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Sediment magnetic properties reveal Holocene climate change along the Minnesota prairie-forest ecotone

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Abstract

We propose a model that explains variations in magnetic parameters of lake sediments as a record of Holocene climate change. Our model is based on records from four lakes and incorporates the effects of erosion, dust deposition, and the authigenesis and diagenesis of the magnetic component of the sediment. Once checked against high resolution multi proxy climate records, which are currently being established for some of our study sites, it will allow us to use magnetic proxies to establish high-resolution climate reconstructions on a regional scale.

Our model utilizes a combination of concentration-dependent parameters (magnetic susceptibility, IRM) and grain-size-dependent parameters (ARM/IRM, hysteresis parameters). Magnetic mineralogy is characterized by a combination of low-temperature measurements and S-ratios, and our magnetic measurements are complemented by XRD, LOI and smearslide analyses.

During periods of forest growth within the watershed, deposition of terrigenous material is low and the sediment magnetic properties are characterized by low concentrations of mainly authigenic minerals (low values of IRM, high ratios of ARM/IRM). During the early to mid-Holocene dry period, deposition of terrigenous material increased due to intensified dust deposition and the erosion of lake margins caused by lowered water levels. Concentration of magnetic minerals increases (high IRM, χ) and so does the grain-size of the magnetic fraction (low ARM/IRM). During the late Holocene, sediment magnetic properties depend on the varied position of the site with respect to the prairie–forest ecotone.

Introduction

Widespread interest in climate change and the likely anthropogenic causes for global warming underscore the need for robust, high-resolution studies of paleoclimate change. Such studies allow us to establish baselines of natural climate variability, to estimate the rates of climate change and to provide high-quality data for testing climate models for their ability to reproduce past climate change. Rock-magnetic parameters of lake sediments reveal lithologic changes that can reflect environmental responses to changes in paleoclimate. In contrast to paleomagnetic techniques, which are concerned with the reconstruction of the geomagnetic field, rock-magnetic studies attempt to characterize the magnetic components of a geologic sample in terms of mineralogy, concentration and particle-size distribution of magnetic minerals. This information can then be used for a variety of purposes, e.g., to assess the role of 'recording noise' in paleomagnetic reconstructions or, as in this study, to reconstruct paleoclimatic change.

Magnetic techniques are in general non-destructive, highly sensitive, fast and inexpensive, and samples can

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later be used for other studies. This allows for the processing of large numbers of samples (several 1000) in relatively short time (weeks) in order to establish high-resolution paleoclimate records. Examples of recent applications of rock-magnetic methods to paleoenvironmental reconstructions include Peck et al. (1994) who analyzed sediments from Lake Baikal and Almquist-Jacobson et al. (1992) who included magnetic measurements in a multi-proxy study to better characterize lithologic changes observed in small Minnesota lakes. Vlag et al. (1997) and Stockhausen and Thouveny (1999) studied several small volcanic lakes in southern France, and Geiss and Banerjee (1997) compared rock-magnetic analyses to the pollen record from a kettle lake in southern Illinois. Additional case studies can be found in Thompson and Oldfield (1986) or Reynolds and King (1995).

However, rock-magnetic parameters are not paleoclimate proxies *per se*. They need to be interpreted in terms of climate by establishing a model that links rock-magnetic variations to climatic change. Such a model is best based on multi-proxy analyses that include both magnetic and non-magnetic techniques.

In this study we measure an identical set of magnetic parameters for four sites in Minnesota to show the response of rock-magnetic properties to large-scale (~500 km) regional patterns of climate change and to develop a regional model that can explain large-scale rock-magnetic changes in our study area. The wealth of paleoclimatic information, collected over the last five decades, makes Minnesota an ideal location for such a study. It should be kept in mind that the high-frequency signal observed in many sites is likely due to a combination of regional and local changes. Its interpretation requires more accurate dating than is currently available as well as the combination of magnetic and non-magnetic techniques of reconstruction. Studies to address these problems are currently under way and will be presented in the future.

Methods

Multiple overlapping sediment cores were obtained in January of 2000 and 2001 with a modified Livingston corer (Wright, 1967). Cores were brought to the core facility of the University of Minnesota's Limnological Research Center, where they were split lengthwise and photographed. Initial core description included macroscopic observations and analyses of smear slides from characteristic horizons. For Kimble Pond, Sharkey Lake and Kirchner Marsh, carbonate and terrigenous fractions were quantified by loss on ignition (LOI) (Dean, 1974). At Steel Lake the relative heights of the quartz and calcite XRD peaks were used to measure the relative influx of terrigenous material. Biogenic silica (Conley, 1998) was measured for samples from Kimble Pond and Sharkey Lake to correct LOI measurements for the presence of diatoms. For magnetic analyses samples were taken from one half of the core and placed in plastic boxes with a volume of 5.28 cm^3. Sample spacing was 1.0 cm for Kimble Pond, 0.5 cm for Steel Lake, and approximately 1.8 cm for Sharkey Lake and Kirchner Marsh.

Magnetic analyses attempt to characterize the magnetic component of the sediment in terms of mineralogy, particle-size distribution and abundance. Volume-normalized magnetic susceptibility (κ) can be used as a first estimate of the abundance of magnetic minerals, such as magnetite/maghemite or hematite. Susceptibility measurements were performed with a Kappabridge KLY-2. Because κ is also influenced by para- and diamagnetic minerals, its interpretation may be less straightforward than the interpretation of magnetic remanence parameters. Isothermal Remanent Magnetization (IRM) acquired in magnetic fields of 100–1500 mT reflects the presence of ferrimagnetic and, to a lesser degree, imperfect antiferromagnetic minerals. It was also used to estimate the concentration of magnetic minerals. Anhysteretic Magnetic Remanence (ARM), acquired in a peak alternating field of 100 mT and a bias field of 50 μT, is strongly influenced by the presence of small single-domain (SD) and small pseudo-single-domain (PSD) particles (Hunt et al., 1995), and the ratio of ARM/IRM can be used to characterize the relative importance of fine SD particles with respect to larger pseudo-single-domain (PSD) or multi-domain (MD) particles. In our experiments we used IRM acquired in a field of 100 mT to avoid the contribution of high-coercivity grains to the ratio of ARM/IRM. S-ratios in a saturating field of 1500 mT and backfields of –100 and –300 mT characterize the presence of magnetically hard minerals, such as hematite and goethite, and SD particles (Robinson, 1986; Bloemendal et al., 1992). Isothermal remanence was acquired in the DC field of an electromagnet. ARM was imprinted with a D-Tech 2000 alternating field demagnetizer. All remanence parameters were measured with a cryogenic magnetometer (2G-model 760-R). Hysteresis loops were measured to estimate bulk particle-size (Day et al., 1977) and to quantify the influence of para- and diamagnetic minerals by using the high field slope

(χ_{hf}) of the loops (Dunlop and Özdemir, 1997). All hysteresis loops were measured in a maximum field of 800 mT using a vibrating sample magnetometer (VSM) built at the Institute for Rock Magnetism. A Quantum Design Magnetic Properties Measurement System (MPMS 5S) was used to measure magnetic properties at low temperatures between 300 and 5 K. Low-T demagnetization of room-temperature remanence can reveal the presence of the Verwey and Morin transitions (Verwey et al., 1947; Morin 1950), which indicate the presence of magnetite and hematite respectively. Thermal demagnetization curves of low-temperature remanence, acquired after cooling in zero field (ZFC) or during cooling in the presence of a magnetic field (FC) can show phase transitions diagnostic of pyrrhotite (Rochette et al., 1990) and magnetite (Moskowitz et al., 1989; Özdemir et al., 1993) or the ordering temperature of siderite (Housen et al., 1996). Due to the often high concentration of organic matter, which has been shown in earlier studies to lead to alteration of the magnetic fraction during heating above 200–300 °C, we did not attempt to measure Curie temperatures.

Studied sites

For this study we investigated four lacustrine records. Three sites, Kimble Pond, Sharkey Lake and Kirchner Marsh are aligned along a NE–SW transect in southern Minnesota, while Steel Lake is situated in north central Minnesota (Figure 1).

Kimble Pond and *Sharkey Lake* are two small kettle lakes in the Altamont stagnation moraine (Hobbs and Goebel, 1982). Kimble Pond, east of Mankato, MN (44°13′15″N, 93°50′24″W), is approximately 250 m in diameter and has a maximum depth of 16 m. Sharkey Lake, west of New Market, MN (44°35′39″N, 93°24′49″W), is slightly larger (700 × 400 m), consists of two basins and has a maximum depth of 15 m in the SE basin. Kimble Pond is located to the west of the present prai-

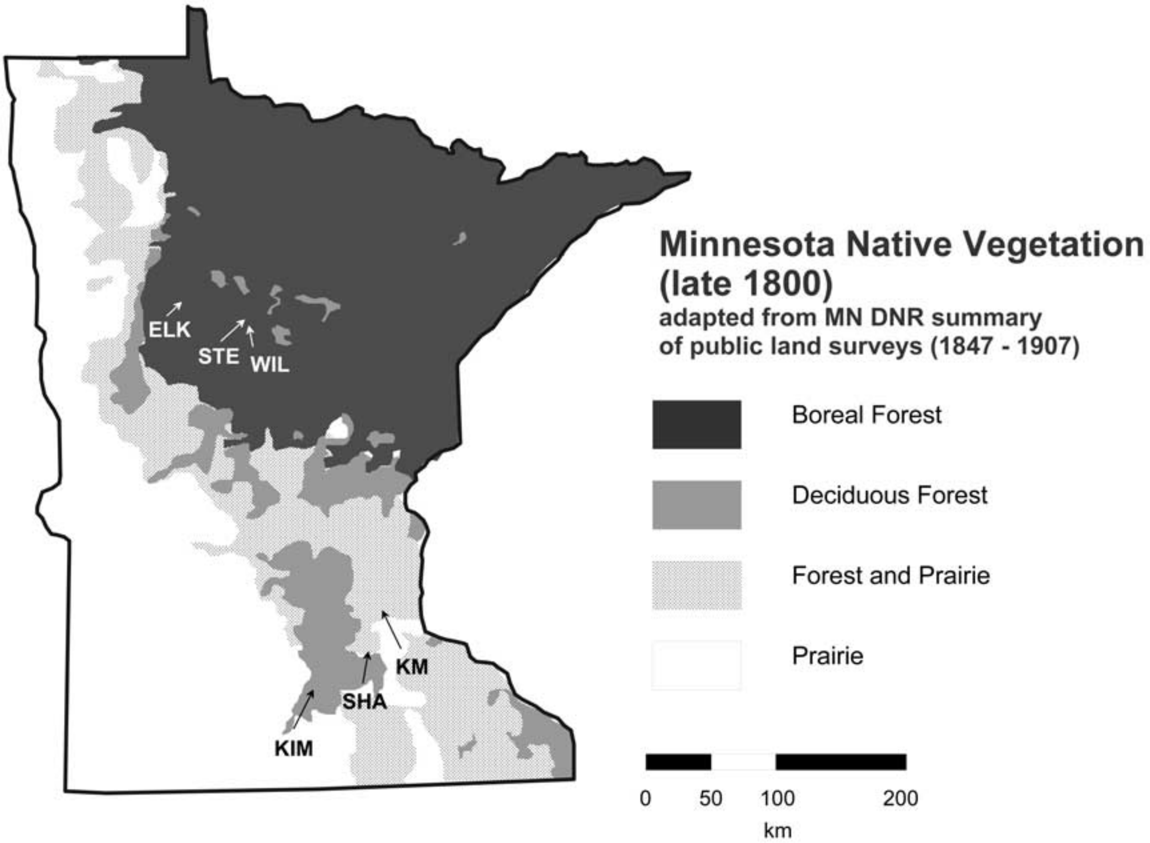

Figure 1. Map of Minnesota showing the locations of sites mentioned in the text. KIM = Kimble Pond, SHA = Sharkey Lake, KM = Kirchner Marsh, STE = Steel Lake, ELK = Elk Lake, WIL = Williams Lake.

rie–forest border, while Sharkey Lake is situated at the present ecotone (Grimm, 1984). Sediments in both lakes are partly laminated organic muds (Figures 2a and 3a). Age control for Kimble Pond is based on eight AMS ^{14}C dates obtained from wood and charcoal (see Table 1 for a summary of all ^{14}C dates). The chronology of Sharkey Lake is based on seven AMS dates from charcoal and plant macrofossils.

Kirchner Marsh is a former kettle lake located south of St. Paul (44°46′18″N, 93°06′36″W) in the St. Croix moraine (Hobbs and Goebel, 1982). Its climatic history has been studied previously using pollen and macrofossil analyses (Wright et al., 1963; Watts and Winter, 1966) as well as diatom assemblages (Florin and Wright, 1969; Brugam, 1980). The sedimentary record beneath a capping of peat consists of sapropel and organic muds (gyttja) with variable amounts of plant detritus and silt (Figure 5a). Low resolution magnetic properties have been studied by (Geiss and Banerjee, 1999) and our chronology is based on lithologic comparisons with previously dated records (Brugam, 1980). Two ^{14}C dates obtained for the new cores confirm our preliminary chronology. Kirchner Marsh was cored again in 2001 and resampled for magnetic studies, LOI and plant-macrofossil analyses.

Low-T demagnetization of room-temperature SIRM for selected samples from Kimble Pond and Sharkey Lake (gray curves in Figure 4) show the slight presence of a Verwey transition, indicating the presence of (partially oxidized) magnetite (Özdemir et al., 1993). FC and ZFC curves (solid and dashed curves in Figure 4) are very similar for most samples, except for some horizons where differences in FC and ZFC behavior below 40 K indicate the presence of siderite (Figure 4c)

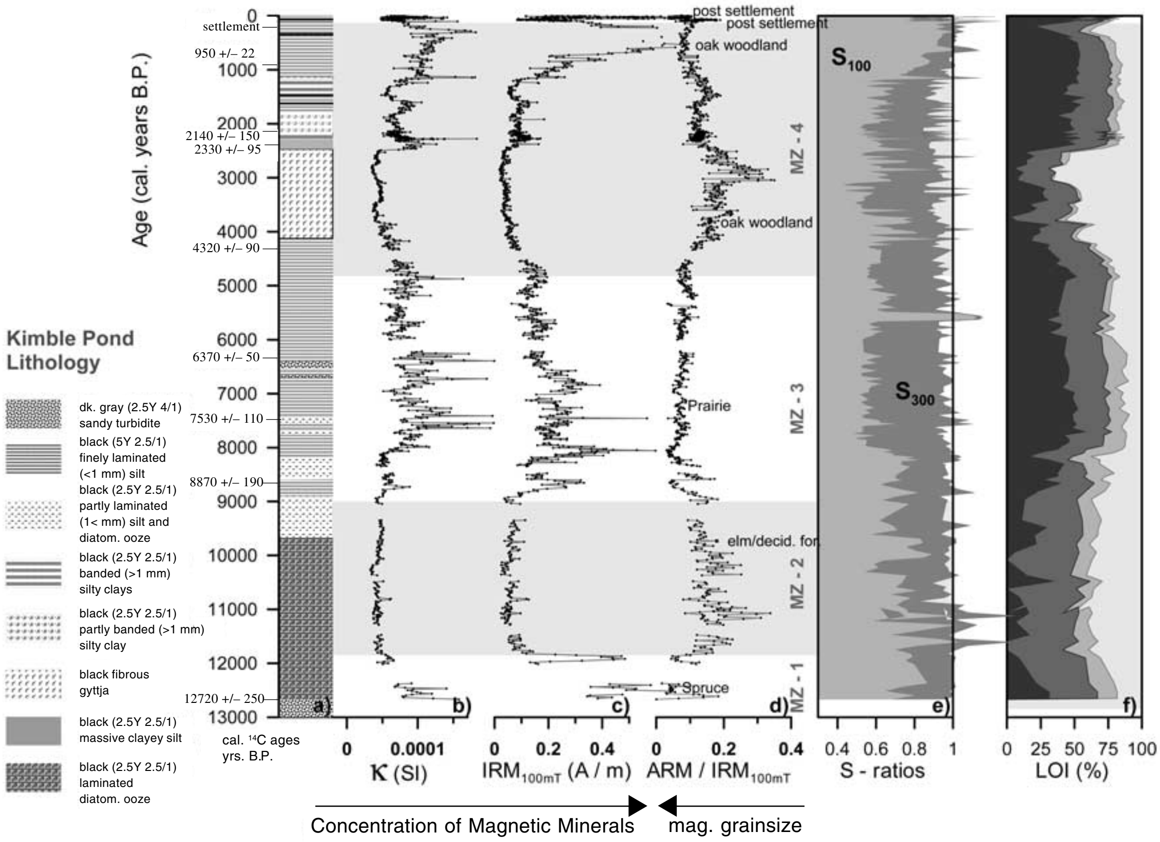

Figure 2. Kimble Pond lithology and magnetic parameters. Magnetic susceptibility (b) and IRM (c) are both concentration-dependent parameters, while ARM/IRM (d) can be used as a grain-size proxy. (d) also contains a summary of our preliminary pollen analyses. S-ratios (e) are close to 1 for magnetically soft minerals (magnetite, maghemite) and <1 for magnetically hard minerals (hematite, goethite). S-ratios using a backfield of –100 mT are plotted in light gray shading, S-ratios using a backfield of –300 mT are plotted using dark gray shading. Loss on ignition (f) is used to quantify the amount of clastic material present in the samples. Plotted are from darkest to lightest shading: clastic component (LOI residue – biog. Si), biogenic silica, carbonate minerals, total organic matter.

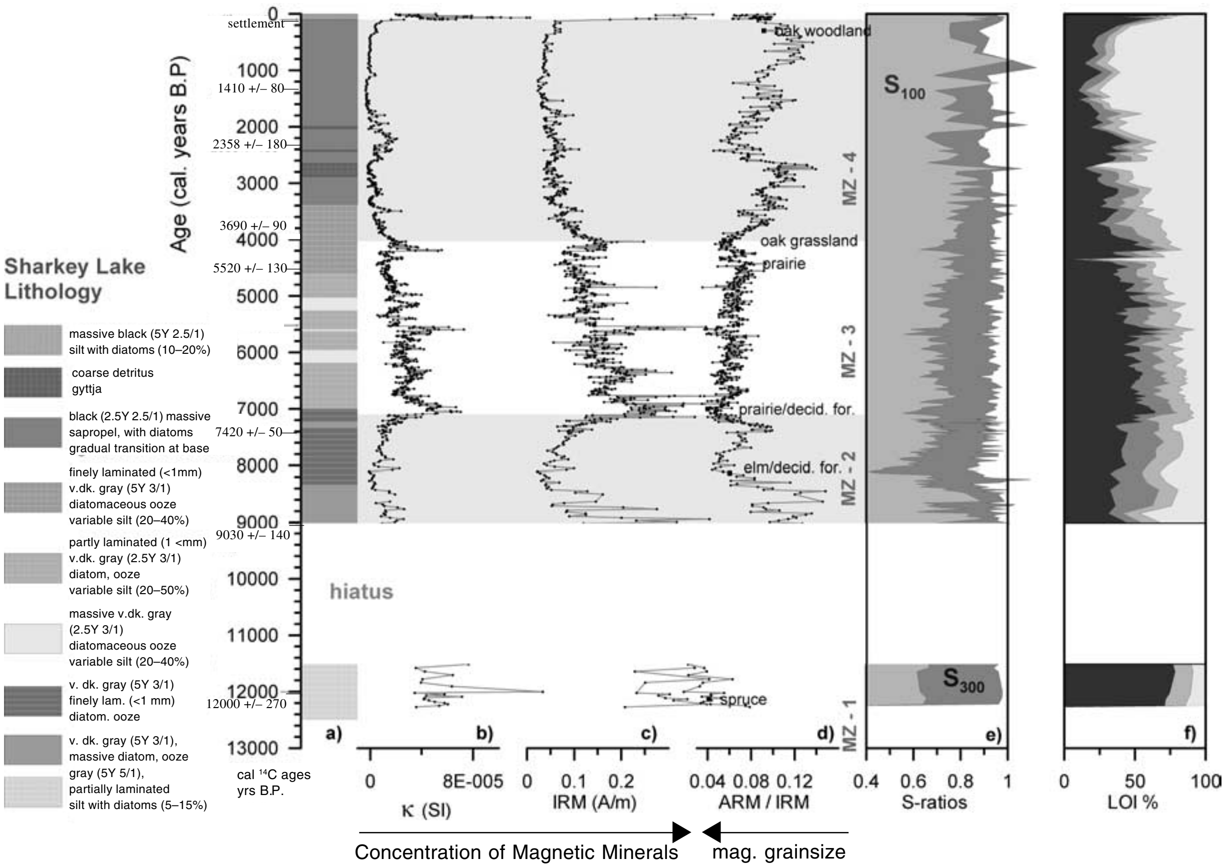

Figure 3. Sharkey Lake lithology and magnetic parameters. For more information see text or caption to Figure 2.

(Housen et al., 1996). Sharp drops in both FC and ZFC curves below 10 K are due to the presence of paramagnetic particles in many of the studied samples (Figure 4a). S-ratios (Figures 2e and 3e) are close to 1 for backfields of 300 mT suggesting magnetically soft ferrimagnetic minerals (magnetite or maghemite) as the main carrier of magnetic remanence. Ratios of S_{100} as low as 0.5 during the early and mid-Holocene indicate the additional presence of either SD ferrimagnets or magnetically harder antiferromagnetic minerals, such as hematite or goethite (Robinson, 1986; Bloemendal et al., 1992). Low-temperature analyses performed on sediments from Kirchner Marsh (Geiss and Banerjee, 1999) reveal partially oxidized magnetite as the main magnetic mineral. During the early to mid-Holocene the additional presence of antiferromagnetic minerals leads S_{100}-ratios as low as 0.5.

Figures 2, 3 and 5 show a summary of important magnetic parameters for Kimble Pond, Sharkey Lake and Kirchner Marsh. The magnetic records of all three sites show similar relative changes in abundance (as expressed by κ or IRM) and particle-size distribution (as expressed by ARM/IRM) of the magnetic component. The basal glacial sediments are highly magnetic, having values of κ and IRM that can be orders of magnitudes higher than in the sediments from upper horizons. These basal samples have been omitted from Figures 2, 3 and 5 in order to show variations in the much more weakly magnetized Holocene sediments. Late-glacial lake sediments (magnetic zone 1 or MZ-1 in Figures 2, 3 and 5) are often strongly magnetic and coarse-grained. They are characterized by a combination of high κ or IRM and low ARM/IRM ratios. Early-Holocene sediments (magnetic zone 2) have high organic content and low concentrations of magnetic minerals. The magnetic grains present tend to be small SD grains, leading to a combination of low κ and IRM, but high ratios of ARM/IRM. During the early to mid-Holocene (magnetic zone 3 in Figures 2, 3 and 5) sediments experienced increased input of terrigenous

Table 1. ^{14}C-ages for Kimble Pond and Sharkey Lake

Sample	Description	Lab code	^{14}C age	1 σ max. cal. age (cal. age intercepts) min. cal. age
Kimble Pond				
KIM 19.73–75	Charcoal	69887	1040 ± 50	972 (950) 927
KIM 21.54–56	Charcoal	69888	2150 ± 80	2307 (2146, 2139, 2125) 2004
KIM 23.34–35	Charcoal	79286	2270 ± 60	2347 (2329) 2159
KIM 26.01–02	Charcoal	79285	3890 ± 50	4414 (4350, 4327, 4299) 4240
KIM 28.57	Wood	65374	5590 ± 50	6409 (6398, 6368, 6350) 6305
KIM 29.66	Wood	65373	6620 ± 50	7568 (7555, 7540, 7506) 7432
KIM 31.39	Wood	65365	7910 ± 50	8977 (8697, 8670, 8651) 8604
KIM 34.05	Wood	65364	10570 ± 50	12844 (12790, 12741, 12643) 12368
Sharkey Lake				
SHA 16.31–33	Charcoal	83724	1530 ± 50	1515 (1410) 1349
SHA 17.46–47	Charcoal	79288	2410 ± 50	2705 (2358) 2350
SHA 20.01	Charcoal	77858	3630 ± 40	4055 (3961, 3949, 3927) 3872
SHA 23.65	Charcoal	77860	4730 ± 60	5585 (5567, 5557, 5470) 5327
SHA 28.65	Charcoal	77859	6840 ± 50	7687 (7671) 7613
SHA 29.76–79	Seed, charcoal	79289	8130 ± 120	9266 (9028) 8993
SHA 29.90–92	Charcoal, spruce needle	83725	10255 ± 45	12310 (12067, 12038, 11957) 11769
Kirchner Marsh				
KM 6.10	Sedge	AA44389	6780 ± 120	6851 (6776, 6774, 6750) 6676
KM 7.25	Sedge	AA44387	7590 ± 90	7768 (7609, 7598, 7590) 7572

Samples were measured at Lawrence Livermore National Laboratory and University of Arizona (lab codes beginning with AA) and calibrated using Calib V.4.01 (Stuiver and Reimer, 1993; Stuiver et al., 1998).

material as expressed in LOI measurements (Figures 2f, 3f and 5f). In this interval sediments have higher concentrations of magnetic minerals but are also coarser-grained, leading to high values of κ and IRM combined with low ratios of ARM/IRM. S_{100} ratios as low as 0.6 (Kimble Pond, Figure 2e) and 0.7 (Sharkey Lake, Figure 3e) indicate the presence of an additional magnetic phase in this interval, such as hematite or goethite (Robinson, 1986; Bloemendal et al., 1992). Low ARM/IRM ratios in this interval show that these low S_{100}-ratios are due to mineralogic changes rather than the addition of magnetically harder SD grains.

The magnetic properties of late-Holocene sediments (magnetic zone 4 in Figures 2, 3 and 5) depend on the position of the site with respect to the prairie-forest ecotone. Sediments at Kirchner Marsh (Figure 5) are characterized by low concentrations of fine-grained particles (low κ and IRM combined with high ratios of ARM/IRM), very similar to sediments found in magnetic zone 2. At Sharkey Lake and Kimble Pond the magnetic properties are more variable. However, magnetic concentration and particle-size are still anti-correlated and sediments have properties similar to those in magnetic zones 2 and 3 respectively. Post-settlement sediments make up the uppermost horizon of most sites except at Kirchner Marsh, where the upper 2 m of peat deposits are not included in this study. The magnetic properties of these sediments are highly dependent on human-induced soil erosion and changes in productivity, leading to highly variable and site-specific results. These sediments will be discussed in detail elsewhere when more data collected in the watersheds of these lakes become available.

Steel Lake is a glacial lake SE of Walker, MN (46°58′30″N, 94°40′55″W) and is situated in the Itasca/St. Croix interlobate area (Winter, 1997). Sediments consist of gray to dark brown calcareous muds rich in diatoms and organic matter. Laminations are present throughout most of the core except for the early- to mid-Holocene hypsithermal, when lake levels were presumably lower, and laminations are only poorly preserved or are entirely absent. Due to the high concentration of diatoms and authigenic carbonates (>90%) we estimated relative changes in terrigenous input from XRD analyses from the relative peak height of quartz (Figure 7f). Dating efforts using a combination of varve counts and detailed AMS dating are currently under way (Hu, pers. commun.), but no reliable chronology is available at this point. Age estimates to delineate the major paleoenvironmental shifts are based on

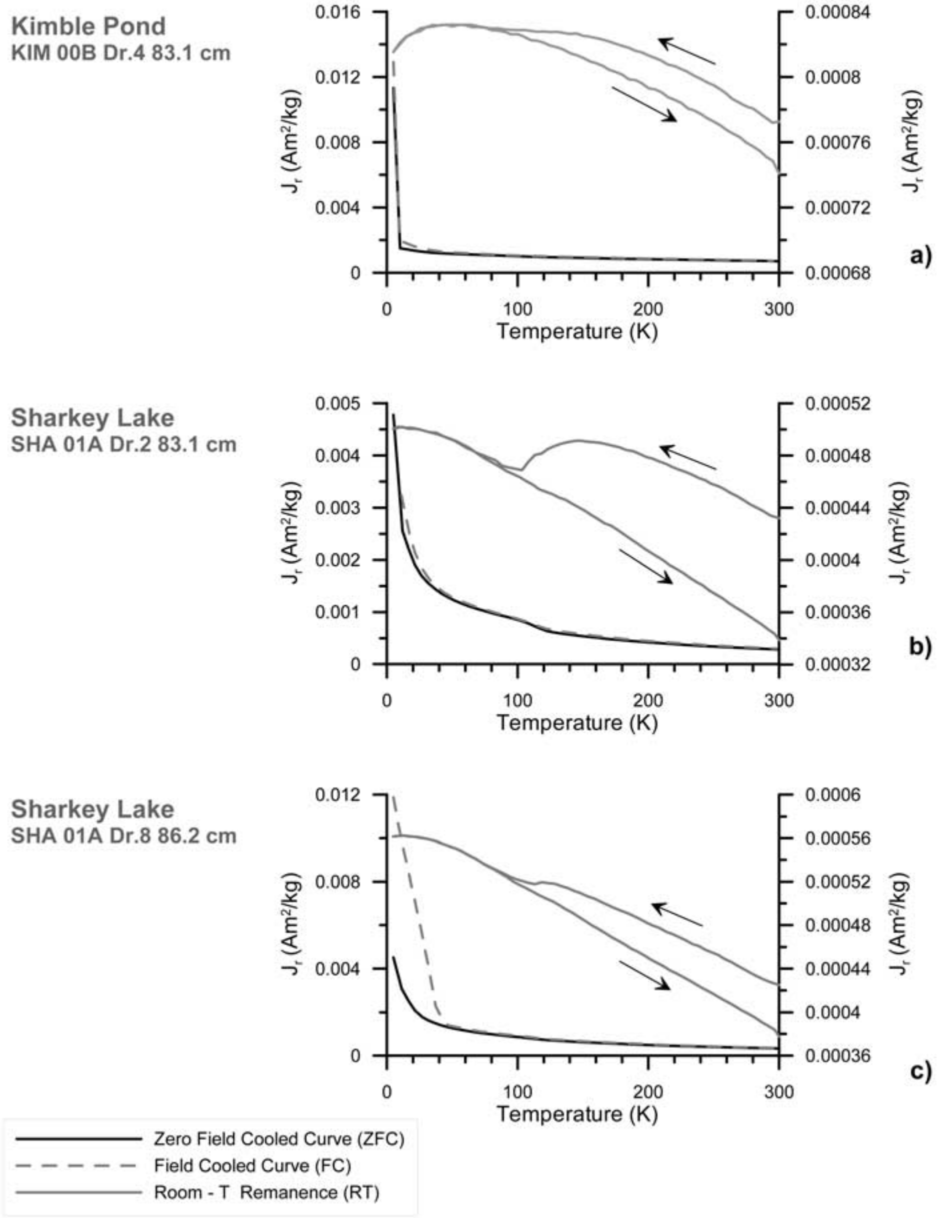

Figure 4. Low-temperature analyses for selected samples from Kimble Pond and Sharkey Lake. (a) Curve dominated by paramagnetic component and (partially oxidized) magnetite (Verwey transition visible in RT curve), (b) Sample dominated by magnetite (Verwey transitions visible in all 3 curves), (c) Sample containing siderite (difference in FC and ZFC below 40 K).

lithologic comparison (input of terrigenous material) with nearby lakes. The increased input in terrigenous material between 26.5 and 31 m is correlated with similar increases observed at Elk Lake (Dean, 1993) and Williams Lake (Locke and Schwalb, 1997) (Figure 1) and is placed in the early to mid-Holocene dry period.

Low-temperature measurements reveal the presence of partially oxidized magnetite throughout the entire core (Figure 6a), with additional occurrence of siderite (Figure 6b), especially between 30.8 and 31.7 m depth. Magnetic susceptibility κ is highly variable throughout the core and is characterized by a mixture of para- and ferrimagnetic minerals. Early lake sediments (magnetic zone 2, Figure 7) are characterized by low concentrations of magnetic minerals, which results in low values of IRM. High ratios of ARM/IRM indicate that

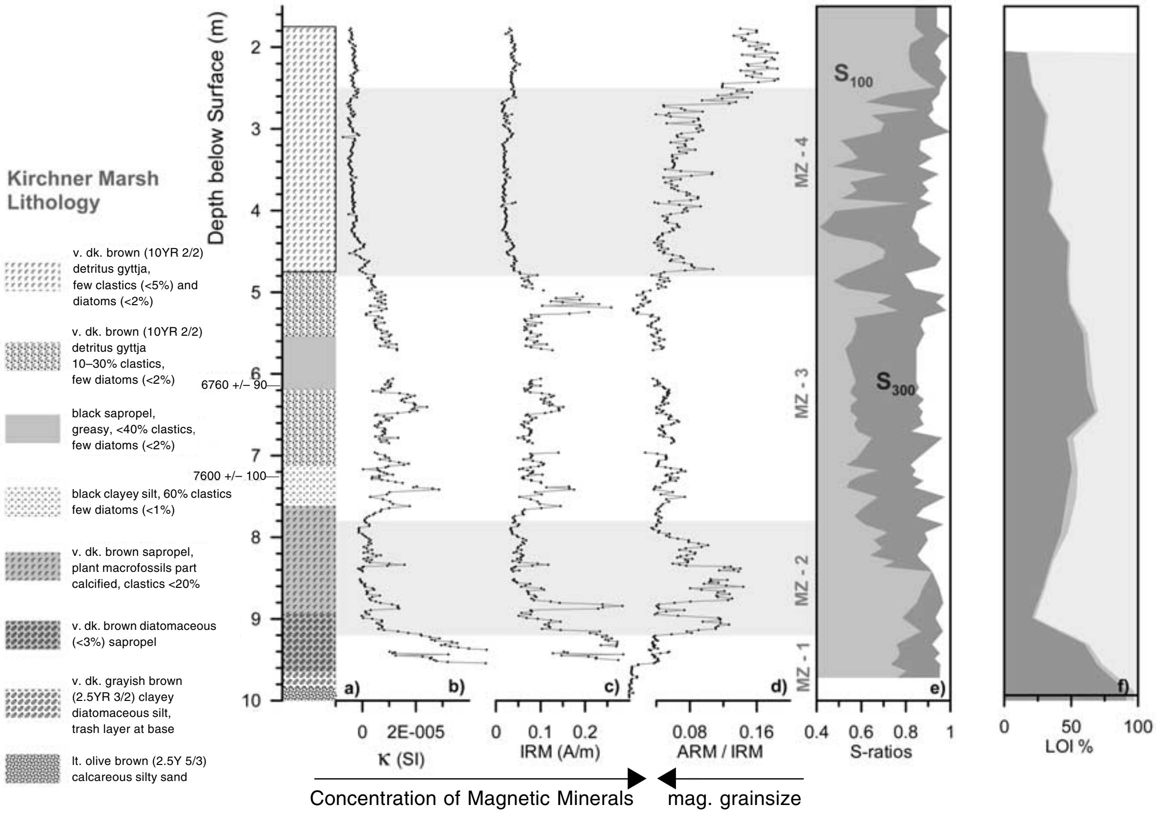

Figure 5. Kirchner Marsh lithology and magnetic parameters. For more information see text or caption to Figure 2.

they are mostly SD and small PSD grains. High values of κ combined with low IRM attest to significant paramagnetic contributions in this interval. Early and mid-Holocene sediments (magnetic zone 3 in Figure 7) are characterized by slightly higher, though variable, concentrations of remanence-carrying coarse-grained (MD) iron oxides, corresponding to increasing terrigenous input (Figures 7c and 7f). These changes lead to higher values in IRM combined with a drop in ARM/IRM ratios similar to magnetic zone 3 in the southern sites. No significant changes in S-ratios are observed. Late-Holocene sediments show low concentrations of remanence-carrying minerals and high variations in ARM/IRM. A sharp increase in concentration and grain-size-dependent parameters at 23.4 m depth is estimated to occur at approximately 1500–2000 yrs BP, based on our preliminary varve chronology. Post-settlement variations of magnetic properties are recorded in a freeze core but not shown in Figure 7, for they are mainly influenced by changes in land use and not directly a function of paleoclimatic change.

Processes that can affect sediment-magnetic properties

Several processes are likely to affect the concentration, particle-size distribution and mineralogy of the lake sediments studied. Dilution of (highly magnetic) terrigenous sediment by weakly-magnetic or non-magnetic biogenic sediments can be caused by changes in lacustrine productivity or input of terrigenous material. It primarily affects the concentration of magnetic minerals and can be detected in variations of magnetic susceptibility or IRM. Dilution per se does not affect the particle-size distribution, but high concentration of organic matter can lead to highly anoxic sediment conditions, which favor reductive dissolution of iron oxides. Dissolution affects both the concentration and particle-size distribution of the magnetic component. Initially, smaller particles are preferentially removed because of their higher surface to volume ratios, leading to a coarsening of the magnetic component. In the final stages of the dissolution process, however, only

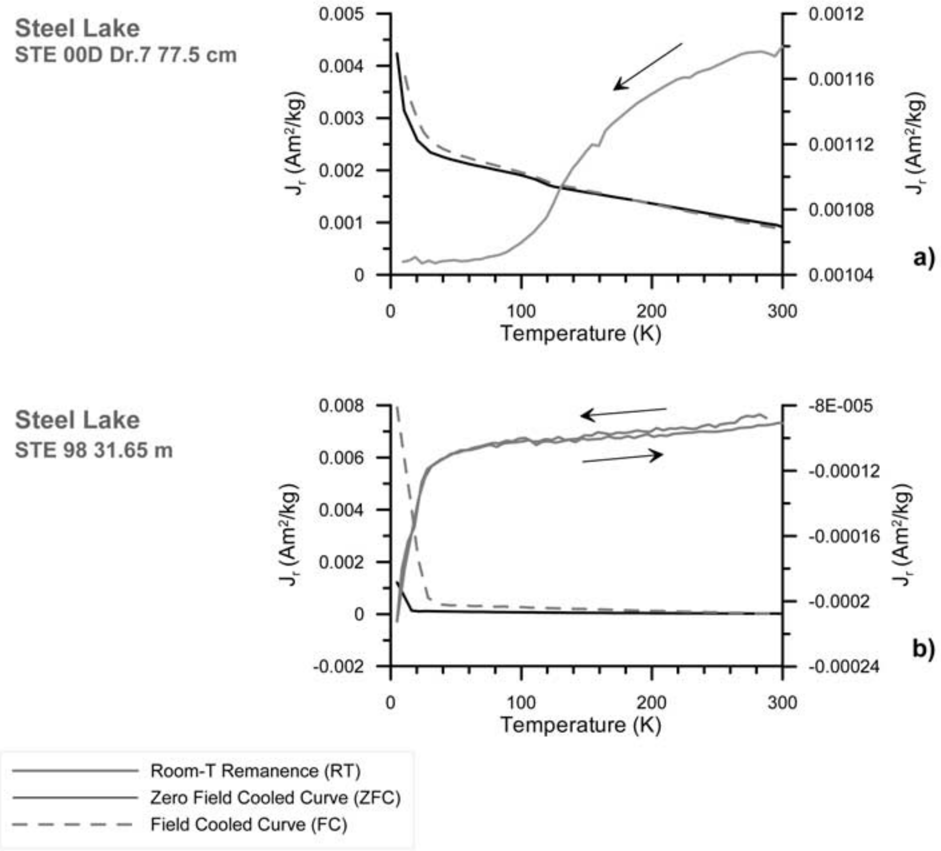

Figure 6. Steel Lake low temperature analyses for selected samples. (a) Sample containing magnetite, (b) sample dominated by siderite. Drop in RT curve at low temperatures is due to non-zero, slightly negative field during low-temperature 'demagnetization' leading to a acquisition of a thermoremanent magnetization (TRM) by the siderite phase.

very small remnants of magnetic grains remain and the magnetic grain-size can become very small (Tarduno, 1995). All lake sediments from the deep, poorly oxygenated part of the lake basin are likely to be affected by dissolution processes to some degree. Sediments less to be affected by dissolution, such as, glacial sediments, found at the base of most of our cores, and debris flows and turbidites, which originate from shallower, often better oxygenated regions, tend to be more magnetic than deep-water sediments. Authigenic mineral formation can be caused by biotic and abiotic processes. Magnetotactic bacteria (Petersen et al., 1989) produce narrowly sized SD magnetite, which is likely to dominate the magnetic properties of Kirchner Marsh in magnetic zones MZ-2 and MZ-4 (Geiss and Banerjee, 1999). This authigenic component may be present throughout the history of the lake, but it is likely to be overshadowed by terrigenous magnetic minerals. Authigenic siderite occurs in some horizons of our sites that may be characterized by combinations of high magnetic susceptibility but low magnetic remanence (e.g., Steel Lake > 30.5 m and Figure 6b). Changes in terrigenous input affect the top meter of the Steel Lake record and many post-settlement sediments. They often reflect the effects of soil erosion either due to changes in lake level or anthropogenic activity.

The large-scale magnetic variations for all four sites involve changes in magnetic concentration and grain-size (magnetic zones 1–4). Intervals with higher concentrations of terrigenous material are generally characterized by higher concentrations of magnetic minerals, which tend to be coarser-grained (MD). Intervals high in organic matter or authigenic sediments, on the other hand, show low concentrations of magnetic minerals consisting of small (SD to PSD) particles. These changes can be explained by a mixing model involving a strongly magnetic, coarse-grained terrigenous component superimposed on an authigenic fine-grained (SD) com-

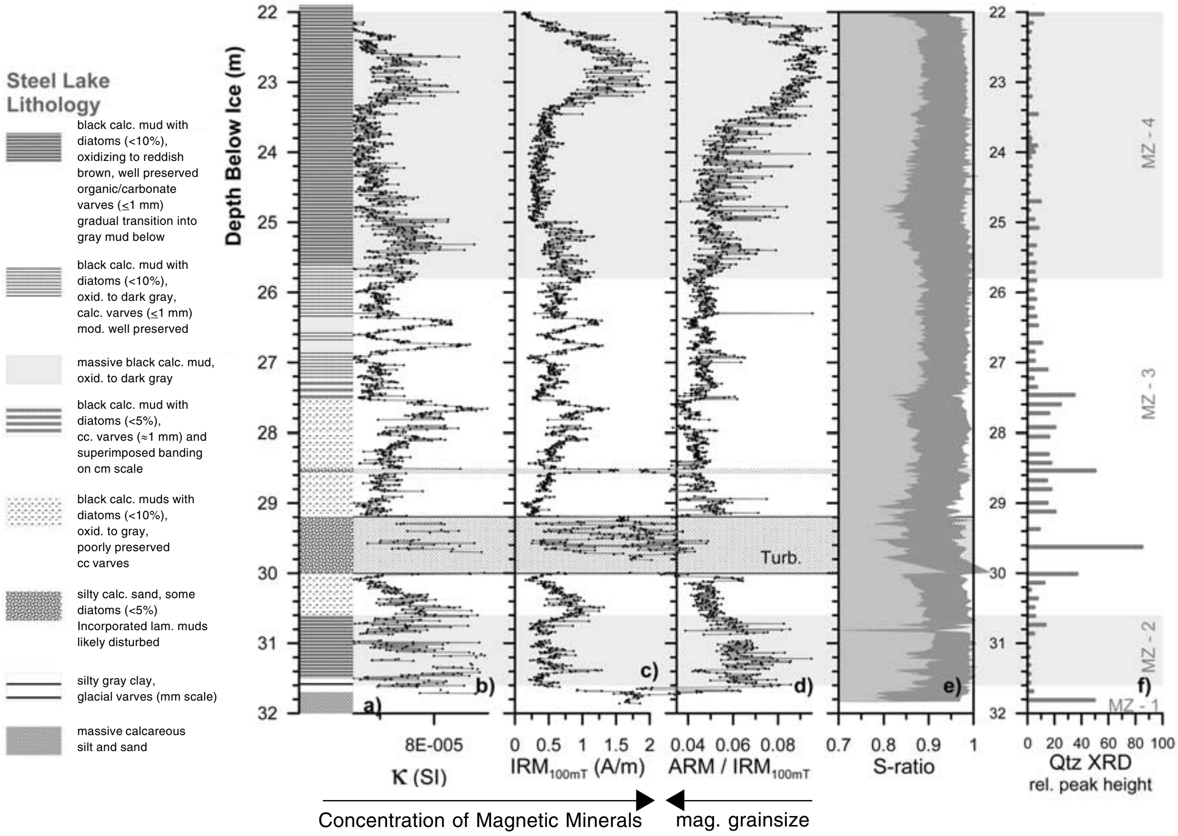

Figure 7. Steel Lake lithology and magnetic parameters. For more information see text or caption to Figure 2f) estimate of clastic input using relative peak height of quartz peak.

ponent, which may occur throughout the entire record but can only be detected when terrigenous input into the lakes is low. Dilution of magnetic minerals by organic or authigenic non-magnetic matter can explain many of the variations in magnetic susceptibility and IRM. Figure 8 compares some magnetic parameters of Sharkey Lake with the concentration of clastic material. Figures 8a and 8b show that there is excellent qualitative correlation between IRM and the abundance of clastic material, demonstrating the effects of dilution on the magnetic properties. However, correlation between IRM and clastic concentration is low as shown in Figure 8c. It partially suffers from the fact that the two parameters were not determined from the same sample or exactly the same depth (LOI and biogenic Si were determined from a different sample set). However, some of the scatter is certainly due to the effects of dissolution or subtle changes in mineralogy and grain-size. At Steel Lake the correlation between IRM and relative abundance of quartz is worse (Figure 9a). The reasons are likely the already low abundance of terrigenous material combined with intense dissolution of magnetic minerals in the anoxic environment of these varved sediments. Magnetic grain-size, as expressed (inversely) by the ratio of ARM/IRM, also correlates with the concentration of terrigenous input (Figures 8d and 9b). This relationship holds even for Steel Lake, where only a weak correlation exists between terrigenous input and concentration-dependent parameters (Figure 9a). According to our interpretation this correlation is due to initial particle-size differences between terrigenous and authigenic magnetic minerals. While the terrigenous component tends to be coarse (MD or PSD), authigenic grains are likely to be small (SP or SD). Dissolution can only decrease the size of magnetic particles, so sediments characterized by terrigenous input are likely to remain coarser-grained than sediments that contained only small authigenic grains initially.

As an alternative explanation we can consider a magnetic signal that is mainly driven by dissolution processes. Sediments rich in organic matter would undergo

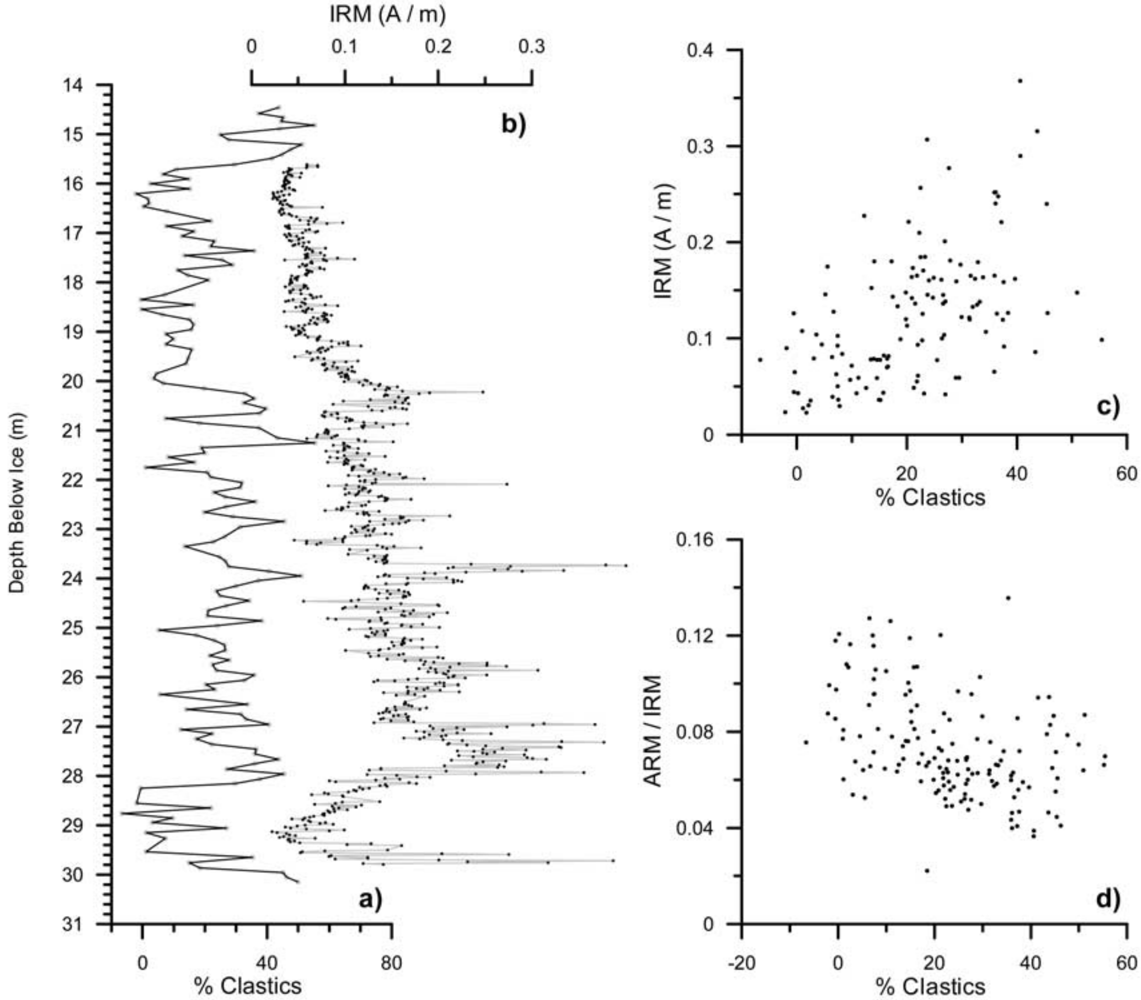

Figure 8. Sharkey Lake (a) variations of clastic component and (b) IRM with depth, (c) scatter plot of IRM vs. clastic component, (d) scatter plot of ARM/IRM vs. clastic component.

increased reductive dissolution, leading to a decrease in concentration and, provided dissolution is intense enough, a decrease in magnetic grain-size. We consider this scenario less likely for the following reasons: four sites with widely differing limnologic conditions show a consistent concentration and grain-size signal throughout the Holocene. Since the SD grain-size range is rather small (0.03–0.06 μm) (Dunlop, 1973) dissolution processes in all sites would have to remove just enough material from PSD to MD sized particles (1–10's of μm) to arrive at a very narrow range of SD grains, but would have stopped short of dissolving the entire population of magnetic grains, a process that seems unlikely for all of the examined sites. Authigenic processes, on the other hand, tend to produce small particles and magnetotactic bacteria are known to produce SD grains within a very narrow grain-size range. The top and bottom sediments of Kirchner Marsh (MZ-2 and MZ-4), for example, are dominated by magnetite of likely magnetotactic origin (Geiss and Banerjee, 1999) and authigenic minerals are a likely source of fine-grained magnetic minerals in the other sites as well.

Erosion of soils is likely to contribute to the terrigenous sediment observed in all sites. Many soils in Minnesota and elsewhere show an enhancement in fine-grained (SD and often SP) magnetic material in the uppermost soil horizons (e.g., Özdemir and Banerjee, 1982). However, our study of several soil profiles in southern Minnesota shows that pedogenic magnetite is unable to produce the fine-grained material observed during early and late Holocene forest periods. Table 2 lists ARM/IRM ratios for five soil profiles that devel-

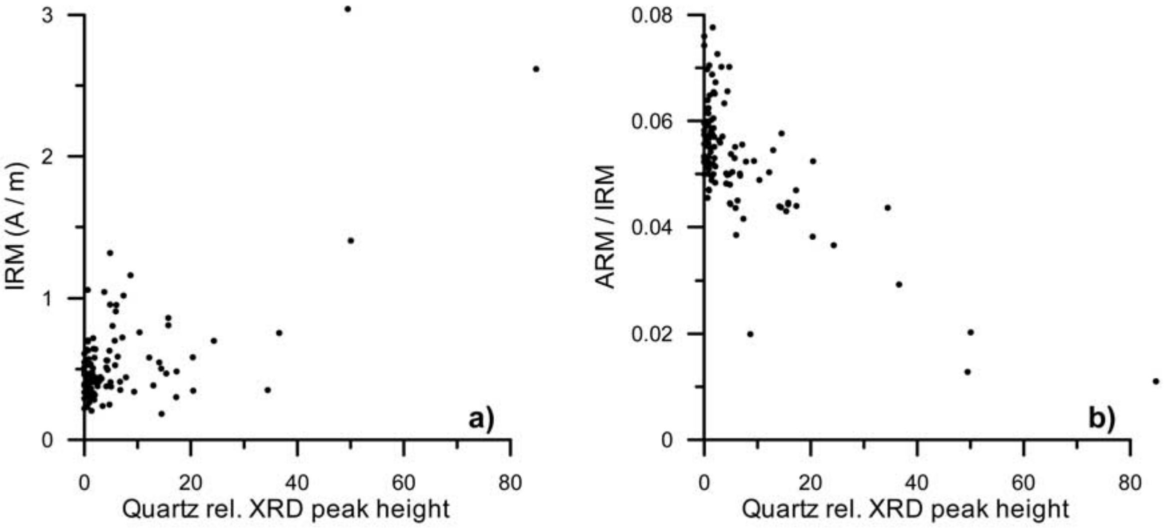

Figure 9. Steel Lake (a) scatter plot of IRM vs. clastic component, (b) scatter plot of ARM/IRM vs. clastic component.

oped under both prairie and forest vegetation. All soils show an increase in fine-grained SD magnetite, leading to an increase in the ratio of ARM/IRM. The observed ratios, however, rarely exceed 5% and are well below the values of 15–30% that have been observed in the lake sediments. The relatively low ARM/IRM ratios observed in soils are due to the mixture of pedogenic SD magnetite with MD magnetite, inherited from the parent material. Soil erosion is therefore unable to provide sufficiently fine-grained material to produce the extremely high ratios of ARM/IRM observed in the Lake sediments.

The influence of forest or prairie on magnetic properties of soils and sediments as proposed by Kletetschka and Banerjee (1995) can also be ruled out. Detailed analyses of charcoal concentrations for both Kimble Pond and Sharkey Lake (Geiss et al., 2002) show little direct correlation with sediment magnetic properties.

Connections between sediment-magnetic properties and paleoclimatic change

At present only one site, Kimble Pond, has sufficient age control to permit reconstructions of paleoclimate, while a crude age model has been established for Sharkey

Table 2. Properties of selected soil profiles

Site	Location		Soil series	Vegetation	ARM/IRM	
	Lat	Long			A horiz	B, C horiz
Townsend Woods	44.248°	–93.549°	Hayden loam	Decid. forest	5%	2.5%
Cannon River	44.386°	–93.189°	Renova silt loam	Decid. forest	4.5%	2%
Kimble Pond	44.219°	–93.84°	Lester	Prairie/pasture	4%	2.5%
Sharkey Lake	44.592°	–93.413°	Hayden loam	Prairie/pasture	4%	2%
Tauer Prairie	44.196°	–94.532°	Dickman	Prairie	5.5%	3.5%
Lake sediments:				Vegetation (in watershed)	Forest periods	Mid-Holocene dry period
Kimble Pond	44°13′	–93°50′		Prairie	30%	5%
Sharkey Lake	44°35′	–93°24′		Prairie/decid. forest	15%	5%
Kirchner Marsh	44°46′	–93°06′		Decid. forest	15%	5%

ARM/IRM ratios for selected soil profiles from southern Minnesota. Data for Kimble Pond, Sharkey Lake and Kirchner Marsh are shown for comparison. Soil series classification from Minnesota Soil Surveys (Harms et al., 1959; Christensen, 1988; Schulzetendberg, 1990; Carlson, 2000).

Lake, Kirchner Marsh and Steel Lake by using a limited number of radiocarbon dates or comparing their lithology to nearby dated sites. A combination of all four sites, however, demonstrates the ability of rock-magnetic parameters to respond consistently to large-scale regional changes in paleoclimate and can help to establish a model that links paleoclimatic change to variations in rock-magnetic parameters in spite of drainage basin and lake size variations. Once such a model is verified by non-magnetic paleoclimate proxies from these sites, whose collection is currently under way, and robust age models are established, the magnetic data presented here can be further used to establish decadal to sub-decadal-scale paleoclimate reconstructions for the entire Holocene.

Large-scale shifts in paleoclimate since the retreat of the Wisconsinan ice sheets in the midwestern United States are well known from over four decades of palynologic analyses (Wright et al., 1963; McAndrews, 1967; Wright and Watts, 1969; Grimm, 1983) as well as diatom (Florin and Wright, 1969; Brugam, 1980; Radle et al., 1989), ostracode (Smith 1991, 1997) and geochemical (Dean, 1993; Schwalb et al., 1995) studies. During the late Pleistocene tundra vegetation, which established itself after the retreat of the Laurentide ice sheet, was replaced by coniferous and later mixed/deciduous forest, which grew under warm and wet conditions prevailing during the early Holocene. During the mid Holocene the region experienced drier and warmer conditions, which led to an eastward expansion of prairie vegetation. During the late Holocene the climate became more humid again, causing the prairie-forest border to shift westward again. A good summary of large-scale regional climate and vegetational change can be found in Webb et al. (1983) and Wright (1992).

The magnetic properties of the four sites can be reconciled with these climatic shifts as changing paleoenvironmental conditions affect the concentration and grain-size of the magnetic component. Many of the changes in magnetic properties can be explained by the mixing model described above. Lake sediments in Minnesota are dominated by authigenic minerals when watersheds are covered by forest vegetation. Terrigenous input increases in dry periods, either due to increased dust deposition (Anderson, 1992) or increased erosion of local sources (Almquist-Jacobson et al., 1992). In our study area magnetic minerals of terrigenous origin tend to be coarse-grained (PSD to MD sized) and occur in higher concentrations. Consistent results from four sites indicate that this simple mixing model is applicable over a wide geographic region of ~ 500 km extent.

Early Holocene lake sediments deposited during the initial period of deciduous forest growth (magnetic zone 2) have low concentrations of terrigenous material and are dominated by authigenic magnetic minerals. At all southern sites (Kimble Pond, Sharkey Lake and Kirchner Marsh) this period is characterized by low values of magnetic susceptibility κ and IRM combined with high ratios of ARM/IRM, i.e., more fine-grained material (Figures 2, 3 and 5). At Steel Lake paramagnetic minerals such as siderite and the possible dissolution of Fe-bearing minerals due to anoxic bottom conditions in the varved sediments can lead to high values in which remanence parameters are not reflected, such as IRM. The grain size signal linked to authigenic magnetic-mineral formation (high ratios of ARM/IRM), however, is well expressed in these units.

Periods where terrigenous input is significant, such as the early to mid Holocene (magnetic zone 3) are characterized by higher concentrations of magnetic minerals, which lead to higher values of κ and IRM. Coinciding with a shift in magnetic concentration is a shift towards coarser MD or PSD grains, expressed in lower ratios of ARM/IRM. Small authigenic particles may still be present, but their magnetic properties are overshadowed by the much larger terrigenous grains. Paleoclimate reconstructions from Clear Lake, IA (Baker et al., 1992) and Kirchner Marsh (Watts and Winter, 1966; Brugam, 1980) place the onset of prairie conditions between 9–8 ka BP and extend it until approximately 5–4 ka BP. These dates correlate well with the onset of magnetic zone 3 in Kimble Pond (Figure 2), though more humid conditions seem to arrive earlier at Kimble Pond as indicated by a peak in ARM/IRM between 4.8 and 3.0 ka. However, the age of the onset of magnetic zone 4 at Kimble Pond is poorly constrained (see position of ^{14}C dates in Figure 2) due to likely changes in sedimentation rates, and it may be younger than indicated in Figure 2. At present we are unable to decide from the available data whether this increased terrigenous component is due to the deposition of eolian dust as suggested by (Anderson, 1992), or by increased erosion of local sources (Almquist-Jacobson et al., 1992). Erosion of soils and lake sediments, exposed during low lake levels, can readily explain changes in concentration and grain size of the magnetic minerals. S-ratios are commonly lower during this period due to the additional presence of antiferromagnetic minerals, such as hematite or goethite.

Such a change in mineralogy can be caused by the influx of dust, as observed by Robinson (1986) and Bloemendal et al. (1992) for marine sediments. Eolian sediments deposited in Minnesota during the late Pleistocene do show S_{100}-ratios as low as 0.6 and are a possible explanation for the observed mineralogic change during the mid-Holocene. Further studies of soils and dried lake sediments, however, are necessary to test the influence of erosional properties on magnetic mineralogy.

The magnetic properties of late Holocene samples (magnetic zone 4) are highly site-dependent and are variously affected by terrigenous input. At Kirchner Marsh we observe a shift to conditions dominated by authigenic minerals, similar to magnetic zone 2. At Kimble Pond and Sharkey Lake, two sites close to the present prairie-forest border, the magnetic record is more variable and appears to record various periods of increased terrigenous input, which seem to depend on the position of the site with respect to the prairie-forest border. Differences between the two sites would also argue for a patchy border rather than a sharp and continuous transition from forest to prairie. Detailed pollen analyses of the two sites will help to clarify these questions and will provide new high-resolution data on climatic variability.

At Steel Lake the peak in κ, IRM and ARM/IRM ratios above 23.4 m depth (Figure 7) can not readily be explained by the regional model described above. Based on preliminary varve counts its onset occurs between 1500–2000 yrs BP. A similar magnetic signal has been observed for various other lakes in northern Minnesota (Banerjee et al., 1981; Sprowl and Banerjee, 1989). Sprowl and Banerjee (1993) find a similar increase in ARM/χ at approximately 2000 yrs BP in sediments from nearby Elk Lake, and Fe increases markedly for the last 4000 years (Dean, 1993). At Elk Lake this increase in Fe is associated with the establishment of coniferous forest vegetation due to the formation of organometallic complexes in the forest soils (Engstrom and Wright, 1984; Dean, 1993). A large fraction of it is deposited in the sediments as iron-hydroxide gels (Anderson, 1993), where it resists redissolution during and after burial. The presence of poorly crystalline Fe can explain increases in magnetic susceptibility. The dramatic increase in SD particles, as indicated by the sharp increase in ARM/IRM at Steel Lake (ARM/χ at Elk Lake), is likely due to the presence of magnetotactic bacteria as already suggested by Sprowl and Banerjee (1993).

Conclusions

1. Rock-magnetic records from four sites in Minnesota reveal a consistent pattern that can be linked to regional climate change throughout the Holocene.
2. Most of the observed magnetic variations can be explained by a bimodal mixing model that links authigenic and terrigenic magnetic minerals to paleoenvironmental changes and outlines magnetic parameters that quantify these components.
3. Magnetic susceptibility is sometimes able to detect these changes, but a combination of concentration- and grain size dependent parameters yields more reliable results, since the magnetic signal is often a combination of concentration and grain-size changes.
4. The sensitivity of magnetic parameters, as compared to other paleoclimate proxies, such as pollen or diatoms, and time lags among the varying proxies, has yet to be determined. Such an analysis will be especially important when considering high-resolution climate studies that use a combination of magnetic parameters and more traditional paleoclimate reconstruction tools.

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