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Paleolimnological Sedimentation of Organic Carbon, Nitrogen, Phosphorus, Fossil Pigments, Pollen, and Diatoms in a Hyper-eutrophic, Hardwater Lake: A Case History of Eutrophication

With 8 figures and 1 table in the text

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Running Head: Paleolimnology of a Hardwater Lake

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ABSTRACT

The sediment history of this productive, hardwater lake (Wintergreen Lake in southern Michigan) developed as five periods of increasing eutrophy, each strongly influenced by a hybrid basin morphometry. This morphometry led to higher productivity per unit area by macrophytic plants in littoral waters of the lake than by phytoplankton in pelagic waters. During the late-glacial, early postglacial period (14,075 - 10,200 B.P.) productivity was apparently inhibited first by low temperatures caused by retreating glacial (Cary) ice and an ice block in the basin, then by competition between phytoplankton and precipitating monocarbonates for phosphorus, micronutrients, and organic constituents. Sediment composition during this interval was primarily clay-marl containing coarse sand and pebbles overlain by marly-gyttja. After 12,640 B.P. the pollen assemblage reflected boreal, open, forests of spruce followed by pine. The main factor controlling productivity in the lake during this period was likely climate.

As the climate ameliorated the lake entered a period of trophic equilibrium (10,200 - 5900 B.P.) during which productivity increased gradually. Towards the end of this interval production of organic matter within the lake apparently exceeded that which could be decomposed by oxygen in the hypolimnion causing rapid accumulation of organic-rich sediments. The rate of eutrophication was likely governed during this period by nutrient loading rates from the stable, forested, drainage basin. The littoral macrophytic period (5900 - 135 B.P.) was distinguished by large numbers of Najas or Potomogeton seeds in the sediments and a change in sediment composition from brown, gelatinous gyttja to highly-organic, black, peaty gyttja. During this and the previous period the pollen assemblage was first dominated by pine and later oak. Fluctuations in precipitation, evident from the proportion of mesic to xeric terrestrial plant

pollen and alternation between predominantly littoral and phytoplanktonic diatom assemblages, may have caused lake levels to fluctuate. Accumulation of organic-rich sediments lakewide caused an increasing proportion of the basin to become shallow enough to be colonized by aquatic macrophytes, which are more productive than phytoplankton per unit area in shallow waters. About 2480 B.P. (200 cm) sedimentation rates in the central basin began to increase markedly and have accelerated steadily to the present.

During the period of settlement (135 - 44 B.P.) evidence of deforestation and increased carbonate loading appeared as marked increases in the pollen influx rates of open-field vegetation (esp. Ambrosia and Rumex), and carbonate content of the sediments. Primary productivity of phytoplankton in the lake during this interval, as reflected in concentrations of sedimentary organic matter, pigments, and organic nitrogen, decreased about four-fold, apparently as a consequence of renewed competition between plants and monocarbonates for nutrients and required organic constitutents. During the contemporary period (44 - 0 B.P.) soil conservation practices around the lake reduced carbonate loading rates. Establishment of resident waterfowl populations in 1926 caused marked increases in the loading rates of organic matter and phosphorus. A nine-fold increase in sedimentation rate during this period illustrates that the high nutrient loading rates accelerated the rate of eutrophication and further increased the degree of eutrophy.

The tripartite zonation in pollen assemblages, spruce to pine to deciduous hardwoods (primarily oak), found, conforms in general to that found elsewhere in the Great Lakes region. Reflected in these zones is a cool climate followed by a warmer period of alternating moist and dry intervals. A marked increase in concentrations of sedimentary pigments, organic matter, and organic nitrogen about 10,000 B.P. suggests the warmer, hypsithermal, climate stimulated productivity in this lake.

INTRODUCTION

Wintergreen Lake is a hypereutrophic, hardwater lake (annual pH range: 7.0 - 9.5) about 14.6 ha in size located in southwestern Michigan. Fragments of woody plant debris and a littoral diatom assemblage in the lower sediments (Martin 1974) suggest the lake originated as an ice-block depression (Florin & Wright 1969) in the outwash plain formed from melt-waters of the Valparaiso Moraine of the Michigan lobe and the Charlotte Moraine of the Saginaw Lobe during the retreat of Cary ice about 14,500 years B.P. (Leverett & Taylor 1915; Wayne & Zumberge 1965). Soils of the area developed upon glacial till high in carbonates and vary from deep, poorly-drained Carlisle muck to sandy, well-drained Fox loam (Perkins & Tyson 1922). Earliest land surveys show presettlement plant communities near Wintergreen Lake were forests of oak, maple, ash, and black walnut surrounding occasional islands of prairie grassland (Durant 1880; Kenoyer 1930; Peters 1970, 1973). After settlement in the early 1830's, the drainage basin was first grazed, then farmed. In 1926, pine plantations were planted around the lake to stabilize eroding soils, and in 1928, a permanent flock of Canada geese was established to attract migrant waterfowl to the lake when it became part of the W.K. Kellogg Bird Sanctuary (R. D. VanDeusen, Pers. Comm.). Each year returning migrant geese contribute more than 4600 kg dry weight of feces to the lake causing, in large part, the current hypereutrophic condition (Manny, Wetzel & Johnson 1975). Today, Wintergreen Lake is nearly surrounded by oak, spruce, and pine trees, behind which are fields under intensive cultivation. Surface area of the drainage basin is about 8 times that of the lake. Other than surface runoff, visible inflow to the lake is limited to one small intermittent stream originating about 0.5 km north of the lake (Manny 1971). In the spring, water flows over a small dam across the outlet. Morphometric and chemical characteristics

An inverse relationship between carbonate content and other indices of past productivity (sedimentary pigments and organic matter) appeared in our data as it has in data from other hardwater lakes studied to date. This finding suggests the inhibition of primary productivity by competion between plants and precipitating monocarbonates for phosphorus and micronutrients is an intrinsic characteristic of hardwater lakes on carbonate-rich glacial till.

As interpreted, the above combination of basin morphometry, edaphic, and *in situ* factors indicate the determinate role productivity by aquatic macrophytes can play in sustaining trophic succession towards a more eutrophic state, and higher rates of eutrophication over geological time. At current rates of sedimentation, without recourse to remedial measures such as sediment removal and/or aeration of the hypolimnion, Wintergreen Lake will become a marsh in about 1200 years.

of Wintergreen Lake have been summarized in Manny (1972). This study was undertaken to better understand the history of eutrophication in this hardwater lake relative to regional climatic changes over geological time and more recent land use practices which brought about its present hypereutrophic state.

METHODS

One primary core 7.23 m long was secured on 10 February 1972 through the ice over the central depression (Fig. 1) using a modified, Livingston corer (Cushing & Wright 1965). In addition, one surface core 82 cm long was collected to better confirm the horizon of land clearance in the sediments by reference to the Ambrosia rise. The primary core was extruded on 10 February 1972, wrapped in plastic (Saran wrap) and aluminum foil, and refrigerated. The following day, the central portion of this core was exposed, subsampled by cutting 1-cm thick slices at 5-cm intervals, and samples were removed for pollen, diatom, and chemical analyses and stored in clean, sealed vials in the dark at 5°C until analysis. Owing to the flocculent nature of sediments in the upper 25 cm of both cores, the first section of each core was frozen in its Livingston sheath, and sawed into 1-cm thick slices at 2-cm intervals. Each slice was placed in a clean petri dish, and subsampled in the middle for pollen and diatom analysis using a clean cork borer. Individual subsamples (1.132 cm^3) were stored in clean, air-tight vials under refrigeration for later microscopic examination. All samples for pollen were concentrated from the unit-volume subsamples using a modification of the method outlined by Faegri & Iversen (1964), and mounted in silicone oil for counting. Each sample was prepared in a manner to provide quantitative estimate of pollen concentrations, using the additive, exotic-pollen technique (Benninghoff 1962). Total pollen influx rates were obtained by multiplying the pollen concentration at each level in the core by

Fig. 1

the appropriate sedimentation rate (Table 1). All unit-volume samples for diatom analysis were oxidized with nitric acid and potassium dichromate, and mounted in Hyrax following procedures of Hohn & Hellerman (1963).

Additional center-slice subsamples for pigment and nutrient analysis were removed from the core, placed in clean glass vials, sealed tightly, and refrigerated in the dark at 5°C. For pigment analysis, about 4 g of wet sediments were removed and homogenized. A 1 - 2 gram portion of the homogenate was weighed to within 0.1 mg, dispersed with a glass rod in about 30 ml of 90% aqueous, basic acetone containing 0.5% dimethylaniline, and extracted with intermittent mixing at 4°C in the dark for 24 hours by techniques slightly modified from Vallentyne (1955). The extracted sediments and supernatant acetone were filtered through fine filter paper (Whatman No. 50), and washed repeatedly with solvent until 100 ml of filtrate were collected. Light absorption of pigments in the filtrates relative to the solvent was immediately analyzed from 350 to 750 nm in a scanning, ratio-recording spectrophotometer (Beckman DK-2A) using a 10-mm light path. Pigment concentrations in lower portions of the core were extremely low necessitating a 100-mm light path.

Little variance was found among replicate pigment analyses at selected depths in the sediments. One standard deviation was less than 9% of mean SPDU (sedimentary pigment degradation unit) per gram, and $< 7\%$, $< 8\%$, and $< 3\%$ of mean water content, organic matter, and carbonate content, respectively. For chlorophyllous pigments, a SPDU is defined here as the optical density of extracted pigments at the wavelength of maximum absorption (10 mm lightpath) in the red end of the spectrum, corrected for baseline absorption of light at 750 nm. Relative SPDUs of carotenoids, about half the measured absorption of which resulted from pheophytins (Fogg & Belcher 1961), were calculated in same manner from the optical density at the wavelength of maximum absorption

in the blue portion of the spectrum. Sedimentary pigment degradation units were expressed per gram of dry sediment and per gram of dry organic matter. The latter expression avoids distortion of the pigment concentrations by inorganic materials in the sediments.

Ash-free weights of organic matter and carbonate content were obtained by weighing a portion of the homogenized wet sediment in flamed, tared crucibles, drying for 24 hours at 105°C, cooling under desiccation, and reweighing to within 0.03 mg. The samples were then heated to 550°C for 1 hr, cooled, reweighed for organic matter lost on ignition, and finally heated to 950°C for 3 hr, cooled, and reweighed to determine carbonate content lost on ignition. About 2 - 3% of the weight loss between 550°C and 950°C is probably not CO_2 but bound water (E. Gorham, pers. comm.).

Samples for phosphorus and nitrogen analyses were each dried in a clean testtube for 24 hr at 105°C, then pulverized with a clean, glass rod. Tared subsamples of 200 - 250 mg were transfered to Kjeldahl for nitrogen analysis and to 100-ml volumetric flasks for phosphorus analysis.

Kjeldahl nitrogen was analyzed by heated digestion of the sediments in the presence of 3 g K_2SO_4, 1 ml of 5% $CuSO_4$ and 10% NaCl solution, 5 ml concentrated H_2SO_4 , and 3 glass beads for 1 hr after the samples had lost all color. Digested samples were transferred to a distillation apparatus (Markham 1942), neutralized with 50% NaOH, and agitated with steam to drive all ammonia from the sample. Exactly 35 ml of distillate was collected in 5 ml of saturated, boric acid containing trace amounts of brom cresol green-methyl red indicator. The distillate was titrated to the gray-pink endpoint at pH 5.6 using 0.02 N H_2SO_4 in a syringe microburet.

Total phosphorus in the sediments was measured by digestion to the white-vapor stage of perchloric acid in the presence of 10 ml distilled water, 6 ml perchloric acid solution, 1 drop of 5% KI solution, and 2 glass beads

after Strickland & Parsons (1968). Neutralization with 10 ml NH_4OH solution preceded evaporation to dryness and resolubilization in 10 ml of distilled water before centrifugation to obtain a 2-ml aliquot of clear supernatant. The 2-ml aliquot was diluted to 12 ml with distilled water before adding 5 ml of ascorbate-H_2SO_4-molybdate solution to develop a blue-colored complex. Within 30 min, the optical density was measured spectrophotometrically at 690 nm in a flow-through cell of 10-mm light path.

SEDIMENT STRATIGRAPHY

General sediment characteristics varied throughout the core (cf. left side of Figure 5). Sediments near the bottom of the core (723 to 720 cm) were coarse sand mixed with rounded, smooth pebbles, 1 - 3 mm in diameter. This material was overlain by about 50 cm of light-gray clay-marl and fine sand -- effervescent upon exposure to 1 N HCl -- interspersed with occasional bands of black, organic material containing recognizable fragments of woody plant tissue. From 670 to about 570 cm sediments alternated between sharp bands of dry, light-gray, marl -- gritty with fine sand -- to more moist, olive-gray, coarser marl containing occasional twigs and plant matter. A marked zone of transition occurred between gritty, light-gray marl at 570 cm (10,200 B.P.) to gelatinous, adhesive, dark-brown, gyttja at 550 cm (9725 B.P.). Between 550 and 490 cm, sharp bands of mottled, dark-gray marl alternated with bands of highly-organic, chocolate-brown-to-black gyttja. From 490 to 380 cm a transition was noted proceeding gradually from less-organic, gray-brown sediments to darker-brown, gelatinous gyttja, high in organic matter content. From 380 to 350 cm sediments changed from brown gyttja to darker-brown, gelatinous gyttja mixed with a few seeds of the aquatic macrophytes <u>Najas</u> and likely <u>Potomogeton</u>. The number of

seeds per unit volume of sediment increased markedly between 350 and 320 cm as the sediments graded from dark-brown to heavy-black, organic gyttja. From 320 to 63 cm the sediments were uniformly heavy-black, organic, gelatinous gyttja containing large numbers of Najas (or Potomogeton) seeds. At 63 cm the black, organic gyttja changed abruptly to lighter-blackish-brown gyttja containing no macrophyte seeds. At 25 cm the blackish-brown gyttja changed to a distinctly lighter-brown, unconsolidated flocculus of undifferentiated, surface sediments. We believe these changes in sediment color, organic-matter content, and composition are closely tied to changes in the past trophic status of Wintergreen Lake and reflect real changes in the long-term rate of eutrophication of the lake. Of particular interest are the marl deposits near the bottom of the core, which clearly indicate the lake was first oligotrophic like many near-by lakes (Wetzel & Manny 1976) but became more eutrophic as factors in the lake and its drainage basin caused the rate of eutrophication to accelerate.

RATES OF SEDIMENTATION

Rates of late-glacial and postglacial sedimentation in Wintergreen Lake were calculated using 10 radiocarbon dates spaced throughout the 7.23 m primary core. Because rates of organic matter sedimentation were currently high, the surface correction of 125 years for carbonates and ^{14}C deficiency (Stuiver 1968) was small (Table 1). From the time of lake inception to the present, sedimentation rates ranged from 0.20 to 5.7 mm yr^{-1}. The mean rate over the entire record was 0.52 mm yr^{-1} (1.93 yr mm^{-1}).

Table 1

Rates of sedimentation were initially low from 12,950 to 12,190 B.P. (680 - 650 cm) ranging from 0.02 - 0.07 cm yr^{-1}. During this period the surrounding vegetation, as reflected in the pollen record, was characteristic of a cold,

boreal, climate (cf. Fig. 4). From 12,190 to 8550 B.P. (650 - 500 cm) the climate apparently ameliorated. During this interval we noted a change in the pollen record from spruce to pine, then to deciduous forest species (mostly Quercus). Rates of sedimentation increased somewhat during this transitional period, then slowed to about 0.4 mm yr^{-1} for about five millennia, from 9,725 to 5,283 B.P. (550 - 350 cm). Sedimentation rates increased slightly from 5,283 to 3,354 B.P. (350 - 250 cm) to 0.62 mm yr^{-1} then reverted to a little less than 0.5 mm yr^{-1} again. At about 2480 B.P. (200 cm) sedimentation rates began to increase and have accelerated until the present time (Figs. 2 & 3). By about 975 B.P. (100 cm), sedimentation rates exceeded 1.0 mm yr^{-1}.

Fig. 2

Fig. 3

Many seeds of aquatic angiosperms were found dispersed among the black, gyttja sediments between 350 and 63 cm. Seed deposition ended abruptly at 63 cm, the point at which sediments changed to less-organic gyttja, light brown in color. This transition coincided exactly with a dramatic rise in the abundance of Ambrosia pollen, which marks the time of regional forest clearance by man about 135 B.P. Sedimentation rates increased at this time to 4.2 mm yr^{-1} (Fig. 3). The present rate of sedimentation is estimated to be 5.7 mm yr^{-1}. This very rapid rate is largely a consequence of intensive land-use practices in the drainage basin and excessive nutrient enrichment of the lake by migrant waterfowl attracted to the lake after it became a wildlife sanctuary in 1926 (Manny, et al. 1975). Assuming present rates of sedimentation, Wintergreen Lake will rapidly fill with marsh vegetation and approach extinction within about 1,200 years.

The present morphology of the lake (Fig. 1) is sinusoidal (Lehman 1975). The central depression is skewed to the northeast and southwest. When the block of glacial ice in the central depression melted, the shallower southeastern portion of the basin was deeper than it is currently, but not greatly different, in relative proportion to the central depression, from the current morphology. The central depression has always been shaped like a frustum or hyperboloid,

which would cause sediments to accumulate most rapidly in the central, deepest area (Davis 1973; Davis & Brubaker 1972). To evaluate this sediment-focusing effect, observed rates of sedimentation in the lake (Table 1) were transformed and compared to basinwide influx rates of sediment based on four geometric models developed by Lehman (1975). Transformation of the observed rates compensates for sediment-focusing effects expected from areal influxes of sediment to ellipsoid, sinusoid, hyperboloid, and frustum-shaped basins (Fig. 3). The ellipsoid transformation gave very aberrant sedimentation rates which we believe do not accurately represent the early deposition in Wintergreen Lake. Among basin shapes, however, sedimentation rates decreased progressively in the order: observed > sinusoid > hyperboloid > frustum. Increases in sedimentation observed between 12,000 to 9,000 B.P. and 5,000 to 3,500 B.P. largely disappeared when the data were transformed to compensate for focusing effects expected of a hyperboloid or frustum-shaped basin. The acceleration in sedimentation rates since land clearance persisted in all cases. Actual sedimentation rates during the post-glacial history between 13,500 and 2,000 B.P. were more realistically expressed by the frustum or hyperboloid transformations yielding values ranging from 0.002 - 0.3 and 0.087 - 0.4 mm yr^{-1}, respectively.

POLLEN STRATIGRAPHY

Pollen data from the sediments of Wintergreen Lake are presented in a summary diagram as percentage values of total pollen counted at each level in the primary core, excluding aquatic pollen and cryptogam spores (Fig. 4). Fig. 4 Sediments below 668 cm contained little recognizable pollen exine; those present were poorly preserved. The tripartite nature of the pollen diagram from our core strongly resembles that found in other lakes in the central Great Lakes region (Ogden 1966; Gilliam et al. 1967; Williams 1974; Bailey 1972),

particularly the sequence of spruce to pine to mixed deciduous hardwood species. Of particular interest in our pollen profile is the bimodal distribution of Fagus in the mid-postglacial period between 7500 and 2500 B.P., and the evidence of land clearance marked by increases in Ambrosia and European agricultural weeds such as Plantago and Rumex. To facilitate discussion, we divided the pollen profile into four assemblage zones and several subzones based largely on changes in percent composition of index pollen types. These zones were delineated only in the stratigraphic sense and were not intended to connote changes in ecological or climatic conditions (Cushing 1967; West 1970).

Zone 1 (12,640 - 10,645 B.P.; 668-588 cm) was characterized by a spruce-mixed hardwood-herbaceous assemblage with an upper limit where Picea decreased to less than 25% and Pinus increased to greater than 30%. Picea and Fraxinus (largely F. nigra-type), at 54% and 22%, respectively, were the major arboreal components of this assemblage. Non-arboreal pollen (NAP), primarily Cyperaceae, Graminaea, and Artemisia, ranged from 15 - 25%. Two subzones were identified within this zone based on samples at thirteen strata. Subzone IA (12640 - 11435 B.P.; 668 - 620 cm) was characterized primarily by pollen of conifer species such as Picea and Cupressaceae, and by maximum values of F. nigra-type. The upper limit of this subzone was placed where Fraxinus decreased to less than 1% and Abies increased to greater than 5%. Pollen below 668 cm were poorly preserved perhaps because ice remained in the lake basin. We found little direct evidence to support the hypothesis that a spruce woodland became established atop a buried ice block at the Wintergreen site as has been suggested for some basins in Minnesota (Florin & Wright 1969). None-the-less, layers of plant fragments and organic sediments mixed with inorganic sediments were found below fossil-bearing sediments dated at 13195 B.P., which suggests Wintergreen Lake may have been ice-blocked for about 1000 years. Evidence of biological activity within the lake was scarce in this early segment of the sediment profile, but this finding

is common in sediment profiles from the Great Lakes region.

In Subzone 1A total pollen influx rates below 650 cm were low (4 - 6 x 10^3 grains cm^{-2} yr^{-1} but increased to between 7.7 - 13.9 x 10^3 grains cm^{-2} yr^{-1} within the next 30 cm. The percentage pollen composition and influx rates for this subzone compare well with other study sites in this region (Williams 1974; Bailey 1972; Kerfoot 1974) and suggest the presence of open stands of spruce forest (Davis, Brubaker & Webb 1973) in the Wintergreen Lake area soon after deglaciation. The character and structure of the vegetation suggested in this assemblage spans the interval of the Valders maximum and retreat in the Lake Michigan basin. Although regional climatic implications of the Valders readvance are controversial (Wright, 1969), the presence of ice masses in the Lake Michigan basin and/or an ice block at the Wintergreen site would have caused cooler temperatures locally which might have favored an open, spruce-dominated forest. If the basin of Wintergreen Lake were ice-blocked for about 1000 years after deglaciation, pollen species in the early record may not reflect the initial, pioneering plant communities, but rather more well-established communities. Deciduous pollen types in upper Subzone 1A were likely not transported long distances (Craig 1972).

Subzone 1B (11435 - 10645 B.P.; 620 - 588 cm) was marked by the dominance of Picea (> 54%) and an Abies maximum (> 5%). These percentage data suggest spruce became well established around Wintergreen Lake at the expense of Cupressaceae species, Fraxinus, and, to a lesser extent, the herbaceous flora. Pollen influx values ranged from 5.8 to 8.3 x 10^3 grains cm^{-2} yr^{-1} near the lower limits of Subzone 1B. Spruce and sedge pollen contributed most to the total pollen influx, although Abies was well-represented. Compared with Subzone 1A, the decrease in total pollen influx in 1B may reflect only decreased abundance of heavy pollen producers, such as ash, in the area; the absolute number of spruce trees may not have changed significantly. With respect to species composition

and the lack of pine, the vegetation represented in Subzone 1B was characteristic of many late-glacial sites in this region. The lack of pine in our core prior to 10,000 B.P. supports the suggestion by Wright (1968b, 1971) that pine immigrated from full-glacial refugia east of the Great Lakes. Except for the lack of pine and the open character of surrounding forests suggested by the low pollen-influx rates, this assemblage is similar to spruce-boreal forests of today in northern latitudes (Birks 1973).

Spruce and NAP declined markedly in Zone 2 (10645 - 9350 B.P.; 588 - 534 cm), whereas maximum values of Pinus were found. The upper limit of this zone was placed where Pinus decreased to less than 38% and Quercus increased to 35%. Jack and/or red pine pollen dominated the lower two-thirds of the zone. White pine pollen did not appear until about 9800 B.P. (553 cm) and then comprised only about 50% of the total pine pollen. Total pollen influx in this zone ranged from 10.5 to 17.9 X 10^3 grains cm^{-2} yr^{-1} to the point where white pine appeared whereupon values increased (from 26.9 to 32.2 X 10^3 grains cm^{-2} yr^{-1}). These data suggest jack and/or red pine, and birch began to replace spruce in the vegetation about 11000 B.P. coincident with the retreat of Valders ice in the Michigan basin. Complete replacement of spruce by pine around Wintergreen Lake occurred about 10200 B.P. as was the case at other sites in the western and central Great Lakes region (cf. Ogden 1967, Wright 1971). Pine was a major component of the vegetation around Wintergreen Lake for about 1000 years. The influx of white pine in the middle of Zone 2 reflected immigration of pine into southwestern Michigan from the east, rather than from the south as suggested by Wright (1964, 1968b).

About 9,000 years of the postglacial period are represented in Zone 3 (9350 - 135 B.P.; 534 - 63 cm). This zone was characterized by mixed deciduous, hardwood pollen types, and is dominated by percentages of Quercus greater than 45%. Total pollen influx rates were relatively constant, ranging from 10.0 -

15.0×10^3 grains cm^{-2} yr^{-1}. Sedimentation rates in Zone 3 also were relatively constant, thus changes in percent composition of pollen types in Figure 4 reflect mostly changes in pollen influx rates. The patterns of vegetation change apparent in this zone appear to have been tied to changes in precipitation regimens; four subzones were identified in Zone 3 based on changes in percent composition of mesic versus xeric hardwoods, particularly Quercus and Fagus.

Subzone 3A (9350 - 7375 B.P.; 534 - 448 cm) was dominated by Quercus (> 60%), Ulmus, and herbs. Upper limits of this subzone were placed where Fagus increased to greater than 5% and Ulmus increased to 15%. Oak apparently succeeded pine in the vegetation as greater warmth and dryness caused pine to decrease. This succession may have been regional because it took place about the same time in northeastern Indiana (Williams 1974), and in northwestern Indiana (Bailey 1972 and unpubl. data). Oak and herbs such as ragweed may have occupied the more xeric sites in hilly, sandy areas while more mesic species such as elm may have occupied lowland areas. Pollen in the upper part of Subzone 3A reflected the establishment of more mesic species in the area about 8500 B.P. suggesting gradual development of a moister, regional climate.

The first appearance of Fagus, an increase in Ulmus, fewer Quercus and NAP pollen in the profile mark the beginning of Subzone 3B (7375 - 5760 B.P.; 448-373 cm). Pollen of mesic species, such as beech, suggest precipitation increased although immigration of beech from the east may have lagged behind that of other mesic species such as Acer, Platanus, Tilia, and Juglans (see Benninghoff 1964, Gilliam et al. 1967). First appearance of beech pollen in this subzone agrees with the appearance of beech pollen around 7400 B.P. in sediments collected elsewhere in the central Great Lakes region (Ogden 1966, 1969; Williams 1974). There was the additional correlation in our core between the appearance of beech and alternation between littoral and planktonic diatom assemblages in this subzone. These events support the hypothesis that water

levels in Wintergreen Lake likely fluctuated somewhat, perhaps as a function of precipitation patterns. Changes in the density of angiosperm seeds, leaves, and diatoms like those we found in Subzone 3B have been recorded at other sites in the western Great Lakes region during the hypsithermal period from 8000 to 4000 B.P. (Watts and Winter, 1966; Watts and Bright, 1968).

Fagus decreased markedly in Subzone 3C (5760 - 2200 B.P.; 373 - 183 cm). Highest percentages of Quercus (> 60%) and high values of NAP (> 10%), especially Ambrosia and Gramineae, characterized this subzone. The upper limit of this subzone was placed where Fagus increased to > 5%. Pollen in this subzone are more typical of the hypsithermal period of the central Great Lakes region from 5000 to 2500 B.P. This period apparently occurred later in Michigan than in Minnesota (Wright 1968a; Waddington 1969).

In Subzone 3D (2200 - 135 B.P.; 183 - 63 cm) precipitation likely increased for about 1000 years permitting mesic species to again colonize the landscape. Thereafter in this subzone, xeric species again replaced mesic species in the pollen record. In the lower portion of this subzone Fagus reached maximum values (> 22%) but subsequently decreased to values of 10% or less. Above 110 cm Carya, Quercus, and non-aboreal species replaced Fagus. From about 1600 B.P. to 135 B.P. the vegetation around Wintergreen Lake appears to have been relatively stable.

The most striking feature in uppermost Zone 4 (135 B.P. to the present; 63 - 0 cm) was the marked increase in NAP, notably Ambrosia and other European agricultural weeds, such as Plantago and Rumex. Pollen of Subzone 4A (135 - 44 B.P., 63 - 25 cm) reflect considerable nonselective, clear-cutting and burning of forest trees, a phenomenon well-documented in early land-survey and historical records (Durant 1880). Concomitant with deforestation pollen influx rates increased six-fold to 60 - 100 X 10^3 grains cm^{-2} yr^{-1}, compared with rates in the

next lower subzone. These high influx rates offer marked contrast also to influx rates in the upper 25 cm of non-compacted, flocculent sediments in Subzone 4B (5 - 20 X 10^3 grains cm^{-2} yr^{-1}). The markedly higher rates of sedimentation and pollen influx in this subzone after land clearance were likely caused in part by resuspension and transport of littoral sediments to the central depression (see Davis 1968; Kerfoot 1974).

During the past 44 years represented in Subzone 4B (44 - 0 B.P.; 25 - 0 cm) agriculture within the drainage basin of Wintergreen Lake decreased and efforts were made to stabilize soils eroding into the lake. Percentages of pollen from Ambrosia, Plantago, and Rumex decreased, whereas pollen from pine trees planted to stabilize the soil appeared in the pollen record. Percentages of other arboreal pollen types such as ash, oak, hickory and maple increased forming an assemblage not unlike that before land clearance in sediments below 63 cm.

DIATOM STRATIGRAPHY

A total of 133 diatom taxa were identified in the Wintergreen core. Diatom data were expressed as a plot of percentage occurrance of all taxa identified within any stratigraphic level (Fig. 5). For discussion, the succession of diatom assemblages was divided into three stratigraphic zones based on changes in per cent composition.

Fig. 5

Zone 1 (12265 - 6390 B.P.; 653 - 403 cm) was characterized by abundant Fragilaria construens and F. construens var. venter (> 35%) which indicated eutrophic, alkaline conditions. The few frustrules found below 653 cm may have been the result of abrasion caused by the high sand content in the sediments or little biological activity prior to 12,000 B.P. The upper boundary of this zone was defined by decreases in both varieties of F. construens to < 20% and increases in Cyclotella bodanica and Neidium spp. to 40% and 20%, respectively.

Several factors may explain the low diversity of planktonic diatoms in this zone. The most likely explanation is differential preservation due to long exposure time at the mud-water interface owing to low sedimentation rates (Haworth 1969; Bradbury and Megard 1972). Although diatoms in this zone represent a littoral community, both varieties of Fragilaria found here can be planktonic (R. Lowe, Pers. Comm.). It is also possible high transparency of the water column permitted a littoral diatom community to establish itself at greater than usual depths (Patrick 1943; Stockner and Armstrong 1971). The lower portion of this zone (653 - 608 cm) overlapped with pollen Zone 1 in which pollen of boreal terrestrial vegetation was found, and corresponds to diatom assemblages in several other studies (Round 1957; Sreenivasa and Duthie 1973). The upper portion of the zone (608 - 403 cm) correlated with pollen Zones 2 and 3A, during which time the climate began ameliorating about 11,000 B.P., as interpreted from the decline of spruce pollen.

Zone 2 (6390 - 135 B.P.; 403 - 63 cm) was characterized by alternating assemblages of littoral and planktonic diatoms representative of mesotrophic and alkaline conditions. Such an alteration of diatom communities appears to be strongly correlated with changes in basin depth (Round, 1961). The upper limit of this zone was marked by increases of F. construens and F. construens v. venter to greater than 50%. Four subassemblages are evident in Zone 2. The first, Subzone 2A (403 - 303 cm) was dominated by C. bodanica (> 20%), and corresponded to pollen Subzone 3B. High percentages of beech pollen in that subzone suggested precipitation may have been plentiful, perhaps increasing nutrient loading to the lake.

In Subzone 2B (4348 - 2787 B.P.; 303 - 218 cm) Cyclotella bodanica decreased to < 1% and Neidium vulpina increased to 33%. This assemblage represented a littoral diatom community corresponding, in geological time, to pollen subzone 3C, which suggests a dry, hypsithermal period prevailed in the central Great Lakes

region. Lower water levels during this period are suggested by the high numbers of littoral diatoms, macrophyte seeds, high amounts of herbaceous detritus, and high carbonate content in the sediments.

In Subzone 2C (218 - 183 cm) Cyclotella bodanica increased to 34% and Neidium vulpina and Neidium spp. decreased to less than 3.3% and 5%, respectively. The reappearance of this planktonic assemblage found in Subzone 2A suggested high water levels may again have prevailed. This planktonic assemblage corresponds in geological time to pollen Subzone 3C in which beech pollen increased, perhaps in response to increased precipitation.

Subzone 2D (2200 - 135 B.P.; 183 - 63 cm) is characterized by littoral diatom species similar to that in Subzone 2B. Cyclotella bodanica decreased to $<$ 20% while Neidium aurora, N. vulpina and Neidium spp. increased to 40%, 27%, and 37%, respectively. This assemblage corresponds to the upper portion of pollen Subzone 3D where hickory and oak replaced beech in the pollen profile, perhaps reflecting a second, less intense, dry interval.

Zone 3 (135 - 0 B.P.; 63 - 0 cm) was characterized by an abundance of Melosira, Stephanodiscus, Fragilaria, and Achnanthes species, all indicators of eutrophic and alkaline conditions. Two subzones were distinguished by variations in the percentages of littoral versus planktonic diatoms. Subzone 3A (63 - 38 cm) is a littoral, eutrophic assemblage dominated by two varieties of F. construens (79%). This assemblage corresponded to pollen Subzone 4A, marked by the beginning of land clearance around the Lake. The lack of planktonic diatoms in the sediments during this interval may be a consequence of increased turbidity in the lake caused by disturbances in the surrounding landscape. Land clearance often causes increased influxes of allochthonous materials. If turbidity were higher during this time period, the distribution of littoral diatoms and macrophytes would likely have been restricted to nearshore areas. Martin (1974) proposed this sequence to explain the absence of Najas seeds above

above 63 cm in our core. However, it appears more likely that biogenic turbidity caused by prolific growth of green and blue-green algae was of greater significance than allochthonous turbidity in reducing light penetration in the littoral zone and thus suppressing macrophytic growth (Wetzel 1975).

The diatom assemblage in Subzone 3B (38 - 0 cm) is unique in species composition in that both planktonic and littoral assemblages occurred. Melosira ambigua, M. islandica, Stephanodiscus astrea v. minulata, F. brevistriata, F. construens, F. construens v. venter, and Achnanthes linearis were most abundant. Several other diatom taxa appeared for the first time in this subzone at < 5%. This most recent subzone corresponds to pollen Subzone 4B, in which Ambrosia pollen decreased and aboreal species, such as pine and several hardwoods, increased. These changes reflect reduced agriculture and soil conservation practices in the Wintergreen drainage basin. As a result, turbidity in the lake likely decreased, encouraging the development of planktonic and littoral diatoms. The distinctly eutrophic character of the diatom assemblage in this subzone reflects high nutrient loading from migrant waterfowl established on Wintergreen Lake towards the beginning of this last subzone.

PERIODS OF TROPHIC DEVELOPMENT

The sandy, marly sediments of the Late-glacial Period (14075 - 10208 B.P.; 723 - 570 cm) likely eroded from till around, and first-growth forest atop, the depression formed by a buried, melting ice block (Florin & Wright 1969). Rapid sedimentation initially (Fig. 3) may have diluted pigment and nitrogen concentrations between 14075 and 12700 B.P. (Figs. 7,8). This dilution effect, discussed at length by Mackereth (1965, 1966), might be expected in a drainage basin recently laid waste by the retreat of a massive glacier. As pine was

Fig. 6

Fig. 7
Fig. 8

replaced by hardwoods, bicarbonate ions trapped by podsolization beneath the pine in soil horizon B (Oosting, 1956) was likely leached to the lake. Initial biological activity in the Wintergreen basin, reflected in the appearance of diatoms and slight increases in pigment, organic matter, and organic nitrogen concentrations, appears to have caused much of the incoming bicarbonate ions to precipitate as marl. Beginning about 10,600 B.P. the percentage carbonate in the sediments increased to the second highest value observed throughout the core (Fig. 6) coincident with this period of climatic amelioration. Between 11,435 and 10,208 B.P. production in Wintergreen Lake, reflected in the values of organic nitrogen and pigments, decreased and stablized at a low but constant rate characteristic of marl lakes (Wetzel 1970; Wetzel & Manny 1976). Low but stable productivity by plants in marl lakes is a consequence of inhibited photosynthesis caused by the limited availability of phosphorus, micronutrients, and organic constituents such as vitamin B_{12} which are scavanged from the water by precipitating monocarbonates (Wetzel 1972, 1975; Otsuki & Wetzel 1972, 1973; White & Wetzel 1975).

Period of Trophic Equilibrium (10208 - 5904 B.P.; 570 - 380 cm)

Between 570 and 550 cm the composition of the sediments changed from gray, marly material to brown, gelatinous, gyttja and the pollen assemblage from pine to oak dominance. During this same interval higher concentrations of pigments, organic matter, and organic nitrogen coincided with more rapid rates of carbonate deposition (Figs. 6-8). These changes were likely caused by warmer temperatures associated with final retreat of Valders ice from Michigan (complete by 9500 B.P., Wayne & Zumberge 1965). There is little doubt this climatic amelioration was widespread about 10,000 B.P. The high pigment concentrations at this time in our core correspond very closely in time with maximum concentrations of chlorophyll derivatives and total carotenoids found in pigment profiles of Pretty Lake, Indiana (Wetzel 1970) and Kirchner Marsh,

Minnesota (Sanger & Gorham 1972). Arguments advanced by Gorham & Sanger (1975) are convincing that these pigments originated from autochthonous productivity and not from terrestrial sources.

Beginning about 10,600 B.P., coincident with this period of climatic amelioration, the percentage carbonate in the sediments increased to the second highest value observed throughout the core (Fig. 6). Except for large plant fragments, organic matter in the sediments of this period was more completely oxidized than at any level higher in the core (Fig. 6). This finding suggests the frustrum morphometry and greater mean depth of the lake at this time (estimated maximum depth was 12 meters) caused 90 - 95% of the organic matter produced in the lake to be mineralized each year (Fig. 4 of Ohle 1956). Under these conditions only a very small hypolimnetic areal oxygen deficit would have occurred each year (Hutchinson 1938), hence the low organic matter content of the sediments below 550 cm during this period.

Between 9727 and 5900 B.P. (550 - 380 cm) the concentrations of all variables except carbonate content increased while sedimentation rates remained essentially constant (Table 1). These findings suggest productivity in the lake increased gradually as the climate warmed over the next 4000 years. During this time interval vegetation in the surrounding landscape, as reflected in the pollen data (Fig. 4), stabilized as deciduous forests. Contemporary forests comprised of many of the same species conserve nutrients well (Likens & Bormann 1974; Dillion & Kirchner 1975); therefore, nutrient loading rates to the lake were likely also stable and low. Conditions like these may explain why Wintergreen Lake remained in a state of relative trophic equilibrium (Hutchinson 1973) from about 9727 to 5900 B.P.

Littoral Macrophytic Period (5904 - 135 B.P.; 380 - 63 cm)

Prior to about 10,500 B.P. productivity in the lake probably was governed largely by temperature. After this time productivity probably came to be limited more by nutrient loading rates and light penetration than by temperature. As sediments accumulated in shallow portions of the basin, an increasing proportion of the basin would have become suitable habitat for the growth of rooted aquatic macrophytes. Colonization is governed primarily by the spectral composition and intensity of light which penetrates to the bottom. The quality and intensity of light are, in turn, governed by concentrations of dissolved organic matter and seston. Towards the end of the previous period, macrophytes likely colonized enough of the lake basin that their annual, areal productivity exceeded that of the phytoplankton. Shortly after this point in time, organic matter produced each year by the macrophytes and phytoplankton probably greatly exceeded that which could be decomposed in the hypolimnion. Between 380 and 365 cm seeds of littoral macrophytes were found in increasing numbers suggesting an increasing contribution to the annual productivity in the lake by these plants at the expense of the phytoplankton. Maximum depth in the central depression about the time was approximately 10.1 meters, judging from the point where seeds of aquatic macrophytes first appeared in our core (5590 B.P., 365 cm). After 5590 B.P., hypolimnetic anoxia likely became the rule for much of the year resulting in slower rates of decomposition and the accumulation of organic-rich sediments. Diatom records for this period showed alternating assemblages of littoral and planktonic species, suggesting water levels may have fluctuated in response to alternating moist and dry periods. Low water levels would likely have encouragedthe growth of aquatic macrophytes, resuspension of littoral sediments by wave action, and focusing of littoral sediments into the central depression. Maximum pigment concentrations of 380 SPDU chlorophyll derivatives and 1100 SPDU of carotenoids per gram of

organic matter, reached at about 1992 B.P. (170 cm; Fig. 7), support the hypothesis the dominate factor limiting productivity in Wintergreen Lake during this period was competition for light between macrophytes and phytoplankton, influenced to some degree by fluctuating water levels. High rates of annual productivity in excess of that which could be decomposed with reserves of dissolved oxygen in the hypolimnion resulted in black, peaty, gyttja between 320 and 63 cm and a marked acceleration in sedimentation rate beginning at about 2500 B.P. (202 cm; Fig. 3).

Period of Settlement (135 - 44 B.P.; 63 - 25 cm)

Settlement of the drainage basin, accompanied by rapid removal of the forests, was reflected in abrupt increases in pollen from open-field herbs (Fig. 4) and a 7-fold increase in sedimentation rate (Table 1). Sediments deposited during this interval were richer in carbonates and lower in concentrations of organic matter, pigments, and organic nitrogen than those of the previous two periods, and about equal to those of the late-glacial period (Figs. 6-8). The absence of clay and sand in this zone suggests incoming materials were largely in dissolved form, in effect, causing metabolism in the lake to again be inhibited by competition between plants and monocarbonates for phosphorus and necessary micronutrients. Increased turbidity and losses of phosphorus and bicarbonate are the usual consequences of forest clearance and the onset of farming (Hobbie & Likens 1973; Dillon & Kirchner 1975). During this period concentrations of phosphorus in the sediments increased and concentrations of pigments decreased in direct proportion to increases in carbonate content. These correlations indicate phosphorus coprecipitated with monocarbonates (Otsuki & Wetzel 1972) causing productivity in the lake to decrease somewhat. During settlement and development of the drainage basin then, acceleration of the eutrophication rate, initiated by macrophyte colonization in the previous period, was continued and increased further by nutrient loading as a result of deforestation.

Contemporary Period (44 - 0 B.P.; 25 - 0 cm)

In 1928 permanent waterfowl populations were established on the lake and soil conservation practices to stabilize eroding soils were begun. Coincident with these events carbonate content of the sediments decreased while concentrations of organic nitrogen, pigments, organic matter, and particularly phosphorus increased (Figs. 6-8). Diatoms in these surface sediments were dominated by a eutrophic assemblage including the indicator organisms of eutrophic conditions, *Melosira ambigua* and *M. islandica* (Hutchinson 1967, p. 387). Competition between macrophytes and phytoplankton for light continues to this day around the perimeter of the central depression but floating-leafed macrophytes (primarily *Nuphar*) dominate the annual productivity of Wintergreen Lake because they now occupy the water column over more than half the lake basin (Manny 1971).

DISCUSSION

The transitions from marly to more organic sediments at about 10,200 B.P. (570 cm) and from gray-brown gyttja to black, gelatinous gyttja containing high numbers of macrophyte seeds at about 4680 B.P. (320 cm) illustrate points in time when the trophic status of Wintergreen Lake changed rapidly. Both transitions in sediment composition are indicative of accelerated rates of eutrophication and are probably a consequence of the hybrid lake basin morphometry in which broad, shallow, littoral zones are contiguous with a deeper, ice-block depression. Because productivity per unit area in littoral regions is generally higher than in pelagic regions, this hybrid basin configuration has supported a spatial imbalance in areal productivity since inception of the lake. This imbalance underlies the sustained increases in eutrophication rate in Wintergreen Lake over geological time. If the ratio of surface area to mean depth in the basin were considerably smaller, Wintergreen would likely have remained a marl

lake until loading rates of nutrients and organic matter were markedly increased by deforestation and establishment of permanent waterfowl populations. Many lakes in the central Great Lakes region began as marl lakes and have remained so to the present time (Wetzel, 1970; Wetzel and Manny, 1976).

As interpreted, the sediment history of Wintergreen Lake provides an excellent example of eutrophication accelerated by increasing macrophyte productivity in littoral regions within the lake. Exceptions to this sequence might frequently be found in the sediment ontogeny of marl lakes on glacial till rich in carbonates, or large lakes possessing extensive marshland. Around such lakes, littoral plant communities frequently colonize the edges of incoming tributaries where they utilize nutrients entering the lake. If natural nutrient-loading rates are accelerated by man's activities in the drainage basin, the capacity of littoral plant communities to "trap" nutrients can be exceeded and the lake's evolutionary ontogeny altered (Wetzel 1975).

Nutrients contributed to Wintergreen Lake by waterfowl may be viewed as an acceleration of nutrient loading rates above that sustained at any previous time by the drainage basin. For example, between the time of land clearance and establishment of a permanent goose population, carbonate content increased 5-fold and organic matter, pigment content and organic nitrogen content each decreased 4-fold (Figs. 6-8). These trends reversed after soil conservation practices were instituted in 44 B.P., in part, because carbonate loading was not sustained. If the drainage basin were reforested and the waterfowl excluded, Wintergreen Lake would likely revert to a less productive state. Reversal of the lake's current progression towards extinction could be accomplished by removing enough littoral sediments to create depths beneath which macrophytic growth over most of the basin would be effectively retarded by shading effects of phytoplankton populations.

Eutrophication could be further retarded by aeration of the hypolimnion to ensure adequate dissolved oxygen to fully decompose organic matter produced each year in the lake. Without recourse to remedial measures, Wintergreen Lake will continue to fill at a rapid rate, providing further suitable habitat for submergent and emergent aquatic macrophytes. While it is difficult to speculate which direction the succession of aquatic plant communities will follow (Gates 1942; Daubenmire 1968), Wintergreen Lake will likely become filled with vegetation within about 1200 years.

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Table 1. Sedimentation rates based on sediment intervals throughout a 7.23 m core from Wintergreen Lake, Michigan. Dates were established by radiocarbon analyses, evidence of land clearance in 1837 reflected in the *Ambrosia* rise, and establishment of a resident Canadian goose population in 1928.

Depth Interval (cm)	Sedimentation Rate (cm yr^{-1})	Sedimentation Rate (yr cm^{-1})	Uncorrected Age (yr B.P.)	Corrected Age (yr B.P.)	^{14}C date number*	Sediment Type
0 - 25 (44 yr)	0.568	1.76				Unconsolidated floc
25 - 63 (91 yr)	0.418	2.39				Brown-black gyttja
63 - 196 (2190 yr)	0.061	16.47				Black, gelatinous gyttja
0 - 5			125±90	-	DAL-175A	Marl carbonate fraction
	0.084	11.93	135±95	10	DAL-175B	Flocculent org. gyttja
194 - 198			2450±135	2325	DAL-177	Black, gelatinous gyttja
	0.041	24.34				
229 - 238			3375±60	3250	WIS-668	Black, gelatinous gyttja
	0.062	16.10				
364 - 368			5500±175	5375	DAL-201	Black, gelatinous gyttja
	0.040	24.96				
499 - 508			8945±90	8820	WIS-670	Marly, organic gyttja
	0.043	23.38				
533 - 543			9740±600	9615	DAL-203	Marly, organic gyttja
	0.045	22.17				
609 - 618			11425±110	11300	WIS-672	Olive-gray marl-gyttja
	0.075	13.37				
649 - 653			11920±770	11795	DAL-205	Olive-gray marl-gyttja
	0.020	51.00				
674 - 678			13195±125	13070	WIS-676	Sandy, clay-marl

*DAL = Dalhousie University, WIS = University of Wisconsin

Figure Captions

Figure 1. Bathymetric map of Wintergreen Lake, Kalamazoo County, Michigan. Core location was at the point of maximum depth (6.3 m) in the central depression.

Figure 2. Rate of sedimentation in the central depression, Wintergreen Lake, with one standard deviation in years (bars at points). The curve of sedimentation rate was generated using a least squares regression equation $\hat{x} = ay^b$, where $\hat{x}$ = age, y = sediment depth, a = 1.9365, b = 1.3505 (J. G. Ogden, III, personal communication).

Figure 3. Rates of sediment accumulation for Wintergreen Lake transformed from observed measurements and calculated as sediment influx per unit of lake surface assuming frustum (F), hyperboloid (H), and sinusoid (S) shaped basin morphology (see text).

Figure 4. Stratigraphic pollen spectrum in a sediment core from the central depression, Wintergreen Lake, Michigan, showing changes in the terrestrial vegetation of the drainage basin.

Figure 5. Stratigraphic diatom spectrum of the primary core from the central depression of Wintergreen Lake, Michigan.

Figure 6. Stratigraphy of A: Moisture content; B: Organic matter; and C: Carbonates expressed as percentage by weight in a sediment core from the central depression, Wintergreen Lake, Michigan.

Figure 7. Concentrations of sedimentary pigment degradation products (SPDU) in a sediment core from Wintergreen Lake, Michigan. A: Chlorophyllous products per gram of dry sediment; B: Chlorophyllous products per gram of organic matter; C: Carotenoid products per gram of dry sediments; and D: Carotenoid products per gram of organic matter.

Figure 8. Stratigraphy of organic nitrogen and total phosphorus in a sediment core from the central depression in Wintergreen Lake, Michigan.

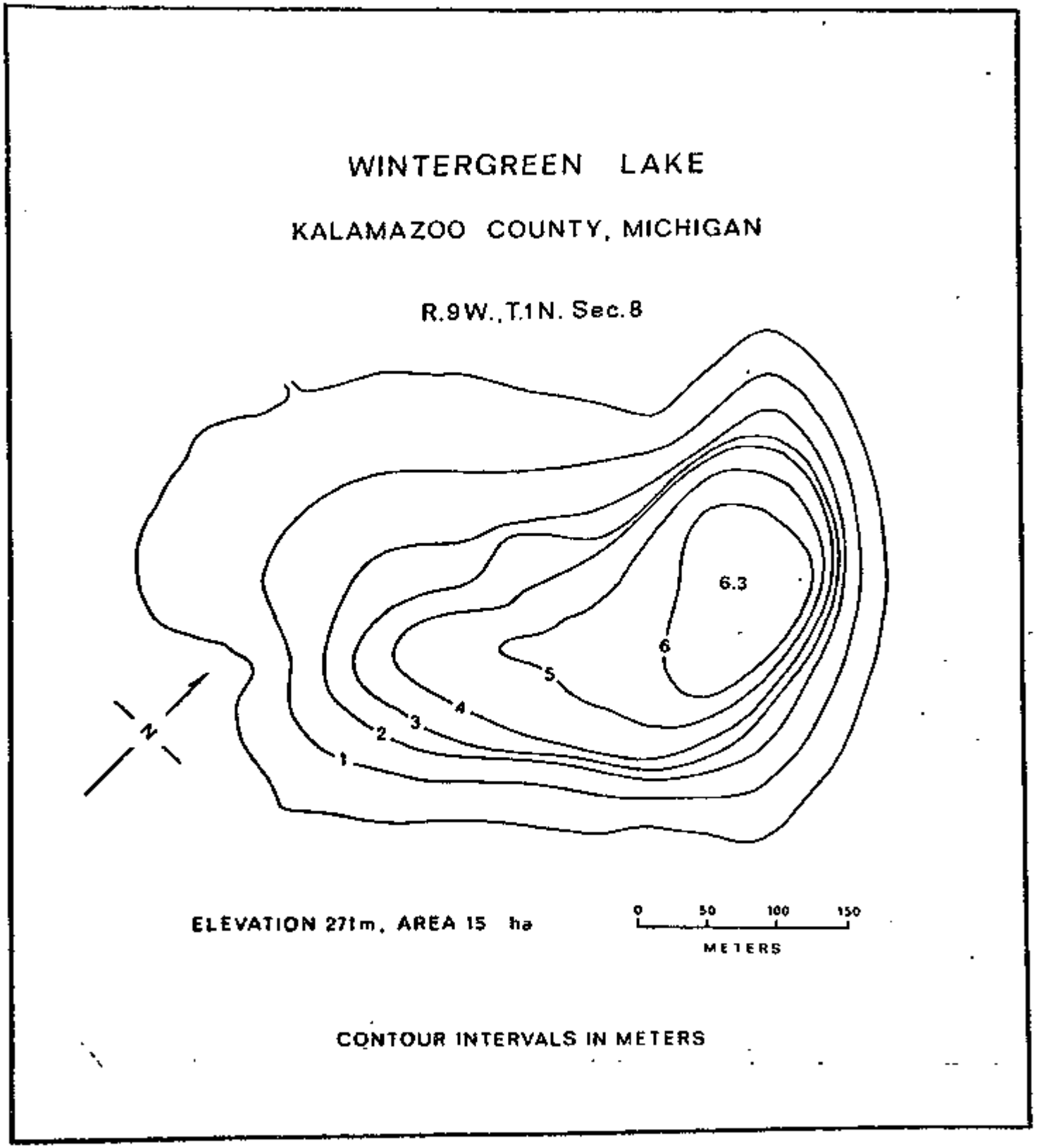

WINTERGREEN LAKE
KALAMAZOO COUNTY, MICHIGAN
R.9W., T.1N. Sec.8
6.3
6
5
4
3
2
1
N
ELEVATION 271m, AREA 15 ha
0 50 100 150
METERS
CONTOUR INTERVALS IN METERS

Figure 1.

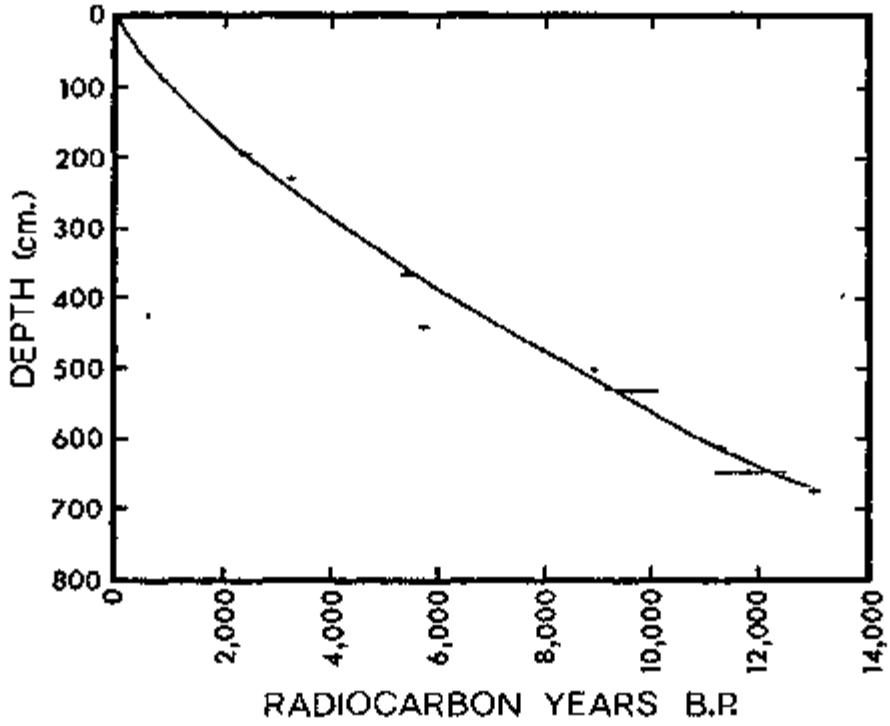

DEPTH (cm.)
0
100
200
300
400
500
600
700
800
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
RADIOCARBON YEARS B.P.

Figure 2.

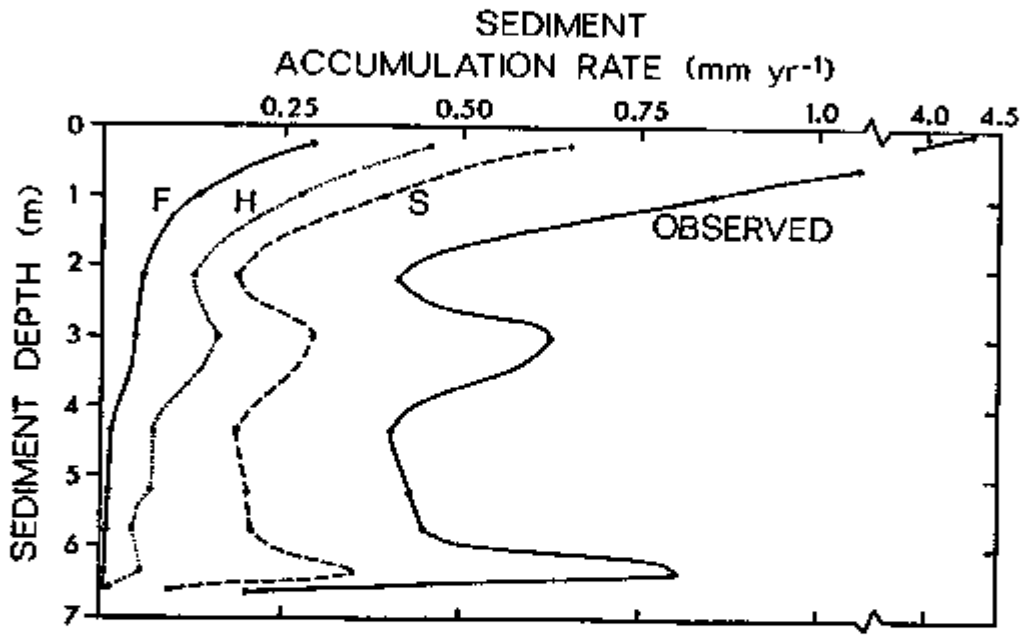
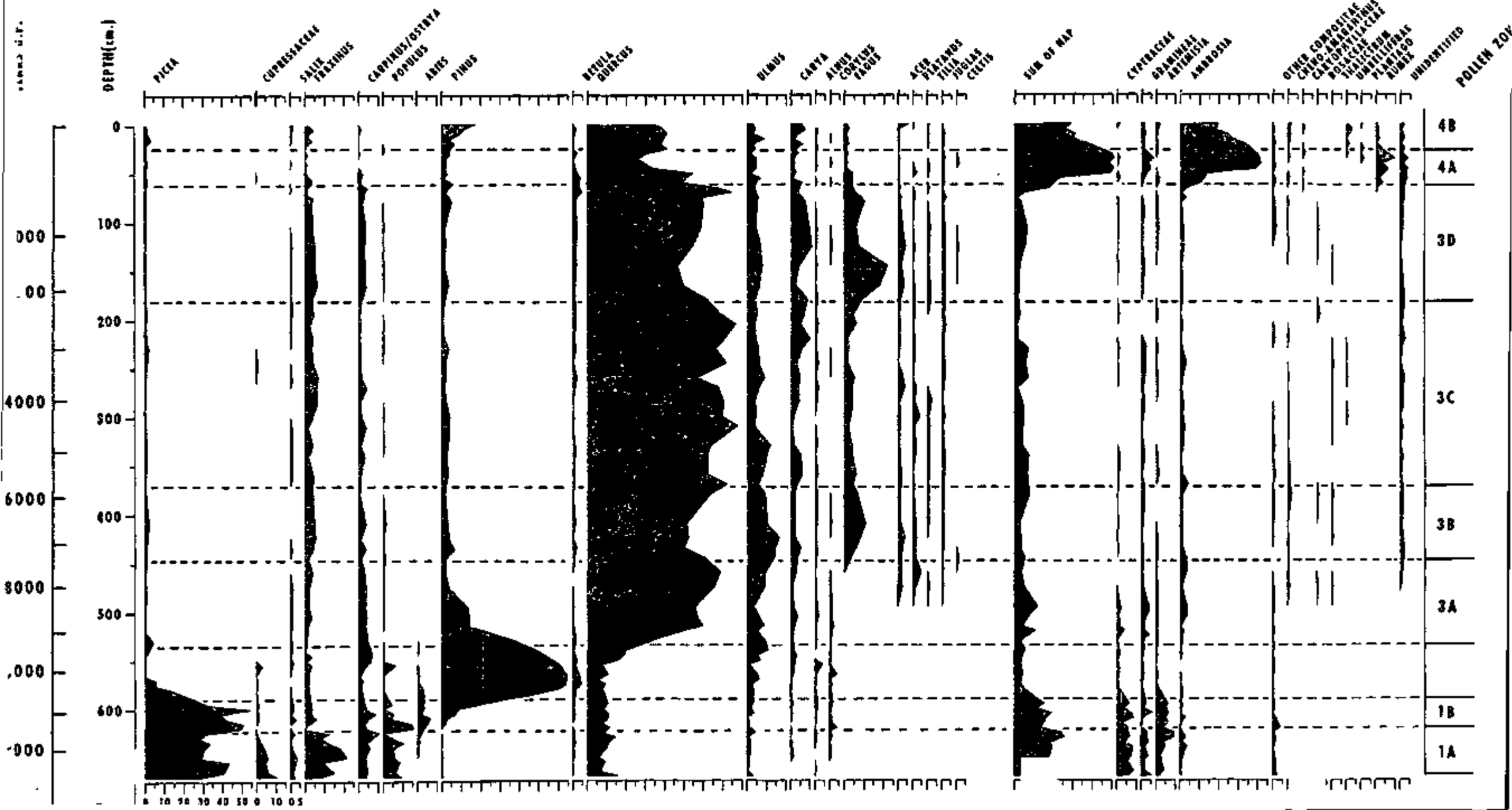

SEDIMENT
ACCUMULATION RATE (mm yr-1)
0.25
0.50
0.75
1.0
4.0
4.5
SEDIMENT DEPTH (m)
0
1
2
3
4
5
6
7
F
H
S
OBSERVED

Figure 3.

WINTERGREEN LAKE
KALAMAZOO COUNTY , MICHIGAN

PERCENTAGE POLLEN DIAGRAM



RADIOCARBON YEARS B.P.
STRATIGRAPHY
DEPTH (c.m.)
DIATOM ZONES
ACHNANTHES EXIGUA
CYMBELLA VENTRICOSA
FRAGILARIA BREVISTRIATA
FRAGILARIA CONSTRUENS f. VENTER
FRAGILARIA PINNATA
NAVICULA DISJUNCTA
AMPHORA OVALIS V. LIBYCA
CYCLOTELLA BODANICA
NAVICULA AURORA
NAVICULA LAEVISSIMA
NAVICULA ORONGA
NAVICULA VULPINA
MELOSIRA ISLANDICA
COCCONEIS PLACENTULA
STEPHANODISCUS ASTRAEA V. MINUTULA
POLLEN ZONES
GYTTJA
HERBACEOUS DETRITUS
SHELLS
MARL
SAND
CLAY
= 5%

Figure 5.

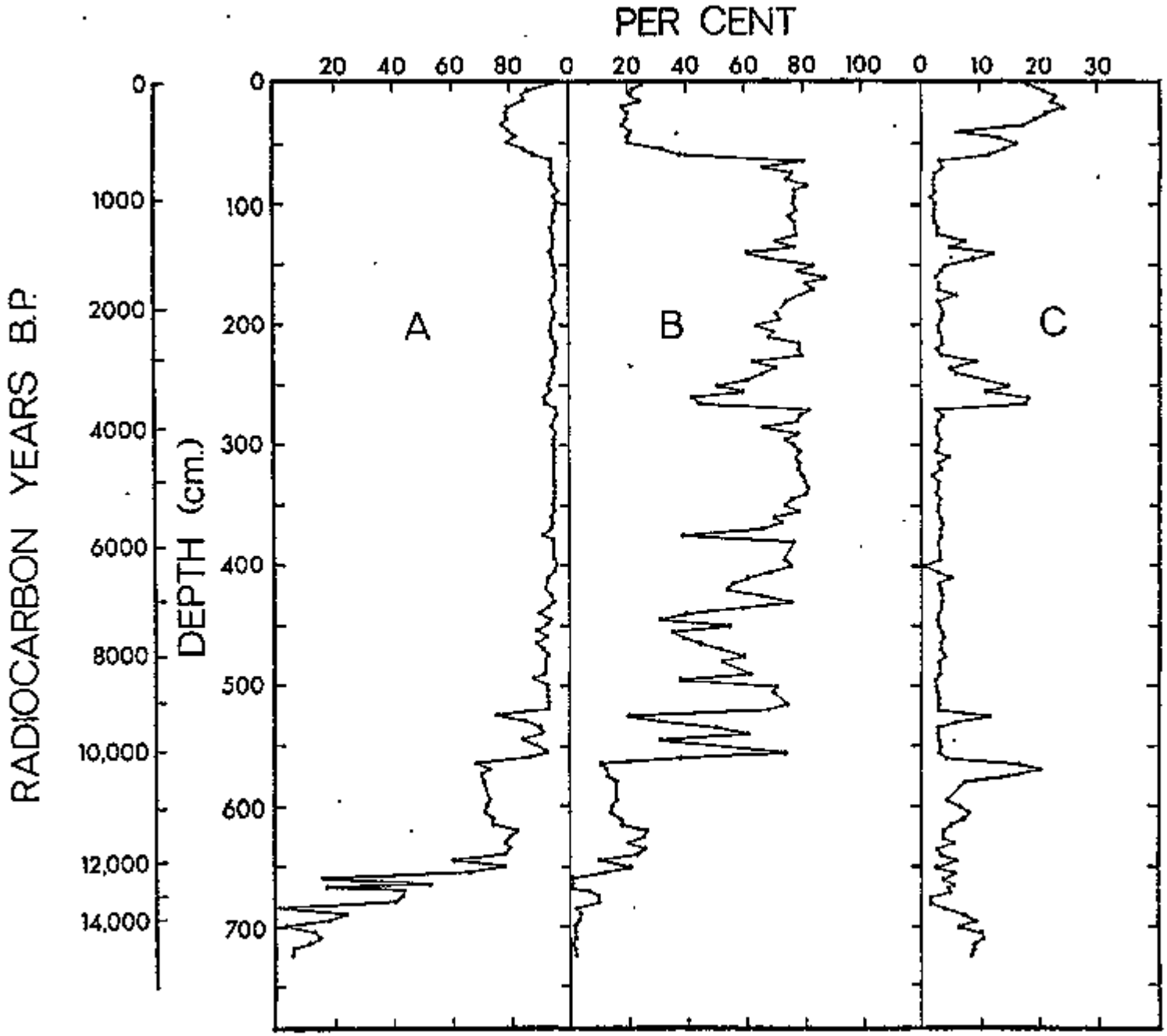

PER CENT
20 40 60 80
0 20 40 60 80 100
0 10 20 30
A
B
C
RADIOCARBON YEARS B.P.
0
1000
2000
4000
6000
8000
10,000
12,000
14,000
DEPTH (cm.)
0
100
200
300
400
500
600
700

Figure 6.

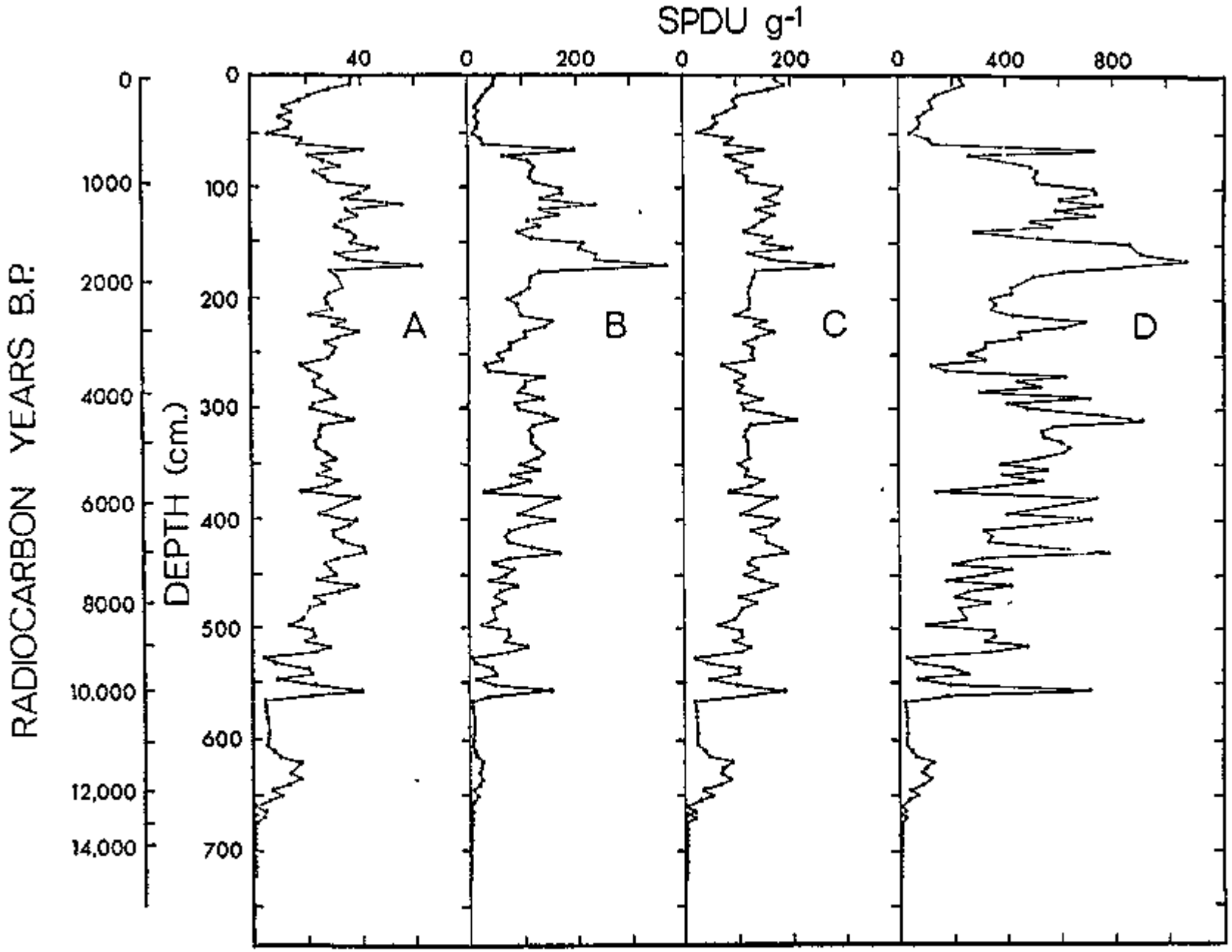

SPDU g-1
40
0
200
0
200
0
400
800
RADIOCARBON YEARS B.P.
0
1000
2000
4000
6000
8000
10,000
12,000
14,000
DEPTH (cm.)
0
100
200
300
400
500
600
700
A
B
C
D

Figure 7.

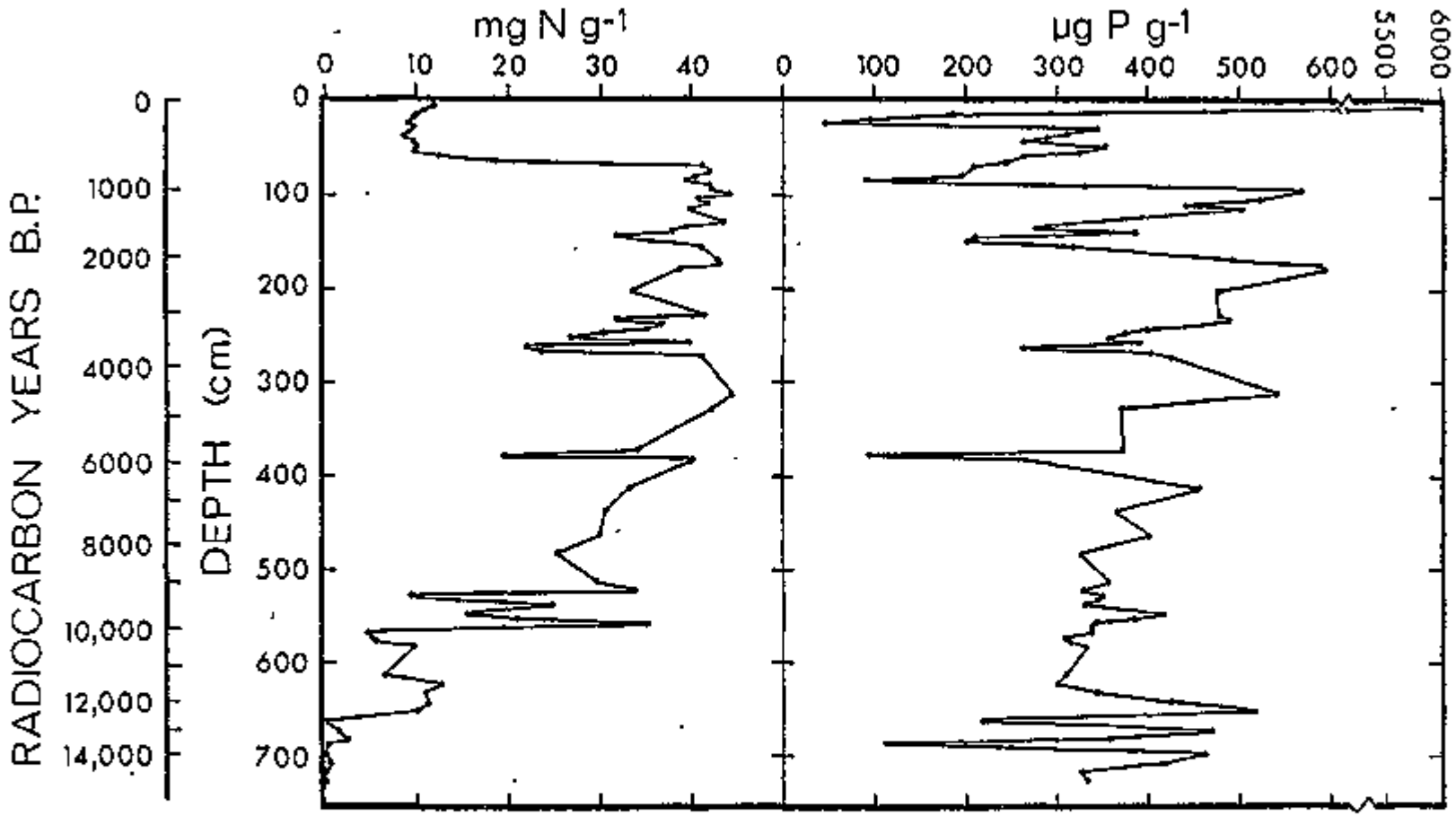

mg N g-1
0
10
20
30
40
µg P g-1
0
100
200
300
400
500
600
5500
6000
RADIOCARBON YEARS B.P.
0
1000
2000
4000
6000
8000
10,000
12,000
14,000
DEPTH (cm)
0
100
200
300
400
500
600
700

Figure 8.