From Magill's Survey of Science: Earth Science
Ed. F.N. Magill and J.A. Woodhead
Salem Press, Pasadena, Calif., 1990

MAGNETIC STRATIGRAPHY

Type of earth science: Geophysics
Field of study: Geomagnetism and paleomagnetism

The earth's magnetic field has fluctuated between a polarity like that of today's field ("normal") and one completely opposite ("reversed") thousands of times in the last 600 million years. The magnetic minerals in erupting lavas and in settling sediments align with the prevailing field at the time the rock forms and thus record the earth's polarity history. The pattern of polarity changes in a thick sequence of rock and can be matched from area to area, providing scientists with a very powerful tool of correlation.

Principal terms

CORRELATION: matching the sequence of events (distinctive layers, fossils, magnetic polarity intervals) between two stratigraphic sections

CURIE POINT: the temperature at which a magnetic mineral locks in its magnetization

MAGNETIC DOMAIN: a region within a mineral with a single direction of magnetization; mineral grains smaller than about 100 microns contain only one domain, while larger grains can contain several domains

MAGNETIC POLARITY TIME SCALE: the geologic history of the changes in the earth's magnetic polarity

MAGNETIC REMANENCE: the ability of the magnetic minerals in a rock to "lock in" the magnetic field of the earth prevailing at the time of their formation

PALEOMAGNETISM: the study of the ancient magnetic field of the earth, as recorded by magnetic minerals in rocks

RADIOMETRIC DATING: the estimation of the numerical age of a rock by measuring the decay of radioactive minerals, such as uranium, rubidium, or potassium

STRATIGRAPHY: the study and interpretation of geologic history from layered rock sequences (usually sedimentary)

Summary of the Phenomenon

A compass shows that the earth's magnetic field lines point toward the North Pole, but 800,000 years ago, a compass needle would have pointed to the South Pole. The earth's magnetic field has apparently changed polarity thousands of times in the geologic past, and an excellent record of its history extends back over the last 150 million years. This history is recorded in the magnetic minerals of rocks that were deposited or erupted in the geologic past.

Several minerals common in the earth's crust are known to be magnetic, but the most important are the iron oxides magnetite and hematite. Magnetite contains three atoms of iron and four of oxygen; hematite contains two atoms of iron and three of oxygen. When a magma cools, the magnetic domains (areas within a crystal that have the same magnetic direction) within crystals align with the field at that time and lock in that direction as the rest of the rock crystallizes. This process is known as thermal remanent magnetization (TRM). Since TRM is formed by cooling, it is found only in igneous and metamorphic rocks. The only igneous rocks that are commonly layered and capable of stratigraphic study are lava flows. Stacked sequences of lava flows were the source of the first discovery that the earth's magnetic field had reversed. The temperature at which this magnetization is locked in is known as the Curie point. For magnetite, the Curie point is about 578 degrees Celsius, but for hematite, it can be as high as 650 degrees Celsius. The actual Curie point varies with the variation in iron and titanium content in the mineral.

When rocks with magnetic minerals are eroded, the magnetic grains become sedimentary particles that are transported by wind and water. As these particles settle, they too align with the prevailing field. As the rest of the sediment is hardened into rock, the sedimentary rock records the direction of the field at the time it was formed. This is known as detrital (or depositional) remanent magnetization (DRM). Since most stratigraphic sequences are sedimentary, most magnetic stratigraphy is concerned with the DRM of sediments.

After a rock is formed, it is possible for water seeping through it to oxidize the iron and precipitate new minerals (particularly hematite and iron hydroxides, such as goethite). Since these new minerals are formed by chemical activity, the magnetic field they lock in is known as chemical remanent magnetization (CRM). These minerals lock in a magnetic field that records the time of chemical alteration rather than the time of the formation of the rock. This magnetization is usually a secondary, "overprinted" one that obscures the original magnetization, which is the most interesting to the paleomagnetist.

Thick sequences of lava flows or layers of sediments that span long periods of time record the changes in the earth's magnetic field through that time interval. By sampling many levels through such a sequence, the paleomagnetist can determine the magnetic sequence, or magnetic stratigraphy, of that local section. Under the right conditions, the magnetic pattern of a section is distinctive. It can be matched to the pattern in a number of other sections of approximately the same age, and these sections can be correlated by the polarity changes. If the pattern is long and distinctive enough and its numerical age can be estimated (usually by radiometric dating), then it is possible to match the pattern to the worldwide magnetic polarity time scale and to estimate an even more precise age.

The worldwide magnetic polarity time scale was first developed in the 1960's, when a group of scientists found that all lava flows with potassium-argon dates less than about 700,000 years were normally magnetized (like the present earth's field), and those older than 700,000 years were usually reversely magnetized (opposite the present earth's field). They began to seek out more and more lava flows around the world, sampling them for both their magnetism and their potassium-argon age. In about five years of sampling, they found a consistent pattern: All rocks of the same age had the same magnetic polarity, no matter where they were located. This immediately suggested that their magnetic properties were caused by worldwide magnetic field reversals rather than by local peculiarities of the rocks themselves.

Continuous sequences of lava flows that could be dated, however, were not available for time periods older than about 13 million years. What was needed was a terrestrial process that continuously recorded the earth's magnetic field behavior and could be dated. Such a process was discovered in the early 1960's at the same time that magnetic polarity reversals were documented. The crust of the ocean floor is constantly pulling apart, and the gap is filled by magma from the mantle below. When the magma cools it locks in the magnetic polarity prevailing at the time. Continual sea-floor spreading pulls apart this newly cooled crustal material and carries it away from the mid-ocean ridge, causing new magma to fill in the rift, to cool, and to lock in a new polarity. This process of cooling, magnetization, and spreading acts as a "tape recorder" that produces a magnetic record of the present field at the center of the ridge and progressively older fields away from the ridge crest. In a few places in the ocean basin, this ocean-floor "tape recording" goes back about 150 million years.

The steady spreading of oceanic plates provides the only continuous record of the changes in the earth's magnetic field between 13 million and about 150 million years ago. In 1968, the first attempt was made to construct a magnetic polarity time scale. Using the known rates of spreading of several mid-ocean ridges, scientists extrapolated several oceanic spreading records back to about 100 million years and placed tentative dates on all the polarity events that were recorded. Since 1968, many attempts have been made to date this polarity time scale more precisely. Ironically, most of the new dates have shown that the original 1968 extrapolation was remarkably good, and new versions of the time scale differ very little from the first version. This proves the assumption that sea-floor spreading is a relatively steady, constant process.

In the last decade, magnetic stratigraphy has proven to be one of the most powerful tools of correlation and dating available. It has many features that other methods of correlation do not. Unlike correlation by distinctive rock units or by the changes in fossils through time, magnetic polarity changes happen on a worldwide basis and can be recorded in any type of rock (lavas or marine or nonmarine sediments) formed at that time. No rock type is formed worldwide, and fossils are restricted by the environments in which they lived. Thus, rocks formed in both the oceans and land can be directly correlated by magnetic stratigraphy, even though the rock sequences are different and they do not share the same fossils.

Another unique feature of magnetic stratigraphy is that polarity changes take place within about 4,000-5,000 years, which is considered instantaneous in a geological sense for any event that occurred more than about a million years ago. Thus, a polarity zone boundary represents a worldwide, geologically instantaneous "time plane" that can be used as a very precise marker wherever it is found. By contrast, the changes in fossil assemblages in a stratigraphic section can seldom resolve events down to a few thousand years, and radiometric dates typically have analytical errors that are anywhere from hundreds of thousands to millions of years.

The major limitation of magnetic stratigraphy is that most magnetic patterns are not unique. When paleomagnetists sample a rock, they get only normal or reversed polarity, not a numerical age. To date a sequence, some other form of dating must be used to place the magnetic pattern on the magnetic polarity time scale. For example, a sequence of "normal-reversed-normal" is not unique by itself; it has occurred many times in the geologic past. If, however, a distinctive set of fossils or a radiometric date can constrain that pattern to a certain period in earth history, then there may be only one part of the magnetic polarity time scale that matches that pattern at that particular point in time. This match gives a more precise age estimate than does the fossil or radiometric date alone.

Methods of Study

Paleomagnetists study ancient magnetic fields by sampling rocks of the proper age and rock type. If it is a lava or other very hard rock, they use a portable drill that collects a short core about 2 centimeters in diameter. Lavas tend to be strongly magnetized compared to other rock types. If the rock to be sampled is a softer sedimentary rock that might break up while drilling, then simple chisels and scrapers are used to extract a hand sample. Sediments tend to have magnetizations that are weaker than those of lavas by a factor of one hundred to one thousand. In addition, only fine-grained sediments (siltstones, claystones, fine sandstones, and limestones) record a remanence; coarse sandstones have more than one magnetic domain within each magnetic grain, which cancel one another out. In both cases, the direction of the present earth's magnetic field is marked on the sample, so it can be compared with the direction recorded in the rock.

The samples are then measured in a device called a magnetometer, which determines the direction and intensity of the field recorded by the sample (its natural remanent magnetization, or NRM). Some magnetometers are portable, but they are only suitable for measuring strongly magnetized lavas. Most labs now use a superconducting cryogenic magnetometer. Its sensing area is kept at 4 degrees Celsius above absolute zero (−269 degrees Celsius) so that it is superconducting, or has almost no resistance to electrical current. When a sample is lowered into the sensing area, even weak magnetic fields in the sample cause changes in electrical current, which are then converted into a magnetic signal.

Typically, the field direction found in the sample (NRM) is a composite of several different magnetic fields. For example, if the rock were deposited during a period of reversed polarity, it may still have a young magnetic overprint acquired during the normal polarity that is seen today. The interaction of these two directions may give an NRM that is neither normal nor reversed, but some intermediate direction. To get rid of unwanted overprinting, the samples must be treated with high temperatures (thermal demagnetization) or high external magnetic fields (alternating field demagnetization), which destroys the less stable (and presumably young overprinted) component of the magnetization. After each treatment at progressively higher temperatures or progressively higher applied fields, the sample is measured again. Interpreting the change of direction and strength of the magnetic component during this stepwise demagnetization enables the paleomagnetist to decide which magnetic mineral is the carrier of the magnetic remanence and also which temperature or field is best for magnetically "cleaning" samples.

After magnetic cleaning, each sample produces a direction that presumably represents the field direction at the time the rock was formed. This remanence is known as the primary, or characteristic, remanence. Because several samples are taken of each lava flow or of each sedimentary bed, the directions of all of the samples from a given site are averaged to omit random "noise." The more tightly all the directions from a site cluster, the more reliable they are likely to be. There are statistical methods that measure this clustering and allow the paleomagnetist to determine the quality of the data. Data that cluster poorly or give nonsensical results can be rejected.

Context

Magnetic stratigraphy has become one of the most powerful tools of dating geologic events. It is critical to understanding geologic history and provides a much greater understanding of certain aspects of the geological past than was previously possible. For example, there has been great controversy over how fast evolution takes place or when mass extinctions occurred. By more precisely dating the sequences in which these events are recorded, scientists can determine rates of evolution much more precisely or determine a much more accurate date for the timing of a mass extinction, which may, in turn, allow the determination of the causes of these events and resolve many long-standing controversies. Magnetic stratigraphy has been used to date the long history of evolution of fossil mammals and dinosaurs in the terrestrial environment and the details of the evolution of the world ocean in marine sections. In many marine sections, the use of magnetic stratigraphy has allowed precise dating of climatic changes, particularly the glacial-interglacial fluctuation of the last ice age. This precise dating, in turn, has allowed scientists to determine that the glacial-interglacial cycles were controlled by changes in the earth's orbital motions, and they thus deciphered the cause of the ice ages. A better understanding of how some of these events (climate change, ice ages, mass extinctions) occurred in the past will help scientists to decide if such events are likely to happen again in the near future.

Bibliography

Boggs, Sam, Jr. *Principles of Sedimentology and Stratigraphy.* Columbus, Ohio: Charles E. Merrill, 1986. A college-level textbook on stratigraphy and sedimentology, which devotes a chapter (chapter 15) to magnetic stratigraphy. This chapter, although brief and not concerned with the practical aspects of magnetic stratigraphy, does give one of the few up-to-date accounts available in any stratigraphy textbook.

Cox, Allan, ed. *Plate Tectonics and Geomagnetic Reversals.* San Francisco: W. H. Freeman, 1973. A collection of the classic papers that led to the plate tectonics revolution, edited by a man who was responsible for the paleomagnetic data that propelled it. It includes many of the pioneering papers that first described the reversals of the earth's magnetic field as well as the discovery of the magnetic polarity time scale and sea-floor spreading. One of its best features is the editorial introductions, which place the papers in historical context.

Cox, Allan, and R. B. Hart. *Plate Tectonics: How It Works.* Palo Alto, Calif.: Blackwell Scientific, 1986. A college-level textbook that explains many facets of plate tectonics, with examples and problem sets. Several chapters give an excellent discussion of paleomagnetism.

Glen, William. *The Road to Jaramollo: Critical Years of the Revolution in Earth Sciences.* Stanford, Calif.: Stanford University Press, 1982. A history of the plate tectonics revolution, recounting the important individuals and their discoveries that led to the discovery of continental drift and sea-floor spreading. The development of the magnetic polarity time scale was a key part of this, and the rivalry between various labs in discovering and dating the magnetic reversals is described in detail.

Kenneth, J. P., ed. *Magnetic Stratigraphy of Sediments.* Stroudsburg, Pa.: Dowden, Hutchinson, and Ross, 1980. An anthology of classic papers on magnetic stratigraphy. Most of the papers deal with magnetic stratigraphy of marine sediments and their application to paleo-oceanographic problems, but some also cover terrestrial magnetic stratigraphy. The editor wrote introductions that place all the papers in historical context.

Lindsay, E. H., et al. "Mammalian Chronology and the Magnetic Polarity Time Scale." In *Cenozoic Mammals of North America*, edited by M. O. Woodburn. Berkeley: University of California Press, 1987. This chapter contains one of the best reviews of the practical aspects of magnetic stratigraphy as applied to terrestrial sections. Although it is written on the professional level, it assumes little or no background in rock magnetism.

McElhinny, M. W. *Palaeomagnetism and Plate Tectonics.* New York: Cambridge University Press, 1973. One of the most popular college textbooks on paleomagnetism. Although some of the text is outdated, it contains an excellent discussion of the field as it was at that time.

Prothero, D. R. *Interpreting the Stratigraphic Record.* New York: W. H. Freeman, 1989. A college-level textbook on stratigraphy, containing a chapter on magnetic stratigraphy. The discussion on magnetic stratigraphy is considerably clearer, more thorough, and more up-to-date than that by Boggs.

__________. "Mammals and Magnetostratigraphy." *Journal of Geological Edu-*

cation 36 (1988): 227. A nontechnical article detailing the practical aspects of terrestrial magnetostratigraphy. It also reviews the progress on the terrestrial, fossil-mammal-bearing record up to the time of the article.

Tarling, D. H. *Palaeomagnetism: Principles and Applications in Geology, Geophysics, and Archaeology*. London: Chapman and Hall, 1983. One of the best books available on paleomagnetism. It discusses magnetic stratigraphy on a much more general level than does McElhinny. A good first resource in reading about the subject.

Donald R. Prothero

Cross-References

Earth's Magnetic Field at Present, 548; The Geologic Time Scale, 874; Magnetic Reversals, 1439; Rock Magnetism, 2217; Stratigraphic Correlation, 2485.