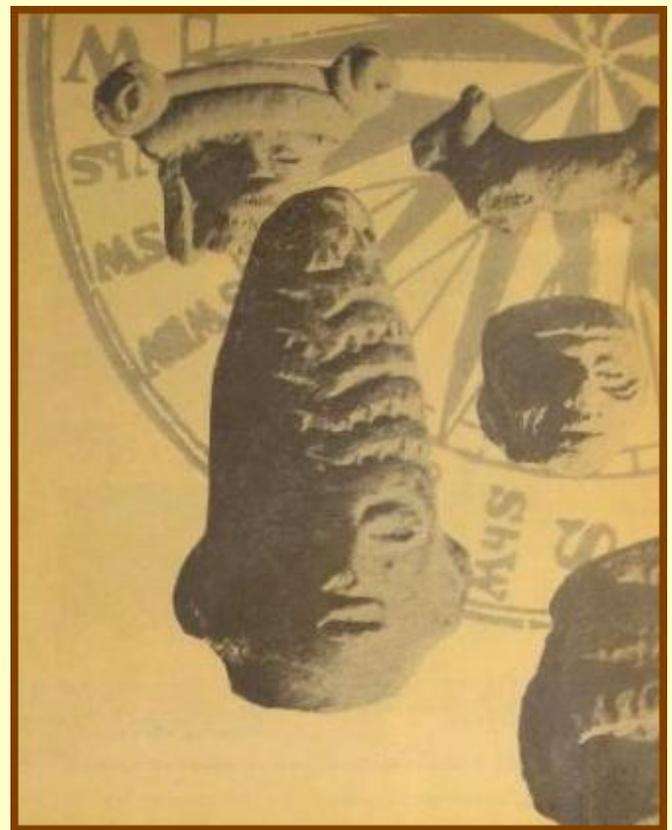


Paleomagnetism & Archeomagnetism

Twin Keys to the Past

By DON LANCASTER

Permanent records of the strength and direction of the earth's ancient magnetic field lie frozen as magnetic recordings in many rocks and artifacts. Measurements of this field, by using magnetometers, computers, demagnetizers, and other instruments provide valuable data about our past.



HOW old is the Earth? What causes the Earth's magnetic field? Why has this magnetic field suddenly reversed dozens of times in the past? What relation is there between these reversals and the extinction of an old or the evolution of new species of animals? Is there anything to continental drift? What causes sea-floor spreading? Westerly drift? Polar wandering?

How does an archeologist accurately date a firepit with no wood present and only chance association with other datable materials? Which quarry did all the stone for a Roman road come from? How far was tradeware pottery carried?

Answers to all these tough questions and more like them are now being answered by the twin sciences of *paleomagnetism* and *archeomagnetism*, sciences as old as the compass and yet as new as today's electronic technology.

Paleomagnetism is the study of the past variations in the Earth's magnetic field, primarily through locked-in magnetic rock recordings of the direction and intensity of the field. *Archeomagnetism* is basically the same game-only it is played by archeologists seeking cultural dates and relations, primarily over the past 10,000 years, instead of by geologists seeking the "how" and "why" of the Earth over its longer 4.5-billion year history.

Only very recently have significant developments been made in these fields, aided by computers, magnetometers, demagnetizers, and other electronic instrumentation. So recently, in fact, that many of today's paleomagnetic results and tentative conclusions would have been considered highly controversial only a few years ago. Today, such concepts as the precession-driven magnetohydrodynamic origin of the Earth's magnetic field, continental drift, and dynamo-caused reversals have a broad base of experimental and theoretical evidence behind them.

Basic Principles

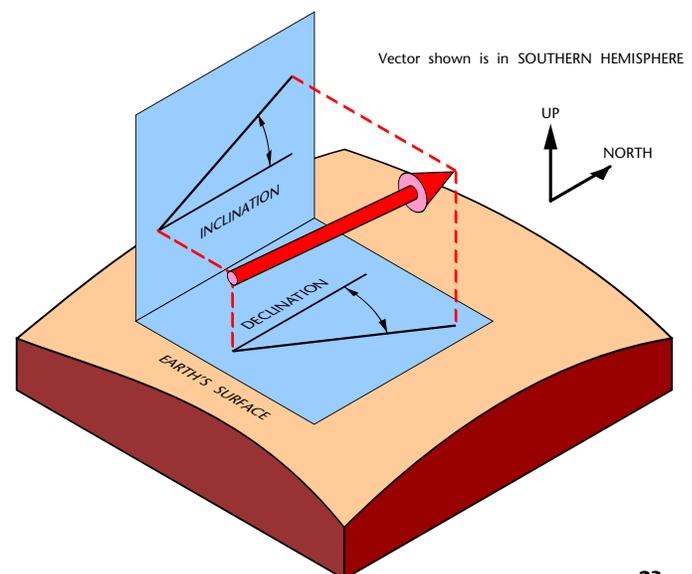
Just like any other magnetic field, the Earth's field can be represented at any given time at a specific place as a vector quantity. The field at any point has both a magnitude and a direction. With Earth magnetism, the vector is manually resolved into two components of direction, called the *declination* and the *inclination*, as shown in Fig.1.

A compass measures declination, or the deviation of magnetic north from true north, usually expressed as 0-360 degrees clockwise. Declination (or compass variation) is the projection vertically downward of the magnetic-intensity vector compared against true (polar) north. (The angle is measured on the horizontal plane.) Compasses do not, of course, point due north, and corrections for declination must be made on all land surveys, aircraft flights, and other precise geographical measurements.

A dipping magnetized needle measures inclination, or the deviation of the magnetic-intensity vector from horizontal. (The angle is measured on the vertical plane.) Values of inclination vary from 0 (horizontal) just south of the equator to nearly +90 (straight down) at the far north and nearly -90 (straight up) at the extreme south.

The strength and the direction of the magnetic-intensity vector at any given geographic location has changed radically

Fig. 1 At any point, Earth's magnetic-intensity vector may be resolved into two components, inclination and declination.



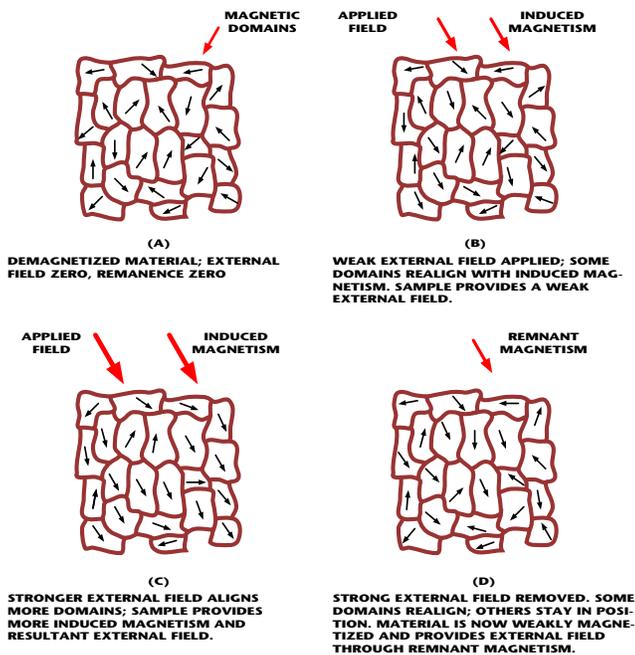


Fig. 2. How induced and remanent magnetism is obtained.

throughout time-so radically that an accurate history of these variations can be made well into the distant past. The variations can often be calibrated against such things as historic records, cultural cross-dating, stratigraphic layering, or the atomic decay dating processes by using carbon-14 or potassium-argon-40. The variations in themselves may, in turn, be used as a secondary calibrated dating standard for new measurements. When many records from many areas are compared against each other, relative motions of the areas with respect to themselves and the magnetic poles become apparent.

Paleomagnetism and archeomagnetism are based upon "freezing" the intensity, declination, and inclination at an instant in the past as a permanent magnetic record in clay, in rock, or other materials. This recording process usually takes place due to the intense heating of the material, either in its volcanic origin, by man in a firepit or kiln, or by accidental coal and forest fires.

If we are able to measure the intensity and direction of the magnetic vector with respect to the original position of the material (either at its location, or by the more common practice of removing the sample to a laboratory after carefully marking its orientation), and if the material has behaved properly magnetically, and if we repeat the process for many tens of thousands of samples, we can trace out the entire history of the magnetic variations of the Earth. From these histories, relative movement, either localized or on a continental basis, of the samples may be readily inferred. Relative ages and, given some calibration, absolute dates may also be obtained.

If we were to inspect a magnetic material under extreme magnification, we would find millions of well-defined, tiny areas called *magnetic domains*. Each domain by itself behaves somewhat like a miniature bar magnet in that it tries to align itself with an externally applied magnetic field.

In the absence of a magnetic field, each domain "points" in a random direction. While each domain has its own magnetic vector the net external sum of all of the randomly oriented magnetic-intensity vectors should be nearly zero. We say the material is *demagnetized*.

There are mechanical forces set up at the domain walls every time a domain tries to align itself with an external field. These are called magnetostriuctive forces and they either prevent a domain from realigning itself or else they allow it to

realign itself, dissipating any constraining energy in the form of heat or a change in sample size.

Some of these forces are strong; others are weak. Suppose as in Fig 2A, we look at a demagnetized material having no externally applied field present. The domains remain the way they were, oriented in a random manner. Now, if we apply a weak magnetic field (Fig. 2B), some of the magnetic domains will align themselves with the field, but others will be constrained by the domain-wall forces and will not be permitted to realign.

A stronger magnetic field (Fig. 2C) will align more of the domains. An exceptionally strong external magnetic field could realign practically all of the domains and *saturate* the material.

We call the domain realignment in the presence of an external magnetic field *induced magnetism*. If we remove the external magnetic field (Fig. 2D) some of the domains should return the way they originally were, driven by domain-wall forces. Others will stay in their new positions. We say the material has been *magnetized* and the strength of the new magnetic-intensity vector produced is called the *remanence* or the *remanent magnetism*.

Eventually, any magnetized material loses its remnant magnetism and the internal domains re-orient themselves in random positions. The time required to demagnetize is called the *relaxation time* and depends upon the material, the temperature, and the domain size. Fortunately for paleomagnetic work, the larger domains in paleomagnetic materials compare with the best of man-made permanent magnets and have relaxation times of millions of years and longer.

A magnetic material is "soft" if it is easy to magnetize and "hard" if it is difficult to magnetize and resistant to demagnetization. Temperature has a profound affect on magnetic hardness and softness. Alnico and other good permanent magnetic materials are first "softened" by heating to high temperatures, and are then easily magnetized. Cooling then "traps" the remanent magnetism in a very hard material. The same thing works for rocks and artifacts and is the key to paleomagnetism.

Magnetism of Rocks

Rocks are made up mostly of nonmagnetic materials, but practically all rocks contain impurities of magnetite and hematite. These are oxides of iron and are strongly magnetic. They, with the help of several related compounds, can give ordinary rocks the ability to record and store a magnetic intensity vector.

There are many ways a rock can acquire magnetism and many ways it can lose magnetism. To be useful paleomagnetically, a rock must acquire its magnetism at a known and well-defined time, while at the same time erasing any previous record and resisting any new changes. The magnetism acquired must, to be useful, be separable from newer effects and must be a faithful record of the intensity, declination, and inclination at the time of recording.

The main ways of becoming magnetized are called *thermoremanent magnetization* (TRM), *chemical remanent magnetization* (CRM), *detrital remanent magnetization* (DRM), and *viscous remanent magnetization* (VRM). Of these methods, thermoremanent magnetization is the best behaved and the most useful. Let us take a closer look at these techniques for acquiring magnetism.

Thermoremanent magnetism is magnetism locked in a sample by intense heat. Magnetite and hematite at room temperatures are extremely "hard" and will have a very long relaxation time. Thus, any magnetism they may have are likely to keep. New magnetism is difficult to obtain.

But whenever these materials are heated, a very unusual thing occurs. At a temperature called the *Curie temperature* (578 C for magnetite), the magnetic domains lose practically all of their restraining forces, and the material becomes very "soft." It is then easily magnetized by whatever external

field happens to be present. If the rock is allowed to cool with the same field present, the remanent magnetism locked in the rock becomes harder and harder as the temperature decreases, finally becoming quite permanent. The acquired intensity is rather strong and while it may be masked by any lower-temperature latter-day magnetizations, it is very difficult to destroy or damage. Reheating the sample beyond the Curie point will, of course, erase the old field record and record a new one.

Other materials have temperatures equivalent to the Curie temperature. These are called the *blocking temperature* or the *Neel temperature*, depending on the material. Whenever these temperatures are exceeded, the material is very easy to magnetize. If allowed to cool with the field present, a remanence proportional to the applied field gets picked up. The cooled sample ends up very hard magnetically and a locked-in record will remain.

Chemical remanent magnetization is caused by chemical processes that change impurities in the rock from nonmagnetic to magnetic compounds, locking in the field at the time of the chemical change. Sandstone turning red with age is one example of this. Any detrital remanent magnetization is caused by fine particles that slowly settle as dust or in water, aligning themselves with the applied field. Neither of these two latter processes is as strong, distinct, or as well-defined as the TRM process. Thus, at present, TRM is far more useful.

Samples with useful TRM come in many forms. Clay is one of the best behaved. Clay gets fired by man in the form of pottery, kilns, and firepits, and it is fired by nature by forest fires and underground coal fires. Second best are volcanic lavas, with TRM taking place as the material cools on the surface of the earth or the bottom of the sea. Other materials, while useful paleomagnetically, often yield less reliable results, with sediments or badly disturbed formations the poorest of all.

There are other ways magnetism can be picked up and methods by which the recording is either altered or made inherently misleading. Before a meaningful paleomagnetic measurement can be made, these other effects must be taken into account.

Viscous remanent magnetism is soft, modern magnetism acquired as a result of the Earth's modern magnetic field, or it can even be caused by leaving a crowbar or other tool near the sample for a period of time. VRM must be removed before measurement. This usually gets done by a demagnetizing process to which the TRM is resistant but the VRM is not, and by making repeated measurements with the sample being stored in different positions for several weeks before each measurement.

Some rocks magnetize more easily in one particular direction, just as a sailboat will prefer to go forward even with the wind at an angle. Whenever a rock does this, it possesses *magnetic anisotropy*, and a casual magnetic measurement will "lie" as to the actual field direction. Modern tests must establish the existence of any anisotropy in many types of samples. This is often done by remagnetizing and noting any preferred directions of remanent magnetism.

Anisotropic remanent magnetism (ARM) gets caused by lightning-which produces such strong fields that it literally blasts a record into the rock that has nothing to do with the Earth's field. For this reason, rock outcroppings, particularly those on the very tops of mountains cannot produce reliable paleomagnetic records.

Other problems include the relaxation time for very old work, the linearity of the remanence (usually good because the intensities are rather low), self-reversals (a rare and peculiar way certain samples have of altering their records long after recording), and the need for many samples to average out inconsistencies and produce reliable results.

To be useful, the magnetic intensity and direction of a sample must be measured to 1/2% and 1/2 degree accuracy, respectively. Samples are usually taken to a laboratory where

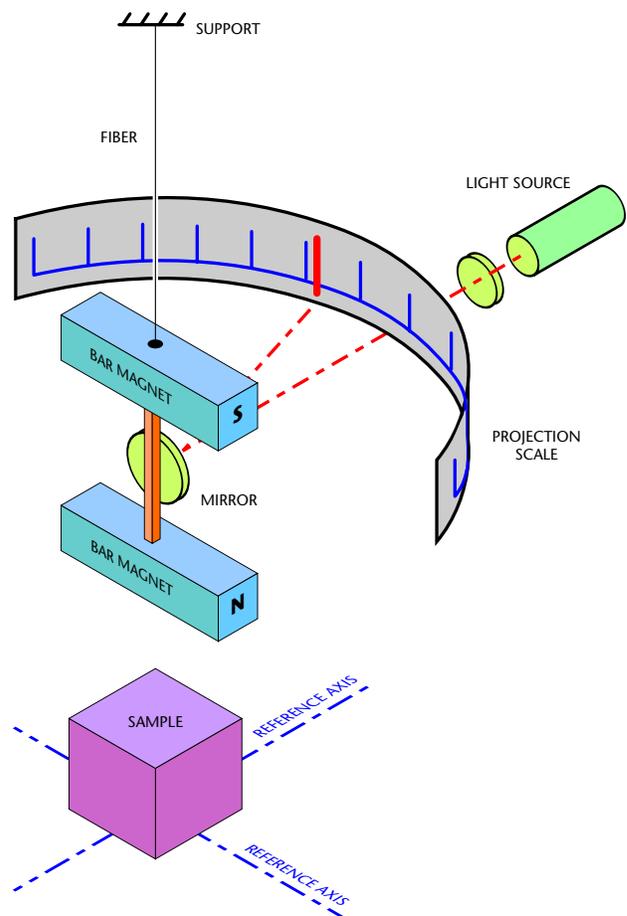


Fig. 3. Astatic magnetometer rotates in proportion to sample's remanent magnetism. Measurement on all three axes yields the total magnetic intensity along with inclination and declination.

this kind of control can be maintained instead of being directly measured in the field. Because of the low levels of magnetism involved and the required accuracy, considerable care and relatively fancy measuring techniques are needed.

An archeologist selects his samples from cultural remains, usually by isolating a smaller piece of firepit or a kiln and, without disturbing its orientation, molds the sample inside a cubical plaster cast several inches on a side. After the plaster has set, its form is removed and the position of the sample with respect to horizontal and true north is carefully marked on the plaster surface. Whenever possible, several samples are taken from the same site.

A geologist usually uses a coring drill to obtain his samples. This drills a hollow circle through a rock stratum, leaving a core sample that may later be broken out and taken to the laboratory. Samples start out around an inch in diameter and several inches long; they are broken up into 1-inch-high cylinders before any measurement. Once again, the exact sample orientation is carefully noted.

Once in the laboratory, the samples undergo a week-long storage to eliminate any newly acquired VRM. They are then demagnetized at low temperatures by a relatively weak a.c. field that removes the VRM but leaves the TRM. The demagnetization is called *magnetic washing*, and after the a.c. field is applied it is gradually reduced in intensity until no field remains. To keep the present, modern Earth's field from introducing any bias into the readings, the entire demagnetizer is built inside a Helmholtz coil system. The Helmholtz coil system has currents flowing through it that neutralize the local effects of the present Earth field. After magnetic washing, the sample goes to a magnetometer for measurement.

A magnetometer is an instrument that can measure the

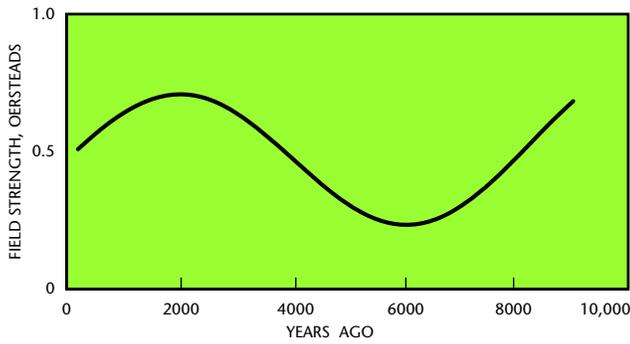


Fig. 4. How the Earth's surface magnetic field strength has varied over the past 9000 years. Note the cyclic variation.

strength of a magnetic field. There are several types. The simplest is called an *astatic magnetometer*, whose operation is diagrammed in Fig. 3.

The astatic magnetometer consists of two opposed permanent magnets supported by a fine fiber. Any torque produced by the Earth's magnetic field on the bottom magnet is canceled by an opposite torque on the upper one. Whenever a sample is brought near the bottom magnet, the magnet system rotates, being attracted to the sample, or away from it, just as a compass seeks magnetic north. Since the lower magnet is closer to the sample, and since the sample's magnetic field falls off with distance, the lower magnet is much more strongly attracted than the top one is repelled. To indicate the degree of rotation, a mirror between the magnets reflects a narrow light beam and projects it on a large scale.

In use, the instrument is zeroed in the absence of a sample. The sample is inserted in a specified direction and the light beam deflection is noted. The sample is then flipped up 90° and remeasured, and then over 90° and measured once again, giving the intensities along each of three axes. By combining the separate vectors geometrically, the magnitude and direction of the locked-in vector are measured directly.

The initial calculation is with respect to the faces of the plaster cube or another test axis. The actual values of inclination or declination can then be found by relating the lab orientation and measurement to the field orientation. To allow for different sample sizes, the intensity usually gets normalized to either the volume intensity or the density intensity of the sample. This is done by dividing the intensity by either the volume or the density as desired, putting all samples on a similar base so they may be compared.

Various types of magnetometers may be used, including the parastatic, the ballistic, the spinner, the resonance, and the fluxgate, among others. Each has its own advantages and disadvantages. While quite simple and extremely sensitive, the astatic magnetometer needs a field-free area well away from power lines and is quite delicate.

The paleomagnetic measurement does not directly measure the strength of the Earth's magnetic field. It merely measures a rock remanent magnetism that is proportional to the strength of the field at the time it was locked in. This proportionality is determined by the sample size, its magnetic impurities, how the field was recorded, and many other factors. To measure the actual intensity, the sample must be

demagnetized, heated to the Curie point, and remagnetized with a known intensity field. Comparing the initial measured intensity against the known modern measurement will give the original intensity in terms of the new field, thus calibrating the sample.

There are many complications with this technique, among which are chemical changes in the sample as it is being heated. There is a detailed and rigorous technique called the *Thellier method*, named after two pioneers in paleomagnetic work. The Thellier method demagnetizes and remagnetizes to progressively higher temperatures until the Curie point is reached. By comparing the linearity of each new result, the internal consistency of the sample is measured along with its paleomagnetism.

The Earth's Magnetic Field

Much has been learned about the Earth's magnetic field through paleomagnetism. We know now that the Earth's magnetic field is internally generated, most likely by a magneto-hydrodynamically driven self-excited dynamo effect caused by relative motions within the Earth's molten core.

The most likely source of the original dynamo energy is the precession of the earth as it wobbles in orbit once every 25,800 years. We know that tremendous amounts of energy are involved - around 10 billion amperes of core current - and that the internal power generated contributes significantly to the core heating.

While the total field energy is quite high, the surface intensity is rather low, around 0.5 Oersted, with localized maxima and minima. We know these maxima and minima, called *isophors*, possess westerly drift in tune with the core motions.

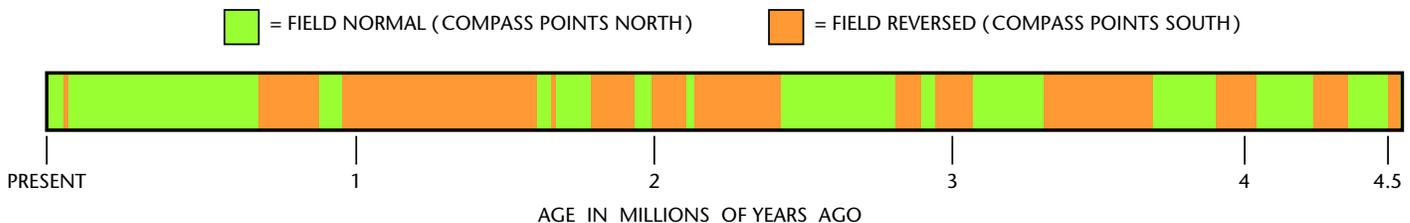
We know the shape of the field is mostly that of a dipole (like a bar magnet) that is now 11 degrees out of line with true north. We also do know there are two important lesser components resulting from various irregularities and internal turbulence. These components are most likely responsible for the self excitation, and are somewhat akin to the exciting field winding on a generator.

When we turn to the paleomagnetic records, we find great variations in both the direction and the intensity of the field. Fig. 4 shows how the field intensity has varied over the past 9000 years. We see that the intensity is now decreasing from about 1.5 times its present value some 2000 years ago, and that the variation is sinusoidal, and presently goes through a single cycle in 9000 years or so.

When the paleomagnetic record is pushed farther back, we find that the Earth's magnetic field has suddenly reversed some 26 times in the last 4.5-million years and probably many times before that. Dates of the known reversals are shown in Fig. 5. Reversals take several thousand years, an extremely short time geologically. The pole position does not change greatly during reversal-the field simply decreases in amplitude, goes through zero, and comes back up the other direction, just like the a.c. power line. During reversal, the other field components prevent a zero field condition, but the intensity does drop below a fifth its normal value during reversals. Either polarity is equally likely over a long time period, and the field has been reversed just about as long as it has been normal.

The Earth's magnetic field is (*Continued on page 70*)

Fig. 5. A history of the Earth's more recent magnetic polarity reversals. Such reversals take several thousand years.



(Continued from page 26)

an effective shield against any outer space *gamma* radiation. During a reversal, much of this shielding is lost. It was once thought that the increase in *gamma* radiation would directly cause mutations of organisms with both extinctions and the creation of new species. This has been generally discounted on the basis of lower atmosphere shielding and other effects.

What the *gamma* radiation increase does accomplish is profound climatic changes through changes in the upper atmosphere ionization levels and shifts in weather patterns. The results are definite changes in habitat. There is some evidence to back up major extinctions with reversals, again through the paleomagnetic record.

Geology Applications

The Layered or stratigraphic ordering in a thick sequence of geological deposits can be uniquely positioned through the presence and length of all the reversals, sort of a "tree-ring" dating technique of use to the geologist. Given suitable calibration, absolute ages of deposits may be determined.

Early magnetic surveys indicated strange anomalies in the middle of each major ocean, very straight areas with wildly varying inclinations and declinations on either side. Closer inspection has indicated that these are not anomalies at all, but are an exactly defined and symmetrical record of all the reversals in the past as newer and newer material is forced up the middle from the depths of the earth. This concept is called *sea-floor spreading*, and all the major oceans expand by an inch or so per year. Earthquakes seem to be somehow related to this spreading process.

Should two samples of the same age in close proximity give different values of declination or inclination, we can conclude that one has moved with respect to the other after the TRM had been picked up. Tracing all of these motions reveals much about the origins of the earth and processes. These motions may be local, wide-area, or world-wide.

Local rock and formation movement help explain faulting, erosion, mountain building, and related phenomena. Wide area motions allow the explanation and dating of any major landform separations, such as the opening of the Gulf of California, or Madagascar becoming an island.

World-wide motions go under the name of *continental drift*. The original theory was based on the assumption that

South America somehow ought to "fit" into the notch in Africa. Paleomagnetic variations were the first to support this theory. Paleogeologists have postulated the existence of two super-continent, Gondwanaland to the south and Laurasia to the north, which broke up some 60 million years ago.

Within the last year, a tremendous amount of independent support for this theory has evolved, including more paleomagnetic measurements, correlation of deposits in Africa and South America, mathematical fitting together of continental shelves, and satellite techniques. The amount of motion produced by sea-floor spreading provides a credible driving force for the drifting.

Wholesale shifts in the positions of the magnetic poles in the distant past have also been observed. This is the theory of *polar wandering*, another paleontological major study area. Again, principal and initial support for this theory is based on paleomagnetism.

Archaeology Applications

Archeologists use paleomagnetism as a support science, to gain cultural information, and as a tool for absolute dating. Since the time scale in archeomagnetism is typically less than 10,000 years, the continents can be assumed to be stationary and the field can be assumed to be free from reversals.

As a support science, paleomagnetism can explain some substantial inaccuracies in the carbon-14 dating technique, particularly a 750-year error some 4000 years ago. The errors are thought to be caused by gamma radiation variations and a new correction curve now exists which can greatly increase the accuracy of the C-14 process.

Cultural information is gleaned from paleomagnetism in special instances. The inclination and declination of the magnetic field of rocks in a road can sometimes be traced to a particular quarry. Tradeware pottery can often be traced to its origin if the pot can be assumed to have been fired right side up. Other stone, materials, and cultural sources may sometimes be located by this technique.

As an absolute dating tool, paleomagnetism can be very accurate (within 50 years or better) and will often work where no other dates can be gotten at all. But it is, however, only a secondary standard that must be carefully calibrated and the calibration is only useful over a 500 mile area or so. ▲