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A PALEOLIMNOLOGICAL COMPARISON OF BURNTSIDE AND SHAGAWA LAKES, NORTHEASTERN MINNESOTA

EDISON, N. J.

Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Corvallis, Oregon 97330

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A PALEOLIMNOLOGICAL COMPARISON OF BURNTSIDE AND SHAGAWA LAKES, NORTHEASTERN MINNESOTA

by

J. Platt Bradbury
U.S. Geological Survey
Box 25046, Denver Federal Center
Denver, Colorado 80225

With pollen analyses by
Jean C. B. Waddington
Department of Geography
University of Minnesota

P.O. No. 04J1PO-0605

Project Officer
Donald W. Schults
Marine & Freshwater Ecology Branch
Corvallis Environmental Research Laboratory
Corvallis, Oregon 97330

CORVALLIS ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CORVALLIS, OREGON 97330

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FOREWORD

Effective regulatory enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory (CERL).

The primary mission of the Corvallis Laboratory is research on the effect of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake systems; and the development of predictive models on the movement of pollutants in the biosphere.

This report describes the results of a paleolimnological comparison of Burntside and Shagawa lakes in northeast Minnesota to determine the historic natural and cultural trophic changes in these lakes.

A. F. Bartsch
Director, CERL

ABSTRACT

The paleolimnological records of Burntside and Shagawa Lakes in northeastern Minnesota reveal that these two adjacent lakes have been limnologically distinct for many years prior to the late 19th century activities of white men that polluted Shagawa Lake. Although both lakes occur within the same vegetation type and share much of their water, the diatom stratigraphy of their bottom sediments indicates that Burntside Lake was less productive in its natural state than Shagawa Lake. The causes for this natural difference are not clearly known, but differences in relative size of drainage area and in bedrock geology may be responsible.

Intensive white settlement around Shagawa Lake beginning in 1866 supplied nutrients that increased its productivity and finally supported the massive blooms of blue-green algae that characterize culturally eutrophic lakes. Burntside Lake was spared such intensive eutrophication, but its diatom record shows that nutrients derived from shoreside recreational cabins and related construction activity are increasing the lake's productivity.

The results of this study show that paleolimnological studies may provide better comparative information for lake rehabilitation programs than do biological and chemical analyses of contemporary unpolluted water bodies.

This report is contribution #155 of the Limnological Research Center, University of Minnesota and was submitted in fulfillment of P.O. 04J1PO-0605 under the sponsorship of the U.S. Environmental Protection Agency.

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This report results from a research contract between the Environmental Protection Agency and H. E. Wright, University of Minnesota. The interest of Donald W. Schults of the EPA Corvallis Environmental Research Laboratory is appreciated.

SUMMARY

The limnologic and paleolimnologic investigation of Shagawa Lake and Burntside Lake places the two lakes in a time perspective that permits a more accurate evaluation of their modern limnology. This was done to help answer the following questions:

1. Does the sediment stratigraphy of Shagawa Lake record the impact of mining and urban settlement that began in the late 1800s, and, if so, can these changes in sediment chemistry and paleontology be distinguished from those produced by natural limnologic causes?

2. Were Shagawa Lake and Burntside Lake limnologically similar before cultural activities at Ely extensively polluted Shagawa Lake?

3. Is Burntside Lake, which is relatively unproductive by present standards, affected in any significant way by settlement activities along its shores?

The first question is affirmatively answered by the paleolimnological study of Shagawa Lake. The diatoms, Cladocera, pollen, and sediment chemistry record various types of perturbations within Shagawa Lake that can be reasonably ascribed to settlement activities. Similar conditions have not existed under the natural environment for the last 2,000 years. It is doubtful that natural changes could replicate those caused by man, considering the year-round human nutrient input to Shagawa Lake and the variety of distinctive pollutants that man places in its water. Nevertheless, confirmation of this likelihood must await detailed knowledge of the life cycles, nutrient requirements, and habitat and environmental preferences of the organisms preserved in lake sediments. Superficially, the diatom community of Shagawa Lake after pollution resembles those of more eutrophic lakes in southern Minnesota (Bright, 1968), but it must be remembered that these lakes have probably also undergone some pollution, and that a detailed comparison would reveal significant differences, particularly with respect to the diversity of the diatom assemblage (Bradbury, 1975).

The second question relates to the advisability of using Burntside Lake as a standard by which pollution-abatement efforts in Shagawa Lake can be measured. The paleolimnological evidence from Shagawa and Burntside Lakes suggests that the two lakes have been dissimilar for a long time. Shagawa Lake has always been more productive (at least for the last 2,000 years) than Burntside Lake. The reasons for this lie partly in the fact that Shagawa Lake occupied a terrane of easily weathered metasedimentary and metavolcanic rocks and that some of its tributaries cross this terrane, bringing dissolved ions and nutrients to the lake. Some ground-water

[illegible] along [illegible] well [illegible] early [illegible]. [illegible] side [illegible] the other and [illegible] granite [illegible] rock and [illegible] low [illegible] nutrients [illegible] conditions [illegible] growth in the water.

The relationship of drainage area to lake volume [illegible] contributes to their limnology differences. Burntside Lake has nearly [illegible] times more water than does Shagawa Lake, yet their drainage areas are [illegible] the same (Table 2). If the drainage areas deliver similar amounts of nutrients to the lakes, it is evident that they would be diluted by the greater volume of Burntside Lake in comparison to their concentration in Shagawa Lake.

The third question addresses both the sensitivity of the lake limnological record and the sensitivity of lake systems to human impact. The present-day limnology of Burntside Lake has not [illegible] within the time spanned by the stratigraphic study--probably at least [illegible] years. It has become slightly enriched, most likely as a result of cabin building along its shores. If this enrichment continues, the limnology of Burntside Lake may come to resemble that of pre-settlement Shagawa Lake, but at the present time Burntside Lake is still less productive than Shagawa Lake was before human settlement.

INTRODUCTION

As population and industrial pressures [illegible] more and [illegible] resources, scientific and public concern over [illegible] caused [illegible] water quality [illegible] and [illegible] identified [illegible] protect lakes and [illegible] rehabilitate [illegible] extensively damaged [illegible] erosion [illegible] recreational use.

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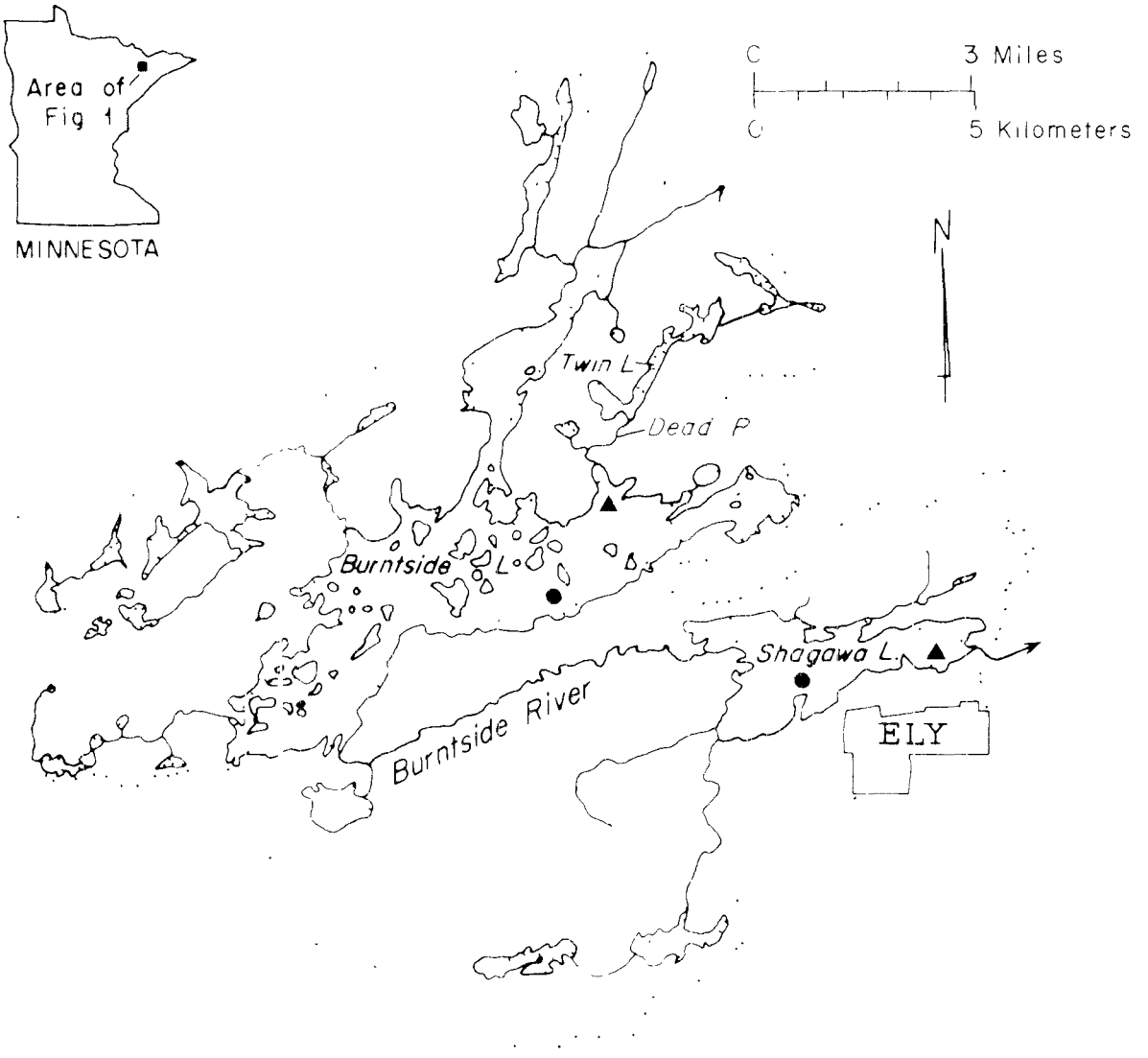


Figure 1 Map of Burntside and Shagawa Lakes and their drainage basins. Large dots show sampling stations and triangles show coring sites. Adapted from Schults et al. (1976).

limnologically distinct from Burntside Lake for at least 2,000 years. It is misleading to compare the present trophic state of Shagawa Lake with that of Burntside Lake, and unwise to expect that sewage treatment facilities now in operation at Shagawa Lake can convert this water body into a limnological counterpart of Burntside Lake.

Three related problems have prompted this paleolimnological study. The first was to attempt to discriminate between natural and cultural limnological changes in the stratigraphic record of Shagawa Lake, and to document those changes caused by the settlement of Ely, Minnesota. The second problem was to see if Burntside Lake, well known as a very clean, oligotrophic lake, has been affected by the relatively minor amount of settlement activity along its shores. The third problem was to test the assumptions that (1) the present limnological and trophic status of Burntside Lake once existed in Shagawa Lake, and that (2) the modern limnology of Burntside Lake could be used to evaluate pollution abatement efforts in Shagawa Lake by comparing the pre-settlement paleolimnological record of the two lakes. These assumptions appear logical because the lakes are adjacent and share the same climate, vegetation, and some of the same water. Their natural morphological differences appear to be slight compared to the massive cultural impact that caused the rapid eutrophication of Shagawa Lake.

GEOLOGY AND LIMNOLOGY

Both lakes are located in St. Louis County, northeastern Minnesota, in a terrane of metamorphosed lower Precambrian sedimentary and igneous rocks (Figure 2). Burntside Lake and its watershed lie entirely within the Vermilion granite, a predominantly granitic intrusive massif that also contains biotite schist, amphibolite, and trondhjemite (Sims, 1973). Just south of Burntside Lake an extensive and complex series of faults has placed the Vermilion massif in contact with the Ely Greenstone and related formations. These consist of a variety of low-rank metamorphosed volcanic rocks (chiefly basalts, but also including intermediate and felsic lavas and tuffs) and their derived sedimentary rocks, mostly graywacke and locally impure siliceous marble along with banded ferruginous cherts (the Soudan Iron-formation Member of the Ely). Shagawa Lake lies within these metamorphic rock types. Hydrothermal alternation and replacement of the Soudan Iron-formation Member has produced a rich lens of hematitic iron ore along the southern shore of Shagawa Lake (Machamer, 1968).

Glacial sediments, including sand, gravel, and lacustrine silts and clays, overlie the Precambrian rocks in a patchy distribution. The lacustrine silty clays are slightly calcareous and appear to continue beneath the organic deposits of Shagawa Lake. They may represent the deposits of a precursor of glacial lake Agassiz. Similar clays are found near the east end of Burntside Lake.

The limnology of Shagawa Lake is fairly well known (Megard, 1969; Bradbury and Megard, 1972; Larsen and Malueg, 1976, Schults et al., 1976). It is 6.5 km long and has a mean depth of 5.7 m. In size (9.2 km^2), volume (0.053 km^3), and depth it typifies many lakes of this region. The lake's long axis is oriented east-northeast, and the lake narrows and drains in that direction. Shagawa Lake has surface inflow at the west end by the Burntside River, which annually provides about 80% of the water to the lake. Excluding Burntside and Shagawa Lakes themselves, the total drainage area is about 231 km^2 (Schults et al., 1976). In general the lakes in northeastern Minnesota are biologically unproductive and characterized by nutrient-poor waters of low conductivity. The specific conductance of Shagawa Lake (65 µmhos cm^{-1}) resembles that of neighboring lakes and major tributaries that lie on the Newton Lake formation or Ely Greenstone (mean of 7 sites = 70 µmhos cm^{-1}). Most of the lakes on the granitic rocks of the Vermilion massif have a lower specific conductance, as do lakes located on the Giants Range Granite southeast of Ely (mean of 21 sites = 47.2 µmhos cm^{-1}) (Figure 2). Concentrations of major and minor elements in Shagawa Lake generally reflect the mean values of lakes in this region (Table 1), although phosphorus is 10 times higher in Shagawa Lake (mean of 5 localities

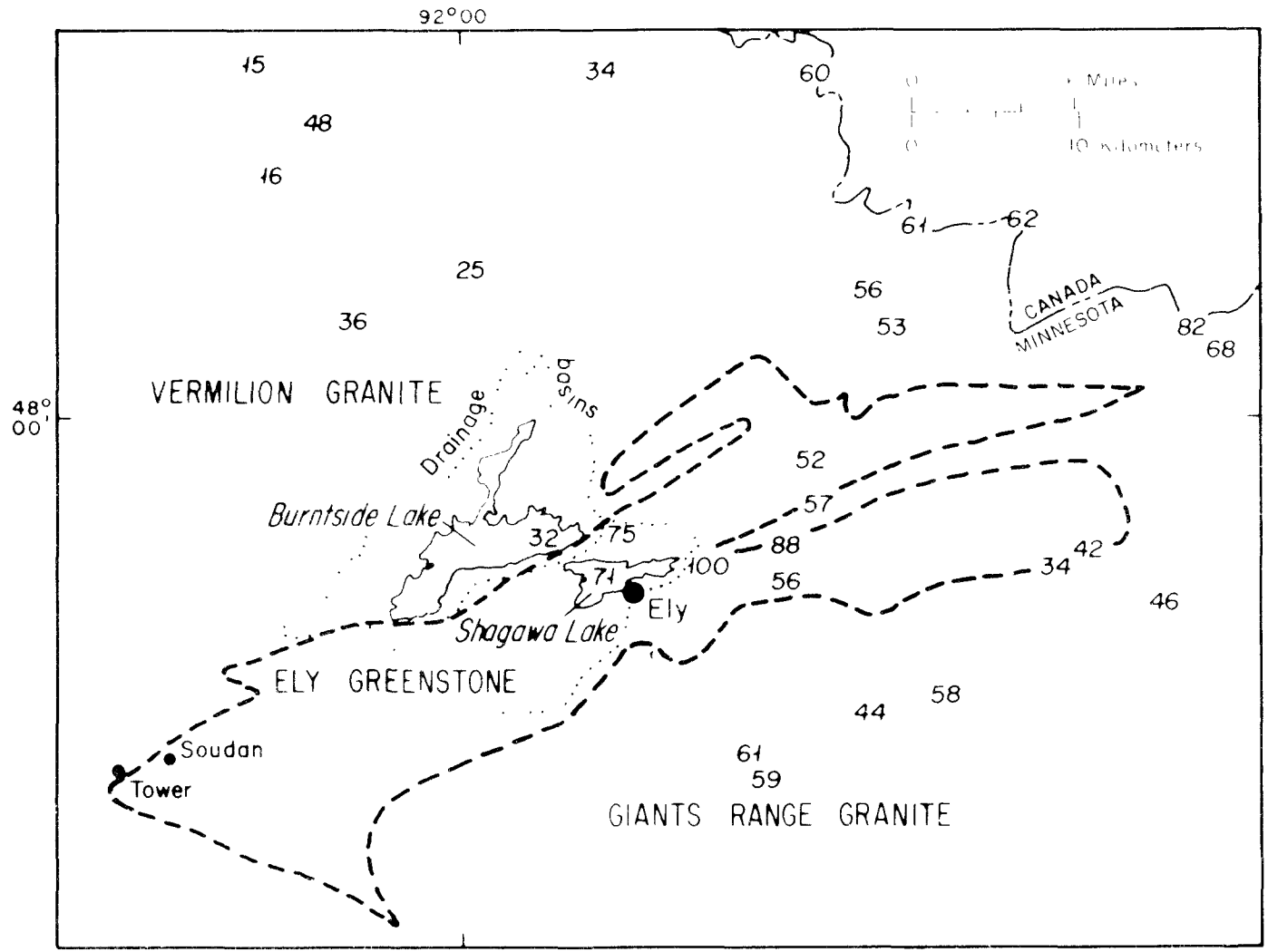


Figure 2 Map showing values of specific conductance in µmhos/cm for lakes and rivers in relation to bedrock geology in the area of Burntside and Shagawa Lakes. Metasediments and metavolcanics (the Ely Greenstone) are enclosed within the dashed line. Mean conductivity (µmhos/cm) of water bodies on the Ely Greenstone = 70.4 (n = 7); on the granitic rocks of the Vermilion Massif and the Giants Range Granite conductivity = 47.2 (n = 21).

TABLE 1. CONCENTRATIONS OF MAJOR DISSOLVED IONS (MG/1) IN SHAGAWA LAKE COMPARED WITH MEAN CONCENTRATIONS IN NORTHEASTERN MINNESOTA AND ONTARIO LAKES

	Shagawa Lake	Mean for 19 northeastern Minnesota lakes*	Mean for 40 Ontario lakes#
Calcium	9.90	10.2	1.6
Magnesium	3.36	3.0	0.9
Sodium	2.00	1.5	0.9
Potassium	0.60	0.8	0.4
Bicarbonate	26.80	39.0	3.8
Chloride	0.10	0.1	1.4
Sulfate	13.80	5.7	3.0
Salinity (meq/1)	1.62	1.7	0.4

*Bright, 1968.

#Armstrong and Schindler, 1971.

in 1968 = 45 ug/l) than in surrounding lakes. Until early 1975, about 75% of the phosphorus and 22% of the nitrogen entering Shagawa Lake came from the municipal sewage treatment plant at Ely (Malueg et al., 1975). This large nutrient influx, particularly phosphorus has produced extensive blooms of blue-green algae.

Because Shagawa Lake is relatively shallow, it overturns easily in the spring. By midsummer, when surface-water temperatures exceed 18°C, it stratifies with a thermocline at approximately 3 m. The epilimnion may have very high chlorophyll a concentrations and a pH greater than 10. Below 4 m, oxygen may disappear and the pH is neutral.

In summer the dominant phytoplankters are blue-green algae (Aphanizomenon flos-aquae and Anabaena spp.), but in the early spring and fall diatoms are comparatively abundant. The seasonal succession of diatom species in 1974 (Figure 3) shows that small species of Stephanodiscus (S. minutus, S. hantzschii, and S. subtilis) characterize the early spring blooms. In some years, blooms of these diatoms occur under clear ice in the winter months (e.g. February and March 1968) (Megard, 1969, 1973). Following the initial bloom of small Stephanodiscus species, Asterionella formosa, Fragilaria crotenensis, Melosira granulata, Stephanodiscus dubius, Stephanodiscus niagarae, and finally Melosira ambigua dominate the planktonic diatom flora. The relative dominance of Asterionella formosa at the end of 1974 is of little quantitative significance because all diatoms become very scarce once the lake freezes over. It is not known if this successional pattern characterized Shagawa Lake before pollution control measures took effect. Evidence from Megard (1969) indicates that early spring blooms of small Stephanodiscus species occurred in 1968, five years before the Environmental Protection Agency (EPA) advanced treatment plant went into operation (Megard, 1973), but the reduced phosphorus levels in the waste water now entering the lake as a result of the plant's operation could very likely be responsible for changes in both the quantity and quality of phytoplankton as well as in other limnological parameters. Analyses of algae during the summer of 1967 (Megard, 1969) show that Melosira ambigua was the only diatom present in a phytoplankton community dominated by the blue-green alga Aphanizomenon flos-aquae on the dates 29 VII 1967 and 14 VIII 1967. For this time period in 1974, the diatom flora is considerably more diverse (Figure 3).

Burntside Lake is about three times the size of Shagawa Lake (about 29.2 km^2)(Table 2), and its long, intricate shoreline and its many islands (Figure 1) suggest a complex limnology. Isolated basins in the east arm of the lake attain depths of 25 to 40 m, and its mean depth (15.7 m) is significantly greater than that of Shagawa Lake. Nevertheless, Burntside Lake's large size (maximum northeast-southwest dimension about 13 km) allows sufficient fetch for the wind to mix its water, which remains aerobic to the bottom throughout the year (Schults et al., 1976). Sandy, relatively inorganic sediments at intermediate depths in mid Lake also suggest that oxygenated water and currents frequently reach the bottom.

The concentration of most chemical parameters in Burntside Lake is less than in Shagawa Lake, although the differences are not consistently

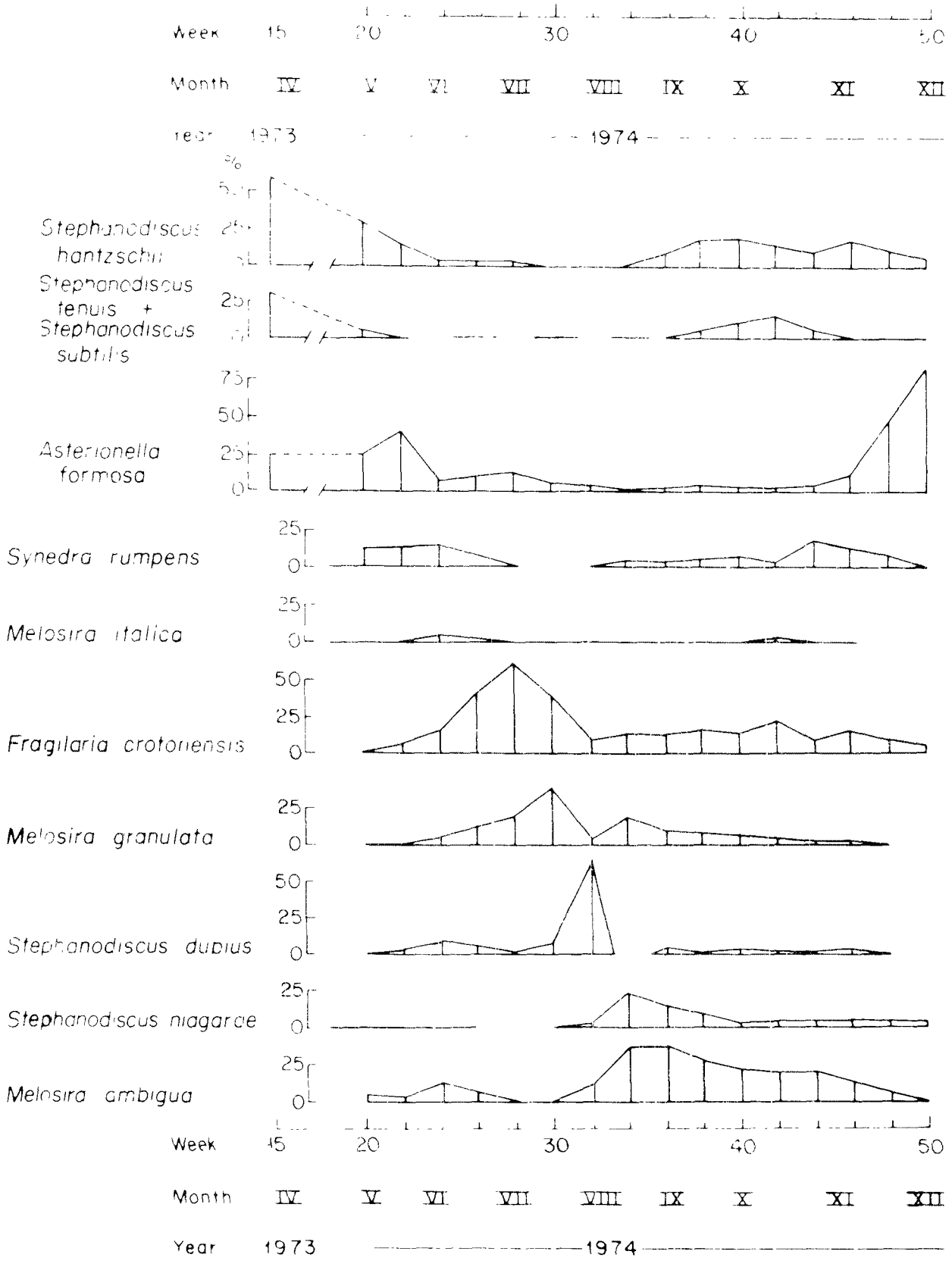


Figure 3 Seasonal distribution of diatoms in the surface water of Shagawa Lake for April, 1973, and the 1974 open-water season.

TABLE 2. SIZE, MORPHOLOGY AND DRAINAGE AREA OF SHAGAWA AND BURNTSIDE LAKES (FROM SCHULTS *et al.*, 1976)

	Shagawa Lake	Burntside Lake
Watershed area (km^2)	100.	131.
Lake surface area (km^2)	9.2	29.2
Mean depth (m)	5.7	15.1
Maximum depth (m)	13.7	48.8
Volume (km^3)	0.053	0.44

proportional (Table 3). Both lakes have nearly the same concentrations of potassium, chloride, and sulfate ions, but sodium, calcium, magnesium, and silica are enriched in Shagawa Lake by factors of nearly 2 to 3. Iron and manganese are highly concentrated in Shagawa Lake, particularly in the lower waters during times of thermal stratification. These differences in concentration result from a number of factors, one being the high concentration of the waste water entering Shagawa Lake from the town of Ely. The high iron and manganese concentrations in Shagawa Lake, however, probably reflect the greater frequency and intensity of anoxic bottom-water conditions in Shagawa Lake than in Burntside Lake, for during such times these elements will be reduced and move from the bottom sediments into the overlying water.

However, not all chemical differences can be easily related to Ely's waste water or to limnological characteristics of the two lakes. Table 4 shows a progressive concentration in specific conductance and major cations as water from Burntside Lake flows along the Burntside River and into Shagawa Lake. This increase in concentration of total dissolved solids is from 75 to 85% of the average Shagawa Lake value, and it is accomplished in only about 5 km of river travel. In addition, the specific conductances of the minor tributaries to Shagawa Lake are all significantly higher than Burntside Lake (Figure 4). These tributaries amount to about 19% of Shagawa Lake's inflow (Malueg _et al._, 1975).

Despite the fact that Malueg _et al._ (1975) did not locate a significant ground-water inflow to Shagawa Lake, there are indications that ground-water plays an important role in controlling water chemistry in the lake. All tributaries to Shagawa Lake either cross or flow along major faults that place slices of mafic metavolcanic and metasedimentary rocks in contact; Armstrong Creek, for example, crosses five such faults in a distance of 3 km. The course of the Burntside River is largely determined by the Burntside fault, in which zones of mylonite indicate extreme slipping and crushing along the fault walls (Sims, 1973). The common minerals of the Ely Greenstone, plagioclase, chlorite, hornblende, epidote, and calcite (Machamer, 1968), are relatively labile and rich in sodium, calcium, and magnesium. The higher concentrations of these elements in the Burntside River is probably related to the abundance of these elements in the bedrock and to the proximity of fracture zones that might serve as conduits for ground-water flow. The fact that the hematite mines of Ely must be dewatered by pumping further attests to the presence and movement of ground-water in the area. Although Burntside Lake is similarly surrounded and underlain by faults, the dominant lithologies of this area are the granites and biotite schists of the Vermilion massif, which in general contain less labile minerals than the mafic rocks nearby. Perhaps this partly accounts for the low conductivity of Burntside Lake.

The biology of Burntside Lake reflects its more dilute water. Diatoms characteristic of oligotrophic lakes such as _Tabellaria flocculosa_ (Bright, 1968; Bradbury, 1975) become important in the Burntside Lake phytoplankton community during the summer months (Figure 5), and the planktonic diatom assemblage in general resembles those of undisturbed lakes in northeastern Minnesota (Bradbury _et al._, 1975) and the Experimental Lakes Area lakes of northwestern Ontario (Stockner, 1971). Summer algal productivity

TABLE 3. MEAN CONCENTRATION (AVERAGES OF MEAN VALUES IN HYPOLIMNION AND EPILIMNION OF SELECTED PARAMETERS IN THE WATER OF SHAGAWA AND BURNTSIDE LAKES DURING 1971 AND 1972 (FROM SCHULTS *et al.*, 1976)

Parameter	Shagawa Lake	Burntside Lake	Ratio Shagawa Lake/ Burntside Lake
Specific conductance (μmho/cm)	65.0	32.0	2.0
Calcium (mg/l)	9.0	3.3	2.7
Magnesium (mg/l)	2.3	1.0	2.3
Sodium (mg/l)	1.60	0.95	1.7
Potassium (mg/l)	0.7	0.6	1.2
Iron (μg/l)	914	50	18.3
Manganese (μg/l)	275	9.0	30.5
Silica (mg/l)	4.9	2.0	2.4
Sulfate (mg/l)	10	10	1.0
Chloride (mg/l)	2.7	2.4	1.1
Total phosphorus (mg/l)	0.11	0.01	11.0
Orthophosphate phosphorus (mg/l)	0.06	0.0025	24.0
Total -N (mg/l)	1.1	0.7	1.6
Ammonia -N (mg/l)	0.17	0.02	8.5
Nitrate -N (mg/l)	0.063	0.024	2.62
pH*	7.3	6.9	1.0
Total alkalinity (mg/l)	23.6	7.4	3.2
Dry weight (seston) (mg/l)	2.0	0.7	2.8
Chlorophyll *a* (μg/l)	10.9	2.3	4.7
Phaeophytins (μg/l)	2.2	0.7	3.1

*median

TABLE 4. COMPARISON OF MAJOR CATIONS IN BURNTSIDE LAKE, BURNTSIDE RIVER, AND SHAGAWA LAKE. DATA FROM SCHULTS et al. (1976) AND LARSEN (ORAL COMMUNICATION, 1974) [MEAN MONTHLY SAMPLES (SHAGAWA LAKE) AND BIMONTHLY SAMPLES (BURNTSIDE LAKE) OF EPILIMNION AND HYPOLIMNION FOR 1971 and 1972]

	Burntside Lake	Burntside River[1]	Shagawa Lake	Ratio Burntside River/Lake	Ratio Shagawa/ Burntside Lakes
Specific Conductance (μmhos/cm)	32	57	62	1.8	1.9
Sodium (mg/l)	1.0	1.2	1.6	1.2	1.6
Potassium (mg/l)	0.6	0.6	0.7	1.0	1.2
Calcium (mg/l)	3.3	7.6	9.0	2.3	2.7
Magnesium (mg/l)	1.0	1.5	2.1	1.5	2.1

[1]Mean of samples taken between 1970 and 1974.

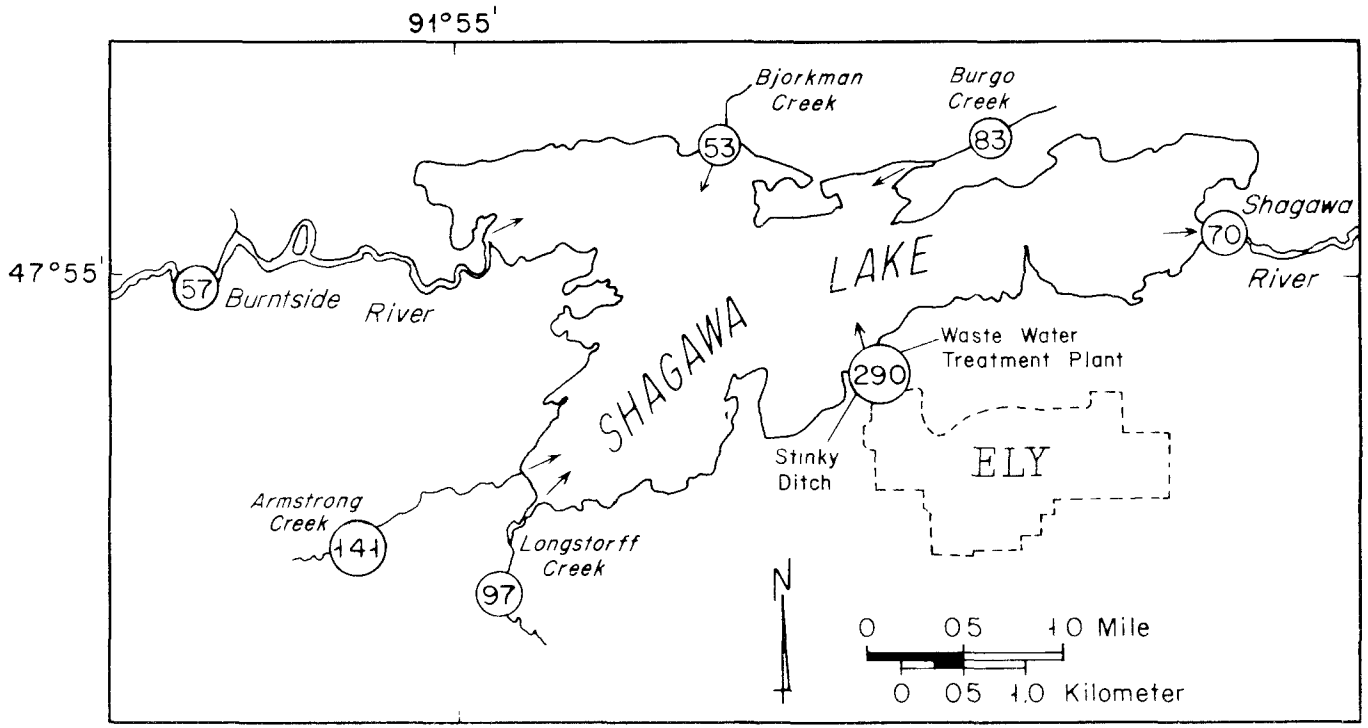


Figure 4 Mean specific conductance (μmhos/cm) of major Shagawa Lake influents and effluents 1970-1976. Data from U.S. Geological Survey, adapted from Malueg et al. (1975).

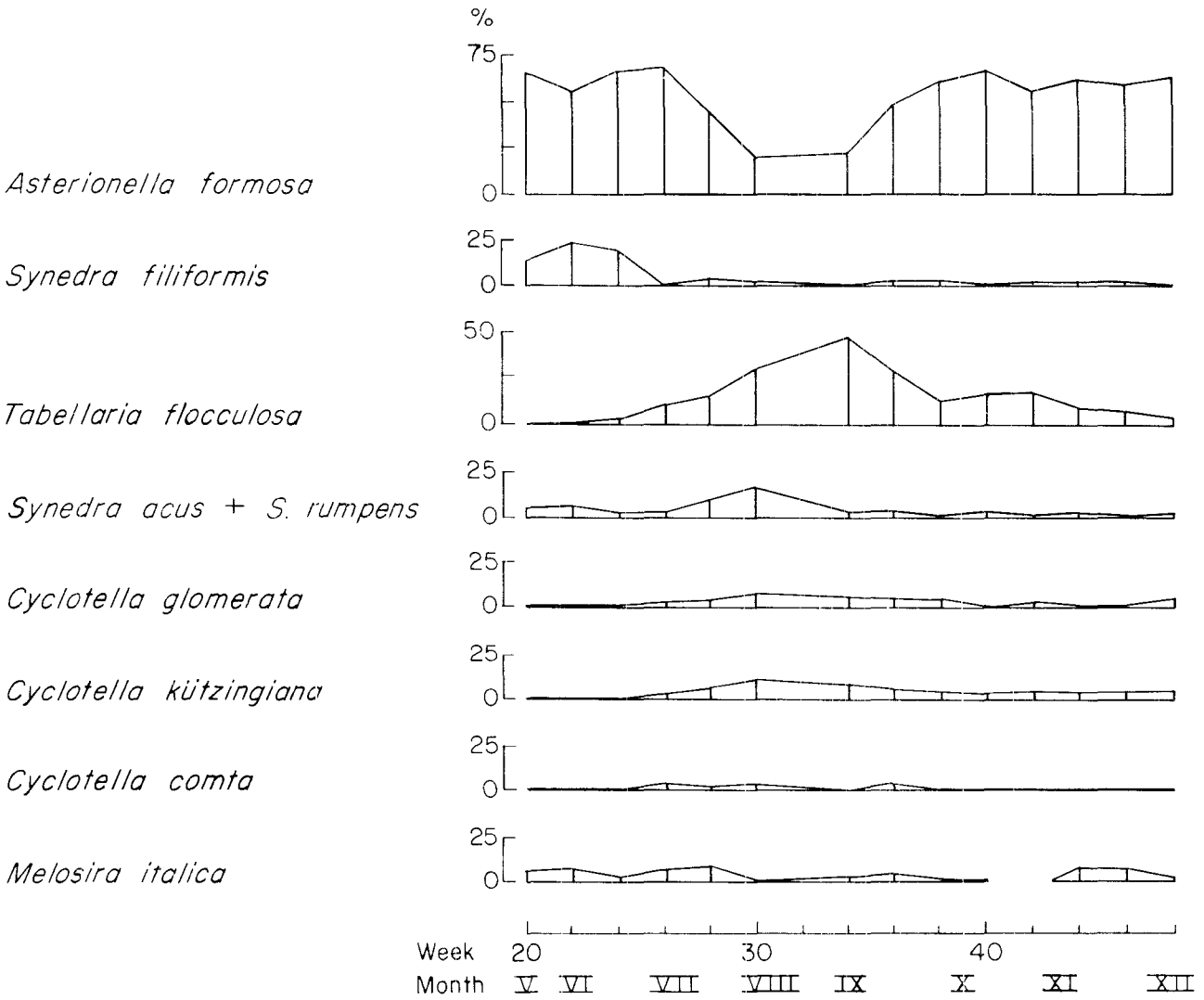


Figure 5 Seasonal distribution of diatoms in the surface water of Burntside Lake for the 1974 oper-water season.

(organisms per ml) in Burntside Lake is one-third to one-tenth that of Shagawa Lake before the phosphorus reduction program began. The composition and abundance of the benthic fauna in Burntside Lake are further indicators of its oligotrophic status (Schults *et al*., 1976).

VEGETATION

The natural vegetation of the area surrounding Burntside and Shagawa Lakes consists of a conifer-hardwood forest whose species show affinities with the boreal regions to the north and the Great Lakes- St. Lawrence forest region to the east (Heinselman, 1973). The principal boreal conifer species are *Pinus banksiana*, *Picea glauca*, *Picea mariana*, *Abies balsamifera*, *Larix laricina*, and *Thuja occidentalis*. *Pinus resinosa* and *Pinus strobus* are elements of the Great Lakes-St. Lawrence forest region to the east. These and many deciduous trees (principally *Populus*, *Betula*, *Quercus*, *Ulmus*, *Fraxinus*, *Juglans*, *Ostrya*, and *Acer*) exist in a complex mosaic of communities that relate to variations in soils, drainage, and fire history (Bradbury and Waddington, 1973; Heinselman, 1973). Since the late 1800's some changes in the local forest character have been brought about by Euro-American settlement activities.

Periodic forest fires have characterized this part of Minnesota for centuries (Heinselman, 1973). All of Burntside Lake's shoreline was burned at one time or another in the last 200 years. There were fires on the islands in the southwest end of the lake in 1742-1755, and again about 1850. The north arm of Burntside Lake had fires in 1822, 1863-64, and 1894 (M.L. Heinselman, written commun., 1976). Most of the fires of this region before 1880 were probably natural.

SETTLEMENT HISTORY

The northern part of St. Louis County was originally surveyed in 1880. At that time the only signs of man's activity were trails that ran short distances through the woods. By 1894 a number of cabins had been erected in the vicinity (Figure 6), and the towns of Tower (1883), Soudan (1887), and Ely (1887) were founded (Figure 2), after the discovery of rich deposits of iron ore (hematite) nearby. By 1900 five mines were in operation near Shagawa Lake, and the tonnage of ore shipped from these mines reached a maximum at this time (Figure 7). Subsequently, mining fluctuated according to national economic conditions. At Ely, the deposits gradually became exhausted after World War II, and the last mine was shut down in 1967.

Lumbering began at the same time as mining, principally in response to the demand for mine timbers and construction materials. The drainage basin of Burntside Lake was logged between 1895 and 1915. Nearly all the big white pine (Pinus strobus) and red pine (Pinus resinosa) were cut as well as some cedar (Thuja occidentalis) and spruce (Picea). Fires frequently followed logging due to uncontrolled slash fires (Heinselman, 1973, and written commun., 1976). Most of the timber around Shagawa Lake was cut by 1895, and it may be assumed that soil erosion associated with all settlement activities including local clearing for agricultural land kept pace with the abrupt population increase from 1890 to 1900 and to a lesser extent thereafter.

The shores of Burntside Lake are shown as subdivided plots in the plat book of 1916 (Hixon and Co., 1916), and cabin building around the lake increased about 1920. Since this time some road work has been done in the vicinity of Burntside Lake, and roads are currently being extended (Heinselman, written commun., 1976). Cabin construction again increased after 1945 and still continues.

The permanent population of Ely reached a maximum (6,000 persons) in 1930 and gradually declined thereafter (Figure 7). Early population increases are clearly related to increasing mine shipments, but after 1900 there is less correlation. Much of Ely's economy today is related to summer tourist use of the north woods lakes. This transient population is not measured by census statistics, but it undoubtedly has a great impact on the lacustrine environment of Shagawa Lake and to a lesser degree of Burntside Lake. Between 1953 and 1963 annual visitor use of the wilderness in this part of northeastern Minnesota increased from 50,000 to 230,000. A large majority of the canoeists, fishermen, and campers spend some time in Ely, a major outfitting center for wilderness travel (Lucas, 1964).

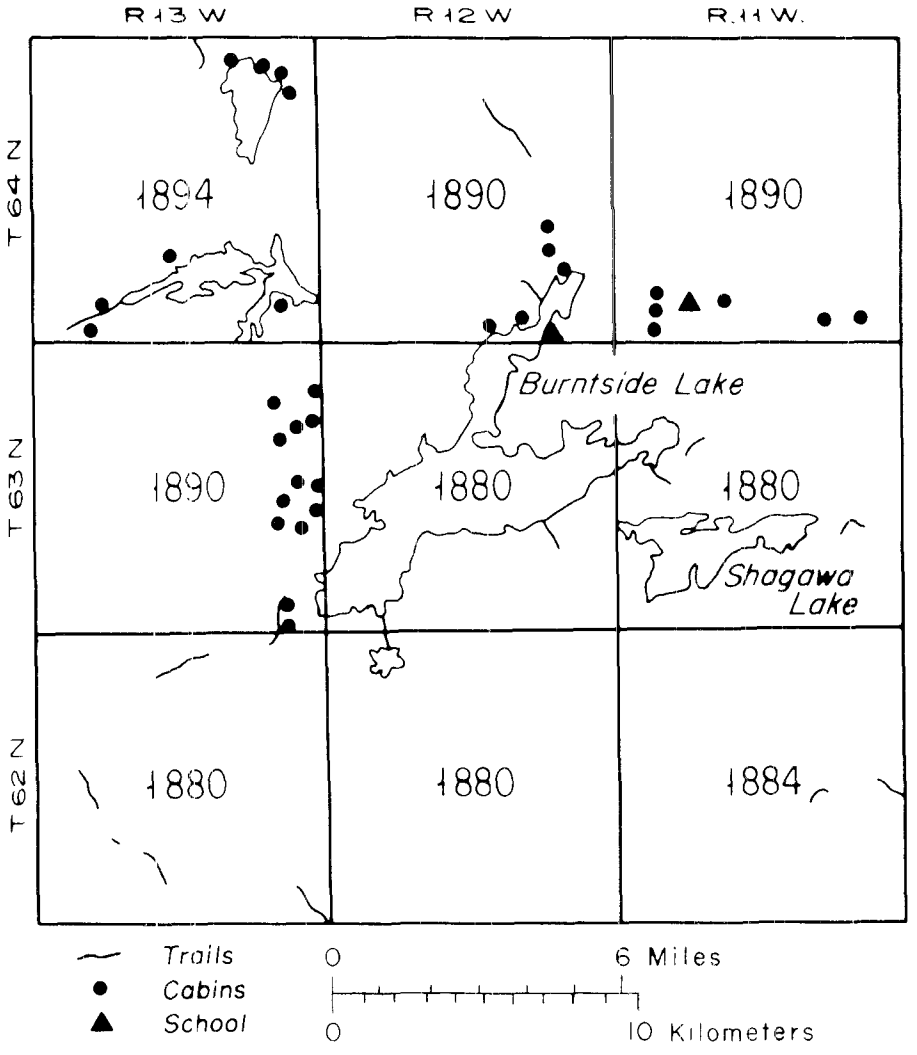


Figure 6 Distribution of settler's cabins near Burntside Lake 1880-1894. Dates indicate when each township was surveyed. Data extracted from land-survey records by Jean C.B. Waddington.

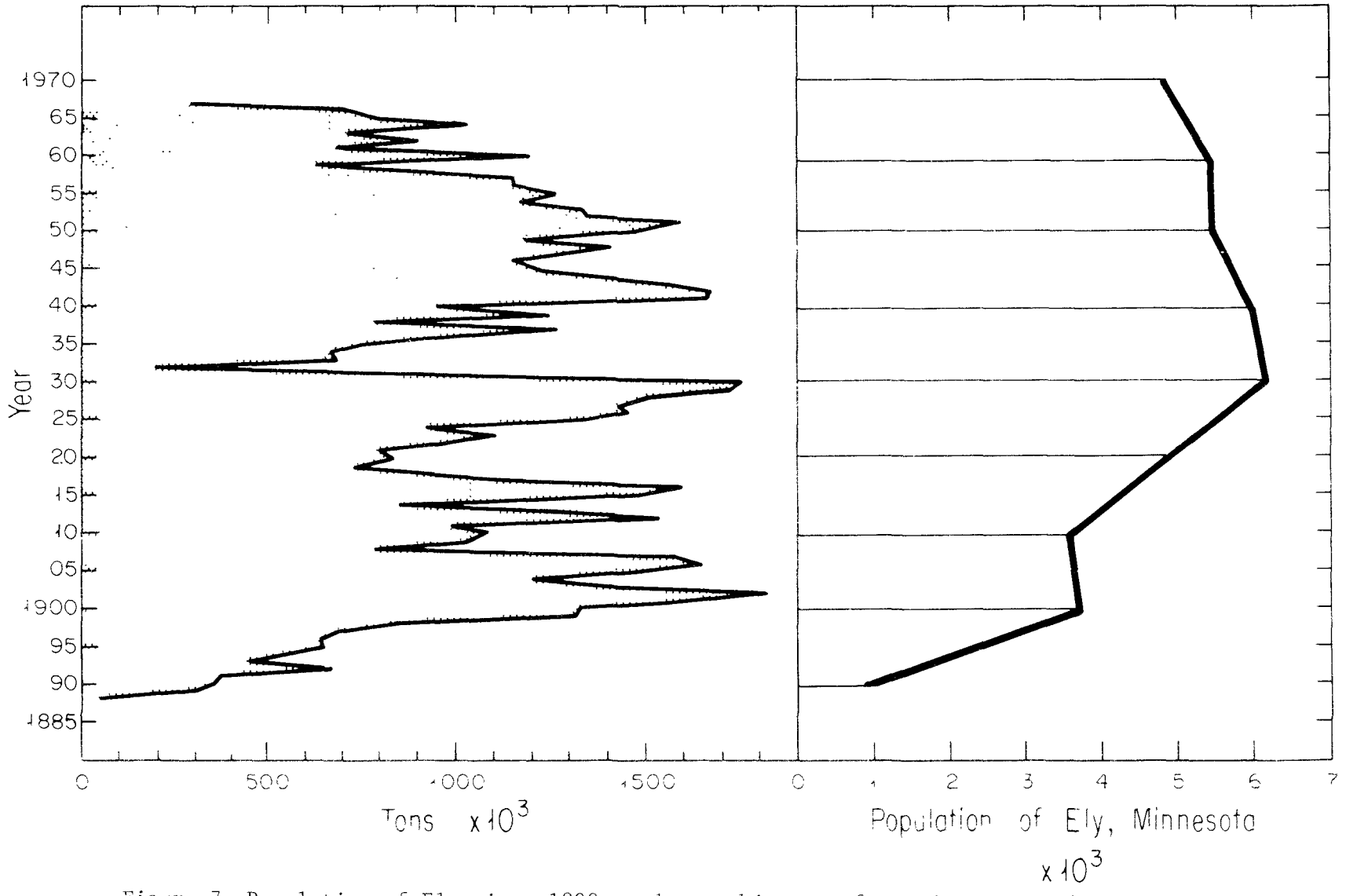


Figure 7 Population of Ely since 1890, and ore shipments from mines near Shagawa Lake.

Ely has had a municipal sewage system since 1901, and since that time municipal wastes have been entering Shagawa Lake. In 1912 two Imhoff tanks (in which particulate sewage settles and is anaerobically decomposed) were installed in the system, and by 1954 treatment facilities included a primary settling tank, a high-rate trickling filter, and a secondary settling tank (Brice and Powers, 1969). Nevertheless, nutrient-rich water was still entering Shagawa Lake causing severe blooms of blue-green algae (Larsen and Malueg, 1976). In 1963 the treatment plant operated within its design capacity and treated up to one million gallons of sewage/day by reducing the biological oxygen demand (BOD) from 100 mg/l to 20 mg/l. Algal blooms continued, however, and in 1973 the Environmental Protection Agency established a tertiary treatment plant for Ely's municipal wastes in which phosphorus and nitrogen were chemically removed from the water before it entered Shagawa Lake.

STRATIGRAPHIC STUDIES

Methods

Lake-sediment cores for stratigraphic paleolimnological analysis of Shagawa and Burntside Lakes were taken with a 5-cm diameter piston sampler (Cushing and Wright, 1965). The 1.64-m Shagawa Lake core (taken in the fall of 1971) came from the east basin of the lake under 12 m of water. The Burntside Lake core (taken in the fall of 1974) came from a protected bay on the east arm of the lake, 0.6 km south of the entrance of Dead River (Figure 1), in a water depth of 15 m. The cores were subsampled at 0.3-to 2.5-cm intervals in the field by controlled upward extrusion from the coring tube. Analytical methods are summarized in Table 5.

Vegetation History

The pollen record from Burntside Lake (Figure 8) is basically similar to that of Shagawa Lake (Figure 9 and Bradbury and Waddington, 1973). The major stratigraphic change in each core is identified by an increase in the percentages of *Ambrosia* (ragweed) pollen and a simultaneous decrease in the *Pinus strobus* (white pine). This change occurs at 18-cm depth in Burntside Lake and at 39-cm depth in Shagawa Lake. Chenopod-Amaranth pollen increases with *Ambrosia*, and other disturbance weeds such as nettles (*Urticaceae*), dock (*Rumex*), and Russian thistle (*Salsola kali*) make their appearance or become more common at this time. *Salsola kali*, introduced to this country from Asia by the 1880's (Weaver and Clements, 1929) positively identifies this upper zone as the post-settlement horizon. In all probability these pollen changes are synchronous in both lakes.

The decline of *Pinus strobus* pollen is best discussed as the ratio of this species to total pine pollen. *Pinus strobus* contributes approximately one-quarter of the total pine pollen rain prior to settlement. After that time, probably because of selective logging of this species. *P. strobus* is reduced to one-sixth of the total pine pollen (Bradbury and Waddington, 1973). This ratio seems to hold true for all the sites in northeastern Minnesota that have been studied to date.

The pollen records from Burntside and Shagawa Lakes are as similar as might be expected from different basins within one lake. The differences probably reflect variation in the local vegetation because of fire history and edaphic factors and differences in lake morphometry and microclimate which influence the amounts of different pollen types that become incorporated into lake sediment. The large variation in importance percentages of

TABLE 5. ANALYTICAL METHODS FOR SEDIMENT CORES FROM SHAGAWA AND BURNTSIDE LAKES

Analysis	Burntside Lake	Sample Size	Shagawa Lake	Sample Size
Pollen, fungi, charcoal.	HF/Acetolysis method (Cushing, 1964). Exotic pollen added to determine absolute concentration. Pollen count 200-600.	0.5 ml	Same method. Pollen count 500-800 (Bradbury & Waddington, 1973).	0.5 ml
Diatoms, Phytoliths, and hematite silt.	Wet sediment digested with conc. HNO_3 + 30% H_2O_2. Residue washed free of oxidants and mounted in "Hyrax". Frequency established by 500-valve count excluding phytoliths and hematite silt.	0.2 ml	Same method. Valve count 1000 per level (Bradbury & Waddington, 1973).	0.5 ml
Cladocera	Not done	---	Fresh sediment disaggregated with 10% HCl, followed by boiling in 10% KOH. Cladocerans concentrated by sieving through 67 μm mesh.	5.0 ml
Organic matter	Percent of dry weight established by loss on ignition at 550°C (Dean, 1974).	1 g	Same method	1 g
Biogenic opal	Percent of dry weight established by digesting ashed sediment in 0.5 N NaOH for 2 hrs at 100°C. Residue washed, centrifuged, and weighed.	0.5 g	Ashed sediment digested in 4N boiling NaOH for 10 min. Residue washed, filtered, and weighed (Bradbury & Waddington, 1973).	0.25 to 0.5 g
Clastics: sand, silt, and clay	Percent of dry weight determined by difference: dry sediment weight - % organic matter - % biogenic opal.	1 g	Same method	1 g

TABLE 5. ANALYTICAL METHODS FOR SEDIMENT CORES FROM SHAGAWA AND BURNTSIDE LAKES

(CONT.)

Analysis	Burntside Lake	Sample Size	Shagawa Lake	Sample Size
Water content	Fresh sediment weighed, dried at 110°C and reweighed	3 g	Same method.	3 g
Iron	Not done.	---	Dried sediment (110°C) digested with conc. HCl. Fe reduced with $SnCl_2$ and titrated with $K_2Cr_2O_4$.	0.4 g
Calcium	Atomic absorption analysis after digestion of sediment ash with conc. HCl.	50 mg	Not done.	---
Tannin and lignin	Dry sediment digested at 0.12 N KOH 1 hr at 100°C. Determination by spectrophotometry (900 μmm) after addition of Tyrosine reagent.	5 to 20 mg	Not done.	---
Phosphorus	Ashed sediment (550°C) digested with 4N HCl. P reduced with ascorbic acid and determined spectrophotometrically after addition of $(NH_4)_2MoO_4$.	6 to 10 mg	Same, but fresh sediment digested with $K_2S_2O_8$ in pressure cooker.	0.1 g

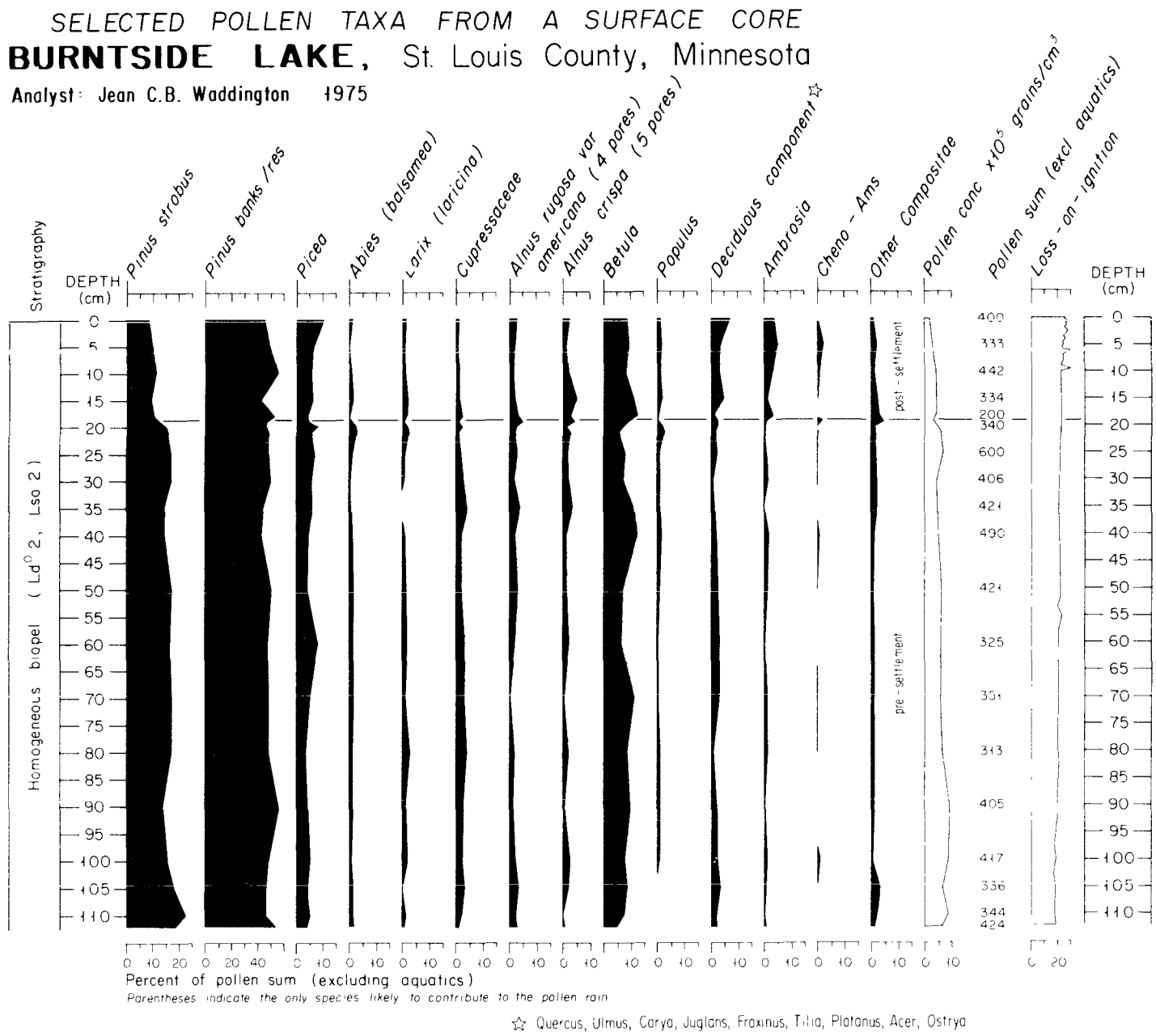


Figure 8 Selected pollen curves for a short core from Burntside Lake. The line at 19 cm marks the rise in pollen of Ambrosia (ragweed) and thus the time of regional vegetation disturbances (about 1890).

Shagawa Lake, St.Louis Co.,Mn.

Selected pollen taxa from a surface core
Anal.: Jean C.B.Waddington, 1972

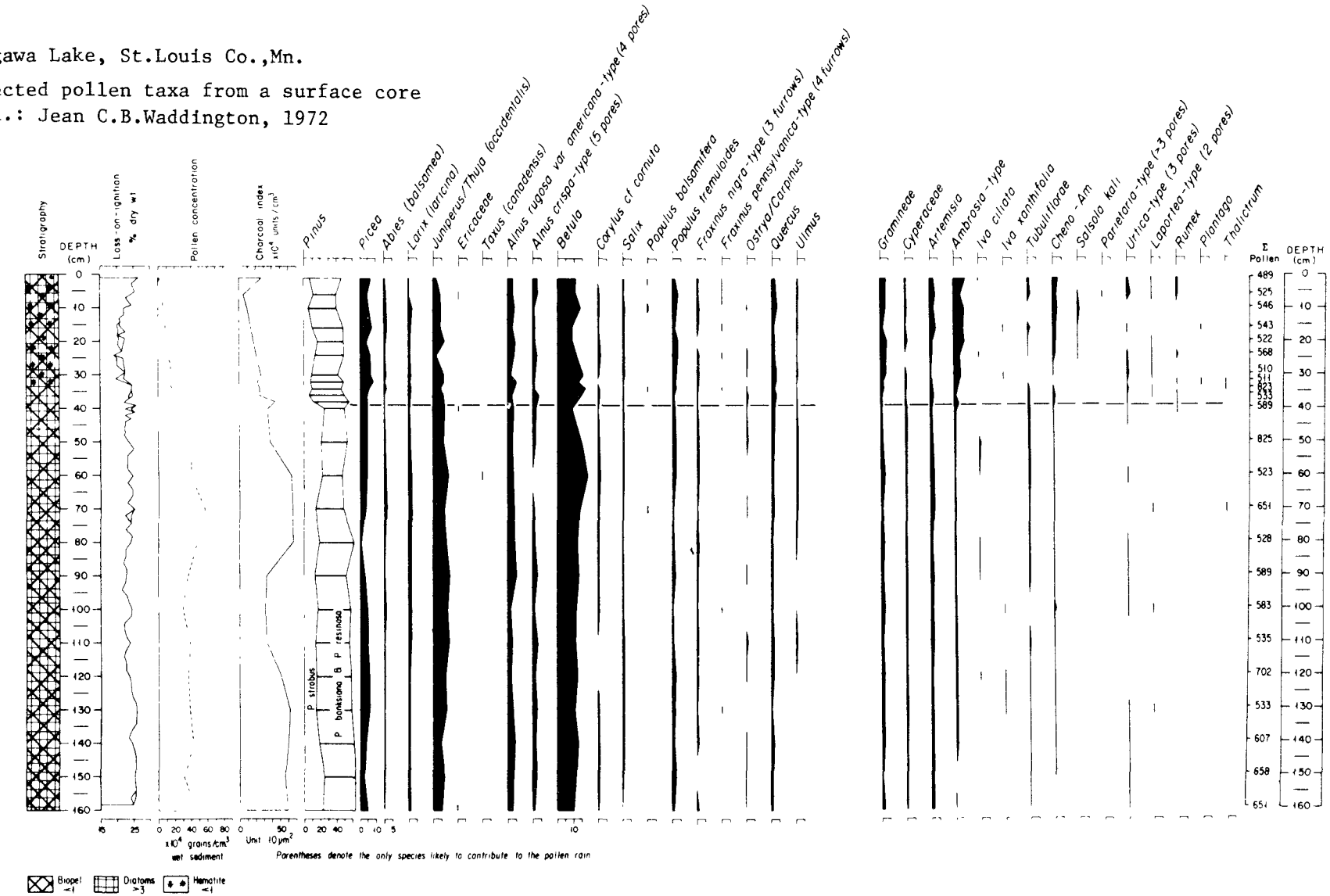


Figure 9 Selected pollen curves for a short core from Shagawa Lake. The line at 39 cm marks the rise in pollen of Ambrosia (ragweed) and thus the time of regional vegetation disturbance (about 1890).

witness trees noted by surveyors around the lakes in 1880 (Table 6) illustrates the patchiness of plant distribution within the forest. The pollen percentages from approximately corresponding pre-settlement levels (20 cm in Burntside Lake and 40 cm in Shagawa Lake) are very similar, however. This relationship supports the concept of a regional pollen rain in northeastern Minnesota, and that local forest inhomogeneities only affect the pollen record of very small lakes in this area. Because of this regional influence, the pollen record of Shagawa and Burntside Lakes cannot be expected to provide much information on the local vegetation history relevant to the development and limnological character of the lakes.

The pollen records from Burntside Lake and Shagawa Lake are generally similar to records in the Boundary Water Canoe Area to the north. For example, the pollen profiles from Dogfish Lake and Meander Lake about 40 km NW of Ely (Bradbury *et al.*, 1975) and from Lake of the Clouds 60 km NE of Ely (Swain, 1973) demonstrate that all these lakes have existed in the mosaic of mixed deciduous-coniferous forest that has resulted from natural forest fires in northeastern Minnesota over the past 10,000 years (Heinselman, 1971, 1973; Swain, 1973). The stability of the vegetation pattern in spite of frequent pre- and post-settlement fires is partly due to the innumerable lakes and marshes in this region that act as fire breaks and prevent the eradication of local seed sources. Thus man's activities so far have caused only minor vegetation changes on a regional scale.

Core Correlation

The cores from Burntside and Shagawa Lakes can be correlated by the percentage increase in *Ambrosia* pollen (the *Ambrosia* rise) and the sharp decrease in *Pinus strobus* pollen. However, it is not known exactly what date these stratigraphic changes represent. A date of 1898 has been established for the *Ambrosia* rise in Lake of the Clouds (64 km NE of Shagawa Lake) based on pollen counts from varved sediments at two-year intervals (Swain, 1973). Because the drainage basin of Lake of the Clouds has never experienced logging or agriculture, it is assumed that the 1898 date for the *Ambrosia* rise is a regional effect which could be applied to Burntside and Shagawa Lakes. Confirmation of the 1898 date comes from the abrupt increase in silt sized particles of hematite in the sediments of both Shagawa and Burntside Lakes, recording the beginning of mining at Ely (Figures 10, 11). The mines had to be dewatered, and it was customary to pump the mine water, charged with hematite dust from the mining operation, into Shagawa Lake, where it settled to produce a distinctive marker layer on the lake bottom. The hematite that entered Burntside Lake was probably airborne. Once the ore was brought to the surface, wind could have transported hematite dust from the ore piles and railroad cars to nearby lakes. The marked increase in hematite silt in the sediment cores from Shagawa and Burntside Lakes should correspond to a date of 1888 (Figure 7). This correlation seems fairly certain, even though organisms burrowing in the lake sediment blur this stratigraphic marker somewhat, and some hematite silt may have entered the lakes naturally by erosion of nearby glacial deposits.

TABLE 6. COMPARISON OF IMPORTANCE PERCENTAGE OF WITNESS TREES AT THE TIME OF LAND SURVEY AT SHAGAWA AND BURNTSIDE LAKES WITH PRE-SETTLEMENT AND RECENT POLLEN PERCENTAGES

	Burntside Lake			Shagawa Lake		
Witness tree	Imp. percent	Pre-settlement pollen %	Recent pollen %	Imp. percent	Pre-settlement pollen %	Recent pollen %
White pine	35.29	15.0	8.3	13.83	25.0	7.0
Jack/Red pine	19.97	46.0	44.5	20.04	35.0	39.5
Aspen	12.28	2.1	0.8	9.51	1.5	1.6
Birch	10.77	7.4	8.5	15.33	9.0	11.0
Spruce	8.66	7.9	10.3	20.50	5.3	7.0
Tamarack	4.75	0.9	1.3	6.88	0.8	0.4
Cedar	3.20	2.1	0.8	5.07	6.8	2.2
Fir	2.95	1.8	1.3	4.11	0.7	0.6
Black ash	1.34	0	0.5	1.43	0.5	0.2
Maple	0.82	0	0.3	0.65	0.4	0.6

[Importance Percentage = $\frac{\text{relative dominance + relative density}}{2}$

where relative dominance = $\frac{\text{Sum of basal areas for taxon i}}{\text{Sum of basal areas for all taxa}}$

and relative density = $\frac{\text{Sum of all trees of taxon i}}{\text{Sum of all trees}}$]

Selected stratigraphic profiles from Shagawa Lake

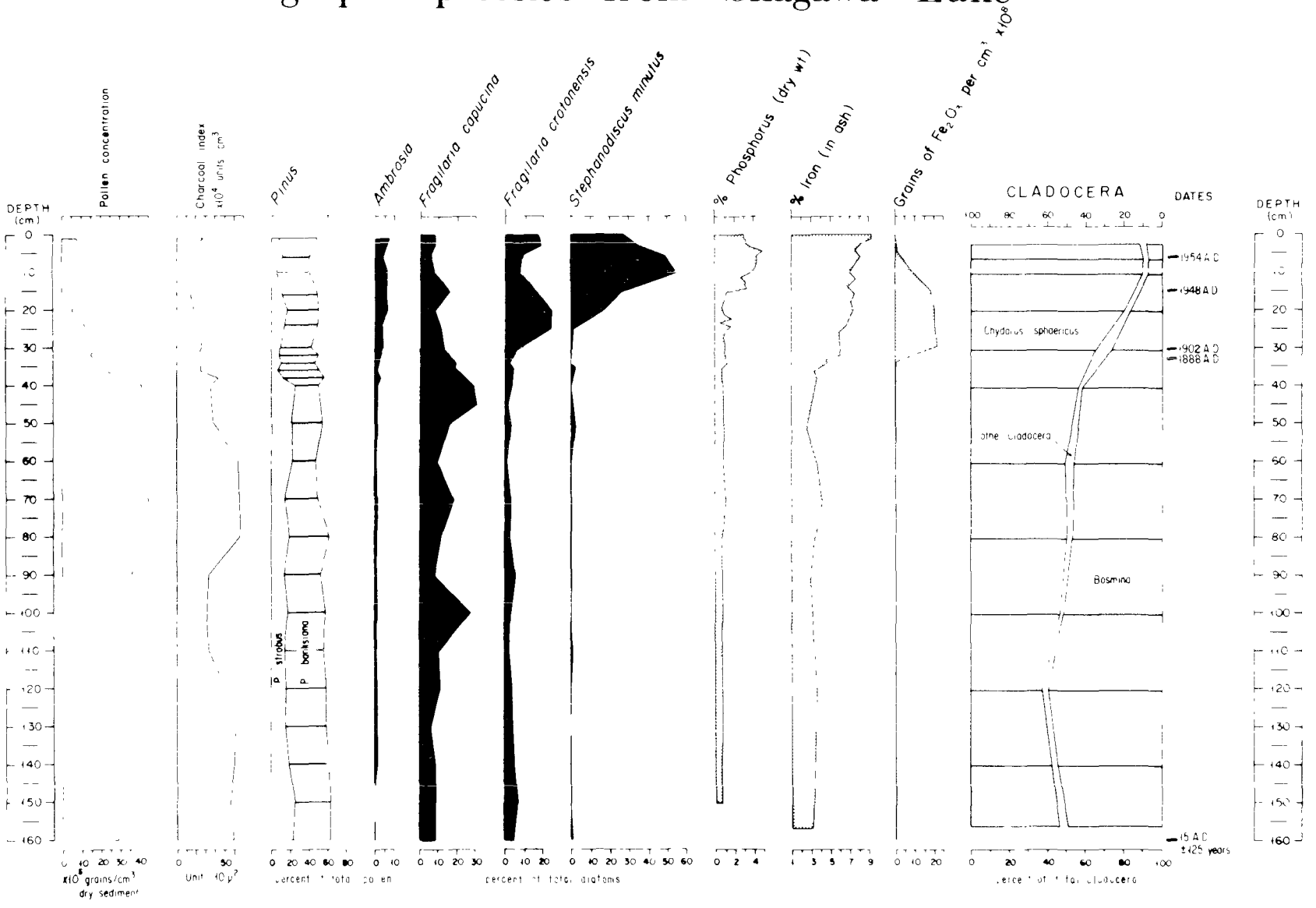


Figure 10 Selected stratigraphic profiles of diatoms, pollen and geochemistry from Shagawa Lake (Bradbury and Waddington, 1973).

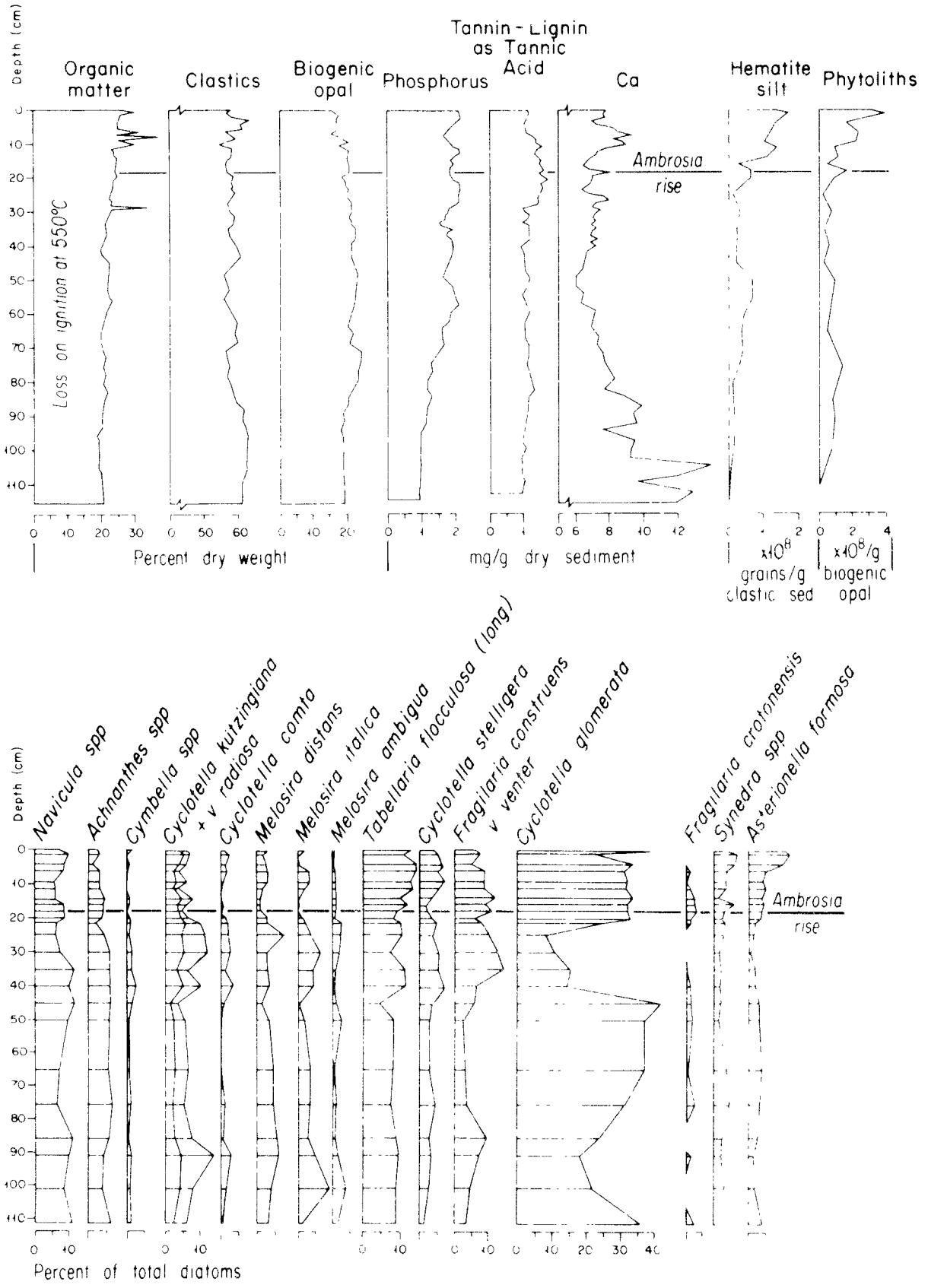


Figure 11 Selected diatom and other stratigraphic profiles from Burntside Lake. The Ambrosia rise marks the time of cultural disturbance.

Paleolimnology

The paleolimnology of Shagawa and Burntside Lakes has been determined largely from the stratigraphic analysis of fossil diatoms and sediment chemistry. Fossil Cladocera stratigraphy has provided additional information in Shagawa Lake. The limnological history of Shagawa Lake has been discussed in some detail previously (Bradbury and Megard, 1972; Bradbury and Waddington, 1973; Bradbury, 1975) and need be only summarized here. The pre-cultural diatom and Cladocera stratigraphy of Shagawa Lake indicates a natural trophic level greater than many lakes in northeastern Minnesota and southern Canada. This is particularly suggested by the persistent dominance of *Fragilaria capucina* and species of *Melosira* (Figure 12). Although these diatoms are widely distributed in Minnesota lakes (Bright, 1968; Bradbury, 1975) and are therefore apparently able to take advantage of a wide range of limnological conditions, *F. capucina* is known to reach its greatest relative abundance in eutrophic lakes (Stoermer & Yang, 1970). Frequently *F. capucina* lives among aquatic vegetation of eutrophic lakes (Jorgensen, 1948). Similarly the stratigraphic distribution of *Melosira ambigua*, *M. granulata*, and *M. italica* in other Minnesota lakes shows that these diatoms generally increase in abundance when erosion resulting from land clearance increases nutrient loads (Bradbury, 1975). The fact that *Cyclotella stelligera* and *Tabellaria flocculosa*--diatoms characteristic of oligotrophic lakes in this region (Stockner, 1971)--are only of minor importance in the pre-cultural record of Shagawa Lake further suggests that this lake had relatively high nutrient levels before settlement.

The Cladocera stratigraphy also indicates that Shagawa Lake was eutrophic or certainly mesotrophic in its natural state (Figure 10). The two dominant cladocerans in the lake during pre-settlement times were *Bosmina longirostris* and *Chydoris sphaericus*. In the oligotrophic lakes of western Ontario, *Bosmina longirostris* generally dominates, and *Chydoris sphaericus* is rare or absent (Patalas, 1971). In enriched lakes, *C. sphaericus* often dominates, sometimes entering the planktonic habitat by attaching itself to floating blue-green algae (Bradbury and Megard, 1972). The background frequency of *C. sphaericus* (50-60%) in Shagawa Lake in pre-cultural times suggests that relatively enriched conditions and perhaps blooms of blue-green algae existed for nearly 2,000 years.

Even though Shagawa Lake was moderately eutrophic before modern settlement began, man's impact in this area considerably increased the load of nutrients entering the lake. Changes in the hematite and phosphorus profiles can be approximately correlated with known cultural events, such as the beginning (1888), maximum (1902), decline (1951), and termination (1967) of mining activities, and the introduction of phosphate detergent (1948) (Figure 10). These time-stratigraphic horizons, together with a C-14 date (15 A.D. ± 125 years) at the bottom of the core, permit the determination of influx values of organisms (in numbers/cm^2/yr) incorporated into the lake sediment (Figure 13). The increase in pollen influx and particularly in the influx of fungal hyphae and spores at 30 cm depth very likely relates to the erosion and subsequent deposition of nutrient-rich top soil in Shagawa Lake, because pollen and fungal material occur abundantly in the uppermost horizons of forest soils. The increase in nutrients to the lake from this

Diatom and Sediment Stratigraphy of Shagawa Lake, Minnesota

Anal J P Bradbury, 1972

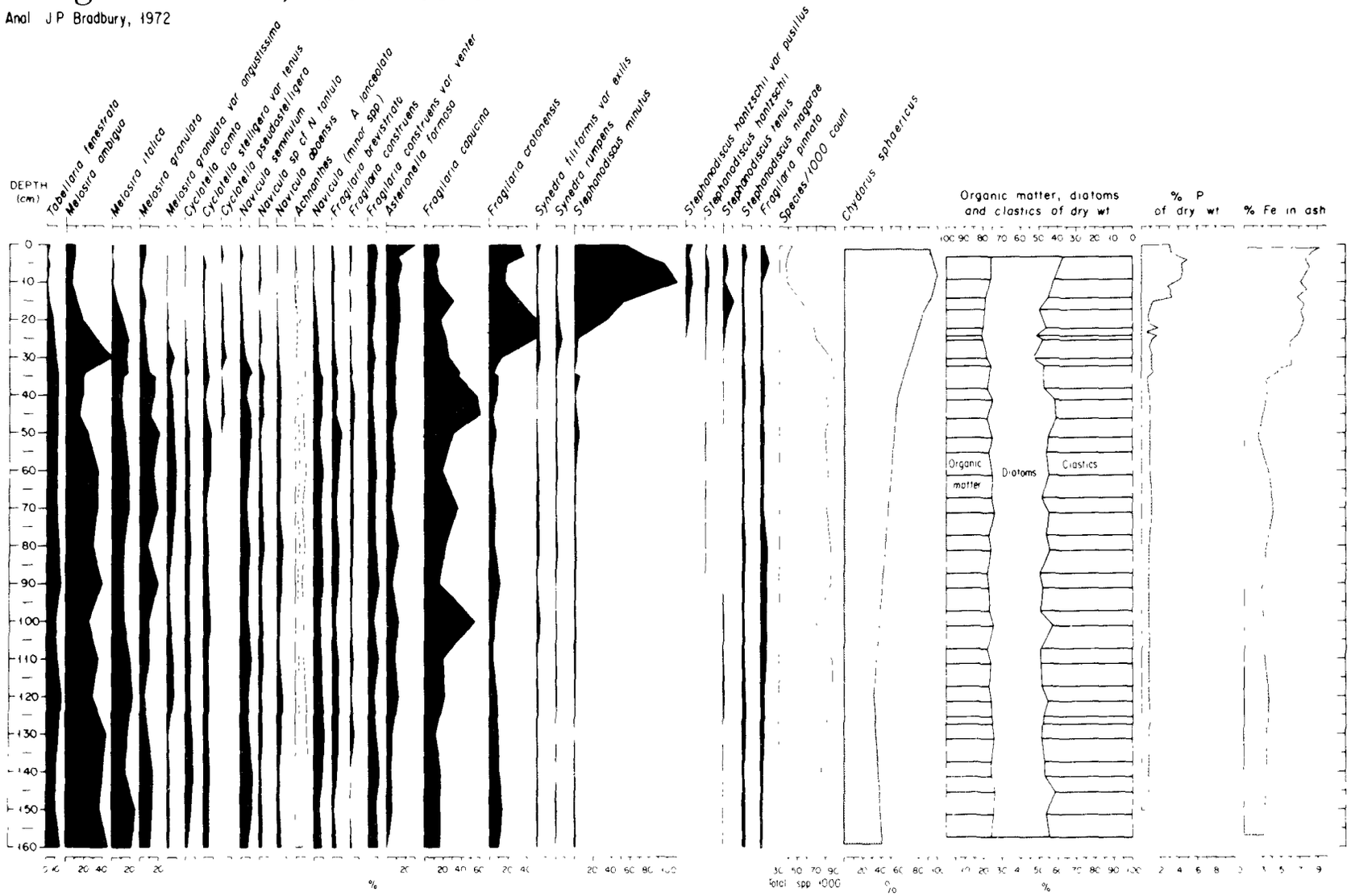


Figure 12 Selected diatom and sediment stratigraphic profiles for Shagawa Lake (Bradbury and Waddington, 1973).

process caused a greater productivity and influx of diatoms and Cladocera that dramatically illustrate the course of eutrophication.

The stratigraphy of diatoms and cladocerans show that the biology of Shagawa Lake changed qualitatively as well as quantitatively in response to this enrichment. Chydoris sphaericus began to increase proportionally at 35cm (ca. 1888 A.D.)(Figure 12), and the diatom flora became dominated first by Melosira ambigua and then by Fragilaria crotonensis as more and more nutrients became available during the summer months for their growth (Figure 12). Nutrient levels continued to increase as a result of the installment of a municipal sewage system (1901) and an increasing resident population (Figure 7). Blue-green algal blooms probably increased in frequency, intensity, and duration (Bradbury and Megard, 1972) and the summer-blooming planktonic diatoms were eliminated. The blue-green algae not only compete with these diatoms for nutrients, but they also float and shade out the diatoms that are too heavy to stay near the surface. The spring-blooming, and perhaps the late fall- and winter-blooming, diatom species were spared active competition with the blue-green algae that dominate in the summer and early fall. During the spring, massive blooms of Stephanodiscus hantzschii and related species occurred in response to high nutrient levels and they alone came to dominate the stratigraphic record (Figure 10, 12). Kilham (1971) suggested that rapid, early growth of these species so depletes the amounts of dissolved silica in the water that summer-blooming species requiring this essential nutrient cannot persist. During this phase of maximum enrichment, Chydoris sphaericus--a likely indirect index to blue-green algal activity--increases to 80-90% of the Cladoceran community. Myxoxanthin, a pigment characteristic of blue-green algae, is a more direct indicator of their activity, and Gorham and Sanger (1976) have shown that the post-settlement sediments of Shagawa Lake contain appreciable amounts of this pigment. Some myxoxanthin is also present in pre-settlement levels (E. Gorham, oral comm., 1977).

Sewage treatment facilities at Ely were improved in 1954 (Brice and Powers, 1969), and it may be possible to see the effect of this installation in the sediments of Shagawa Lake. In the upper 5 cm of the Shagawa Lake core, phosphorus levels (Figure 10)--which in general mirror the increase in Stephanodiscus hantzschii and related species--are reduced. Fragilaria crotonensis and Asterionella formosa began to replace Stephanodiscus in these same levels, and Chydoris sphaericus, while still very abundant, began to decline. These trends may represent the installation of secondary treatment facilities in 1954. This treatment involved a high rate trickling filter and a secondary settling tank. It is not clear just how efficiently these modifications worked and the system was equipped with bypasses that were in operation some of the time (D.W. Schults, written comm., 1977). Nevertheless, additional filtering and settling facilities would probably reduce the load of particulate sewage to Shagawa Lake. Even though phosphorus in particulate sewage is not immediately available for algal growth, it could become so once it was deposited and reduced in anoxic, hypolimnetic regions of the lake and recirculated to the epilimnion during periods of turnover. The removal of some of the phosphorus-rich particulate sewage load to Shagawa Lake would therefore cause a reduction in the total nutrient load for the lake. Following this reasoning, nutrient loading to Shagawa Lake

would have been greatest between 1948 (introduction of phosphate detergents) and 1954 (establishment of secondary treatment facilities). This time period (6 years) would be represented in the core by the sediment between 14 and 5 cm and would have accumulated at the rate of 1.5 cm/year. After that time, the sedimentation rate dropped to about 0.3 cm/year, a rate characteristic of the average sediment deposition rate between 1902 (30 cm) and 1948 (14 cm).

The effect of the current (beginning in 1973) tertiary treatment plant for Ely's wastes can be seen in the modern algal samples (1974) from Shagawa Lake (Figure 3). Diatoms that bloom in summer and early fall are abundant, particularly F. crotonensis, Melosira spp., and Asterionella formosa. The diatom flora is becoming more diverse, and algal blooms in general are decreasing in intensity (Larsen et al., 1975).

Shagawa Lake has still not returned to its pre-cultural limnological and trophic status as judged by the sediment record, and phosphorus, entering the lake from profundal sediments, produces large algal blooms in some years. Nevertheless, the trend is towards less eutrophy and further changes can be expected as the nutrient influx decreases.

In Burntside Lake the increase in hematite silt is more gradual than at Shagawa Lake. If the Ambrosia rise is taken as 1898, the average sedimentation rate from that time to the present is 0.2 cm per year. This is less than half the average sedimentation rate for Shagawa Lake during the same time interval (Figure 13, and Bradbury and Waddington, 1973). The lower sedimentation rate partly reflects the lower productivity of Burntside Lake, and partly the fact that the core came from a basin slope rather than its center. Unfortunately the age of the bottom of the Burntside Lake core is not known, and it is not possible to calculate pre-settlement sedimentation rates. Even though the same diatom species are found throughout the core (Figure 11) and suggest a general similarity between pre- and post-settlement limnology, it is doubtful that the average sedimentation rates of the post-settlement period can be applied to the pre-settlement levels.

The diatom stratigraphy of Burntside Lake suggests that it has been limnologically different from Shagawa Lake for a long time. The dominant species are Cyclotella glomerata and Tabellaria flocculosa. Subdominants are Fragilaria construens v. venter, Cyclotella kutzingiana, Achnanthes spp., and Melosira spp. In general the diatom flora of Burntside Lake is very similar to that of Meander and Dogfish Lakes, largely undisturbed wilderness lakes about 30 km to the northwest (Bradbury et al., 1975).

The pre-settlement diatom stratigraphy in Burntside Lake is characterized by two zones (105-80 cm and 42-22 cm) where Cyclotella glomerata is less frequent and is replaced by higher percentages of Melosira italica spp. subarctica, Cyclotella kützingiana v. radiosa, and Fragilaria construens v. venter (Figure 11).

Much remains to be learned about the habitat and ecological preferences of all these species. Tabellaria flocculosa characterizes oligotrophic lakes in several parts of the world (Stockner, 1971), and it occurs in both

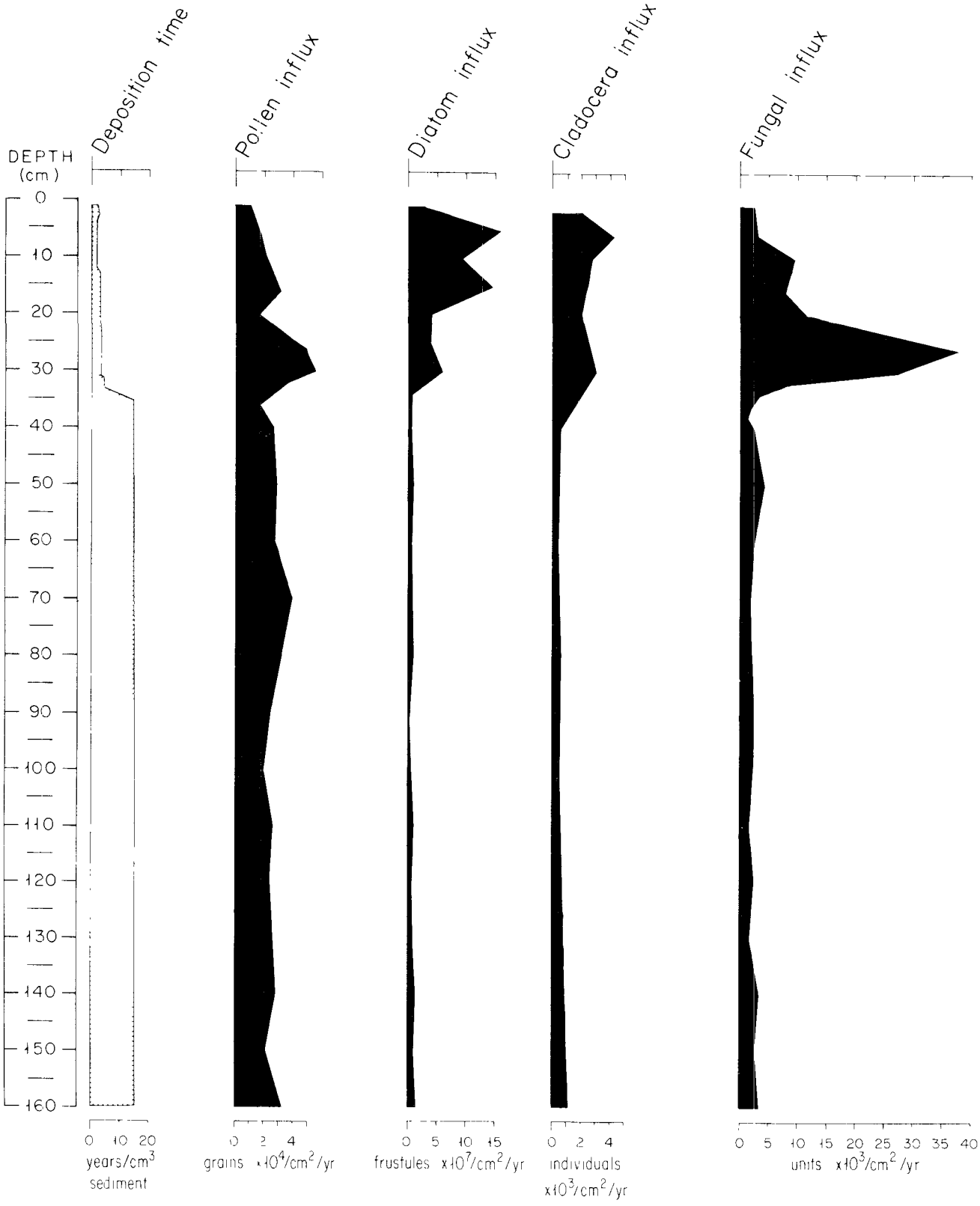


Figure 13 Influx of microfossil types for Shagawa Lake (Bradbury and Waddington, 1973).

planktonic and benthic habitats. Its wide distribution, however, suggests that it is a eurytopic species (Stoermer and Yang, 1970; Bradbury, 1975).

The distribution of C. glomerata is not well known, although it is generally considered a planktonic diatom of mesotrophic to eutrophic lakes (Sreenivasa and Duthie, 1973; Huber-Pestalozzi, 1942). Alive, C. glomerata is recognized by its chain-like filaments, but after death and sedimentation or after acid cleaning, the chains break apart and the individual cells appear very much like those of C. stelligera, particularly C. stelligera v. tenuis. The density of marginal striae separates the two species for the most part (Plates 1 and 2), and if this distinction were consistently made the distribution of C. glomerata might be much larger and would extend to the very oligotrophic lakes of northern Minnesota. For example, in an earlier report (Bradbury et al., 1975), C. stelligera was stated to dominate the sediments of Meander Lake, St. Louis County, Minnesota. On reexamination, the dominant Cyclotella species more closely resembles C. glomerata, although C. stelligera is present as well.

In Meander Lake, C. glomerata makes up about 40% of the surface-sediment diatom assemblage. The sediment contains approximately 40 x 10^7 frustules of this species per gram dry weight, yet it did not dorinate the limnetic plankton during the open-water season of 1972 (B. Speziale, written commun., 1975). Its distribution in Meander Lake seems to be related to turbulence, when other diatoms of littoral and benthic environments enter the plankton. Bright (1968) also reported C. glomerata from benthic habitats of a variety of Minnesota lakes, some of which are rather productive (water conductivity 200-400 μmhos/cm).

Cyclotella stelligera is considered both a planktonic diatom (Stockner, 1971; Merilainen, 1971) and a meroplanktonic (opportunistically planktonic) that spends some time in the littoral zone (Huber-Pestalozzi, 1942). Even though it can dominate the profundal sediments of oligotrophic lakes (Stockner, 1971) it is not always found in abundance in corresponding plankton samples (Schindler and Holmgren, 1971). It was common in the littoral periphyton (especially at a depth of 1 m on glass slides) in Lake 240 in northwestern Ontario in early May, 1969 (Stockner and Armstrong, 1971). Merilainen (1971) suggested that this species inhabits the deeper zones of the mixolimnion of meromictic Lake Velkiajarvi, Finland. It is reported in the plankton of meromictic Green Lake, Fayetteville, New York (Culver and Brunskill, 1969), where it also dominates the laminated profundal marls. Paerl et al. (1974) reported a massive bloom of C. stelligera in the spring of 1973 in Lake Tahoe, California-Nevada. Huber-Pestalozzi (1942) listed C. stelligera as a littoral diatom that sometimes becomes planktonic, and current information supports this generalization.

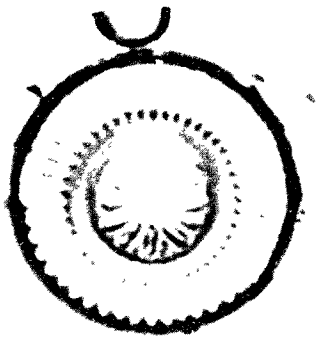
However, the likelihood of taxonomic confusion between C. glomerata and C. stelligera (particularly the smaller varieties) casts some doubt on validity of habitat and nutrient requirements for these species as reported in the literature. The colonial growth form of C. glomerata seems appropriate for a planktonic existence, or at least a meroplanktonic existence. Planktonic diatoms require limnetic nutrients, and it is not surprising that C. glomerata is recorded from the plankton of eutrophic and mesotrophic

PLATE 1. LIGHT MICROGRAPHS OF CYCLOTELLA STELLIGERA CL. & GRUN. AND CYCLOTELLA GLOMERATA BACHMANN. BURNTSIDE LAKE, 0-0.3 CM.

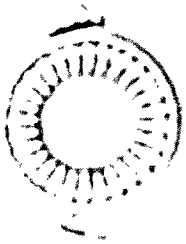
1.	Cyclotella stelligera	Cell diameter = 10 µm, 9 striae/10 µm of circumference.
2.	Cyclotella stelligera	Cell diameter = 10 µm, 9 striae/10 µm of circumference. Same specimen as 1.
3.	Cyclotella stelligera	Cell diameter = 13 µm, 11 striae/10 µm of circumference.
4.	Cyclotella stelligera	Cell diameter = 9 µm, 10 striae/10 µm of circumference.
5.	Cyclotella stelligera	Cell diameter = 7 µm, 12 striae/10 µm of circumference.
6.	Cyclotella glomerata	Cell diameter = 6 µm, 13 striae/10 µm of circumference.
7.	Cyclotella glomerata	Cell diameter = 6 µm, 14 striae/10 µm of circumference.
8.	Cyclotella glomerata	Cell diameter = 5.5 µm, 17 striae/ 10 µm of circumference.

1

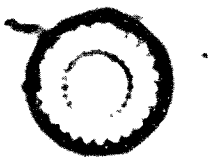
2



3



4



5

6

7

8

Plate 1

PLATE 2. SEM MICROGRAPHS OF CYCLOTELLA STELLIGERA CL. & GRUN. AND CYCLOTELLA GLOMERATA BACHMANN. BURNTSIDE LAKE, 40.5 CM. Scale = 1 µm

1. Cyclotella stelligera. Cell diameter = 8 µm, 11 striae/10 µm of circumference. The internal view of this and the following specimens illustrates the striae characteristics. Note that this individual does not have a central stellate pattern of striae (Lowe, 1975).

2. Cyclotella stelligera. Cell diameter = 7 µm, 11 striae/10 µm of circumference. Note presence of central stellate arrangement of striae.

3. Cyclotella stelligera. Cell diameter = 8 µm, 11 striae/10 µm of circumference.

4. Cyclotella glomerata. Cell diameter = 4.5 µm, 20 striae/10 µm of circumference. Note the short, interposed striae on this specimen. These can also be seen on the specimens in Plate 1, and may be a potential character for separating C. glomerata from small varieties of C. stelligera.

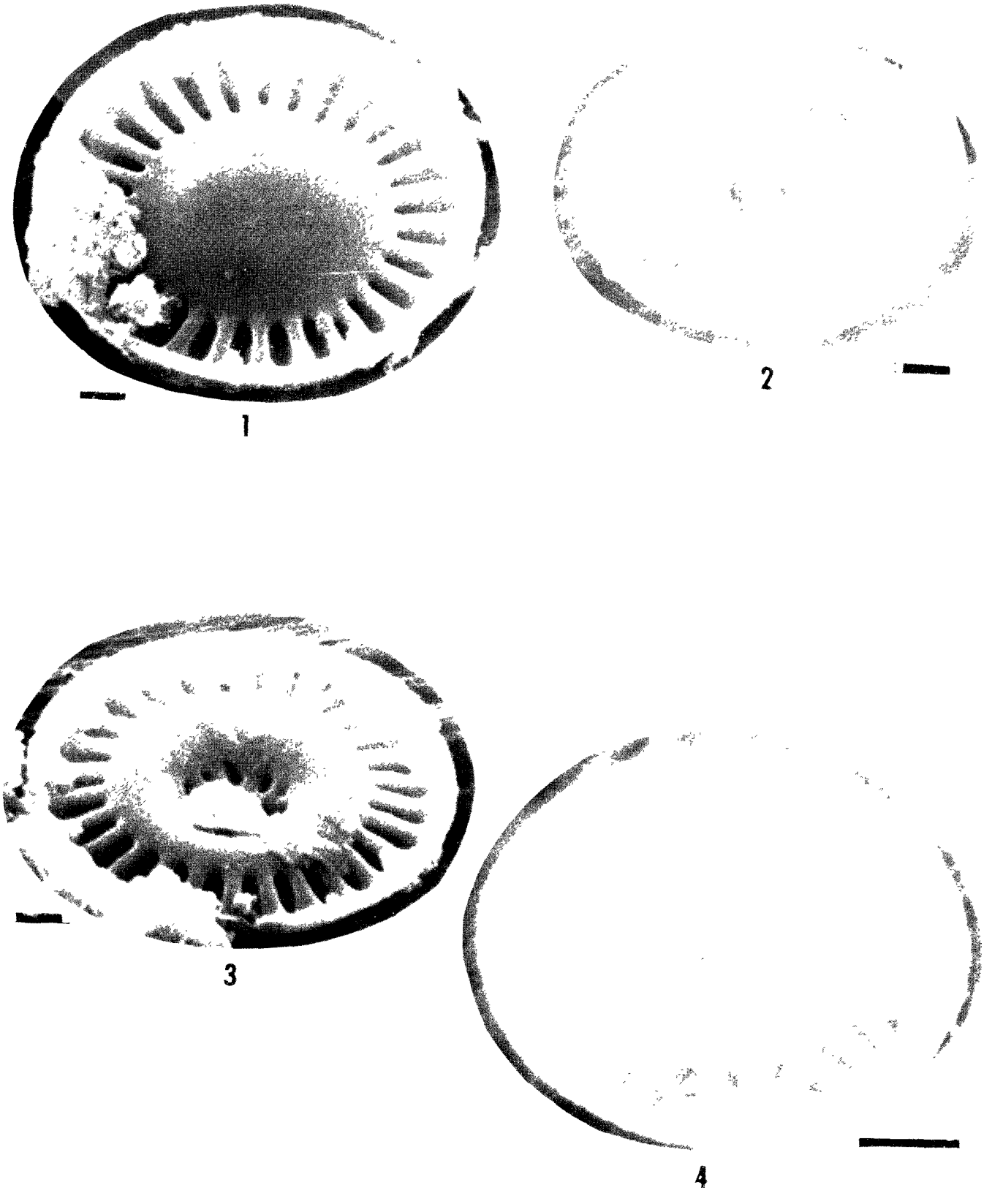


Plate 2

lakes (Duthie and Sreenivasa, 1971). Perhaps in oligotrophic lakes [illegible] glomerata remains close to the nutrient rich bottom and is only distributed to the limnetic region and the profundal sediments during periods of turbulence. This may be the case in Meander Lake, where Cyclotella glomerata became a significant representative of the plankton only in the early spring, before thermal stratification is established. The [illegible] Cyclotella stelligera are basically similar, although conclusive data about its distribution and life cycle remain to be gathered.

Cyclotella kützingiana is frequently identified in [illegible] oligotrophic lakes, and occasionally it is found in large numbers. In the Experimental Lakes Area of northwestern Ontario, [illegible] found to dominate only in one of the 10 lakes he studied (Hilliard Lake, [illegible] large, exposed lake of very low productivity and gen[illegible] from [illegible] sediments (Schindler, 1971; Schindler and Noirgren, 1971). [illegible] kützingiana is considered a benthic or littoral [illegible] 1912; Molder and Tynni, 1968), but in large lakes it [illegible] plankton as in Lake Michigan (Stoermer and Yang, 1970). It [illegible] tant of streams and other flowing waters. [illegible] of C. kützingiana are also reported in the sediments of [illegible] lakes, particularly Lake Storo Vakijärvi and Lake Vähäjärvi [illegible] and 39% respectively) (Meriläinen, 1971), and it is present but not particularly abundant in the sediments of Green Lake, Fayetteville, New York. [illegible] Lake in Ontario also contains large number[illegible] of this species (Stoermer and Duthie, 1973), as does Lower LeSalle Lake in Hubbard County, Minnesota.

Little is known about the nutrient requirements of [illegible] kützingiana. Although it is commonly found in oligotrophic lakes, it is not unknown from the sediments of slightly eutrophic lakes [illegible]. The availability of nutrients in benthonic [illegible] characterization of meroplanktonic diatoms difficult [illegible] measurements are made for limnetic waters, and limnetic nutrient content is only occasionally relevant to meroplanktonic [illegible] limnological and culture studies of these [illegible] requirements have not been made to [illegible] ecology of C. kützingiana can be [illegible] associates in paleolimnological studies.

In Parchner Marsh in Minnesota, Kützingiana [illegible] as C. caspia by Florin, 1970), rises to dominate the [illegible] depth of approximately 1[illegible] m. Here it is [illegible] and with varieties of Fragilaria construens [illegible] are of minor importance. At this same level [illegible] reported high levels of sedimentary chlorophyll [illegible] tary carotenoids which they interpreted as [illegible] ciated with climatic amelioration about [illegible] with the abundance of F. crotonensis, indicating [illegible] lakes (Stoermer and Yang, 1970) at that [illegible].

In Sunfish Lake, Ontario, Cyclotella kützingiana dominates the lower 80 cm of the lake-sediment profile studied by Stoermer and [illegible], 1974, and Stephanodiscus hantzschii. Cyclotella [illegible] and [illegible] are

subdominants. S. hantzschii is still known as a dominant in very eutrophic lakes (Bradbury, 1975).

Along the Elbe river in northern Germany, the Eemian diatomites and related peats and lake sediments of Lüneburg Heath also contain C. kützingiana as an important associate of S. hantzschii, S. astraea v. minutula, and Melosira ambigua (Lehre, 1962). Here too the diatom assemblage containing C. kützingiana indicates a lake of moderate to high productivity. At the bottom of Lehre's (1962) Lüneburg profile frequencies of C. kützingiana may be as high as 60% but at the top it falls to 10% as Melosira granulata becomes the dominant diatom. Lehre (1962) interpreted these changes as a transition from slight oligotrophy (C. kützingiana dominance) to marked eutrophy (Melosira granulata dominance). In the long period between these two extremes C. kützingiana shares dominance with Melosira ambigua and Stephanodiscus hantzschii.

A similar assemblage is also found in Elk Lake, Minnesota, consisting of C. kützingiana, Melosira ambigua, Stephanodiscus sp. cf. S. minutus, and Fragilaria crotonensis (Stark, 1971). This assemblage existed during the Quercus-Gramineae-Artemisia and Quercus-Ostrya pollen zones (ca. 8,000-2,000 years ago), when the climate was thought to be warmer and drier than today. Presumably increased turbulence from winds associated with savannah-like vegetation during this time accounted for this assemblage (Bradbury, 1975).

These examples indicate that Cyclotella kützingiana is not restricted to oligotrophic lakes. It appears to be a eurytopic diatom that can increase with light enrichment.

The ecology of Melosira italica ssp. subarctica is somewhat better known through the studies of Lund (1954) who considered it a planktonic diatom requiring turbulent conditions to remain suspended. It seems to prefer neither strongly oligotrophic nor strongly eutrophic water, and it is able to persist in benthic environments for considerable periods of time until it is resuspended by turbulence to the limnetic environment.

Fragilaria construens v. venter is a very widespread diatom that commonly resides in or near the littoral zone of small lakes or in slightly deeper waters of larger lakes (Bradbury, 1975, Jorgensen, 1948). Its distribution in lakes in Minnesota (Wright, 1968) and Finland (Molder and Tynni, 1970) indicates that it is tolerant of a wide variety of water types and nutrient conditions.

These general ecological comments allow a tentative interpretation of the pre-settlement paleolimnological events in Burntside Lake. The fact that Fragilaria construens v. venter, Cyclotella kützingiana and v. radiosa, and Melosira italica ssp. subarctica twice partly replace a dominance of Cyclotella glomerata (Figure 11) suggests one or more basic controlling factors, perhaps related to climatic or hydrologic changes outside the lake, rather than to random fluctuations between separate diatom populations. These pulses most likely relate to an expansion of the littoral and sublittoral diatom communities of Burntside Lake, or at least a greater input from them. The increase in diatoms closely associated with the littoral environ-

ment occurs at the expense of planktonic diatom inputs, chiefly identified by the distribution of Cyclotella glomerata, which shows a large pre-settlement increase between 85 and 45 cm. It is noteworthy that other planktonic diatoms frequently associated with moderate limnetic enrichment, such as Fragilaria crotonensis, Asterionella formosa, and species of Synedra, increase in concert with C. glomerata. The stratigraphic changes for these species are not so marked as that of C. glomerata, but they are clearly significant (Figure 11). It is also important to note that these species and C. glomerata regain their dominance during post-settlement times (after the Ambrosia rise, Figure 11), when lumbering and cultural activities would be expected to maintain an increased nutrient loading of Burntside Lake.

The littoral pulses (identified principally by the distribution of Fragilaria construens v. venter and Cyclotella kützingiana v. radiosa) suggest either lower water levels, with an increased sedimentation of littoral species, or increased oligotrophy, with a diminished importance of planktonic and meroplanktonic diatoms. Higher water levels and slight enrichment could account for the observed diatom distribution between 85 and 45 cm.

Profiles of sediment mineralogy and chemistry only approximately reflect the changes in pre-settlement diatom stratigraphy. Biogenic opal (Figure 11) is somewhat higher in the zone where C. glomerata is most abundant (85-45 cm), supporting the interpretation of greater diatom productivity during this time. Hematite silt, and to a lesser extent opal phytoliths, are also more abundant at this time (Figure 11) and might relate to generally higher water levels from increased precipitation, which could have resulted in increased transport of nutrients to Burntside Lake via tributaries such as the Dead River (Figure 1). The profiles for calcium and for clastics suggest increased input of littoral sediments for the lower pulse of littoral diatoms (105-85 cm) but not for the upper one (42-22 cm). Other sediment profiles (phosphorus, tannin-lignin, and organic matter) show gradual stratigraphic changes, but it is not clear how (or if) they relate to the diatom stratigraphy. Furthermore, the lack of an absolute time scale makes limnological interpretation of such changes very speculative.

However, the time over which the stratigraphic changes in diatoms took place can be suggested in a general way by analogy to Shagawa Lake, where a C-14 date at the bottom of the core provides information about sedimentation rates. The pre-settlement sedimentation rate in Shagawa Lake is about 0.7 mm/year, so about 15 years would be required for 1 cm of sediment to accumulate. The Shagawa Lake pre-settlement sedimentation rate is probably higher than that for Burntside Lake, because the latter has been less productive and the Burntside Lake coring locality (Figure 1) was not in the deepest part of a basin. Nevertheless, by assuming sedimentation rates of about the same magnitude for Burntside Lake, the changes in diatom stratigraphy become several hundred years in length. Possibly they correlate in some way with climatic changes such as the "Little Ice Age" (ca. 1550-1850 A.D.), whose climatic effects are suggested by the charcoal stratigraphy of nearby Lake of the Clouds (Swain, 1973). However, speculation about the limnologic and climatic mechanisms for pre-settlement diatom stratigraphy are premature without an absolute time scale for the Burntside Lake sediments.

Tentative correlation between the Burntside Lake pre-settlement diatom profiles and the Shagawa Lake pre-settlement profiles remains a topic for future study. The two peaks of Fragilaria capucina (110-90 cm and 50-35 cm) in the Shagawa Lake diatom stratigraphy might indicate an increase in littoral diatom populations similar to those suggested for the Burntside Lake core, and the flow-through characteristics of the two lakes could easily link the diatom stratigraphies to the same cause. However, their correlation also requires an independent time scale for the two cores.

Increases in opaline phytoliths, hematite silt, and Ambrosia pollen signify that the top 18 cm of the Burntside Lake core were deposited in the late 1800's, probably about 1890. The opaline phytoliths probably reflect increased erosion (and possibly increased herbaceous vegetation) in the Burntside Lake area and thus represent events related to the Ambrosia rise.

Dramatic limnological changes do not coincide with the beginning of settlement, however. The increase in relative frequency of Cyclotella glomerata began before the Ambrosia rise, possibly as a result of climatic factors, as mentioned earlier. Immediately after the Ambrosia rise, diatom populations remained comparatively stable, and no significant changes are recorded until the upper 5 cm, where Asterionella formosa increases to unprecedented levels.

Asterionella formosa is a widespread planktonic diatom that occurs in a wide variety of trophic conditions. It occurs in the more productive lakes of the English Lake District (Lund, 1949), and stratigraphic studies in Lake Windermere show that Asterionella formosa becomes dominant probably as a consequence of human settlement in the drainage area (Pennington, 1943). This is in accord with the hypothesis of Kilham (1971), who postulated that A. formosa is more successful than other species in eutrophic but low-silica environments.

The distribution of A. formosa in Burntside Lake very likely relates to a slight enrichment of the water caused by settlement activities along the lake shore. Nutrients such as phosphates and nitrates supplied by lakeside cabins would seem the most obvious cause, because cabin building in this area, which has been increasing since the 1920's and particularly since 1945, is a comparatively late phenomenon. If the hematite rise (15 cm) in Burntside Lake is taken as 1888, and sedimentation since that time is assumed to be about constant, the increase in Asterionella formosa at 5 cm would date to 1949, approximately coinciding with both an increase in cabin-building activities (post-1945) (M.L. Heinselman, written commun., 1976) and with the introduction of phosphate detergents (1948) (Bradbury and Waddington, 1973).

The most noteworthy aspect of the Burntside Lake post-settlement diatom stratigraphy is that even though this lake is generally regarded as oligotrophic and unaffected by human settlement, the present-day plankton diatom community with large spring and fall maxima of Asterionella formosa (Fig. 5) is clearly a recent, and in this case probably man-caused phenomenon. It emphasizes the sensitivity of diatom populations to environmental changes, and how easily the delicate limnologic balance of a natural lake can be changed.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

The paleolimnological records of Burntside and Shagawa Lakes in Northeastern Minnesota reveal that these two adjacent lakes have been limnologically distinct for many years prior to the late 19th century activities of white men that polluted Shagawa Lake. Although both lakes occur within the same vegetation type and share much of their water, the diatom stratigraphy of their bottom sediments indicates that Burntside Lake was less productive in its natural state than Shagawa Lake. The causes for this natural difference are not clearly known, but differences in relative size of drainage area and in bedrock geology may be responsible.

Intensive white settlement around Shagawa Lake beginning in 1886 supplied nutrients that increased its productivity and finally supported the massive blooms of blue-green algae that characterize culturally eutrophic lakes. Burntside Lake was spared such intensive eutrophication, but its diatom record shows that nutrients derived from shoreside recreational cabins and related construction activity are increasing the lake's productivity.

The results of this study show that paleolimnological studies may provide better comparative information for lake rehabilitation programs than do biological and chemical analyses of contemporary unpolluted water bodies.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Lakes	paleolimnology	06F
Limnology	eutrophication	08H
Algae		
Diatoms		

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