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A mineral magnetic and scaled-chrysophyte paleolimnological study of two northeastern Pennsylvania lakes: records of fly ash deposition, land-use change, and paleorainfall variation

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Abstract

A combined mineral magnetic and scaled chrysophyte study of lake sediments from Lake Lacawac and Lake Giles in northeastern Pennsylvania was conducted to determine the effects of land-use and sediment source changes on the variation of pH, conductivity, and alkalinity inferred from biotic changes. Ten 30–40 cm long gravity cores were collected from Lake Lacawac and three from Lake Giles. Isothermal remanent magnetizations (IRMs) were given to the lake sediments in a 1.3 T magnetic field to measure magnetic mineral concentration variations. IRM acquisition experiments were conducted to identify magnetic mineralogy. The bedrock, soils and a peat bog on the shores of Lake Lacawac were also sampled for magnetic analysis to determine possible lake sediment sources. The top 10 cm of sediment collected from Lakes Lacawac and Giles was two to four times more magnetic than deeper sediment. ^{210}Pb dating suggests that this intensity increase commenced circa 1900. SEM images of magnetic extracts from the highly magnetic sediments indicates the presence of magnetic fly ash microspheres from fossil fuel burning electric power generation plants. The similarity in magnetic coercivity in the top 8 cm lake sediments and in the peat bog supports an atmospheric source for some of the magnetic minerals in the youngest lake sediments. The highly magnetic sediments also contain an antiferromagnetic mineral in two cores closest to Lake Lacawac's southeastern shore. This magnetic mineral is only present deep in the soil profile and would suggest erosion and significant land-use changes in the Lacawac watershed as another cause for the high magnetic intensities (concentrations) in the top 10 cm of the lake sediments. The most significant changes in the scaled chrysophyte flora occurred immediately above the 10 cm level and were used to infer a doubling of the specific conductivity between circa 1910 and 1929. These variations also support land-use changes in the Lacawac catchment at this time. A similar shift in the scaled chrysophte flora was not observed in the top of Lake Giles, however, distinct changes were found in the deeper sections of the core coupled with a smaller peak in magnetic concentration. Fourier analysis of the ^{210}Pb-dated lake sediment magnetics indicates the presence of a 50 year period, low amplitude variation in the Lake Lacawac, Lake Giles, and Lake Waynewood (Lott et al., 1994) magnetic concentration records. After removal of the land-use/fly ash magnetic concentration peak by Gaussian filtering, the 50 year variation correlates strongly from lake to lake even though the lakes are in different watersheds separated by up to 30 km. When this magnetic variation is compared with Gaussian-filtered rainfall variations observed in New York City and Philadelphia over the past 120–250 years there is a strong correlation suggesting that magnetic concentration variations can record regional rainfall variations with an approximately 50 year period. This result indicates that magnetics could be used to document regional variations in climatic change.

Introduction

In 1990 two to three gravity cores were collected from the bottom sediments in each of three lakes in the Pocono Mountains of northeastern Pennsylvania to determine if any relationship existed between the time variation in the type and concentration of magnetic minerals and the taxa of scale-bearing chrysophytes.

Both parameters have been demonstrated to be useful paleoenvironmental indicators. Lakewater pH, specific conductivity, and alkalinity are important factors controlling the distributions of many chrysophyte taxa at the specific and subspecific levels (see Siver, 1995 and references therein). As a result, scaled chrysophytes have been used to infer the past variations of these three variables in lakes (e.g. Charles & Smol, 1988; Dixit et al., 1988; Dixit & Dixit, 1989; Cumming et al., 1992; Marsicano & Siver, 1993; Siver, 1993). Mineral magnetic properties have been used as important environmental indicators in terrestrial settings, particularly in post-glacial lake sediments. Magnetic minerals are used to correlate multiple cores from one lake basin, trace sediment sources and monitor land-use changes within a lake's catchment area (Thompson, 1973; King et al., 1982; Dearing, 1983; Thompson & Oldfield, 1986). Comparing the scaled chrysophyte and mineral magnetic records in lake sediments can provide information about the effects of land-use and sediment source changes on the variation in pH, conductivity, and alkalinity inferred from biotic changes.

One of magnetic minerals' predominant paleoenvironmental roles has been as a measure of global climatic cycles. Kent (1982) was the first to demonstrate that magnetic mineral concentration variations downcore could be correlated to the oxygen isotope and calcium carbonate records. Kent showed that magnetic intensity variations were the result of climatically-driven changes in carbonate accumulation rates. Since then workers have shown the importance of mineral magnetic properties as a proxy for the global climatic variations indicated by the oxygen isotope record or caused by the orbitally-driven Milankovitch cycles (Mead et al., 1986; Robinson, 1986; Bloemendal et al., 1988; Bloemendal & Menocal, 1989; Hall et al., 1989). While mineral magnetic properties in marine sediments have been shown to be important measures of global scale processes, the record in terrestrial lake sediments has been confined more to the processes occurring within a lake catchment or watershed. One of the next important steps in collecting paleoclimatic and paleoenvironmental data would be to move up from the watershed scale and down from the global scale to an intermediate, regional scale. This paper presents results indicating that mineral magnetic properties in post-glacial sediments may be used not only to measure land-use and climatic changes in a single watershed, but also to measure paleoclimatic variations across lake catchments within a geographical region.

The three lakes targeted in the initial study span a range in trophic status. Lake Waynewood is a eutrophic lake. Results of a joint scaled-chrysophyte and mineral magnetic study is reported in Lott et al. (1994). Results from the other two lakes, Lake Lacawac, a mesotrophic lake, and Lake Giles, an oligotrophic lake, are reported here as well as the findings from a more detailed sampling of Lake Lacawac that was conducted in 1992. Lake Lacawac is a 13 000 year old glacial ice scour lake located in Wayne County, Pennsylvania (Figure 1). It is the smallest of the three lakes and has a surface area of 0.21 km^2 and a drainage area of 0.70 km^2. Its maximum depth is 13.5 meters. Lake Giles is located approximately 20 km east of Lake Lacawac and has a surface area of 0.47 km^2 and a maximum depth of 24.1 meters. It is located in Pike County, PA and has a watershed of 1.83 km^2 (Figure 1).

Methods

Ten short cores were collected from Lake Lacawac at even spacings along a 440 meter long northwest-southeast transect which crossed the deepest part of the lake (Figure 1). Cores were taken with a modified K-B gravity corer and sectioned on shore with a Glew extruder (Glew, 1989). The cores ranged from 6 cm long at the southeasternmost end of the transect to 40 cm long at the northwestern end. They were sectioned in 2 cm intervals for magnetic analysis. Core material was placed in $2 \times 2 \times 2$ cm plastic boxes for magnetic measurements. A core was collected in the initial phase of the study 5–10 meters northwest of the deepest part of the lake and was used for magnetic analysis, chrysophyte analysis and ^{210}Pb dating. It was sectioned in 1 cm intervals. Three cores were collected from near the deepest part of Lake Giles with the K-B gravity corer and sectioned in 1 or 2 cm intervals for magnetic analysis, chrysophyte analysis and ^{210}Pb dating (Figure 1). The magnetic susceptibility of the lake sediments from Lake Lacawac and Lake Giles were too weak to be accurately measured with Lehigh University's Sapphire Instruments SI-2 susceptibility meter, so measurement of isothermal remanence (IRM) was used to determine the downcore variation in magnetic mineral concentration. All remanence measurements were made on a 2-axis CTF Systems, Inc. superconducting magnetometer and normalized by sample dry weight. IRM acquisition experiments were conducted for 3 samples from each core (top, middle, and bottom) in 12 steps up to 1.3 T to help determine the magnetic

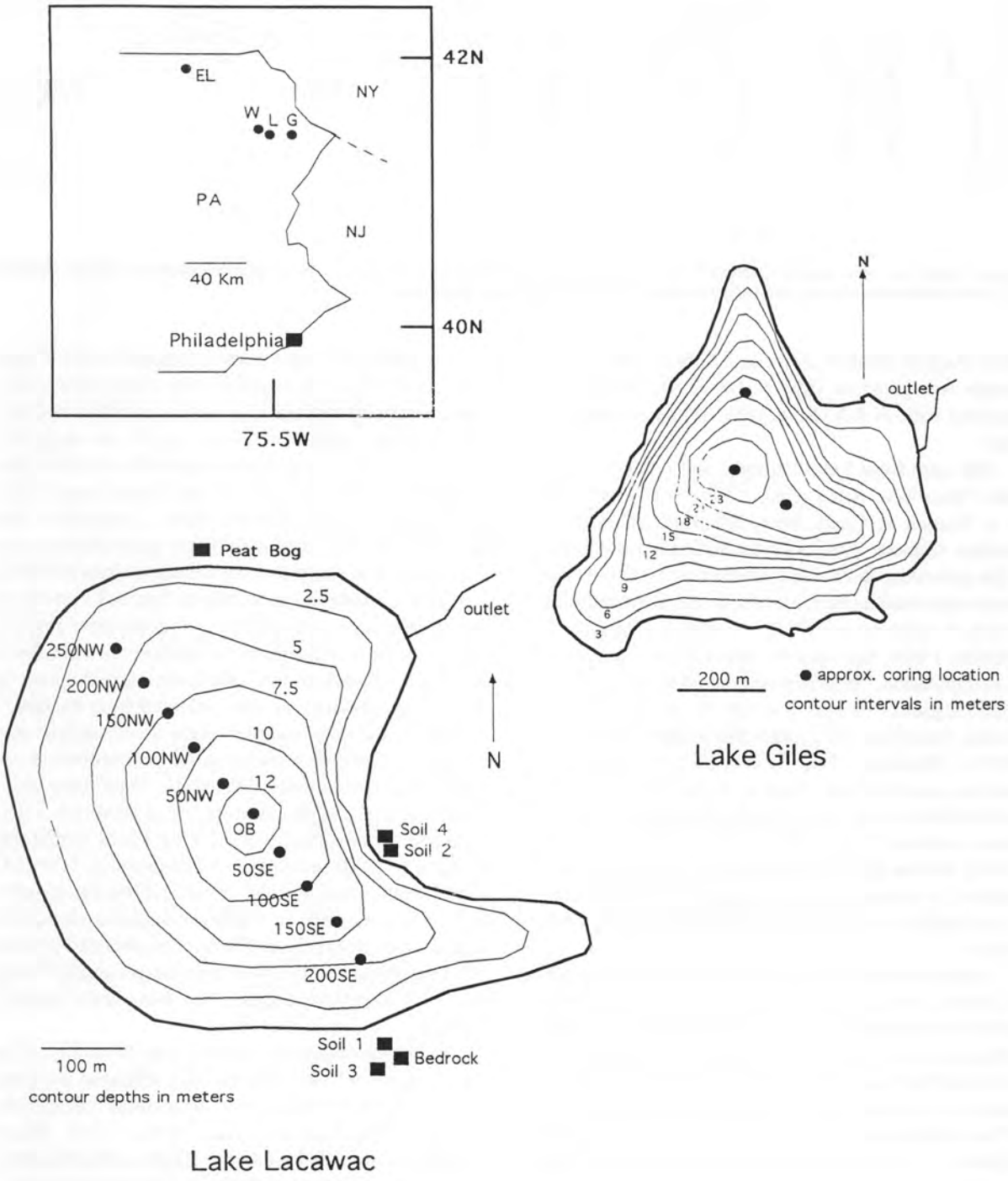


Figure 1. Sketch maps of Lakes Lacawac and Giles showing location of gravity cores. Contours show the depth of the lake in meters. Sampling localities of soil cores, bedrock sample and the peat core on the shores of Lake Lacawac are also shown. Inset shows location of Lake Waynewood (W), Lake Lacawac (L), and Lake Giles (G) in northeastern Pennsylvania.

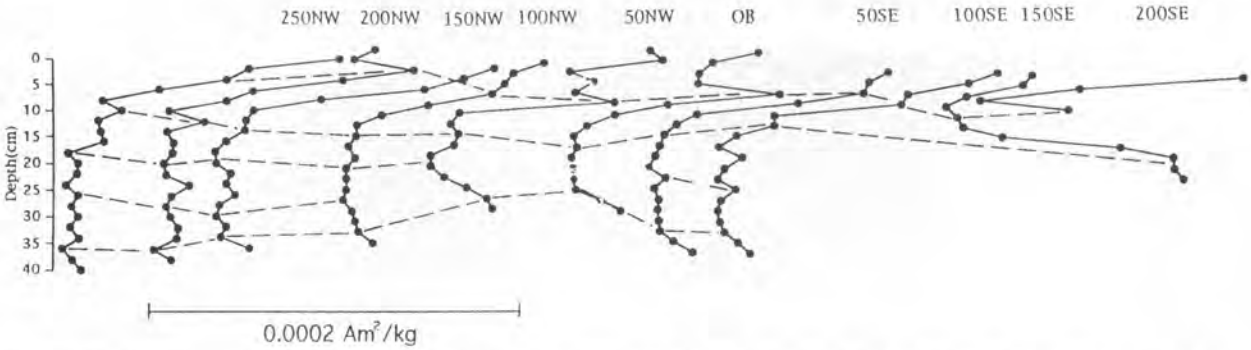


Figure 2. $IRM_{1.3T}$ versus depth in sediment for the 10 gravity cores collected from Lake Lacawac. Scalebar shows magnetic intensity. Dashed lines show correlations between small amplitude and large amplitude magnetic variations.

mineralogy in the lake sediments. Subsequently every sample was given an IRM at 1.3 T. All IRMs were imparted with an ASC Model IM-10 Impulse Magnetizer.

One core from Lake Lacawac and one core from Lake Giles were dated using ^{210}Pb by B. Risto and R. J. Cornett at Chalk River Nuclear Laboratories, Ontario, Canada. Analysis was performed according to the procedure outlined by Cornett et al. (1984). The cores were dated by the Constant-Initial-Concentration model of sediment and ^{210}Pb deposition (Appleby & Oldfield, 1983). Ages greater than 150 years are based on extrapolation. The linear correlation between ^{210}Pb-dated magnetics records and rainfall records, the fast Fourier transform (FFT) and Multi-Tapered Method (MTM (Thomson, 1982; Yiou et al., 1991)) spectral analysis, and Gaussian filtering of the lake magnetics and rainfall records were calculated using the Analy-Series software supplied by Paillard and Labeyrie (1993). Before spectral analysis the time series were sampled in equal intervals, interpolation being conducted with a cubic spline, and windowed to limit end effects.

To help determine the source of the magnetic minerals in the Lake Lacawac sediment cores, samples were collected for magnetic analysis from the bedrock, soils, and a peat bog located on the lakeshore. A sample was collected from an outcrop of the Devonian Catskill Formation on the south shore of the lake directly southeast of the southeasternmost part of the lake core transect (Figure 1). A 25 mm diameter core was drilled from the sample and two specimens, one from the weathered rind of the rock and one from the fresh interior, were trimmed for magnetic analysis. IRM acquisition experiments in DC fields up to 1.3 T were conducted with each specimen. Four soil cores were collected with an AMS soil auger from soils near the lake shore. Two cores were collected from the south shore of the lake near where the bedrock sample was collected (Figure 1). These cores were 24 cm and 34 cm deep (S1 and S3). Two soil cores were also collected from the east shore of the lake near to the deepest part of the lake (Figure 1). These cores were 22 cm and 4 cm deep (S2 and S4). IRM acquisition experiments were conducted with samples from the top, middle and bottom of the southern cores and the top and bottom of the eastern cores. As part of a Lehigh class project to determine if atmospheric sources could contribute magnetic minerals to the Lake Lacawac sediments, a 27 cm long gravity core was collected from the deepest part of the lake (sampled every 2 cm) and the top 19 cm of peat from a peat bog on the northern shore of the lake (10 samples; Figure 1). These lake sediment and peat samples were given an IRM in a 1.0 T field and then exposed to a 0.1 T backfield so that the S ratios ($-IRM_{0.1T}/IRM_{1.0T}$ (Thompson & Oldfield, 1986)) could be calculated. S ratios allow the proportion of ferrimagnetic to antiferromagnic minerals in a sample to be determined. The S ratios obtained using a 0.1 T backfield will be lower than those acquired using the 0.3 T backfield suggested by King and Channell (1991).

To aid identification of the magnetic minerals in the most recent Lake Lacawac lake sediment, magnetic extracts were made from core material taken from the top 10 cm of several Lake Lacawac cores. These extracts were made by passing a lake sediment slurry between the pole pieces of an electromagnet maintaining a 0.2 T DC field. The magnetic extracts were examined with a JEOL JSM-840F field emission scanning electron microscope (SEM). The elemental composi-

tion of possible magnetic minerals was determined by EDS (energy dispersive spectroscopy).

Results

For scaled chrysophyte analysis a known amount of sediment was removed from each core sample, oxidized with H_2SO_4 and potassium dichromate, and washed a minimum of 5 times with distilled water. The resultant slurry of siliceous microfossils was then diluted to 10 ml and stored in a glass vial (Batterbee, 1986). An aliquot of each cleaned slurry was diluted to 20 ml with distilled water, poured into a Batterbee tray equipped with 22 mm cover glasses and allowed to air dry. Cover glasses with microfossil remains were mounted onto glass slides in Hyrax medium. Another aliquot of each slurry was diluted and air dried onto a piece of aluminum foil. The foil was trimmed, mounted onto aluminum stubs with Apiezon wax, coated with gold using a Polaron Sputter coater, and observed with a Coates and Welter field emission SEM. A minimum of 300 chrysophyte scales were counted for each sample with light microscopy (LM). Before a count was made, the relative abundances of all taxa present were made with SEM. For taxa in each sample that could not be distinguished by observation of isolated scales with LM, proportional estimates were made with SEM, and the LM counts subsequently separated according to the estimates (Siver & Hamer, 1990).

The inferences for pH and specific conductivity were made using models developed previously by Marsicano (1993) and Siver (1993), respectively. Each model is based on weighted averaging (WA) regression as outlined by Birks et al. (1990). Samples from Lake Lacawac and Lake Giles were added as passive samples in the analysis.

Magnetic mineral

The most striking feature of the downcore plots of $IRM_{1.3T}$ from Lake Lacawac is the strong magnetic intensities in the top 10 cm of each core (Figure 2). The magnetization varies from $2\text{–}5 \times 10^{-4}$ Am^2kg^{-1} and is about four times more magnetic per unit mass than the lower part of the cores. This magnetic peak can be correlated from core to core across the lake basin. In the core from the deepest part of the lake, OB, it breaks into a double peak. Other cores also show this double peak either in subdued (e.g. 100NW, 50SE, 100SE) or distinct form (e.g. 200NW, 50NW). IRM

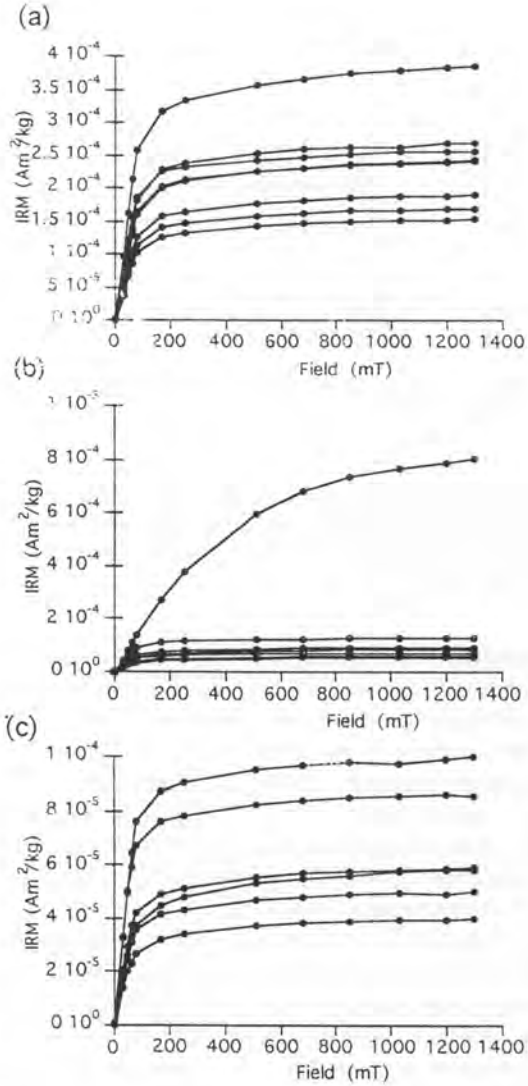


Figure 3. (a) IRM acquisition curves for samples taken from the top 10 cm of the cores. This part of the cores is dominated by low coercivity, ferrimagnetic minerals with some contribution by antiferromagnetics. (b) IRM acquisition for samples taken from the bottoms of the cores. Most of the cores from the northwestern and central part of the lake basin contain only low coercivity minerals. The high coercivity sample which does not saturate at 1.3 T is from the bottom of core 150SE and shows an influx of antiferromagnetic minerals from the southeast. (c) IRM acquisition for samples collected from the middle portions of the cores. These samples contain predominately low coercivity, ferrimagnetic minerals.

acquisition curves for samples from this highly magnetic portion of the cores indicates that the predominant magnetic mineral saturates by fields of 0.3 T and is probably ferrimagnetic (e.g. magnetite). There is also some contribution from a higher coercivity magnet-

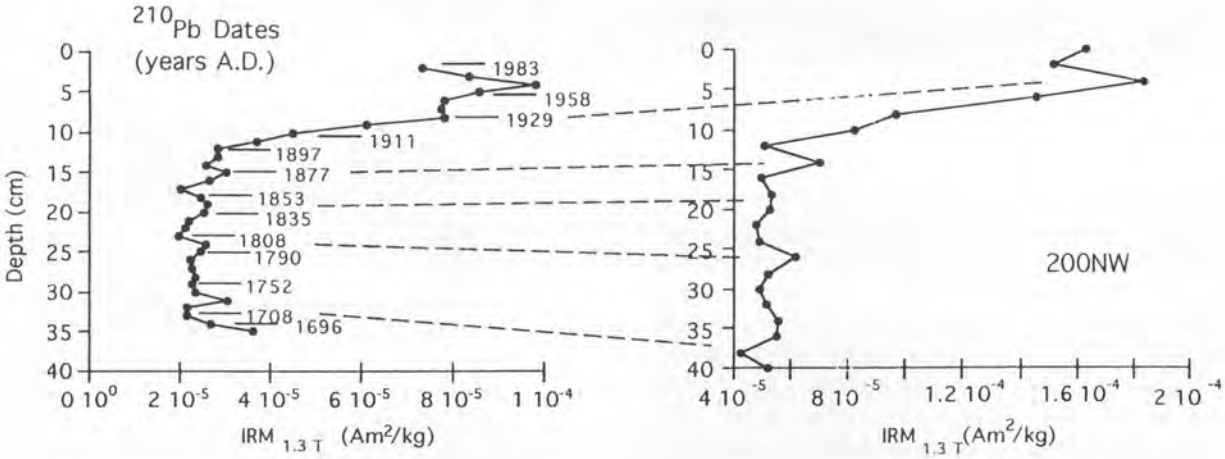


Figure 4. ^{210}Pb dates (in years A.D.) for a Lake Lacawac core collected in the initial phase of the study. The core records deposition over the past 300 years. The dramatic magnetic high observed in the top 10 cm of the core appears to have commenced circa 1900. Dashed lines show the correlation of magnetic intensity variations to those in core 200NW which was collected for the more detailed magnetic/chrysophyte phase of the Lake Lacawac study.

ic mineral, which is probably antiferromagnetic (e.g. hematite) (Figure 3a), however, the results indicate that the $IRM_{1.3T}$ is close to the saturation IRM (SIRM) for this portion of the cores. There is also a minor increase in magnetic intensity at a depth of about 30 to 40 cm (cores 250NW–100SE; Figure 2). IRM acquisition results indicate that the magnetic mineral in this portion of the cores is low coercivity and saturates by 0.3 T (ferrimagnetic) (Figure 3b). At the most southeastern part of the transect (cores 150SE and 200SE) there is a very strong increase in magnetization at the bottom of the cores (8×10^{-4} Am^2 kg^{-1} for 150SE). This increase could be correlated with the bottom half of the double magnetic intensity peak observed in the top 10 cm of the other lake sediment cores or with a small peak just below it (Figure 2) since the two southeasternmost cores are much shorter than those taken to the northwest. IRM acquisition experiments show that a high coercivity magnetic mineral (antiferromagnetic) occurs at this strong magnetic high (Figure 3b). Finally, there appears to be a lower amplitude, short period (approx. 5–10 cm) variation in $IRM_{1.3T}$ intensity in cores 250NW to 100SE (Figure 2). It is evident mainly in the middle and bottom part of the cores, but may continue up through the high amplitude peak in the top 10 cm of the cores, and can be correlated from core to core. IRM acquisition results from the middle part of the cores are similar to those for the top and bottom parts of the cores from the central and northwestern part of the transect showing a mixture of ferrimagnetic

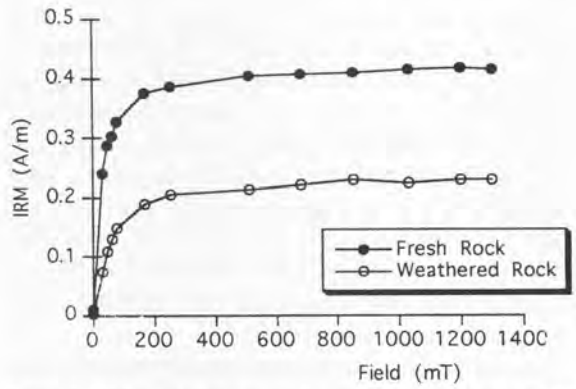


Figure 5. IRM acquisition curves for weathered and fresh Catskill bedrock collected from the south shore of Lake Lacawac. Both samples contain mainly low coercivity, ferrimagnetic minerals.

and antiferromagnetic minerals with the ferrimagnetic minerals predominating. The middle parts of the cores nearly reach saturation by 0.3 T. The IRM at 1.3 T appears to be close to the SIRM (Figure 3c). Since there appears to be little variation in coercivity downcore, with the exception of the bottom part of the two southeasternmost cores of the transect, it is reasonable to use the $IRM_{1.3T}$ as a measure of variations in magnetic mineral concentration.

The core used for ^{210}Pb dating appears to correlate magnetically best with core 200NW. This correlation can be used to tie the ^{210}Pb dates to other cores in the transect (Figure 4). ^{210}Pb ages suggest that the cores from Lake Lacawac record sedimentation over the past 300 years with an average sedimentation rate of about

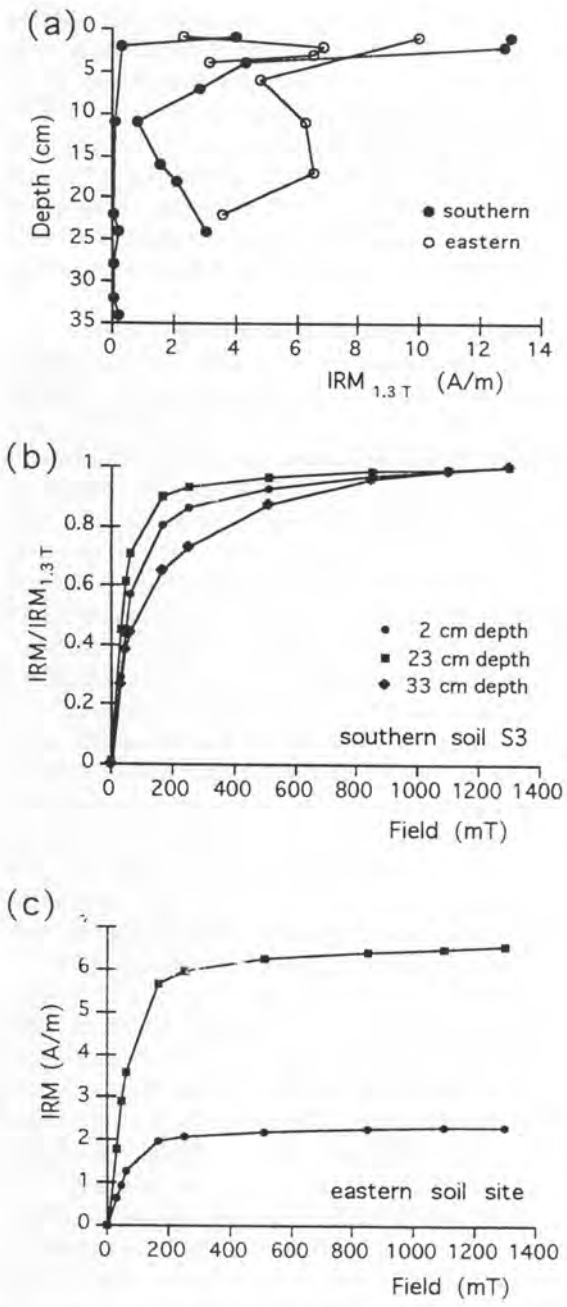


Figure 6. (a) Downcore variation in $IRM_{1.3T}$ for the soil cores collected from the southern and eastern shores of Lake Lacawac. All cores show the strongest magnetic intensity in the top 5 cm. (b) IRM acquisition curves for soil core S3 collected from Lake Lacawac's southern shore. The curves for samples collected from the top and middle of the core show little or no contribution of antiferromagnetics whereas the sample collected from the bottom of the core shows domination by an antiferromagnetic mineral. All curves are normalized to the IRM acquired at 1.3 T. (c) IRM acquisition curves for samples from cores S2 and S4 collected from Lake Lacawac's eastern shore. Both curves show predominately ferrimagnetic minerals.

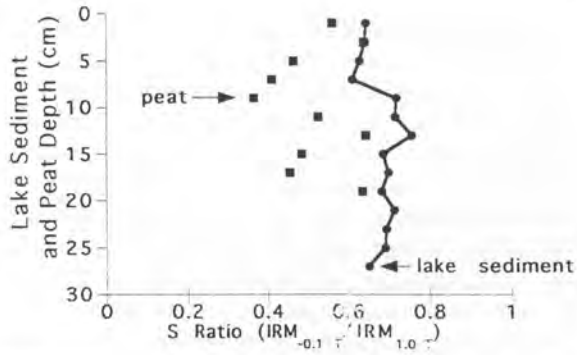


Figure 7. S ratios ($IRM_{0.1T}/IRM_{1.0T}$) for lake sediment collected from Lake Lacawac and from the peat bog which lies on the lake's northern shore. The S ratios for the youngest lake sediments (top 8 cm) are lower than those deeper in the core and similar to the S ratios observed for the peat. This supports an atmospheric source for the magnetic minerals in the most recent lake sediments.

1.4 mm yr^{-1} during the past 150 years, the limit of the ^{210}Pb dating technique. The highly magnetic peak in the top 10 cm commenced approximately 100 years ago and the low amplitude, short period variations have a period of approximately 50 years.

IRM acquisition data from weathered and unweathered bedrock samples collected from the Lacawac watershed show that both materials saturate by 0.3 T and are, therefore, dominated by low coercivity, ferrimagnetic minerals (Figure 5). The $IRM_{1.3T}$ data from the soil cores indicate that the top 1–5 cm of the soils is more magnetic than the deeper soils (Figure 6a). IRM acquisition data from the southern soil cores showed that there is an increase in high coercivity, antiferromagnetic minerals deeper in the cores (Figure 6b). The eastern soil cores were dominated by a low coercivity, ferrimagnetic mineral (Figure 6c). The S ratios for the lake sediments show a slightly lower ratio of 0.6 in the top 8 cm of the core with deeper parts of the core having S ratios between 0.7 and 0.75 (Figure 7). The S ratios for the peat vary from 0.4 to 0.6 and average to 0.5 (Figure 7).

SEM examination of the magnetic extract from the top 10 cm of the Lake Lacawac lake sediment shows the presence of microspherules of two different sizes, larger spherules that range in size from 10–12 μm and smaller spherules that are 4 to 5 μm in size (Figure 8). EDS analysis of the two different size spherules indicates that the larger spherules only contain Si and are probably chrysophyte cysts. The smaller spherules produce Fe peaks (Figure 8) and are probably a magnetic iron oxide.

The Lake Giles $IRM_{1,3T}$ downcore results are similar to those observed at Lake Lacawac. The Lake Giles magnetics show a strong increase in magnetic intensity (6×10^{-4} Am^2 kg^{-1}) in the top 10 cm of the lake sediments approximately two times stronger than that observed in the lower portion of the cores (Figure 9). In the core sampled in 1 cm intervals for magnetics and ^{210}Pb dating there is also the suggestion of a double peak in this magnetic high similar to that observed in the Lake Lacawac sediment cores. Also evident is an increase in magnetization at the bottom of the cores and a low amplitude, short period variation in magnetization which is correlatable from core to core. ^{210}Pb dating indicates that the cores record deposition over the past 250 years (average sedimentation rate about 1.1 mm yr^{-1} over the past 150 years) and that the short period variations have a period of 50 to 100 years (Figure 9).

Scaled Chrysophytes

Seventeen taxa of scaled chrysophytes were observed throughout the Lake Lacawac core, the most abundant being *Synura spinosa* Korsh, *Synura petersenii* Korsh, *Synura uvella* Stein em Korsh, *Mallomonas duerschmidtiae* Siver, Hamer and Kling and *Mallomonas acaroides* Perty emend. Ivanov var. *muskokana* Nicholls (Figure 10). Except for several shifts, the most apparent at approximately the 10 cm interval, the flora has remained relatively stable since circa the early 1700s. *Synura spinosa* was the most abundant taxon throughout the core, accounting for between 30% and 60% of the total at all sections below 10 cm. The importance of *S. spinosa* began to decrease slowly at the 10 cm mark (ca. 1910), and more precipitously at 5 to 6 cm (ca. 1958), reaching a low of 18% at the surface (Figure 10).

Concurrent with the decline of *S. spinosa* was an abrupt decline in *M. duerrschmidtiae*. Between approximately 10 cm and 20 cm (ca. 1840) *M. duerrschmidtiae* accounted for between 10% and 16% of the total. Above 10 cm the occurrence of this taxon dropped significantly, and it was absent in the most recent sediments. The importance of *S. petersenii* also significantly dropped at two other intervals in the core, 25 to 26 cm and 20 to 21 cm, only to increase above each point (Figure 10). Concurrent with the declines in *S. petersenii* were an increase in *S. uvella* and *M. duerrschmidtiae* at 25 to 26 cm, and *M. duerrschmidtiae* at 20 to 21 cm.

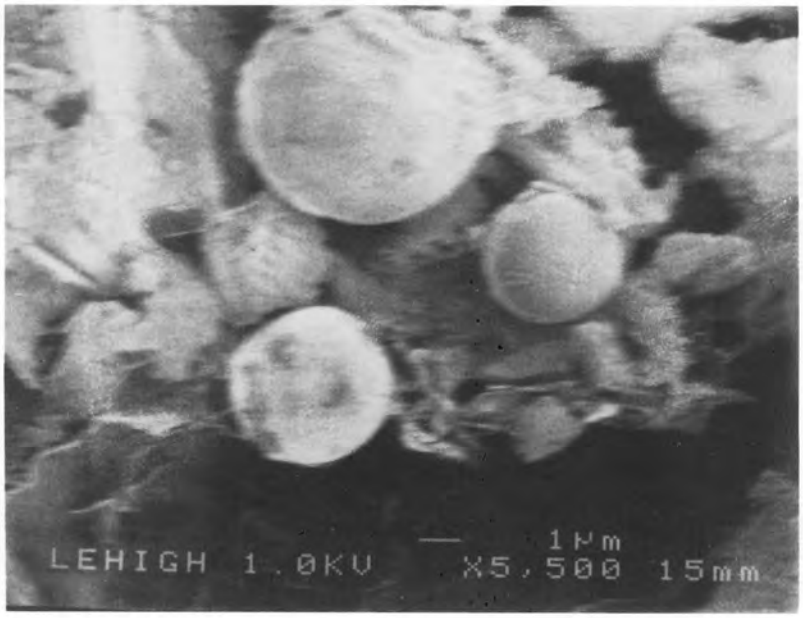
The chrysopyte inferred pH varied only slightly, from 6.2 to 6.6, over the length of the Lacawac core. The inferred specific conductivity ranged from 16 μS to 40 μS, with the only significant shift occurring above the 10 cm level. Between 10 cm (ca. 1910) and 8 cm (ca. 1929) the inferred specific conductivity more than doubled, from 16 μS to 36 μS, in the lake. The inferred pH and specific conductivity at the surface of the core were within the range of values observed in the lake today.

Twenty one species of scaled chrysophytes were observed throughout the Lake Giles core, including *Synura petersenii*, *M. duerrschmidtiae*, *M. caudata* Ivanov, *M. akrokosmos* Ruttner in Pascher, *M. transsylvanica* Peterfi & Momeu and *M. pseudocoronata* Prescott (Figure 11). Although species abundances fluctuated throughout the core, several trends were observed. The most significant shift in the flora occurred in the lower portion of the core. At the very bottom of the core (ca. 1742) *S. petersenii* was rare accounting for only 4% of the flora, however, this taxon significantly increased to a high of 66% at the 24 to 25 cm mark (ca. 1776). Coupled with the sharp increase in *S. petersenii* at 24 to 25 cm was an equally sharp decrease in both *M. duerrschmidtiae* and *M. pseudocoronata*; these two species accounted for collectively 80% of the chrysophyte flora at the 26 to 27 cm level, but only 3% at 24 to 25 cm (Figure 11). By the 20 to 21 cm interval (ca. 1800) the abundance of *S. petersenii* had dropped to 14%, while *M. durerrschmidtiae* and *M. pseudocoronata* increased to a combined 61%.

In general, *S. petersenii* slowly increased in abundance between 20 cm and the surface of the core, while *M. pseudocoronata* also became less abundant above the 20 cm mark. Minor peaks of *M. trannsylvanica* and *M. caudata* were observed at the 4 to 6 cm level and the surface, respectively. Although the inferred pH of Lake Giles ranged from a low of 6.1 at 4 cm (ca. 1958) to high of 6.7 near the bottom, no significant trends were observed. Similarly, no significant trends in inferred specific conductivity, which ranged between 11 μS and 32 μS, were observed.

Discussion

The most obvious feature in the Lake Lacawac sediment cores is the four fold increase in magnetization in the top 10 cm of the sediment pile. The detailed mineral magnetic and SEM studies of sediment from this part of the lake cores suggest two possible causes for



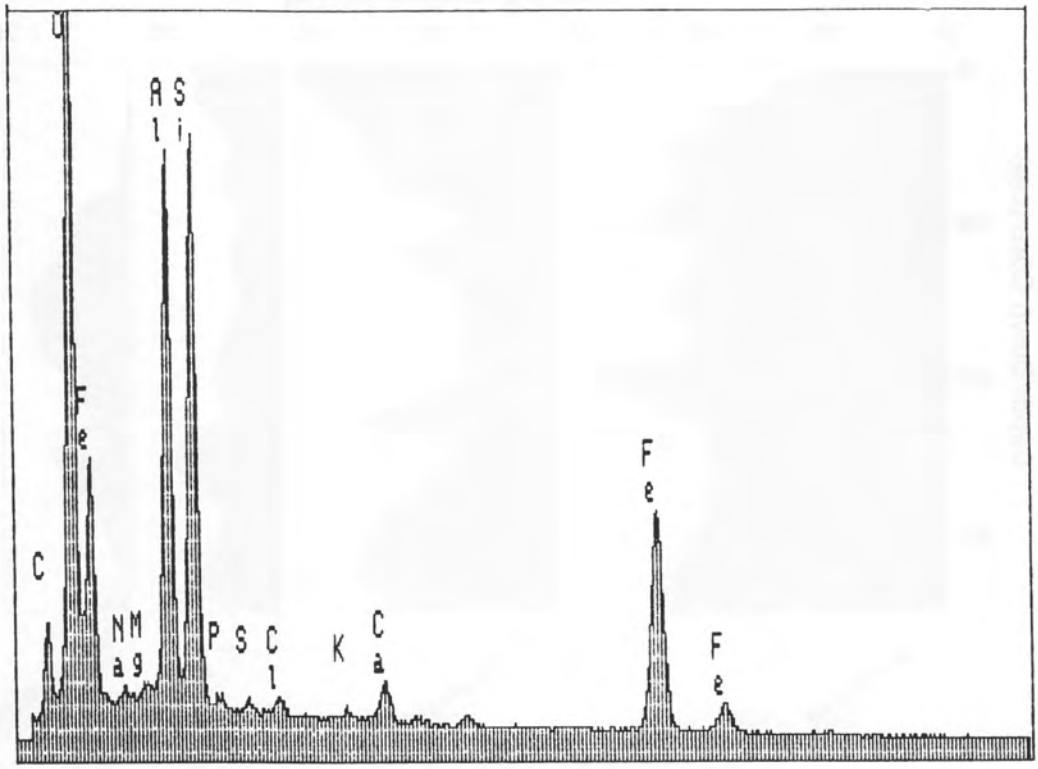


Figure 8. (top) SEM photomicrograph of microspherules in the magnetic extract collected from the top 10 cm of a Lake Lacawac core. The SEM image shows the two populations of microspherules observed in the magnetic extracts, 10–12 μm and 4–5 μm diameter spherules. (bottom) EDS (energy dispersive spectrometry) results from the small 45 μm microspherule in the center of the SEM photomicrograph showing Fe peaks. This suggests that the smaller microspherules are magnetic iron oxides. The larger microspherules did not contain Fe.

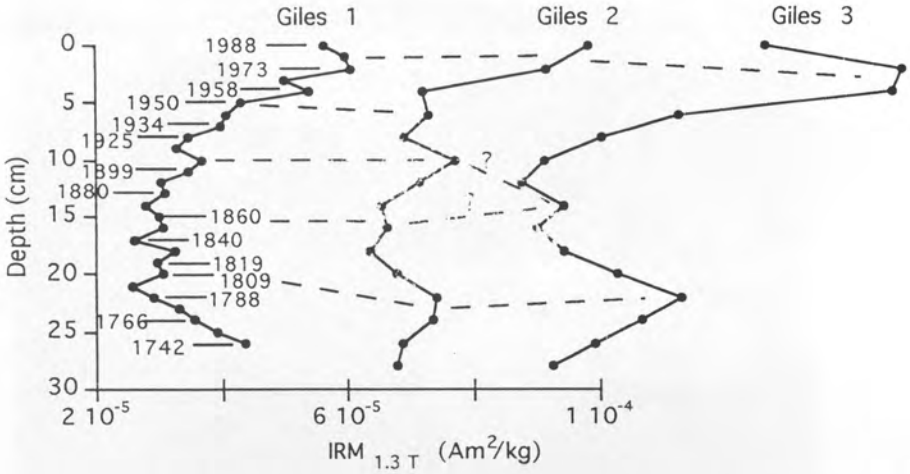


Figure 9. $IRM_{1.3T}$ versus sediment depth results for three cores from Lake Giles. Dashed lines show possible correlations between magnetic features. Dates are ^{210}Pb dates (in years A.D.) for core Giles 1 and show the core records deposition over the past 250 years.

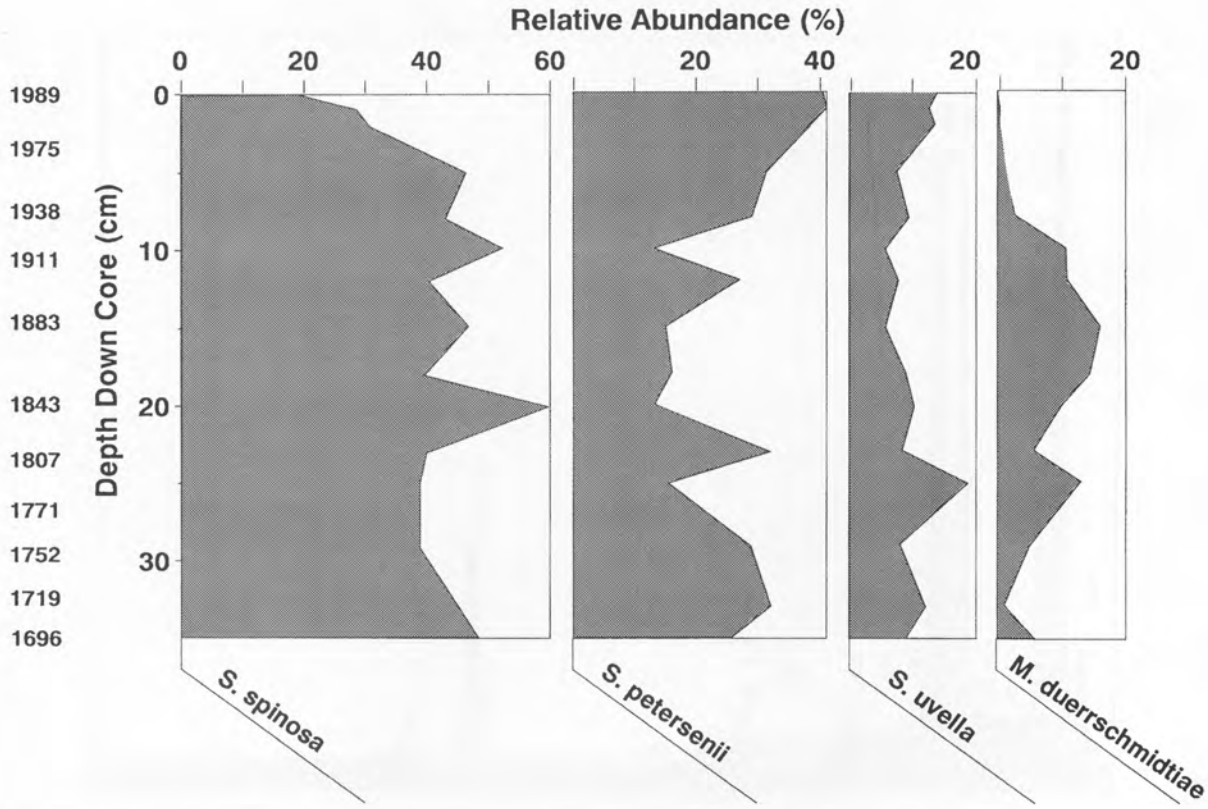


Figure 10. Stratigraphies of common taxa of scaled chrysophytes from a core taken from Lake Lacawac. Relative abundances of each species vs. depth in the core are illustrated.

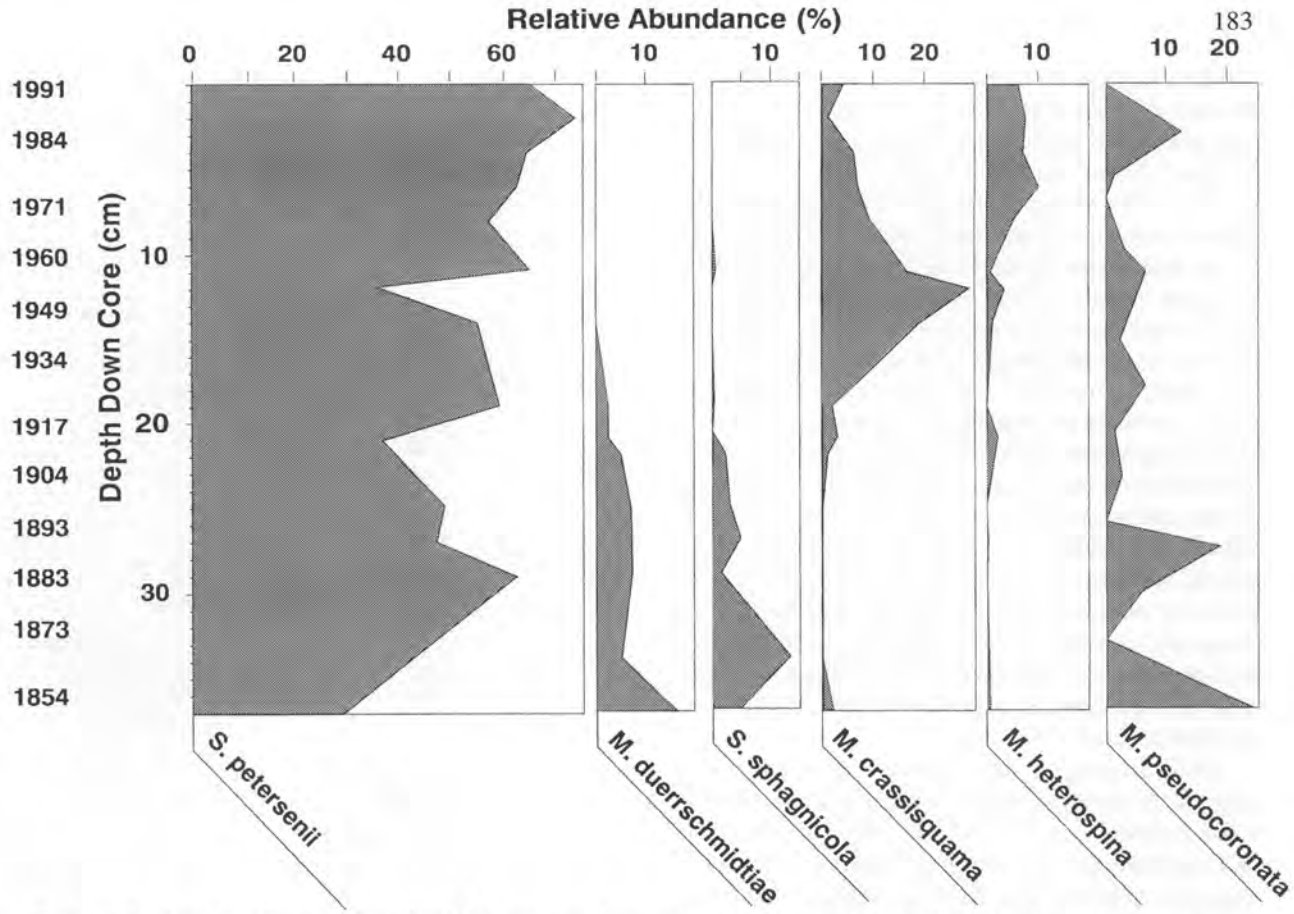


Figure 11. Stratigraphies of common taxa of scaled chrysophytes from a core taken from Lake Giles. Relative abundances of each species vs. depth in the core are illustrated.

this increase: atmospheric deposition of magnetic fly ash from electric power generating stations and land-use changes in the Lacawac catchment. The presence of magnetic fly ash in the youngest lake sediments is supported by the SEM images and EDS analyses which indicate 4–5 μm diameter, Fe-bearing microspherules in the magnetic extracts. These appear very similar in size and appearance to the ferrimagnetic magnetic particles created during the burning of fossil fuels in electric power stations (Ondov et al., 1979; Hansen et al., 1981; Lauf et al., 1982). The IRM acquisition results indicate the presence of ferrimagnetic minerals in the top 10 cm of the sediment column. In addition, the similarity of lower S ratios in the peat and the youngest lake sediments supports the hypothesis of atmospheric deposition of magnetic minerals into the Lake Lacawac catchment. Since peat bogs are built up above the ground water table they are not influenced by deposition from inflowing drainage and thus preserve a record of atmospheric deposition (Thompson & Oldfield, 1986). Oldfield et al. (1979) present evidence that the increase in magnetization in the top 2–6 cm of a peat bog in the English Lake District is due to the deposition of magnetic spherules discharged by fossil fuel combustion. Oldfield (1990) also appeals to atmospheric deposition of magnetic fly ash as the explanation for the increase in magnetic intensity in the uppermost sediments collected from Big Moose Lake in the Adirondak Mountains. The relatively high ratio of lake surface area to catchment area for Lake Lacawac would also enhance the importance of atmospheric sources for the lake sediments. Finally, the onset of the magnetic peak circa 1900 would suggest it could be related to the increase in industrialization in the northeastern United States in the past century. It is interesting to note that although the magnetics provide evidence of atmospheric deposition of products from fossil fuel burning during the past 100 years, there is little change in the inferred pH of the lake throughout the 300 year long sediment record. It is possible that changes in land

use have masked the effects of atmospheric deposition by increasing watershed inputs of alkalinity. A similar hypothesis was proposed for lakes in southern New England (Marsicano & Siver, 1993).

The ^{210}Pb dating of the Lake Lacawac sediments allows correlation of the double peaked magnetic high in the top 10 cm of the Lake Lacawac sediments to the large double peaked magnetic high reported for Lake Waynewood sediments (Lott et al., 1994), as well as the double peaked nature of the topmost magnetic high in one of the Lake Giles cores (Figure 12). This correlation may indicate that land-use changes in the Lake Lacawac catchment could also be an explanation for the increase in magnetization in the top 10 cm of the sediment column. Scaled chrysophyte results from Lake Waynewood, approximately 10 km distant from Lake Lacawac, show that lakewater specific conductivity increased threefold during the Waynewood magnetic high and that both parameters commenced to increase circa 1900 when historical records indicate that extensive logging started in the Lake Waynewood catchment (Lott et al., 1994).

IRM acquisition data indicates that the strong increase in magnetization observed in the bottom of Lake Lacawac cores 150SE and 200SE is due to the influx of material containing highly coercive, antiferromagnetic minerals. Soil IRM acquisition results suggest that this material comes from deep in the soil profile collected from the southern shore of the lake. Neither the weathered nor the fresh Catskill Formation bedrock contains any antiferromagnetic minerals. The IRM data for the soils collected from the east shore of the lake, as well as the top soil from the southern lake shore sites, show that these materials contain very little antiferromagnetic minerals. The most likely source is the deeper part of the soil profiles collected from the southern lake shore. If the magnetic peaks observed in the bottom of cores 150SE and 200SE can be correlated with the bottom half of the double peak observed in the more northwesterly Lake Lacawac sediment cores, or the small peak just below, this would suggest that deep soil erosion occurred early in the 20th century in the southern part of the Lake Lacawac catchment. This interpretation would lend further support for a land-use change explanation for at least the lower part of the magnetic high observed in the top 10 cm of Lake Lacawac sediments.

The change in land use hypothesis for Lake Lacawac is also supported by the scaled chrysophyte record. The most significant shifts in species abundances correlated with the abrupt increase in

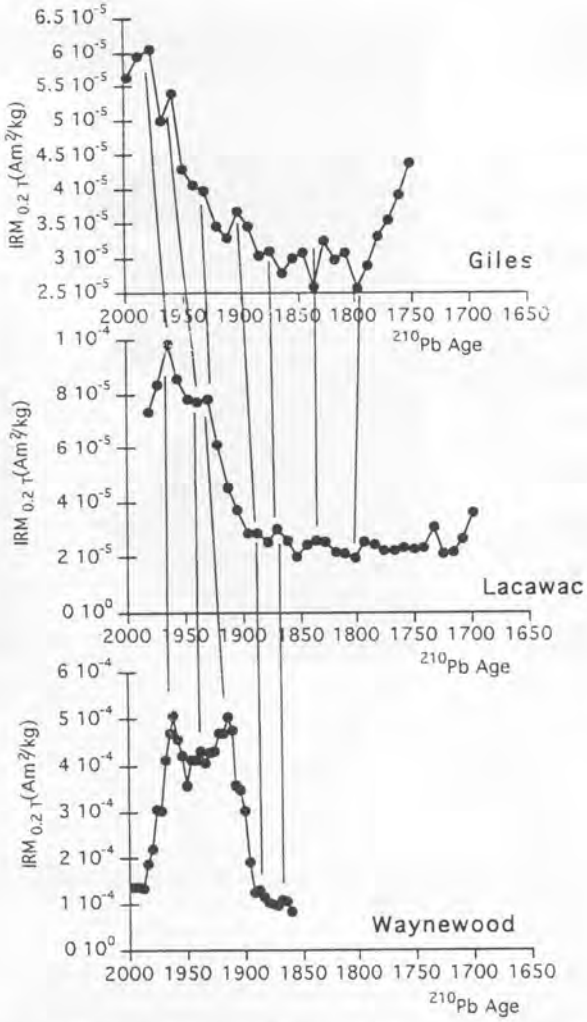


Figure 12. $IRM_{0.2T}$ versus ^{210}Pb date (in years A.D.) for cores collected from Lakes Giles, Lacawac and Waynewood and sampled in 1 cm intervals. The tie lines show the correlation between the onset of the large amplitude magnetic high circa 1900 and the small amplitude, 50 year long magnetic variations observed in all three lakes back to circa 1800. These correlations occur even though the lakes are located in separate watersheds.

magnetization at the 10 cm mark. Above 10 cm *M. duerrschmidtiae* decreased in importance and was absent in surface sediment. Likewise, other species, such as *S. petersenii*, increased significantly. Declines in *M. duerrschmidtiae* have been linked to anthropogenic alterations in nearby watersheds including logging (Lott et al., 1994), and urbanization and farming (Marsicano & Siver, 1993), as well as acidic deposition (Cumming et al., 1992). The known declines in M. duerrschmidtiae have often been coupled with increas-

es in *S. petersenii* (Marsicano & Siver, 1993; Lott et al., 1994).

Land-use changes in the Lake Lacawac catchment, as well as atmospheric deposition of magnetic fly ash, could account for the large increase in magnetization which commences circa 1900. However, before the onset of the large magnetic changes in both Lake Lacawac and Lake Waynewood circa 1900 there appear to be small amplitude, 50 year long variations in magnetic intensity which apparently correlate between the two lakes (Figure 12). Unfortunately, the Waynewood record only extends to circa 1850 (Lott et al., 1994), so it is not possible to see whether these small variations correlate further back in time. Lake Giles, approximately 20 km distant from Lake Lacawac and almost 30 km from Lake Waynewood, shows similar recent, large changes in lake sediment IRM intensities. The magnetic high in the top 10 cm of the Lake Giles sediment cores does not increase as rapidly as similar highs in the Lake Lacawac or Lake Waynewood sediments, but ^{210}Pb dating indicates that the magnetic high commenced soon after A.D. 1900. It is possible that this high, like at Lake Lacawac, is due to a combination of land-use changes in the Lake Giles catchment and atmospheric deposition of magnetic fly ash. Unlike the Waynewood and Lacawac cores where distinct changes in the scaled chrysophyte flora were correlated with increases in magnetization, the scaled chrysopyte flora did not noticeably change in the top of the Giles cores. Interestingly, the pre-A.D. 1900 Lake Giles sediment magnetics record also shows small amplitude, approximately 50 year long variations in magnetic intensity which appear to correlate with those observed in Lake Waynewood back to circa 1850 and to those seen in Lake Lacawac to circa 1800 (Figure 12).

Fast Fourier transform (FFT) and MTM (Multi-Tapered Method) spectral analysis of the lake sediment magnetic intensity record indicates power in long periods of several hundred years (Figure 13). This is probably the frequency-domain expression of the high magnetic intensities commencing at A.D. 1900 due to land-use change in the catchments. The FFT and MTM spectra also suggest the presence of power in an approximately 50 to 70 year period in the lake sediment magnetic intensity record. This is probably the signature of the small amplitude, approximately 50 year long variations we observe in the ^{210}Pb-dated lake sediment IRM intensity record (Figure 12). Unfortunately the shortness of our records may obscure the significance of these peaks. In light of this limitation of the dataset the 50 year long variations were isolated with band-pass filtering. The band-pass filter was centered at a 45 year period and passed frequencies with periods between 31 and 83 years. The filtering would also serve to reduce the effect of the land-use changes that commenced at A.D. 1900.

This Gaussian filter was also applied to the historic rainfall records from New York City (World Weather Records, 1959; Bair, 1992) and the eastern US reconstructed to Philadelphia (Landsberg et al., 1968; Baron, 1992) and the Palmer Drought Severity Index (PDSI) record derived from dendrochronology for the northeastern United States (factor 2 in Cook et al. (1992)). Comparison of the Gaussian-filtered historic rainfall and dendrochronology records shows good correlation between the historic records to the end of the NYC record at A.D. 1869 and good correlation between the historic and the dendrochronologic records only until about A.D. 1900 (Figure 14). Before A.D. 1900 there appears to be a 30–40 year offset between significant peaks in the historical rainfall at Philadelphia and dendrochronological records. For this reason the dendrochronological record was not used further for comparison to the lake sediment magnetics records. Although it is likely that Landsberg et al. (1968) used the New York City record in part to derive the historic record reconstructed to Philadelphia, the correlations emphasize that there is meaningful content in the rainfall and dendrochronology records in the 50 year period range. Therefore it is reasonable to compare the Gaussian-filtered historic rainfall records from New York City and Philadelphia to the Gaussian-filtered IRM intensity records from the ^{210}Pb-dated lake sediments (Figure 15). The Gaussian-filtered data show good correlation between the IRM intensity fluctuations and the historic rainfall variations with typical linear correlation coefficients of about 0.6 and strong correlation between the magnetics from the different lake catchments with correlation coefficients of about 0.7 to 0.8. The almost 50 year offset needed to bring the older portion of the Lake Giles record into agreement with the Lake Lacawac record may be due to errors in the ^{210}Pb dating technique for ages greater than 150 years.

Since the magnetics correlate across watersheds and with rainfall from both NYC and the eastern US reconstructed to Philadelphia, the signal is apparently regional and is not controlled by local microclimates in the Poconos. The approximately 1 mm yr^{-1} sediment accumulation rate for these lakes dictates that the 1–2 cm thick mineral magnetic samples average

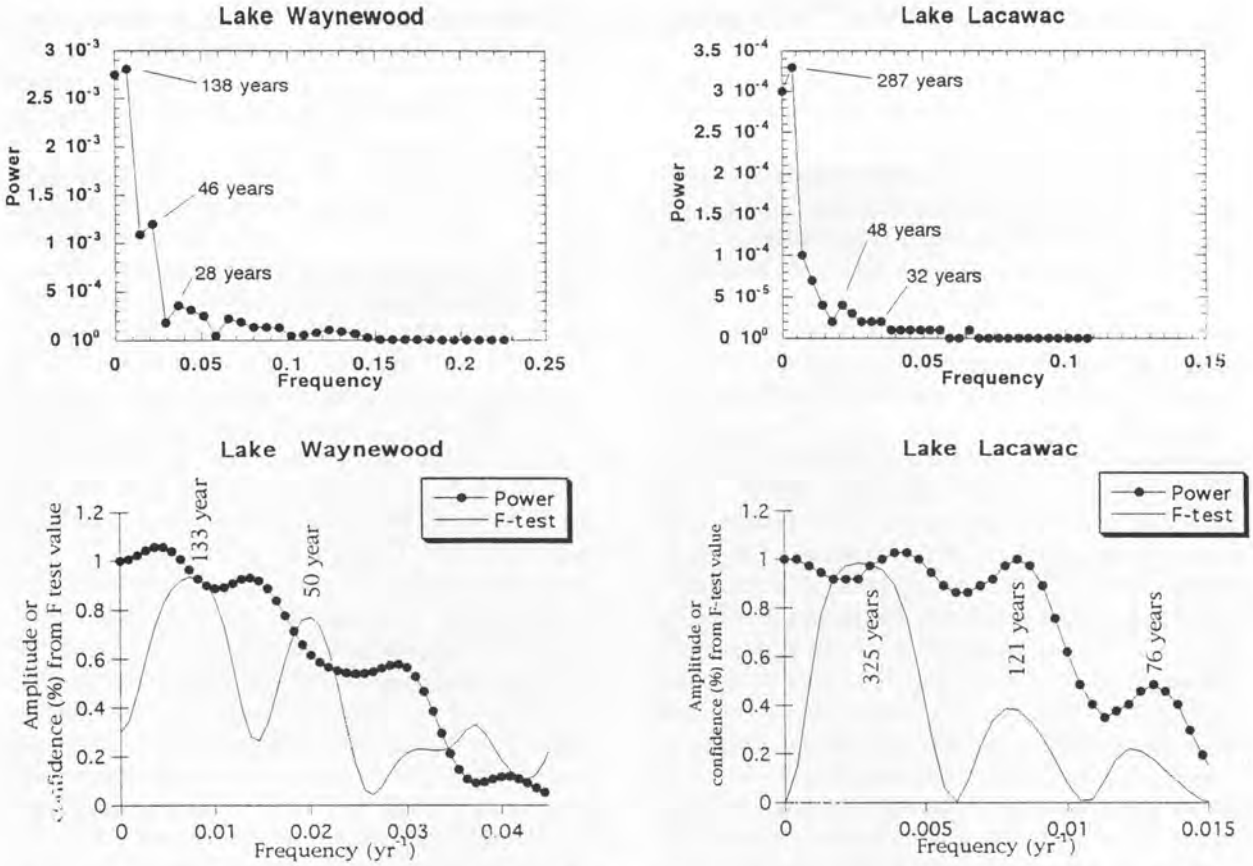


Figure 13. (top) FFTs of ^{210}Pb-dated IRM intensity variations for Lakes Lacawac and Waynewood. (bottom) MTM (MultiTapered Method) spectral analysis of the same data. IRM curves were interpolated with a cubic spline before spectral analysis to provide a regularly-spaced time series. The F-test parameter in the MTM spectra provides a measure of the confidence of peaks. A value of 0.8, for example, indicates 80% confidence that the peak is not white noise. In the MTM spectra the amplitudes have been normalized to the largest peak. Note the power at long (100s of yrs) periods and 50–70 year periods.

time over 10–20 years, hence this method could only resolve 50 year or longer fluctuations.

The most robust IRM intensity signal comes from Lake Waynewood. This is probably due to Waynewood having the largest catchment area and being the only lake with streams transporting sediment from the catchment into the lake. This observation suggests that the mechanism for the rainfall-IRM intensity fluctuations is a simple erosional model. The magnetic mineral concentration signal could originate, then, from dilution by increased influx of nonmagnetic materials or, if the sediment accumulation rate is constant, from small variations in the influx of magnetic minerals into the lake. The latter model would predict a direct correlation between rainfall and IRM intensity peaks. The ^{210}Pb dating used in this study does not have the accuracy to resolve this, however, Dearing and Flower's (1982) study of sedimenting material in Lough Neagh which showed a direct correlation between susceptibility and monthly precipitation would suggest a direct correlation rather than the anticorrelation between rainfall and IRM intensity peaks the dilution model would predict. The Dearing and Flower (1982) study correlated rainfall and magnetic mineral concentration over a much shorter time scale (months) and their results may not be applicable to correlations made over 50 year or longer periods.

IRM intensity can be sensitive to variations in a sediment's magnetic grain size distribution, so another possibility is that the rainfall-IRM intensity correlation observed is due to variations in the magnetic grain size distribution. In this case subtle changes in the source, or variations in the contributions from several sources,

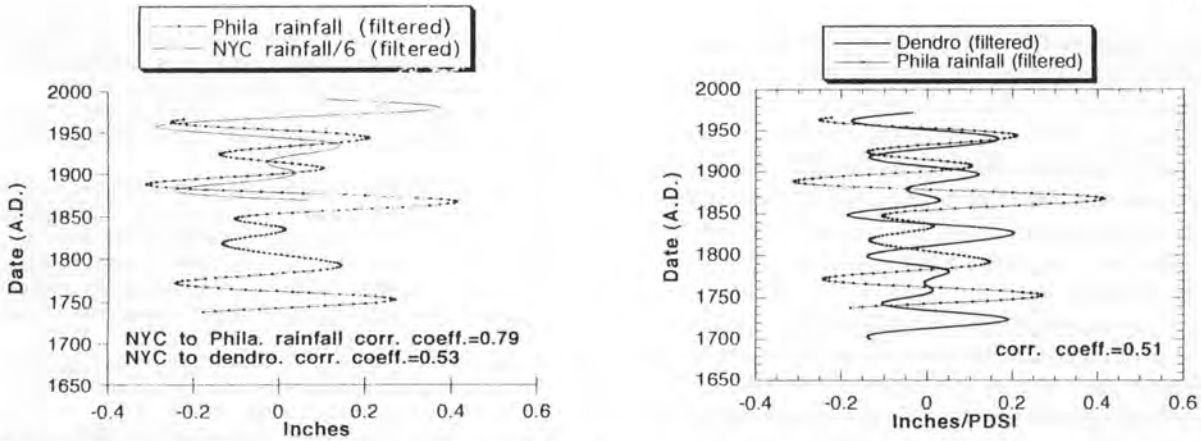


Figure 14. Comparison of Gaussian-filtered historic rainfall records and dendrochronological estimates of soil moisture (PDSI, Palmer Drought Severity Index). The historic records are from New York City, which is 150 km to the southeast, and for the eastern US reconstructed to Philadelphia, which is 200 km to the south of the study area. The PDSI is for the northeastern US. The New York City rainfall record has been divided by 6 to allow more accurate comparison to the Philadelphia rainfall record. The correlation between the historical records from NYC and Philadelphia is quite good ($r = 0.79$) while the correlation of the historic records to the dendrochronological record ($r = 0.53$ and 0.51) becomes poor before A.D. 1900. These results suggests the existence of a regional rainfall signal with a period of about 50 years.

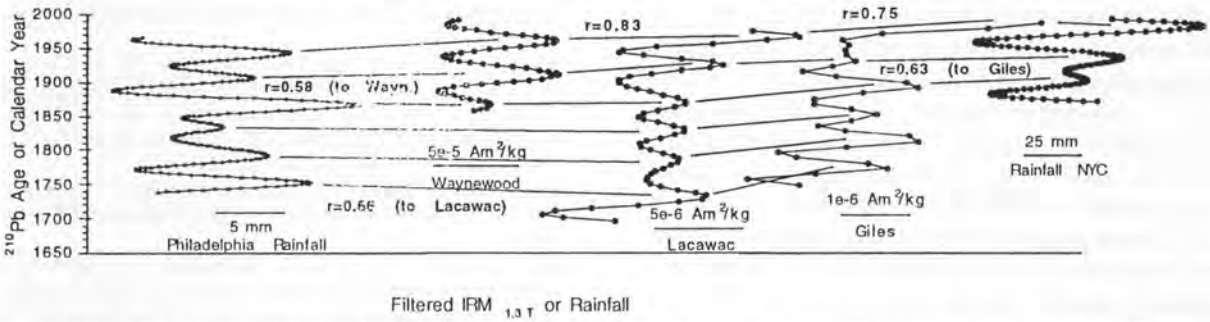


Figure 15. Correlation between Gaussian-filtered historic rainfall records from New York City and Philadelphia (see Figure 14) and Gaussian-filtered IRM intensity (magnetic concentration) records from Lakes Giles, Waynewood, and Lacawac. The tie lines show the correlations used for calculating the correlation coefficients. Representative correlation coefficients are shown between lake sediment magnetic concentration records and between rainfall and lake sediment magnetic concentration records. Scalebars show magnetic intensities and rainfall for each record. These results suggest that magnetic mineral concentration variations in lake sediments can record regional variations in rainfall and may be used as a paleoclimatic measure.

of the magnetic minerals may vary with precipitation in the watershed.

The delivery of magnetic minerals to the watershed during a rainstorm will probably be sensitive to conditions in a lake's catchment (e.g. vegetation cover and type). This possibility could be one explanation for the lack of a direct correlation between amplitudes of the historic rainfall fluctuations and amplitudes in the IRM intensity variations (Figure 15). Another possibility is that the erosional model is too simple and that the IRM intensity variations are indirectly related to rainfall fluctuations through chemical or biologic processes. Increased rainfall, for example, could wash more organics or nutrients into the lake and create conditions that would enhance biologic production of magnetic minerals (greigite or magnetite) or chemical reactions that could cause either production of secondary magnetic minerals or dissolution of primary ones.

Conclusions

A combined mineral magnetic and scaled chrysophyte study of lake sediments from Lake Lacawac and Lake Giles in northeastern Pennsylvania indicates that a large increase in magnetic intensity in the top 10 cm of the sediment column may be due to both land-use changes in the watershed that commenced circa 1900 and atmospheric deposition of magnetic fly ash gener-

ated by increased fossil fuel burning in the northeastern United States during the past 100 years. Changes in land use patterns in the watershed of a third lake, Lake Waynewood, were also previously correlated with significant changes in both magnetic intensities and scaled chrysophytes. The large increases in magnetic intensities in Lake Lacawac and Lake Waynewood were both coupled with a significant increase in specific conductivity inferred from the shifts in the abundances of scaled chrysophyte taxa. A similar change in the top section of the Lake Giles core was not noted for scaled chrysophytes. It is also of interest that although our results support the idea that the region has been receiving atmospheric deposition from the burning of fossil fuel since circa 1900, the inferred lake water pH has not significantly declined in any of the three lakes.

Small amplitude, 50 year long variations in the magnetic intensity of Lake Lacawac sediments correlate with similar magnetic variations in Lake Giles and Lake Waynewood sediments for at least the past 150 years and as far back as 200 years. This across-watershed correlation of magnetic intensity variations may be a record of regional rainfall variations since they correlate with rainfall variations measured at New York City back to the 1880s and eastern US rainfall reconstructed to Philadelphia back to the 1740s. If future work supports this conclusion, magnetic intensity variations in lake sediments may provide a new method to monitor climate change on a regional scale.

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