# Recent history of fire and vegetation from laminated sediment of Greenleaf Lake, Algonquin Park, Ontario

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Laminated sediment (presumed varved) from Greenleaf Lake was examined for evidence of forest fires. A 500-year section dating approximately 770–1270 A.D. was analysed for influx of pollen, charcoal, aluminum, and vanadium using decadal samples. Intervals showing concurrent peaks in charcoal, aluminum, and vanadium influx, varve thickness, and charcoal:pollen ratio were interpreted as representing major fires within the drainage basin of Greenleaf Lake. By these criteria, six fires occurred within 500 years, or one fire approximately every 80 years. The pollen diagram indicates a stable forest composition for the past 1200 years. This, coupled with abundant charcoal fragments in all sediment samples, suggests that fire has been a frequent, natural phenomenon affecting the landscape during this period. There is a significant positive correspondence between peak charcoal influxes and peak influxes of aluminum and vanadium, indicating that increased soil erosion is responsible for their deposition.

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L'auteur a examiné les sédiments laminés (présumément des varves) du lac Greenleaf pour y rechercher des témoignages de feux de forêt. A l'aide d'échantillons décennaux, la déposition de pollen, de charbon, d'aluminium et de vanadium a été analysée dans une colonne de 500 ans âgée d'environ 770–1270 ans. Les périodes présentant des pics simultanés dans la déposition de charbon, d'aluminum et de vanadium, dans l'épaisseur des varves et dans le rapport charbon:pollen sont interprétées comme représentant des feux importants dans le bassin de drainage du lac Greenleaf. D'après ces critères, six feux ont eu lieu durant la période de 500 ans, soit approximativement un feu tous les 80 ans. Le diagramme pollinique montre que la composition de la forêt a été stable au cours des 1200 dernières années. Ces observations et l'abondance de fragments de charbon dans tous les échantillons de sédiments suggèrent que le feu a été un phénomène naturel fréquent dans le paysage au cours de cette période. Il y a une corrélation positive significative entre les pics de déposition de charbon et les pics de déposition d'aluminum et de vanadium, ce qui démontre qu'une érosion accrue du sol est responsable de cette déposition.

[Traduit par le journal]

## Introduction

Recent dendrochronological studies have increased our knowledge of the frequency and extent of fire in forest ecosystems (Frissel 1973; Heinselman 1973; Taylor 1973; Cwynar 1977), providing insights into the importance of fire as a factor influencing fundamental ecosystem processes (Loucks 1970). The limiting factor in these investigations is the longevity of trees. In eastern North America the longest records are about 300 years, mostly from red pine and to a lesser extent jack and white pine (Frissel 1973; Heinselman 1973; Cwynar 1977). Ideally the past natural fire regime ought to be determined from extensive virgin forests but such forests are rare. The Boundary Waters Canoe Area, Minnesota, is a notable exception that has yielded an impressive fire history (Heinselman 1973). Dendrochronological fire histories for eastern North America however lie within the European period and may not represent the natural fire regime.

The purpose of this paper is to extend the dendrochronological fire record for Barron Township, Algonquin Park (Cwynar 1977), to pre-European times in the manner of Swain (1973), who recently reconstructed a fire history from varved sediment of Lake of the Clouds.

There is abundant evidence that the removal of vegetation, whether by artificial means (Bormann *et al.* 1974) or naturally as by fire (Ahlgren and Ahlgren 1960) generally increases runoff and erosion. The degree to which erodibility is increased and persists depends upon the severity of the initial disturbance, climate, topography, soils, and the rate of vegetation recovery. Davis (1976) has shown that settlement around Frains Lake was accompanied by a significant increase in erosion, as indexed by the influx of ash weight into the sedi-

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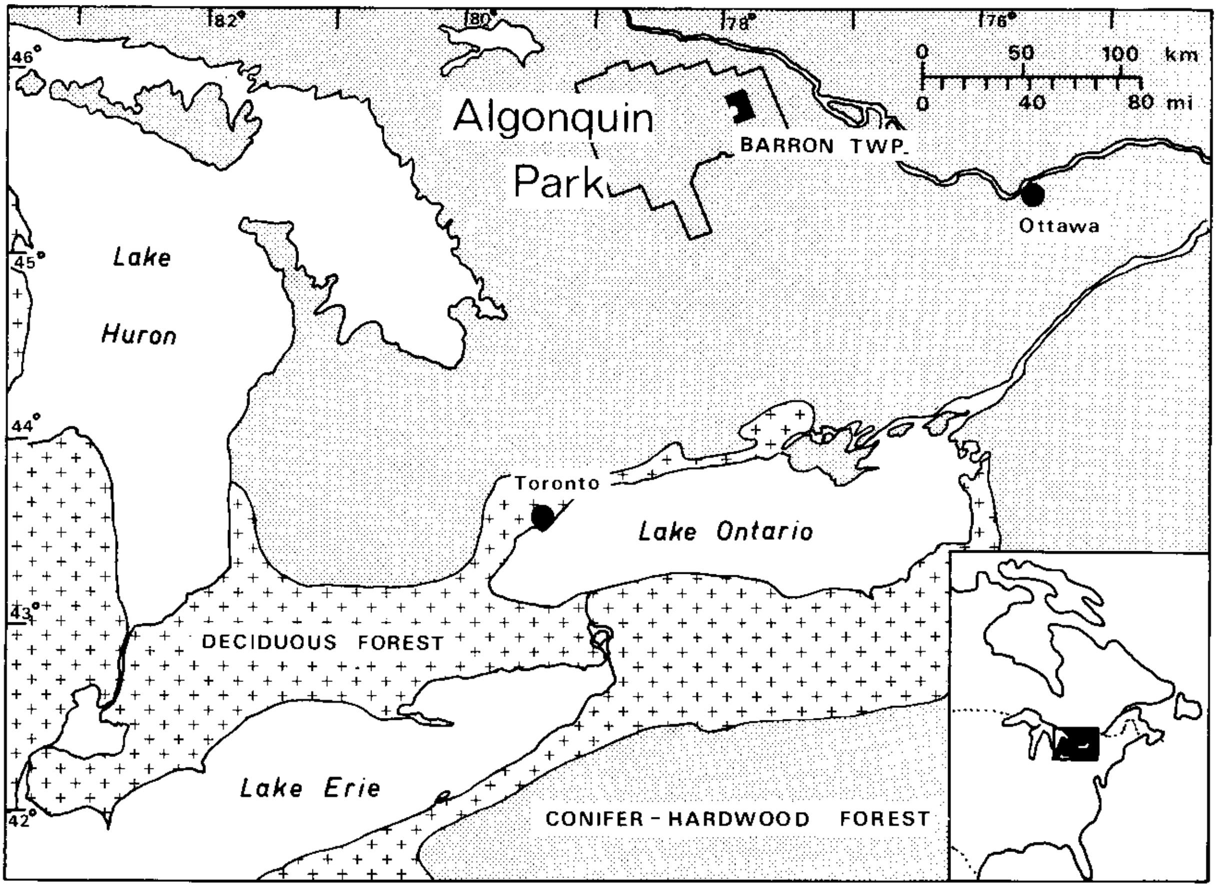

FIG. 1. Location map of Algonquin Park and Barron Township. The dot within Barron Township marks the position of Greenleaf Lake.

ment. The denudation of a lake's drainage basin by fire can thus be expected to be reflected in the lake sediment by (1) increased charcoal influx, (2) increased sedimentation rates resulting from greater erosion, and (3) changes in the total pollen influx and composition of pollen incorporated in the sediment.

The sediment of Greenleaf Lake was analysed for evidence of fire. Charcoal influxes were determined because they provide the most direct evidence of fire. Erosion rates were monitored by changes in varve thickness and the influx of aluminum and vanadium into the sediment. Aluminum is the second most abundant element (7.75% average) of rocks of the Precambrian Shield whereas vanadium is a common minor element averaging 53 ppm (Shaw *et al.* 1967). Aluminum is also the second highest constituent (7.4% ± 1.6 of ash weight) of sediments of the Experimental Lakes Area (Brunskill *et al.* 1971). It is thus a likely erosion indicator. Pollen influx was determined to show changes in the vegetation of the landscape. A ratio of *Pinus* pollen (indicating later successional stages) to *Betula* pollen (early colonizers, rapidly sprouting and seeding in after fire) was used in an attempt to recognize postfire successional changes.

## The Study Area

### *Greenleaf Lake*

Greenleaf Lake (Figs. 1, 2, and 3) lies on the Precambrian Shield along a fault, is 3.1 km long, less than 0.4 km wide, and has a surface area of 56.9 ha. A narrows divides the lake into two unequal basins. The smaller eastern basin is relatively shallow (12-m maximum) with surrounding land showing little topographic relief. In contrast, the larger western basin, surrounded by steep hills and cliffs, is 76 m deep. A cliff about 90 m high descends 60 m into the water on the southwest side of the basin. The northern part of the basin has a broken terrain of talus blocks and prominent bedrock exposures. Sedimentary rocks, which may be a potential source of charcoal, are absent from the drainage basin.

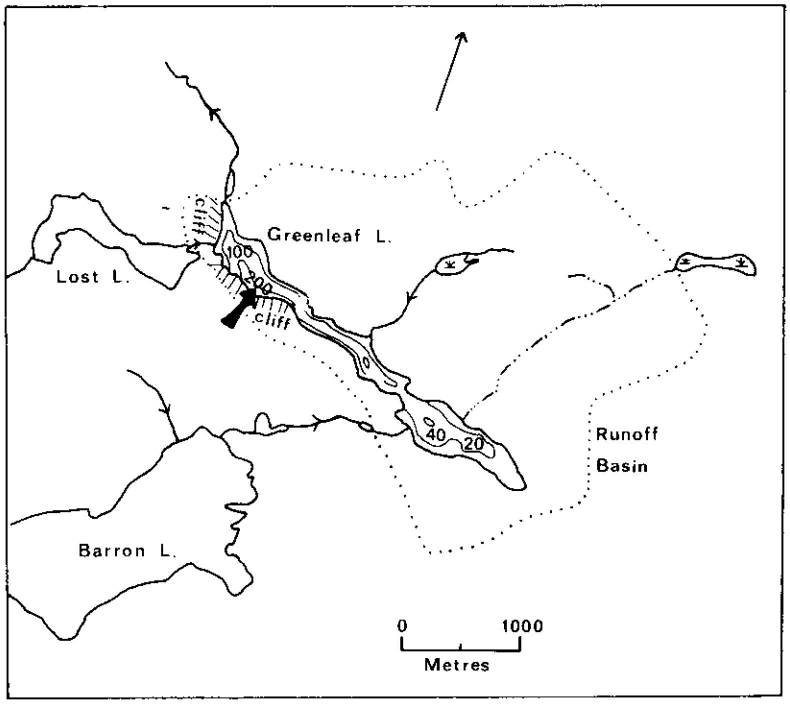

FIG. 2. Morphometric map of Greenleaf Lake. Contours are approximate and in feet. The arrow marks the coring site.

Figure 2 shows the runoff basin and the streams that enter Greenleaf Lake. The stream draining Barron Lake is the largest, closely followed by the one draining Lost Lake. The two streams flowing from the northern slope are small and intermittent.

*Vegetation*

Greenleaf Lake falls within the Algonquin–Pontiac section of the Great Lakes – St. Lawrence Forest Region described by Rowe (1972). The forest is a complex mosaic of conifers and hardwoods reflecting the varied topography, microclimate, soil types, and lumbering and fire history. White pine (*Pinus strobus*) dominates the runoff basin growing in both pure stands and mixed with other species. Red pine (*Pinus resinosa*) is common throughout, especially on talus slopes on the north shore. It rarely forms pure stands here. Poplar (mostly *Populus grandidentata* and to a lesser extent *P. tremuloides*) is abundant, forming stands atop the cliffs of the southwest side of the lake. Coppiced red oak (*Quercus rubra*) grow on exposed south-facing slopes and cliffs. A stand of sugar maple (*Acer saccharum*) and yellow birch (*Betula lutea*) dominates the central portion of the ridge parallel to the north shore. White birch (*Betula papyrifera*) and some red maple (*Acer rubrum*) are scattered throughout the essentially coniferous woods that cover the level southwest portion.

The talus below the cliffs supports white birch predominantly, with some white cedar (*Thuja occidentalis*) and the occasional hemlock (*Tsuga canadensis*). White spruce (*Picea glauca*) grows in small clumps near the southwest shoreline but it is generally uncommon. Some black spruce (*Picea mariana*) grow within the runoff basin although the species is more common elsewhere in the township. Isolated individuals of tamarack (*Larix laricina*) are present. A few black ash (*Fraxinus nigra*) grow in the ravine through which the stream draining Lost Lake enters Greenleaf Lake. Balsam fir (*Abies balsamea*) is an occasional understorey tree.

## Methods

Cores of laminated algal gyttja were collected at a depth of 65 m employing the freezing tube technique (Swain 1973), wrapped in plastic and aluminum foil, and stored in a freezer. The chronology was determined working in a walk-in freezer kept at −5°C. The surface of each core was scraped and allowed to freeze-dry for 15–30 min. Couplets of light and dark laminations were then distinguished and counted on the basis of color and texture using a four-power hand lens. Four massive layers (the largest 3 cm) were considered to be instantaneous events. The chronology for core B (collected within 10 m of core A), accurate to about 100 years, is estimated from core A (Fig. 4).

Duplicate sets of 50 10-year samples (one set for pollen and charcoal analysis, the other for metal analysis) were obtained in the following manner from core B. A pin stuck through the center of a piece of thread was inserted at every 10th couplet.

The thin rind of dried sediment was scraped away and the thread stretched and pinned at either end along the couplet. The center pin was removed and the position of each thread along the central portion of the section marked on millimetre graph paper for calculating sedimentation rates. The core was removed from the freezer and as it thawed samples were packed into a 0.3-ml spoon. Contaminating sediment from adjacent intervals probably forms no more than 5% of each sample; a decrease in varve thickness with depth is offset by a parallel trend to a thicker sediment rind (the freezing effect of the sampler being greatest at its base) with less radial curvature.

Sediment was prepared for pollen analysis by standard procedures (Faegri and Iversen 1964), stained with safranin, and mounted in silicone oil. Tablets containing *Lycopodium clavatum* spores (Stockmarr 1971) were added to each sample prior to processing. A minimum of 400 tree and shrub pollen grains were counted per sample together with exotic *Lycopodium*. Pollen percentages (based on a sum of total tree and shrub pollen) and influx values were calculated for all taxa. Confidence intervals for the counts of five of the major pollen taxa of core B were estimated using Maher's (1972) nomograms.

Reference samples for comparison with subfossil charcoal were prepared of uncharred and charred leaves of *Danthonia spicata* (the most abundant grass on the slopes surrounding Greenleaf Lake), wood and leaves of *Pinus strobus*, and leaves of *Pinus resinosa*. Both charred and uncharred samples were processed in the same manner as sediment, with acetolysis treatment for 1 min. There is no evidence from uncharred reference samples that the acetolysis treatment produced spurious charcoal. Within sediment samples, opaque, usually planar, black or grey fragments were identified as charcoal. Brown fragments were ignored. Black, angular pyrite crystals were rare and caused no confusion with charcoal.

Charcoal fragments were tallied by areal size classes (Waddington 1969; Swain 1973) from 20 traverses spaced 1 mm apart, along with accompanying *Lycopodium* spores. The surface area of each fragment was estimated with an occular grid divided into 400 (20 × 20) squares each 10.75 $\mu$m on a side. Fragments smaller than one-half of a grid square were ignored, larger ones placed in classes of 0.5–2.5, 2.5–4.5, 4.5–9.5, and 9.5–14.5 grid squares, and fragments 15 grid squares or larger recorded individually. The total area of charcoal recorded in the 20 traverses was then calculated by summing, over all the size classes, the product of the number of pieces and the midpoint of the class. This total multiplied by the area per grid square gave the total area of charcoal encountered; areal charcoal influx in square micrometres per square centimetre per year ($\mu$m$^2$/cm$^2$ per year) was then calculated. Palynomorphs and charcoal were recorded together along the 20 traverses.

The variability of charcoal influx within and between sediment samples was tested by a one-way analysis of variance on three samples from the same stratigraphic position of core B (1260–1269 A.D.) using the charcoal influx for each of five slides from each sample.

Aluminum and vanadium were analysed by neutron activation analysis. The University of Toronto SLOWPOKE-1 research reactor was used to irradiate 50-mg subsamples of dried sediment at a flux of $1 \times 10^{11}$ neutrons/cm$^2$·s$^{-1}$ for 1 min. Samples were counted for 5 min with a 49-cm$^3$ Canberra Ge (Li) detector coupled to a Canberra 4096-channel analyser (Model 8100) after a 14-min delay required due to high background activity resulting from the relatively large concentrations of Al. The gamma energies used for the analysis of Al ($^{21}$Al) and Va ($^{52}$Va) were 1778.9 and 1434.4 keV respectively. Prior to each run of samples the multichannel analyser was calibrated using $^{141}$Ce (145 keV) and $^{60}$Co (1173 and 1332 keV) sources. Stan-

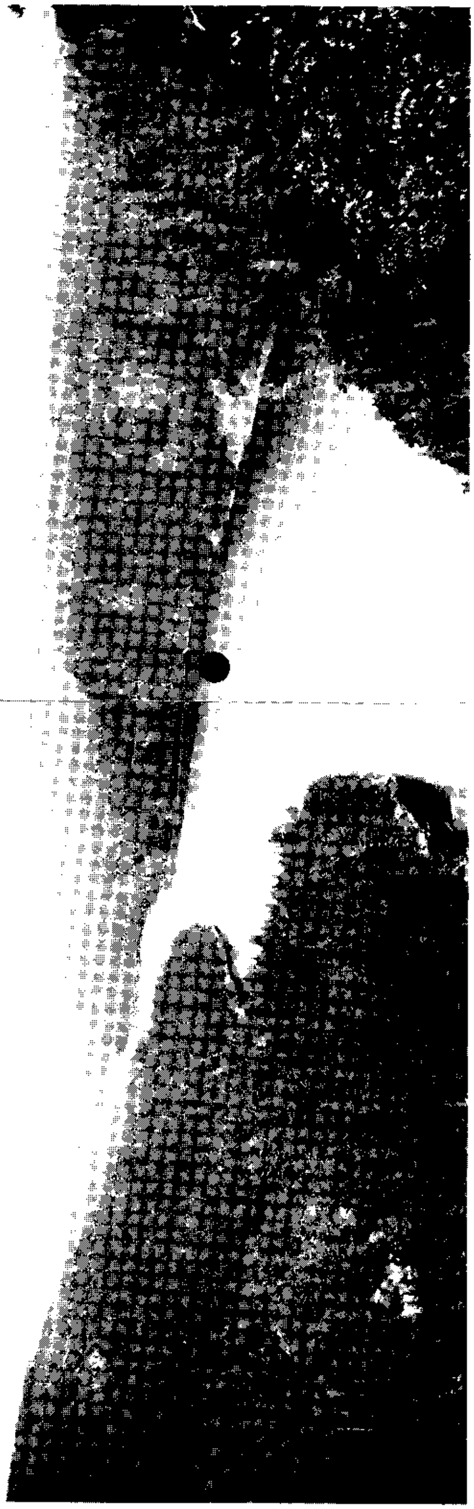

FIG. 3. View to the southeast down Greenleaf Lake. White pine is the dominant tree. The dot shows the approximate location from which sediment cores were retrieved.

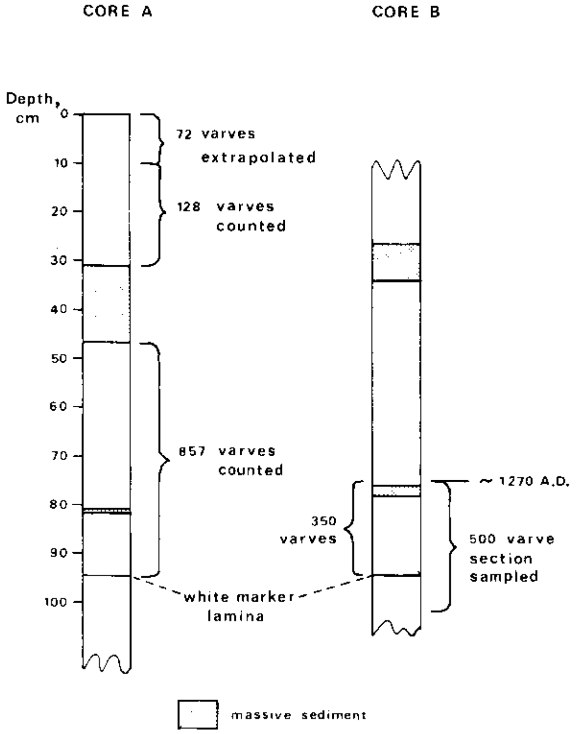

FIG. 4. Method of correlating cores A and B to estimate the chronology of B. The upper 72 years are estimated by extrapolating the sedimentation rate of the underlying 128 varves.

dards were not run with the samples because SLOWPOKE-I provides a constant neutron flux of $\leqslant \pm 2\%$ (R. Hancock, personal communication).

The influx for each element was calculated analogously to pollen influx using the equation:

$$I_E = W \times C_E / V \times S,$$

where $W$ is the total dry weight of each 0.3-cm$^3$ sample; $C_E$ is the concentration of element $E$ as a percentage of the dry weight; $V$ is the volume of the wet sediment in cubic centimetres; and $S$ is the sedimentation rate in years per centimetre.

## Results

### *Sediment Description*

The core stratigraphy is divided into three sections. The first section, from 0 to 35 cm, is infrequently laminated dark brown to black algal gyttja with a transition from brown to black between 16 and 18 cm. The second section consists of massive greyish-brown silty gyttja from 31.5 to 46 cm; it occurs in all cores but varies in thickness from 7.8 to 14.8 cm. In two of the cores a thin layer of blue–grey clay capped the second section. The third section from 46 cm to at least 110 cm (the longest core recovered) is regularly laminated brown algal gyttja with small massive layers scattered throughout. Laminations immediately below the second section were contorted to a depth of about 5 cm and could be counted but not sampled. Relatively buff to brown laminae alternate with thinner black ones forming couplets from 0.3 to 0.7 mm thick. Nodules of vivianite were intercalated throughout.

Four small sandy massive layers occurred in the third section. The thickest was 3 cm and graded similarly to turbidite layers described from Fayetteville Green Lake (Ludlam 1969, 1974). Truncated or slumped varves did not underlie these massive layers.

A distinct white lamina at 94.8 cm in core A was the most reliable stratigraphic and chronological marker horizon, although a series of large, prominent, light-brown laminations between 56 and 59 cm was also suitable.

### *Pollen Analysis of Core A*

The percent pollen diagram from core A (Fig. 5), which spans the past 1200 years, is divided into zones following the zonation of McAndrews (1972). Zone 7 is dominated by *Pinus* which comprises 50–67% of the pollen sum. *Pinus strobus* is the most abundant pine type ranging between 39 and 57% compared with only 10–18% for *P. banksiana – P. resinosa*. Both *Pinus* types remain relatively constant in this zone. *Betula* ranges from 10 to 22%, Cupressineae declines from 10 to 5%, and *Tsuga* also decreases from 7 to 2%. The remaining arboreal taxa are generally constant at less than 4%. The few *Populus* grains found were excellently preserved. *Alnus* is the most abundant shrub represented, ranging between 2 and 7%, with *Corylus* and *Myrica* occasionally present. Herb pollen is infrequent.

Zone 8 (*Ambrosia* zone) differs from zone 7 by a distinctive increase in herb pollen, particularly *Ambrosia* which rises abruptly to 4%. *Rumex* and *Plantago*, also weedy species, are confined to this zone. Gramineae increase slightly, but remain less than 2%.

Both zone 7 and 8 pollen assemblages represent a mixed conifer–hardwood forest and suggest that the composition of the forest has changed little during the past 1200 years represented by core A. The herb rise characteristic of zone 8 reflects land clearance in southern Ontario and probably the Ottawa Valley in particular. Although logging has been widespread in the Algonquin Park region, little land has been cleared for agriculture because of unsuitable soils.

### *Core B Analysis*

Details of the pollen analysis are shown in Fig. 6. A summary of the analysis of core B is presented in Fig. 7.

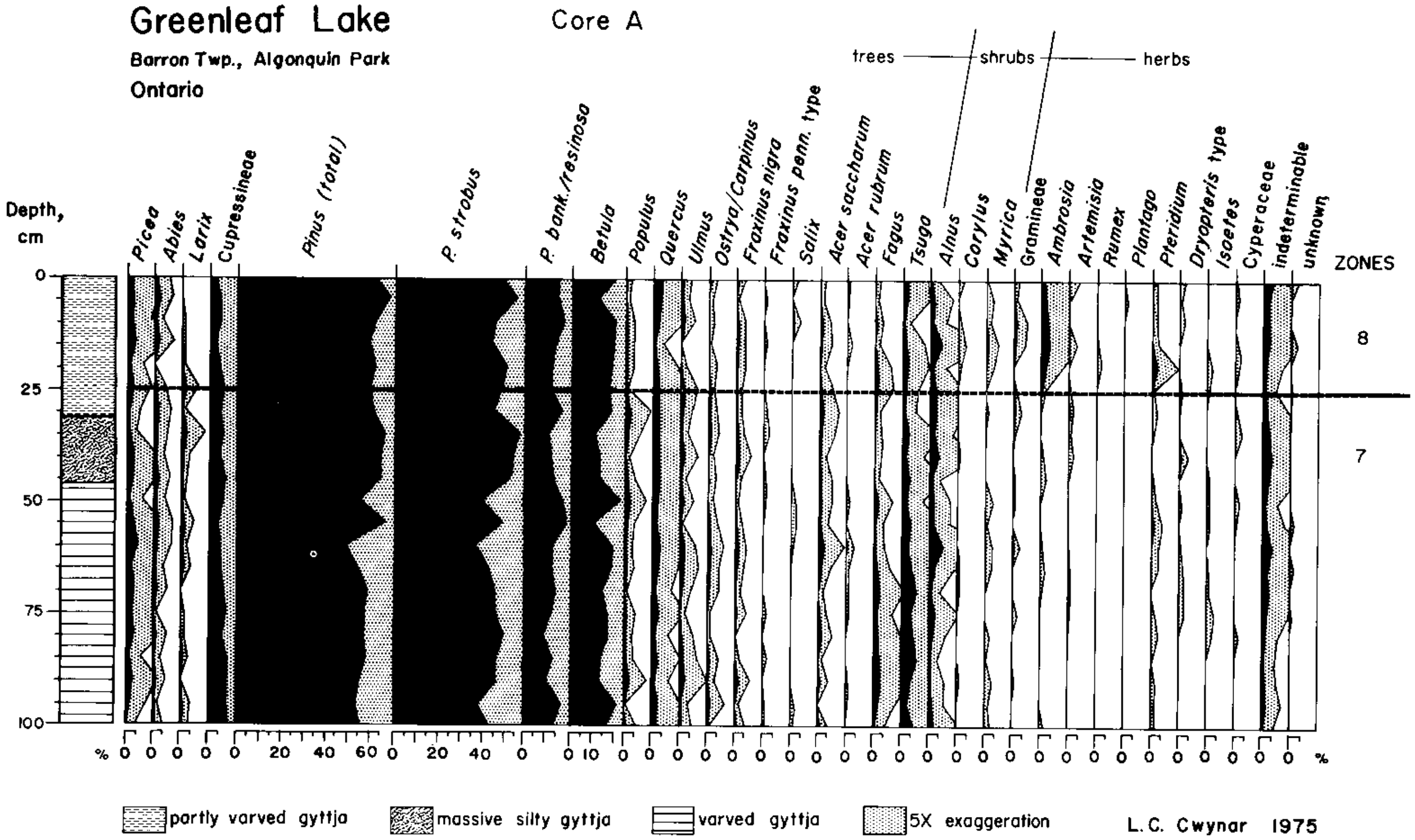

FIG. 5. Percent pollen diagram from core A, Greenleaf Lake, only showing major types.

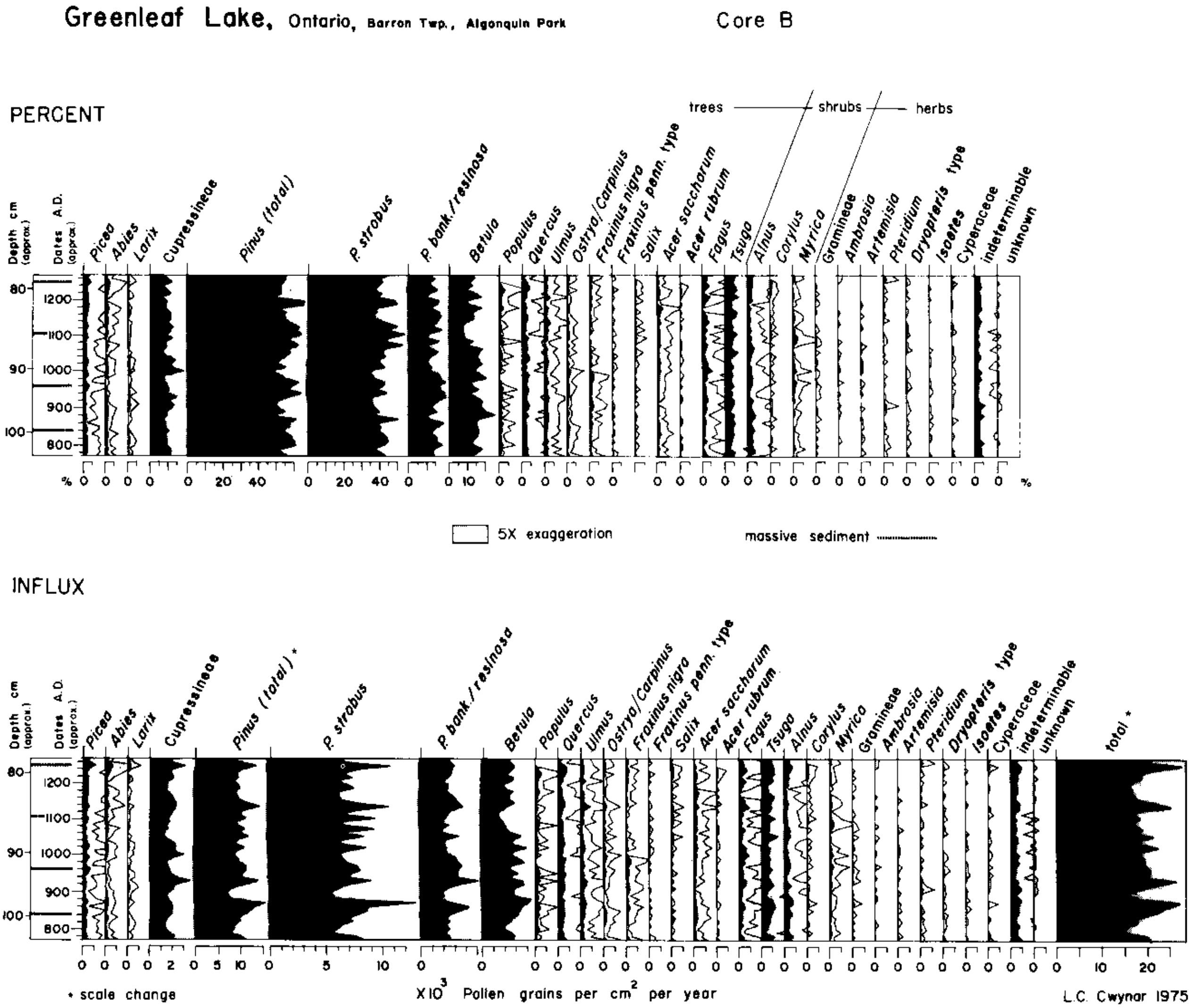

FIG. 6. Percent and influx pollen diagrams for a 500-year section of core B, Greenleaf Lake.

*Pollen Analysis*

A percent and influx diagram was constructed for the 50 contiguous decadal samples (Fig. 6). The relative diagram belongs in zone 7 without any significant differences compared with core A. The total pollen influx varies from 14 000 to 28 000 grains/cm² per year. The values have a greater amplitude than the percentage values, but otherwise influx closely parallels the relative trends.

The salient feature of the pollen analysis of cores A and B is that the composition of the forest has not altered during the past 1200 years. Thus the fire history derived from core B samples ought to be a reasonable approximation of the natural fire regime of the present forest.

Total pollen influx was strongly positively correlated with charcoal influx, varve thickness, and aluminum influx (Table 1). The *Pinus:Betula* ratio did not correlate significantly with charcoal influx, varve thickness, or aluminum influx. A relative increase of *Pinus* to *Betula* beginning in 1080–1089 A.D. continues until it suddenly declines following the peaks in charcoal influx, aluminum influx, and varve thickness at 1130–1139 A.D. This suggests a general postfire succession from birch (and probably poplar) to pine and then birch again.

*Charcoal*

Charcoal fluctuates between 1.8 and 9.4 × $10^6$ $\mu m^2 \cdot cm^{-2} \cdot year^{-1}$. Distinct peaks occur during the intervals 1240–1249, 1130–1139, 1050–1059, 960–969, 870–879, and 850–859 A.D. (Fig. 7).

Charcoal influx showed significant positive correlations (Table 1) with charcoal:pollen ratio, total

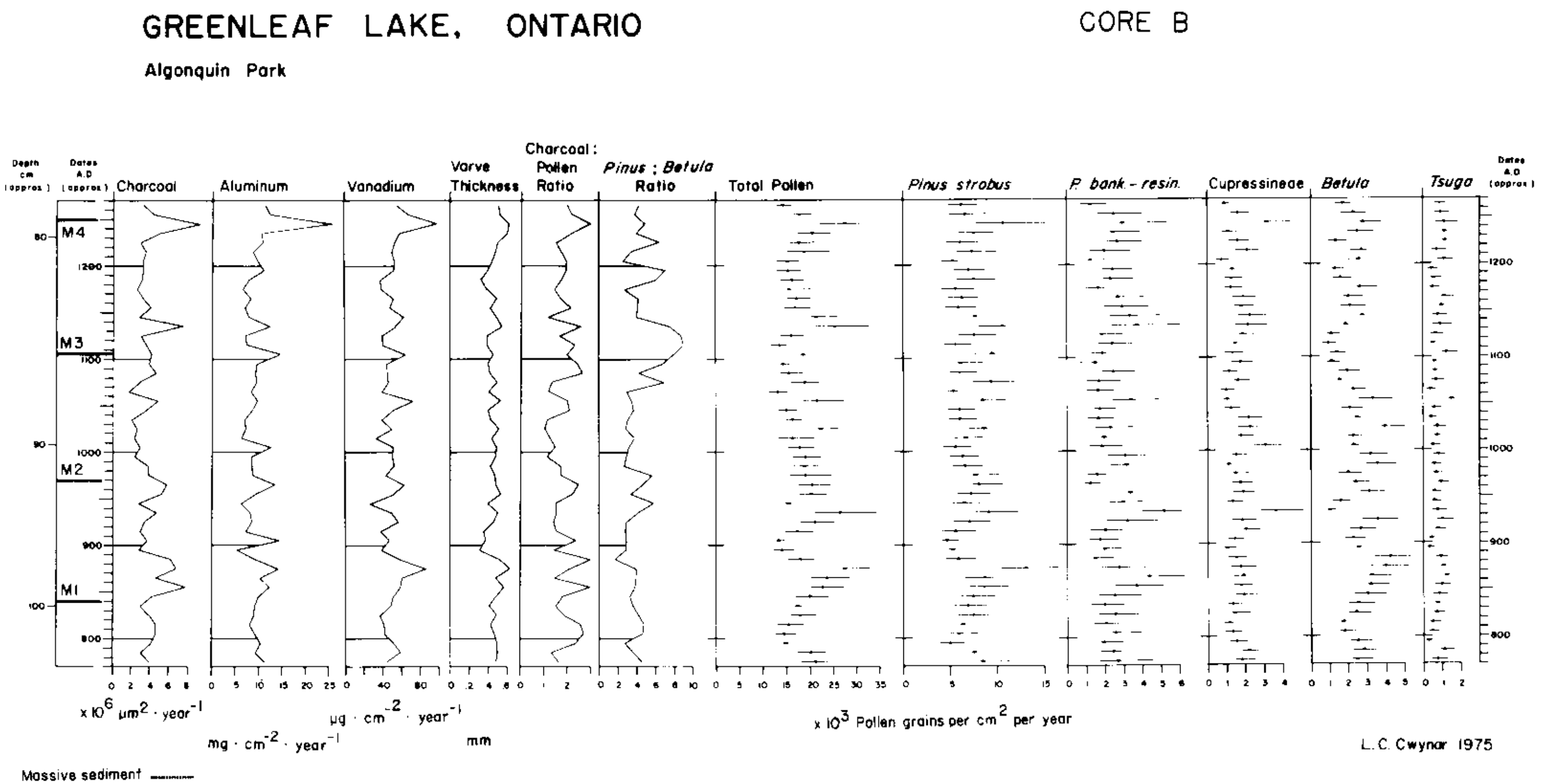

FIG. 7. Summary diagram of pollen, charcoal, and metal analysis of a 500-year section of sediment from core B, Greenleaf Lake.

TABLE 1. Correlation coefficients for selected sediment parameters

| | Charcoal:pollen ratio | *Pinus*:*Betula* ratio | Total pollen influx | Aluminum influx | Varve thickness |
|---|---|---|---|---|---|
| Charcoal influx | 0.804* | 0.102 | 0.634* | 0.706* | 0.674* |
| Varve thickness | 0.321 | −0.028 | 0.746* | 0.573* | — |
| Aluminum influx | 0.512* | 0.114 | 0.462* | — | — |

NOTE: *, significant at $p = 0.01$.

pollen influx, aluminum influx and varve thickness, but not the *Pinus:Betula* ratio.

The variability of areal charcoal influx within and between samples of the same stratigraphic position of a single core is shown in Table 2. No significant difference in the mean charcoal influx was detected by the one-way analysis of variance.

*Metal Analysis*

Both aluminum and vanadium influxes exhibit periodic fluctuations with the most prominent peak during the interval 1240–1249 A.D. Less prominent peaks are shown for both elements for the intervals 1190–1199, 1100–1109, 1050–1059, 1130–1139, 960–969, 900–909, and 870–879 A.D. An aluminum peak at 1000–1009 A.D. is unaccompanied by a similar increase in vanadium. Overall, it is important to note that neither aluminum nor vanadium has a constant influx, but these influxes fluctuate, often peaking in the same intervals.

The concentration of aluminum and vanadium for three of the four small massive layers intercalated within the 500-year section of core B are presented in Table 3, together with the mean concentration and range for each element for the 50 10-year samples from core B. The concentration of aluminum in all three massive layers exceeds the mean for the laminated samples by 2–3 times. In fact, the concentration of aluminum for each massive layer lies outside the range of concentrations for the 50 laminated samples. Vanadium concentrations are also greater for the massive layers, but only those of M2 and M4 lie outside the range of the laminated samples.

The most useful approach for identifying past fires from lake sediment is to observe a number of indices affected by landscape changes resulting from burning. Concurrent, relatively rapid increases in charcoal influx, aluminum and vanadium influx, varve thickness, and charcoal:pollen ratio are therefore interpreted as representing major fires occurring within the basin of Greenleaf Lake. By these criteria, fires occurred within the intervals 850–859, 870–879, 960–969, 1050–1059, 1130–1139, and 1240–1249 A.D., for a mean frequency of one fire every 83 years. It must be emphasized that this is a conservative estimate. Surface fires may not be reflected in the sediment because erosion is not appreciably increased and rapid vegetation recovery stabilizes the soil surface.

TABLE 2. Charcoal influxes for three replicate samples from 1260–1269 A.D.

| | Charcoal influx, × $10^6$ $\mu m^2 \cdot cm^{-2} \cdot year^{-1}$ | | |
|---|---|---|---|
| Slide | Sample A | Sample B | Sample C |
| 1 | 3.23 | 4.49 | 3.37 |
| 2 | 3.31 | 2.89 | 3.24 |
| 3 | 3.41 | 5.01 | 3.07 |
| 4 | 2.94 | 4.01 | 3.33 |
| 5 | 2.65 | 3.13 | 3.99 |
| Mean and standard deviation | 3.11±0.31 | 3.90±0.90 | 3.40±0.35 |

NOTE: $F = 2.31$ on (2, 12) degrees of freedom is not significant at the 5% level.

## Discussion

The determination of fire occurrence from lake sediments is not as straightforward as hoped. Charcoal influx is the most direct sediment evidence of fire but several factors affect its representation (Swain 1973). The quantity eroded into a lake from a given fire varies with the amount and pattern of subsequent precipitation, variation in wind velocity and direction, and the rate of soil stabilization by vegetation recovery. Even if charcoal is rapidly deposited into the lake in a stepwise fashion, many other factors add to the relativity of individual peaks. Each sediment sample represents 10 years of sedimentation; thus a sample with 1 year of high charcoal preceded by 9 years of low influx will have a relatively low mean charcoal influx. A varve counting error of 1 year also results in a 10% error. Redeposition may produce prolonged or spurious

TABLE 3. Metal concentrations for massive layers and laminated sediment of core B

| | Metal concentration | | | | |
|---|---|---|---|---|---|
| | Massive layer | | | Laminated sediment[a] | |
| Metal[b] | M1 | M2 | M4 | Mean | Range |
| Aluminum, % | 3.69 | 2.36 | 3.22 | 1.21 | 0.92–2.27 |
| Vanadium, ppm | 73 | 118 | 130 | 63.8 | 43–88 |

[a] Fifty 10-year samples.
[b] Concentrations on a dry weight basis.

charcoal peaks because sediment is transported from littoral to profundal zones and from the shallow, holomictic east basin to the deeper, probably meromictic, west basin. Davis (1968) has shown that pollen and sediment (including inorganic matter and, presumably, charcoal fragments) are redeposited together. This means that the charcoal:pollen ratio will likely remain a sensitive, relative indicator of fire. Redeposition phenomena are minimal in Greenleaf Lake because of its stagnant bottom waters and narrow littoral zone. The arguments concerning the relative heights of individual charcoal peaks apply to other influxes as well.

Charcoal influxes for Greenleaf Lake (50 samples) ranged from 1.79 to 9.41 × $10^6$ $\mu m^2 \cdot cm^{-2} \cdot year^{-1}$ with a mean and standard deviation of 3.98 ± 1.51 × $10^6$ $\mu m^2 \cdot cm^{-2} \cdot year^{-1}$. By comparison, charcoal influxes from Lake of the Clouds (values abstracted from Swain's (1973) Fig. 3) were of the same order of magnitude but with a range of about 1 to 17 × $10^6$ $\mu m^2 \cdot cm^{-2} \cdot year^{-1}$ and a mean of 6.6 × $10^6$ $\mu m^2 \cdot cm^{-2} \cdot year^{-1}$. Despite these differences, the relativity of individual peaks identified as fire horizons was about the same. The higher mean charcoal influx for Lake of the Clouds supports and reflects the greater frequency of 26 years for 'major' fires for the Boundary Waters Canoe Area compared with 45 years for Barron Township (Cwynar 1977). The charcoal influx differences may also be due to differences in lake morphometry, drainage basin topography, and soil types.

Charcoal increases are generally accompanied by an increased influx of aluminum and vanadium, as predicted by the erosion hypothesis. However, sharp peaks in charcoal influx and charcoal:pollen ratio for the interval 1080–1089 A.D. indicate a fire period, but there are no corresponding changes in the aluminum or vanadium influx nor an increase in varve thickness. This may result from wind-transported charcoal with proportionately lower amounts of inorganic particles compared with water erosion. Swain (1973) attributed a high sediment charcoal influx from Lake of the Clouds, Minnesota, during 1930–1939 A.D. to long-distance transport of charcoal from fires that burned in Canada and other parts of Minnesota in 1936.

Two intervals, 1000–1009 and 1100–1109 A.D., show sharp increases of aluminum and (or) vanadium with a simultaneous increase of varve thickness but little or no increase of charcoal influx or charcoal:pollen ratio. These intervals suggest either periods of higher erosion rates due to increased precipitation or other disturbances such as windthrow, which might increase erosion without increasing charcoal within the soil.

Total pollen influx did not decrease with greater charcoal influx as one might expect, but generally increased (Table 1). Swain (1973) also found that conspicuous peaks of total pollen accompanied charcoal peaks and suggested that greater erosion and redeposition accounted for this phenomenon. This view is supported by corresponding peaks of aluminum in this study. O'Rourke and Solomon (1976) have recently found that total pollen influx was a direct function of sediment influx in varved sediments from Seneca Lake, New York. Peck (1973) reported a significant correlation between total pollen caught in fluvial traps and stream discharge, and points out that water-borne pollen may contribute substantially to the influx of pollen into lake sediments. It appears that the reduced pollen production resulting from the destruction of vegetation by fire is more than offset, with respect to pollen influx into lake sediment, by increased erosion of polleniferous soil.

The increased pollen influx that accompanies high charcoal influx may also be related to the filtering capacity of the vegetation (Tauber 1967). The destruction by fire of the forest canopy within a drainage basin allows more pollen to be deposited on the lake surface by the regional pollen rain. Because neither the extent of the fires contributing charcoal nor the pollen source area is known, the importance of this effect cannot be determined.

Every major charcoal peak is accompanied by a similar peak in the charcoal:pollen ratio despite the high pollen influxes associated with these levels. This indicates a greater increase in charcoal than in pollen influx. Further, it shows that fluctuations in charcoal influx are not the result of sampling errors, such as differential packing of sediment into the sample spoon.

Lack of correlation between the *Pinus*:*Betula* ratio and charcoal influx may be the result of predominantly regional rather than local pollen rain. However, the pollen rain may be local, but the approximate 10-year lag in pollen production between pines and birches may be too short an interval to be recorded by the decadal samples. Also, the variation in topography within the drainage basin results in a patchy burning pattern; continued pollen production from surviving trees might maintain the existing proportions of *Pinus* and *Betula* pollen.

The sandy massive layers without associated slumped varves probably represent exceptionally high discharges from the stream draining Lost Lake into the northwest side of Greenleaf Lake. The lake bottom from this point slopes rapidly toward the center of the deep basin from which the laminated sediment was retrieved.

The charcoal:pollen ratios for these massive layers do not convincingly suggest a fire origin. M4 has a charcoal:pollen ratio of 3.36, greater than any of the laminated samples; the ratios for M1 and M2 are 1.34 and 2.01 respectively, well within the range for laminated samples. The intervals 960–969 and 1240–1249 A.D., however, indicate fire periods and occur immediately below massive layers. These sandy massive layers represent erosion features that probably resulted from fire.

Fire frequency of one local fire approximately every 80 years was derived from the sediment for the period 770–1270 A.D. This contrasts with the 45-year frequency of major fires determined for the past 300 years in Barron Township from dated fire scars (Cwynar 1977). Undoubtedly the sediment record is conservative, in part accounting for the difference. Swain (1973) identified local fires from sediment of Lake of the Clouds on the basis of concomitant increases in varve thickness and charcoal influx, but by these criteria two known fires were not documented. Only severe fires burning to mineral soil are likely to be reflected in sediment. Many surface fires and some rapid crown fires may not be registered in sediment since erosion does not increase significantly and vegetation recovers quickly.

The fire frequency may also have been lower during the interval 770–1270 A.D. than it was during the past 300 years. The overall fire frequency derived from sediment analysis of Lake of the Clouds, also located in mixed coniferous–hardwood forest on the Precambrian Shield, was about 70–80 years. The occurrence of three major fires in Barron Township (including the Greenleaf Lake runoff basin) within a 22-year span (1854–1875) may be unusual, although the relative pollen record shows no evidence of sudden vegetation change that might be expected with a significant shift in the fire regime. The dendrochronological and sediment fire histories cannot be directly compared because of disrupted laminations associated with the gray massive layer. This precludes an insight into the accuracy with which fire events are registered in the sediment of Greenleaf Lake, and a comparison of modern charcoal influxes with those of the past.

## Summary

The presence of abundant charcoal throughout the 500-year period of pre-Columbian sediment and the relatively constant forest composition during the past 1200 years show that fire has been a natural phenomenon throughout at least the past 1200 years. Concurrent peaks in charcoal, aluminum and vanadium, varve thickness, and the charcoal: pollen ratio indicate that major fires occurred within the Greenleaf Lake drainage basin on the order of once every 80 years. This conservative record suggests that the frequency of one major fire every 45 years determined from fire scars for the past 300 years in Barron Township may represent a period of unsually high fire incidence, although not severe enough to cause major changes in the vegetation and be reflected in the relative pollen record.

The correspondence of high charcoal influx with increased influx of aluminum and vanadium into sediment adds support to the erosion hypothesis.

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