapter 15). The post-1970 lake water pH recovery in Baby and Clearwater lakes corresponds with the reductions in sulfur dioxide emissions by almost 80% within the past two decades (see Chapter 4).

The inferred aluminum data indicate that since pre-1880, aluminum has consistently increased in lakes that have current measured pH of 5.6 or lower (Fig. 3.7). In other lakes, aluminum has either increased or decreased. Although by 1930 aluminum had increased in some lakes, most of the increases occurred after 1950, the period of maximum acidification. Between 1970 and recent time, aluminum has declined in those lakes where pH has increased, whereas in other low pH lakes, aluminum has increased further.

The increase in nickel in almost all lakes (Fig. 3.7) suggests that these increases were largely independent of pH changes. With the exception of Hannah Lake, increases in nickel generally occurred after 1930, and by 1970 the maximum increase had occurred in most lakes. Generally the highest inferred nickel concentrations are for lakes located close to smelters and/or for mine tailing ponds in a few cases. The decline of lake water nickel in these lakes since 1970 follows the post-1970 reductions in smelter emissions. The absence of a close relationship between aluminum and nickel increases was expected, because nickel inputs were mainly atmospheric, whereas aluminum inputs were from the mobilization of aluminum from watersheds and possibly lake sediments.

Temporal and Spatial Patterns in Lake Water pH

Temporal and spatial patterns in lake water pH were further examined by drawing distribution maps for five inferred pH categories for preindustrial time, about 1930 and 1970, and recent time (Fig. 3.8). These maps provide a graphic display of lake water pH changes over space and time.

In the 22-lake data set (Fig. 3.8) during preindustrial time and 1930, none of the lakes had pH less than 5.0, whereas 13.6% of the lakes were in this category by 1970. In the pH range 5.0–5.6, the percentage of lakes contin-

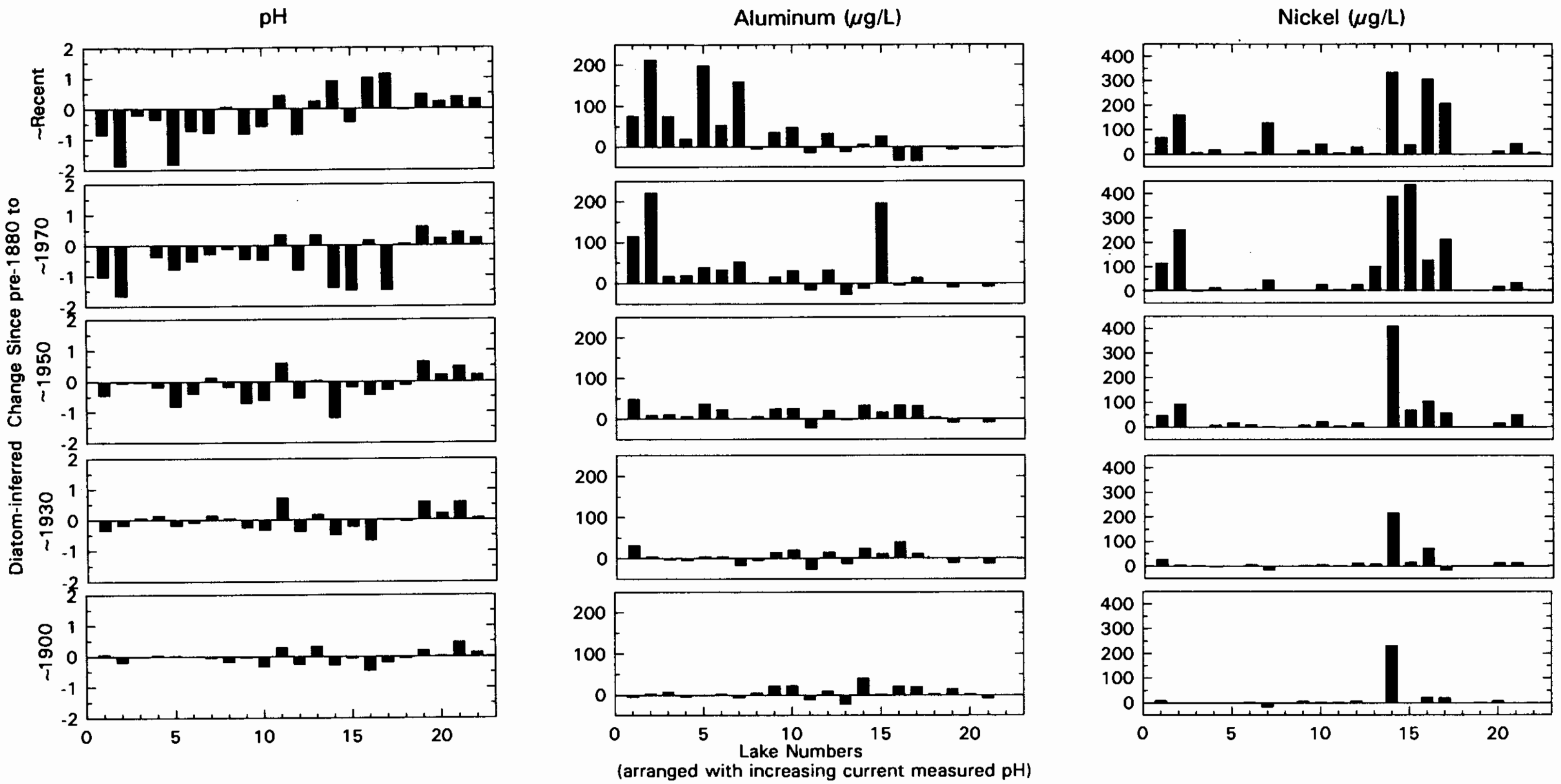

FIGURE 3.7. Inferred changes in lake water pH, aluminum, and nickel in 22 lakes between preindustrial time, about 1900, 1930, 1950, and 1970, and recent time. The lakes and their recent measured pH are (1) Clearwater, 4.5; (2) Daisy, 4.7; (3) Mountaintop, 4.8; (4) Wavy, 4.8; (5) Chiniguchi, 4.9; (6) Telfer, 5.0; (7) Swan, 5.6; (8) Alphretta, 6.2; (9) Laura, 6.3; (10) Whitson, 6.4; (11) Horseshoe, 6.7; (12) Southeast Baby, 6.7; (13) Labelle, 6.8; (14) Hannah, 6.8; (15) Baby, 6.9; (16) Clarabelle, 6.0; (17) Middle, 7.1; (18) Emerald, 7.3; (19) Fairbank, 7.5; (20) Ramsey, 7.5; (21) Round, 7.5; (22) Little Panache, 7.8.

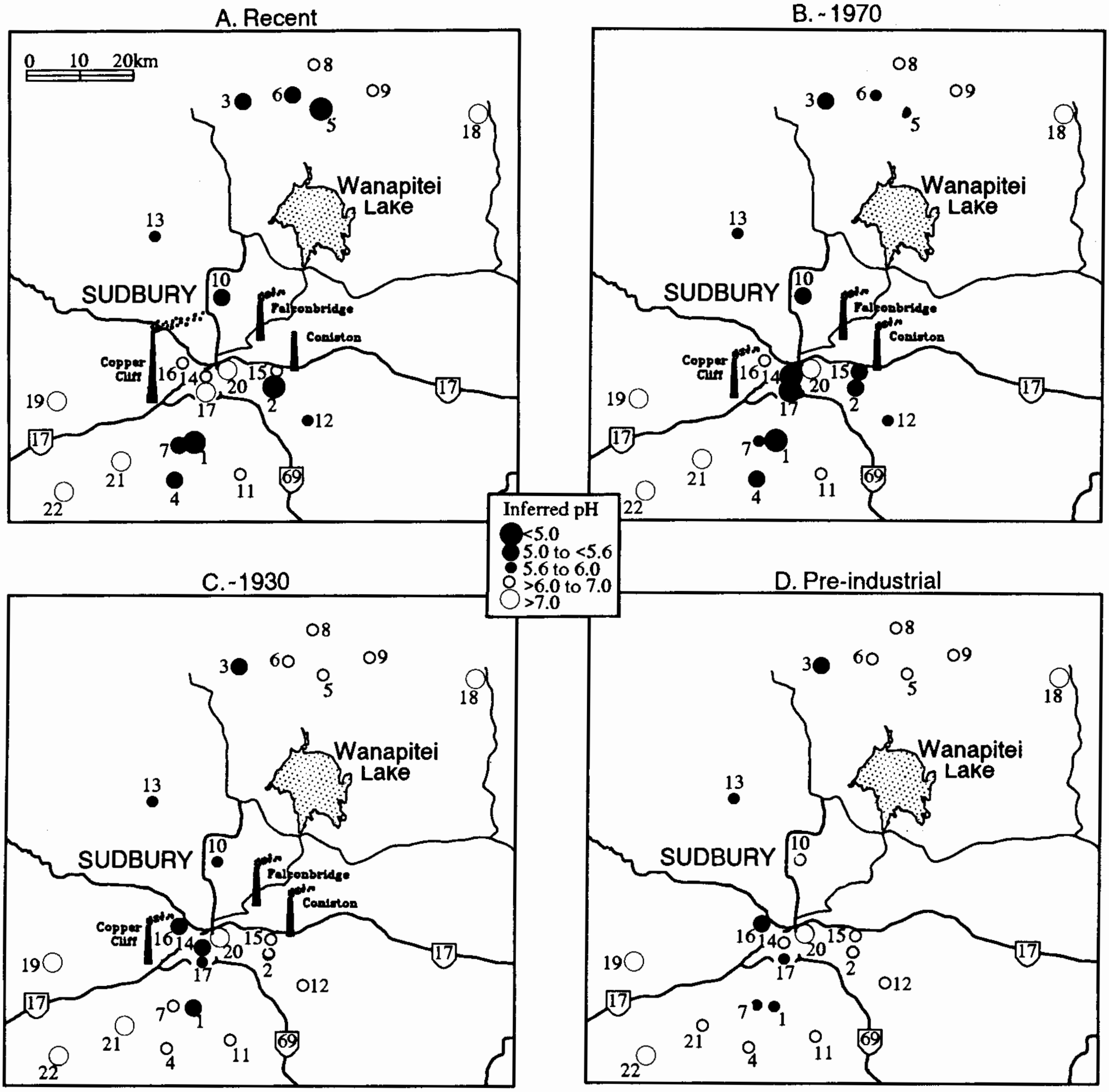

FIGURE 3.8. Spatial and temporal distribution of inferred pH for 22 lakes.

ued to increase from 9.1 in preindustrial time to 18.2, 22.7, and 22.7% in 1930, 1970, and recent time, respectively. Only two lakes were naturally acidic (pH <5.6). In the pH range 5.6–6.0, the percentage of lakes reached a maximum of 22.7 in 1970. Only 9.1% of the study lakes are presently in this pH range, most likely due to emission reductions. The percentage of lakes in the pH range 6.0–7.0 declined from 54.5 (preindustrial) to 18.2 in 1970 but since then increased to 27.3% (recent). In the pH category of more than 7.0, the percentage of lakes gradually increased from 18.2 (preindustrial) to 27.3 in recent time. In addition to identifying that many Sudbury lakes have acidified as a result of industrial activity, this study has shown that almost all high-pH lakes have become more alkaline during this century. Similar results were obtained for Adirondack region lakes (New York) (Cumming et al. 1992). Various factors are responsible for the alkalization of high-pH lakes (Cumming et al. 1992; Dixit et al. 1992a).

The pH distribution maps show that, in general, maximum acidification occurred by 1970, and the lakes that experienced most acidification are located close to smelters and/or lie within the northeast–southwest zone of impact. However, not all lakes were affected. Alkaline lakes are often located in close proximity to recently acidified lakes. This is explained by the presence of acid-neutralizing minerals in some watersheds, which allowed lakes to maintain a high pH despite high atmospheric acid loadings. Inferred pH has even increased in these lakes since preindustrial times.

Summary and Conclusions

Lake sediments have revealed the history of damages to Sudbury lakes from smelter emissions. Inferred patterns of increasing lake water acidity and metal concentrations began about 1920 for many lakes close to the smelters and later, in the 1950s and 1960s, in many lakes farther from the emission sources. Only a few Sudbury lakes appear to be naturally acidic, and these acidified further after industrialization of the region. With high-acid deposition, some well-buffered lakes became even more alkaline over time. Recent increases in pH and decreases in metal concentrations, related to reduced smelter emissions, are evident in the sediment record for several lakes.

Because paleolimnological techniques provide long-term data on ecosystem condition and changes, they are being used as an integral part of environmental monitoring and assessment programs. The approach can be used to detect and quantify lake water quality changes, provide data on preindustrial (predisturbance) conditions, establish natural variability, identify long-term trends, and monitor the effects of remedial action plans on aquatic environments. Although this chapter mainly deals with lake acidification, this approach has been used to address a wide variety of environmental issues, such as lake eutrophication and climate change. The research in the Sudbury region has not only provided answers to questions that could not be answered in any other way, but it has also helped to refine paleolimnological techniques currently being used in other lake regions.

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