

9 Synthesis: The Effects of Paleoenvironmental Change on Sediment-Magnetic Properties

9.1 Introduction

In chapters 6 through 8 I described the sediment-magnetic characteristics of several kettle lakes and attempted to link magnetic variations to changes in paleoenvironment. This chapter offers a more generalized view of how paleoenvironmental changes affect magnetic characteristics of the sediment and how changes in magnetic properties can be used to reconstruct the paleoenvironmental history of a lake. The discussion is based on the sedimentary history of a hypothetical kettle lake similar to Pittsburg Basin, Catfish Pond and Kirchner Marsh. Since it is based on the experimental results from only three lakes the scenario is by no means definitive. The results are probably appropriate for small freshwater or moderately saline lakes typical of Minnesota. The diagrams presented in section 9.2 are based on my experience from Pittsburg Basin and Kirchner Marsh, but they are highly simplified, especially with respect to the actual vegetation cover and sedimentary sequence.

When discussing the sediment magnetic response of a lake record to paleoclimatic variations it is useful to consider relative changes rather than absolute numbers. Therefore most of the following discussion refers to “finer” or “coarser” grainsizes, “higher” or “lower” concentrations etc.. All these changes are with respect to earlier or later horizons in the same core or at one location. Considering relative changes instead of absolute ones normalizes for many of the variations that can occur between otherwise similar lakes and basins.

9.2 Sediment Magnetic Changes Throughout the History of a Small Kettle Lake

Figure 9.1 shows a block diagram of a small kettle lake in its initial stage, soon after the retreat of the ice sheet and the melting of the ice block. The lake formed in till, whose composition is not specified, but it is assumed that it has relatively high concentration of magnetic minerals (e.g. tills from the Superior or Michigan lobes).

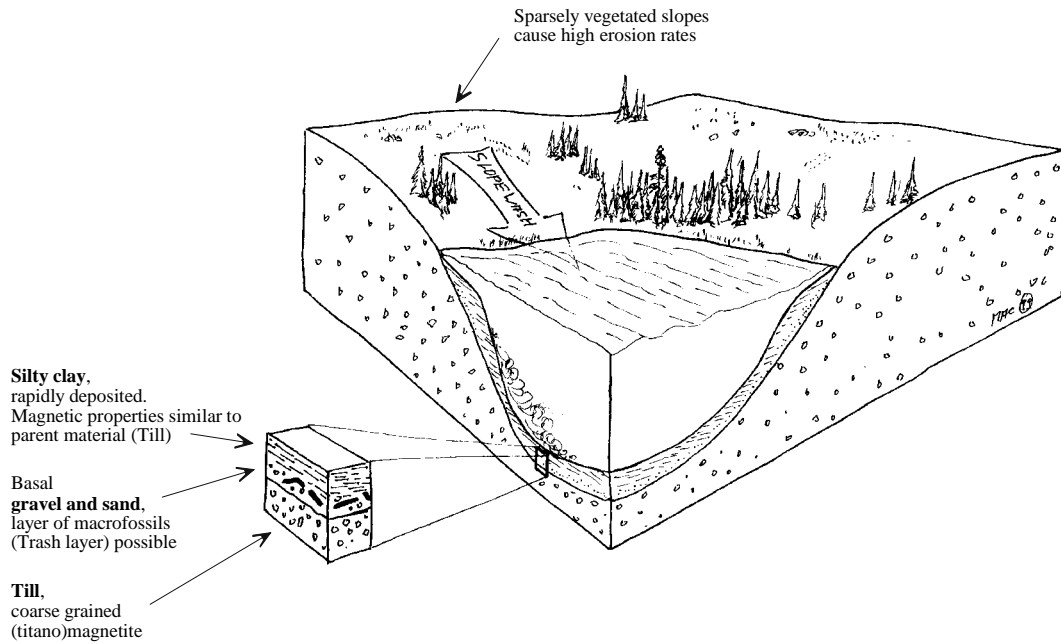


Fig. 9.1: Idealized lake shortly after the retreat of the ice sheet and melting of the ice block. The landscape is still sparsely vegetated and the slopes are steep, which results in high erosion rates. Sediments deposited during this period tend to have magnetic characteristics similar to those of the parent material.

The lowermost lacustrine sediment consists of a basal sand or gravel layer, overlain by silty clays. A “trash layer”, containing an abundance of macrofossils, may be present. Such trash layers are common in many Minnesota kettle lakes [Wright, 1980]. They can form when a block of dead ice is covered with superglacial soil and vegetation. Upon melting of the underlying ice this layer collapses and forms a horizon rich in terrestrial macrofossils [Florin and Wright, 1969]. Erosion rates during this period are high, with slopewash and turbidites playing important roles in supplying sediment to the lower parts of the lake. High erosion rates combined with low productivity lead to the deposition of silty clays that have magnetic characteristics similar to the underlying till. In this postglacial stage the bottom water was likely to be oxic due to the low overall temperatures and low productivity. The concentration of magnetic minerals is high, and the magnetic particles are likely to be coarse-grained. This basal zone is therefore characterized by high values of magnetic susceptibility and SIRM, combined with low ARM/SIRM and frequency-dependent susceptibility values due to the coarse-grained nature of the sediments. In a plot of remanence ratio M_{rs}/M_s vs. coercivity ratio H_{cr}/H_c such samples are likely to plot in or near the multidomain (MD) field. Postglacial lakes that are surrounded by coniferous forests may still show similar, organic-poor sediments. In this case the acidification of coniferous forest soils results in acidic lake water and decreased productivity [Almquist-Jacobson *et al.*, 1992]. Strongly magnetic basal zones are observed for many kettle lakes in the Midwestern United States [Almquist-Jacobson *et al.*, 1992; Keen and Shane, 1990; Schwab *et al.*, 1995]. The high concentrations of magnetic minerals observed in these lowest sediments can lead to the (often premature) conclusion that the magnetic minerals above this basal layer are seriously affected by dilution and dissolution, show little variation, and occur in concentrations too low for any useful paleoenvironmental analysis.

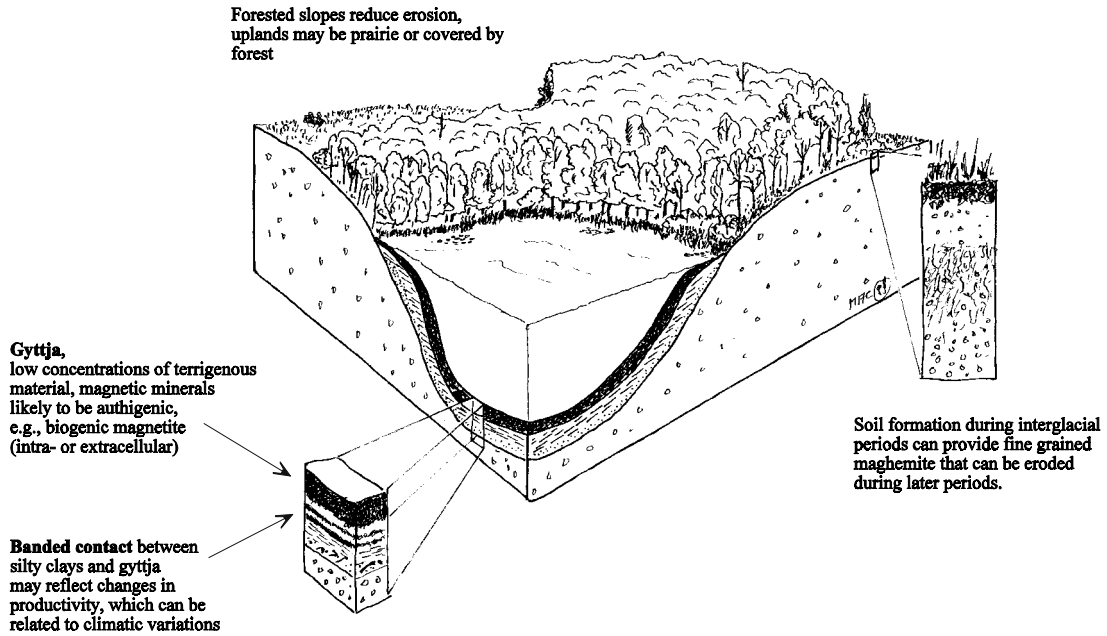


Fig. 9.2: Warm and wet climate leads to development of forests on the slope of the basin, reducing the input of terrigenous material. Warm temperatures favor high organic productivity, leading to gyttjas with low concentrations of terrigenous magnetic particles. The magnetic component of these sediments can be of authigenic origin. Biogenic magnetite, produced by magnetotactic bacteria, can produce a characteristic low-temperature signature and high ARM/SIRM ratios. High values of frequency-dependent susceptibility χ_{FD} are due to the presence of ultrafine-grained magnetite which can be produced extracellularly by iron-reducing bacteria.

Figure 9.2 shows forest on the slopes of the basin and the shoreline covered by dense vegetation. This vegetation cover reduces the input of terrigenous material into the lake. High rates of productivity combined with low erosion rates lead to the deposition of organic sediments. The sediments are characterized by low concentrations of magnetic minerals. Both Pittsburg Basin (pollen zone PB-2) and Kirchner Marsh (200 - 400 cm, 1050 - 850 cm depth) show the presence of fine-grained SD and SP magnetite in these zones. This fine-grained component is likely of authigenic origin, probably caused by the presence of magnetotactic and iron-reducing bacteria. It is possible that such an authigenic component exists throughout the entire history of the lake, but it is generally covered up by the presence of detrital magnetic minerals and can only be observed when erosion rates are low. These sediments are characterized by low values of magnetic susceptibility, but high ratios of ARM/SIRM and high values of frequency-dependent susceptibility χ_{FD} . In a plot of M_{rs}/M_s vs. H_{cr}/H_c (e.g. Figure 5.14) these samples tend to plot in the PSD field near the SD boundary, but the presence of large amounts of SP-grains may shift the samples towards the lower right (Figure 2.6). Soils that form within the watershed may produce fine-grained superparamagnetic maghemite, which can be deposited in the lake at a later stage.

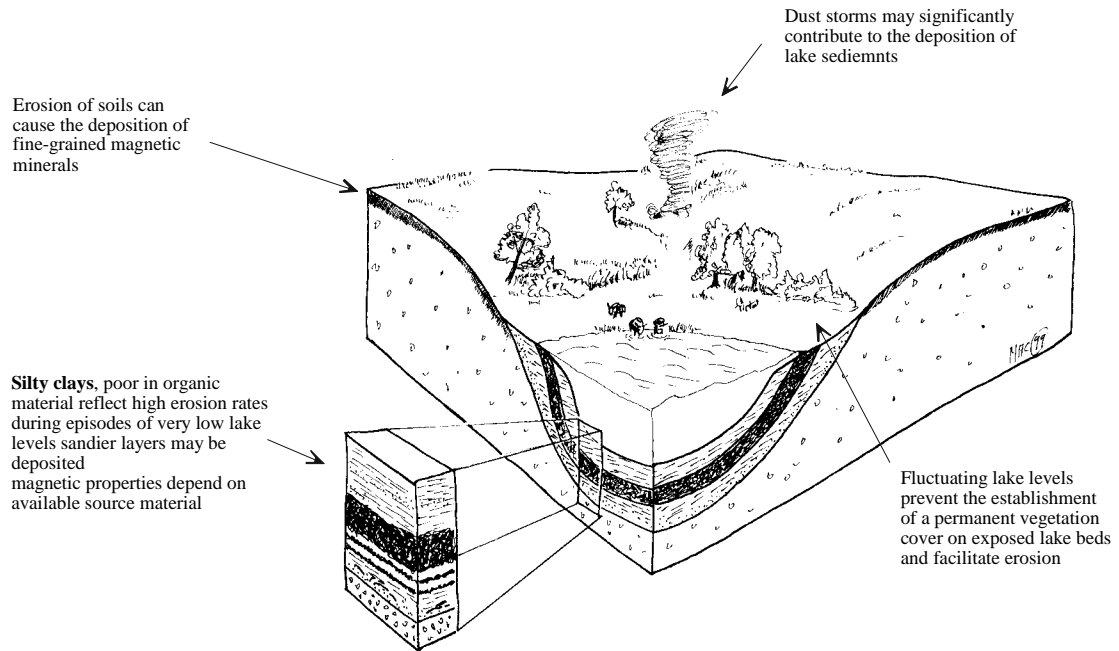


Fig. 9.3: Drier climatic conditions cause a drop in lake level. If lake levels are fluctuating the exposed lake bed will not be covered by a stable vegetation cover and is susceptible to erosion. The change from forested slopes to prairie vegetation increases wind exposure which may promote redeposition of littoral sediments, increased shoreline erosion and deposition of eolian particles. If the vegetation cover is sparse or disturbed erosion due to slopewash may also increase.

The effects of low but fluctuating lake levels are illustrated in Figure 9.3. Fluctuations in lake levels prevent the establishment of a stable vegetation cover on the exposed lake beds and allow for the erosion of previously deposited muds. The change in vegetation from forest to open prairie can also increase the input of terrigenous material, even when the lake level remains fairly constant [Almquist-Jacobson *et al.*, 1992]. In this case the influx of terrigenous sediments can increase due to eolian deposition, shoreline erosion or redeposition of previously deposited sediments. Many lakes record the increased input of terrigenous material into the lake, either through eolian activity [Dean, 1993; Keen and Shane, 1990] or an increase in erosion rates, as observed in Pittsburg Basin [Geiss and Banerjee, 1997b].

Increased input of terrigenous material generally results in increased concentrations of magnetic minerals. The nature of the magnetic component, however, depends critically on the characteristics of the sediment source. In Pittsburg Basin the erosion of pedogenically altered material led to the deposition of fine-grained maghemite, while a similar dry period in Kirchner Marsh resulted in a relatively coarse-grained magnetic component. Cycles of subaerial weathering followed by anoxia during high lake stands may cause reductive dissolution of iron (hydr)oxides and their partial reprecipitation as hematite. Since dissolution acts preferentially on the smaller grains first, this process can lead to an apparent coarsening of the magnetic component. Losses due to dissolution may be detected by relatively low ARM/SIRM and χ_{FD} values. Scatter plots of ARM and SIRM vs. total organic carbon (TOC) (e.g. Figures 5.12b, 6.8) or total susceptibility χ_{total} vs. ferrimagnetic susceptibility χ_{ferri} (Figure 8.9) may also help to detect the effects of dissolution. Since for many sites there is a good inverse correlation between sample mass and TOC, plots of ARM and χ vs. sample mass (dried) might yield similar results. The presence of magnetically hard minerals is reflected in low S-ratios (Figures 6.3, 8.4a), lack of saturation in IRM-acquisition curves (Figures 5.9a,b) and hysteresis loops that plot the data points to the right of the PSD-field in a plot of M_{rs}/M_s vs. H_{cr}/H_c (Figures 5.14, 6.4c, 8.4).

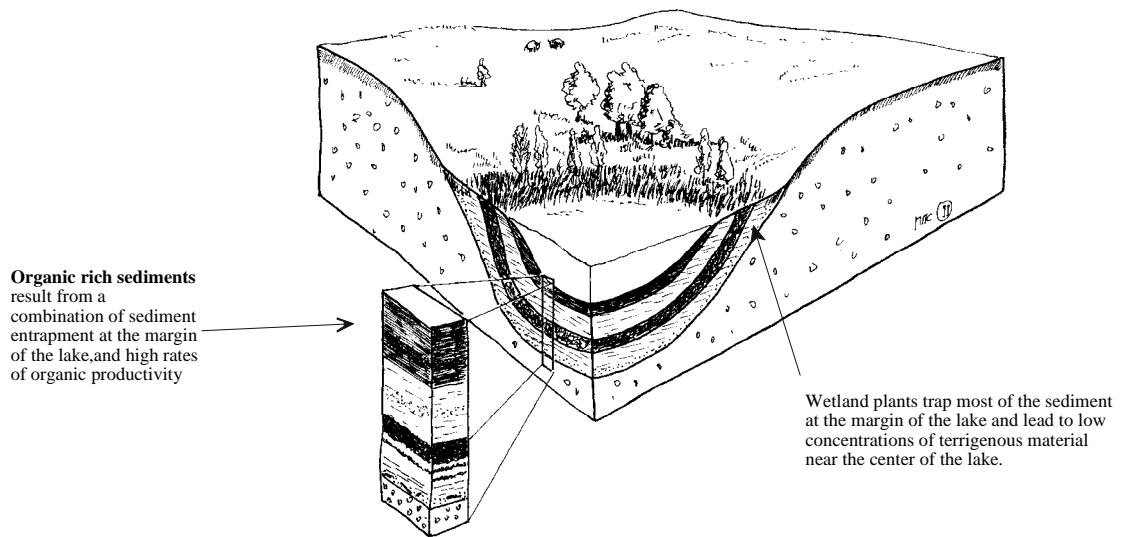


Fig. 9.4: Stable lake levels can lead to the development of wetlands around the lake. Such wetland fringes trap most of the terrigenous sediment near the margin of the lake and can lead to organic rich sediments near the center. The magnetic properties of such sediments are likely influenced by chemical dissolution and/or authigenic formation of fine-grained magnetic minerals.

The deposition of eolian material could in principle lead to a similar magnetic signal, since windblown material tends to be enriched in hematite [*Evans and Heller, 1994*]. A study of varved sediments, which were not exposed to the effects of subaerial weathering, may thus help to clarify whether eolian dust contributes significant amounts of magnetically hard material during dry periods.

The effects of a wetland fringe are illustrated in Figure 9.4. Marginal wetlands can occur when lake levels are relatively stable. They can be the result of an outflow channel that limits the maximum depth of the lake and stabilizes lake levels. Erosion rates may still be high, but most terrigenous material is trapped before it reaches the center of the lake. If productivity is high the resulting sediment will be rich in organic matter with low concentrations of magnetic minerals. Pittsburg Basin possessed such a wetland fringe at the beginning of Wisconsinan glacial conditions, but the magnetic record is unfortunately overprinted by the effects of later low lake levels.

These effects are shown in Figure 9.5. Even during periods of extreme drought, the lake bed is unlikely to be subjected to erosion because it is still the lowest part of the watershed, but a depositional hiatus is likely to occur. Deflation of lake sediments is possible but would result in an erosion surface that is visible on top of the old paleosol horizon. Moving water is able to deposit coarse-grained sediment at the center of the basin. In Pittsburg Basin such a gravel layer is observed at 316 cm depth. The effects of subaerial weathering have already been described earlier. The loss of fine-grained iron oxides can affect older sediments and is able to erase parts of the magnetic signal. In Pittsburg Basin all of the Wisconsinan sediments were affected by the effects of severe drought during the middle Wisconsinan and the recent drainage of the lake.

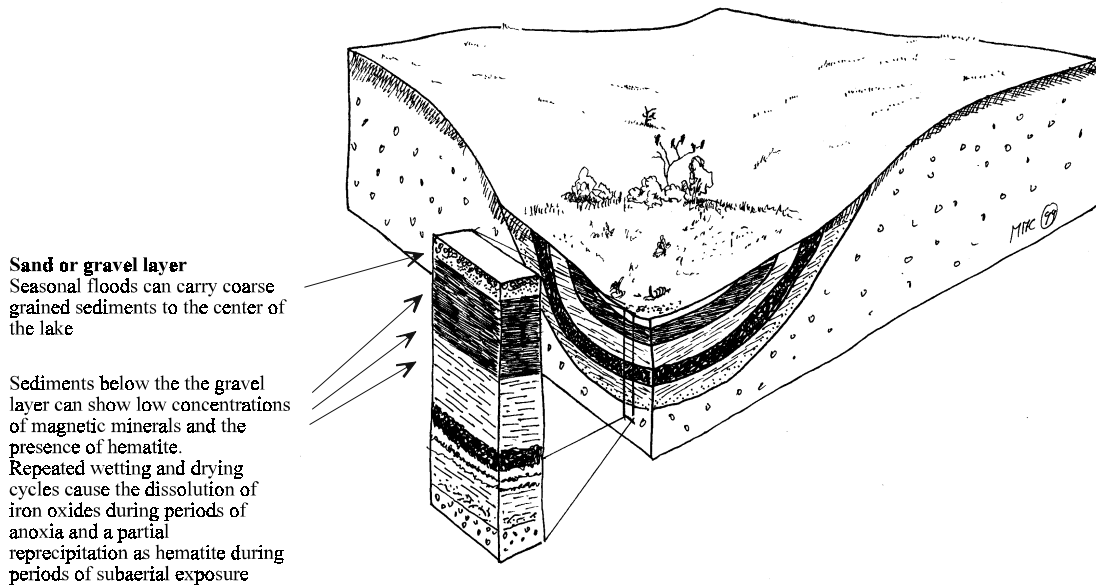


Fig. 9.5: Severe droughts can cause the lake to dry up completely. Seasonal floods are able to deposit rather coarse-grained sediments at the center of the former lake. Seasonal wetting and drying cycles can dissolve parts of the iron oxide minerals and reprecipitate some of the dissolved iron as hematite or ferrihydrite. This dissolution process affects older sediment and can degrade or even erase the magnetic signal of previous paleo environments.

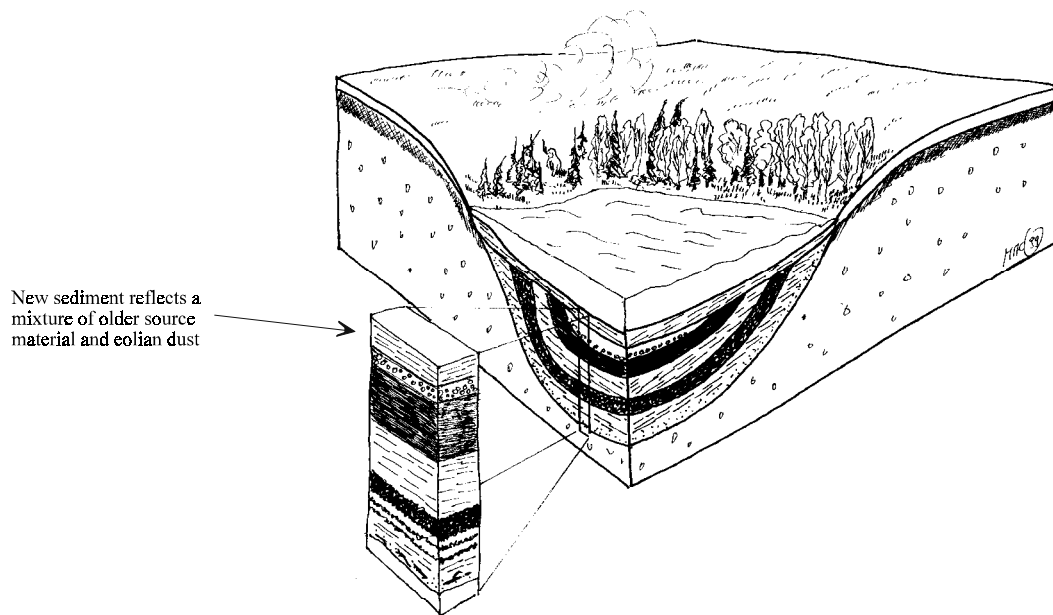


Fig. 9.6: Loess deposition during the Wisconsin glacial period covers old paleosols and provides new source material for the lake sediment. Loess can be trapped directly by the lake when it hits the water surface or can be deposited as slopewash. The change in source material from old glacial till and weathered soils to loess can be reflected in both geochemical and magnetic properties of the sediment.

Figure 9.6 illustrates late-glacial paleoenvironmental conditions. A drop in temperatures led to a decrease in evaporation rates and a rise in lake levels. Eolian deposition causes a change in sediment source material. Old paleosols within the basin are covered by loess and windblown material can be trapped by the lake directly when dust particles hit the water surface. This change in source material can be detected geochemically (Figure 3.14), but it may also be possible to detect such changes in the magnetic properties of the sediment also. The influence of loess accumulation could be reflected in a change in grain size or mineralogy. Unfortunately both the records from Illinois are affected by subaerial weathering, and it is not possible to test for the effects of loess deposition on the magnetic signal. Several scenarios are possible, depending on the depositional regime during loess deposition. Starting out with fairly coarse-grained terrigenous material from slopewash, the introduction of eolian dust may lead to an increase of fine grains if the eolian transport mechanism biases towards finer particles. On the other hand, if most coarse particles are trapped in marginal wetlands, the direct deposition of dust on the water surface may actually lead to coarser particles being deposited at the center of the lake. Changes in mineralogy such as a shift to more goethite- or hematite-rich deposits, could also be observed.

High erosion rates lead to the deposition of sediment rich in magnetic minerals. The magnetic component is likely to be relatively fine grained because dissolution had little time to remove small grains.

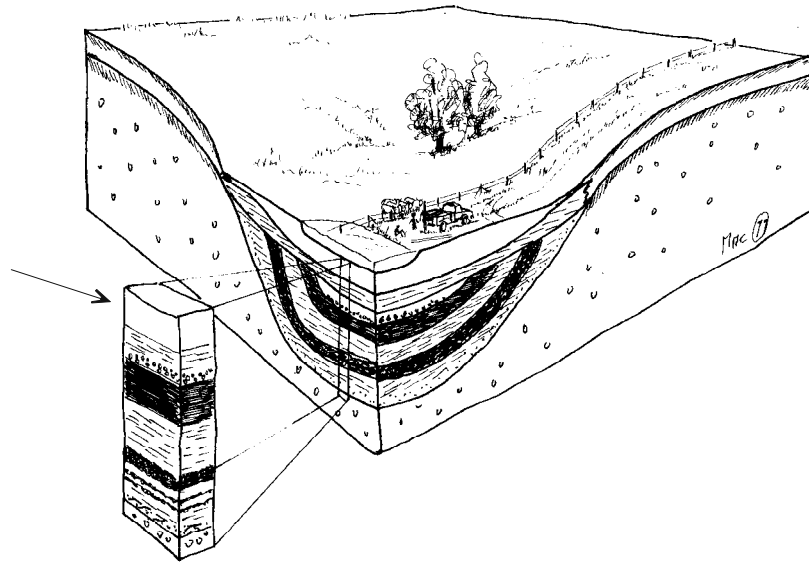


Fig. 9.7: Human disturbance of native vegetation leads to a drastic increase in erosion rates. Modern sediments are rich in terrigenous material and magnetic minerals. The magnetic component tends to be fine-grained. This is generally due to the absence of dissolution in these young sediments. It can also be caused by the erosion of soil material which is enriched in fine-grained iron oxides.

The modern lake is shown in Figure 9.7. Disturbance of the natural vegetation due to farming causes a dramatic increase in sedimentation rates, leading to sediments rich in magnetic minerals. These sediments are often fine-grained, partially because they result from the erosion of soils that are enhanced in fine-grained magnetic minerals, partly because dissolution had less time to remove the smaller crystals.

It is interesting that many of the extremely fine-grained iron-oxide particles can survive in anoxic environments for many thousands of years. Due to the oxidation of organic matter in the uppermost layers most sediments are anoxic below a depth of only a few centimeters. Under such conditions many iron oxides are thermodynamically unstable and should be readily dissolved [e.g. *Garrels and Christ, 1990*]. The effects of dissolution are evident in many parts of the sediment from Pittsburg Basin, Catfish Pond and Kirchner Marsh, but not all horizons were affected to the same degree. *Wersin et al. [1991]* observe that iron oxides are metastable under anoxic conditions and the kinetics of the dissolution process are controlled by the redox conditions of the sediment-water interface. Obviously, the dissolution process can be very slow because SP and SD grains of magnetite are observed in sediments that are approximately 100 ka old.

9.3 Summary

Several processes that are linked to paleoclimatic or paleoenvironmental conditions have been shown to affect the sedimentological and magnetic properties of lake deposits. High erosion rates in the early stages of lake development result in sediments that reflect the magnetic properties of the source material. These sediments tend to be strongly magnetic, and the magnetic particles are coarse-grained. During interglacial times, when deciduous forest covers large parts of the basin, erosion rates decrease, while lake productivity increases. The sediment is likely to carry an authigenic magnetic signature, it has low concentrations of fine to ultra-fine-grained magnetic minerals. Dry periods generally result in an increase of terrigenous material, which is reflected in the concentration of magnetic minerals. However, a variety of magnetic changes can be observed during such periods, depending on the severity of the drought

and the sedimentary processes involved. In the extreme case of a subaerial exposure or fluctuating lake levels, the magnetic signal is likely affected by the dissolution of fine-grained magnetite and the precipitation of hematite. The input of eolian dust can also change the magnetic mineralogy to a more hematite-rich composition, but its influence on magnetic grain-size needs further investigation. The high erosion rates caused by modern-day farming lead to sediments with high concentrations of magnetic minerals. Since these sediments have been affected by dissolution for only a short time span they tend to be relatively fine-grained (provided that fine-grained iron-oxide particles are present in the source material).