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Environmental magnetism: Past, present, and future

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Abstract. Environmental magnetism involves the application of rock and mineral magnetic techniques to situations in which the transport, deposition, or transformation of magnetic grains is influenced by environmental processes in the atmosphere, hydrosphere, and lithosphere. The first explicit description of environmental magnetism as a distinct field was in 1980. Since that time environmental magnetism has become a broad field that is finding application in an ever-increasing array of scientific disciplines. In this review of the present state of environmental magnetic studies, we divide the field into three broad, but arbitrary, categories. The first involves the use of mineral magnetic assemblages in the geological record to study physical processes in depositional environments. This category includes the correlation of sediment cores using magnetic susceptibility measurements, studies of geomagnetic field behavior, the analysis of depositional and postdepositional mechanical processes that affect sediments, and the examination of magnetic parameters that might represent proxies for paleoclimatic variation. The second category encompasses studies of the processes responsible for variations in the magnetic minerals brought into a sedimentary environment. These provenance investigations include studies of changes in catchment-derived sediment in lakes, fluctuations in contributions from terrigenous, aeolian and glaciogenic components in deep-sea sediments, and the origin of atmospheric particulates. The final category addresses in situ changes and transformations of magnetic minerals in sedimentary environments, including pedogenesis, authigenetic/diagenetic formation of ferrimagnetic phases, dissolution of magnetic minerals due to reductive diagenesis, and contributions of biomagnetism to sedimentary magnetism. Because environmental magnetism can address problems in so many disciplines and because many of these problems may be inaccessible to other techniques, it is likely that the scope of environmental magnetism will continue to expand rapidly. Environmental magnetism is capable of providing important data for studies of global environmental change, climatic processes, and the impact of humans on the environment, all of which are major research initiatives in the international scientific community. These factors suggest that environmental magnetism has a bright and diverse future.

Introduction

Rock magnetists and paleomagnetists have developed many techniques for determining the nature of the magnetic carriers in rocks and sediments. These techniques are now used extensively to understand the origin of the remanent magnetization of geologic materials, and they are critically important in establishing the validity of paleomagnetic studies. Environmental magnetism involves the use of these techniques in situations in which the transport, deposition, or transformation of magnetic grains is influenced by environmental processes in the atmosphere, lithosphere, and hydrosphere (Figure 1). The range of materials studied in this way includes rocks, sediments, soils, atmospheric particulates, and biological materials, and the methods of environmental magnetism have been used in such diverse fields as climatology, ecology, geomorphology, hydrology, land-use studies, limnology, meteorology, oceanography, sedimentology, and soil science. An important aspect of environmental magnetism is that its techniques are relatively rapid, simple, nondestructive, and inexpensive. In addition, and perhaps more significantly, environmental magnetism can be used to address problems that may be inaccessible using other chemical and physical techniques [*Oldfield*, 1991].

Many types of studies that are now classified as environmental magnetism have been in existence for some time. However, the first explicit description of environmental magnetism as a distinct field did not appear until 1980. In a landmark article in *Science*, *Thompson et al.* [1980] showed how mineral magnetic parameters can be used in a wide range of environmental studies. The publication of *Environmental Magnetism* by *Thompson and Oldfield* [1986] brought the field to the attention of a wider audience and was instrumental in the recent, rapid expansion in the use of mineral magnetic techniques to solve a variety of environmental problems. Although British workers played a pioneering role in the establishment of environmental magnetism as an independent, multidisciplinary sphere of research, the field has become international in scope and its techniques are used extensively by researchers in North America and around the world. Recent reviews of environmental magnetism include those by *Oldfield* [1991] and *King and Channell* [1991].

Mineral Magnetic Parameters

Before describing the types of studies encompassed by environmental magnetism, we will briefly describe the mineral magnetic parameters often used in these studies. A more detailed discussion of many of the mineral magnetic concepts presented here is given in the companion paper by *Dunlop* [this issue]. One of the most commonly used mineral magnetic parameters is the magnetic susceptibility (χ) which

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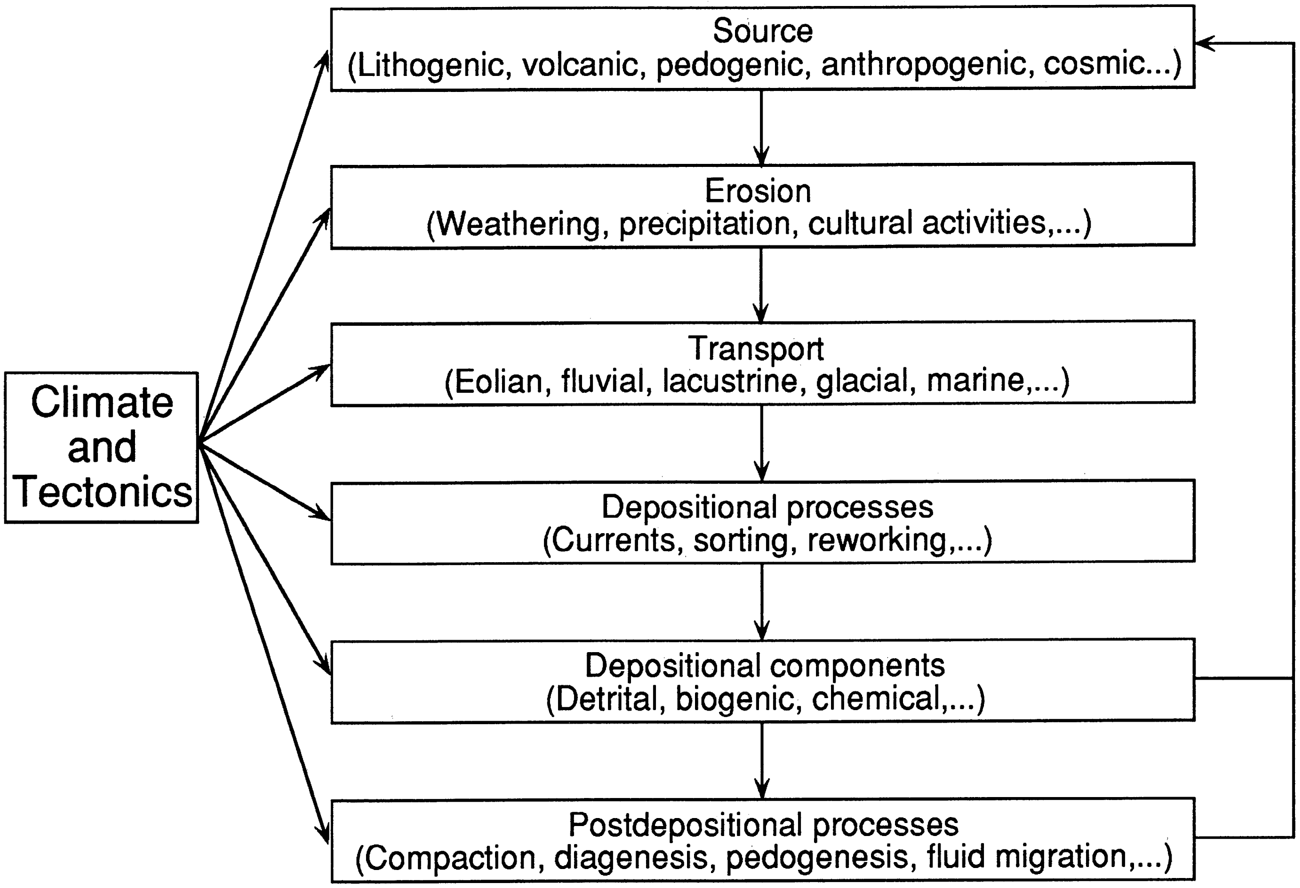

Figure 1. Schematic diagram showing the sources of magnetic minerals with some of the driving forces (climate and tectonics) and processes in the atmosphere, lithosphere, and hydrosphere that give rise to the movement of magnetic minerals into depositional environments, and the postdepositional processes that can modify these minerals. Each aspect shown can be investigated using the techniques of environmental magnetism.

is the ratio of induced (temporary) magnetization acquired by a sample in the presence of a weak magnetic field, to the applied field itself. Magnetic susceptibility is usually measured with an inductance bridge that produces weak alternating fields of high frequency. Magnetic susceptibility is directly proportional to the quantity and grain size of ferromagnetic or ferrimagnetic materials in a sample. Because the response of small (submicron) magnetic grains near the superparamagnetic/single domain (SP/SD) boundary depends on the frequency of the applied field, the frequency dependence of the magnetic susceptibility can be used to estimate whether SP material is present in a sample [*Bloemendal et al.*, 1985; *Thompson and Oldfield*, 1986]. The term "frequency dependence of magnetic susceptibility" or χ_{fd} is usually used to designate the percent decrease in the magnetic susceptibility over a tenfold increase in the frequency of the field used to measure the susceptibility [*Bloemendal et al.*, 1985]. *Mullins* [1977] suggested a likely upper limit on χ_{fd} of about 8%, however, in practice, it is not uncommon to observe values above 10%.

Anhysteretic remanent magnetization (ARM) and isothermal remanent magnetization (IRM) are also frequently used in environmental magnetic studies. Both of these are permanent magnetizations produced in the laboratory by exposing a sample to an external magnetic field. In the case of ARM, the sample is subjected to a dc bias field in the presence of a decreasing alternating magnetic field. Usually the bias field is comparable in intensity to Earth's magnetic field. It is customary to analyze an ARM in terms of its susceptibility, that is, the ARM intensity acquired per unit of applied bias field. This quantity is designated as χ_{ARM}: it is particularly sensitive to the presence of small grains (SD and small pseudo-single domain (PSD) grains) whereas χ is relatively more sensitive to the presence of larger grains (large PSD and multidomain (MD) grains). As outlined by *Banerjee et al.* [1981] and *King et al.* [1982, 1983], plots of χ_{ARM} versus χ can be used as indicators of grain size. Changes in slope on this type of plot indicate changes in magnetic grain size while changes along a line of constant slope are indicative of changes in the concentration of the magnetic material. However, χ_{ARM}/χ provides a measure of the average mineral magnetic properties of a sample and may not be useful when a sample contains a bimodal mixture of grain sizes. Furthermore, the presence of a significant SP fraction complicates use of the χ_{ARM}/χ ratio [*King et al.*, 1982; *Bloemendal et al.*, 1985] because SP grains contribute only to χ and not χ_{ARM}. Thus an increase in the proportion of SP to stable SD grains will appear as a relative increase in grain size rather than a decrease [*King et al.*, 1982]. If used with caution, however, χ_{ARM}/χ can be a useful parameter for assessing relative variations in the amount of fine versus coarse magnetic grains in geological materials.

An IRM is the magnetization acquired by a sample that is exposed to a (strong) dc magnetic field. As the intensity of the field increases, the acquired magnetization increases until the sample becomes as magnetized as its mineralogy and the laws of thermodynamics permit. At this point, the magnetization of the sample is said to be saturated. If this magnetization is measured in the applied field, it is called the saturation magnetization (M_s). If this magnetization is measured after the applied field is removed, it is called the saturation remanence (M_r). M_r is lower than M_s because of the partial loss of alignment of magnetic moments that occurs when the applied field is removed. The saturation remanence is, by definition, equivalent to the saturation IRM (or SIRM). If the applied field is cycled between high values of both forward and reversed polarity, the magnetization of the sample follows what is called a hysteresis loop (Figure 2). The point at which the applied reversed field drives the magnetization from saturation back to zero is called the coercivity (B_c). The applied back-field that drives the remanence of the sample from saturation to zero is called the coercivity of remanence (B_{cr}).

Sugiura [1979] and *King et al.* [1983] pointed out that the ability of a material to acquire an ARM is heavily dependent on the concentration of magnetic particles in a sample. Because of this, *Tauxe* [1993] suggested that SIRM/χ may be preferable to χ_{ARM}/χ for estimating relative grain size variations. SIRM is relatively insensitive to changes in the inducing field, and it varies as a simple function of concentration in sediments with a low concentration of magnetic minerals.

Ferrimagnetic minerals, such as magnetite (Fe_3O_4) and maghemite (γ-Fe_2O_3), fully saturate in applied fields of the order of 300 milliteslas (mT), while canted antiferromagnetic minerals, such as hematite (Fe_2O_3) and ferromagnetic goethite (α-FeOOH), require fields in excess of 2.5 T for saturation to occur. In most laboratories the maximum field that can be applied is of the order of 1-2 T. The presence or absence of saturation at these values is often used to differentiate between ferrimagnetic and canted antiferromagnetic magnetic carriers. A quantitative measure of the degree of saturation is the S ratio, where S is the absolute value of the IRM remaining after exposure to a reversed field of 300 mT divided by the SIRM, which is usually acquired in a field of 1-2 T [*King and Channell*, 1991].

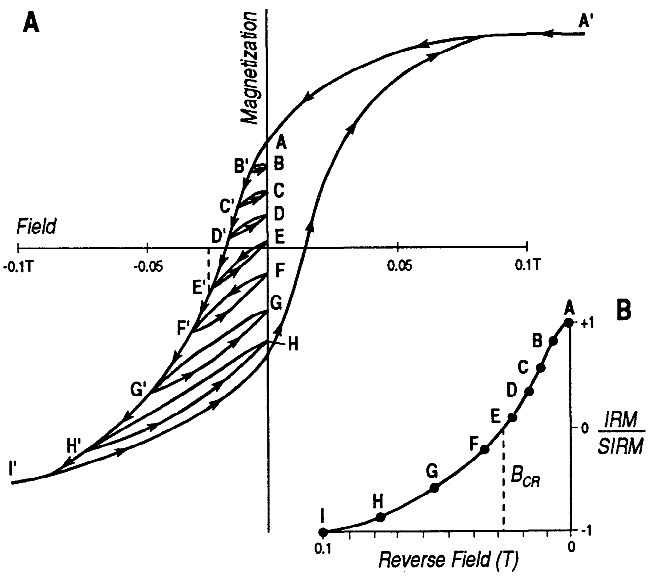

Figure 2. Magnetic hysteresis parameters, including (a) magnetic hysteresis properties of a sample subjected to a forward saturating field (A') followed by fields of decreasing strength and a series of reverse fields (B' to I'). The changes can be measured as a series of minor hysteresis loops (B'B, C'C,..., H'H). The outer envelope marks the major hysteresis loop of the material. The magnetization at A' is the saturation magnetization (M_s) and the remanent magnetization at A is the saturation remanence (M_{rs}). The point at which the magnetization is reduced to zero (i.e. between D' and E') is the coercive force (B_c); (b) measurements of the remanent magnetizations (A to I) left after application of each back field (minor loops). The reverse field which reduces the remanence to zero (i.e., between E and F) is the coercivity of remanence (B_{cr}). Modified from *Thompson and Oldfield* [1986].

$$S = (-IRM_{-300})/(SIRM_{1000}).$$

For ferrimagnets such as magnetite, this ratio will be close to one. As the concentration of canted antiferromagnets such as hematite increases, the value of the ratio becomes smaller.

Magnetic minerals usually occur only in trace amounts in sediments, and definitive mineralogical identification can sometimes be difficult. Fortunately, different magnetic minerals have distinct Curie temperatures, and thermomagnetic methods can be employed to identify magnetic minerals. However, Curie balance analysis, as used in most rock magnetic studies, is usually not feasible on weakly magnetized bulk sediments. Measurement of the temperature dependence of magnetic susceptibility provides one alternative in bulk sediment samples [*Hrouda*, 1994]. Another technique, as outlined by *Lowrie* [1990], takes advantage of the fact that different magnetic minerals not only have different Curie temperatures and generally different ranges of magnetization blocking temperatures but also different coercivities. In this method, a sample is sequentially exposed to strong, moderate, and weak magnetic fields along three mutually orthogonal axes. The resulting three-component IRM is then thermally demagnetized, and under favorable circumstances it is possible to distinguish between minerals with widely differing coercivities by observing the thermal unblocking behavior (and, by inference, the approximate Curie temperatures) of the different components of the magnetization.

If there is only one magnetic mineral and it is known to be magnetite or titanomagnetite, the grain size can often be estimated from the ratios of M_r/M_s and B_{cr}/B_c [e.g., *Day et al.*, 1977]. Fine, SD grains are characterized by $M_r/M_s > 0.5$ and $B_{cr}/B_c < 1.5$ and coarse, MD grains are characterized by $M_r/M_s < 0.05$ and $B_{cr}/B_c > 4$ [*Day et al.*, 1977]. Values between these two extremes are usually considered representative of PSD grains. *Heider et al.* [1987] have noted, however, that there are significant discrepancies between the hysteresis properties of magnetite crystals precipitated from solution and those of crushed sieved grains, as measured by *Day et al.* [1977]. These differences are presumably due to the highly stressed state of crushed material. Care should therefore be taken in making direct grain size inferences from hysteresis data because the state of stress of a material under investigation is usually unknown. Results from low stress hydrothermally grown magnetites [e.g., *Heider et al.*, 1987] may be more appropriate for natural materials than the results of *Day et al.* [1977].

Large, MD grains of magnetite often result from geologic processes associated with slow cooling of magmas in Earth's interior, whereas smaller, SD or PSD grains are often produced by rapid cooling of magma at Earth's surface or by other surficial processes, such as erosion, weathering, chemical alteration, biogenesis, or pedogenesis. The different types of magnetic grains produced by these, and other, processes form the basis for many environmental magnetic studies.

Nature of Environmental Magnetic Research

In this paper, we arbitrarily divide studies involving environmental magnetism into three broad categories. The boundaries between the categories are not always well-defined, but the threefold division provides a workable framework. Studies in the first category simply use the variations in mineral magnetic assemblages in the geological record to study physical processes in depositional environments. Studies in the second category address questions about the nature and origin of the detrital magnetic grains that are carried into a depositional envronment. The key issues in these studies relate to the processes that led to the creation of the particular assemblage of minerals and grain sizes, and, perhaps more importantly, the processes that led to changes in the observed assemblage. Studies in the final category deal with changes and transformations of the magnetic grains that occur during and after deposition. These studies address in situ processes within the sedimentary environment, such as alteration, biogenesis, and diagenesis.

Geologic Processes in Sedimentary Environments

Magnetic Susceptibility Correlation

While magnetic susceptibility has long been known to be a sensitive indicator for characterizing and differentiating different loess deposits [e.g., *Jones and Beaver,* 1964], lake sediments provided the main impetus for the development of environmental magnetism [*Oldfield,* 1991]. In the early studies, downcore variations in magnetic susceptibility were used to correlate cores from a single lake catchment [*Thompson et al.*, 1975; *Bloemendal et al.*, 1979; *Thompson and Turner,* 1985]. These susceptibility variations were interpreted as resulting from changes in the amount and nature of the magnetic grains transported into the lake from the surrounding catchment (Figure 3). Such changes can arise, for example, from alteration of a drainage basin due to stream capture, exposure of bedrock by landslides, denudation of the landscape by fire, or fluctuations in the intensity of weathering due to climate change. Although these variations have the potential of providing information about environmental processes (see below), the focus of attention initially was on correlation, and the primary goal was to establish time stratigraphic horizons for suites of cores. Radiometric techniques applicable to lake sediments (^{14}C, ^{210}Pb, ^{137}Cs) could then be used to provide a chronological framework for the correlations.

A similar approach has been frequently used with deep-sea sediments. Here the primary causes of the variations in magnetic susceptibility are changes in the amount and nature of terrigenous material reaching the site and changes in grain size associated with sorting by currents and/or aeolian processes [*Amerigian,* 1974; *Bloemendal et al.*, 1992]. These factors are ultimately related to climate and tectonics, but as with lake sediments, the initial focus was on correlation. The scale on which it is possible to correlate marine sediments using magnetic susceptibility is quite impressive, often extending over an entire sedimentary basin. In many cases, the magnetic susceptibility record can be tied to the δ^{18}O record at one or more sites in the basin, thereby providing a time scale for long-range correlations.

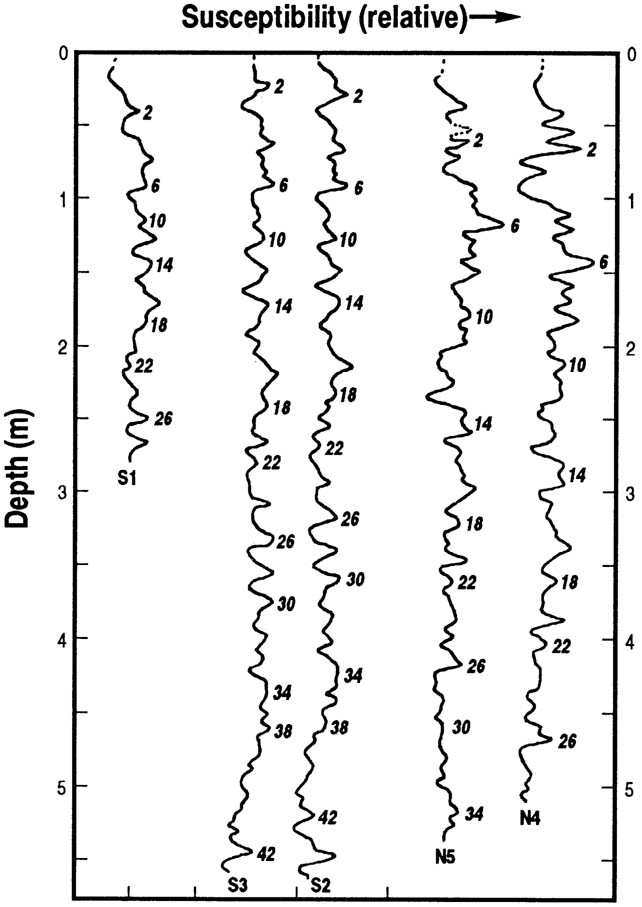

Figure 3. Whole core initial susceptibility records from Lake Vatnsdalsvatn, Iceland [after Figure 3 of *Thompson and Turner,* 1985]. Even numbers indicate susceptibility maxima which can be correlated between cores (core numbers are labeled at the bottom of each susceptibility curve).

Magnetic susceptibility measurements are now used extensively and routinely in most studies of deep-sea sedimentary cores [e.g., *Bloemendal et al.*, 1988a]. For both lake and marine sediments, magnetic susceptibility correlation is an attractive technique because it does not require physical disturbance or subsampling of the core. If the cores are collected in plastic liners, measurements can be made on whole cores without opening them. The information from such measurements can even be made available in the field or on deck and can be used to determine how and where to collect the next core.

Magnetic susceptibility measurements have also been used in studies that go beyond simple correlation. For example, *Karlin and Abella* [1992] used magnetic susceptibility measurements to study the paleoseismic record of the Puget Sound area of the western United States. The history of paleoseismicity in this region is difficult to decipher because of a lack of well-defined topographic features such as fault scarps. *Karlin and Abella* [1992] used downcore magnetic susceptibility patterns, supplemented with sedimentary grain size analyses, to identify and correlate episodic turbidite sequences in the sediments of Lake Washington, near Seattle. These turbidites are interpreted as being triggered by large earthquakes. Radiocarbon dating of the cores indicates that the sedimentary disturbances in the lake are synchronous with independently documented paleoseismic events.

Paleointensity Correlation

A somewhat different application of environmental magnetism to the problem of correlation involves determination of the paleointensity of the geomagnetic field. During the past 30 years, the focus of attention in sedimentary paleomagnetism has been on the direction of the paleomagnetic vector rather than on its intensity. The reason for this "two-dimensional" view of a three-dimensional quantity is that the intensity of magnetization of a sample is controlled by several factors, including the intensity of the geomagnetic field at the time the magnetization was acquired and the concentration and grain size of magnetic carriers. The relationship between these factors is also affected by depositional and postdepositional processes.

Several years ago, it was suggested that the effect of concentration could be taken into account by normalizing the measured intensity of magnetization (i.e., the natural remanent magnetization, or NRM) with some parameter proportional to the concentration of magnetic carriers [*Opdyke et al.*, 1973; *Banerjee and Mellema*, 1974; *Levi and Banerjee*, 1976; *Tucker*, 1981]. The resulting ratio would be a measure of relative paleointensity rather than absolute field intensity but, in a sedimentary sequence, that would at least provide information about relative changes in paleointensity. The three quantities most frequently proposed as normalization parameters are ARM, SIRM, and χ. Subsequently, it was recognized that too much variation in the size or concentration of the magnetic grains could produce spurious features in the apparent paleointensity curves [*Levi and Banerjee*, 1976; *Amerigian*, 1977]. To address this problem, *King et al.* [1983] proposed criteria to determine if the magnetic carriers are sufficiently uniform to obtain relative paleointensity records. *Tauxe* [1993] has recently suggested a more stringent set of criteria for paleointensity studies, particularly because of nonlinearity in the acquisition of some laboratory-induced remanences when modest variations occur in the concentration of magnetic carriers.

In many cases, sediments that pass various tests for magnetic uniformity appear to yield credible records of relative paleointensity. More importantly, there is growing evidence for the global coherence of relative paleointensity features. For example, *Tric et al.* [1992] produced a record of NRM/ARM from the Mediterranean Sea that extends back to 80 kyr (Figure 4). This record is in agreement with, and has been calibrated against, paleointensity data from lava flows covering the period from 0 to 40 kyr. The record also shows significant agreement with earlier studies from the western equatorial Pacific by *Constable and Tauxe* [1987] and *Tauxe and Wu* [1990]. *Meynadier et al.* [1992] also obtained a record of NRM/ARM back to 140 kyr in the Somali Basin. This record closely reproduces features in the Mediterranean record of *Tric et al.* [1992]. More recently, *Schneider* [1993] obtained a record of NRM/χ from the Sulu Sea for the period from 0 to 110 kyr and *Weeks et al.* [1994] obtained records of NRM/ARM and NRM/SIRM covering the last 240 kyr from the North Atlantic Ocean. The records of *Schneider* [1993] and *Weeks et al.* [1994] diverge significantly from the records of *Tric et al.* [1992] and *Meynadier et al.* [1992] in some stratigraphic intervals, perhaps due to mineral magnetic problems resulting from lack of magnetic uniformity or to nondipole geomagnetic effects. However, all of these records show a high degree of coherence with lows in paleointensity at about 40 and 60 kyr and a high at about 80 kyr. *Tric et al.* [1994] have obtained absolute paleointensity data from lava flows on Mt Etna (Sicily) that show a reasonable agreement with the calibrated relative paleointensity record of *Meynadier et al.* [1992] for the interval from 80 to 150 kyr. The coherence of these records from around the world indicates that the normalized intensity records are dominated by changes in the dipole intensity of the geomagnetic field. This marks a significant step toward the establishment of a credible paleointensity reference curve for the last several hundred thousand years. *Meynadier et al.* [1994] have proposed that paleointensity of the geomagnetic field may provide the basis for a new global stratigraphy that has a higher temporal resolution than that provided by magnetic polarity stratigraphy.

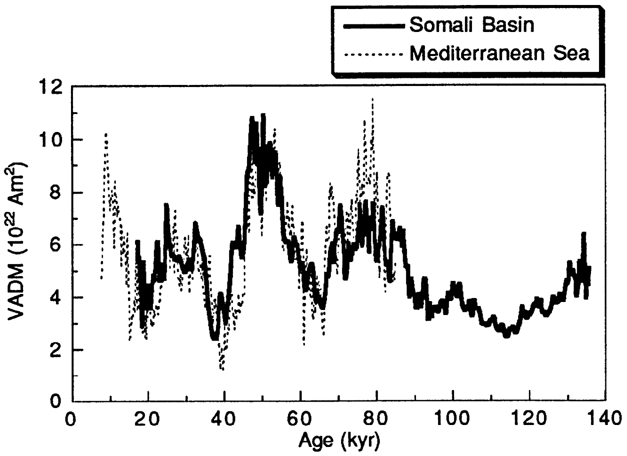

Figure 4. Comparison of relative paleointensity records from the Mediterranean Sea (dashed line, *Tric et al.* [1992]) and the Somali Basin (bold line, *Meynadier et al.* [1992]). The relative paleointensities were transformed to virtual axial dipole moments (VADMs) by the original authors by comparison with absolute paleointensity data from lava flows.

For environmental magnetism, one of the most important implications of a possible globally coherent relative paleointensity stratigraphy is that it may provide a means of correlating between sedimentary environments. For example, *Roberts et al.* [1994a] suggested that variations in relative paleointensity may provide the basis for comparing the paleoclimate record of a lacustrine sequence with marine paleoclimate records. Such connections could provide important insights about the relationship between marine/continental climate systems and may help to test computer models of atmospheric and oceanic circulation.

Depositional and Postdepositional Processes

Environmental magnetic studies can also provide information about the circumstances surrounding the deposition of a sediment. Some of the important questions in this regard relate to the influence of flowing water and the existence of postdepositional disturbances. When magnetic grains larger than about 10 μm settle through the water column, their behavior is controlled more by mechanical and gravitational forces than by magnetic forces [*Ellwood*, 1979]. These grains also make significant contributions to the magnetic susceptibility signal. If the grains are elongate, as most grains are, their long axes will tend to lie in the bedding plane. Because the magnetic susceptibility along the axis of an elongate grain is higher than that perpendicular to the grain, the overall magnetic susceptibility will be anisotropic. This anisotropy is also known as the magnetic fabric, and in the case of deposition in quiet water, the magnetic fabric will have a foliation in the bedding plane.

If a foliation is not present, it can be taken as evidence for postdepositional reorientation of the grains. Various processes can produce such reorientations, including bioturbation, seismic activity, and, in lakes, cryoturbation. In one early study, *Marino and Ellwood* [1978] found that a zone of anomalous paleomagnetic directions in a lake core also corresponded to a zone of anomalous magnetic fabric, ending speculation that the zone had recorded a geomagnetic excursion as had been reported earlier by *Noltimier and Colinvaux* [1976].

If a sediment is deposited in flowing water, the magnetic grains with high aspect ratios can become aligned parallel to the current direction. This alignment manifests itself as a lineation in the magnetic fabric. Much of the early work in this area was done by Rees and his colleagues [*Rees*, 1961; 1965; *Rees et al., 1968*] and is summarized by *Hamilton and Rees* [1970]. Subsequently, *Ellwood and Ledbetter* [1977] used magnetic anisotropy and grain size determinations to identify directions and amplitudes of current flow in the Vema Channel.

Measurements of anisotropy of magnetic susceptibility have also been used as a rapid method for determining the fabric and ice-flow direction in glacial tills [*Fuller*, 1962; *Stupavsky et al.*, 1974]. Bulk magnetic susceptibility has been frequently identified as a useful parameter for identifying the source area of tills deposited by ice lobes from different areas underlying large ice sheets [e.g., *Von der Haar and Johnson*, 1973; *Gravenor and Stupavsky*, 1974; *Chernicoff*, 1984]. In addition, the anisotropy of magnetic susceptibility can be used to determine the mode of emplacement of glacial tills [e.g., *Eyles et al.*, 1987]. If a till is deposited by the melting of an ice mass over water, the magnetic fabric should be relatively uniform with a weak foliation in the bedding plane. If strong currents are present, there might be a lineation as well. For a lodgement till deposited by melting of ice on land, the grains should be randomly oriented, and there should be no pronounced magnetic fabric. If the till was subsequently affected by shearing associated with the movement of ice over the till, the magnetic fabric might reflect this by showing distinct patterns on a local scale [*Eyles et al.*, 1987].

Although out of the realm of environmental studies, it is important to note that anisotropy of magnetic susceptibility can also be used to study magma flow directions in volcanic rocks [e.g., *Knight and Walker*, 1988] and petrofabrics in both plutonic and metamorphic rocks [e.g., *Hrouda*, 1982; *Rochette et al.*, 1992].

Paleoclimate Proxies in Marine and Lacustrine Environments

Environmental magnetic parameters such as magnetic susceptibility are extremely useful in studies of marine and lake sediments because they can be sensitive indicators of temporal variations in the concentration and grain size of terrigenous/lithogenous material deposited on the sea floor or lake bottom. Fluctuations in concentration and size of magnetic grains in deep-sea and lacustrine cores are climatically modulated in many environments [e.g., *Amerigian*, 1974; *Kent*, 1982; *Oldfield and Robinson*, 1985; *Bloemendal and DeMenocal*, 1989; *Snowball*, 1993; *Peck et al.*, 1994].

In the North Atlantic Ocean, high concentrations of magnetic minerals characterize sediments deposited during glacial periods, with low carbonate productivity and increased amounts of ice-rafted detritus, while interglacial periods are characterized by low magnetic mineral concentrations and high carbonate contents (Figure 5) [*Robinson*, 1986]. Cyclic-

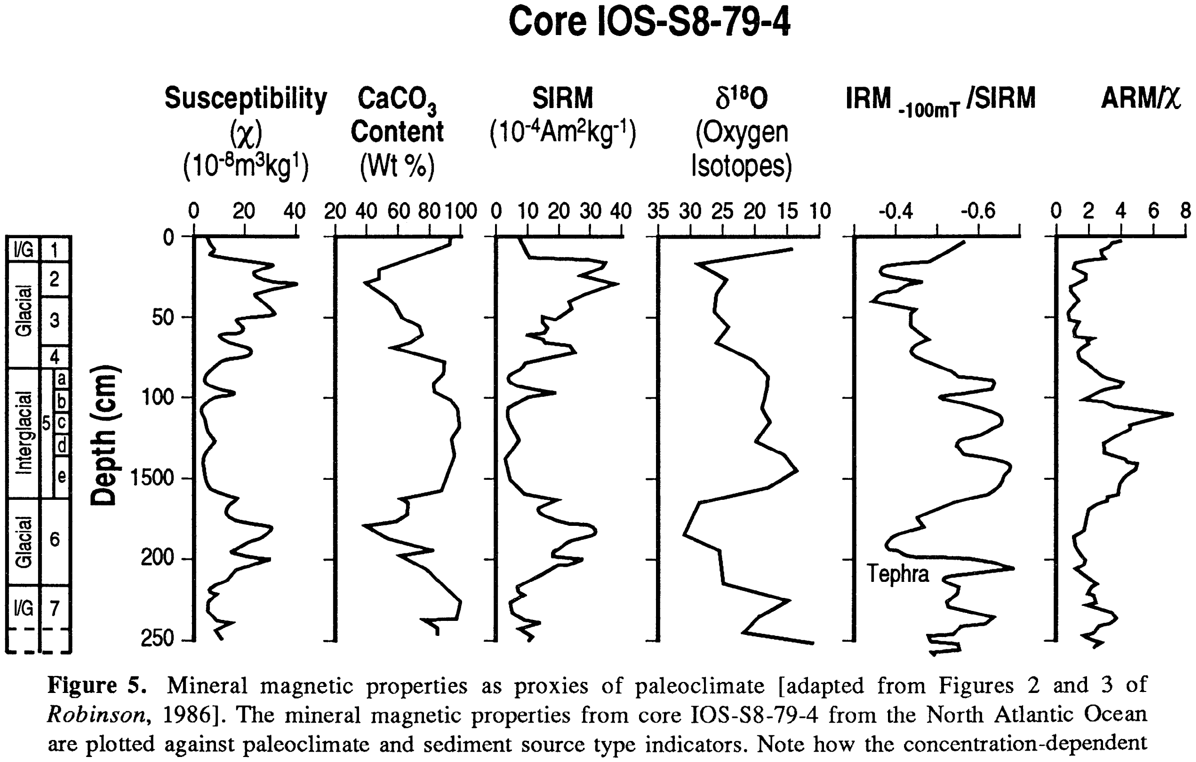

Figure 5. Mineral magnetic properties as proxies of paleoclimate [adapted from Figures 2 and 3 of *Robinson*, 1986]. The mineral magnetic properties from core IOS-S8-79-4 from the North Atlantic Ocean are plotted against paleoclimate and sediment source type indicators. Note how the concentration-dependent (χ and SIRM), mineralogy-dependent ($IRM_{-100\ mT}$/SIRM), and grain size-dependent (ARM/χ) magnetic parameters relate closely to the oxygen isotope stages that are labeled on the left of the figure.

ally deposited sediments rich in ice-rafted detritus, known as the Heinrich layers, are characteristic of the late Pleistocene glacial North Atlantic Ocean [*Heinrich*, 1988; *Broecker et al.*, 1992] and are also easily detected by magnetic susceptibility and ARM measurements [e.g., *Weeks et al.,* 1994]. Numerous studies of fossiliferous deep-sea sediment cores, from different marine environments, have demonstrated that mineral magnetic parameters can be used to define fluctuations that are coincident with Earth orbital periods (Figure 6). These studies can be done with a speed and stratigraphic resolution that would be difficult to match with conventional sedimentological or geochemical techniques [e.g., *Kent,* 1982; *Mead et al.*, 1986; *Doh et al.*, 1988; *Bloemendal et al.*, 1988b, 1992; *Bloemendal and DeMenocal,* 1989; *Park et al.*, 1993].

The study of stratigraphic records of local climate change is also a major emphasis in paleolimnology. Changes in climate affect weathering and sedimentation processes in ways that can give rise to distinct mineral magnetic variations. For example, at high latitude and high altitude sites, periods of glacial retreat are marked by a lower output of glacial sediment, and pedogenesis will occur in the catchment as a result of climatic amelioration. The mineral magnetic properties of the sediments in such environments should therefore reflect the changing balance between glacially derived sediments and those originating from weathered soil profiles. *Snowball* [1993] studied Holocene lake sediments from Swedish Lappland and found that the S ratio is an excellent proxy indicator of climate change. During warmer, drier periods, the supply of detritus to the lake was reduced, and more deeply weathered iron oxides (derived from soil material) were deposited, as reflected in lower S ratios. During periods of glacial advance, sedimentation rates were higher, and magnetite was preserved in the sediments, giving rise to very different S ratios.

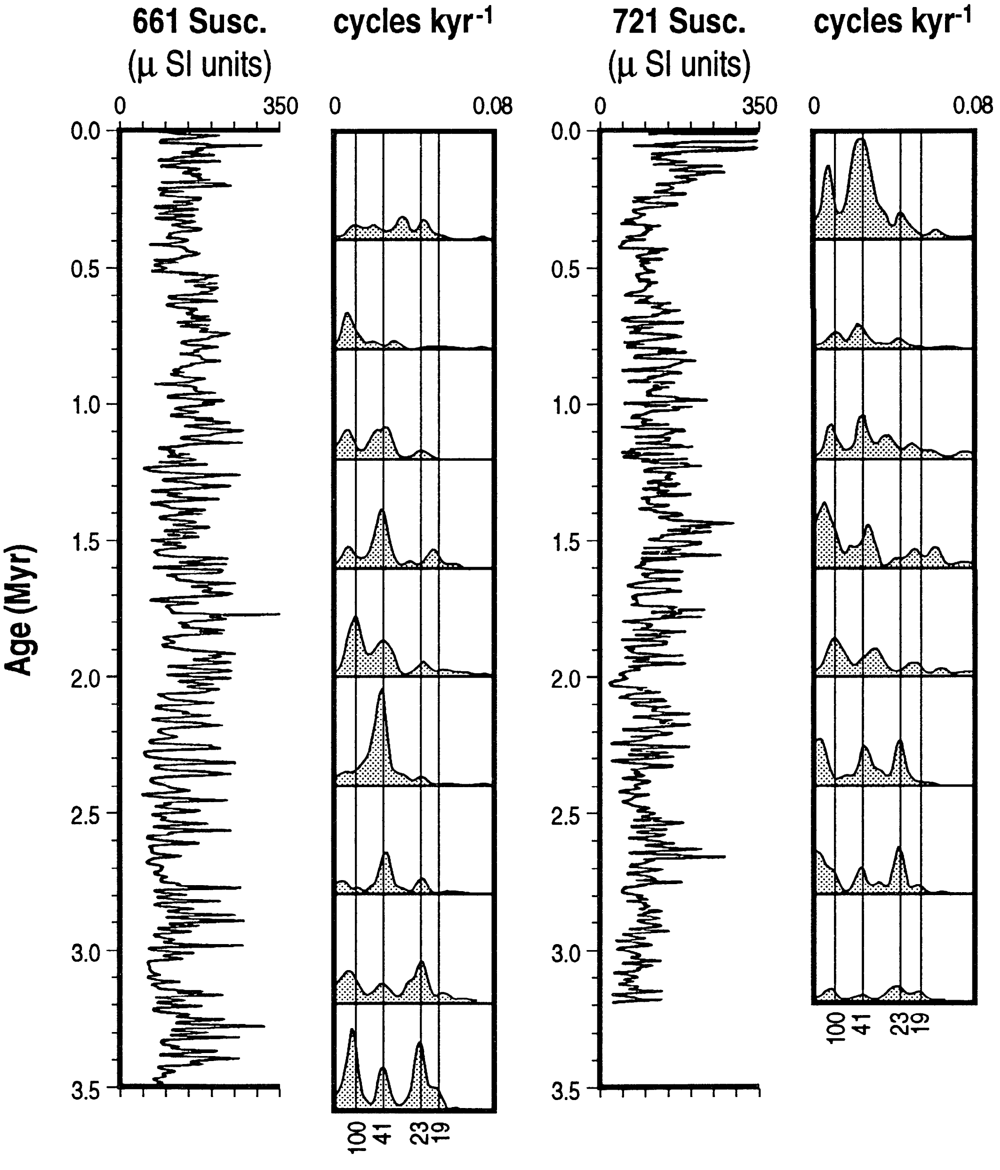

Figure 6. Susceptibility time series for ODP Site 661 (eastern equatorial Atlantic) and ODP Site 721 (Arabian Sea) [after Figure 2 of *Bloemendal and DeMenocal,* 1989]. The time series were divided into 0.4 Myr intervals and spectral analysis was performed on each of these intervals. The vertical lines represent (from left to right) the 100 kyr, 41 kyr, 23 kyr, and 19 kyr Earth orbital periodicities. Note the increase in power at the 41 kyr periodicity at both sites after about 2.4 Myr. Reprinted with permission from *Nature,* 1989, Macmillan Magazines Limited.

Similar observations have been made in lakes in the southern Cascade Range of northern California and southern Oregon [*Roberts et al.*, 1994b; *Rosenbaum et al.*, 1994], although glaciation is not necessarily a direct factor in these catchments. Here high susceptibilities and soft coercivities (indicative of magnetite) are dominant in sediments containing palynomorphs indicative of a cool climate while low susceptibilities and hard coercivities (indicative of mixtures of magnetite and hematite) predominate in sediments deposited during warmer intervals.

Mineral magnetic analyses of sediment cores from Lake Baikal (Siberia), the world's deepest and most voluminous lake, indicate that interglacial intervals are characterized by low concentrations of low-coercivity minerals, whereas glacial intervals are characterized by high concentrations of magnetic minerals with increased amounts of high-coercivity minerals [*Peck et al.*, 1994]. This variation is consistent with dilution of magnetic minerals by high diatom fluxes in the biologically more productive interglacial periods and with an increased contribution of aeolian sediment during the colder, windier, and more arid glacial periods when loess was deposited extensively throughout Eurasia. There is a close correspondence between the variations in magnetic concentration and mineralogy of Lake Baikal sediment and the SPECMAP marine $\delta^{18}O$ record [*Imbrie et al.*, 1984], indicating that the Lake Baikal mineral magnetic record may contain a 250 kyr history of climate change in central Asia [*Peck et al.*, 1994].

Origins of Magnetic Minerals in Sedimentary Environments

As rocks are broken down by weathering processes, the concentration, size, and mineralogy of magnetic grains eroded from the rocks are affected by prevailing environmental conditions. When these magnetic grains are subsequently deposited as sediment in a body of water or incorporated as terrestrial material in a soil or similar deposit, they preserve a record of the tectonic, environmental, and climatic processes that produced them. Environmental magnetic studies can shed light on the nature of the magnetic minerals in a sedimentary sequence and on the processes that change the magnetic minerals.

Provenance Studies: Lake Sediments

One of the primary motivations for the development of environmental magnetic methods was the speed with which magnetic measurements, such as magnetic susceptibility and SIRM, could provide an empirical basis for calculation of sediment influxes within lake catchments [*Bloemendal et al.*, 1979]. If a large proportion of the sediment in a lake can be shown to be derived from the surrounding watershed, the paleoenvironmental record can be interpreted in terms of changes in the ecosystems draining into the lake. Variations in the type and concentration of magnetic minerals in lake catchments are often related to soil and slope processes and land-use changes. The lake watershed ecosystem framework [*Oldfield*, 1977] therefore provides a basis for using the magnetic properties of rocks, soils, and lake sediments as sources of quantitative information concerning ecological and physiographic changes within lake watersheds.

Dearing et al. [1981] were the first to use magnetic parameters to determine the history of erosion and the influx of detrital materials from a lake watershed, which enabled them to estimate the impact of different anthropogenic activities. A striking correlation between pollen frequencies and magnetic susceptibility led these authors to postulate a link between susceptibility and erosion. *Dearing and Flower* [1982] went on to test the hypothesis by examining the relationship between erosion and the magnetic susceptibility of modern material deposited in sediment traps in Lough Neagh, Northern Ireland. They showed that susceptibility peaks correspond with monthly rainfall maxima and concluded that susceptibility peaks in the lake sediment record result from hydrological controls that reflect forest clearance and cultivation. These processes accelerate runoff and increase stream discharge, with a resulting increase in deposition of coarser and more magnetic sediments in the lake. Environmental magnetism is therefore a powerful method for tracing sediment sources and detecting ecological change.

Stream bedload studies are important for identifying the provenance of material deposited in lake environments. Magnetic parameters such as susceptibility, SIRM, S ratio, and B_{cr} have all been used to identify the dominant sources of suspended sediment in stream bedloads during flood events. For example, *Oldfield et al.* [1979] and *Walling et al.* [1979] compared the magnetic properties of material from potential source areas within a catchment with those of samples of sediment in transit. Their studies demonstrate that the magnetic parameters and interparametric ratios provide an exceptionally rapid and sensitive basis for distinguishing undisturbed woodland topsoil, arable topsoil, and material derived from streambank erosion of unmodified bedrock. Such studies have many potential uses including tracing the provenance of nonpoint pollutants [e.g., *Oldfield et al.*, 1985a] and elucidation of patterns and rates of erosion [e.g., *Oldfield et al.*, 1989].

Since the early studies, lake sediment research has become increasingly important in many branches of the environmental sciences because of the need for paleoenvironmental reconstructions and a need to put modern, including anthropogenic, environmental processes into perspective over longer periods of time. Sedimentation rates in lakes are usually more rapid than in marine environments, and the period of accelerated human environmental impact is usually well-resolved in the upper part of lake sediments. For example, *Higgitt et al.* [1991] documented the environmental impact of successive stages in the settlement of the Annecy catchment in eastern France over a period of 2000 years using environmental magnetic and palynological data. Episodes of land use and soil loss identified in the sediment record of the Petit Lac d'Annecy from susceptibility, frequency dependence of susceptibility, IRM, and B_{cr} data correspond well with historical evidence of forest clearance during medieval and postmedieval times (Figure 7).

Recent studies of large lakes also confirm the usefulness of mineral magnetic parameters in studies of paleolimnology, when used in conjunction with other limnologically sensitive stratigraphic variables. For example, the limnology of Lake Michigan has changed dramatically in part due to deglaciation, isostatic control of the lake outflow, and climate change since the late Pleistocene, when the Laurentide ice sheet dominated the limnology of the lake [*Colman et al.*, 1994; *Forester et al.*, 1994]. Magnetic susceptibility records of sediment cores from deep parts of Lake Michigan appear to reflect a lake level signature, with the influx of detrital magnetic minerals varying in phase with lake level and lake volume, as indicated by fossil ostracode assemblages and $\delta^{18}O$ data. Peaks in susceptibility during high lake levels may be due to greater erosion

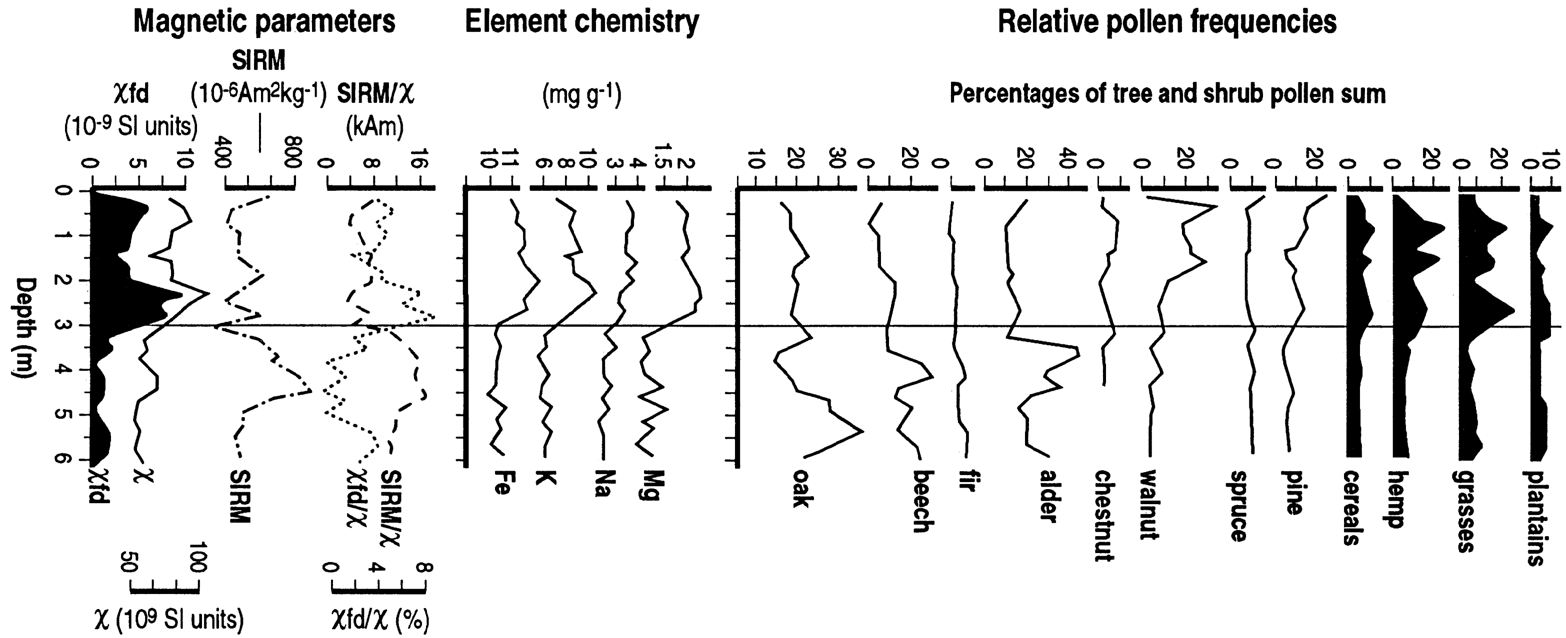

Figure 7. Magnetic properties plotted alongside chemical concentrations and relative pollen frequencies for a 6-m core from Petit Lac d'Annecy in eastern France [after *Higgitt et al.*, 1991; *Oldfield*, 1991]. The line at a depth of 3 m marks a major change in the magnetic, geochemical, and pollen indicators. Frequency-dependent susceptibility (χ_{fd}) increases dramatically as a result of soil erosion that originated from the activities of medieval peasant farmers who tilled land in the catchment in the wake of Cistercian monastic developments.

of the magnetite-rich till bluffs that line the shores of Lake Michigan [*Colman et al.*, 1994; *Forester et al.*, 1994]. Deep lake sediments such as these appear to be an excellent and continuous source of paleoenvironmental and lake level information, in contrast to the discontinuous records commonly obtained from deposits above the present lake level.

Provenance Studies: Marine Sediments

Provenance studies of marine sediments operate on the same principles as magnetic susceptibility correlations because changes in the nature of the detrital magnetic minerals are often responsible for the basin-wide variations in magnetic susceptibility that make correlation possible. A series of studies of sediments of the Arabian Sea and Somali Basin illustrates this relationship, as well as the ways in which environmental magnetic methods can be used to discriminate between terrigenous and aeolian components.

In the initial study of cores from the Arabian Sea from Leg 117 of the Ocean Drilling Program, *Bloemendal and DeMenocal* [1989] showed that variations in the magnetic susceptibility signal were closely correlated with variations in Earth's orbital parameters and that intervals of high magnetic susceptibility corresponded to interglacial periods. Subsequent work demonstrated a relationship between the concentration of terrigenous material and various mineral magnetic parameters such as magnetic susceptibility, SIRM/ARM ratios and quantities related to the S ratio [*DeMenocal et al.*, 1991; *Bloemendal et al.*, 1993]. These observations led to the conclusion that the mineral magnetic record of the Arabian Sea reflected changes in the input of dust transported by the Asian summer monsoon. In the nearby Somali Basin, *Meynadier et al.* [1991] found that intervals of high magnetic susceptibility corresponded to glacial periods. *Meynadier et al.* [1991] used the S ratio and related quantities to show that the ratio of magnetite to hematite had remained fairly constant despite the occurrence of major climatic changes. On the basis of this and other mineral magnetic evidence, they argued that the local terrigenous input to the Somali Basin had been relatively small and that the primary source of sediment was transported via bottom currents that drive Antarctic deep water. Thus, although the environmental magnetic records from two adjacent basins are dominantly controlled by climatic processes related to changes in the patterns of atmospheric and oceanic circulation, the provenance of the sediments exerts the critical influence on whether peaks in the environmental magnetic signal occur within glacial or interglacial intervals.

Provenance Studies: Atmospheric Particulates

The occurrence of atmospherically transported magnetic particles in sediments has been known for many years. Black magnetic spherules of supposed meteoritic origin have been reported from sediments ranging in age from the Holocene to the Paleozoic [e.g., *Crozier*, 1960]. Magnetic spherules resulting from fossil fuel combustion are also common in post-industrial age sediments such as those of Lake Mendota, Wisconsin [*Nriagu and Bowser*, 1969], and those of the greater New York City area [*Puffer et al.*, 1980]. Only in the last 10 years, however, have attempts been made to use the magnetic properties of these and the many other sources of atmospheric particulates to differentiate between different emission types and other atmospheric aerosols. Several studies have demonstrated that magnetic parameters such as SIRM, ARM, χ, and χ_{fd} can be of considerable value in distinguishing the ferrimagnetic component of atmospheric dust derived from soil-sized particles from different source regions as well as fly ash from different industrial sources (Figure 8) [e.g., *Hunt et al.*, 1984; *Chester et al.*, 1984; *Oldfield et al.*, 1985b; *Hunt*, 1986].

As briefly mentioned above, environmental magnetic studies of the aeolian components of deep-sea sediments have been widely used in paleoclimate studies, particularly in the Atlantic Ocean [*Robinson*, 1986] and the Arabian Sea [*Bloemendal and DeMenocal*, 1989] where large amounts of dust are derived from North Africa and the Arabian Peninsula. Environmental magnetism has not been used widely to study aeolian sediments in the North Pacific Ocean. Instead, sedimentological analyses have been used to determine changes in aeolian fluxes from the Asian continent to derive a history of atmospheric circulation for the Cenozoic [*Janacek and Rea*, 1983]. The magnetic susceptibility record of the Chinese loess plateau [*Kukla et al.*, 1988] was used by *Hovan et al.* [1989] to correlate the continental loess stratigraphy with a record of dust flux to the northwest Pacific Ocean. *Maher and Thompson* [1992] demonstrated that such a correlation is not ideal, however, because the susceptibility variations in the Chinese loess appear to be pedogenically controlled (see below) and the physical basis for correlation is unclear.

Transformations of Magnetic Minerals in Sedimentary Environments

Detrital magnetic minerals do not necessarily remain unaltered after deposition. Quantification of the contribution of different sources of fine-grained magnetic minerals and the in situ changes to which they have been subjected are vital parts of many applications of environmental magnetism [cf. *Oldfield*, 1992], particularly for studies related to climate, relative paleointensity of the geomagnetic field, and provenance of magnetic minerals. Thus a third area of research in environmental magnetism involves processes that lead to in situ changes in the assemblage of magnetic minerals.

Pedogenesis

Pedology, the study of soils, is a field in which the transport and transformation of iron is of particular importance. For example, it has been known for many years [*Le Borgné*, 1955; *Mullins*, 1977] that the development of a soil profile is accompanied by an increase in the magnetic susceptibility of the A horizon. This enhancement has been attributed to a variety of processes, including fire, biological activity, and oxidation/reduction reactions [*Le Borgné*, 1955; *Mullins*, 1977; *Vodyanitskiy*, 1981; *Schwertmann*, 1988; *Maher and Taylor*, 1988].

Our understanding of the enhancement process has been improved by environmental magnetic studies of soil chronosequences. Soil chronosequences are suites of soils that have developed over different periods of time from the same parent material and under more or less the same climatic conditions, such as the soils on a flight of uplifted marine or river terraces. Comparisons of magnetic susceptibility profiles through the different soils in a chronosequence have shown that the enhancement extends well into the B horizon of a soil and that the mechanism of enhancement involves both preferential accumulation of inherited (lithogenic) magnetic minerals and formation of new (pedogenic) magnetic minerals by soil-forming processes [*Fine et al.*, 1989; *Singer et al.*, 1992].

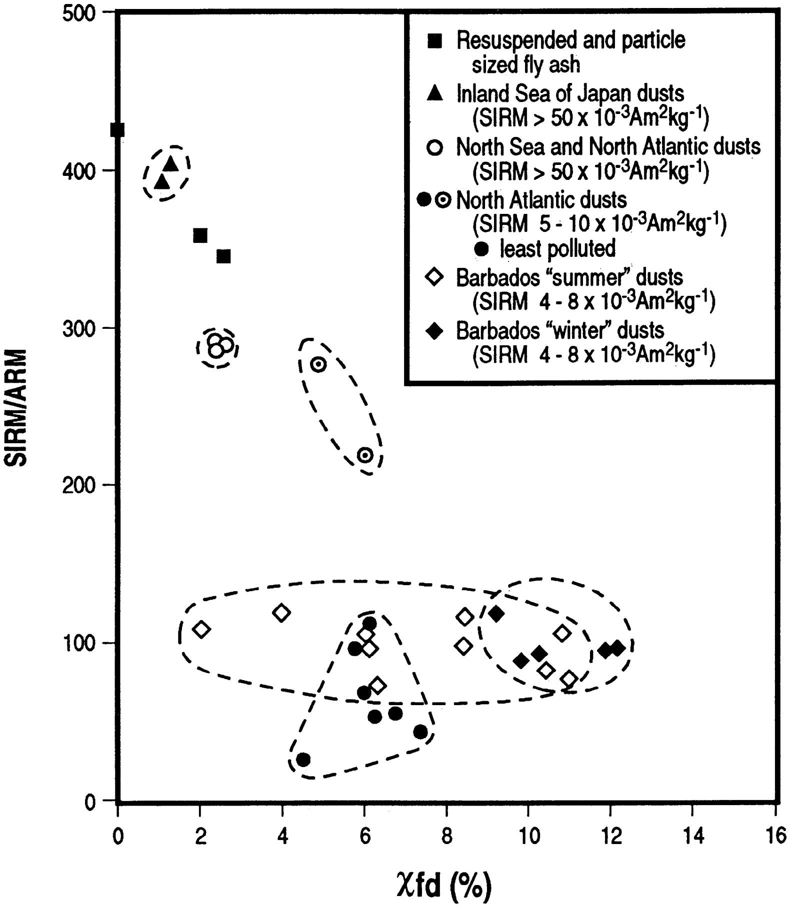

Figure 8. Plot of SIRM/ARM versus frequency-dependent susceptibility (χ_{fd}) for dust samples from the North Sea, North Atlantic, Sea of Japan, and Barbados [after Figure 1 of *Oldfield et al.*, 1985b]. The data demonstrate that magnetic measurements can clearly differentiate between industrially derived dusts and those generated by wind erosion of different source areas. Reprinted with permission from *Nature*, 1985, Macmillan Magazines Limited.

In order to separate the contributions of the lithogenic component from the pedogenic component, *Fine et al.* [1989] and *Singer et al.* [1992] measured the magnetic susceptibility before and after treating the samples with a citrate-bicarbonate-dithionite (CBD) extraction procedure. This procedure was originally developed by soil chemists to remove clays from samples subjected to X ray studies [*Mehra and Jackson*, 1960]. More recently, X ray diffraction and Mössbauer studies have shown that pedogenic magnetic grains are selectively dissolved by the CBD treatment whereas lithogenic magnetic grains that are not too fine-grained are unaffected by the treatment [*Singer et al.*, 1994; *Hunt et al.*, 1994]. The combined magnetic and chemical approach can also be used to characterize the magnetic grains of the two components of the soil. For example, *Fine et al.* [1992] have shown that the grain size of the pedogenic magnetic material is independent of the age of the soil. This result may imply that continued growth of individual grains or formation of clusters of grains is not an important process in soils.

Environmental magnetism has played a major role in the interpretation of the 2.6 m.y. paleoclimate record of the thick loess/paleosol deposits in China. The paleosols, which represent warmer interglacial periods, have higher magnetic susceptibilities than the loesses which represent cooler glacial periods. In addition, there is a strong correlation between variations in magnetic susceptibility in the loess/paleosol sequence and variations in $\delta^{18}O$ in marine sediments (Figure 9), making the Chinese loess/paleosol deposits one of the best records of terrestrial paleoclimate [*Heller and Liu*, 1984; *Kukla et al*, 1988, 1990; *Wang et al.*, 1990].

Initially, *Heller and Liu* [1984] and *Kukla et al.* [1988] proposed that the magnetic susceptibility variations were due to an inert magnetic component that had been diluted to different extents in the loess and the paleosols. Several groups [*Zhou et al.*, 1990; *Maher and Thompson*, 1991; *Zheng et al.*, 1991; *Liu et al.*, 1992] then found that the mineral magnetic properties of the loess and the paleosols were different, thereby demonstrating that pedogenesis had played a role in the transformation of the magnetic minerals, at least in the paleosols. Recently, *Verosub et al.* [1993] and *Fine et al.* [1993] used the CBD method to show that most of the magnetic susceptibility signal of both the paleosols and loesses is due to pedogenesis and that loess deposition and pedogenesis were competing processes at all times. These same workers [*Verosub et al.*, 1994] have also used the mineral magnetic properties of the lithogenic and pedogenic material to determine how the iron is partitioned among various mineral phases in the loess and paleosols. Other workers have used mineral magnetic methods to separate the local climate signal from the regional paleomonsoon record [*Banerjee et al.*, 1993]

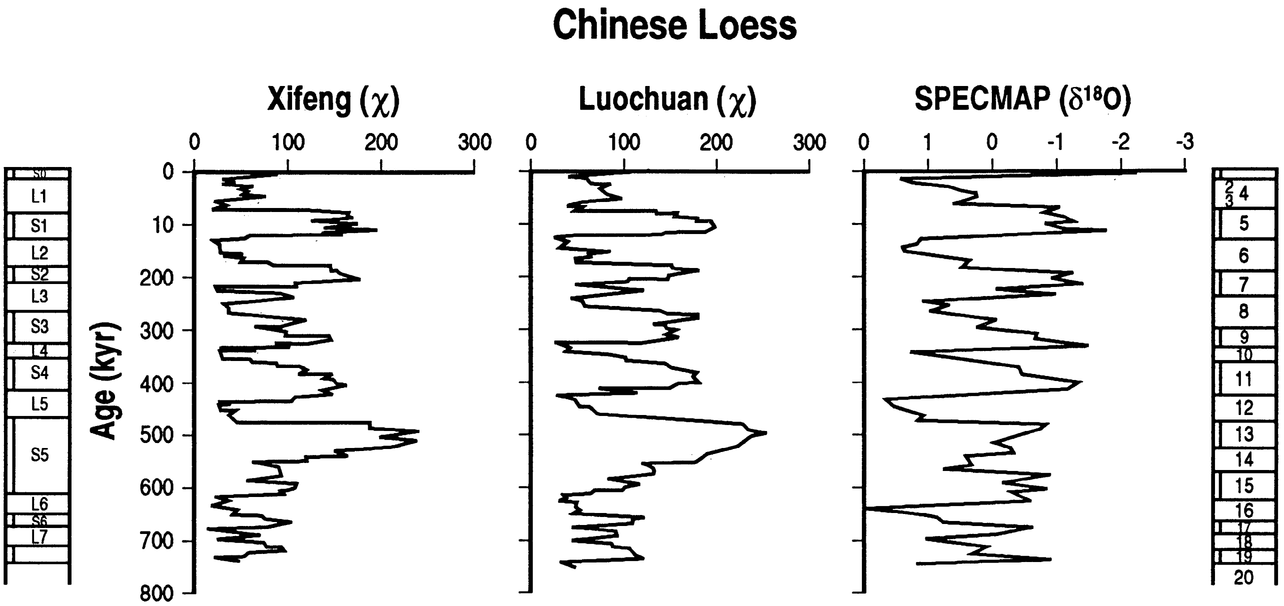

Figure 9. Mineral magnetic properties of the Chinese loess as proxies of paleoclimate [after Figure 7 of *Kukla et al.*, 1988]. Magnetic susceptibility variations in loess sections from Xifeng and Luochuan show remarkable similarities with the SPECMAP oxygen isotope record for the last 700 kyr [*Imbrie et al.*, 1984]. Successive loess (L1,..., L7) and paleosol (S0,..., S6) units are shown in the column on the left of the figure. Oxygen isotope stages are shown in the column on the right of the figure.

and to study the relationship between the formation of pedogenic magnetic minerals and paleoclimate [*Hus and Han*, 1992; *Heller et al.*, 1993; *Liu et al.*, 1993; *Evans and Heller*, 1994].

If the paleoclimate record of the loess/paleosol deposits is primarily a record of pedogenesis, then the magnetic susceptibility signal has been smoothed by pedogenic processes. One consequence of this conclusion is that the underlying paleoclimate signal may have had higher amplitude, shorter-term variations than is generally believed [*TenPas et al.*, 1994].

Authigenic/Diagenetic Formation of Ferrimagnetic Phases

The aim of many of the early environmental magnetic studies was to quantify sediment yields, erosion, and deposition patterns in lake catchments. A detrital origin was assumed for the magnetic minerals in many of the early studies. However, recognition of the existence of ferrimagnetic authigenic and diagenetic iron sulfide phases, in particular, greigite (Fe_3S_4), in lacustrine sediments [*Snowball and Thompson*, 1988, 1990; *Hilton*, 1990], organic-rich coal deposits [*Krs et al.*, 1990, 1992] and marine sediments [*Tric et al.*, 1991; *Horng et al.*, 1992; *Roberts and Turner*, 1993; *Reynolds et al.*, 1994], has cast doubt on the appropriateness of an exclusively detrital model for the origin of magnetic minerals.

Most marine sediments and sedimentary rocks contain at least traces of iron sulfide minerals because a major proportion of the world's mud is, and was, buried under anoxic, sulfate-reducing conditions [*Berner*, 1984]. Pyrite is the most stable iron sulfide phase under reducing conditions [*Berner*, 1971], however, pyrite is paramagnetic and does not directly contribute to sedimentary ferrimagnetism. The process by which pyrite forms in sedimentary environments is well-known and involves the formation of intermediate ferrimagnetic iron sulfides, such as pyrrhotite and greigite [cf. *Roberts and Turner*, 1993]. Because pyrite is ubiquitous in many geological environments, it is at least possible that greigite and pyrrhotite will also be trace constituents of many sediments. If either of these intermediate ferrimagnetic phases are preserved in a sediment, the environmental magnetic and paleomagnetic signal will be affected significantly.

Greigite was not recognized as a mineral in the English literature until it was identified in a Tertiary lacustrine sequence in California [*Skinner et al.*, 1964]. Since that time, greigite has received little attention because it was considered to be a relatively rare ferrimagnetic mineral, except perhaps in very young sediments [cf. *Thompson and Oldfield*, 1986]. Particular geochemical conditions are required for the preservation of ferrimagnetic sulfide phases [*Westrich and Berner*, 1984; *Canfield and Berner*, 1987], however, greigite has increasingly been recognized as an important remanence carrier in sediments deposited under sulfate-reducing conditions, largely as a result of more frequent application of mineral magnetic (thermomagnetic and SIRM/χ) and geochemical (X ray diffraction) techniques in paleomagnetic studies.

Hilton et al. [1986] proposed an authigenic/diagenetic origin for a potentially large part of the mineral magnetic content of organic sediments from productive lakes, however, the significance of authigenic magnetic phases in marine environments is underestimated in the model of *Hilton* [1987]. This is particularly the case because greigite has been so widely identified in marine sediments [e.g., *Tric et al.*, 1991; *Horng et al.*, 1992; *Roberts and Turner*, 1993; *Reynolds et al.*, 1994]. Recent identification of early diagenetic greigite of probable Cretaceous age [*Reynolds et al.*, 1994] indicates that this phase can persist in the geological record for extremely long periods of time and is therefore much more than hypothetically important in the geological record. Other authigenic and diagenetic phases, such as siderite [*Ellwood et al.*, 1986, 1988], are also important in some depositional environments.

Dissolution of Magnetic Minerals in Marine and Lake Environments

Although authigenic or diagenetic growth of secondary magnetic minerals is a possible consequence of deposition in reducing environments, dissolution of detrital magnetic minerals is ubiquitous in sediments deposited under sulfate-reducing conditions [*Canfield and Berner,* 1987]. Environmental magnetic methods can be used to investigate the effects of diagenesis on the detrital paleomagnetic record but, equally importantly, the magnetic minerals can also provide insight into the processes active in the depositional and postdepositional environment. Magnetic phases are intimately involved in the natural sequence of reactions related to the decomposition of organic matter in sedimentary environments. Decomposition proceeds from oxidation by O_2 to microbially mediated metabolic reactions of nitrate, manganese, iron, and sulfate reduction, which are followed by fermentation and methanogenesis [*Berner*, 1980]. The extent of magnetic mineral dissolution and the nature of the resulting phases depends on the availability of nutrients and metabolites.

In slowly deposited oxic sediments with little organic matter, hydrogenous Fe-Mn hydroxides and oxides can form and these minerals often obscure any primary depositional remanence [*Johnson et al.*, 1975; *Henshaw and Merrill*, 1980]. In more rapidly deposited sediments with higher organic contents, manganese oxides are precipitated, and biogenic magnetites can be formed in the sediments just above the iron reduction zone [*Karlin et al.*, 1987; *Petermann and Bleil*, 1993; *Hesse*, 1994]. Deeper in the sediment column, in the iron reduction zone, many of these fine-grained magnetites and detrital magnetic phases are dissolved. If sulfate reduction occurs, the magnetic oxides invert to iron sulfides, particularly pyrite. However, iron monosulfides such as mackinawite and greigite are sometimes preserved [e.g., *Karlin and Levi*, 1983, 1985; *Canfield and Berner*, 1987; *Karlin*, 1990a,b; *Leslie et al.*, 1990a,b]. In sulfate-limited environments (e.g., lakes, bogs, estuaries, and some rapidly deposited marine sediments), pyritization does not go to completion and ferrimagnetic greigite can be preserved [e.g., *Suttill et al.*, 1982; *Tric et al.*, 1991; *Horng et al.*, 1992; *Roberts and Turner*, 1993; *Reynolds et al.*, 1994]. Greigite-producing bacteria can also contribute to the authigenic magnetic signature [*Mann et al.*, 1990; *Bazylinski et al.*, 1993]. In iron-limited anoxic environments, pyritization can go almost to completion, and most of the ferric phases are converted to pyrite.

Because it is possible to detect changes in minute quantities of magnetic oxides with environmental magnetic parameters, they can be used as sensitive indicators of paleoenvironments. This makes possible the use of magnetic techniques to trace cycles of magnetic mineral dissolution which may be due to fluctuating redox conditions that reflect paleoproductivity changes through time [*Tarduno*, 1992, 1994]. However, because various combinations of sedimentary processes can give rise to authigenic growth of secondary magnetic phases, to partial or complete dissolution of detrital grains, and to further modifications of the environmental magnetic record, there is a need for the development of criteria to determine the contributions from each of these processes.

Biomagnetism

Magnetotactic bacteria are an additional source of in situ magnetic phases in sedimentary environments. Discovery of magnetotactic bacteria that may either contain magnetosomes of magnetite [*Blakemore*, 1975; *Kirschvink et al.*, 1985; *Mann*, 1985; *Petersen et al.*, 1986; *Vali et al.*, 1987] or greigite [*Mann et al.*, 1990; *Bazylinski et al.*, 1993] has led to the suggestion that magnetosome chains, which are preserved as fossils after the death of the bacteria, can be significant carriers of remanent magnetization in marine and freshwater sediments [*Kirschvink*, 1983; *Stolz et al.*, 1986; *Snowball*, 1994]. An occurrence of magnetic bacteria has even been reported from soils [*Fassbinder et al.*, 1990], however, it is unclear if magnetic bacteria can contribute significantly to the magnetic properties of soils given the many inorganic magnetic phases that can exist detritally or that may arise through pedogenic processes (see above).

Substantial amounts of magnetite have also been produced extracellularly in incubated cultures of another class of bacteria, dissimilatory iron-reducing bacteria [*Lovley et al.*, 1987]. The importance of this class of bacteria in producing magnetite in sedimentary environments is, at present, unknown.

The possibility that fossil magnetosomes may be significant contributors to an environmental magnetic or paleomagnetic signal has sparked considerable debate between "biomagnetists" and the more traditional "detrital" school [e.g., *Oldfield,* 1992]. Claims that magnetofossils can be significant contributors to sediment magnetism are strengthened by electron micrographs of magnetic extracts from sediments that reveal magnetite grains in chains, and in isolation, that are indistinguishable from those found in magnetotactic bacteria. In cases where further evidence is provided to demonstrate that the magnetosome contribution dominates the stable single-domain sized ferrimagnets in a sediment [e.g., *Petersen et al.*, 1986], it is clear that biomagnetism cannot be ignored when considering the origin of magnetic minerals in sedimentary environments. It is also clear that environmental magnetic data should not be interpreted in a framework that is mutually exclusive of other possible sources of fine-grained ferrimagnets in sediments [*Oldfield,* 1992]. Means of discriminating between the various sources are necessary. To this end, *Moskowitz et al.* [1993] and *Oldfield* [1994] have recently published mineral magnetic criteria that may be helpful in detecting biogenic magnetite and other fine-grained ferrimagnets in sediments.

Future Directions

Environmental magnetism is a relatively new field, and it is always difficult to predict where and how a new field will evolve. We believe that the scope of environmental magnetic studies will expand rapidly and that these studies will represent a significant part of work done by rock magnetic and paleomagnetic laboratories. This expansion will be driven by several factors, not the least of which is the shift in support from basic to applied research.

Clearly, at present there is a great emphasis on studies of global change, climatic processes, and anthropogenic impact on the environment. Many of the environmental magnetic studies discussed above fall in these categories. In other cases, the work that has been done simply serves to demonstrate the enormous potential for additional studies. Furthermore, the current repertoire of mineral magnetic parameters is by no means exhaustive. In several studies, researchers found that new parameters were needed to discern the environmental signal. As additional parameters are recognized and defined and as combinations of these parameters come into greater use, more details and complexities of the environmental magnetic record will be revealed.

The interpretation of data from mixed magnetic mineral assemblages provides another opportunity for the development of new methods and new approaches. The occurrence of such assemblages is being increasingly recognized in environmental magnetic studies, in part because their mineral magnetic records have proven difficult to interpret. There is an urgent need for strengthening the mineral and rock magnetic basis for environmental magnetic studies of mixed magnetic mineral assemblages. In the realm of chemistry, other extraction procedures, besides CBD, are presently available, but their usefulness in studying magnetically composite systems has hardly been explored [*Fine and Singer*, 1989].

The development of new instrumentation has played, and will continue to play, a major role in the expansion of environmental magnetism. The availability of inexpensive, compact pulse magnetizers made it feasible to conduct detailed studies of IRM on large suites of samples. Similarly, the use of hysteresis parameters increased dramatically when the alternating gradient magnetometer was developed [*Flanders,* 1990]. This instrument is capable of measuring much smaller samples at a much faster rate than its predecessor, the vibrating sample magnetometer. Other important innovations have been the development of reliable, high-precision instruments for measuring magnetic fabrics and the magnetic properties of materials at high and low temperatures.

In the near future, the instrument that might have the greatest impact on the field of environmental magnetism is the narrow-access, long-core, pass-through cryogenic magnetometer. This instrument is designed to make almost continuous measurements on 1.5 m long (by 2 cm high and 2 cm wide) u-channel samples [*Weeks et al.*, 1993; *Nagy and Valet,* 1993]. The instrument has a high spatial resolution and much higher throughput than measurements of single samples on conventional cryogenic magnetometers. This makes it feasible to make whole core measurements of a suite of mineral magnetic parameters.

A final factor that should contribute to the expansion of environmental magnetic studies is the increasing emphasis on interdisciplinary and multidisciplinary studies. Most environmental magnetic studies have been undertaken in an interdisciplinary context, particularly in conjunction with sedimentary geochemistry. However, as the scope of environmental research becomes wider, there will be new opportunities for finding a broader context for environmental magnetic studies.

Recent work on the environmental availability and bioavailability of toxic metals, such as lead, arsenic, and zinc, found in mine tailings and contaminated soils, are an example of how these factors can come together. Although standards for acceptable levels of these elements are based on bulk concentration, recent work, using surface analysis by laser ionization and by X ray photoelectron spectroscopy, has shown that the mobility of these metals under environmental (or gastric) conditions is determined by the way in which they are bound to the surfaces of rock and soil particles [*Tingle et al.*, 1993]. Furthermore, the binding of these elements appears to be mediated by secondary iron oxides that also form on the surfaces. Because these secondary iron oxides are CBD extractable [*Borch et al.*, 1993], the methods of environmental magnetism can be used to study the availability of toxic metals and to help in the development of new remediation technologies. The wide range of environmental magnetic applications suggests that the field will have a diverse and bright future.

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