Comparison of two interglacial records from the midwestern U.S.A.

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Abstract. The sediment records from 2 kettle lakes were used to compare the magnetic signature of interglacial climate. Pittsburg Basin in southern Illinois recorded Sangamonian climate variations, while Holocene climate variations were studied at Kirchner marsh, Minnesota. Pollen studies from both sites indicate the occurrence of a dry prairie period during both interglacials. Both magnetic records show many similarities in their response to climate change. Glacial sediments are characterized by an abundance of coarse grained magnetic grains, while deciduous forests and oak savanna tend to be characterized by SD and SP grains which occur in very low concentrations. These fine grains are likely to be biogenic. The two prairie periods showed an increase in magnetic concentration, but the grain-size of the magnetic fraction depends on the effects of chemical dissolution and pedogenesis in the catchment and may reflect the evolutionary history of the basin.

1 Introduction

In recent years rock-magnetic techniques have been shown to be a valuable tool in the reconstruction of paleoclimate (for a review see Reynolds and King, 1995; Verosub and Roberts, 1995). They are fast, cheap, in most cases non-destructive and offer the opportunity for high resolution studies of climate change. The use of such techniques for paleoclimate reconstruction, however, is complicated by the fact that they do not qualify as a paleoclimate proxy per se. One needs a model that links rock-magnetic variations to climate variations and many models seem to be "lake specific". This often makes the widespread use of rock-magnetic techniques unpractical. In this study we test the validity of regional models that, once established for certain types of lakes over a given region, can be used to readily interpret magnetic variations in terms of climate change.

Studies of the Sangamon and Holocene interglacial stages have shown that in the midwestern United States both interglacials were bisected by a dry period that caused distinct changes in vegetation. Many lakes in southern and central Illinois recorded a dry period during the Sangamon that caused a vegetational change from deciduous forest to savanna or prairie vegetation (Zhu and Baker, 1995). In Minnesota and the eastern United States the Holocene is characterized by a similar drier period between 8000 and 4000 yrs B.P. (Webb III et al., 1993) which caused an eastward advance of savanna vegetation (McAndrews, 1967), the remobilization of dune fields (Keen and Shane, 1990) and deposition of eolian sediments (Bradbury et al., 1993).

We studied the magnetic records of two small lakes in Minnesota and Illinois that recorded similar climatic changes, but are separated from each other by a distance of approximately 500 km and have different sedimentological characteristics.

2 Site Selection

Both lakes are small kettle lakes of comparable size (diameter ≈ 1 km) that developed in glacial sediments of similar composition (Fig. 1). They record a glacial-interglacial transition and a dry prairie period during the following interglacial. To test the robustness of the rock-magnetic method the selected lakes cover a large geographical region, have different sedimentation rates, represent different ages and have different lithology. Pittsburg Basin covers the change from the Illinoian glacial to the Sangamonian interglacial and the dry period during the interglacial. In Kirchner Marsh the Wisconsinan - Holocene transition and the Holocene hypsithermal period are recorded in the sediments.

Pittsburg Basin is located in southern Illinois (38°54'N, 89°11'W). It is a small, now drained kettle lake in glacio-fluvial sediments of Illinoian age and the sedimentary record

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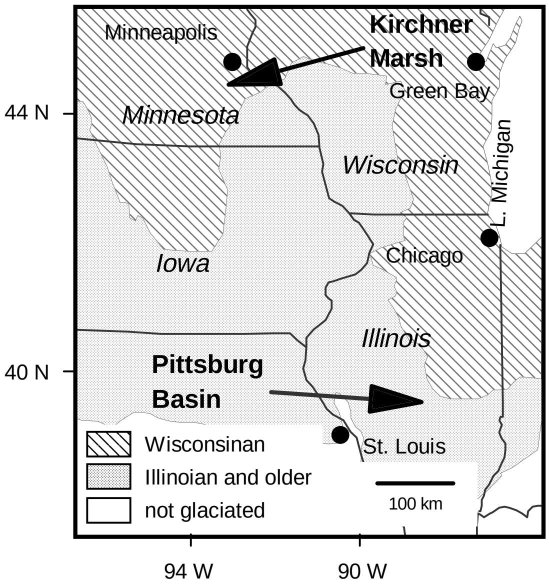

Fig. 1. Locations of Pittsburg Basin and Kirchner Marsh

most likely covers the last 130 ka. Unfortunately, most of the Holocene record is lost to alteration as the lake sediments oxidized after the drainage of the lake. The sediments have been previously studied by (Grüger, 1972) and our study is part of an ongoing multidisciplinary project to reconstruct late Pleistocene climate variations in Illinois.

Kirchner Marsh is a small glacial lake in a terminal moraine, south of St. Paul (44°16'N, 93°07'W). The base of the core is approximately 13 ka old. Brugam (1980), Watts and Winter (1966) and Wright et al. (1963) studied the lake, using pollen, plant-macrofossil and diatom analyses to reconstruct Holocene climate variations. The Holocene hypsithermal period was first detected at this site.

Both sites were chosen because they have a proven record of interglacial paleoclimate and because previous and ongoing work allows us to compare our magnetic results with non-magnetic studies.

3 Methods

Pittsburg Basin was cored in 1994 and 1996, using a hollow stem augur and a modified Livingston piston corer. Kirchner Marsh was cored in 1997 with a modified Livingston piston corer. Magnetic susceptibility (κ) was measured at room temperature with a Geofyzika Kappabridge KLY-2. Remanence parameters, such as anhysteretic remanent magnetization (ARM), saturation isothermal remanent magnetization (SIRM) and S-ratios were measured on a cryogenic magnetometer (2G, model 760-R). The saturating field for SIRM was 1.5 T, ARM was acquired in a bias field of 50 µT with a maximum AC field of 99 mT. S-ratios were calculated by using a backfield of -300 mT. Frequency dependent susceptibility ($\chi_{\sigma\rho} = (\chi_{\iota\eta\eta\varsigma'} - \chi_{\iota\eta\eta\eta\varsigma'}) / \chi_{\iota\eta\eta\varsigma'}$) was measured at room temperature for 20 frequencies between 40 Hz and 4 kHz on a Lakeshore 7000 susceptometer. The values corresponding to 400 Hz and 4 kHz were obtained from a best fit through all the data points. To observe low temperature phase transitions and possible contributions of biogenic magnetite (Moskowitz et al., 1993) we cooled the sample in a saturating field of 2.5 T to a temperature of 10 K (field cooled experiment) and measured its SIRM as the sample was heated back to room temperature. In a second run the sample was cooled to 10 K without the presence of a field (zero field cooled experiment), acquired a SIRM at 10 K in a field of 2.5 T and the decay of its SIRM was again monitored during the heating process. These experiments were performed on a Quantum Design MPMS-2 magnetic properties measurement system. Total organic carbon content (TOC) was determined by heating the sample in air to 550°C for 2 h and monitoring the weight loss due to the heating process (Dean, 1974).

4 Results

The magnetic properties have already been published in Geiss and Banerjee (1997) and we give a brief review of their results. Figure 2 shows a summary of magnetic properties for both sites. For Pittsburg Basin the climatic interpretation is based on pollen analyzes by Teed et al. (1996), for Kirchner Marsh we correlated our cores by lithology with earlier paleoclimatic work by Wright et al. (1963). A few additional pollen counts, conducted by R. Low, confirmed our correlation and helped to confine the position of the prairie period.

4.1 Pittsburg Basin

The base of the Pittsburg Basin cores is formed by sandy glacial outwash. The overlying sequence of sediments consists of clays and silt-sized sediments with varying amounts of TOC. Variations in magnetic susceptibility κ (Fig 2a) show an initial decrease in κ as glacial silt and clay grade into interglacial sediments. Its lowest values occur during the lower deciduous forest period (690 - 755 cm depth). κ increases during the following prairie period (570 - 690 cm depth) and drops again during the upper deciduous forest period (< 570 cm depth).

Grain-size dependent parameters, such as ARM/SIRM (Fig. 2b) or frequency dependent susceptibility χ_{FD} (Fig. 2c) indicate that sediments deposited during the lower deciduous forest period and the prairie period show an increase in both single domain grains (SD), as expressed by high ARM/SIRM ratios, and superparamagnetic (SP) grains, as expressed by high values of χ_{FD}. Hysteresis parameters (not shown here) support this interpretation.

Magneto-mineralogical measurements, such as the determination of Curie-temperatures, the observation of mineral specific phase transitions at low temperatures and XRD analyses, indicate that magnetite and maghemite are the

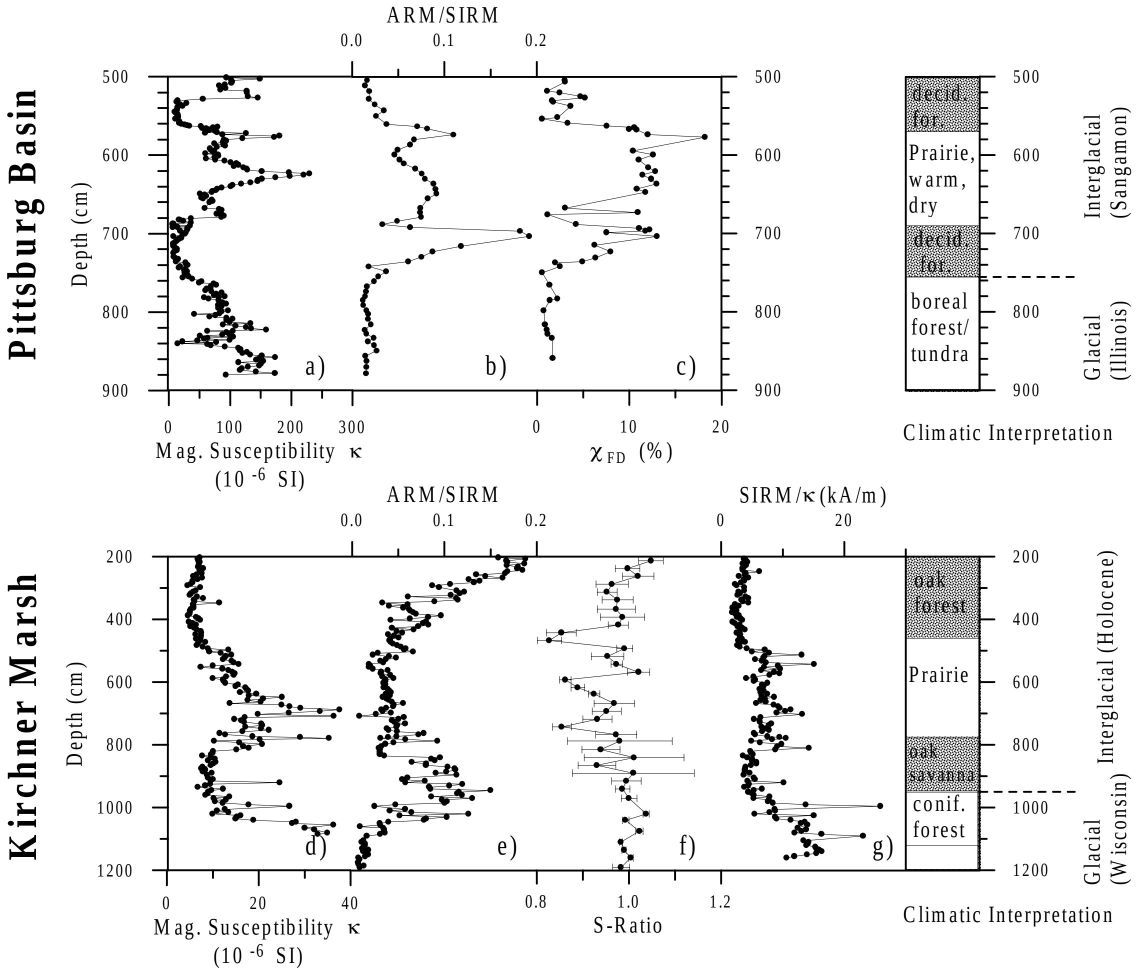

Fig. 2. Magnetic properties of Pittsburg Basin and Kirchner Marsh sediments. Magnetic susceptibility is a proxy for concentration of magnetic minerals, ARM/SIRM is sensitive for SD-grains, χ_{FD} is used as a proxy for SP-grains, S-ratios indicate presence of magnetically hard minerals and SIRM/κ tests for the presence of greigite.

main magnetic minerals. Recent SEM observations and EDAX analyzes of magnetic extracts show a relative increase of (hemo)ilmenite with respect to magnetite/maghemite in the sediments corresponding to the prairie period. The Ti-content of these grains, however, is too high for these grains to carry a remanence at room temperature. Iron-sulfides do not significantly contribute to the remanence properties discussed here.

4.2 Kirchner Marsh

The base of the Kirchner Marsh cores consists of glacial till and sand (1160-1200 cm depth) which is followed by olive gray clays (1100 - 1160 cm depth). These sediments have very high values of κ ($\approx 10^{-3}$ SI) and are not included in Fig. 2d in order to show the variations in the much weaker magnetized sediments above. These clay rich layers grade into organic gyttjas (1000 cm - 1100 cm depth) and κ decreases steadily with increasing TOC content. Above 1000 cm depth the sediments consist of organic gyttjas and κ values are generally very low ($< 10^{-5}$). Fig. 3a (open symbols) shows a good inverse correlation between κ and TOC of these sediments. In this case, concentration dependent parameters, such as κ and SIRM reflect the concentration of non-organic, terrigenous material in the sediments.

Figure 2e shows the variations of ARM/SIRM with depth. In contrast to Pittsburg Basin the samples of the prairie period appear to have a coarser magnetic grain size than the sediments above and below. A plot of ARM/SIRM ratios vs. TOC (Fig. 3a, solid symbols) shows that organic rich sediments tend to have smaller magnetic grain sizes. No measurements of χ_{FD} were performed on the Kirchner Marsh samples.

Because of the high organic matter content of the gyttjas we did not attempt to measure Curie-temperatures of the bulk samples. Low-temperature measurements of selected samples show distinct Verwey transitions in sediments with high ARM/SIRM ratios (Fig. 4a), characteristic of the presence of magnetite. Furthermore a sample's demagnetization behavior depends on whether it was cooled down in a magnetic field (solid line) or in zero field (dashed line), indicating that part of the magnetite might be produced by magnetotactic bacteria (Moskowitz et al., 1993). Samples from the prairie period with low ARM/SIRM ratios show only traces of a suppressed Verwey transition and much smaller differences between field cooled and zero field cooled curves (Fig. 4b). Variations in the S-parameter (Fig. 2f) show the presence of a magnetically

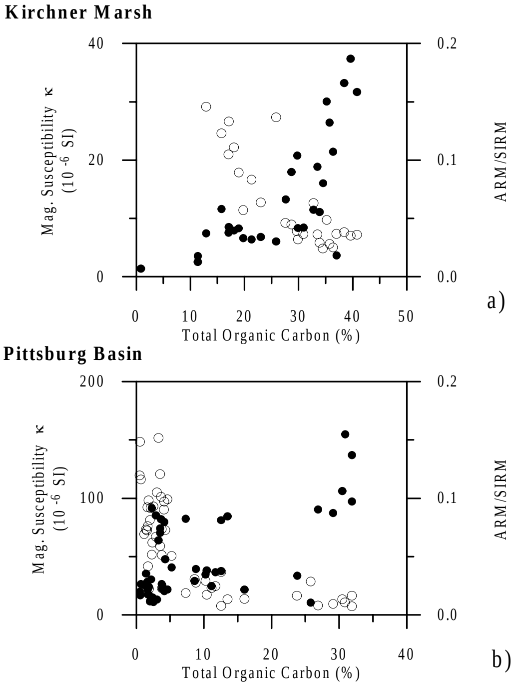

Fig. 3. Scatter plots of magnetic susceptibility (open symbols) and AREM/SIRM (solid symbols) vs. TOC.

harder component between 400 cm and 800 cm depth that could not be re-saturated in a backfield of -300 mT.

5 Discussion

Pittsburg Basin and Kirchner Marsh sites recorded a change from late glacial conditions to warm, interglacial climate which changed the vegetation from boreal forest and parkland to deciduous forest. The following dry period resulted in shifts to open grasslands, and as the climate turned again more humid, deciduous forests reoccupied both sites. In this chapter we compare how the magnetic properties of both sites react to this climatic signal. One of the main differences between the two sites is the amount of time recorded. Recent, preliminary IRSL dates from Pittsburg Basin (S. Balescu, pers. comm.) suggest that the "interglacial" sediments span most of marine isotope stage 5, therefore representing approximately as much as 60 ka. Kirchner Marsh, on the other hand developed after the retreat of the Holocene ice sheets from Minnesota. Here the sediments are much younger, with the base of the core dated at approximately 13 ka (Wright et al., 1963).

The base of both lakes consists of clay and silt rich sediments that were deposited shortly after the retreat of the ice sheets. The sediments have very high concentrations of coarse grained (titano)magnetite.

With the onset of warmer conditions the abundance of clays and silt-sized sediments decreases and concentration dependent parameters, such as κ or SIRM decrease. During the initial forest periods the magnetic signal in both lakes is very similar. The magnetic component is very fine grained magnetite and thermal demagnetization curves of a low-T SIRM suggest the presence of biogenically produced magnetite, leading to very high ARM/SIRM ratios and characteristic differences between the zero-field-cooled and field-cooled demagnetization curves (Fig. 4a).

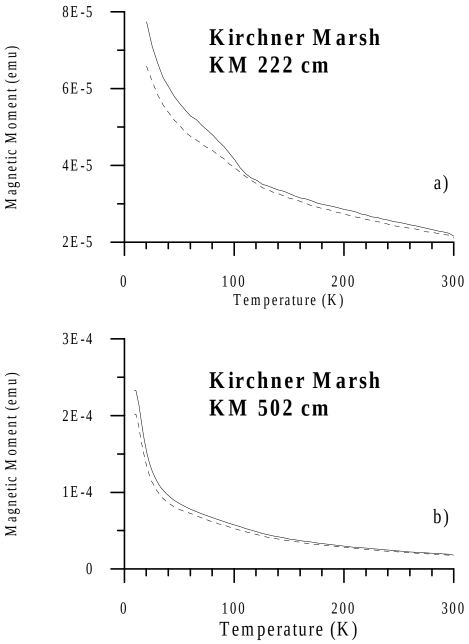

Fig. 4. Thermal demagnetization curves of low-T SIRM for samples from the deciduous forest (KM 222) and the prairie (KM 502). Solid lines: field cooled, dashed lines: zero field cooled experiments.

During the following prairie period the amount of terrigenous material in the sediment increases, and so do the values for κ and SIRM. The two records, however, differ in their magnetic grain sizes. Sediments in Pittsburg Basin show relatively high values of ARM/SIRM and χ_{FD} (Fig. 2b,c), indicating the presence of SD and SP grains. Kirchner Marsh sediments, on the other hand, show very low values of ARM/SIRM, which is consistent with coarser grained magnetic material. S-ratios as low as 0.8 indicate the presence of an additional high coercivity component, probably carried by hematite or goethite.

The magnetic properties of Kirchner Marsh can, to a first approximation, be described by a relatively simple binary mixing model between a detrital terrigenous component, which is relatively coarse grained, and a likely authigenic, SD-component. Fig. 3a shows that the concentration of magnetic minerals is controlled by the amount of terrigenous material. The strongly grain size dependent ratio of ARM/SIRM shows a direct correlation with TOC (Fig. 3a), showing that the SD-component dominates in the sediments least influenced by terrigenous material. Low-T results (Fig. 4a) suggest the presence of some magnetosome chains from magnetotactic bacteria in these sediments.

For Pittsburg Basin, these relationships are not as clear-cut. A scatter plot of κ vs. TOC (Fig.3b, open symbols) shows that, especially for low values of TOC, κ is nearly independent of the amount of terrigenous material present. Figure 3b (solid symbols) indicates that fine grains can occur in both, organic rich and organic poor sediments. A simple binary mixing model between an authigenic and a terrigenous component cannot explain these grain-size variations.

The age differences represented in the two sites might be able to explain the observed differences in grain size. In Kirchner Marsh the parent material of the sediments is relatively young and the climate was, according to pollen analyses, fairly cold until the beginning of the Holocene (Wright et al., 1963). Therefore, the parent material had approximately 3 ka for soil development, differentiation and magnetic enhancement as compared to 10 ka at Pittsburg Basin. Studies of several chronosequences on uplifted terraces of the California coast (Singer et al., 1992) showed that the magnetic differentiation and enhancement of soils can continue over several 100 ka. Maher and Thompson, (1995), however, argue that pedogenic enhancement in soils can occur almost instantaneously within a few 100 years if the soil develops in well drained parent material that undergoes regular wetting and drying cycles. Soils that developed on glacial till in Iowa show increasing weathering indices over a time span of 10^5 yrs or more (Birkeland, 1984). Such slow development rates for soils developed on glacial till would make it reasonable to assume that the parent material around Kirchner Marsh is relatively unaffected by pedogenesis. Therefore a simple binary mixing model can explain most of the variations observed in Kirchner Marsh.

Increased input of terrigenous material during dry periods can be caused by several processes. Changes in vegetation can cause an increase in erosion rates. Lower lake levels expose parts of the lake sediments and cause redeposition in deeper parts of the basin. Subaerial weathering can cause the formation of goethite and hematite which can lead to lower S-ratios. Increased eolian influx during this period is another possible source of detrital material. Higher concentrations of goethite or hematite in these deposits, as reported by Eyre and Dickson, (1995) for Chinese loess and Pye, (1987) for a variety of eolian deposits, could explain the suppressed Verwey transitions and lower S-ratios during that period. One argument against the presence of iron-(hydr)oxides is their low saturation magnetization, which requires very large amounts of hematite or goethite to lower the S-ratios to the observed numbers (Bloemendal et al., 1992).

Detrital or authigenic iron sulfides, such as pyrrhotite and greigite are further possible candidates for the observed hard fraction. Remanence acquisition curves for pyrrhotite (Dekkers, 1988) and greigite bearing sediments (Krs et al., 1992) show that the remanence of both minerals are not necessarily saturated in backfields up to 300 mT. Their higher saturation magnetization and greater stability under reducing conditions would favor iron sulfides as a possible explanation over iron(hydr)oxides. Fig. 2g shows the variations of SIRM/κ with depth. High ratios of SIRM/κ are an indicator for the presence of greigite (Roberts, 1995; Fassbinder and Stanjek, 1994). At Kirchner Marsh low S- ratios do not correspond with high values of SIRM/χ. Greigite is therefore an unlikely hard component. To test for goethite we thermally demagnetized several samples. Prior to thermal demagnetization the samples acquired a thermal remanent magnetization (TRM) at 150°C in a field of 50 µT. The sample was then AF demagnetized (peak field 100 mT) to remove any "soft" component. Thermal demagnetization curves (not presented here) show a drop in remanence above 150°C, which continues to temperatures as high as 275°C. Since goethite has a Curie-temperature near 120°C (Özdemir and Dunlop, 1996) this drop in remanence cannot be due either to the demagnetization or alteration of goethite. The remaining candidates are therefore pyrrhotite or hematite and either one may be enriched in these sediments.

According to our preliminary age model the parent material for the Pittsburg Basin sediments had probably as much as 10 ka during warm, interglacial conditions to develop and mature before they were deposited in the lake. The result of this process is the Sangamon geosol, which is well developed in the watershed. Unlike at Kirchner Marsh, at Pittsburg Basin high ratios of ARM/SIRM are not confined to sediments high in TOC (Fig. 3b). Eroding magnetically enhanced soils into the lake can explain the high ARM/SIRM ratios during the prairie period.

At Kirchner Marsh, the period of deciduous forest that follows the prairie period is characterized by sediments with low values of κ and SIRM. These sediments show increasing ARM/SIRM ratios as the influence of the terrigenous component decreases. ARM/SIRM ratios are even higher than in theearly Holocene oak savanna. The amount of fine grains decreases after burial, as part of the grains get dissolved under reducing conditions. Obviously the effects of dissolution on the small magnetic grains must be limited, since there is still a large amount present at greater depths.

At Pittsburg Basin the sediments are initially very rich in organic material and consequently the values for κ and SIRM are low. However, ARM/SIRM ratios and χ_{FD}-values are low as well, the large magnetic grains that are responsible for these low ratios are probably the effect of progressive dissolution of iron oxides. Higher concentrations of inorganic carbon and the presence of ostracode shells in these sediments indicate slightly more saline water conditions which may have aided in the dissolution of fine-grained magnetic minerals.

6. Conclusions

Our study shows that certain climatic environments and stages of lake development can leave distinctive patterns in the magnetic properties of sediments. Both lakes recorded the change from glacial to interglacial conditions and a shift towards drier climate during the interglacial. The two records cover different periods of time, which shows that the processes governing the magnetic properties of lake sediments can be relatively independent of time, and, within the studied area, similar environmental processes tend to result in similar magnetic responses. However, chemical alteration, such as the dissolution of iron oxides in the lake sediments or the authigenesis of new magnetic minerals in both, the parent material and the sediments, becomes more and more important in older sediments. The distance between the studied lakes is approximately 500 km. Our magnetic results can therefore be used for the establishment of regional models that link climatic change and magnetic properties of the corresponding sediments. They can be summarized as follows:

1. During the early stages of lake formation the landscape is characterized by boreal tundra and forest vegetation. High erosion rates and low organic productivity lead to sediments rich in clay, silt and low organic carbon content. The magnetic component of these early sediments consists mostly of coarse, detrital grains. Their mineralogy depends on the composition of the parent material.
2. In the following deciduous forest stage, which represents warm and humid climatic conditions, the sediments show little detrital input and are characterized by high concentrations of organic carbon. In many cases the magnetic component of these sediments consists of fine grained (SD and SP) magnetite. Low temperature experiments indicate that magnetic bacteria are a likely producer of these magnetic grains. It is possible that this authigenic component is present in all sediments, but can only be detected during periods of very little detrital input.
3. During dryer climatic conditions we observe increased input of detrital material and therefore an increase in the concentration of magnetic minerals. This increase can be attributed to several processes: A change in vegetation can lead to increased erosion during dry periods, lower lake levels expose previously deposited sediments, which can be redeposited in deeper parts of the lake, or the decrease in humidity and vegetation cover can increase the frequency of dust storms and deposition of eolian material. It is possible that the differences observed during the prairie periods are due to differences in the source of the detrital components or the effects of chemical alteration prior to deposition.
4. Chemical alteration effects are visible in both cores and become more important with age of the sediment. However, the existence of SD and SP magnetite grains in the oldest deciduous forest period at Pittsburg Basin shows that dissolution is not an inevitable fate for small iron oxide grains.

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