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Reversals of the Earth's Magnetic Field

Recent paleomagnetic and geochronologic data provide information on time and frequency of field reversals.

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The idea that the earth's main magnetic field changes its polarity was first advanced during the early decades of this century by geophysicists who were investigating the remanent magnetization of volcanic rocks and baked earth (*1–3*). They found that these materials, when heated to their Curie temperatures and cooled in the present weak field of the earth, acquire a weak but extremely stable remanent magnetization parallel to the present direction of the geomagnetic field. They further found that bricks and baked earth from archeological sites, as well as rock samples from young lava flows, possess a similar natural magnetization, undoubtedly acquired when the baked earth and lava flows originally cooled. The direction of this magnetization was found to be close to that of the present geomagnetic field at the sampling site, with differences of the order of 10 degrees attributable to secular variation of the geomagnetic field. However, when the early paleomagnetists studied rocks of early Pleistocene age or older, they discovered that a substantial proportion were magnetized in a direction more nearly 180 degrees from that of the present field. In explanation of these reversed remanent magnetizations they proposed 180-degree reversals of the direction of the geomagnetic field.

During the two decades (1928 to 1948) that followed this early work there was surprisingly little scientific reaction to the hypothesis of geomagnetic field reversal. This silence reflects the embarrassing lack, even at so late a date, of a theory adequate to account for the present geomagnetic field, let alone reversed magnetic fields which may or may not have existed earlier in the earth's history. The problem of field reversals was taken up again around 1950 by scientists who became involved in problems of geomagnetism from theoretical as well as observational starting points. The theory of magnetohydrodynamic motions in an incompressible fluid was interpreted to show how magnetic fields may be generated in rotating spheres of electrically conducting fluid. It was further shown that reversals in polarity are a possible, if not a necessary, property of simplified dynamo models for the magnetohydrodynamic motions. Moreover, conditions necessary for the maintenance of such a magnetic system were shown to be consistent with conditions thought to exist in the earth's core (*4*).

The observational basis for field reversals has been greatly extended since 1950, partly as a result of improvement in techniques of determining the stability and reliability of rock magnetism for determining past geomagnetic field directions, and partly as a result of the vast increase in paleomagnetic data available. Although many of these paleomagnetic studies have focused on the problems of continental drift and polar wandering, interest in the reversal problem has also continued up to the present, and the observations of the early workers have been amply confirmed. The directions of remanent magnetization in many tens of thousands of rock samples, with ages in the range 0 to 30 million years, show a strikingly bimodal distribution; the directions are grouped about either the present geomagnetic field directions at the sampling sites or about antiparallel (reversed) directions. Remarkably few intermediate directions have been observed.

Solid-state physicists have also made important contributions to the study of reversals. In 1950 Graham (*5*) concluded that reversals he had observed in sediments were due not to reversals of the earth's field but, rather, to mineralogically controlled self-reversal along the lines earlier reported by Smith, Dee, and Mayneord (*6*). Informed of this result, Néel (*7*) was able to predict, on the basis of contemporary advances in ferromagnetism and ferrimagnetism, that rock-forming minerals might acquire remanent magnetizations at an angle 180 degrees from the direction of the ambient magnetic field in which they cool. This prediction was almost immediately confirmed by Nagata and Uyeda's (*8*) discovery of a volcanic rock from Japan that possessed this predicted property of self-reversal. As we discuss more fully later on, this discovery of mineralogically controlled self-reversal, in offering a possible alternative explanation for reversed magnetization, considerably clouded the experimental evidence for geomagnetic field reversal.

What, then, is the present state of knowledge about geomagnetic field reversals? Our conclusion, based upon

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recent paleomagnetic-geochronometric evidence presented in this article, is that after a period of considerable uncertainty the balance has finally tipped in favor of geomagnetic field reversals as the cause of the reversals in most rocks. Recent experimental evidence not only confirms this interpretation but also tells us exactly when some of the most recent switches in polarity occurred.

Early Discoveries

Some of the most compelling evidence favoring the field-reversal hypothesis appears in the earliest investigations. In 1906 Brunhes (*1*) made the experimental observations that are summarized in Fig. 1. Faced with these results, and the experimentally verifiable fact that bricks and other baked earths acquire remanent magnetization parallel to the ambient magnetic field in which they cool, Brunhes concluded that the reversed natural remanent magnetization had been acquired in a reversed magnetic field which existed during the epoch when the lava flow originally cooled.

Although Brunhes's classic work was done decades prior to the discovery of mineralogically controlled self-reversals, his results from baked sediments have a direct bearing on this problem. When lava flows and other igneous bodies are emplaced, the sediments or other rocks in contact with them are heated and also commonly are altered chemically. The ferromagnetic minerals in the igneous body are generally different from those in the surrounding baked country rock. As the igneous body and the baked rocks cool in the same ambient geomagnetic field, they become magnetized in the same direction unless magnetization of the ferromagnetic minerals in one of them is self-reversing. If the fraction of self-reversing ferromagnetic minerals in all rocks is x and if these self-reversing minerals are randomly distributed between igneous and baked rocks, then the fraction of pairs of igneous rock and baked rock with opposing polarities will be $2(x - x^2)$. In a recent review of paleomagnetic studies of igneous and baked rocks, Wilson (*9*) found 50 pairs with the same polarity and three pairs for which the original paleomagnetic data were ambiguous and which may or may not have opposing polarities. On the basis of these data, it appears that, at most, 3 percent of the reversals in igneous rocks and baked sediments are due to mineralogically controlled self-reversals.

The next important step in the study of reversals came with the stratigraphic investigations of Mercanton and Matuyama (*3*), in which an attempt was made to delineate the times when the geomagnetic field was reversed. Matuyama's study of volcanic rocks from Japan and Korea is especially important because it was the first successful attempt to determine the age of the most recent switch from a reversed-polarity epoch to the present epoch of normal polarity. He found that "there is a group of specimens whose directions of magnetization falls around the present earth's field. A number of other specimens forms another group almost antipodal to the former. [Although] the ages of the collected basalts are not always clearly known, . . . we may consider that in the earlier part of the Quaternary Period the earth's magnetic field in the area under consideration was probably in the state represented by the second group, which gradually changed to the state represented by the first group." This result, like that of Brunhes, has been amply confirmed by subsequent investigations.

Worldwide Extent of Reversals

If we accept for the moment the hypothesis that most reversely magnetized rocks were formed in reversed magnetic fields, the question arises, Were such reversed fields anomalies restricted to the paleomagnetic sampling sites or were they worldwide phenomena? A theory of field reversals due to local concentrations of ferromagnetic minerals in the earth's crust may be eliminated at the outset on several grounds, one of them magnitude: the magnetizations of rock formations are generally too small by a factor of 10 to produce a reversed field. From the theoretical point of view, if field reversals occur at all, they should be worldwide events. This follows from the very nature of the earth's magnetic field. Since the time of Gauss we have known from spherical harmonic analysis of the field that its source lies within the earth, and from physical reasoning it is equally clear that this source is within the earth's fluid core. The only proposed physical mechanism for producing the field which at present appears tenable is the magnetohydrodynamic mechanism, in which generation of the field is attributed to the interaction between fluid motions and electrical currents in the core.

The shape of the geomagnetic field is approximately that of a dipole at the earth's center, the direction of the field observed at any locality today differing from that of the dipole field by 5 to 25 degrees. The worldwide fit to the dipole-field configuration is vastly improved if average rather than instantaneous field directions at each locality are considered. With paleomagnetic techniques it is possible to obtain the direction of the earth's field at a given locality averaged over thousands of years, and when this is done it is found that young rocks from all over the

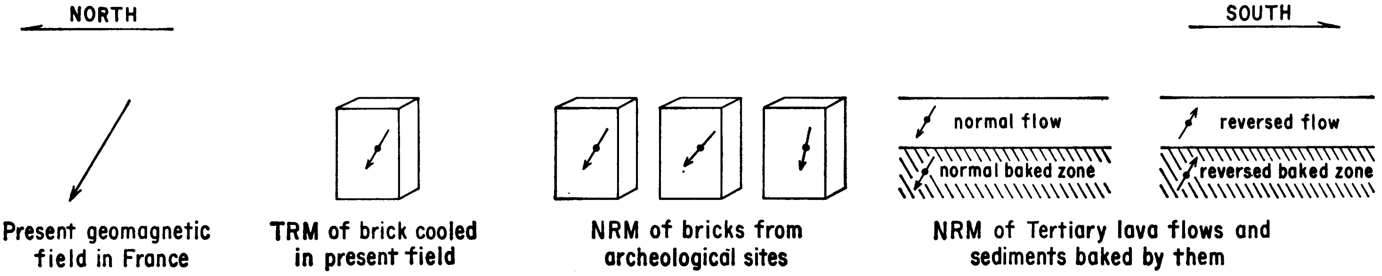

Fig. 1. Brunhes's observations of experimentally produced thermoremanent magnetization (TRM) and of natural remanent magnetization (NRM), which led him to propose geomagnetic field reversals.

world fit a dipole-field configuration with the dipole axis parallel to the earth's present axis of rotation (*10*). Two such rotationally symmetrical dipole configurations are possible, one normal (Fig. 2, *a*) and one reversed (Fig. 2, *b*). Only two processes appear capable of explaining why the remanent magnetizations of rocks from all over the world are tightly grouped about these two field configurations. Either 180-degree self-reversals controlled mineralogically are responsible, or else the fluid and current systems in the earth's core have changed in such a way as to produce 180-degree reversals in the direction of the main dipolar component of the earth's magnetic field.

Self-Reversal

Self-reversal is defined as the acquisition of thermoremanent magnetization in a direction 180 degrees from that of the ambient magnetic field in which a rock or mineral specimen cools. Knowing as we do that some rocks, such as the Haruna dacite (*8*), are reproducibly self-reversing in the laboratory, the crucial question is whether all reversely magnetized rocks have undergone self-reversal. If they have, the experimental basis for seeking evidence of geomagnetic field reversal vanishes, and the hypothesis must be discarded. If not, we are faced with the difficult task of sorting out reversals due to mineralogy from those due to reversals of the geomagnetic field.

The obvious experiment might seem to be to heat and cool rocks in known magnetic fields and determine whether these rocks are self-reversing. This experiment has been performed by numerous investigators on thousands of rocks from many localities; in the laboratory, only a small fraction of 1 percent of the rocks have been found to be self-reversing. However these experiments do not tell the entire story or completely rule out the possibility of self-reversal. The inconclusiveness of simple heating and cooling experiments is illustrated in the studies by Uyeda (*8*) and Ishikawa and Syono (*11*) on minerals of the ilmeno-hematite series. Minerals of this series were found to be self-reversing only over a limited range of chemical composition and only for certain rates of cooling. Thus, a natural self-reversal in a rock containing these minerals might not be reproduced if the rate of cooling in the laboratory were different from that when the rock originally formed.

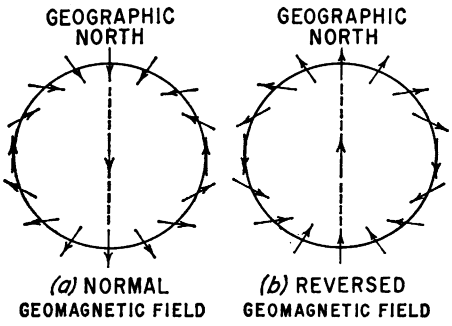

Fig. 2. Directions of an axial dipole geomagnetic field over the earth for (*a*) normal polarity (present configuration) and (*b*) reversed polarity.

Self-reversal requires the coexistence and interaction of two ferromagnetic constituents. Of the many types of interaction that may produce self-reversal, the simplest involves the magnetostatic energy of interaction between two closely intergrown ferromagnetic minerals, A and B, having different Curie temperatures. If the geometry of the mineral intergrowths is appropriate, and if the intensity of the magnetization of the A constituent is sufficiently large when the rock has cooled to the Curie temperature of the B constituent (the Curie temperature of A being greater than that of B), B will become reversely magnetized. The rock will undergo reproducible self-reversal if, after complete cooling, the remanent magnetization of B is greater than that of A. Even if the remanent magnetization of B is initially less than that of A, the rock may still become self-reversed if A is selectively dissolved during the geologic history of the rock, or if the remanent magnetization of A undergoes spontaneous decay to a value less than that of B.

The two constituents, A and B, need not be different ferromagnetic minerals. In ferrites they are the two interpenetrating cubic sublattices which make up the crystal structure. Because the exchange interaction between the cation sites in the two sublattices is negative, the B sublattice acquires a spontaneous magnetization exactly antiparallel to that of the A sublattice when the ferrite cools through its Curie temperature. Given appropriate temperature coefficients for the two spontaneous magnetizations, reproducible self-reversal will occur on further cooling. Self-reversing minerals of this type have been synthesized (*12*) but have not been discovered in rocks.

Ferrites may also undergo self-reversal through cation migration between adjacent lattice sites. At temperatures above the Curie temperature the equilibrium distribution of cations on lattice sites is disordered, but at low temperatures it is more highly ordered. On rapid quenching, however, such as may occur when a lava flow cools, a ferrite could temporarily retain a disordered cation distribution and later undergo a self-reversal through slow diffusion of cations toward the more ordered low-temperature distribution. Verhoogen (*13*) has shown that a self-reversal of this type would not take place in magnetites containing impurities or vacancies on certain lattice sites until 10^5 or 10^6 years after cooling. These self-reversals would not be reproducible in the laboratory.

In view of the complexity and nonreproducibility of many types of self-reversal, what approaches are open to the investigator attempting to assess the prevalence of self-reversal in rocks? One is to look for correlation between mineralogic properties and magnetic polarity. If all the reversely polarized members of a suite of rocks possess a unique mineralogy, self-reversal is probable even if it cannot be reproduced in the laboratory.

Balsley and Buddington (*14*) have discovered such a correlation in their study of metamorphic rocks in the Adirondack Mountains. Rocks of reversed polarity invariably contain ilmeno-hematite; normal rocks invariably contain magnetite. These mineralogical differences indicate self-reversal and also indicate that the geomagnetic field was not reversing its polarity during the long interval when these rocks were acquiring their remanent magnetizations.

Significant as these results from the Adirondack Mountains are, they appear to be the exception rather than the rule. In our own petrologic and paleomagnetic studies of many hundreds of samples from normal and reversely polarized lava flows, no significant correlation between polarity and petrography has emerged. However, some uncertainty lingers even after the most careful search fails to reveal a physical property correlated with reversals. New theoretical mechanisms which might produce reversals are still being advanced, and it is possible that the significant variables controlling self-reversals have not been isolated and identified.

A much stronger and more direct approach to the problem of self-reversal is available where two different ferromagnetic minerals have become magnetized at the same place and the same time. The magnetization of igneous bodies and sedimentary deposits baked by them was discussed earlier. Recently we have been able to extend this technique to some igneous rocks not associated with baked sedimentary rocks by demonstrating that the natural remanent magnetization of these rocks resides in two distinct ferromagnetic minerals—hematite, with a Curie temperature of 680°C, and magnetite or titanomagnetite, with a Curie temperature below 580°C. The remanent magnetization of the two minerals has thus far always been found to have the same polarity. These results, like those from the baked sedimentary rocks, suggest that self-reversals in nature are rare.

Stratigraphic Relations of Reversals

If the field-reversal theory is correct and if self-reversals are rare, then the same magnetic polarity should be found in rocks of the same age all over the globe. Conversely, a demonstration that groups of strata of normal and reversed polarity are exactly correlative in age all over the earth would constitute the strongest possible demonstration of the validity of the theory of geomagnetic field reversal. The success of the stratigraphic approach is contingent, however, on one principal condition: the duration of epochs in which magnetic polarity is constant must be sufficiently long to be resolved by means of the available geologic techniques for establishing global contemporaneity of events. For example, if polarity epochs lasted only 50,000 years, the classic techniques of paleontology could hardly be used to establish contemporaneity. The pace of evolution and the rates of dispersal of organisms are not sufficiently rapid to produce significant changes in widely separated fossil assemblages in so short a time.

Matuyama's discovery that the youngest reversely magnetized rocks are early Quaternary in age has been confirmed by paleomagnetic studies in many parts of the world. Thus, in a general way, these stratigraphic relations lend support to the theory of geomagnetic field reversal. If, however, a substantial proportion of the rocks studied contain minerals which undergo self-reversal after an interval about equal to the duration of the Pleistocene, as suggested by Verhoogen (*13*) for impure magnetite, then a similar stratigraphic distribution of rocks of normal and reversed polarity is to be expected without a field reversal's having occurred. If this explanation is correct, one might expect variations, from place to place, in the age of the youngest reversely polarized rocks, reflecting variations in magnetite composition, cooling rate, and other factors which might control the time required for self-reversal. However, if field reversal is the correct explanation, the transition from reversed to normal polarization must occur at exactly the same stratigraphic horizon everywhere in the world.

For the past 5 years we have attempted to determine whether the most recent transitions from reversed to normal polarization in volcanic rocks from the Snake River Plain of Idaho, from Alaska, from California, from Hawaii, and from New Mexico are contemporaneous. In a general way, our results agree with those from other continents. Reversals are lacking in rocks from the upper Pleistocene and appear first in strata designated middle or lower Pleistocene. However, our attempts to determine whether the most recent transitions at all these localities are exactly contemporaneous have proved inconclusive. Much of the difficulty lies in the fact that this last transition occurs during the Pleistocene Epoch. Due to both the slow rate at which evolution proceeds and the time required for plant and animal migrations, paleontological techniques are not capable of precisely resolving separate events occurring within such a short time interval as the Pleistocene. Independent indicators of difficulties encountered in attempts to obtain early Pleistocene correlations are the well-known problems of correlating the Pliocene-Pleistocene boundary from place to place, and the equally great difficulty of correlating glaciations over even moderate distances. In working with volcanic rocks, as we do, the difficulties are compounded by the paucity of intercalated sedimentary deposits bearing fossils or indicators of glacial climatic fluctuations.

Our stratigraphic studies of reversals indicate that the adjustments one must make in local stratigraphic assignments to make all data consistent with the hypothesis that a worldwide transition from reversed to normal polarity occurred during the Pleistocene fall well within the uncertainties of the original assignments. However, this is far from proving stratigraphically that the transition occurred everywhere at the same time. Indeed, if the most favored stratigraphic assignments at all localities are taken at face value, then it must be concluded that the most recent transitions were not contemporaneous.

Paleomagnetic-Geochronometric Studies

An obvious way to resolve this ambiguity is to obtain dates by radiometric methods from groups of rocks of normal and reversed polarity. On the basis of general stratigraphic considerations, the duration of geomagnetic polarity epochs is estimated to have been between 0.25 and 0.5 million years (*15*). Until recently, none of the radiometric methods used for dating carbonaceous materials or for dating minerals could be used in this time range. The development, by J. Reynolds at the University of California, of a gas mass spectrometer with improved sensitivity and low background has made it possible to date young rocks by means of the decay of potassium-40 to argon-40, despite the low concentration of radiogenic argon (a 10-g sample of a half-million-year-old rock containing 2 percent of potassium contains only 1.78 $\times 10^{-11}$ mole of radiogenic argon-40). The group at the University of California led by G. H. Curtis and J. F. Evernden has been particularly successful in dating young volcanic rocks by using refined extraction techniques to reduce contamination from atmospheric argon and using the Reynolds spectrometer for argon analysis. For several years the time has been ripe for applying the potassium-argon geochronometric method to the study of reversals of the magnetic field.

The polarities of volcanic rocks which have been dated by radiometry are shown in Fig. 3. Both the paleomagnetic and the geochronometric data represent the results of independent investigations by several laboratories (*16*). We obtained the paleomagnetic data for rocks from North America; Tarling obtained the results for Hawaii; Rutten, the results for Europe; and Grommé and Hay, the results for Africa. The radiometric analyses were made by Curtis and Evernden at the University of California, by McDougall at the Australian National University, and by Dalrymple at the University of California and later at the U.S. Geological Survey.

Except for the samples from Europe, all the samples in these studies were treated in alternating magnetic fields to test stability of the remanent magnetization, and in several instances other reliability tests were made. For example, in our paleomagnetic investigations of radiometrically dated volcanic rocks we have been especially concerned with the problem of detecting possible self-reversals, because even a few undetected self-reversals could greatly obscure the age relations of rocks of normal and reversed polarity. In an attempt to detect reversals dependent on cooling rate, we have collected from each outcrop multiple samples that cooled at different rates. Where available, baked zones were sampled, as were xenolithic inclusions containing ferromagnetic minerals different from those in the parent lava flow. Never in the course of collecting several thousand samples from several hundred lava flows and intrusive bodies have we encountered both normal and reversed polarity in the same igneous cooling unit. [A trivial exception is the occasional sample that has been struck by lightning; the magnetization effects of lightning are easily detected and removed (*17*).] When heated and cooled in the laboratory, none of these samples is self-reversing—a finding which suggests, as does the field evidence, that self-reversals dependent on cooling rate have not occurred.

In addition, a variety of thermomagnetic, crystallographic, and chemical experiments and observations were made in an attempt to find a correlation between magnetic polarity and other physical properties. None was found. It is therefore very unlikely that lavas of self-reversed polarity contributed to the data for North America cited in Fig. 3. Moreover, the agreement of all the data from the diverse sources is remarkably good. The ten volcanic rocks with ages between 0 and 1.0 million years all have normal polarization, whereas over 30 reversely magnetized volcanic units have ages in the range 1.0 to 2.5 million years. The only normally magnetized rocks in this interval are two normally magnetized lava flows, both with ages of 1.9 million years; their significance is discussed later. Some of the dates are for mineral separates of sanidine, biotite, and plagioclase; two are for glass; and some are for total rock basalt, this being by far the largest category. The ferromagnetic minerals have a wide range of composition, including magnetite, titanomagnetite and oxidized titanomagnetite, and hem-

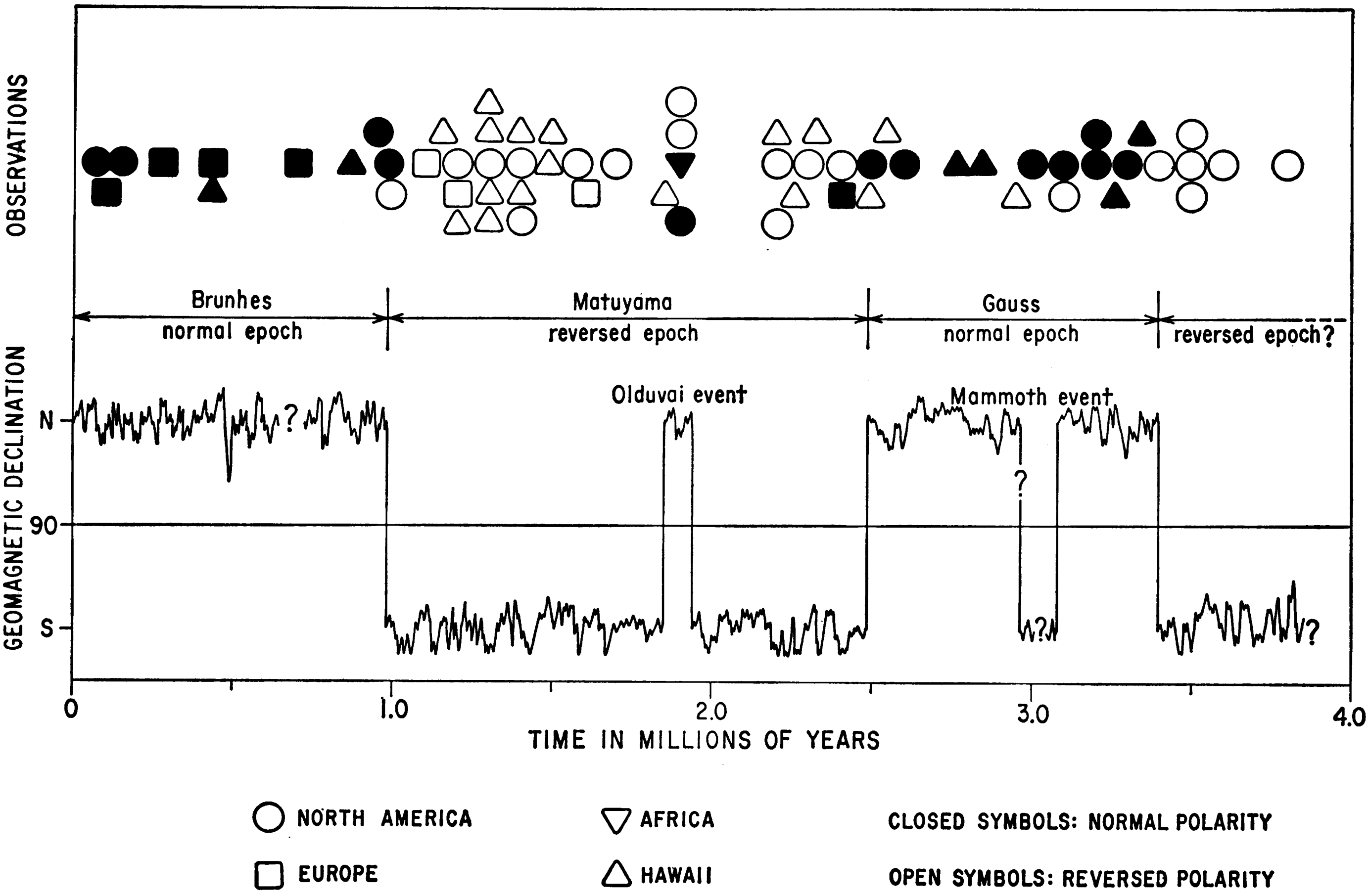

Fig. 3. Magnetic polarities of 64 volcanic rocks and their potassium-argon ages (*16*). Geomagnetic declination for moderate latitudes is indicated schematically.

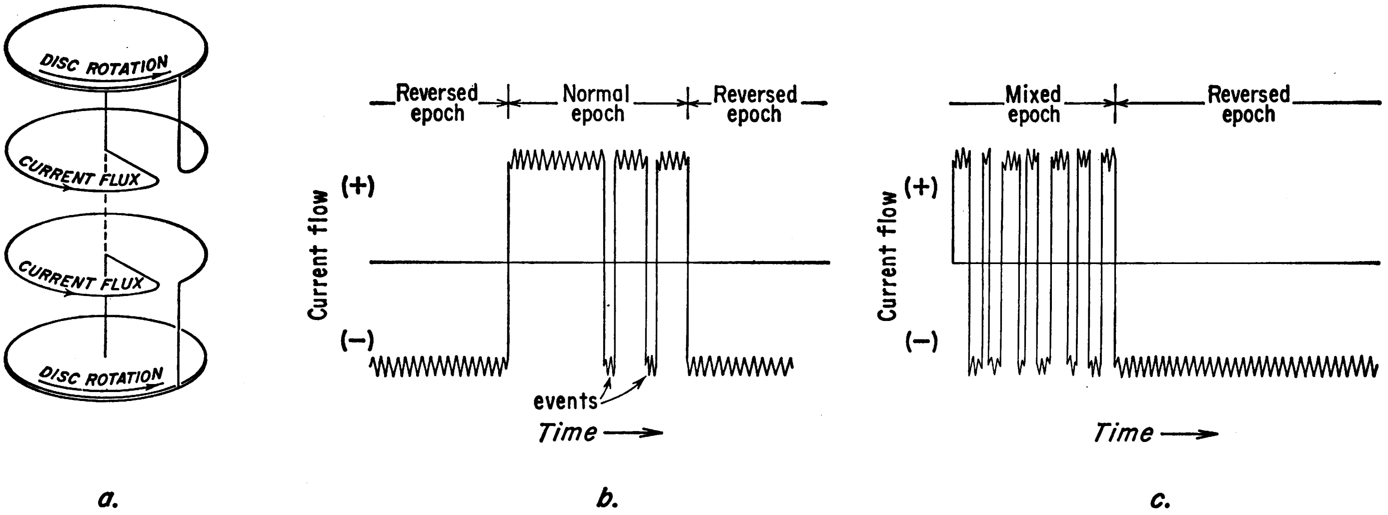

Fig. 4. (*a*) Two-disc dynamo model with two solutions (*b* and *c*) for current flow. [After Mathews and Gardner (*21*)]

atite, and they also show a wide range of intergrowth textures. In the samples we have studied, ferromagnetic minerals of all types occur in both the normal and the reversely polarized groups. Faced with these data, one must conclude (i) that the geomagnetic field has reversed polarity repeatedly; (ii) that self-reversals in young volcanic rocks are rare; and (iii) that the potassium-argon technique for dating young volcanic rocks is remarkably precise.

Discussion

The succession of young volcanic rocks at any one locality rarely if ever is sufficiently continuous to give a complete record of the history of the geomagnetic field. Nonetheless, because the polarity of the field is a global phenomenon, data from all over the world may be synthesized, as has been done in Fig. 3, to indicate the declination that would be observed at any sampling site that possessed a continuous record. The short-period deviations shown schematically about the north and south directions are typical of the amplitude of secular variation in moderate latitudes; little is known as yet about the actual periods of the variation. The general character of the geomagnetic field appears to change abruptly at the boundaries of certain time intervals which we have termed polarity epochs. Epochs of two types may be recognized —those represented wholly or predominantly by rocks of normal polarity and those represented wholly or predominantly by rocks of reversed polarity.

Within the youngest reversed-polarity epoch there occurs a short interval of normal polarity, identified in Fig. 3 as the Olduvai event. This event is now supported by data from both Africa and North America and may be considered well established. Less securely documented is the Mammoth event (Fig. 3), based on two points of reversal near 3.0 million years ago; the time interval between these points is about equal to the precision of the potassium-argon dating method; thus, additional data will be needed to determine whether these two points represent one or two events. At several other places in the reversal time scale there are gaps in the data sufficiently broad to suggest the possibility of additional events, but the pattern of epochs appears well established.

The accuracy with which the boundaries of epochs and events may be drawn depends on the accuracy of individual datum points, on their density and distribution, and on the time required for transitions between polarity epochs. For this time interval, it is estimated that the standard deviation of ages obtained by potassium-argon dating averages about 5 percent, although the precision of individual dates may vary considerably. We estimate that the boundary shown at 1.0 million years is precise to within 0.05 million years; that at 2.5 million years, to within 0.2 million years; and that at 3.4 million years, to within 0.1 million years.

The time required for transitions between polarity epochs is not known from direct measurement. Estimates of the order of 10^4 years have been made on the basis of the proportion of all strata that are intermediate stratigraphically between rock sequences of normal polarity and sequences of reversed polarity and that also have intermediate directions of magnetization (*18*). Another estimate may be made on the basis of the observation that of the 64 flows for which we have radiometrically determined dates, none has an intermediate direction of magnetization. Under the assumption that each of the seven transitions shown in Fig. 3 lasted 50,000 years, the probability that 64 randomly distributed dates would all fall outside all of the transition zones is 3½ percent, suggesting that the transitions are shorter than 50,000 years. The corresponding probability for transitions lasting 10,000 years or less is 28 percent or more; thus such transitions are more compatible with the radiometric and paleomagnetic data. The rapidity of the transitions makes it difficult to study the important problem of the global shape of the field and the intensity of the field during the transitions, both of which factors control the magnetic shielding of the earth from cosmic rays and hence may have significant biological effects (*19*). On the other hand, the sharpness of the epoch boundaries makes them especially useful for worldwide stratigraphic correlation and also for assessing the precision of radiometrically determined dates. For example, the overlap, near the 2.5-million-year transition, of normal and reversed polarity, although conceivably due to rapid oscillation of the geomagnetic field, more probably reflects the precision of the individual dates. Reversals may thus provide a convenient method for directly comparing radiometric measurements on different types of rocks from all parts of the world.

We have given names rather than numerical or sequential designations to the polarity epochs for the following reasons. The previously used numerical systems count back sequentially from the present at each change in polarity (first normal, first reversed, second normal, and so on). However, if even a short-lived polarity interval is missed when a numerical system is set up, all older designations must be changed when the new polarity interval is identified. This would undoubtedly introduce considerable confusion into attempts to use the epochs for purposes of stratigraphic correlation. For example, in the first four articles linking paleomagnetic and radiometric results, most of the polarity data in the period 1.0 to 2.5 million years ago were reported, yet the significance of the short normal-polarity event at 1.9 million years ago was missed. The numerical systems also preclude designation of any given interval between polarity changes until all later intervals have been recognized.

The magnetohydrodynamic theory for the origin of the geomagnetic field, generally considered the only reasonable theory yet proposed, seems capable of the accommodating reversals (*4*). Complete hydrodynamic analyses of the homogeneous-type dynamos that could be operating within the fluid core of the earth have not yet been made. In fact, the very formidable mathematics required has precluded all but the most simple analyses. However, analogies, suggested by Bullard and Rikitake (*20*), to the self-excited single-disc dynamo and the mutually excited two-disc dynamo may be analyzed more completely, and several solutions have been obtained for certain configurations in which the oscillating currents in the models change sign.

An axially symmetric two-disc dynamo recently analyzed by Mathews and Gardner (*21*) is depicted in Fig. 4, *a*. One of their solutions for this model (Fig. 4, *b*) suggests the features shown in Fig. 3 for the geomagnetic field. Another of their solutions (Fig. 4, *c*) infers a third type of epoch in which the field rapidly and repeatedly changes polarity. Epochs of this type, which may be termed mixed, have not yet been recognized.

Striking as these similarities are, the two-disc dynamo model is vastly different from a more realistic homogeneous dynamo model, and care should be used in interpreting the solutions for current flow as indicative of geomagnetic-field behavior. Nonetheless, the solutions do suggest that the magnetohydrodynamic theory is capable of explaining polarity reversals of the types observed, as well as the origin of the geomagnetic field itself. Conversely, any complete model or theory for the geomagnetic field must be capable of producing reversals of irregular duration.

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22. Publication of this article has been authorized by the director of the U.S. Geological Survey.