CLIMATE CHANGE AND ENVIRONMENTAL MAGNETISM

VEROSUB, KENNETH L., Dept. of Geology, University of California, Davis, California 95616 USA

Summary

The transport, deposition, and transformation of magnetic grains can often be influenced by the physical environmental. In environmental magnetic studies, the magnetic properties of soils and sediments are used as tracers of paleoclimatic and other environmental processes. A prime example of this approach involves interpretation of the paleoclimatic record of loess/paleosol sequences, particularly those in China. Initially, the magnetic susceptibility record of these sequences was used as a quantitative proxy for paleoclimate change. More recently, other magnetic parameters, especially those used in conjunction with methods adapted from soil science, have made it possible to obtain a more complex and more sophisticated interpretation of the paleoclimate record. This new interpretation makes it possible to separate the lithogenic and pedogenic components of the magnetic signal and to take into account the different mineral magnetic pathways that contribute to the overall paleoclimate record. It has even been possible to detect an environmental magnetic signature for the transition from greenhouse to icehouse conditions in Antarctica at the Eocene/Oligocene boundary. Because the methods of environmental magnetism are rapid, non-destructive and inexpensive, they represent an effective means of augmenting traditional methods of studying the paleoclimate record.

Introduction

Over the past forty years, rock magnetists and paleomagnetists have developed many techniques for determining the nature of the magnetic carriers in rocks and sediments. These techniques are 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. However, in many situations, the mineralogy, concentration, and grain-size of the magnetic carriers can be strongly influenced by environmental processes. In environmental magnetic studies, the magnetic properties of soils and sediments are used as tracers of paleoclimatic and other environmental processes. 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; Verosub and Roberts, 1995).

Methodology

Perhaps the most commonly measured parameter in environmental magnetic studies is the magnetic susceptibility, which 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 directly proportional to the quantity of magnetic material in a sample. Because the response of submicron magnetic grains depends on the frequency of the applied field, the frequency dependence of the magnetic susceptibility can be used to estimate whether these grains are present in a sample (Bloemendal *et al.*, 1985; Thompson and Oldfield, 1986).

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. ARM is particularly sensitive to the presence of small grains whereas the magnetic susceptibility is more sensitive to the presence of larger grains. Thus, the ratio of the ARM magnetization to the low-frequency magnetic susceptibility is a useful parameter for assessing relative variations in the amount of fine *versus* coarse magnetic grains in geological materials (Banerjee *et al.*, 1981; King *et al.* 1982, 1983).

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. If this magnetization is measured after the applied field is removed, it is called the saturation remanence. 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. The point at which the applied reversed field drives the magnetization from saturation back to zero is called the coercivity. The applied backfield that drives the remanence of the sample from saturation to zero is called the coercivity of remanence.

Magnetic susceptibility, susceptibility of ARM, saturation magnetization and saturation remanence are generally indicative of the concentration of magnetic material in a sample. The coercivity and the coercivity of remanence are more diagnostic of magnetic mineralogy, and in many situations, the ratios of the saturation remanence to the saturation magnetization and of the coercivity of remanence to the coercivity provide information on magnetic grain size.

The behavior of a sample during the acquisition or loss of a laboratory magnetization can also provide information about the mineralogy and grain size. Ferrimagnetic minerals, such as magnetite and maghemite, fully saturate in applied fields of the order of 300 milliteslas, while antiferromagnetic minerals, such as hematite and goethite, require fields in excess of 2.5 tesla for saturation to occur. In most laboratories the maximum field that can be applied is on the order of 1-2 tesla. The presence or absence of saturation at these values is therefore often used to differentiate between ferrimagnetic and antiferromagnetic magnetic carriers.

The magnetization of a sample containing ferrimagnetic grains can be reduced by subjecting the sample to a decreasing alternating magnetic field. In practice, this is a step-wise process that involves alternating fields of progressively higher peak intensities. The magnetization is measured after each demagnetization step, and the applied alternating field required to reduce the magnetization to half its initial value is called the median destructive field. For ferrimagnetic material, the median destructive field increases as the grain size decreases. In contrast, samples containing anti-ferromagnetic grains show little change in intensity during alternating field demagnetization.

Quaternary Paleoclimate

Researchers in the Paleomagnetism Laboratory at University of California-Davis are engaged in a variety of projects that involve the application of environmental magnetism to the study of paleoclimates. One major project concerns the transformation and transport of iron in soils. For this project, a combination of magnetic and chemical methods have been used to separate the magnetic properties of the iron grains produced by soil-forming processes from those of grains inherited from the parent material of the soil (Fine *et al.*, 1989; Singer *et al.* 1992). The work began with studies of soil chronosequences in California (Fine and Singer, 1989) and has been expanded to include soil sequences in Hawaii, New Zealand, Italy, France and Israel. These studies have shown that iron-bearing minerals are produced by various pathways in soils and that magnetic methods can serve as sensitive tracers of pedogenic processes. The primary inorganic pathways are neoformation, translocation, lessivage, solubilization and dissolution (Singer *et al.*, 1996). Organic pathways involving microbial interactions are also believed to be important, but less work has been done in this area. Since climate is one of the primary determinants of soil formation, understanding the extent to which different pathways have contributed to the iron minerals in a soil can provide important insights about paleoclimatic conditions.

The same methodology has been applied to the study of the loess/paleosol sequence in China. This sequences is over 150 m thick and extends back 2.6 million years. Because the paleosols formed during warm, humid intervals (interglacials) while the loess accumulated during cold, dry intervals (glacials), the Chinese loess deposits are generally regarded as the world's longest and most continuous record of terrestrial climate and climate change. The magnetic properties of the paleosols are different from those of the loess (Maher and Thompson, 1991), which implies that measurements of these properties can provide information about climate. Work at the University of California-Davis (Fine *et al.*, 1993; Verosub *et al.*, 1993) showed that soil-forming processes affected the magnetic properties of both the paleosols and the loess rather than just the paleosols. This result challenged the assumptions that formed the basis for previous interpretations of the paleoclimate record in the loess/paleosol deposits (for example, Kukla *et al.*, 1988) and led to a complete revision of our understanding of this record.

Part of this revision involves a better understanding of the nature of the lithogenic and pedogenic components of the Chinese loess/paleosol sequence. The lithogenic component is carried predominantly by coarse-grained ferromagnetic grains while the pedogenic component is carried by finer-grained magnetic material. We have shown that a citrate-bicarbonate-dithionite (CBD) extraction procedure (Mehra and Jackson, 1960), which selectively removes pedogenic iron compounds, can be used to obtain an estimate of the contribution of the two components to the total magnetic susceptibility signal (Hunt *et al.*, 1995; Singer *et al.*, 1995). However, the CBD procedure is time-consuming, and we have recently been able to obtain similar results from a mixing model that uses the pre-CBD magnetic susceptibility and its frequency dependence plus a single post-CBD frequency dependence that can be estimated or determined from post-CBD measurements on a small subset of samples (TenPas *et al.*, 1999).

The combination of an environmental magnetic and soil chemistry approach has also allowed us to determine how iron is partitioned in samples from the loess-paleosol sequence. In a typical paleosol, less than 4% of the iron occurs as lithogenic and pedogenic magnetite and maghemite; about 25% exists as hematite and the remainder is bound up in paramagnetic silicate minerals (Fine *et al.*, 1995). These values explain how the paleosols can be darkened with hematite even though the magnetic susceptibility signal is carried by magnetite. These results also place new constraints on paleoclimate models since the climate processes incorporated into the models must influence pedogenesis and iron transformations in such a way that they result in production of the appropriate amounts of magnetite and hematite.

An important implication of the recognition that pedogenesis is responsible for most of the magnetic susceptibility signal in both the paleosols and the loess is that at any instant in time, the magnetic susceptibility is being enhanced throughout the interval in which pedogenesis is occurring. Conversely, at any level in the sequence, the magnetic susceptibility value represents the accumulated enhancement that has occurred over the entire time interval that the level was within the zone of active pedogenesis. In the language of signal theory, the magnetic susceptibility record is the convolution of the original paleoclimate signal with a pedogenic transfer function. We have developed techniques for deconvolving the magnetic susceptibility signal and recovering the primary paleoclimate signal. The most important conclusion that can be drawn from the deconvolution is that the paleoclimate record showed higher rates of change and much greater variability than would be inferred from a point-by-point interpretation of the magnetic susceptibility record.

Although, the loess and associated paleosols of the Chinese loess plateau have long been regarded as an excellent source of continuous records of terrestrial paleoclimate, most studies have dealt with the Lishi Formation, which represents most of the upper two-thirds of the 2.6 million year-long sequence. Many of these studies have focused on the paleoclimate record of only the past 100,000 to 150,000 years. The Wucheng Formation represents the lower one-third of the sequence, and its physical appearance is considerably different from that of the Lishi Formation. This difference is not surprising since the Wucheng Formation represents a time when the climate regime was being influenced quite differently by Milankovitch forcing. In addition, deposition of the Wucheng Formation corresponds to the Tibetan uplift, which is believed to be a primary determinant of Asian and western Pacific climate.

At the University of California-Davis, we are conducting an environmental magnetic study of samples of the Wucheng Formation from Jiaodao, about 50 km from the classic Luochuan loess locality. The samples encompass over 70 meters of section at a 20 cm sampling interval. Initial measurements of the magnetic susceptibility are consistent with published profiles, but the higher resolution reveals considerable structure that has not been seen before. The frequency dependence of the magnetic susceptibility shows considerable variability over short distances and has a very different signature than the Lishi Formation. These results indicate that the Wucheng Formation will serve as an important counterpoint to studies of the Lishi Formation and should result in significant improvement of our ability to interpret the paleoclimate record of the Chinese loess-paleosol sequence.

Eocene/Oligocene Paleoclimate

We are also using environmental magnetic methods to study the transition from greenhouse to icehouse conditions in Antarctica at the Eocene/Oligocene boundary. Despite the importance of the Antarctic ice sheets and their impact on Earth's climate, the timing and precise nature of the events that led to the development of widespread glaciation on the Antarctic continent are still poorly understood. Global syntheses indicate that in response to tectonic isolation of the Antarctic continent, major climatic change and a reorganization of ocean circulation patterns took place during a transition period that lasted at least 10 million years, from the middle Eocene to early Oligocene.

Samples from the CIROS-1 core from the Victoria Land Basin in Antarctica have been used to develop an integrated magnetobiostratigraphic chronology of glaciomarine sedimentation (Wilson *et al.*, 1997) and an environmental magnetic record of climatic deterioration on the Antarctic craton (Sagnotti *et al.*, 1998a). The environmental magnetic data show that there is an alternation between intervals of high concentration and low concentration of magnetic minerals and that other magnetic properties vary in a similar way. The boundaries of these intervals do not correspond to the lithostratigraphic zonation of the core; however, sharp decreases in magnetite concentration appear to correspond to changes in the clay mineralogy that reflect a transition to physical weathering under a cooler climate. This leads to the conclusion that larger amounts of detrital magnetite were shed from the continent into the basin during periods of intense weathering in a relatively warm and humid climate, whereas smaller amounts of magnetite were deposited in a relatively cold and dry climate. By this interpretation, the environmental magnetic properties can be used to trace the alternation of gross and small scale fluctuations in the Antarctic paleoclimatic regime.

These data show that while the Eocene-Oligocene boundary appears to mark a major increase in glaciation of the Antarctic craton, there were several periods of cold climate in the late Eocene. Thus, the climate had begun to deteriorate by the middle/late Eocene boundary but a major East Antarctic ice sheet did not develop until the early-late Oligocene boundary, toward the end of the Eocene-Oligocene transition. Initial environmental magnetic studies of cores from the Cape Roberts Project in the Ross Sea, Antarctica, indicate that alternations in magnetic properties continue through the Oligocene and into the Miocene and that these alternations may be recording less severe fluctuations of the ice sheet (Sagnotti *et al.*, 1998b).

Conclusion

Environmental magnetism is a relatively new field of geophysics that has already demonstrated its potential to add important new dimensions to studies of paleoclimate and climate change. As the field continues to evolve, new environmental magnetic indicators of climate will be found, and more details and complexities of the paleoclimate record will be revealed.

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