ARTICLES

PALEOMAGNETISM II

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WHAT THIS ARTICLE IS ABOUT

The magnetic information that is stored in the various types of rocks is providing geoscientists with a wealth of information about the earth and its history. However, for this information to be of greatest use, an understanding of the source of the field as well as its overall properties such as "shape" and strength is necessary. The Barnes Free Decay model for the source of the geomagnetic field is compared to the available data and to the conventional dynamo model as possible models for the source of the geomagnetic field. Which model fits the data best and what implications does it have for creationists?

Paleomagnetic data is proving to be useful in numerous applications, but the data really has little meaning unless certain assumptions are made. What are these assumptions, and do they appear to be valid from a creationist perspective?

Paleomagnetism is responsible for the widely held idea that the geomagnetic field of the earth has reversed itself many times in the course of the history of the earth. This reversal information has been used to establish a "magnetic reversal time scale" that is being widely used to study "magnetic stratigraphy." Another application of paleomagnetic data has been in the study of the dynamics of the earth's crust and the subsequent development of the theory of plate tectonics. This theory has had a tremendous impact on the geosciences. What problems do these models of earth history present for creationists, and have creationists seriously addressed them? Are there other valid explanations for these phenomena that fit well with a short earth history?

Paleomagnetism I *reviewed the basic principles of geomagnetism. In* Paleomagnetism II *we discuss the various models for the source of the earth's magnetic field and the implications these models have for a creationist viewpoint. We must also give some attention to the highly complicated science of paleomagnetic sample collection and analysis.*

I. INTRODUCTION

The magnetic information that is stored in the various types of rocks can tell us a great deal about the earth and its history. However, in order to appreciate and understand this information, an understanding of some properties of the geomagnetic field as well as the ways in which magnetic information is actually obtained from the rocks is needed. As is often the case in science, this process of getting the information about the paleomagnetic field is not always as direct as one would wish and involves certain assumptions.

II. SOURCE OF GEOMAGNETIC FIELD

The general shape of the geomagnetic field has been known since the time of Gilbert, some 400 years ago. Since then, there has been a great deal of speculation about the source of this field (Jacobs 1963). In the last 20 years our understanding of possible generating mechanisms has made significant progress, but the source of the earth's field is not yet completely understood.

A. Possible Source Models

Geomagnetism, as it is known today, owes much to the early analysis made by Gauss in 1839 (Garland 1979, Jacobs 1963). It was readily apparent to Gauss that the field was primarily due to an internal dipole. More precise data and calculations in recent years have substantiated Gauss' conclusion that the "main" geomagnetic field is internal in origin and not from outside the earth.

Could the source of geomagnetic field be charges on the surface of the rotating earth? The electric field of about 100 V/m at the surface of the earth can be used to calculate a surface charge (Feynman 1964). It can then be easily shown that the rotation of this surface charge is much too small to account for the geomagnetic field (Garland 1979).

Could the earth's field be due to ferromagnetism frozen into the rocks of the earth? The temperature gradient observed in the crust is about 30ºC/km. This means that at a depth of about 25 km, the temperature would be approximately at the Curie point for iron, or about 750ºC (Jacobs 1963). Since there is no evidence that the Curie point increases with increasing pressure, it is reasonable to conclude that the only part of the earth that could have ferromagnetic properties is the outer shell in which rocks would be cool enough to exhibit ferromagnetism (Wasilewski et al. 1979, Jacobs 1963).

To further narrow down the source of the earth's field it would be helpful to measure the strength of the field as a function of depth below the surface. Runcorn et al. (1951) made just such a study and their results suggest that the source is deep inside the earth, thus ruling out ferromagnetism of the surface rocks as the source. This leads us to seriously consider the role of the earth's core in the production of the geomagnetic field. Geochemical, geophysical, and density considerations are consistent with a liquid outer core that is composed of iron and possibly nickel. Could the geomagnetic field be due to large electric currents (circa 10^9 amps) within the conducting core of the earth?

There are two fundamentally different ways that the currents in the core might produce the geomagnetic field. These theories might best be referred to as the "free decay" model and the "regenerative dynamo" or "dynamo" model.

B. Barnes Free Decay Model

The free decay theory assumes that the motion of the charges in the core is simple circular motion around the magnetic polar axis of the earth. In addition it is generally assumed that the energy of the "original" electric currents is being continually dissipated away as heat in the conductor and that none is being supplied to take its place. Stacey (1969) and Jacobs (1963) both make estimates of the necessary time for the earth's magnetic field to decay exponentially to 1/e (37%) of its original value and arrive at times of 10^4 years and 10^5 years respectively.

The free decay theory has been favored by several creationist groups since it seems to imply a short age for the earth. Perhaps the leading spokesman for this view is Thomas G. Barnes, of the University of El Paso, Texas, who in 1971 wrote an article under the title "Decay of the Earth's Magnetic Moment and the Geochronological Implications," thus launching a new creationist method of dating the age of the earth based on the decay of its magnetic field. His free decay theory is based exclusively on the available direct measurements of the intensity of the earth's field as a function of time (see Figure 8 in PALEOMAGNETISM I).

McDonald (1967), Akridge (1980), and Barnes (1971, 1972, 1973a, 1973b, 1975, 1981) have made statistical analyses of the laboratory intensity data which was collected between 1835 and 1965. In addition, recent Magsat satellite data obtained in 1979 and 1980 has been analyzed (Wilford 1980). All of these studies conclude that the intensity of the earth's magnetic field has been decreasing during this period of time.

Barnes & Akridge (1980) calculate from mathematical fits to the data that the geomagnetic field must be decaying exponentially with a half life of 1400 years. Barnes then extrapolates this 130 years worth of data back (154-fold) to 20,000 BC and finds that the strength of the geomagnetic field would have been 18,000 gauss! He then argues that organic life would have been impossible in such a strong magnetic field and that an 18,000 gauss field would require unfeasibly large currents in Earth's core on the order of 50,000 times larger than the presumed present value (10^9 amps, Chapman 1940). Based on these arguments Barnes concludes that the earth must be less than 10,000 years old and more likely 6 to 7,000 years old, in agreement with the traditional interpretation of the Biblical record.

The magnetic decay method of dating, as it is called, has been proclaimed to be the most reliable evidence for a young earth age and thus the strongest evidence against the long ages of radiometric dating. Henry Morris (1983) states "If any process should be a *reliable* indicator of the earth's age, *this* should be — and it indicates an upper limit for the age of about 10,000 years!" In another discussion (Morris & Parker 1982) the Barnes method of dating is listed as the first in a list of 68 scientific evidences for a young earth.

On the other hand, Barnes hasn't been without his critics both from the ranks of creationism and from the geologic community in general. A comprehensive rebuttal of the magnetism decay method of dating was recently published in the *Journal of Geological Education* by G. Brent Dalrymple (1983), who is employed by the U. S. Geological Survey as an expert in radioactive dating, especially the potassium-argon method. In reaction to Dalrymple's criticisms, Barnes has written a response (Barnes 1983) entitled "Earth's Magnetic Age: The Achilles Heel of Evolution." Others have also entered the controversy on both sides of the issue (Young 1982, Morris 1983).

Warren Johns (1984) has put together a well-written layman's discussion of this controversy from the point of view of a creationist interested in evaluating the theory's scientific support.

He (1984) concludes that "In spite of its seemingly impressive scientific credentials, it falls short of being a valid scientific method of dating because of at least four major problem areas." Three of the four points are pertinent to this discussion.

1) *Magnetic age dating is more rigidly uniformitarian than the uniformitarianism of conventional geologists.* Uniformitarianism means that the present is assumed to be an adequate key to the past. A good example of uniformitarianism is radioactive dating. Although radioactive dating extrapolates backwards in time, it does not do so without some independent cross checks. There are many radioactive isotopes that can be checked against each other to provide some "quality control." However "the magnetic decay dating method looks for virtually no checkpoints prior to 1835; it ignores any possible evidence from archeomagnetism, paleomagnetism, geology, or historical records to test the validity of its extrapolation.... It is ... more rigorously uniformitarian than the age-dating methods used by geologists" (Johns 1984).
2) *Paleomagnetic intensity measurements indicate that the earth's magnetic field has been decreasing in intensity only in the last 2800 years and more rapidly only in the last 800 years*. The advocates of the magnetic dating method claim that there is no validity to paleomagnetic intensity measurements. Burlatskaya et al. (1969) show that paleomagnetic data for the last 750 or 800 years is consistent with the direct laboratory measurements. It seems that if the paleointensity data parallels the observatory measurements this well we must accept the paleointensity data as accurate for at least the last several thousand years. When one looks at the paleomagnetic intensity data (see Figure 8 in PALEOMAGNETISM I) one sees that the Barnes approach totally ignores the fact that at times in the past the paleointensity has clearly been less than it is at present, and may in fact have reversed many times.

3) *The equation developed for predicting past intensities of the earth's magnetic field is entirely arbitrary*. Akridge's studies showed very little difference (2%) between the goodness of fit for the linear and exponential decay models for the intensity of the magnetic field. The exponential decay fit is chosen because it is the type of magnetic moment decay that is produced by real currents which dissipate energy through Joule heating (Barnes 1975). However, since very little is really known about what is happening in the core, without some type of corroborating data, major reliance should not be placed on the exponential decay assumption.

   Although heralded by many creationists as the "answer" to their long age problems, this free decay model of Barnes does not seem to be well supported by the data if one carefully considers *all* the available data.

C. Dynamo Model

In the dynamo model the charge motions are envisioned to be complicated motions resulting from the interactions between a moving conducting fluid and a magnetic field. In brief, the dynamo theory states that a conducting liquid core moving in a pre-existing magnetic field produces an electric current. These moving charges are assumed to sustain and intensify the initiating magnetic field. In this way, especially with an external energy source, the earth's magnetic field could be produced and sustained over an extended period of time.

The dynamo theory of generation of the earth's magnetic field was first proposed in detail by Elsasser (1946a, 1946b, 1950) and by Bullard (1949). Since Elsasser's time, the discussion and investigation of whether this dynamo process can indeed occur centers on 1) the existence of suitable motions of the liquid, 2) low resistance electrical flow in the fluid, 3) a suitable energy source to maintain the motion, and 4) a small original field (Garland 1979). There has never been much question about 2) or 4), but 1) and 3) have generated a great deal of discussion.

The physics involved in solving this problem is very difficult. Fuller (1983) puts it well when he states "The origin of the geomagnetic field remains a mystery. There is no argument that some sort of dynamo in the outer core is responsible for it, but there is little agreement as to which sort it is." For example, the forces and energies necessary to produce the fluid motions in the dynamo are not known. The promising possibilities are (Levy 1979, Stacey 1969): 1) thermal buoyancy or convection as a result of heat produced by radioactive decay, 2) chemical separation and latent heat at the boundary between earth's solid inner and liquid outer core, 3) different precession rates of the core and mantle, 4) gravitational energy release by shrinking of the earth as the denser solid core grows. The actual amount of energy necessary to maintain the geomagnetic field is dependent on the model as well as the conditions in the core, which are not well known.

It is readily apparent that much work needs to be done in this important and fascinating area of geophysics. Much more complete discussions of this topic and many more references may be found in several review articles (Busse 1978, Carrigan 1979, Hoffman 1983, Levy 1976, Rees 1961) and books (Cox 1973, Gubbins 1979, Jacobs 1975, Merrill & McElhinny 1983, Moffatt 1978).

The dynamo model seems to be the only viable model for the source of the earth's field and as such is accepted by virtually all geophysicists. This doesn't make it the right model but it does seem to be the best model available at the present time.

What are the implications of the various dynamo models for creationists? It is difficult to answer this question without a better understanding of the type of dynamo responsible for the geomagnetic field. This would then seem to be an area of study that has significant potential for helping the creationists better understand the complexities of the world that God has made.

III. METHODOLOGY

Geomagnetic data may be obtained in a number of ways. The magnetic field above the surface of the earth is usually measured using magnetic field sensing instruments called magnetometers. These instruments are carried by ships, aircraft or spacecraft, or are housed in stationary observatories. Aside from the data on the magnetism of the ocean floor collected by ships and aircraft, most paleomagnetic data is obtained by laboratory study of the magnetic field frozen into small oriented rock samples.

A. Sample Collection

Because of the sophisticated nature of the analysis that is done on paleomagnetic samples, it is usually not possible to accurately determine either the direction or intensity of a rock sample in the field. This means that many carefully oriented samples must be collected by drilling a cylindrical plug out of the formation under study. Needless to say, the original orientation of the sample must be measured as accurately as possible. If the bedding or deposition plane has been tilted since deposition, the original orientation before tilting must be determined. Irving (1964) and Tarling (1971) have more complete discussions of sample collection.

B. Determination of Sample Properties

The determination of the direction and intensity of the paleomagnetic field of the earth necessitates the careful measurement, using a magnetometer, of the direction and magnitude of the magnetic moment or field of a cylindrical sample of material having a volume of a few cubic centimeters.

These magnetometer measurements are sufficient to determine the direction and magnitude of the magnetization of the sample, assuming that the sample contains no complicating secondary effects. If there are secondary effects, a process called demagnetization must be carried out to remove the unwanted "soft" components of the field. This is done in one of two ways. Both methods involve processes that randomize these easily changed secondary components of the magnetic field so that their net contribution to the total magnetic field of the sample will then be zero. This randomizing can be done either by careful heating of the sample or by exposing the sample to a weak alternating external magnetic field. When the direction and strength of the field of the sample seems to be stabilized as this demagnetization process is carried out, it is generally assumed that all the secondary magnetic effects have been randomized and that the direction of the magnetic field remaining in the sample is the same as when magnetism was originally "frozen" into the sample. This residual magnetic direction is then used to establish the directional properties of the ancient magnetic field of the earth.

The magnetic direction of any particular sample or set of samples must be referred to some common datum. This is usually done by calculating a predicted or virtual magnetic north and south pole based on the magnetic field direction data from a particular sample.

Determination of the intensity of the ancient field is inherently a much more difficult task than determining the direction of the ancient field. The magnetometer measurements determine the strength of the field frozen into the sample but it is a difficult step to get from the strength of the sample's field to the strength of the earth's field that caused the sample field in the first place. Due to these experimental difficulties, and the fact that paleointensity is of lesser importance in geological studies, there has been relatively little study of paleointensity. Smith (1967) has made an extensive study of the methods and data related to the intensity of the ancient field.

To determine the paleointensity (Tarling 1971) one must make a comparison of the intensity of the natural remanent magnetization of the sample with the intensity or strength of the thermal remanence acquired by the rock during heating and subsequent cooling in a known magnetic field.

Since the intensity varies systematically from a minimum at the equator to a maximum at the poles it must be corrected to some common point on the surface of the earth for comparison. Another means of comparison of intensity data is to calculate a corresponding magnetic moment or strength for the overall earth field assuming a dipolar field.

C. Paleomagnetic Data Quality

An ideal paleomagnetic sample would be isotropic, homogeneous, and have no secondary magnetizations. If all samples were ideal, then paleomagnetic studies would be quite straightforward. In reality, very few samples are ideal and secondary effects slightly change the direction of magnetization from its original value. There are usually ways to identify the problems mentioned above, and in many cases reliable data can be obtained after proper corrections are made.

Many rocks acquire a secondary or "soft" component of magnetization at some time after the original formation of the rock. It is therefore normal for the initial results of a paleomagnetic study to show a considerable degree of scatter in direction of magnetizaton as shown in Figure 1. As mentioned in PALEOMAGNETISM I, these "soft" components may be due to a number of causes such as exposure to an external field other than the original field, or lightning induced fields. Examples of effects due to lightning have been found (Cox 1961, Rees 1961), but are probably not common. Furthermore, the current caused by the lightning usually travels horizontally through the rocks, soil, and water and decays exponentially with depth. This means that the magnetization induced by lightning will have a characteristic pattern that is identifiable and that will not penetrate beyond a depth of about 20 meters.

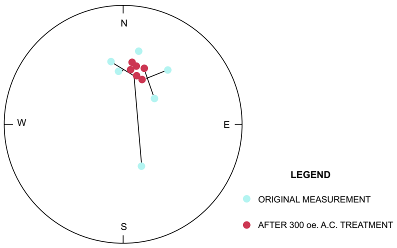

FIGURE 1. Effects of partial demagnetization on directions of natural remanence in six specimens from a single lava flow. The data are plotted on the lower hemisphere of an equal area projection. Open circles represent directions before treatment and solid circles after partial demagnetization. (Redrawn from Cox & Doell 1960).

When all the possible factors that can affect the paleomagnetic measurements are considered, it is usually possible to define the natural remanence direction to within ±3° and the intensity to within ±20%. How stable is the remanence observed in the sample? One test for stability has to do with the clustering of the magnetization directions determined from a group of samples from the same site. If the directions from a particular site are well clustered or consistent, a stable remanence is indicated. Tests for consistency, and thus stability, are the most meaningful if several different types of rock from the same location are compared.

D. Age of Remanence

At this point it is appropriate to ask how old the observed remanence is. There are two types of answers that can be given — the absolute age and the relative age. Both of these types of answers can, of course, often be checked for consistency with other paleomagnetic measurements as well as other paleoclimatic or geologic data that is pertinent. There are also objective tests to determine if the stable remanence is primary, i.e., of the same age as the rock.

The most important of these is referred to as the fold or tilt test (Tarling 1971) and can give a relative age for the remanence. Primary remanence that is acquired in the usual fashion from the earth's field at the time of rock formation will have the same direction throughout a particular formation. If this formation is then later tilted or folded, the primary magnetization directions will also be tilted or folded. Careful study of the tilting and folding will allow the experimenter to correct the magnetization directions for individual samples within the formation into a tight cluster. If the remanence is not tilted or folded but all the same direction in spite of the tilting and folding of the formation, the remanence obviously was acquired after the tectonic activity. Tarling (1971) also mentions several other tests for relative age of remanence.

To obtain an "absolute" age for the rocks and thus for their primary remanence, either standard stratigraphic correlation techniques or radiometric methods, typically potassium-argon dating, are used. It should be cautioned that there are numerous difficulties that can be encountered with both the relative and absolute dating methods, and the experimenter must proceed with great care.

IV. PALEOMAGNETIC ASSUMPTIONS

As we shall see in the next section, there are numerous potential areas of application for paleomagnetic data. However, we should ask the following question. What does the paleomagnetic data tell us directly without any assumptions other than those discussed in the METHODOLOGY section above? It tells us the direction and intensity of an ancient geomagnetic field that *could have* produced the measured remanent magnetism at the location of the rock sample. This information is not very useful in itself. What we would like to know are the predicted positions of the ancient geomagnetic poles and some measure of the overall strength of the ancient geomagnetic field. Consequently, in order for the paleomagnetic data to have the most utility, three basic assumptions are generally made.

A. Primary Magnetization Parallel to the Ancient Field

The direction of the primary magnetization of samples obtained from historic sites has been determined and compared to the historically known direction of the field at the time the rock was formed. Mount Etna, which deposited ash and lava over a wide area in an A.D. 1669 eruption, provides just such an opportunity. The direction of the primary magnetization of the samples was determined after demagnetization to remove secondary fields. The geomagnetic pole calculated from this direction agreed to within one degree with the known location of the geomagnetic pole at the time of the eruptions (Seyfert & Sirkin 1979). More recently, a similar study was made of the volcanic ash deposited by the eruption of Mount St. Helens in 1980. Steele (1981) has shown that "ash from the May 18, 1980 eruption of Mount St. Helens, deposited from the air, faithfully records the direction of the local geomagnetic field in eastern Washington."

It would appear then that the primary magnetization of carefully chosen rocks can accurately record the direction of the ancient geomagnetic field at the time of formation. The consistency of the data from all over the world seems to support this conclusion.

B. Dipolar Nature of Ancient Field

Since the early 1950s, studies of rocks from relatively recent geologic periods (60 to 70 million years of assumed geologic time) have found that the main geomagnetic field for the corresponding time periods has been stable and dipolar (Cox 1973, Opdyke & Henry 1969, Tarling 1971, Takeuchi & Uyeda 1970, Torreson et al. 1949). Figure 2 shows inclination data from deep sea cores which support the dipolar assumption. Based on this and other evidence, the earth's magnetic field is generally assumed to have always been primarily dipolar, with one north and one south geomagnetic pole.

The dipolar assumption, although generally accepted, certainly needs further study. As more data is amassed from all over the world, it should eventually be possible to evaluate the possibility of a non-dipolar ancient field. If the dipolar assumption is not valid, the generally accepted plate tectonic model of the history of the surface of the earth would have to be dramatically revised.

C. Coincidence of Average Geomagnetic and Geographic Poles

The average direction of primary magnetization from a consistent group of samples can be used, assuming a dipolar field in the past, to infer an apparent or virtual ancient magnetic pole position on the surface of the earth. This virtual pole position is merely another mathematical method of expressing the magneti-

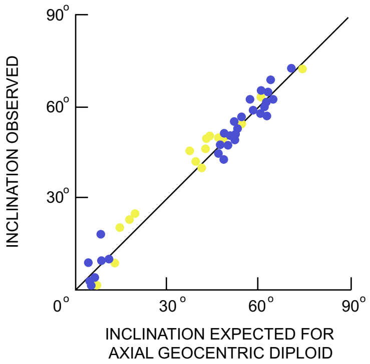

FIGURE 2. The inclination in deep-sea sedimentary cores, less than 2×10^6 conventional years old, showing inclinations which are statistically identical to those expected for an axial geocentric dipole during this period. (After Opdyke & Henry 1969).

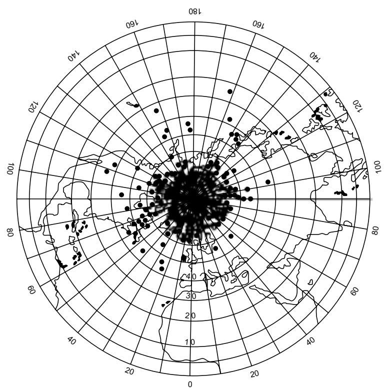

FIGURE 3. Virtual geomagnetic pole positions for over 2000 igneous rocks up to 20 million conventional geologic years old. (Tarling 1971).

zation direction and is not necessarily the same as the actual location of the ancient geomagnetic pole. When the virtual geomagnetic pole, VGP, positions corresponding to sample magnetization directions for igneous rocks (Cox 1973, McElhinny 1973) and for sediments (Opdyke 1969, Tarling 1971, Torreson et al. 1949) are plotted for samples from all parts of the world, their distribution is clearly centered on the earth's rotation axis as shown in Figure 3. The conclusion of these studies is that paleomagnetic data can best be interpreted in terms of an axial geocentric dipole.

V. PALEOMAGNETIC APPLICATIONS

Finally we are in a position to briefly discuss some of the promising applications of paleomagnetism. Most of the ideas to be discussed in this section are so well accepted by the scientific community that few individuals still question whether the current theories might have serious flaws. What weaknesses are there in the accepted theories? What are possible alternative explanations for creationists?

A. Reversals of the Earth's Field

The rather unexpected idea that the earth's main geomagnetic field periodically reverses polarity was first suggested, early in this century, by geophysicists who were studying the remanent magnetization of volcanic rocks and baked earth (Brunhes 1906, Chevallier 1925, Matayama 1929, see also Cox 1973 for reprints of old classic papers). In studying rocks of early Pleistocene age, or older, these scientists discovered that a large proportion of the samples were magnetized in a direction nearly 180º from the present field direction. Even baked earth in contact with the reversely magnetized rocks was reversely magnetized. Based on these results, they proposed that the geomagnetic field had, in the past, actually been in the reverse or opposite direction.

Since these early studies, tens of thousands of paleomagnetic samples of many types of rocks from all over the world have been studied. Surprisingly it is found that there are on the average about as many samples that are reversely magnetized as are normally magnetized (Cox, Doell, Dalrymple 1967; Cox 1973). Any theory that is proposed to account for the reversely magnetized rock must account for this bimodal distribution of polarities.

One of the commonly mentioned explanations by creationists involves lightning strikes. These can certainly magnetize rock, but it is very unlikely that they can account for 50% of the rocks studied worldwide. Furthermore, lightning effects are generally easily detected and removed (Cox 1961, 1973; Graham 1961).

There are two other possible explanations for this data. Either the geomagnetic field actually did reverse, or self-reversal on a global scale took place. Self-reversal is a phenomena in which rocks can be spontaneously magnetized at 180º to the ambient field at the time of cooling.

The significant question here is whether all reversely magnetized rocks have undergone self-reversal. Cox (1967, 1973) heated and cooled hundreds of reversely magnetized samples in a known field and then measured their acquired magnetization to check for self-reversal and found fewer than 1% were self-reversing. Other studies (Wilson 1962; Cox 1963, 1973) have reached the same conclusion and consequently it is generally believed that self-reversal is a very unlikely explanation for reversely magnetized samples.

In addition to the evidence supporting reversals there is one apparently significant piece of contrary evidence involving the differences in chemistry or oxidation state between reversed lavas and adjacent normal lavas that have been reported by several authors (Ade-Hall & Wilson 1963, Ade-Hall 1964, Wilson 1967, Balsley 1954) but not by others (Larson & Strangeway 1966, Ade-Hall & Watkins 1970). This data is generally considered to be paradoxical but not crippling to the field reversal hypothesis (Cox 1973). This area would seem a fertile one for creationists to investigate. For example, what are the implications for the marine basaltic reversals (to be discussed later)?

The second, and perhaps the most convincing, approach for testing for self-reversal, is a worldwide test of the correlation of reversals with mineralogy and rock age. To carry out this type of test it is important to be able to accurately correlate rocks over large global distances. At least for igneous rocks with age assignments of less than 4 or 5 m.y., the dating method of choice is potassium-argon dating. The early studies done between 1963 and 1969 by at least three separate groups of investigators were able, using K-Ar dating, to extend the time scale of reversals back to 4.5 m.y. of presumed geologic time (Cox 1973, McDougall 1964, 1966; Doell 1966, Dalrymple 1967). Their results rapidly converged to what is known today as the geomagnetic-reversal time scale which is shown in Figure 4. Note that this figure includes worldwide data from many investigators and many types of rocks.

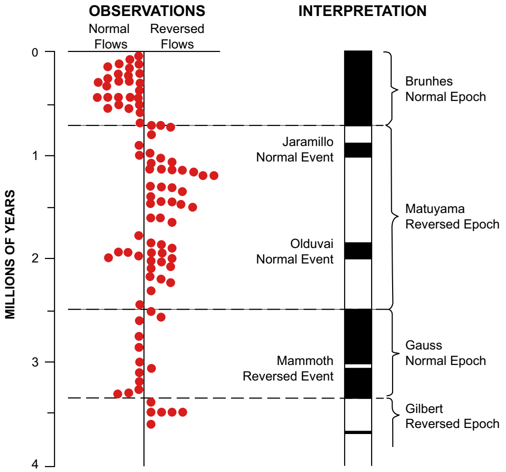

FIGURE 4. Time scale for reversals of the earth's magnetic field that was established on the basis of nearly 100 volcanic formations in both hemispheres. It is clear that the flows fall into four principal groupings, or geomagnetic polarity "epochs," during which the field was predominantly of one polarity. Superimposed on the epochs are shorter polarity "events" (After Cox 1973).

Examination of this data leads one to conclude that there appear to have been four major worldwide *epochs* of one polarity lasting approximately 10^6 K-Ar years, with brief *events* within these epochs during which the polarity reversed for 10^4 to 10^5 K-Ar years. For an exhaustive review of land-based polarity stratigraphy, see the work by Irving et al. (1976).

Further confirmation of the early evidence for reversals, which was primarily from igneous rocks on land, came from cores of deep-sea sediments that formed over the last 2 to 3 m.y. of presumed geologic time. Since the oceanic deposition processes appear to be quite continuous, they have the potential of supplying a detailed record of the earth's magnetic field over the time that the present oceans have been in existence. Figure 5 shows the magnetic reversal time scale as determined from land-based rocks as it compares to the magnetic reversal

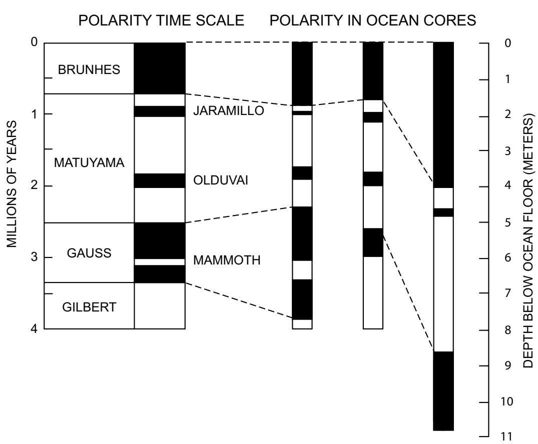

FIGURE 5. Magnetic reversal patterns for deep-sea sediments compared to the reversal time scale compiled from land based date. Magnetic particles become oriented in the direction of the earth's field as they settle through the water. (Cox 1973).

patterns from deep-sea sedimentary cores. These comparisons confirm a worldwide pattern of polarity changes (Tarling 1971, Opdyke et al. 1974, Harrison 1974) and give strong support to the idea that the earth's geomagnetic field has reversed in the past. A comprehensive review of the magnetic reversal time scale is given in *Magnetic Stratigraphy of the Sediments* edited by Kennett (1980).

One last and powerful argument in favor of reversals of the earth's magnetic field comes from measurements of the total intensity of the earth's magnetic field above the ocean floor. These studies have revealed a series of dramatic north-south trending magnetic anomalies that are found over almost all the ocean floor. Comparing these anomalies, which have magnitudes of several hundred gammas, to the geomagnetic reversal time scale from land based rocks and sediments, one sees a striking resemblance as shown in Figure 6. The reader is referred to Blakely (1979) and Cox (1973) who give extensive lists of references on this topic.

Using standard stratigraphic dating techniques combined with polarity determinations of continental rocks, the reversal time scale can be extended back (Ness et al. 1980) into the Mesozoic or to about 140 million years of conventional geologic time, as shown in Figure 7. In summary, magnetic reversals have been observed in igneous rocks on land, oceanic sedimentary rocks, deep-sea sediment cores, anomaly patterns above the ocean floor, basaltic cores from the ocean floor (Johnson et al. 1978), and even some slowly cooled, large intrusive igneous masses. The generally accepted conclusion based on this data is expressed well by Cox (1963), one of the foremost geophysicists in the study of reversals:

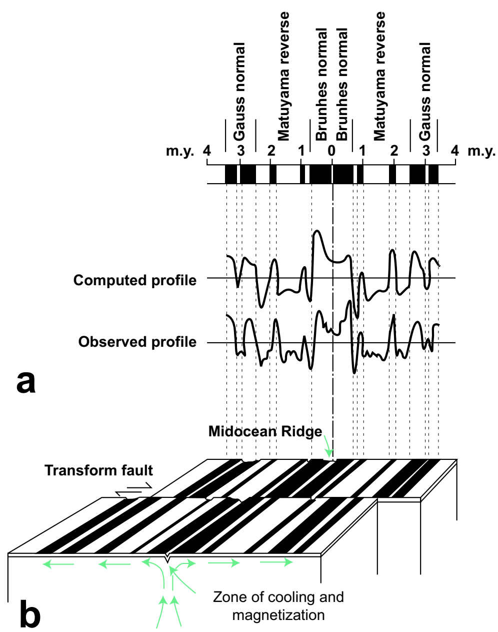

FIGURE 6. Comparison of the observed geomagnetic anomaly profile with the computed profile for the east pacific rise and with the reversal time scale derived from continental rocks (Takeuchi & Uyeda 1967).

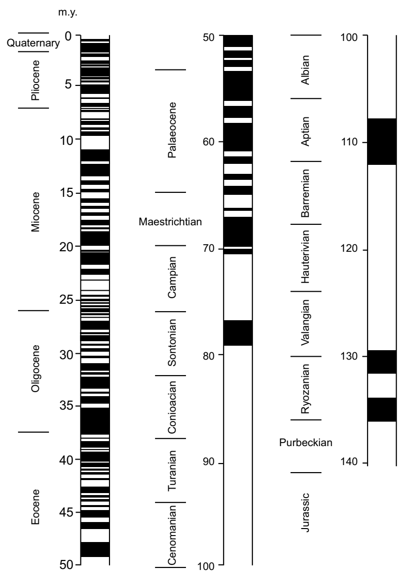

FIGURE 7. The polarity time scale for the last 140 million years of presumed geologic time as determined from thousands of paleomagnetic samples and ocean floor anomaly data. The younger rocks are typically dated by potassium-argon dating, but the older samples from the ocean floor can only be dated assuming constant spreading rates for the ocean floors. (After Tarling 1971).

The abundance and distribution of reversely magnetized rocks preclude their being dismissed as rare, unexplained accidents: these rocks exist on all continents; they occur among many petrological rock types, and they constitute about half of all Tertiary and Pleistocene rocks. Moreover, their stratigraphic distribution is not random. Normal and reversed rocks usually occur in stratigraphic groups of like polarity, and in areas of late Pleistocene volcanism, the youngest group is invariably normal.

What counter arguments are there to this rather impressive array of data? It is difficult to find careful, thorough discussions of alternative viewpoints in the recent literature. Perhaps the most comprehensive collection of papers presenting criticism of plate tectonics (see the next section) and hence also of paleomagnetism is the volume titled *Plate Tectonics — Assessments and Reassessments* edited by Kahle in 1974. Barnes (1971, 1972, 1973a, 1973b, 1975), Akridge (1980), and Overn (1980) have also made arguments against reversals. These authors typically cite many possible exceptions, i.e., various means of self-reversal, but are either unaware of or refuse to carefully consider the bulk of the magnetic reversal data that has been discussed above. Creationists need to take a more thorough and careful approach to the study of this very complex problem.

C. Plate Tectonics

Paleomagnetism has made important contributions to the theory of plate tectonics. The magnetic reversal time scale, magnetic reversal stratigraphy, as well as magnetic direction information have been used extensively to refine the theory of plate tectonics. Although it is not the purpose of this discussion to give a comprehensive review of the theory of plate tectonics, a brief summary is desirable in order to make the following discussion more meaningful.

Concisely stated, plate tectonics is based on the following ideas. Studies of seismic wave velocity within the earth have established that the top 100 km of the earth's crust are relatively rigid, and lie on top of a layer with low seismic velocity which implies that it has a low viscosity and is relatively soft. The outer rigid layer is envisioned to be floating on top of and carried along by convection currents occurring in the soft layer. The convection currents rise up at the mid-ocean ridges creating new ocean floor as indicated by the sea floor magnetic anomalies. This means that new ocean floor is continually being created and that the continents, as part of large crustal plates, are mobile and have moved considerable distances over the surface of the earth. The movements of the plates and hence of the continents are indicated by the magnetic anomaly patterns on the ocean floor and by what are known as geomagnetic polar wander paths. For further reading on plate tectonics and continental drift see Runcorn (1962), Marvin (1975), Hallam (1972), Hurley (1968), and McElhinny (1973).

Specifically what kind of tectonic information can be obtained from the paleomagnetic data? If paleomagnetic studies are done at several locations on a continent using rocks of the same age, an accurate location for the apparent ancient or paleomagnetic pole can be determined. This pole position may indeed not coincide with the present geographic pole of the earth. However recall that one of the basic assumptions normally made is that the geomagnetic poles have, on the average, coincided with the geographic pole of the earth. If this assumption is true, and if the apparent geomagnetic pole, as determined from the paleomagnetic study of the rocks, is at a different location, the continent must have moved about on the surface of the earth.

Where was the continent earlier? Nothing can be said about the longitude since the magnetic field of a dipole is symmetric with respect to the longitude. However the magnetic field direction for different latitudes is different as shown in Figure 8a. This means that from the direction of the "frozen in" magnetism in the rock one can get a good idea of the latitude of the rock at the time of the rock's formation. A very nice example of this involves India. The Jurassic rocks there have an inclination direction as shown in Figure 8b. This means that, if the geomagnetic field has always been dipolar, the Jurassic rocks of India must have been at a much more southerly latitude when formed. Figure 8c shows how India must have moved with time if the assumptions of paleomagnetism are true. If the geographic and geomagnetic poles are assumed to have always coincided, at least approximately as at present, the ancient magnetic poles for all continents should have been at the same location for all continents. One way to use this information is to calculate the paleomagnetic poles for similar aged rocks from all the continents. Then we could try to move

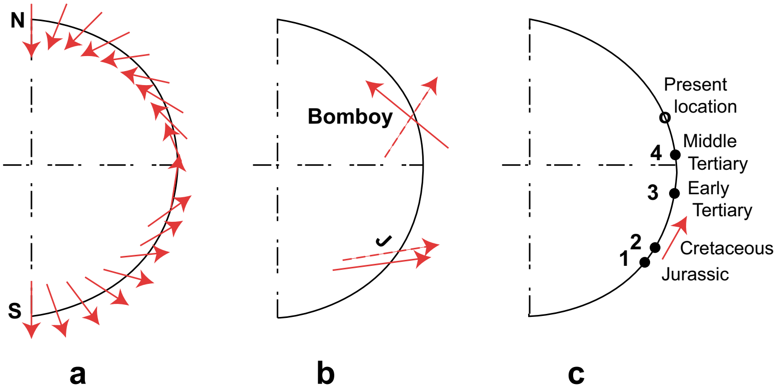

FIGURE 8. a) Magnetic inclination as a function of latitude. b) Jurassic position and paleomagnetic direction of India compared to present values. c) Positions of India as a function of time as inferred from paleomagnetic data. (Redrawn from Takeuchi & Uyeda 1967).

FIGURE 9. Carboniferous paleomagnetic pole positions for a Pangea reconstruction of the continents. NA = North America, EA = Eurasia, Af = Africa, SA = South America, Au = Australia, In = India. (After Seyfert & Sirkin 1979).

all the continents about such that the poles from all the continents are in the same small region on the surface. An example of this is shown in Figure 9. When this is done for Carboniferous, Permian, and Triassic age rocks we find that we can, within the constraints of the paleomagnetic data, fit all the continents into a single super continent usually called Pangea. The general thrust of plate tectonics is that this super continent gradually split up into the continents that we have today.

Many other kinds of paleontological, mineralogical, and paleoclimatic data seem to support these ideas concerning plate tectonics. The theory of plate tectonics has risen rapidly to the position of almost universal acceptance by geologists and geophysicists. To put this in perspective for the discussion of this paper, we should say that paleomagnetic data had a key part in this rapid revolution in geologic thinking and consequently must be taken seriously by creationists as they try to understand the history of the earth.

Where do creationists find themselves with reference to the theory of plate tectonics? Perhaps the embarrassing question is: Have creationists seriously studied these theories and seriously tried to pick the best points with which to build a coherent history of the earth? The answer, unfortunately, would seem to be negative.

IV. IMPLICATIONS, QUESTIONS AND CONCLUSIONS

This paper was written with several goals in mind. The first goal was to provide the reader with a fairly complete introduction to this fascinating and yet challenging area of geophysics. For those readers with professional interests that could make use of paleomagnetic data, it is hoped that these two articles can provide enough background to enable them to intelligently read and utilize the paleomagnetic literature related to their discipline. In addition to just providing information, it is hoped that these articles will challenge some readers to seriously study paleomagnetism and then try to find meaningful ways to interpret the data so as to enhance their understanding of God's revelations concerning the wonderful world he has made.

Paleomagnetism, as we have seen, can provide a wealth of information about the history of the earth. How does one interpret this data? What are the implications? The answers to these questions depend on one's philosophical perspective. Indeed, no scientist comes to the study of nature without some philosophical framework within which to work.

The "standard" evolutionary geological and geophysical interpretation of paleomagnetic data is that reversals of the earth's field occurred many times during the last several hundred million years. This data has, in fact, been compiled and refined into what is referred to as the magnetic reversal time scale. Furthermore it is generally accepted that the remanent magnetization directions in rocks can be used to support the theory of plate tectonics over the past several hundred million years of presumed geologic time.

On the other hand, Biblical creationists study nature using models that generally call for a much shorter age for life on earth, and in many cases for the earth itself. This apparent age discrepancy means that the Biblical creationist must ask several important questions concerning paleomagnetism. It seems that paleomagnetism, plate tectonics and other geophysical areas of study pose significant problems to the Biblical creationist above and beyond the usual concerns about radiometric dating. It would seem that the following areas of concern need to be given intense study by properly qualified creationists.

1. Are the various lines of evidence for global scale reversals of the earth's magnetic reversals as strong as claimed by most scientists? Are there other possible and feasible mechanisms that might reasonably account for this apparently global phenomena?
2. If the reversals did indeed take place, what fundamental physical constraints are there on how fast the reversals can take place?
3. How reliably do the extensively used potassium-argon radiometric dates, that are used to calibrate the reversal time scale, indicate real time? How close and necessary are the ties between the standard geologic column and the reversal time scale? Is it reasonable to significantly compress the reversal time scale on a worldwide basis?
4. Are there sound approaches for revising the plate tectonic theory so that it would be more acceptable for creationists who try to support a short chronology?
5. What fundamental physical constraints can be put on how fast the plates can separate?
6. Is there a correlation between core processes, such as the geomagnetic dynamo, and mantle processes such as plate tectonics?

These questions point out a definite need for creationists to look deeper inside the earth. Besides just looking at the crust, they need to be concerned with the processes going on in the mantle and core if they are going to attempt to answer the questions above. Only by doing this will creationists be able to ascertain the fundamental physical constraints that these processes place on their speculations concerning the history of the earth. Geophysicists, in particular, have significant contributions to make in the study of the available data and in the development of creationist theories concerning the history of the earth and the interior of the earth.

Scientists, theologians, and others tend to concentrate so much on their particular area of interest that they neglect to *synthesize* information from their disciplines with data from other areas. *Synthesis* is never easy because it necessitates both good communication between disciplines and a knowledge of subject areas outside narrow areas of specialty. Creationists, however, must utilize the input from a broad range of disciplines if they are to carefully and intelligently construct a viable model for the history of the earth and life on earth.

Hopefully, greater utilization of a broad data base will help creationists avoid the tendency to concentrate on various "exceptions to the rule," even though these exceptions may be supportive of the creationist point of view. Indeed, exceptions are useful pieces of data that need to be studied, but all too often it seems that creationists completely ignore or easily dismiss the great bulk of data available for study. For this reason their attempts to explain the physical world are often seriously hampered. In addition, this frequent neglect of the great body of available data puts any theory proposed by creationists under immediate suspicion by the scientific community. *In short, creationists need to do a better job of doing their homework*. Balance, thoroughness, and completeness are essential to any endeavor and certainly the study of earth history is no exception.

Can creationists come up with a serious global tectonic model for earth history that fits *all* the evidence from nature *and* from revelation? Since nature and revelation have the same author, shouldn't there ultimately be some way of harmonizing the frequent apparent conflicts between them? Ultimately, the answer must be yes. Certainly progress can be made, but it will require a great deal of creativity and careful study to come up with new approaches to the significant problems that exist. It is somehow particularly uncomfortable for creationists to cope with unanswered questions and with data that doesn't fit into their present models of the history of the earth. Creationists need to learn to live with disagreements between what nature and revelation seem to be telling them. They also need to realize that these experiences are crucial to the ongoing process of studying the world in order to obtain deeper insights and bring harmony between their understandings of revelation and nature.

It seems fitting to close with the following quote from Van der Voo (1979):

> *... throughout this review, uncertainties and unresolved problems have been identified. It is impossible to speculate which of these problems will be solved in the near future or which will have to wait another decade. One thing is certain: there is plenty of work that remains to be done.*

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