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# Holocene and recent sediment accumulation rates in Southern Lake Michigan

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**Abstract**

Rates of sediment accumulation in Lake Michigan are a key component of its geologic history and provide important data related to societal concerns such as shoreline erosion and the fate of anthropogenic pollutants. Previous attempts to reconstruct Holocene rates of sediment accumulation in Lake Michigan, as well as in the other Laurentian Great Lakes, have been bedeviled by the effect of refractory terrestrial material on radiocarbon ages from total organic carbon samples of lake sediments. AMS radiocarbon ages on small samples of biogenic carbonate (ostracodes and mollusks) in Lake Michigan provide accurate Holocene ages. The present bicarbonate reservoir effect is estimated from shells of mollusks collected live before atmospheric nuclear testing to be 250 yr. From paired samples of biogenic carbonate and terrestrial macrofossils, the past reservoir effect is thought to be less than 500 yr. The radiocarbon ages indicate a distinct decrease in sediment accumulation rates throughout the southern basin of Lake Michigan at about 5 ka, about the time when lake level stabilized at the Nipissing level after rising rapidly for several thousand years. Average rates of sediment accumulation for the historic period (the last 150 yr) can be estimated from radioisotopes ($^{210}$Pb and $^{137}$Cs), pollen stratigraphy, and changes in sediment properties associated with human activity. Multiple methods are necessary because at any given site, problems arise in the assumptions or applicability of one or more methods. In general, the mass accumulation calculations suggest that sediments were deposited 4 to 11 times faster in the historic period than before human settlement. The character of the sediment did not change in a dramatic way, but sediment magnetic properties suggest shifts in the sources of sediment. The data suggest that some of the changes in sources and (or) character of the sediment occurred just before human settlement and were probably related to climatic changes associated with the Little Ice Age. Published by Elsevier Science Ltd.

## 1. Introduction

Rates of sediment accumulation in Lake Michigan are important for a variety of both academic and practical reasons. These sediments record a dramatic series of events associated with glacial, isostatic, and lake-level changes in the basin, beginning at least 14,000 yr ago (Hough, 1958; Wickam et al., 1978; Lineback et al., 1979, Colman et al., 1994). The basin is the primary repository of sediments eroded from beaches and nearshore bluffs, as well as those brought to the lake by rivers. Estimates of sediment volumes and ages can be used to construct sediment budgets for the basin (Colman and Foster, 1994). Finally, the lake sediments record the effects of human activities, both directly through incorporation of pollutants and other effluents (e.g. Edgington and Robbins, 1976; Cahill, 1981; Eadie and Robbins, 1987) and indirectly through changes in components such as pollen and diatoms (King et al., 1976; Stoermer and Yang, 1970; Schelske, 1985).

Despite the importance of sediment accumulation rates in Lake Michigan, relatively few reliable data exist, especially for the period prior to about 150 yr ago. The scarcity of data for long-term rates is largely due to difficulties with radiocarbon and other dating methods. For more recent times, $^{210}$Pb methods, historical records, and radioisotopes introduced by nuclear testing provide more abundant and reliable data.

Radiocarbon ages from sediments in all of the Laurentian Great Lakes have long been problematic. Because of the scarcity of other datable material, almost all ages have been derived from samples of total organic carbon. Typically, TOC ages are either significantly older than

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expected, or else show an erratic relation to depth in the sediments. Anomalously old ages in Lake Michigan have been attributed to terresterial detrital carbon that is older than the sediments in which it was deposited (King et al., 1976; Rea et al., 1980). This suggestion is in accord with the geochemistry of the organic carbon in the sediments in Lake Michigan (Meyers and Ishiwatari, 1993) that indicates a substantial terrestrial component. The magnitude of the difficulties are such that Mothersill and Brown (1982) declared that for stratigraphic sequences in the Great Lakes basin "$^{14}$C has not proved to be reliable for dating."

Prior to our study, few radiocarbon ages of any kind had been reported from sediments in Lake Michigan. A number of studies have reported individual ages from cores, mostly on total organic carbon (TOC), but in one case, on a fragment of wood (Lineback and Gross, 1972). Several TOC ages from a core in southern Lake Michigan indicated an age of about 2 ka for the sediment surface and about 7 ka from a depth of about 1 m (Gross et al., 1973). King et al. (1976) compared radiocarbon ages on TOC from two cores in southern Lake Michigan with ages based on pollen horizons, especially the dramatic increase in ragweed pollen at about 1840 AD. Their radiocarbon ages show a good linear trend with depth, but extrapolation of the trend to the sediment surface indicates apparent surface ages of 1.8 to 3.6 ka. Rea et al. (1980) also analyzed a core from southern Lake Michigan and obtained four radiocarbon ages on TOC. They made a correction for an apparent surface age of 1.86 ka and inferred a major decrease in sediment accumulation rate at about 3.3 ka.

The Great Lakes region has long been the focus of studies of the history of secular variation in the direction of the earth's magnetic field. In at least some cases, part of the motivation for paleomagnetic secular variation (PSV) studies has been their application to sediments of the Great Lakes, where radiocarbon dating has been problematic. Notable examples of studies that have attempted to develop curves of PSV with age for Lake Michigan or the larger Great lakes region include Creer et al. (1976), Vitorello and van der Voo (1977), Dodson et al. (1977), Kean and Klebold, 1981; Creer and Tucholka (1982), King et al. (1983), Johnson and Fields (1984), Mothersill (1984, 1988), Sprowl and Banerjee (1985), and Lund (1996).

A great deal of work has been done on the distribution of $^{210}$Pb and isotopes produced by atmospheric nuclear testing, such as $^{137}$Cs. Robbins and Edgington (1975) and Edgington and Robbins (1976) examined the detailed relationships between the distributions of $^{210}$Pb and $^{137}$Cs and sediment accumulation rates in Lake Michigan, and developed coherent age models. Although their data for prehistoric rates were limited, they concluded that modern sediment accumulation rates were not much different than average rates for the last 7000 yr. Hermanson and Christensen (1991) compared $^{210}$Pb distributions and sediment accumulation rates in various depositional environments in Lake Michigan and documented the effect of storms and sediment focusing in some locations.

In this paper, we attempt to provide reliable estimates of long-term (Holocene) sediment-accumulation rates in southern Lake Michigan and changes in these rates through time. We use accelerator mass spectrometry methods on discrete components of the sediments to overcome difficulties previously encountered in radiocarbon dating. We correlate paleomagnetic secular variation measurements to well-dated standards in order to provide additional support for the radiocarbon chronologies. Finally, we use $^{210}$Pb, $^{137}$Cs, pollen, and magnetic properties to estimate accumulation rates for the last 100–150 yr at the same sites as those for which long-term rates were derived.

## 2. Methods and data

In this study, we focus on three sites where cores were collected in 1988 and 1989 as part of a larger study of erosion and sedimentation in the Lake Michigan basin (Colman et al., 1994). Sites 4, 6, and 9 (Fig. 1), are in the eastern, central, and western part, respectively, of the southern basin of Lake Michigan. Multiple cores, including box cores (B), were taken at each site; a vibracore was

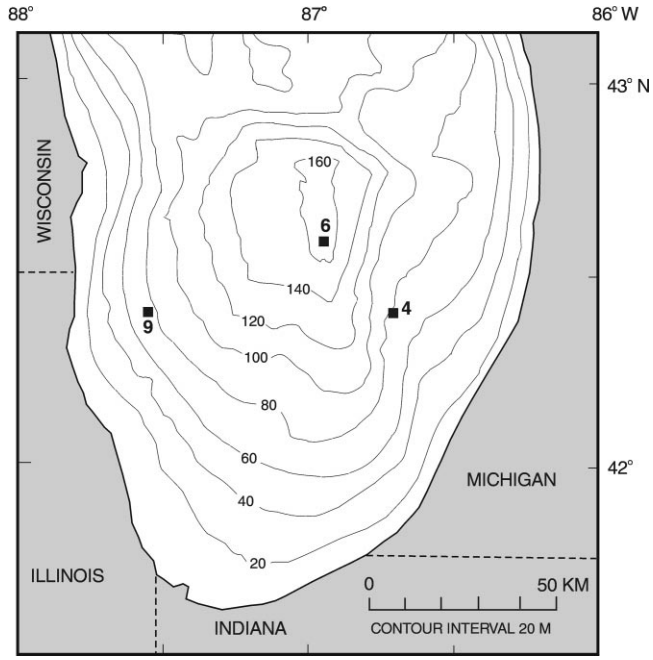


Fig. 1. Bathymetric map of southern Lake Michigan showing location of core sites. Latitudes and longitudes (degrees and minutes north and west) are: site 4, 42 24.05, 86 42.99; site 6, 42 35.51, 86 56.88; site 9, 42 23.80, 87 33.20.

collected at site 9 (V), whereas a gravity (G) and a piston core (P) were each collected at sites 4 and 6. Details of the coring methods and descriptions of the cored sediments are given in Colman and Foster (1990). Seismic-reflection data (Foster and Colman, 1991; Colman and Foster, 1994) indicate that Holocene sediments are relatively thick at the center of the basin (site 6) and thin on the western margin (site 9), but that the thickest Holocene accumulation in the basin is beneath the eastern margin (site 4).

We refer to the change in thickness of sediment per unit time as sediment accumulation rate (cm/yr) and the change in mass per unit time and area as mass accumulation rate ($g \cdot cm^{-2} \cdot yr^{-1}$). Sediment accumulation rates are calculated in two ways: (1) the age of a given horizon divided by its age, and (2) the inverse of the slope of a line fit to ages or time-dependent properties (e.g. $^{210}Pb$ concentrations) with depth. For the former method, the error of the rate is given if a quantitative estimate of the error in the age is known, otherwise, no error is given. For the second method, the error in the rate is calculated from the standard error of the estimate of the slope of the line.

### 2.1. Radiocarbon dating

Three fractions of the sediments were isolated for radiocarbon dating using accelerator-mass spectrometer (AMS) methods: (1) total organic carbon (TOC), (2) biogenic carbonate, and (3) macroscopic terrestrial organic matter. Ostracodes, mollusks, and macroscopic organic matter were separated from the sediment and processed by gentle disaggregation and sieving, according to the procedures detailed in Colman et al. (1990). Biogenic carbonate samples were obtained by hand-picking 5 to 10 mg of ostracodes and (or) small ($< 2$ mm diameter) mixed-species mollusk shells. Carbon dioxide was obtained by acidifying the shells with phosphoric acid in vacuo (Jones et al., 1989). Comparison of results from different taxa from the biogenic carbonate fraction of the same samples indicated no significant differences (Colman et al., 1990).

Total organic carbon in southern Lake Michigan sediments is typically 1–3% by weight (Meyers and Ishiwatari, 1993). For TOC $^{14}C$ samples, about 40 g of bulk sediment was acidified with organic-free HCl and filtered through a nominal 1 μm pre-cleaned quartz-fiber filter. The sediment and filter (or the hand-picked macroscopic organic matter) were added to reaction tubes along with 2 g of copper oxide and a 2 mm × 12 mm strip of silver foil. Reaction tubes were cleaned by soaking overnight in a chromerge solution, then roasted in air at 550°C for two hours. The tube was evacuated, flame sealed, and then heated in a muffle furnace at 550°C for 5 h.

Carbon dioxide from the carbonate, picked organic matter, or TOC samples was reduced to carbon monoxide over hot zinc and further reduced over hot iron to elemental graphite (Slota et al., 1987). The graphite targets were analyzed at the National Accelerator Facility at the University of Arizona. Results are reported in Table 1.

### 2.2. Paleomagnetic secular variation

Although construction of a high-precision paleomagnetic secular variation (PSV) record was not a primary goal of this study, paleomagnetic analyses were performed, primarily to provide additional age control. For the cores at sites 4 and 6, paleomagnetic directions were determined at 3 cm intervals from whole cores by using an automated, pass-through, superconducting magnetometer. For core 9V, paleomagnetic remanence was measured on individual samples taken in oriented 3.2 $cm^3$ plastic cubes using a spinner magnetometer. The data presented here were obtained following alternating-field (AF) demagnetization at 10 or 15 milliteslas (mT). These demagnetization levels were confirmed to be appropriate on the basis of paleomagnetic results from individually oriented samples that were subjected to detailed AF demagnetization, typically at eight peak-field steps from 2.5 to 60 mT, and that were analyzed by principal component analysis (Kirschvink, 1980).

### 2.3. Sediment-magnetic properties

These properties are commonly useful in interpreting a variety of paleoenvironmental conditions, including the effects of human activity on sedimentation in lakes (Thompson and Oldfield, 1986). We used a combination of magnetic and petrographic methods to determine the amounts, types, and origins of magnetic minerals. The magnetic properties measured on Lake Michigan sediments include magnetic susceptibility (MS; a measure of magnetic mineral content determined in a 0.1 mT induction at frequencies of 600 and 6000 Hz); isothermal remanent magnetization (IRM, acquired at 0.3 and 1.2 T, respective measures of ferrimagnetic mineral content and antiferromagnetic plus ferrimagnetic mineral content); and anhysteretic remanent magnetization (ARM, acquired in a DC bias induction of 0.1 mT, in an alternating induction of 100 mT). A measure of the content of high-coercivity ferric oxides minerals, such as hematite, is given by the HIRM parameter (IRM1.2T − IRM0.3T)/2. In these sediments, the ratio of IRM0.3T/IRM1.2T, the $S$ parameter, is a measure of the relative proportion of magnetite to all iron oxide, including hematite. High $S$ values (to a maximum value of 1) indicate large amounts of magnetite relative to hematite and decreasing values indicate increasing amounts of hematite. The ARM/MS ratio is a measure of magnetic grain size; in Lake Michigan sediments, higher values reflect a higher proportion of single-domain magnetite (about

Table 1
Radiocarbon ages

| Sample | Core[a] | Top (cm) | Bottom (cm) | Corrected depth[b] (cm) | Age[c] (Yr BP) | Corrected age[d] | Error (1 σ) | Material[e] | Lab no. | Comment |
|---|---|---|---|---|---|---|---|---|---|---|
| 4GBR-1 | 4G | 0 | 3 | 1.5 | 1400 | | 50 | TOC | AA-5902 | |
| 4PS16RB | 4G | 150 | 153 | 151.5 | 5540 | 5290 | 70 | CARB | AA-6870 | |
| 4PS16RA | 4G | 150 | 160 | 155.0 | 6870 | | 100 | POM | AA-6874 | 4PS16A,B,C |
| 4PS19R | 4G | 180 | 183 | 181.5 | 6520 | 6270 | 80 | CARB | AA-5448 | Bivalves |
| 4GBR-2 | 4G | 180 | 183 | 181.5 | 8030 | | 70 | TOC | AA-5903 | |
| 4PS21R | 4G | 200 | 203 | 201.5 | 6970 | 6720 | 70 | CARB | AA-5910 | Bivalves |
| 4PS23R | 4G | 220 | 223 | 221.5 | 7600 | 7350 | 80 | CARB | AA-5384 | Bivalves |
| 4PS25R | 4G | 240 | 243 | 241.5 | 8150 | 7900 | 70 | CARB | AA-5912 | Bivalves |
| 4PS27R | 4G | 258 | 261 | 259.5 | 8600 | 8350 | 80 | CARB | AA-5385 | Bivalves |
| 4GBR-3 | 4G | 258 | 261 | 259.5 | 10,980 | | 70 | TOC | AA-5904 | |
| 4PBR-1 | 4P | 150 | 153 | 261.5 | 10,150 | | 70 | TOC | AA-5905 | |
| 4PP1RA | 4P | 153 | 160 | 266.5 | 10,310 | | 100 | POM | AA-6875 | |
| 4PP1RB | 4P | 156 | 160 | 268.0 | 8840 | 8590 | 70 | CARB | AA-6868 | Bivalves |
| 4PP3 | 4P | 170 | 173 | 281.5 | 9160 | 8910 | 70 | CARB | AA-5897 | Bivalves |
| 4PP5 | 4P | 190 | 193 | 301.5 | 10,050 | 9800 | 70 | CARB | AA-5898 | Bivalves |
| 4PP10 | 4P | 240 | 243 | 351.5 | 10,480 | 10,230 | 70 | CARB | AA-5899 | Bivalves and gastrapods |
| 4PBR-2 | 4P | 240 | 243 | 351.5 | 15,410 | | 120 | TOC | AA-5894 | |
| 4PP14RB | 4P | 283 | 286 | 394.5 | 10,470 | 10,220 | 100 | CARB | AA-6869 | |
| 4PP14RA | 4P | 286 | 290 | 398.0 | 12,500 | | 120 | POM | AA-6879 | Picked OM |
| 4PP27RA | 4P | 410 | 420 | 525.0 | 18,540 | | 160 | POM | AA-6942 | Picked OM |
| 6B1A | 6P | 0 | 4 | 2.0 | 120 | | 60 | TOC | AA-5020 | |
| 6P12R | 6P | 110 | 113 | 146.5 | 7960 | 7710 | 120 | CARB | AA-6871 | Bivalves |
| 6P201A | 6P | 113 | 118 | 150.5 | 8140 | 7890 | 70 | CARB | AA-4986 | Ostracodes |
| 6P140R | 6P | 410 | 420 | 450.0 | 7550 | | 90 | POM | AA-6880 | Contaminated |
| 6P143R | 6P | 440 | 450 | 480.0 | 7960 | | 80 | POM | AA-6943 | Contaminated |
| 9B1A | 9B | 0 | 4 | 2.0 | 550 | | 60 | TOC | AA-4972 | |
| 9P1R | 9V | 0 | 3 | 16.5 | 2500 | | 80 | POM | AA-6945 | |
| 9P4R | 9V | 29 | 32 | 45.5 | 5360 | 5110 | 70 | CARB | AA-4612 | Bivalves |
| 9B2 | 9V | 29 | 32 | 45.5 | 5820 | | 60 | TOC | AA-5003 | |
| 9P7R | 9V | 59 | 62 | 75.5 | 6260 | 6010 | 80 | CARB | AA-4613 | Bivalves |
| 9P9R1 | 9V | 79 | 82 | 95.5 | 6920 | 6670 | 60 | CARB | AA-4977 | Bivalves |
| 9B3 | 9V | 79 | 82 | 95.5 | 7820 | | 80 | TOC | AA-5006 | |
| 9P11R | 9V | 99 | 102 | 115.5 | 7390 | 7140 | 80 | CARB | AA-4614 | Bivalves |
| 9P13R | 9V | 119 | 122 | 135.5 | 8290 | 8040 | 70 | CARB | AA-4978 | Bivalves |
| 9P15R | 9V | 139 | 142 | 155.5 | 9140 | 8890 | 90 | CARB | AA-4615 | Bivalves |
| 9B4 | 9V | 139 | 142 | 155.5 | 10,060 | | 90 | TOC | AA-5005 | |
| 9P18R | 9V | 169 | 172 | 185.5 | 9430 | 9180 | 80 | CARB | AA-4616 | Bivalves |
| 9P20R | 9V | 189 | 192 | 205.5 | 10,200 | 9950 | 70 | CARB | AA-4979 | Bivalves |
| 9B5 | 9V | 189 | 192 | 205.5 | 11,230 | | 90 | TOC | AA-4973 | |
| 9P32 | 9V | 209 | 218 | 228.5 | 12,400 | 12,150 | 80 | CARB | AA-5900 | Ostracodes and Bivalves |
| 9B6 | 9V | 209 | 218 | 228.5 | 17,960 | | 170 | TOC | AA-5004 | |
| 11R1B | 11G | 121 | 125 | 123.0 | 9230 | 8980 | 110 | CARB | AA-5011 | Ostracodes |
| 11R1E | 11G | 121 | 125 | 123.0 | 9110 | 8860 | 70 | CARB | AA-4985 | Bivalves |
| 11R1A | 11G | 121 | 125 | 123.0 | 9950 | | 80 | TOC | AA-5008 | |
| 13R1C | 13G | 195 | 195 | 195.0 | 8820 | | 80 | POM | AA-5027 | Well preserved wood |
| 13R1A | 13G | 193 | 197 | 195.0 | 9090 | | 90 | TOC | AA-5007 | Spruce needle; Wilmette bed |
| 20PW2 | 20P | 178 | 188 | 183.0 | 10,150 | | 100 | POM | AA-5895 | |
| 24GR-1B | 24G | 55 | 59 | 57.0 | 8520 | 8270 | 100 | CARB | AA-6950 | |
| 24GR-1A | 24G | 55 | 59 | 57.0 | 8120 | | 90 | POM | AA-6848 | |
| 24GR-3B | 24G | 182 | 186 | 184.0 | 9880 | 9630 | 90 | CARB | AA-6949 | Mollusks |
| 24GR-3A | 24G | 182 | 186 | 184.0 | 9190 | | 90 | POM | AA-6947 | |

[a]Core types: B, box; G, gravity; P, piston; V, vibracore. Details of core locations, quality, and descriptions are given in Colman and Foster (1990).
[b]Depths corrected for missing core tops: 9V, 15 cm; 6P 35 cm; 4P, 110 cm.
[c]Ages calculated using measured $\delta^{13}C$ values for carbonate and an assumed $-25‰$ for organic matter.
[d]Ages corrected for a reservoir effect of 250 yr (text and Rea and Colman, 1995).
[e]TOC, total organic carbon; POM, picked organic matter; CARB, organic carbonate (ostracodes, mollusks).
Note: All ages are in radiocarbon years, not calibrated to calender years. Ages from core sites 11, 13, 20, and 24 (locations given in Colman and Foster (1990)) are included here for completeness, but are not discussed in the text.

0.03–0.1 μm). Frequency-dependent magnetic susceptibility (FDMS; for our samples, the difference between MS at 600 Hz and that at 6000 Hz) indicates mainly the presence of ultrafine ( < 30 nm), superparamagnetic iron oxide (such as magnetite or maghemite) typically produced via pedogenesis.

### 2.4. Magnetic petrology

Magnetic minerals, separated from bulk sediment using a slurry-pump system (Petersen et al., 1986) and were mounted in epoxy, polished, and examined using reflected-light microscopy. For particles > 3 μm, we could identify minerals from optical properties and commonly recognize their origins on the basis of texture, whether derived originally from rock or produced via industrial combustion processes for electric power generation or manufacturing. Because the lake sediment is dominantly very fine-grained, silt-size clumps of bulk sediment, incorporating magnetic particles, were captured in the magnetic separates. Many such clumps also contained detrital fragments of organic matter. We did not try to distinguish among the many kinds of carbonaceous debris, such as different forms of charcoal (see Goldberg et al., 1981), but we could qualitatively estimate its overall abundance.

For this study, we examined magnetic minerals from core 4B in 3 cm intervals from the core top to 30 cm, and in thinner (about 1 cm) intervals centered at 15, 33, 35, 40, 50, and 60 cm depths. The petrographic observations assist the interpretation of magnetic property data and enable the recognition of the onset of industrialization and the period of intense coal burning in the region by the identification of spherical magnetic fly-ash particles produced by coal combustion. Industrially produced magnetic spherules have been previously reported from Lake Michigan sediments (Griffen and Goldberg, 1981; Locke and Bertine, 1986), along with data on the distribution of charcoal from various sources and elemental enrichment from urban and industrial effluent (Goldberg et al., 1981). Our petrographic observations, however, cannot resolve any of the generally much smaller particles associated with pedogenesis. The petrographic observations, along with detailed geochemical data, importantly show no evidence for magnetic effects of post-depositional alteration, caused either by magnetite dissolution or greigite ($Fe_3S_4$) authigenesis (Reynolds et al., 1991).

### 2.5. Radioisotopes

$^{210}$Pb and $^{137}$Cs activities were typically measured on 5–25 g of sediment. The samples were sealed in screw cap plastic jars for 30 d prior to counting to allow for the in-growth of $^{222}$Rn and $^{214}$Pb to approximate equilibrium values. The counting system consists of a germanium detector (2000 mm$^2$ area) for low-energy gamma rays and a 4096 channel analyzer. Samples were typically counted for 48 h. The system was calibrated using EPA standard pitchblende ore in the same geometry as samples. A self-absorption correction (Cutshall et al., 1983) was applied to each sample. Excess $^{210}$Pb was determined by the difference between total $^{210}$Pb and $^{214}$Pb. Excess $^{210}$Pb and $^{137}$Cs activities were decay corrected to the date of collection. Results of $^{210}$Pb and $^{214}$Pb analysis in the Canadian ore standard DH-1a were within two standard deviations (5.6%) of the accepted value.

Ages and sediment accumulation rates were estimated using both constant initial concentration (CIC) (Robbins and Edgington, 1975) and constant rate of supply (CRS) models (Appleby and Oldfield, 1978; Oldfield and Appleby, 1984). Differences in the assumptions and results from these two models are discussed in the section on historic sediment accumulation rates.

### 2.6. Pollen stratigraphy

Pollen is rather poorly preserved in the sediments of southern Lake Michigan (King et al., 1976), and in most of our cores, preservation was insufficient to define the level at which ragweed pollen, associated with human settlement, increased. However, significant amounts of ragweed pollen were observed in the upper 10 cm of core 4G (R.S. Thompson, U.S. Geological Survey, written commun., 1994).

### 2.7. Grain-size analyses

The sand fraction (wt%) was measured using standard sieving techniques. The silt and clay fractions were measured in 1-phi increments (phi = $-\log_2$ of size) using a multi-aperture model TA-2 Coulter counter.

## 3. Pre-historic sediment accumulation rates

Prehistoric sediment accumulation rates in Lake Michigan are determined primarily from radiocarbon ages (Table 1 and Fig. 2). Additional age information is provided by our paleomagnetic secular variation (PSV) data, which can be compared to dated standard PSV curves.

### 3.1. Radiocarbon analyses

Previously collected cores from southern Lake Michigan have yielded a series of $^{14}$C ages on TOC that are nearly linear with depth, but which project to surface ages of 1860 yr (Gross et al., 1973, King et al., 1976), 3630 yr (King et al., 1976), and 1870 yr (Rea et al., 1980). Our cores produced near-surface TOC ages of 1400 yr at

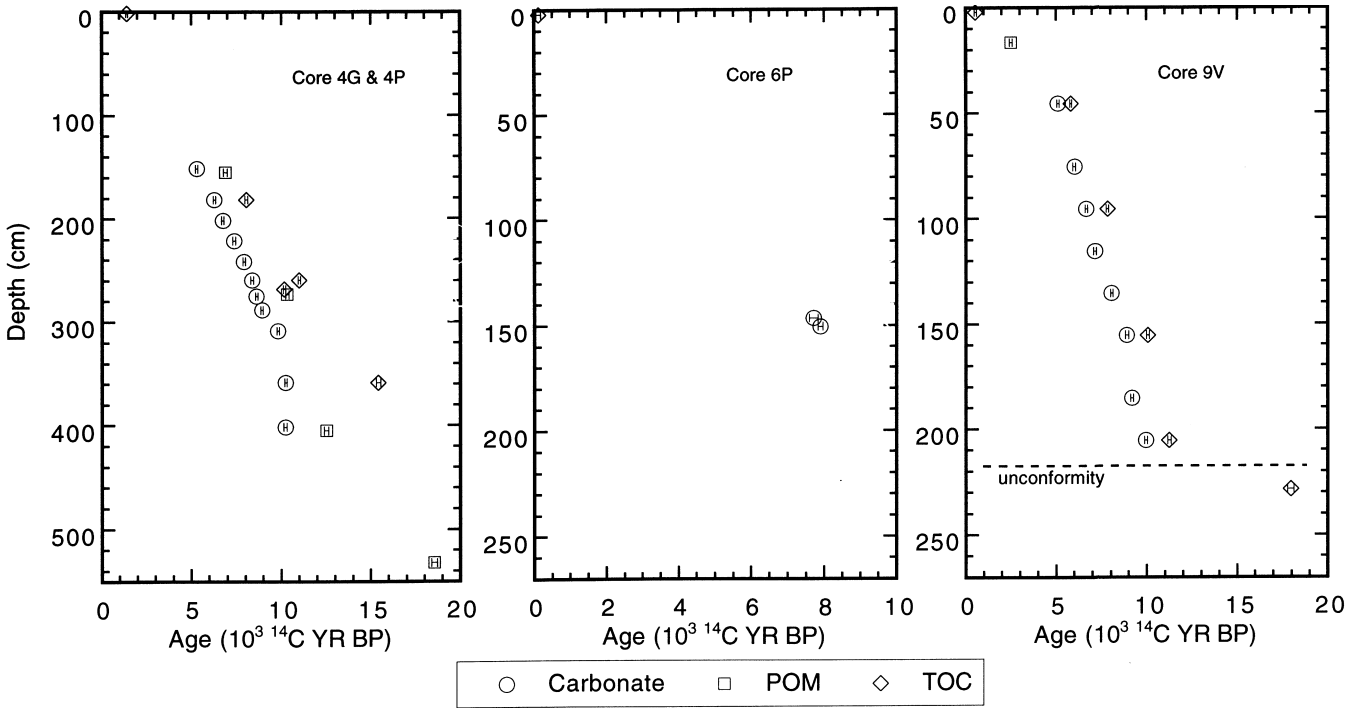


Fig. 2. AMS radiocarbon ages on samples of biogenic carbonate, total organic carbon (TOC), and picked organic matter (POM) from core sites 4, 6, and 9. Error bars (inside symbols) indicate 1 $\sigma$ errors in the $^{14}$C measurement.

site 4 (4GBR-1), 120 yr at site 6 (6B1A), and 550 yr at site 9 (9B1A) (Table 1). These three near-surface ages are minima because the samples may include radiocarbon from atmospheric nuclear testing.

AMS radiocarbon methods make it possible to date small samples of discrete organic matter, ostracodes, and mollusks from the sediments of Lake Michigan. We separated discrete pieces of organic matter from samples where possible. In some cases, this hand-picked organic material (POM in Table 1) consists of material such as wood fragments, conifer needles, and insect parts, but much of it was difficult to identify specifically.

Using the biogenic carbonate fraction of sediments (ostracodes and small mollusks in this case) avoids many of the problems associated with detrital organic carbon. The delicate shells are well preserved and unabraded, suggesting that redeposition is not a problem (Colman et al., 1990). Paired samples of ostracodes and mollusks and of different species of ostracodes yield indistinguishable ages (Table 1).

The main source of uncertainty in interpreting radiocarbon ages on biogenic carbonate is a potential reservoir ("hard-water") effect, caused by dissolved carbonate from sediments or bedrock, leading to disequilibrium between the $^{14}$C content of bicarbonate in the lake water and that in $CO_2$ in the atmosphere. For the modern lake, we have determined that the reservoir effect is about 250 yr, based on apparent ages of shells collected from living organisms in the lake before the advent of atmospheric nuclear testing (Rea and Colman, 1995). In the absence of other definitive information, we have applied a 250 yr correction to the biogenic carbonate ages in Table 1. The possibility that the reservoir effect may have changed with time is discussed later.

In all cases, the radiocarbon ages on biogenic carbonate yield monotonic curves of increasing age with depth, without any age reversals (Fig. 2). Also, the carbonate ages are always younger than ages derived from total organic carbon samples or from hand-picked organic matter (POM). Radiocarbon ages for the POM fraction were generally intermediate between TOC and biogenic carbonate (Fig. 2), but in some cases, the POM fraction yielded ages equivalent to those estimated from the biogenic carbonate fraction. Sufficient biogenic carbonate for dating exists in most cores for sediments older than about 5 ka. Unfortunately, shells are rare in the sediments less than about 5 ka, probably because of a change in the chemistry of the lake water (Forester et al., 1994).

### 3.2. Palemagnetic Secular Variation (PSV) comparison

Our coring and sampling methods were not optimized for obtaining PSV records, and our primary goal was not to produce a new reconstruction of the history of the regional magnetic field. Many problems with the records are evident, not the least of which is localized physical

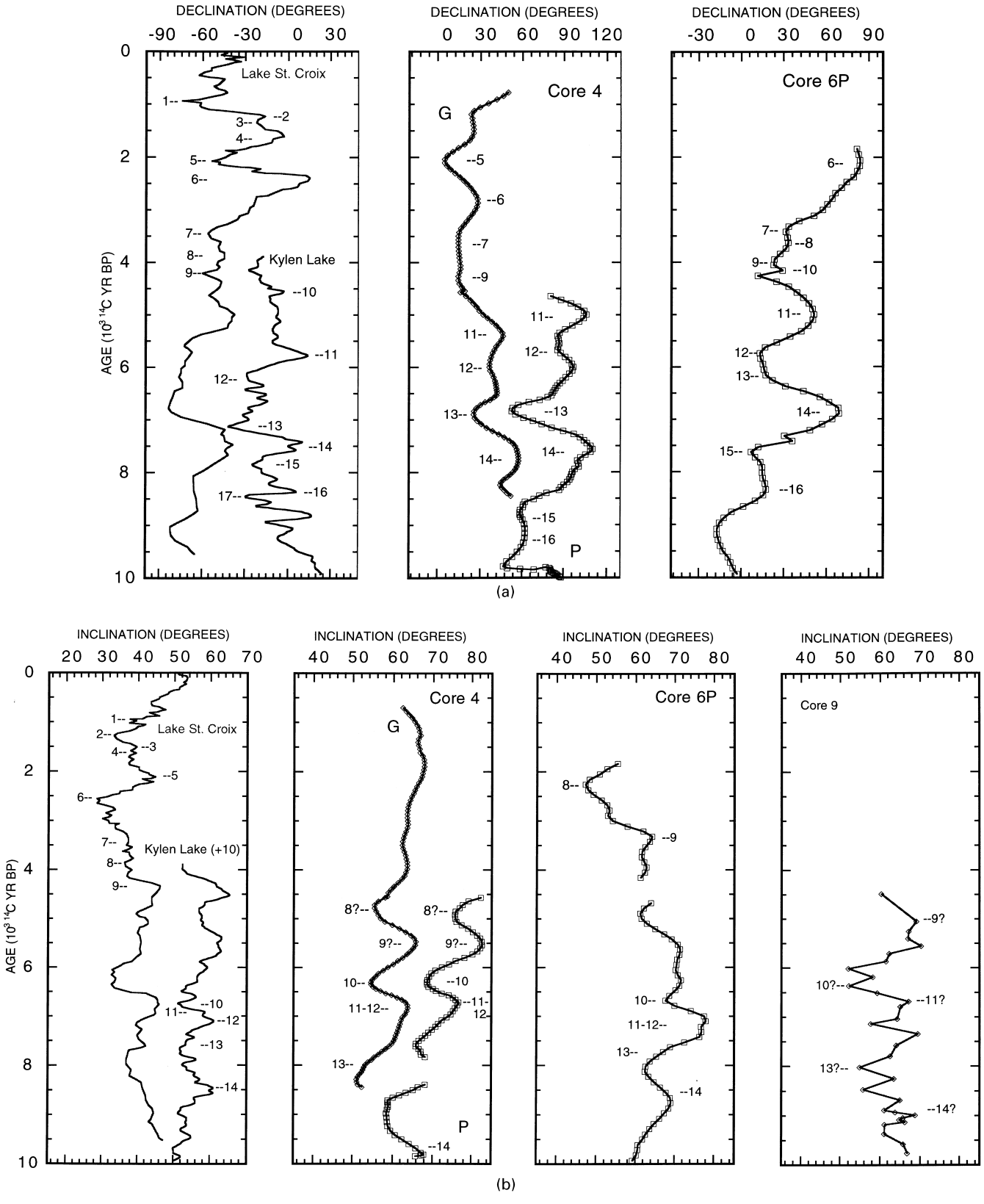


Fig. 3. Paleomagnetic secular variation (PSV) curves for Lake St. Croix and Kylen Lake (Lund, 1996) compared to those from Lake Michigan. A, declination (arbitrary north); B, inclination. Ages for Lake Michigan sites are derived from the biogenic carbonate $^{14}$C ages shown in Fig. 2 (see text). Numbered events (D, declination; I, inclination) are those defined by Lund (1996). "G" and "P" refer to gravity and piston cores, respectively, at the same sites. Because of relatively large sample spacing in core 9, the comparison with Lake St. Croix and Kylen Lake is considered tenuous.

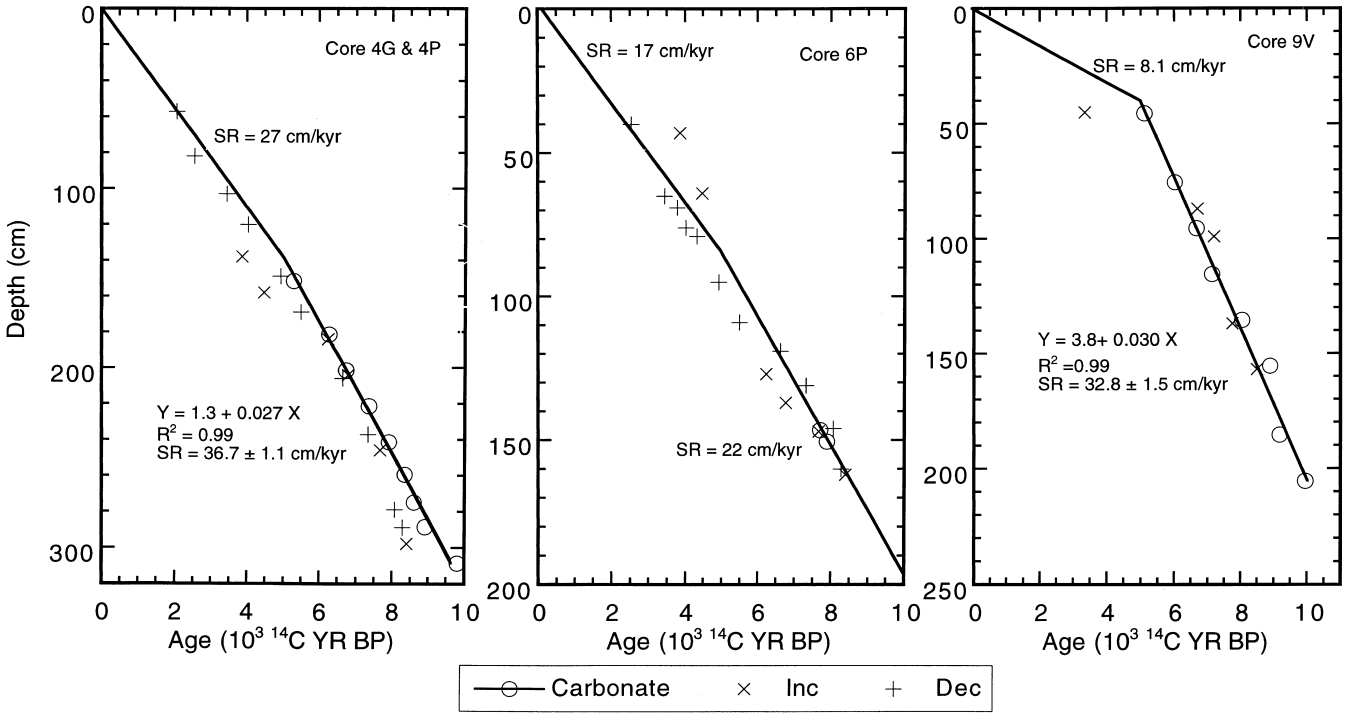


Fig. 4. AMS radiocarbon ages on biogenic carbonate and ages derived from matching PSV events (Inc, inclination; Dec, declination) in Fig. 3 to the Lake St. Croix-Kylen Lake PSV time scale. Regression lines from 5 to 10 ka are calculated for the biogenic carbonate $^{14}C$ ages; the equivalent line for site 6 (no error estimate on slope) is drawn through a deeper datum (not shown) and the two carbonate $^{14}C$ ages shown. Remainder of the lines are drawn through zero and the end of the regression line at 5 ka. Sedmentation rates (SR) are given for each line segment.

disturbance of the sediments. Nevertheless, some undisturbed sections of the cores produce PSV records that are useful for comparison with nearby high-quality, independently dated PSV records (Fig. 3A and B).

Many studies have attempted to develop curves of PSV with age for Lake Michigan and the surrounding region (Creer et al., 1976; Vitorello and van der Voo, 1977; Dodson et al., 1977; Creer and Tucholka, 1982; King et al., 1983; Johnson and Fields, 1984; Mothersill, 1984, 1988; Sprowl and Banerjee, 1985; Lund, 1996). From these studies, we selected the Lake St. Croix and Kylen Lake records of Lund (1996) for comparison, because of their apparent quality and the degree of focus they have received in the most recent review study (Lund, 1996).

We plotted the Lake St. Croix and Kylen Lake inclination and relative declination records on their own time scale, along with the corresponding records for core sites 4, 6, and 9 (Fig. 3A and B). The time scale for the Lake Michigan cores was obtained by linear interpolation between the corrected biogenic carbonate $^{14}C$ ages for each core (Table 1). The sediment surface (zero age) was used as an interpolation point, and in the case of core site 6, the average sediment accumulation rate was extrapolated beyond the depth of the oldest available $^{14}C$ age. We then attempted to match the PSV events identified by Lund (1996) in the St. Croix and Kylen Lake records with events in our records. In the case of core site 9, sample spacing was coarse, so only the inclination record was considered, and matches there are considered tenuous.

In matching features of our PSV records with those in the Lake St. Croix and Kylen Lake records, we assume that our radiocarbon ages are approximately, but not necessarily exactly, correct. As long as our ages are accurate within about 2500 yr, the approximate period of the major cycles of PSV variation (Lund, 1996), our procedure is valid. Once PSV features were matched, we obtained age control points for the associated depths in the Lake Michigan cores from the ages of the matched events in the Lake St. Croix and Kylen Lake records (Fig. 4).

When the ages obtained from correlations with the Lake St. Croix and Kylen Lake records are plotted with the radiocarbon ages on biogenic carbonate, the two data sets are mutually supportive (Fig. 4). In addition, the PSV-derived ages strongly suggest a linear connection between the youngest radiocarbon ages around 5 ka and the sediment surface (0 ka).

### 3.3. Summary

For the last 10,000 yr, the carbonate and PSV age estimates are consistent and form two nearly linear

trends with depth at each site. Sediment accumulation rates appear to change at about 5 ka, becoming slower for the last 5000 yr. For the period 5–10 ka, the data suggest sediment accumulation rates of 0.0367 ± 0.0011, 0.022, and 0.0328 ± 0.0015 cm/yr for core sites 4, 6, and 9, respectively (Table 2). For the period 0–5 ka, the rates are 0.027, 0.017, and 0.008 cm/yr, respectively.

## 4. Historic sediment accumulation rates

### 4.1. $^{210}$Pb and $^{137}$Cs

Analyses of the $^{210}$Pb and $^{137}$Cs inventories at our three core sites (Fig. 5) yield age information for the last 100–150 yr. Estimating ages from $^{210}$Pb profiles is complex and involves many assumptions and approximations,

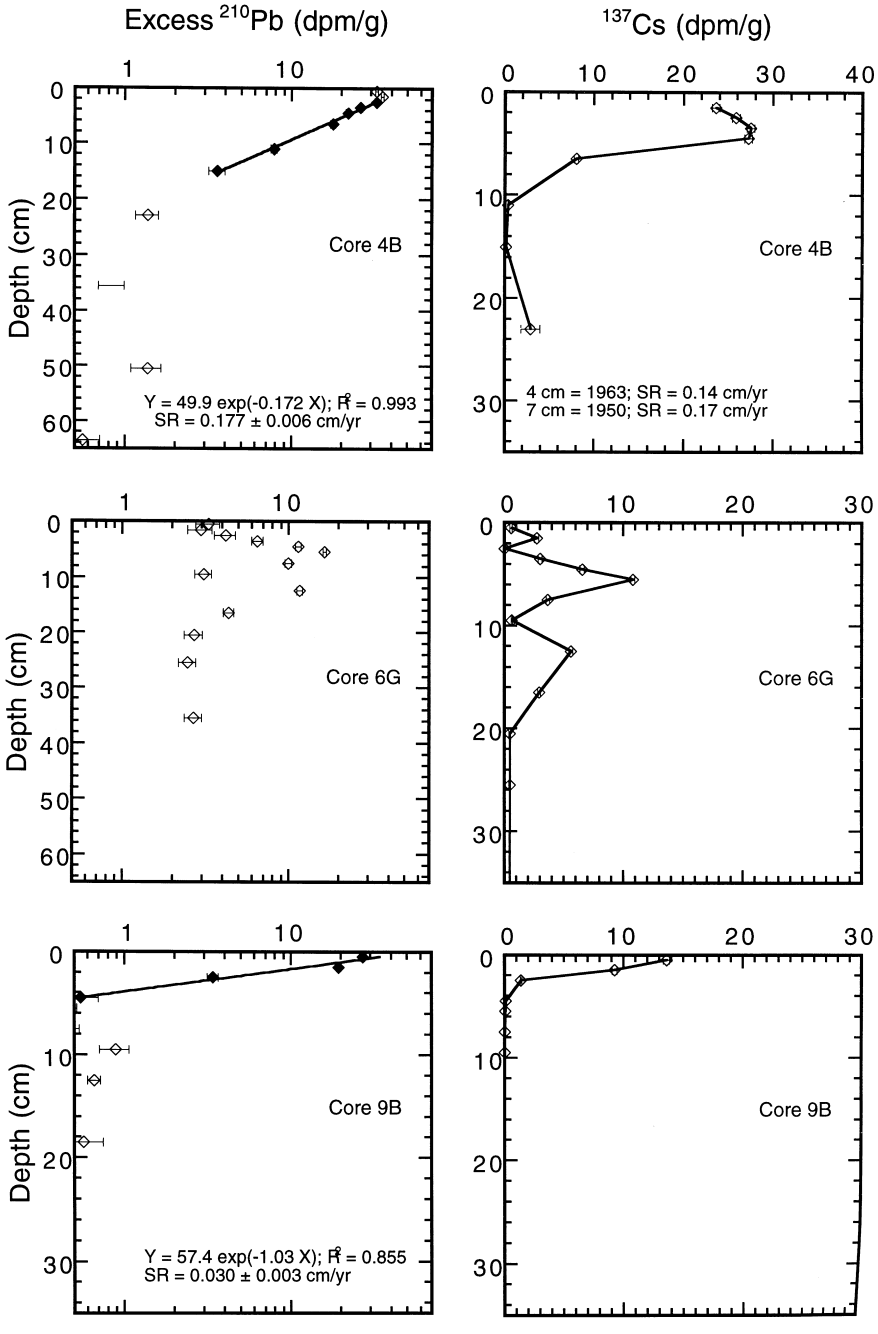


Fig. 5. $^{210}$Pb and $^{137}$Cs profiles with depth for cores at sites 4, 6, and 9. For cores where a regression of excess $^{210}$Pb against depth was calculated (4B and 9B), $Y$ is logarithm of $^{210}$Pb concentration and $X$ is depth; only points indicated by solid symbols were used in the regressions.

which are beyond the scope of this paper (reviews are provided by Robbins (1978) and Oldfield and Appleby (1984)). Two principle methods are in common use: (1) The Constant Initial Concentration (CIC) method, which assumes that the rate of mass accumulation and the concentration of unsupported $^{210}$Pb at the time of deposition are constant, and (2) the Constant Rate of Supply (CRS) method, which assumes that rate of supply of $^{210}$Pb is constant despite changes in mass accumulation rates and (or) initial $^{210}$Pb concentration. In their basic form, both methods assume no mixing.

Complexities in historic depositional processes in southern Lake Michigan include variations in sediment accumulation rates, local sediment focusing, storm events, surficial mixing, and uncertainty about the rate of supply of $^{210}$Pb. Because of these complexities, we use the $^{210}$Pb and $^{137}$Cs data to calculate only average sediment accumulation rates for the historic (post-1840) period, rather than exact ages of specific horizons. $^{210}$Pb profiles with segments that form exponential curves with depth suggest intervals with relatively constant sediment accumulation rates, which can be calculated using the CIC method. The CRS method yields specific ages for individual horizons, but given the uncertainties, we rely on the mean of the incremental sediment accumulation rates calculated between individual horizons.

The $^{210}$Pb profile for core 4B has the exponential shape associated with constant sediment accumulation over the last 100 + years, consistent with the CIC method (Fig. 5). The upper two cm of the profile deviate from this trend, which could be interpreted as due to either physical mixing or a very recent acceleration in deposition. Given the apparently constant rate of deposition for the rest of the profile, we interpret the upper 2 cm as a mixed zone. This interpretation is consistent with that of Robbins and Edgington (1975) who calculated mixed zone depths of 1–4 cm for several cores in southern Lake Michigan. Excluding the values for the upper 2 cm and those below 30 cm depth (see Methods), the slope of the regression line through the data (Fig. 5) can be used to calculate a sediment accumulation rate of $0.177 \pm 0.006$ cm/yr using the CIC method. Using the CRS method for all the data, and ignoring the possible effect of a mixed surface layer, results in an average accumulation rate of $0.226 \pm 0.048$ cm/yr. However, because the average rate calculated by the CIC method (0.177 cm/yr) is less susceptible to uncertainties at both the shallow and deep extremes of the profile, we consider this estimate more reliable.

Contribution of $^{137}$Cs to lake sediments began with atmospheric testing of nuclear weapons. Detectable amounts began to accumulate in sediments in about 1950, and the peak flux occurred in 1963. In the $^{137}$Cs profile for core 4B (Fig. 5), the initial rise in activity occurs between 7 and 11 cm, and the peak value is at 4 cm. Ignoring the effects of mixing, the upper horizon yields a sediment accumulation rate of 0.14 cm/yr (29 yr at 4 cm). The depth for the 1950 horizon that is most consistent with the post-1963 accumulation rate is 7 cm, which yields a post-1950 accumulation rate of 0.17 cm/yr.

The $^{210}$Pb and $^{137}$Cs profiles for core 6G are generally consistent with each other, but highly irregular with depth (Fig. 5), making detailed age estimates impossible. Possible causes for the erratic behavior include mixing of the sediments by storms or disturbance during core recovery. Using the total inventory of $^{210}$Pb in the profile, the CRS method yields an age of 81 yr for a depth of 17 cm, and an average sediment accumulation rate of 0.21 cm/yr, but these estimates are considered highly uncertain.

Almost all of the unsupported $^{210}$Pb in core 9B is in the upper 5 cm (Fig. 5), suggesting very slow rates of sediment accumulation. Both the CIC and CRS methods applied to the upper 5 cm of the profile yield average sediment accumulation rates of 0.03 cm/yr ($\pm 0.003$, CIC; $\pm 0.013$, CRC). This is consistent with the occurrence of significant $^{137}$Cs only in the upper 3 cm of the core (Fig. 5).

### 4.2. Pollen

Widespread forest clearance around the southern Lake Michigan basin was underway by 1840 AD, and this date is assigned to the abrupt increase in *Ambrosia* (ragweed) pollen associated with land clearance (King et al., 1976). This date and the *Ambrosia* rise are convenient datums for the beginning of "historic" sedimentation in the Great Lakes. The increase in *Ambrosia* pollen in cores has been used to systematically estimate average rates of sediment accumulation in all of the Great Lakes (e.g. Kemp and Harper, 1977) except Lake Michigan. Unfortunately, because of particularly poor preservation of pollen in Lake Michigan, such sediment-accumulation-rate estimates are difficult (King et al., 1976). In our cores, significant amounts of *Ambrosia* pollen were observed only at site 4, where it first appears at a depth of about 10 cm in core 4G (R.S. Thompson, US Geological Survey, written commun., 1994). If this increase in ragweed represents the initiation of widespread land clearance in about 1840, as it does in other lakes in the region, the indicated average sediment accumulation rate is 0.067 cm/yr. This rate is somewhat low compared to the rate indicated by other methods (Table 2). However, the poor preservation of pollen in these samples makes derived sediment accumulation rates very tenuous.

### 4.3. Magnetic properties

The magnetic properties of sediments in core 4B show significant changes in the upper part of the core (Fig. 7). At about 34 cm, the ARM/MS ratio increases strongly upward as IRM begins to increase slightly; these changes

Table 2
Comparisons of estimates of rates of sediment accumulation for different periods in southern Lake Michigan

| Parameter/site | Historic (0–150 BP) | Late Holocene (0—5 ka) | Early Holocene (5—10 ka) |
|---|---|---|---|
| Accumulation rate (cm/yr)[b] | | | |
| Site 4 | ($^{210}$Pb): 0.177 $\pm$ 0.006<br>($^{137}$Cs): 0.14–0.17<br>Magn.: 0.15 | 0.027 | 0.0367 $\pm$ 0.0011 |
| Site 6 | ($^{210}$Pb): 0.21[c] | 0.017 | 0.022 |
| Site 9 | ($^{210}$Pb): 0.030 $\pm$ 0.003 | 0.008 | 0.0328 $\pm$ 0.0015 |
| Ave. dry bulk density[a] (g/cm$^3$) | | | |
| Site 4 | 0.470 | 0.655 | 0.846 |
| Site 6 | 0.310 | 0.373 | 0.373 |
| Site 9 | 0.630 | 0.563 | 0.799 |
| Accumulation rate ($g \cdot cm^{-2} \cdot yr^{-1}$) | | | |
| Site 4 | 0.071 | 0.017 | 0.031 |
| Site 6 | 0.065 | 0.006 | 0.008 |
| Site 9 | 0.019 | 0.005 | 0.026 |

[a]Based on data from Colman and Foster (1990).
[b]Standard errors shown where applicable; see text for abbreviations and discussion.
[c]Tenuous, based on total $^{210}$Pb inventory.

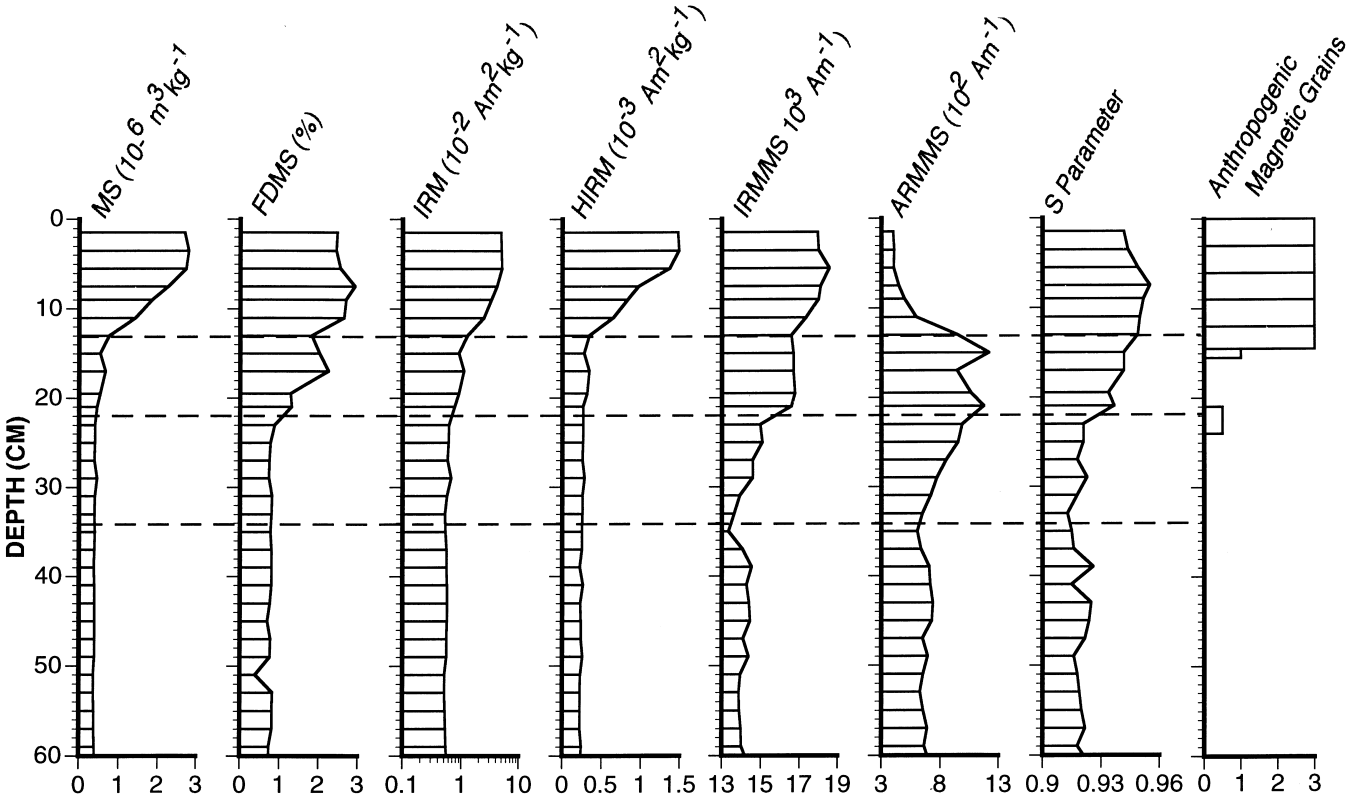


Fig. 6. Selected magnetic properties plotted against depth for core 4B. MS, magnetic susceptibility; FDMS, frequency-dependant magnetic susceptibility; IRM, isothermal remanent magnetization; HIRM high-field remanent magnetization; ARM, anhysteric remanent magnetization; S parameter, ratio of two IRM measurements. See text for definitions of these parameters and measurements. Also shown is a plot of the relative abundance (scale: 0, absent; 0.5, trace; 1, rare; 3, abundant) of anthropogenic magnetic grains. Dashed lines indicate horizons discussed in the text.

signal substantial input of single-domain magnetite (see Thompson and Oldfield, 1986; Mullins, 1977) along with a slight overall increase in magnetite. Moreover, carbonaceous debris within sediment clumps in the magnetic mineral separates also appears to increase above the 34 cm depth. The changes are not accompanied by observable differences in magnetic minerals.

At about 22 cm, magnetite content (IRM) increases, magnetic grain size shows a reversal in its fining trend (ARM/MS decreases), and the proportion of magnetite to hematite jumps abruptly (*S* parameter increases) (Fig. 6). These changes correspond to the first (trace) appearance of magnetic fly-ash spherules, probably related to initial coal combustion, perhaps distant from Lake Michigan.

The most dramatic shifts in magnetic properties occur at 13 cm, the depth above which fly-ash magnetite with associated hematite becomes especially abundant, approaching approximately half of the separated magnetic particles. Contents of magnetite (IRM and MS), hematite (HIRM), and ultrafine magnetite or maghemite (FDMS) increase greatly, whereas magnetic grain size continues to coarsen (ARM/MS decreases). The close correspondence of ultrafine, superparamagnetic magnetite (indicated by high FDMS values) with larger ( > 30 nm), ferrimagnetic magnetite (high IRM values) is probably not related to high FDMS of fly-ash magnetite (Reynolds et al., 1998).

### 4.4. Other sediment properties

Compared to the changes in magnetic properties in the uppermost part of the sediments the overall texture of the historic sediments appears to change little from the sediments that precede them (Fig. 7). No obvious changes in grain size occur in the upper 60 cm of core 4G or 6B, except that the sand content of the upper 20 cm of core 4G is slightly higher than below, and the average grain size of the sediments in core 6B increases slightly (lower phi values) toward the top (Fig. 7). At core site 9, the sandy top of the core and the coarsening upward of the average grain size probably are related to sediment accumulation rates that are so slow that the upper 50 cm (deposited over the last 5000 yr) has been winnowed.

The historic sediments are more water-rich than older sediments (Colman and Foster, 1990), but this contrast may be due to normal changes resulting from compaction. The less compacted and less dense sediment in the upper part of the cores partly masks a change in mass accumulation rate at about 5 ka. When considered as

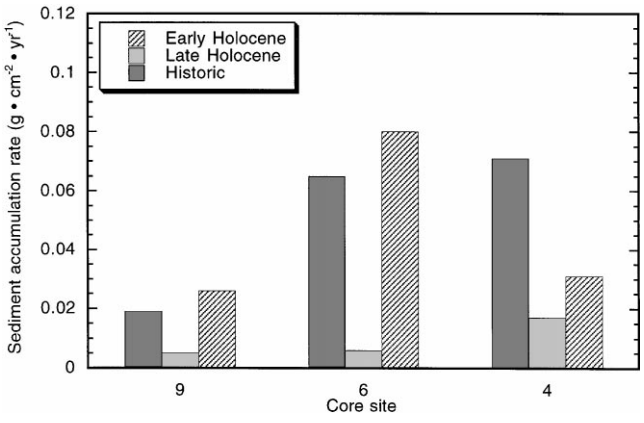


Fig. 8. Comparison of sediment mass accumulation rates for different time intervals. Data from Table 2.

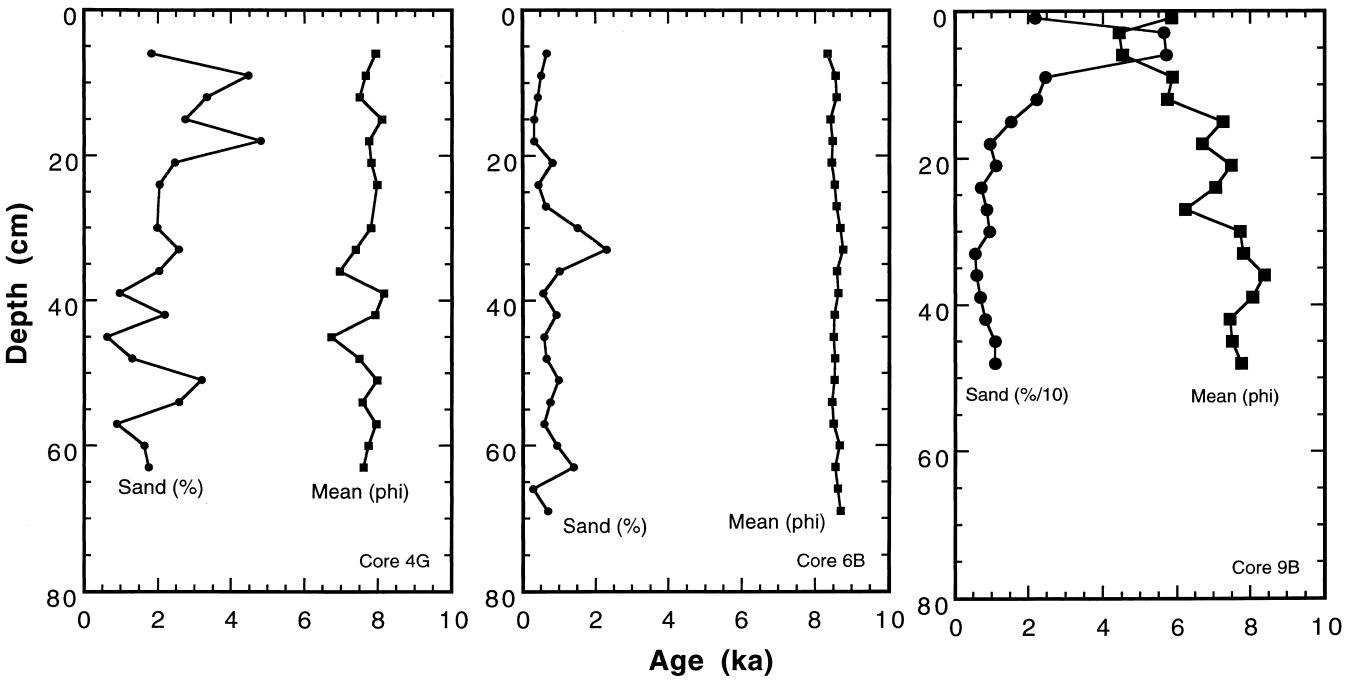


Fig. 7. Mean grain size (phi scale) and sand content (weight percent) of sediment from the upper parts of cores from sites 4, 6, and 9. Data from Colman and Foster (1990).

a change in sediment thickness over time (Fig. 4) the change is less apparent than when considered as a change in mass accumulation over time (Fig. 8).

In addition to changes in physical and magnetic properties, the historic sediments are different chemically. Most notably, they contain heavy metals and pesticides that have accumulated as a result of human activity (Edgington and Robbins, 1976; Cahill, 1981; Eadie and Robbins, 1987).

## 5. Discussion

### 5.1. Chronology and sediment accumulations rates

Our results provide the first down-core series of reliable radiocarbon ages for sediments anywhere in the Laurentian Great Lakes. In a sense, the radiocarbon dating "problem" has been solved, by using AMS methods on biogenic carbonate, but our results confirm the problems with dating TOC in this environment. Our paleomagnetic records, although not useful for reconstructing PSV variation *per se*, provide correlations that support the $^{14}C$ ages on biogenic carbonate. They also provide additional age estimates where biogenic carbonate is absent.

Sediment accumulation at each of the three core sites appears to slow at about 5 ka. The magnitude of the change varies among the sites (Table 2) but is nonetheless distinct. In order to examine mass accumulation rates and to correct for sediment compaction, we used average dry bulk densities (Table 2) derived from the values in Colman and Foster (1990) to calculate sediment mass. The changes in mass accumulation rates at about 5 ka (Fig. 8) is distinctly larger than the change in the age–depth curves (Fig. 4). At about 5 ka, relative lake level stabilized at the Nipissing level, after rising rapidly for most of the preceding 5000 yr (Hansel et al., 1985; Larsen, 1985; Colman et al., 1994). A decrease in the rate of relative lake-level rise might conceivably decrease the rate of shoreline erosion, which is the major source of sediment in the southern lake Michigan Basin (Colman and Foster, 1994). On the basis of four TOC ages from a core near our site 4, Rea et al. (1980) also suggested a decrease in accumulation rates during the mid-Holocene, but somewhat later, at 3.3 ka, during the fall from the Nipissing level.

Our data confirm the spatial distribution of sediment accumulation rates in southern Lake Michigan, which has been previously documented from radioisotope data (Robbins and Edgington, 1975; Edgington and Robbins, 1976; Hermanson and Christensen, 1991), from pollen profiles (King et al., 1976), and from the pattern of overall thickness of Holocene sediments (Robbins and Edgington, 1975; Edgington and Robbins, 1976; Lineback et al., 1979; Colman and Foster, 1994). All of these studies indicate that for both the Holocene in general and for the historic period, sediment accumulation was fastest on the eastern side of the southern basin, slowest on the western side, and intermediate in the middle. However, our data suggest that before 5 ka, sediment accumulation rates were almost as fast on the western side of the basin as on the eastern side (Table 2). After 5 ka, sediment accumulation slowed at all three sites, but the pattern changed, such that slowest accumulation was on the west side of the basin and the center of the basin had an intermediate rate (Table 2).

Despite problems with TOC radiocarbon ages, they have been used to derive pre-historic sediment accumulation rates in three cores in southern Lake Michigan, using the slope of the age–depth plot. For a core near our site 4, King et al. (1976) estimated a rate of 0.065 cm/yr, compared to our estimates of 0.037 (5–10 ka) and 0.027 (0–5 ka) cm/yr; for a core near our site 6, the corresponding values are 0.018 compared to 0.022 and 0.017 cm/yr (Table 2). Rea et al. (1980) estimated an accumulation rate of 0.014 cm/yr for the last few thousand years on the basis of two TOC ages from a core near our site 4.

For the historic period, our limited radioisotope data are generally consistent with more extensive previous studies of this type (Robbins and Edgington, 1975; Edgington and Robbins, 1976; Hermanson and Christensen, 1991). These studies show very slow rates of accumulation on the west side of the southern basin, generally 0.01–0.05 cm/yr, consistent with our estimate of 0.03 cm/yr for site 9 (Table 2). Radioisotope-derived rates for the center of the basin range from about 0.06 to 0.20 cm/yr compared to our tenuous estimate of 0.21 cm/yr for site 6. Finally, previous estimates of the rate for the east side of the basin are quite variable, ranging from about 0.05 to as much as 0.32 cm/yr, but are mostly about $0.20 \pm 0.05$ cm/yr, quite consistent with our various estimates for site 4 (Table 2).

Magnetic properties of the sediments were relatively constant during the late Holocene, but began to change significantly at about 34 cm in core 4B. Comparable changes in sediment magnetic properties have been observed in well-dated records from small lakes in Minnesota (King et al., 1982). For example, data from Long Lake, Minnesota (Young, 1979) indicate that the initial change in magnetic properties occurred at about 600 BP in conjunction with an increase in tree pollen and a decrease in prairie pollen (Fig. 9). This vegetation change to progressively more fire-intolerant tree types has been attributed by Grimm (1984) to a decrease in fire frequency caused by a wetter, possibly cooler, climate. The increase in $ARM/\chi$ ( = ARM/MS) and Jrs/Js (saturation remanent magnetization/saturation magnetization) values is caused by an increase in the flux of fine-grained detrital magnetite at this time (King et al., 1982). Studies of soils within the watershed (Özdemir and Banerjee,

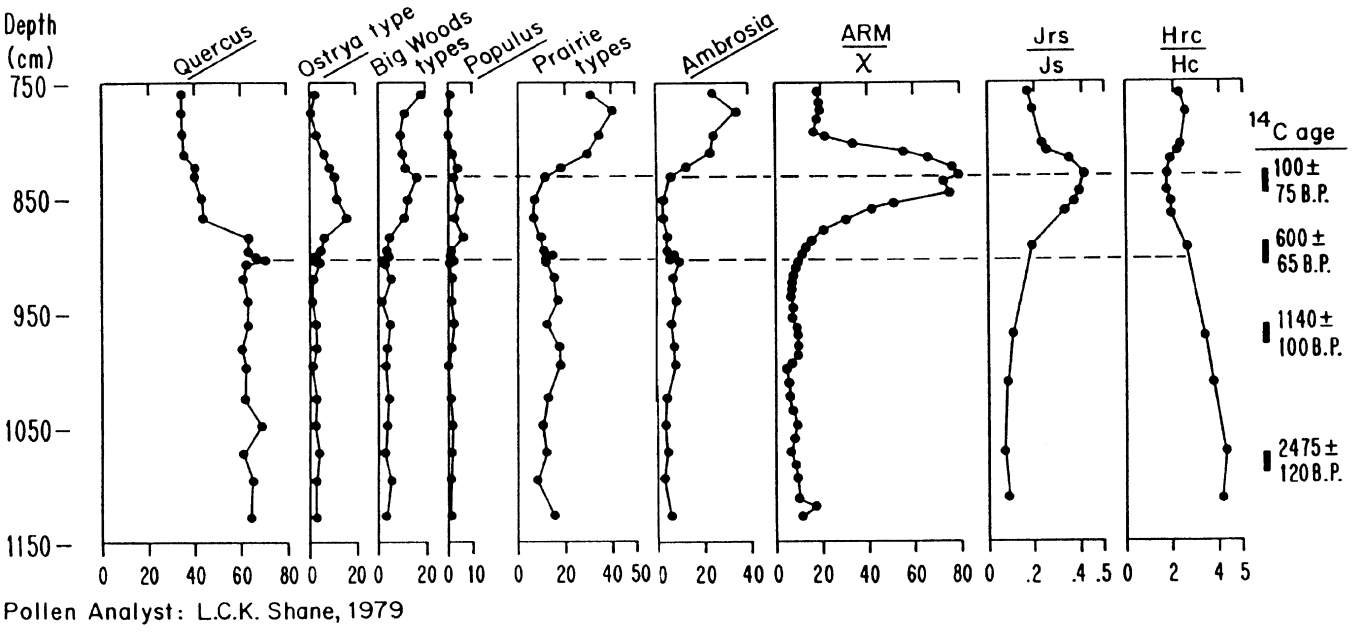


Fig. 9. Pollen and magnetic-property profiles from Long Lake, Minnesota. $\chi$ ( = MS), magnetic susceptibility; Js, saturation magnetization; Jrs, saturation remanent magnetization; Hc, coercivity; Hcr, coercivity of remanence. (Modified from Young, 1979).

1982; Hackenmueller, 1983) indicate that the most likely source of the fine-grained magnetite is topsoil (A2 horizon). The wetter and possibly cooler climate indicated by the pollen would cause increased erosion of topsoil into the lake.

The climate change observed at Long Lake coincides with the global expansion of alpine glaciers and generally colder, wetter climates known at the Little Ice Age (Porter, 1986; Grove, 1988). Porter (1986) described the Little Ice Age as starting about 1250 AD and ending about 1850 AD. He viewed the Little Ice Age as a 600 yr cold interval interrupted by a more clement interval between about 1480 and 1550 AD. The Long Lake record indicates that a wetter and possibly colder climate existed there from about 600 to 100 BP.

A distinct change in the vegetation and magnetic properties occurs in many lake records between 100 and 150 BP. The abrupt rise in *Ambrosia* pollen in the Long Lake record indicates European settlement and widespread cultivation and land disturbance, in Minnesota between 1860 and 1880 (Young, 1979; King et al., 1982). European settlement also generally coincides with the amelioration of climate in the Midwest that signaled the end of the Little Ice Age. Magnetic susceptibility (not shown in Fig. 9) indicates that a 3–4-fold increase in the influx of magnetic material occurred after European settlement, and the parameter ARM/$\chi$ (Fig. 9) indicates that this material was relatively coarse-grained magnetite. The changes in magnetic properties in Long Lake have been interpreted as indicating increased soil erosion from sources relatively deep in the soil profile (i.e. below the A horizon) due to intensive cultivation.

Because the magnetic properties in sediments from Lake Michigan are similar to those seen in the well-dated Long Lake, Minnesota record, that record can be used in conjunction with historical events to estimate a chronology for the youngest Lake Michigan sediments. Accordingly, the changes in magnetic properties at about 34 cm at core site 4 are interpreted as a response to climate changes associated with the Little Ice Age. The changes in magnetic properties at about 22 cm and the first appearances of anthropogenic magnetic grains probably marks the beginning of settlement and extensive land clearance, which occurred about 1840 AD in the southern Lake Michigan Basin (King et al., 1976). A date of 1840 for 22 cm yields an average sediment accumulation rate of 0.15 cm/yr.

Finally, the changes in magnetic properties at about 13 cm, accompanied by a dramatic increase in anthropogenic magnetic particles, are probably related to the beginning of extensive industrialization and coal combustion at about 1900. This date also marks the appearance of other kinds of industrial particles in the sediments (Griffen and Goldberg, 1983). A date of 1900 for 13 cm yields an average sediment accumulation rate of 0.15 cm/yr, the same as that for the post-1840 period.

Rates of sediment accumulation during the historic interval appear to be much greater than that during the pre-historic period (Table 2). However, because of

compaction in the upper part of the sediment column, this comparison needs to be made on the basis of mass accumulation rather than on thickness. We calculate that the rate of mass accumulation for the historic period increased over that during the late Holocene (0–5 ka) by factors of 4, 11, and 4 at sites 4, 6, and 9, respectively (Fig. 8). For the site with the least complicated history and the best data (site 4), the historical sediment accumulation rate is also more than twice that in the early Holocene (5–10 ka).

### 5.2. Carbon sources and reservoirs

Direct comparison of the $^{14}C$ ages of different fractions from the same horizons (Fig. 10) reveals several things about carbon reservoirs in the lake. Most of the POM ages are intermediate between the TOC and the biogenic carbonate ages (Fig. 2). From these observations, we infer that the picked organic matter samples, being detrital, suffer from the same problem as the TOC samples, but to a lesser degree. That is, they contain organic matter that has resided in terrestrial environments for some time before being deposited with the lake sediments. The POM fraction apparently contains lesser amounts of refractory detrital material having long terrestrial residence times than the TOC fraction.

Two of the POM ages are slightly younger than the associated biogenic carbonate (Fig. 10). Because we believe that the biogenic carbonate ages are accurate within the uncertainties of the reservoir correction, these two POM ages are probably also accurate. The difference between one pair of ages (150 ± 190 yr) is within the counting errors of the two ages; the difference between the other pair (440 ± 190 yr) is significant. Together, the two paired ages may indicate that the reservoir effect may have been somewhat higher than the current 250 yr (Rea and Colman, 1995) during the early Holocene, but that it probably was always less than 500 yr. This range is consistent with that observed in the modern Lake Michigan-Lake Huron system, where differences in bedrock and circulation result in a range in reservoir age of about 250 to 500 yr (Moore et al., 1998). A reservoir age of less than 500 yr is also consistent with relatively constant water chemistry that, although more concentrated during the early Holocene, probably has been continuously undersaturated with respect to calcium carbonate except during a brief period in the early middle Holocene (Forester et al., 1994).

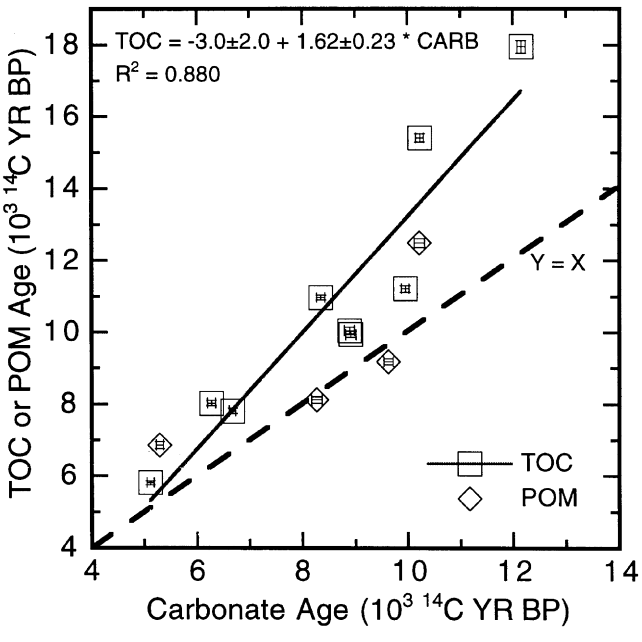


Fig. 10. Plot of radiocarbon ages of TOC or POM fractions against those for the biogenic carbonate fraction of the same horizons. Heavy dashed line indicates concordancy ($Y = X$). Solid line is linear regression of TOC against carbonate ages; an exponential regression yields a slightly higher $R^2$ (0.914).

The difference between TOC ages and biogenic carbonate ages from the same horizon decreases systematically with time in Lake Michigan (Fig. 10), from a few thousand years in the early Holocene to a few hundred years in the late Holocene. A similar relation was observed between TOC $^{14}C$ ages and varve ages in Elk Lake (Anderson, 1993). At Elk Lake, this relationship was ascribed to exponentially decreasing amounts of old carbon in bicarbonate ions in the lake water derived from leaching of calcareous glacial drift (Anderson, 1993). For several reasons, we do not believe this is the case in Lake Michigan. First, an exponentially decreasing reservoir effect would affect the biogenic carbonate ages at least as much as the TOC ages, and would therefore not explain the difference in Lake Michigan. Second, in at least two cases, the biogenic carbonate ages are close to those from terrestrial organic matter during the early Holocene (Fig. 10). Finally, as discussed earlier, we believe that the dissolved-bicarbonate reservoir effect has always been less than 500 yr, too small to explain TOC ages that are thousands of years older than expected.

If a reservoir effect is insufficient to explain the anomalously old TOC ages, then the TOC fraction must contain refractory terrestrial carbon, which resides on the landscape for thousands of years before being deposited in the lake. This has been the traditional explanation for anomalously old ages for Lake Michigan sediments (e.g. King et al., 1976). Significant terrestrial (allochthonous) carbon in the sediments of Lake Michigan is supported by the presence of organic compounds indicative of land plants (Meyers and Ishiwatari, 1993). A constant proportion of old (infinite age) carbon in TOC would produce ages that increasingly diverge from the true ages as sediments get younger. We observe the opposite, so either the amount of allochthonous carbon, or its average residence time on the landscape, must have decreased with time.

### 5.3. Character of historic sedimentation

The primary change in the character of the historic sediment appears to be its rate of deposition and its magnetic properties. Faster mass accumulation (Table 2) would favor higher water contents in the sediments, exaggerating the apparent rate of accumulation. Grain size and the spatial pattern of accumulation of the sediments seem to change very little, suggesting that transport and depositional processes have not changed in character or intensity during the historic period. The changes in magnetic properties of the sediments, however, suggests changes in the sources of these materials.

The magnetic properties of the sediments in core 4B (Fig. 6) suggest a significant change in sediment character during and immediately before the historic interval. The changes in IRM/MS and ARM/MS at about 34 cm are consistent with a shift in source area from magnetically relatively coarse-grained sediments in the lake and river bluffs around the lake toward magnetically relatively fine-grained top soil in the drainage basin (Harlen et al., 1998). We hypothesize that this change took place about 600 yr ago, at the beginning of the so-called Little Ice Age.

These sediments are moderately rich in hematite throughout ($S > 0.92$), but the relative proportion of hematite decreased markedly at about 22 cm. The increases in MS, IRM, and HIRM at about 22 cm may reflect increased erosion of coarser-grained magnetic material from soil parent materials, mostly glacial drift. At the same time, the increase in ultrafine magnetite/maghemite (high FDMS) indicate erosion of soil materials different from those ascribed to magnetic properties between 34 and 22 cm. The difference may be related to deeper soil erosion or different soil source areas. These changes are consistent with the effects of extensive cultivation, beginning about 1840 AD. Similar changes in the quantity and concentration of magnetic grains have been observed in other lakes and have been attributed to changes in the source of the material eroded from the landscape (King et al., 1982).

The coarser-grained magnetic material continued to increase, along with the addition of abundant anthropogenic magnetic particles, especially fly ash, beginning about 1900 (at about 13 cm). Widespread coal combustion began about 1990, the date that also marks the appearance of other kinds of industrial particles in the sediments (Griffen and Goldberg, 1983). Based on studies of fly ash in a variety of settings, the coarser magnetic grain size above 13 cm may be partly caused by the increase in anthropogenic grains.

Other changes in magnetic properties occur near the top of the core. In the upper few cm, contents of ferrimagnetic magnetite and hematite become constant or decrease slightly, and the sediment becomes relatively enriched in hematite, trending toward pre-industrial $S$ parameter ratios. These relations likely reflect the decrease in industrial effluents with the installation of emission-control devices beginning in the 1960s (see Goldberg et al., 1981; Locke and Bertine, 1986). Ultrafine magnetite/maghemite also decreases above 5 cm perhaps reflecting diminished runoff from disturbed soil or better control of surface runoff.

## 6. Conclusions

AMS radiocarbon ages on biogenic carbonate provide the first reliable estimates of Holocene sediment accumulation rates in southern Lake Michigan. The ages indicate that sedimentation in the lake slowed considerably at about 5 ka, about the time the lake stabilized at the Nipissing level. Radiocarbon ages on biogenic carbonate are affected by a reservoir effect that amounts to 250 yr at present and that was probably no more than 500 yr during the Holocene. Total organic carbon yields radiocarbon ages that are as much as several thousand years older than the sediment in which it was deposited, but the difference between biogenic carbonate and TOC ages decreases with time.

A combination of $^{210}$Pb, $^{137}$Cs, and magnetic-property analyses yields estimates of sediment accumulation rates during the historic period, about the last 150 yr. Sedimentological changes related to anthropogenic disturbance of the watershed were preceded by changes ascribed to climate fluctuations during the Little Ice Age. The level at which *Ambrosia* pollen increases, commonly used as a stratigraphic marker is not very useful in southern Lake Michigan because of poor pollen preserved. Detailed reconstruction of accumulation rates during the historical period are difficult, but average rates for the period are likely valid. The data suggest that sediment mass has accumulated between 4 and 11 times as fast during the historic period as it did during most of the previous 5 ka. The gross properties of the sediment did not change much, but the magnetic properties suggest changes in the source of magnetic material in the sediments.

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