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Cross-references

Archeomagnetism
Biomagnetism
Paleomagnetism
Rock Magnetism

ENVIRONMENTAL MAGNETISM, PALEOMAGNETIC APPLICATIONS

Introduction

Environmental magnetism involves magnetic measurements of environmental materials, including sediments, soils, rocks, mineral dust, anthropogenic pollutants, and biological materials. The magnetic properties of these materials can be highly sensitive to a broad range of environmental processes, which makes mineral magnetic studies widely useful in the environmental sciences. More detailed treatments of the breadth of environmental magnetic research applications, and definitions of magnetic parameters and their interpretation, can be found in recent review articles and books (e.g., Verosub and Roberts, 1995; Maher and Thompson 1999; Evans and Heller 2003; see also *Environmental magnetism*). Most environmental magnetic studies aptly focus on environmental interpretations. Nevertheless, environmental magnetism, whether explicitly stated as such or not, routinely plays an important role in paleomagnetic studies, including tectonic, geochronological, and geomagnetic applications. It is the paleomagnetic applications of environmental magnetism that are in focus here, especially in relation to studies of sediments and sedimentary rocks. These paleomagnetic applications are discussed below following four broad themes:

1. Inter-core correlation and development of relative age models;
2. Development of astronomically calibrated age models;
3. Testing the hypothesis of orbital forcing of the geomagnetic field;
4. Determining the origin of the paleomagnetic signal.

Inter-core correlation and development of relative age models

Sedimentary environments receive inputs of detrital magnetic minerals that vary with time and that are diluted by varying supply of lithogenic mineral components and production of biogenic mineral components, respectively. Stratigraphic variations in magnetic properties within sedimentary basins are usually spatially coherent on scales of tens of meters; in some cases, magnetic property variations can be traced over large portions of an ocean basin. Variations in magnetic properties, such as the low-field magnetic susceptibility, therefore, provide a fundamentally important physical parameter for stratigraphic correlation among cores from a coherent depositional environment. Variations in magnetic susceptibility are routinely used for inter-core correlation and provide the basis for development of relative age models in paleomagnetic studies of geomagnetic field behavior. For example, classic studies of paleosecular variation (see *Paleomagnetic secular variation*) recorded by postglacial lake sediments depended on inter-core correlation based on magnetic susceptibility variations (Turner and Thompson, 1979). The resultant correlation provided independent confirmation that the same paleomagnetic variations were observed at the same time in the respective cores. This procedure yielded a coherent relative age model that was then transformed into a numerical age model by combined use of radiocarbon dating, correlation to historical secular variation measurements from the Greenwich observatory and correlation to archaeomagnetic secular variation data (Turner and Thompson, 1979).

Inter-core correlation, based on magnetic susceptibility variations, is widely performed in paleomagnetic studies of lacustrine and marine sediments. For example, thick marine sedimentary sequences are routinely cored by the Ocean Drilling Program (ODP), and its successor the integrated ODP (IODP), by taking successive ~10-m cores from a single hole. Modern high-resolution studies require acquisition of continuous records, which necessitates coring of multiple holes at the same site with slight depth offsets among cores from adjacent holes to ensure complete stratigraphic recovery. A continuous stratigraphic record is then "spliced" together by correlating high-resolution measurements of physical properties such as magnetic susceptibility from multiple cores (Hagelberg *et al.*, 1992). This routine procedure of using magnetic susceptibility variations for stratigraphic correlation provides the basis for high-resolution paleomagnetic studies of sediment cores as well as for a wide range of other studies. An example of the type of high-resolution inter-core correlation that is possible using magnetic susceptibility variations is shown for two ODP holes from the North Pacific Ocean in Figure E37. The two holes are separated by 00°26′ and were cored at water depths of 2385 m (Hole 883D) and 3826 m (Hole 884D), respectively, on the flanks of Detroit Seamount. The sediments from the two depositional environments have different carbonate and volcanic ash concentrations. The magnetic susceptibility variations for the two holes, measured at 1-cm intervals on u-channel samples, therefore have significant differences (Figure E37a,b). Regardless, the records can still be readily correlated and the depths of correlative horizons from one hole can be transferred into equivalent depths in the other hole (Figure E37c). The physical correlation between ODP holes 883D and 884D shown in Figure E37c enabled Roberts *et al.* (1997) to independently correlate relative geomagnetic paleointensity records for the two holes and to produce a stacked paleointensity record for the North Pacific Ocean for the last 200 ka. This approach to inter-core correlation can also help with analysis of finer details of geomagnetic field behavior. For example, the interval between 8.5 and 9.5 m below seafloor (mbsf) at ODP Site 884 contains a detailed record of a geomagnetic excursion (Roberts *et al.*, 1997). By correlating whole-core magnetic susceptibility records from three holes cored at Site 884 (Figure E38a), in the same way as shown in Figure E37, it is possible to place detailed records of the excursion on the same relative depth scale (Figure E38b).

Inter-core correlation using environmental magnetic parameters that are independent of paleomagnetic variations (Figures E37 and E38) enable powerful direct comparison of details of geomagnetic field behavior in paleomagnetic analyses of the spectrum of geomagnetic field behavior, including studies of paleosecular variation, relative paleointensity of the geomagnetic field, excursions, and polarity transitions. It should be stressed that this technique of inter-core correlation simply provides a relative stratigraphic age model; development of numerical age models depends either on direct dating or on correlation of magnetic properties with an appropriate astronomical target curve, as described below.

Development of astronomically calibrated age models

Stratigraphic variations in magnetic properties are climatically controlled in many depositional environments. This can occur, for

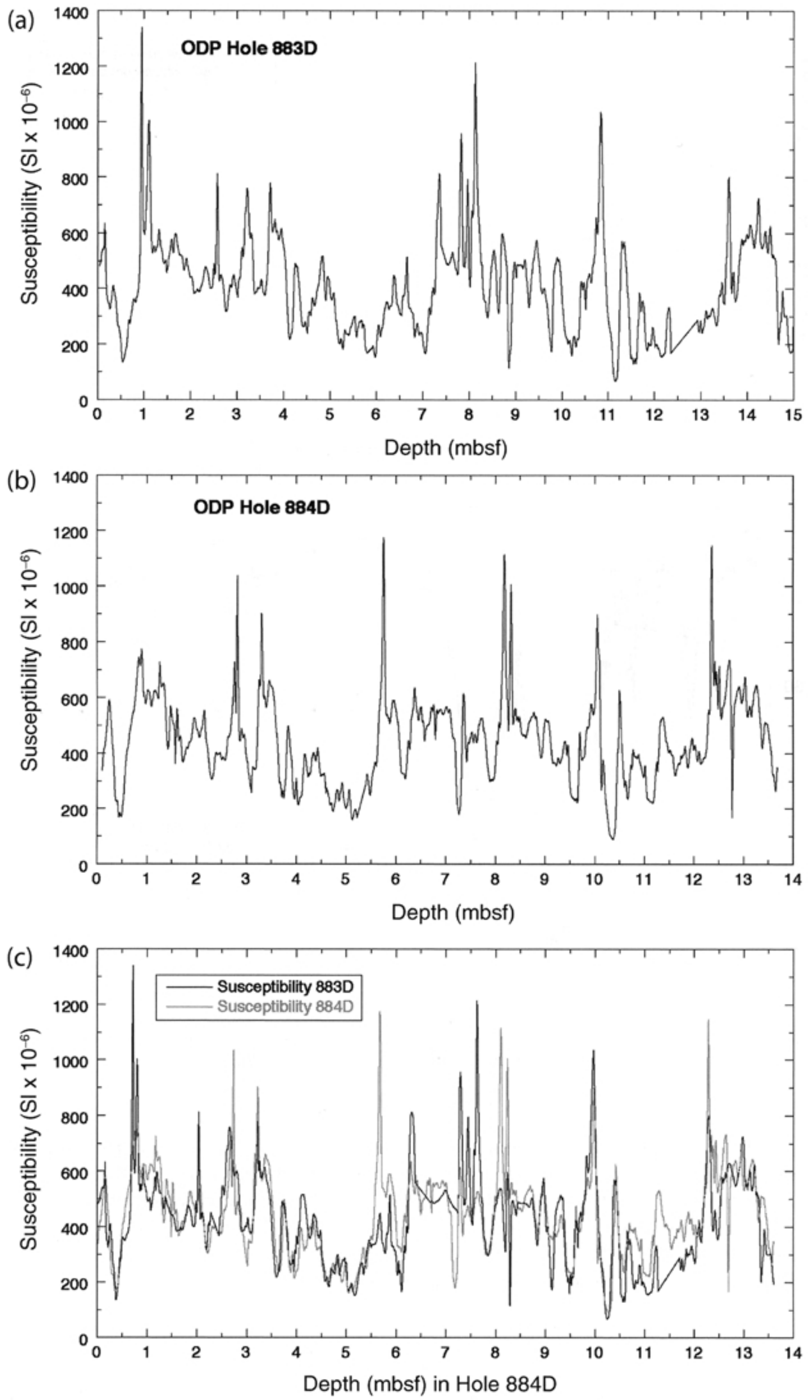

Figure E37 Example of inter-core correlation using low-field magnetic susceptibility. (a) Magnetic susceptibility profile for ODP Hole 883D. (b) Magnetic susceptibility profile for ODP Hole 884D. (c) Correlation of magnetic susceptibility profiles (both for u-channel samples) for ODP holes 883D and 884D, with data from Hole 883D transformed onto the depth scale for Hole 884D (see Roberts *et al.*, 1997 for details). Such correlations based on environmental magnetic parameters provide an independent basis for detailed correlation of paleomagnetic features in cores.

example, as a result of climatic modulation of the supply of lithogenic mineral components eroded from a source rock or through dilution of a roughly constant lithogenic component by a climatically controlled biogenic mineral component. The result is an environmental magnetic record that responds coherently to orbitally forced variations in climate (e.g., Kent, 1982). In some cases, environmental magnetic parameters provide such a good representation of an orbitally controlled forcing parameter (e.g., summer insolation) that the magnetic parameter can be used to directly date the sediment core (e.g., Larrasoaña *et al.*, 2003a). Paleomagnetic studies of relative geomagnetic paleointensity are often conducted on cores where the magnetic properties are climatically controlled. In such cases, age models are routinely developed

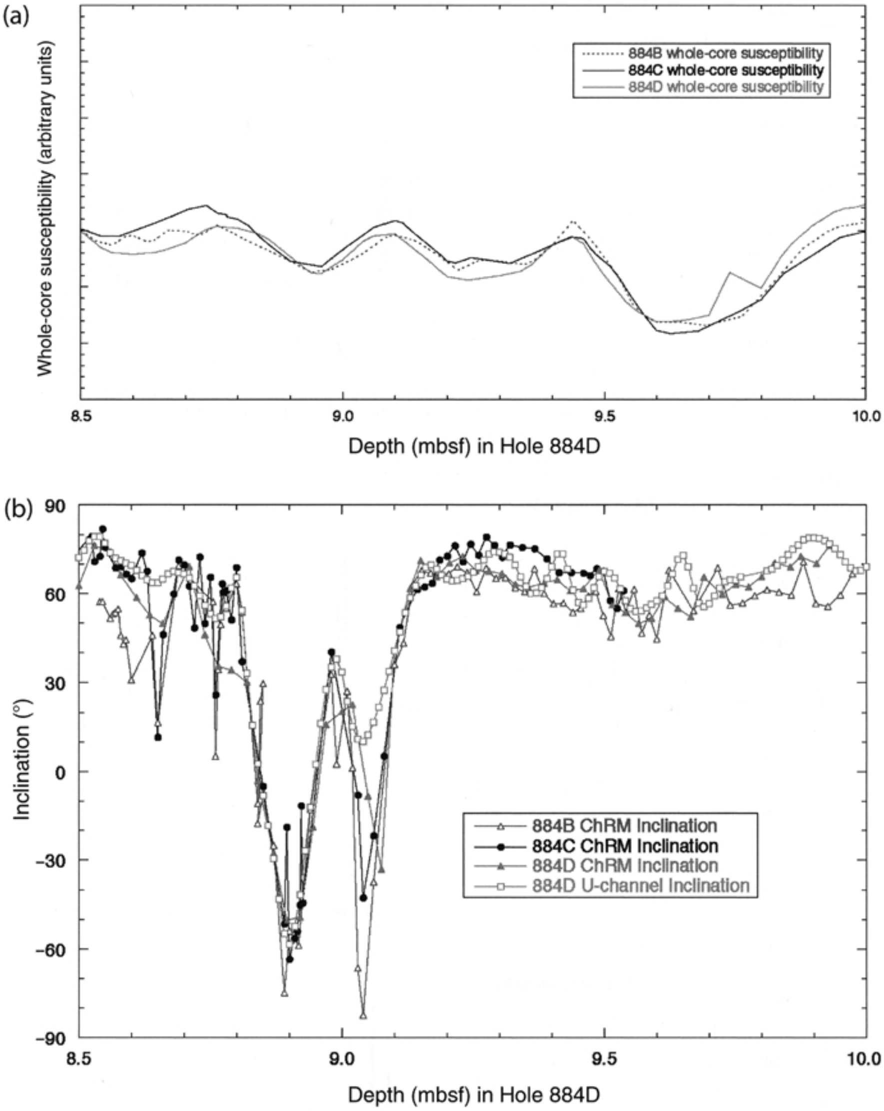

Figure E38 Example of comparison of fine-scale paleomagnetic features based on inter-core correlation using low-field magnetic susceptibility. (a) Correlation of whole-core magnetic susceptibility profiles for ODP holes 884B, 884C, and 884D in the vicinity of a geomagnetic excursion (see Roberts *et al.*, 1997). (b) Paleomagnetic inclination records for the geomagnetic excursion for the characteristic remanent magnetization (ChRM) for discrete samples (holes 884B, C, and D) and for u-channel samples after alternating field demagnetization at 25 mT (Hole 884D). Susceptibility correlation provides a good independent first-order constraint for tying together different high-resolution paleomagnetic records of geomagnetic features.

by correlation of environmental magnetic parameters with astronomical target curves (e.g., Guyodo *et al.*, 1999; Dinarès-Turrell *et al.*, 2002). It is preferable to test such age models against, for example, oxygen isotope records for the same sediment core (e.g., Larrasoaña *et al.*, 2003a); however, age models are often developed solely by correlating environmental magnetic parameters with astronomical target curves.

Environmental magnetic parameters can be routinely used not only for constructing chronologies for individual cores but also for calibrating geological timescales. While development of the astronomical polarity timescale (APTS) (Hilgen, 1991; Langereis and Hilgen, 1991) has been independent of environmental magnetism, extension of the APTS beyond the Miocene-Pliocene boundary has in some cases relied on magnetic properties of sediments. For example, magnetic susceptibility variations have been used to astronomically calibrate the Oligocene and Miocene (Shackleton *et al.*, 1999) via correlation with calculated records of variations in Earth's orbital geometry (Laskar *et al.*, 1993) (see Figure E39).

The APTS was developed by identifying the positions of magnetic reversals in cyclically deposited marine sediments from the Mediterranean Sea, in which organic-rich sapropel deposits provide key tie points to astronomical target curves (Hilgen, 1991; Langereis and Hilgen, 1991). Magnetic minerals are highly sensitive to diagenetic alteration associated with degradation of sedimentary organic matter during early burial, and variations in the burial of organic carbon has produced cycles of nonsteady state diagenesis that has left a characteristic signature in the magnetic properties of these sediments (e.g., Larrasoaña *et al.*, 2003b). In many cases, sapropels that were originally present have been completely removed from the record by postdepositional oxidation, yet magnetic properties can preserve the

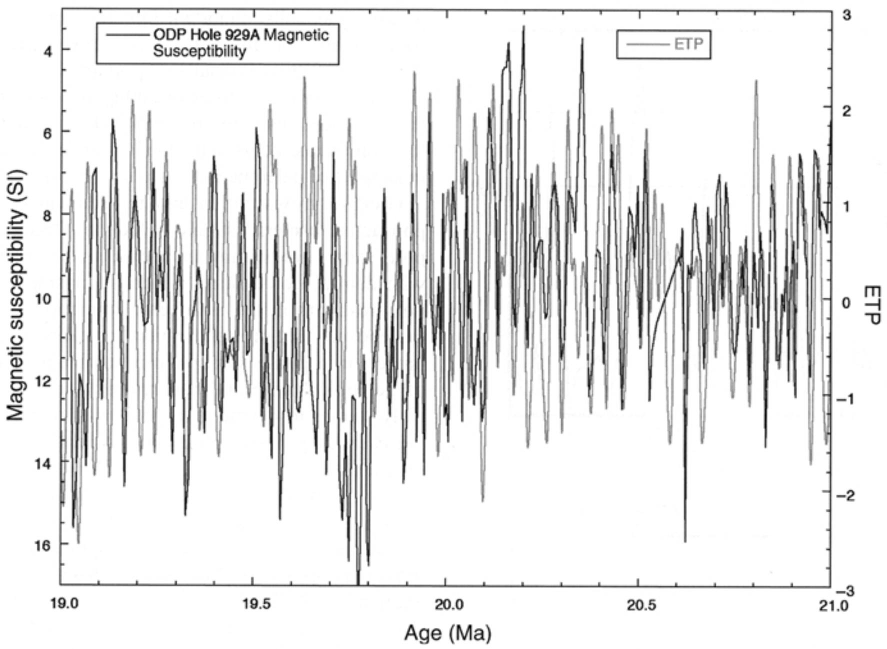

Figure E39 Example of how an environmental magnetic parameter (low-field magnetic susceptibility) can be used to calibrate geological time. The example is from the Early Miocene in ODP Hole 929A from Ceara Rise (Shackleton *et al.*, 1999), with the astronomical target curve being the eccentricity-tilt-precession (ETP) parameter that was extended from the data of Laskar *et al.* (1993). Differences between the curves result from numerous factors (see Shackleton *et al.*, 1999).

characteristic signal associated with the former presence of sapropels (Larrasoaña *et al.*, 2003b). Environmental magnetic analysis of sediments that have undergone orbitally controlled variations of nonsteady state diagenesis can therefore enable development of astronomically calibrated timescales with age tie points in addition to those that are identifiable using standard lithological observations.

Testing the hypothesis of orbital forcing of the geomagnetic field

Long, continuous records of vector variability of the geomagnetic field are needed to understand long-term field evolution and to constrain models of field generation. While it is straightforward to determine the horizontal and vertical components of the paleomagnetic vector in sediments, estimating the intensity of the ancient geomagnetic field has often proved problematical (see *Paleointensity, relative, in sediments*). The problem can be overcome in ideal sediments by normalizing the natural remanent magnetization (NRM) by an appropriate parameter that can remove the effects of variation in magnetic grain size and magnetic mineral concentration. Environmental magnetic parameters such as the low-field magnetic susceptibility, the anhysteretic remanent magnetization, and the isothermal remanent magnetization are routinely used to normalize the NRM to determine the relative geomagnetic paleointensity.

It is accepted that the geomagnetic field is generated by dynamo action within the Earth's electrically conducting fluid outer core (where buoyancy-driven convection generates a self-sustaining dynamo). Calculations indicate that any energization of the dynamo by external orbital forcing is insufficient (by at least an order of magnitude) to control the geomagnetic field (e.g., Rochester *et al.*, 1975). Nevertheless, recent recovery of long, continuous high-resolution vector paleomagnetic records has provided the type of geomagnetic time series needed for testing whether there is any relationship between the field and orbital forcing parameters. Surprisingly, several paleomagnetic records of both the intensity (e.g., Tauxe and Shackleton, 1994; Channell *et al.*, 1998) and direction (e.g., Yamazaki and Oda, 2002) of the field have resurrected the suggestion that orbital energy could drive the geodynamo.

In the case of orbital periodicities embedded within relative paleointensity records, periodograms of these records suggested that orbital periodicities were not present in the environmental magnetic parameters used for relative paleointensity normalization. This was taken to suggest that statistically significant signals at Earth orbital periods in the relative paleointensity records indicate orbital energization of the geomagnetic field (Channell *et al.*, 1998). However, when Guyodo *et al.* (2000) performed wavelet analysis on both the relative paleointensity signals and on the magnetic parameters used for normalization, they found statistically significant periodicities in both the paleointensity estimate and in the normalization parameter during the same time intervals. Guyodo *et al.* (2000) concluded that, overall, there is a subtle climatic contamination of the magnetic parameters that was not removed in the normalization process. The claim of orbital modulation of the geomagnetic field by Channell *et al.* (1998) was therefore retracted.

In another intriguing case, Yamazaki and Oda (2002) reported a link between the paleomagnetic inclination and orbital parameters and explained it by using a model based on long-term regions of nondipole field behavior at the Earth's surface. Horng *et al.* (2003) studied a core that spanned the same age interval from the same region of nondipole field behavior and found no such relationship. Roberts *et al.* (2003) used the data of Yamazaki and Oda (2002), and, while they found the same spectral peaks, they demonstrated that these peaks were not statistically significant. Even when it is considered that sediments might record a forcing signal in a nonlinear manner, comparison of the spectral signal of Yamazaki and Oda (2002) with that of the orbital solution of Laskar *et al.* (1993) demonstrates a lack of coherence between these signals (Figure E40a). In contrast, a demonstrably orbitally controlled environmental magnetic signal (Larrasoaña *et al.*, 2003a) is convincingly coherent with orbital parameters (Figure E40b). Roberts *et al.* (2003) therefore concluded that the hypothesis of (partial) orbital energization of the geomagnetic field remains undemonstrated. Environmental magnetic signals have played a fundamental role in the debate concerning this interesting paleomagnetic application.

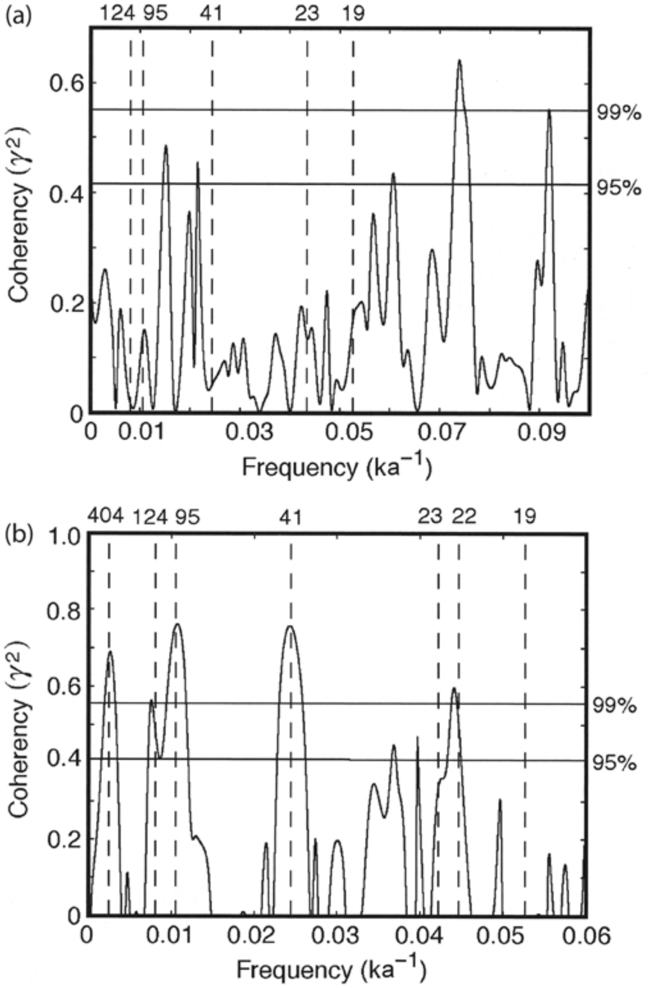

Figure E40 Example of a test of the hypothesis of orbital forcing of the geomagnetic field. (a) Coherency for the ETP parameter from the data of Laskar *et al.* (1993) and the inclination record of Yamazaki and Oda (2002). There is no statistically significant coherency at the 100-ka period (or at other Milankovitch periodicities). (b) Coherency for the ETP parameter from the data of Laskar *et al.* (1993) and the Saharan dust record of Larrasoaña *et al.* (2003a) for the last 3 million years. Orbital forcing of the dust record is clearly demonstrated, with statistically significant coherency with the orbital solutions at the 99% confidence level (see Roberts *et al.*, 2003 for details). This comparison suggests that the hypothesis of orbital forcing of the geomagnetic field is undemonstrated.

Determining the origin of the paleomagnetic signal

Rock magnetic and environmental magnetic investigations constitute a fundamentally important component of most modern paleomagnetic studies. This is because the fidelity of a measured paleomagnetic signal is directly related to the magnetic mineral(s) and the magnetic grain size distribution of the magnetic mineral(s) within a rock. For example, it is generally expected that an assemblage of detrital single-domain or pseudosingle-domain magnetic grains in an undisturbed sediment will faithfully record the geomagnetic field at or near the time of deposition. On the other hand, similar sediments that are magnetically dominated by multidomain grains would not be expected to faithfully record field information dating from the time of deposition. To complicate matters, paleomagnetically important minerals can authigenically grow within some sediments. In such cases, constraining the time of magnetic mineral growth is crucially important for interpretation of paleomagnetic data. Two examples of authigenic iron sulfide minerals, greigite (Fe_3S_4) and monoclinic pyrrhotite (Fe_7S_8), are given here to illustrate the importance of rock magnetic and environmental magnetic studies in support of paleomagnetic studies (see *Iron sulfides*).

Greigite grows within anoxic sedimentary environments that support active bacterial sulfate reduction. Dissolved sulfide forms within pore waters (or within an anoxic water column), which then reacts with detrital iron-bearing minerals, causing their progressive dissolution, resulting in the authigenic formation of pyrite (FeS_2). Pyrite is the end product of sulfidization reactions, with greigite forming as a precursor to pyrite. Greigite can survive in sediments for long periods of geological time and can retain a stable paleomagnetic signal. In early studies involving greigite, it was interpreted to have formed during early diagenesis within tens of centimeters of the sediment-water interface (e.g., Tric *et al.*, 1991; Roberts and Turner, 1993). Subsequently, however, sedimentary greigite has been found to frequently carry a late diagenetic paleomagnetic signal that makes it a highly problematical mineral in many paleomagnetic applications, including magnetostratigraphy (e.g., Florindo and Sagnotti, 1995; Horng *et al.*, 1998; Sagnotti *et al.*, 2005) and tectonics (e.g., Rowan and Roberts, 2005). Paleomagnetic field tests, in particular the fold test, become extremely important for constraining the timing of magnetizations carried by greigite (e.g., Rowan and Roberts, 2005). The reversals test can be misleading and false polarity stratigraphies, resulting from patchy or variably timed remagnetizations (e.g., Florindo and Sagnotti, 1995; Horng *et al.*, 1998; Rowan and Roberts, 2005; Sagnotti *et al.*, 2005), can easily go unidentified if careful rock magnetic and environmental magnetic investigations are not conducted in support of paleomagnetic studies.

Similar to the case with greigite, it is often assumed in paleomagnetic studies that pyrrhotite forms during early diagenesis and that it can carry a stable syndepositional paleomagnetic signal. Geochemical literature, however, indicates that the formation of pyrrhotite is kinetically inhibited at ambient temperatures typical of early burial and that pyrrhotite cannot form during early diagenesis (e.g., Schoonen and Barnes, 1991; Lennie *et al.*, 1995). This presents an apparent conundrum because Horng *et al.* (1998) reported that pyrrhotite carried an identical paleomagnetic signature to detrital magnetite in sedimentary rocks from Taiwan. Horng and Roberts (2006) carried out a source to sink study in southwestern Taiwan and demonstrated that the pyrrhotite in the studied sediments is detrital in origin and that it is sourced from metamorphic rocks in the Central Range of Taiwan. While it is now recognized that pyrrhotite can carry a detrital magnetization (Horng and Roberts, 2006), and while it can also carry late diagenetic remagnetizations (e.g., Jackson *et al.*, 1993; Xu *et al.*, 1998; Weaver *et al.*, 2002), pyrrhotite clearly cannot carry an early diagenetic magnetization. Knowing which type of magnetization is being carried by monoclinic pyrrhotite grains within a sediment is of crucial importance in arriving at a correct paleomagnetic interpretation. These two examples involving different magnetic iron sulfide minerals demonstrate that the assumptions made in many paleomagnetic studies are incorrect. They also make clear the need for careful rock magnetic and environmental magnetic investigations in support of determining the origin, nature, and age of the magnetization in paleomagnetic studies.

Summary

While most environmental magnetic studies appropriately focus on environmental interpretations, environmental magnetism routinely plays an important role in a wide range of paleomagnetic applications. These applications include correlation of paleomagnetic features in suites of sediment cores, development of astronomically calibrated age models, testing the hypothesis of orbital forcing of the geomagnetic field, and determining the origin of the paleomagnetic signal.

The importance of environmental magnetism to this range of paleomagnetic applications therefore makes it fundamentally valuable to paleomagnetism.

Andrew P. Roberts

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Cross-references

Environmental Magnetism
Iron Sulfides
Paleointensity Relative in Sediments
Paleomagnetic Secular Variation