Ancient Magnetic Reversals: Clues to the Geodynamo

Is the earth headed for a reversal of its magnetic field? No one can answer this question yet, but rocks magnetized by ancient fields offer clues to the underlying reversal mechanism in the earth's core

by Kenneth A. Hoffman

For well over a century geophysicists have observed a steady and significant weakening in the strength of the earth's magnetic field. Indeed, if this trend were to continue at the present rate, the field would vanish altogether in a mere 1,500 years. Most investigators are inclined to think that the decay is merely an aspect of the restlessness inherent in the field and that the field will recover its strength. Yet one cannot dismiss out of hand the possibility that the weakening portends a phenomenon that has recurred throughout geologic time: the reversal of the geomagnetic field.

Which of these two scenarios is correct? The answer lies concealed 3,000 kilometers below the earth's surface within the outer core, a slowly churning mass of molten metal sandwiched between the mantle of the earth and the solid inner core. It is now generally accepted that the earth's magnetic field is generated by the motion of free electrons in the convecting outer core. This theory supposes the core behaves like a self-sustaining dynamo, a device that converts mechanical energy into magnetic energy. In the geodynamo the earth's rotation, along with gravitational and thermodynamic effects in and around the core, drives the fluid motions that produce the magnetic field [see "The Source of the Earth's Magnetic Field," by Charles R. Carrigan and David Gubbins; SCIENTIFIC AMERICAN, February, 1979].

Although the basic principles of dynamo action are well established, geophysicists do not yet understand the thermodynamics, fluid mechanics and electrical properties of the earth's interior well enough to construct a universally accepted model of the geodynamo. Yet its workings can be glimpsed indirectly by observing the present-day field. These measurements yield many details of the short-term behavior of the field, such as its shape and "secular variation," or ordinary fluctuation. To study the activity of the dynamo over aeons one must turn to the paleomagnetic record—the ancient magnetism frozen into rocks from the time of their formation.

Indeed, paleomagnetic evidence led to the first proposal that the earth's field has reversed itself, put forward in 1906 by the French physicist Bernard Brunhes. Brunhes was intrigued by the discovery of rocks that were magnetically oriented in the direction opposite to the earth's field. His startling suggestion was furiously debated for more than five decades. It was not until the early 1960's, at about the time J. S. B. Van Zijl and his colleagues published the first detailed study of a paleomagnetically recorded field reversal in lavas from South Africa, that the idea was accepted by the scientific community at large. Today it is a fundamental tenet of geophysics that the earth's magnetic field can exist in either of two polarity states: a "normal" state, in which north-seeking compass needles point to the geographic north, and a "reverse" state, in which they point to the geographic south.

In the 1960's studies of radiometrically dated lavas yielded a consistent log of past polarity changes, including no fewer than nine major reversals in the past 3.6 million years, the most recent of which occurred 730,000 years ago [see "Reversals of the Earth's Magnetic Field," by Allan Cox, G. Brent Dalrymple and Richard R. Doell; SCIENTIFIC AMERICAN, February, 1967]. The time scale of polarity transitions has since been extended back nearly 170 million years.

Paleomagnetic records show that the geomagnetic field does not reverse instantaneously from one polarity state to the other. Rather, the process involves a transition period that typically spans a few thousand years. Hence for perhaps 98 percent of the time the field is stable and its shape is well understood. But for the remaining 2 percent of the time the field is unstable and its shape is not obvious. The foremost task for geophysicists in my field has been to chronicle the behavior of the reversing field—its shifting shape and fluctuating intensities—based on the sometimes faint and complex record of past events, imprinted in stone. The findings provide an invaluable probe into the hidden mechanisms of the geodynamo.

Clues to the Field's Geometry

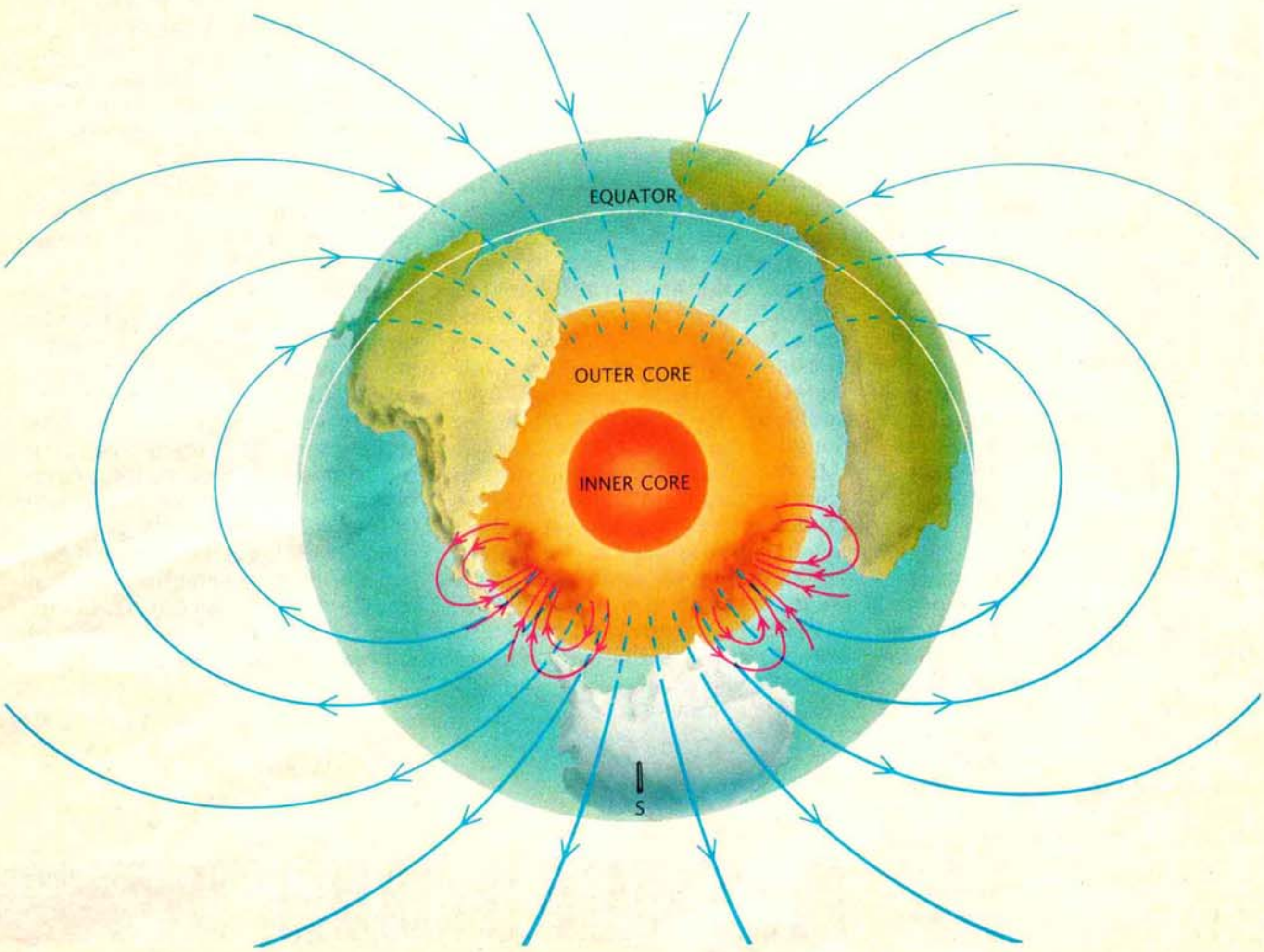
The paleomagnetic record has enabled investigators to deduce the geometry of ancient fields during both stable and unstable periods. It is well known that during times of stable polarity the magnetic field of the earth is dominated by a dipole shape, as though there were a bar magnet in the core, slightly tilted away from the earth's axis of rotation. During normal polarity a free compass needle—one that can swing in three dimensions—would everywhere point northward, dipping into the ground in the Northern Hemisphere and aiming skyward in the Southern Hemisphere. The angle of dip depends on the latitude of the compass. Conversely, at times of reverse polarity the needle would point to the south, tilting upward in the Northern Hemisphere and downward in the Southern Hemisphere.

But what of the field during the process of reversal? This question can be resolved by examining records of the same reversal from sites scattered around the globe. For each recorded magnetic direction it is possible to determine the location of the magnetic pole from the angle of dip and the horizontal orientation [*see top illustration on page 79*]. Hence by examining the change in paleomagnetic field direction at various intervals during a transition, one can track the virtual, or suspected, geomagnetic pole (VGP) as it travels from one polarity to the other. Moreover, if paleomagnetic records from different sites yield the same locations for the path of the pole, one can conclude that the field was indeed dipolar. But if the different records suggest wildly dissimilar VGP paths, one must conclude that the geometry of the reversing field was more complicated than a dipole.

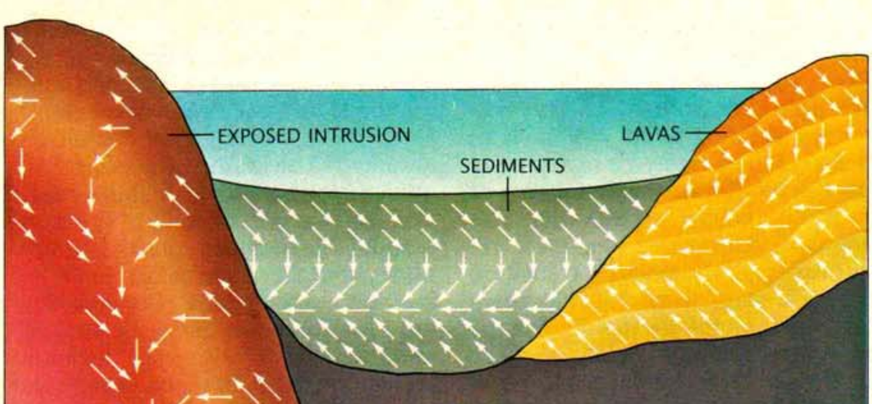
John Hillhouse and the late Allan Cox, both then at Stanford University, were the first to attempt such an analysis. They studied a record they had discovered in the sediments of dry Lake Tecopa in California. The sediments chronicled the most recent reversal, the polarity transition that took place some 730,000 years ago and brought the field from the Matuyama reverse epoch into the Brunhes normal epoch. Noting that the VGP path obtained from their data was quite different from the path associated with a marine-sediment record from Japan, they concluded that the configuration of the transitional field was complex and predominantly nondipolar. Similar paleomagnetic records of the same reversal from other locations also indicated quite disparate VGP paths [*see top illustration on page 80*].

Assuming that these data are reliable, can one analyze them in some other way to help determine the geometry of the transitional field during the Matuyama-Brunhes reversal? Since the reversing field cannot be assumed to be dipolar, the VGP method described above is of limited use. One needs a way to analyze the data without making any prior assumptions about the shape of the field. The method I now employ is to consider only the direction of the paleomagnetic field vectors at each location and to plot the path of the vectors on the surface of a "directional sphere" [*see top illustration on page 79*].

For the Matuyama-Brunhes reversal there are now many records from separate locations in the Northern Hemisphere. One can therefore compare the data by plotting all the directional paths on the same sphere [*see top illustration on page 80*]. When this is done, an interesting feature emerges: during the change in polarity from reverse to normal, most of



MAGNETIC LINES OF FORCE (*blue*) emanate from the earth's molten outer core in this see-through view. David Gubbins of the University of Cambridge has determined that patches of oppositely oriented field lines (*red*) exist near the tip of Africa and of South America. These "core spots" can account for the observed weakening of the earth's field. The spots are growing in size and strength and are moving southward. Gubbins suggests that this may be the process that eventually reverses the earth's field.



ROCKS can record the direction (*arrows*) of the earth's magnetic field at the time of their formation. Igneous rocks contain magnetic grains whose magnetic moments become oriented with the prevailing field as the rock cools. Lava flows (*yellow*) cool rapidly and provide the most accurate "snapshots" of the paleomagnetic field. Because of the irregularity of eruptions, such records may contain significant gaps. Intrusions (*brown*), formed by magma cooling underground over thousands of years, provide a more continuous record, but because they take a longer time to cool, the recorded field orientation may be averaged over some time. Intrusions cool inward, so that the paleomagnetic record is oldest near the surface and youngest in the interior. Sediments (*gray*) contain magnetic grains that become aligned with the field and fixed in place as the sediment consolidates. Sediments take time to "lock in" their magnetic remanence.

the intermediate field vectors—those that stray more than 30 degrees from either of the axial dipole field directions (or "pseudopoles")—sweep along the "underside" of the plot. That is, if one imagines that all over the Northern Hemisphere north-seeking compass needles are swiveling from geographic south to north as the field reverses polarity, most of the needles would flip downward rather than upward. Moreover, the needles would not stray far from the north-south vertical plane. The implication is that the transitional field does not change much in the east-west direction and hence that it is roughly symmetrical about the earth's rotational axis.

"Hot Spots" in the Geodynamo?

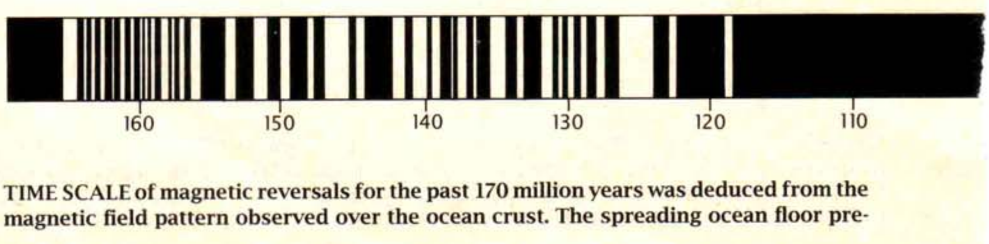
If all sites in the Northern Hemisphere recorded similar field behavior during the Matuyama-Brunhes reversal, one would strongly suspect that the underlying activity in the earth's core was also roughly symmetrical about the earth's rotational axis. Such axisymmetry can be explained by supposing the reversal process begins within latitudinal—that is, axisymmetric—bands in the core fluid [*see bottom illustration on page 80*]. Such bands would be associated with local field lines oriented in a direction opposite to that of the overall field. The bands might grow, flooding their way through the rest of the core and bringing about a reversal of the entire field.

The Matuyama-Brunhes data impose constraints on such a theory: they are consistent with models in which this process begins near the equatorial plane of the core or in its southern hemisphere but are inconsistent with a process that begins in the core's northern hemisphere [*see bottom illustration on page 80*]. Before one can decide whether this model is plausible it will be necessary to obtain reliable paleomagnetic data from additional sites, particularly in the Southern Hemisphere.

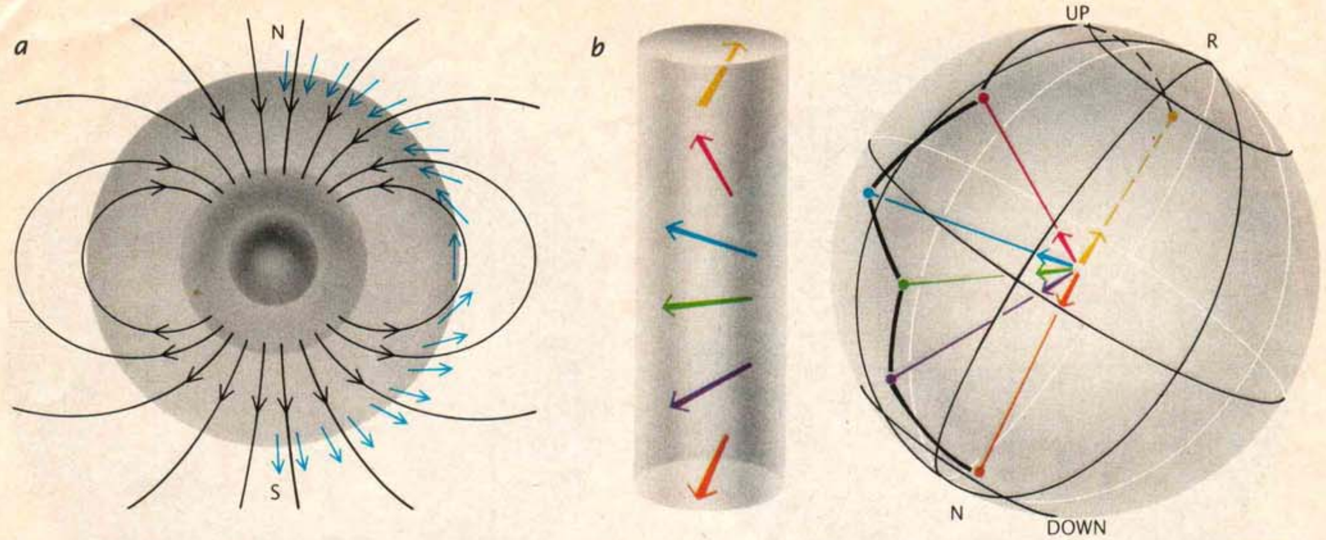
In the meantime, support for this model comes from the investigation of the ongoing decline of today's field. David Gubbins of the University of Cambridge surmises that the waning strength of the dipole field results from the growth and intensification of regions at the surface of the outer core from which emerge magnetic field lines, or flux, whose direction is opposite to present-day polarity. These regions are at high southern latitudes of the core, below the tip of Africa and of South America [*see illustration on preceding page*]. They are thought to be associated with particularly hot parts of the lowermost mantle, directly above the outer core. If this trend continues, Gubbins suggests, the sense of the dipole can ultimately reverse.

Gubbins' findings enable one to speculate that the reverse-to-normal Matuyama-Brunhes event and the possible onset of a normal-to-reverse transition today are both consequences of a similar process, initiated in the southern hemisphere of the core. If they are, the field lines of the earth should eventually change direction in a manner similar but antipodal to the behavior observed for the Matuyama-Brunhes reversal. In other words, one would expect compass needles around the world to trace out a path largely confined to the vertical plane. In contrast to the behavior of hypothetical compasses during the Matuyama-Brunhes reversal, however, compass needles in both hemispheres should rotate upward instead of downward.

Yet what reason is there to believe the reversing dynamo can repeat itself in this way? Are there particular "hot spots" within the core that trigger geomagnetic field reversals? Actually there exists very good paleomagnetic evidence that the triggering process in the core can remain essentially unchanged over the time span of several reversals. The most striking evidence comes from a series of reversals recorded in marine sediments from the island of Crete. Of four recorded transitions (two of which were reverse-to-normal and two normal-to-reverse) reported by Jean-Pierre Valet and Carlo Laj of the French National Center for Scientific Research, the three oldest events



TIME SCALE of magnetic reversals for the past 170 million years was deduced from the magnetic field pattern observed over the ocean crust. The spreading ocean floor pre-



DIPOLE FIELD has a clearly defined shape (*a*). Hence for a given paleodirection one can deduce the location of the magnetic pole, or virtual geomagnetic pole (VGP), simply from the field vector's horizontal direction and angle of dip. One can analyze a reversal by plotting the path of the VGP as the field changes polarity. This method is not wholly suited for more complex fields. A "directional sphere" (*b*) makes no assumption about the shape of the field. The sphere is imagined to enclose a particular site. One can picture an observer standing at the site, plotting on the sphere's surface the directions indicated by a free compass needle. In practice one can take field directions recorded in strata of rock, such as the vertical sediment core depicted here, and trace out the path (*black line*) of the field vector during a reversal. "Up" and "down" are reference points corresponding to vertically upward and downward. The "pseudopoles" (*N, R*) represent directions associated with pure axial dipole fields that have normal and reverse polarity. The "equator" defines all directions that are 90 degrees from each pseudopole, or midway between them.

exhibit directional field behavior that indicates a similar underlying core mechanism. The two reverse-to-normal events trace out paths that are antipodal to the normal-to-reverse event. (In contrast to the Matuyama-Brunhes reversal, these events were characterized by strong east-west movements.)

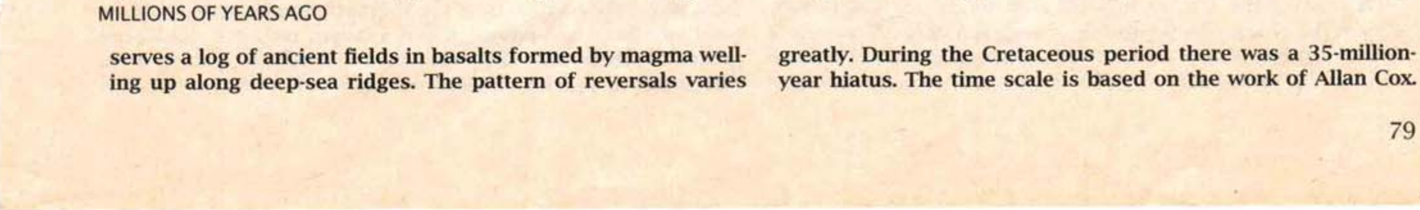
The most reasonable interpretation of this finding is that the geometry of the reversal process in the core did not change throughout the time interval—well over a million years—spanned by the three events. Demonstrating that other sets of contemporaneous paleomagnetic records show a similar pattern would increase confidence in the interpretation, however.

It must also be pointed out that just as there is repeatability in the reversal process, there is also variability. For example, the fourth and youngest of the transition records from Crete displays directional changes that are distinct from those in the older records, suggesting that the core process changes its spatial characteristics from time to time. Other back-to-back reversals reported by Scott W. Bogue and Rob S. Coe of the University of California at Santa Cruz and by Bradford M. Clement and Dennis V. Kent of the Lamont-Doherty Geological Observatory show back-to-back reversals in which the field directions follow similar rather than antipodal paths. These findings suggest that after a transition the dynamo sometimes "rewinds" like a film running backward.

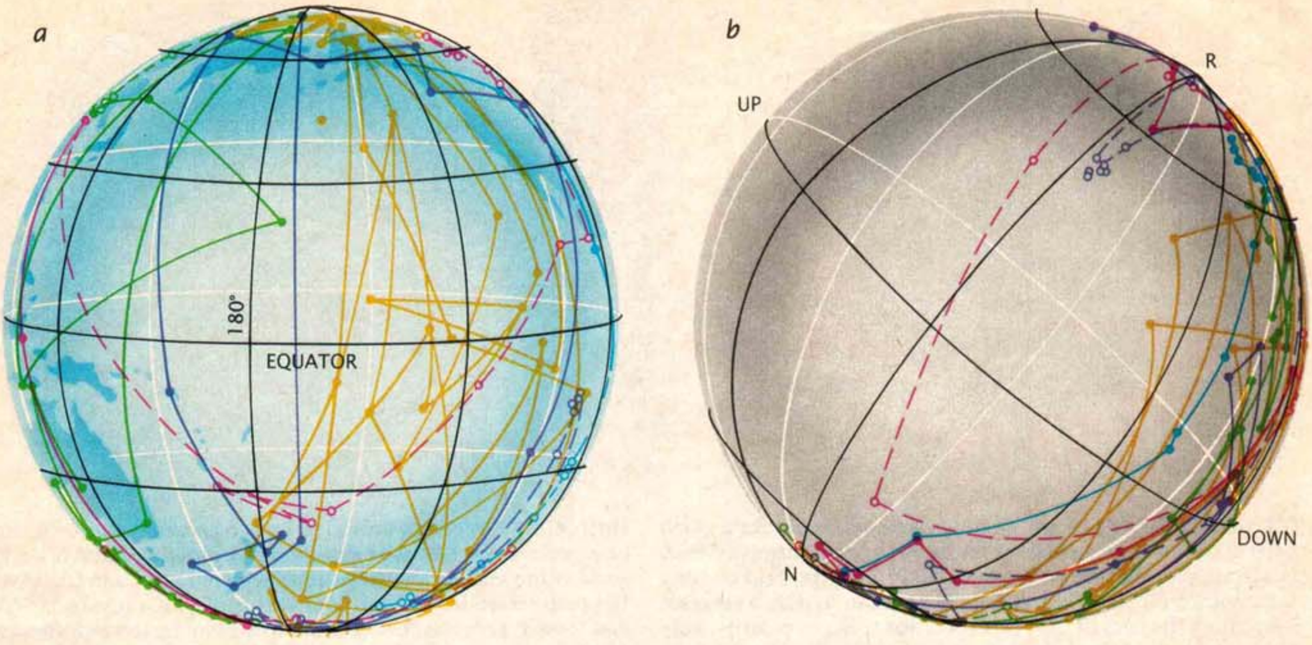
Excursions and Rebounds

The "rewinding" reversals make one wonder whether the dynamo sometimes fails to complete the reversal process and ends up backtracking. A similar question is raised by the observation of geomagnetic excursions, or large leaps in field direction, a phenomenon that has long been noted in the paleomagnetic literature. The chief question about these excursions is whether they are produced in times of abnormal secular variation and have no relevance to the phenomenon of polarity reversal or, alternatively, are manifestations of unsuccessful, or aborted, reversal attempts.

Evidence that there may indeed be a link between certain geomagnetic excursions and polarity reversals comes from a 34-million-year-old sequence of lavas from the Liverpool Volcano in eastern Australia. I have found that these basalt flows record a series of three apparently rapid departures from reverse polarity to essentially the same intermediate field



serves a log of ancient fields in basalts formed by magma welling up along deep-sea ridges. The pattern of reversals varies greatly. During the Cretaceous period there was a 35-million-year hiatus. The time scale is based on the work of Allan Cox.

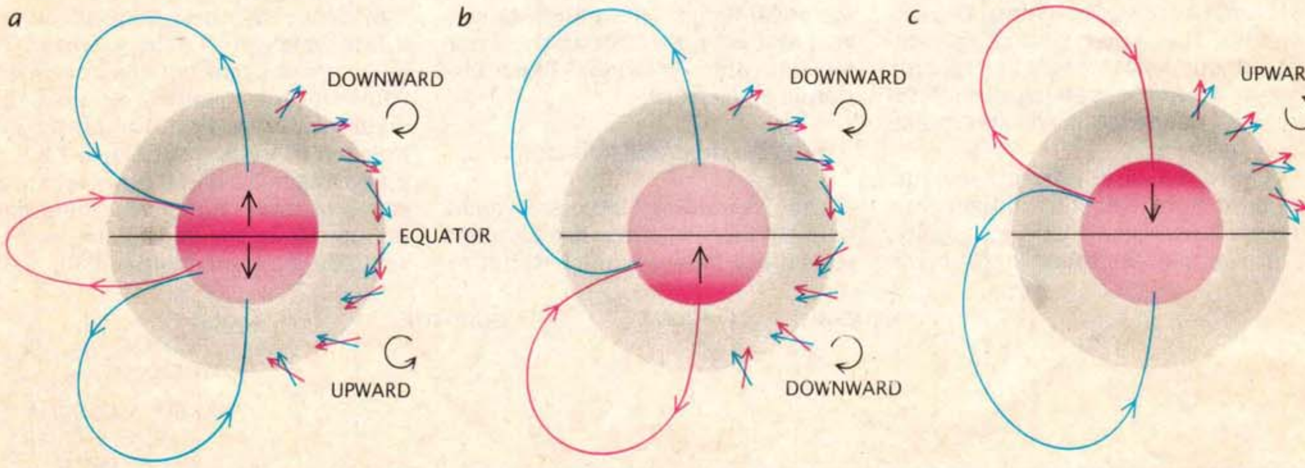


PALEOMAGNETIC RECORDS of the Matuyama-Brunhes reversal are analyzed by the VGP method (*a*) and by the directional method (*b*). The paths are based on data from five northern-latitude sites: Japan (*green*), Maui (*purple*), California (*yellow*), the North Atlantic (*blue*) and West Germany (*red*). If the reversing field were a dipole, all the VGP paths should coincide. But in fact the paths are widely scattered, proving that the field was nondipolar. Directional analysis reveals that during the transition the field vectors at all sites tended to tilt through a downward direction. This suggests east-west movements were small during reversal and hence the process was roughly symmetrical about the earth's axis. Maui data (unpublished) courtesy of Rob S. Coe.

orientation [*see illustration on page 82*]. The first two of these advances appear to be excursions because the lavas that immediately follow record the same (reverse) polarity direction that prevailed before the excursion. The lavas extruded directly after the third departure, on the other hand, possess normal polarity, indicating a successful reversal.

The Liverpool data are consistent with the contention, first made by John Shaw of University College Cardiff in Wales, that the reversal process may involve an intermediate dynamo state. This state seems to act as a kind of springboard from which reversal attempts, both successful and unsuccessful, are made. Such relatively stable intermediate field directions, or "hang-up" points, are in fact quite common and suggest that certain field geometries may offer energy states that are preferred by the geodynamo during reversal events.

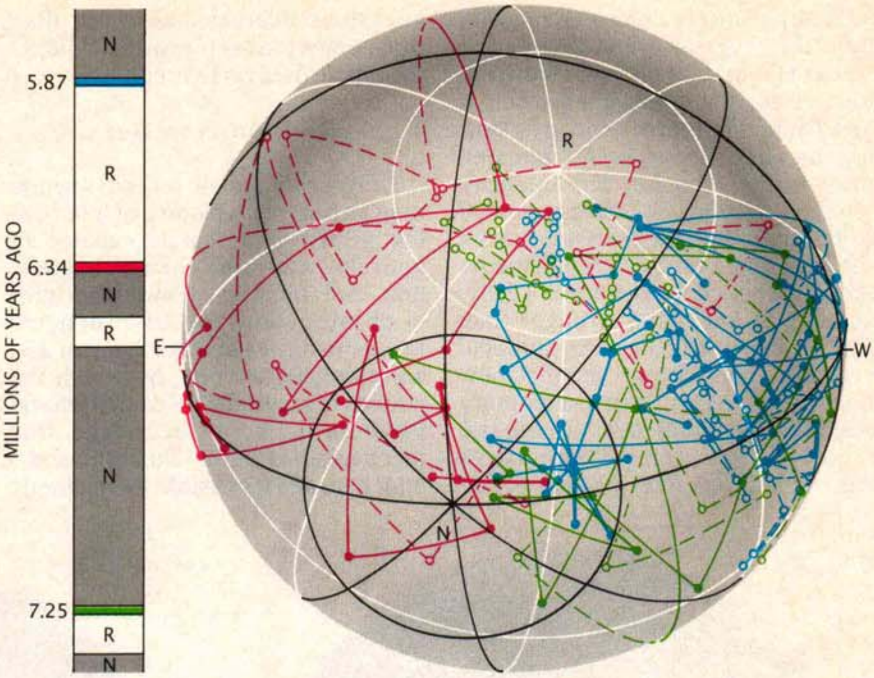
The first investigator to describe apparently stable intermediate directions was the late Norman D. Watkins of the University of Rhode Island, who in the late 1960's made a study



AXISYMMETRY during the Matuyama-Brunhes reversal can be explained by a process that begins with a latitudinal band (*dark red*) of core fluid that produces a field opposite to the dominant field. The field shown here begins in the reverse dipole state (*blue arrows*); the arrows point, like north-seeking compasses, toward the geographic South Pole. An equatorial band spreading northward and southward (*a*) would cause field vectors (*red arrows*) in the Northern Hemisphere to rotate downward (*black arrow*). A band starting near the geographic South Pole and expanding northward (*b*) would also cause field vectors to tilt downward. But a band near the geographic North Pole spreading southward (*c*) would result in an upward rotation, contrary to the observed pattern. Data from the Southern Hemisphere would reveal whether the reversal process began near the equatorial plane, in which case field vectors would rotate upward, or in the south, in which case field vectors would rotate downward.

of the 15-million-year-old reverse-to-normal transition recorded in the lavas from Steens Mountain in southeastern Oregon. The extent of this lava record is without parallel: it contains numerous, successive flows that preserve the field direction at some 55 distinct times throughout the reversal. Because of the rarity of such complete, high-resolution paleomagnetic records of a reversing field, the Steens Mountain lavas have remained the focus of an intensive investigation.

The work has proved well worth the effort. The study, carried out by Coe, Michel Prévot of Montpellier, France, and Edward A. Mankinen and C. Sherman Grommé of the U.S. Geological Survey, provides the most detailed account of both the field's directional behavior and its changes in intensity during a polarity transition. Their result suggests that the core process is rather complicated. A free compass needle at the Steens Mountain site at first would have traced out a generally downward path. But when the field reached a particular intermediate orientation, it apparently made a rapid directional jump and attained normal polarity. The new polarity, however, did not last for long, because what is observed next is yet another directional jump in which the field vector rebounded to the very same intermediate orientation. After the rebound the field direction swept out a loop to the east while again approaching normal polarity. This time the polarity change was successful.



THREE SEQUENTIAL REVERSALS recorded in sediments from Crete all seem to have been initiated in the same manner. The oldest reversal (*green*) and the youngest reversal (*blue*), both of which took the field from reverse polarity to normal polarity, followed paths on the west side of the sphere. In contrast, the middle reversal (*red*) from normal to reverse polarity followed an eastward path. This antipodal behavior suggests that spatially the same process was played out in the core during all three events.

Stop-and-Go Dynamo

The Steens Mountain lavas give the distinct impression that changes in polarity involve a kind of stop-and-go behavior of the dynamo. Furthermore, the investigators argue that because the observed jumps return the field vector to the same intermediate position, the changes result not from gaps in the record but from rapid shifts, perhaps taking only a few years, in the direction of the field. Support for this idea comes from the discovery of significant differences in paleomagnetic field direction between the faster-cooling edges and slower-cooling center within a single lava flow. If these results are reliable, they suggest that certain mechanisms for rapidly changing the magnetic flux must play a dominant role in the core dynamo during reversal.

The best way to test our confidence in this interpretation is to compare records such as the one from Steens Mountain with contemporaneous records, preferably from a nearby site, obtained from material that provides more continuous data than intermittent lava flows do. Unfortunately transition records of any kind are hard to find. A reversal from a similar period, however, has left a detailed record at the Tatoosh Intrusion from Mount Rainier, not far from Steens Mountain. Although the reverse-to-normal polarity change recorded in this intrusion is most likely not the same event recorded at Steens Mountain, the two sets of data share certain features in common.

Michael D. Fuller and his fellow workers at the University of California at Santa Barbara reported that early directional changes appearing in the Tatoosh Intrusion record are dominated by what appears to be a quite rapid movement to an intermediate position, where the field more or less stabilized. The field then underwent an unsuccessful attempt to reverse: normal polarity was approached and then lost as the field direction returned to about the same intermediate position in a pattern resembling the rebound seen in the Steens Mountain record. Following that aborted attempt the polarity change was successfully completed.

Thus two different types of record—the lava record from Steens Mountain and the Tatoosh Intrusion record—both support the contention that during reversal attempts the field can move rapidly as well as remain stationary and can undergo directional rebounds and unsuccessful attempts to complete the reversal process. Remarkably similar behavior in another reversal from the same geologic epoch has just been reported by Laj and his colleagues, who obtained their data on the island of Zakinthos in Greece from yet a third type of paleomagnetic record, marine sediments.

So far I have focused exclusively on the directional aspects of the reversing field, and yet a complete comprehension of the underlying dynamo activity also requires one to know about accompanying changes in field strength, or paleointensity. The latter is considerably more difficult to determine than direction. Nevertheless, many sites have now yielded intensity data, which indicate that intermediate orientations tend to be associated with weak field strengths, sometimes as low as 10 percent of the stable-polarity field strength.

The most detailed information on

intensity changes comes once again from the reversal event recorded at Steens Mountain. The field recovered to pretransition intensities when it approached full reverse polarity during its first, unsuccessful attempt, prior to the rebound. The intensity plunged again as the field retreated to the intermediate position. During the final stage of the reversal the intensity seems to have varied widely, sometimes becoming stronger than the ordinary field, as the dynamo regained equilibrium in the new polarity state. My own preliminary results from studies of a reversal recorded in lavas on the Hawaiian island of Molokai indicate that paleointensities fluctuated to more than three times the pretransition value as the dipole field recovered.

Two Core Processes

The paleomagnetic record is beginning to provide a picture of a reversing geodynamo that is capable of both slow and rapid changes in direction and intensity. First principles of physics allow two basic dynamo mechanisms, a slow mechanism and a potentially fast one, by which the pattern of magnetic field lines emerging from the core can change. One mechanism rests on "flux diffusion," which makes it possible for magnetic lines of force to move through the core fluid from higher to lower flux concentrations. Diffusion is a passive process that provides a way for the field to decay but not regenerate.

The dipole field today, however, is decaying about 10 times faster than can be accounted for by diffusion alone. Clearly there must be a more active process that builds up and alters the field dynamically. This mechanism is provided by "frozen-in flux," in which the magnetic flux lines are carried along with the flowing core fluid. The more closely the core fluid resembles a perfect conductor of electricity, the more rigidly the field lines move along with it.

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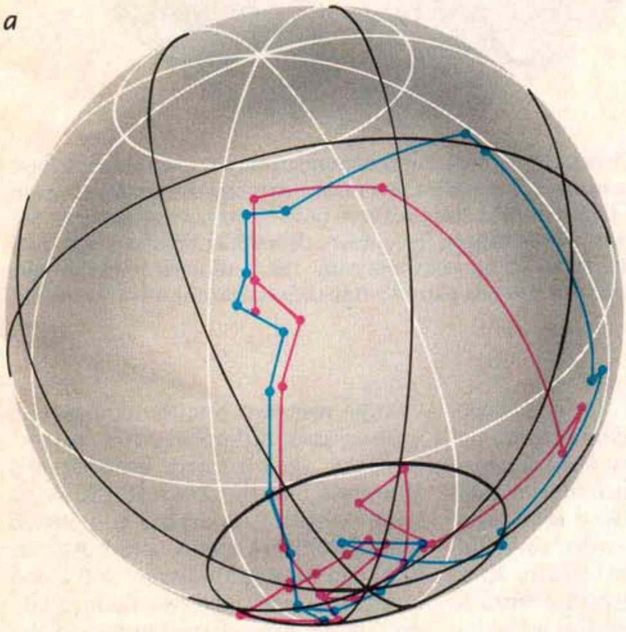

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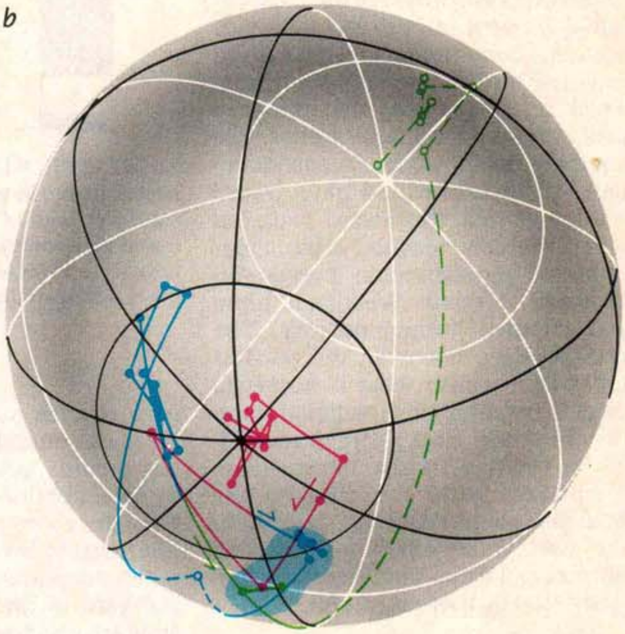

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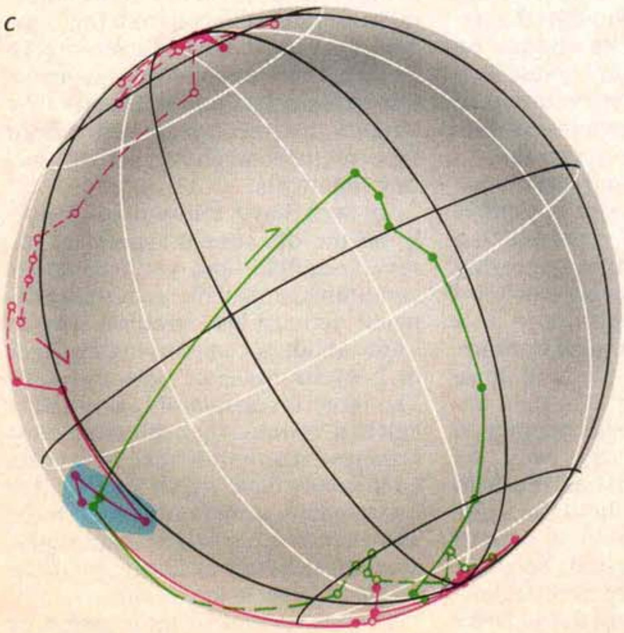


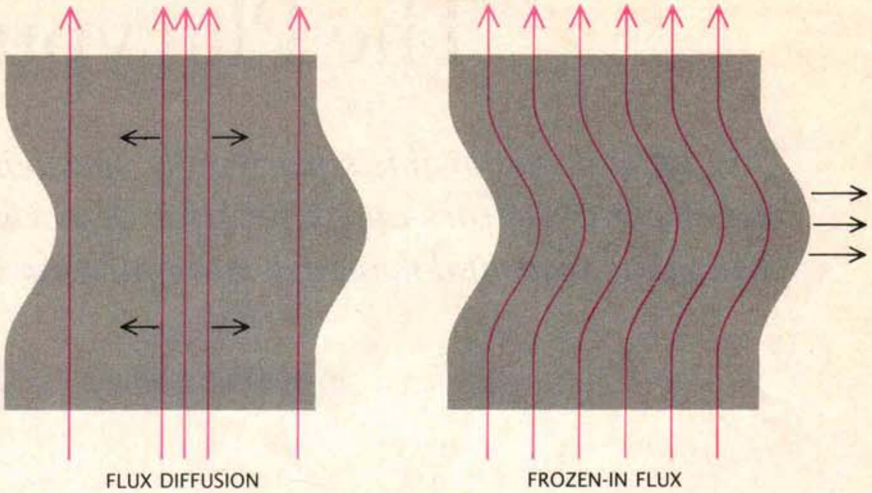
LOOPING EXCURSION by the earth's magnetic field to a position halfway between the two polarity states was recorded in 28,000-year-old sediments at Mono Lake, Calif. (*a*). Could this excursion represent an attempt by the dynamo to reverse its polarity? Evidence from Liverpool Volcano in Australia (*b*) suggests that excursions can be correlated with successful reversals. The evidence, from lavas dating from the Oligocene, some 34 million years ago, testifies to a series of three advances (*red and blue lines*) by the field to essentially the same intermediate orientation (*blue patch*), just prior to a completed reversal (*green line*). Lavas at Steens Mountain, Ore. (*c*), indicate that a newly reversed field can "rebound" (*green line*) to an intermediate orientation. The reversal depicted here occurred in the Miocene, about 15 million years ago. Mono Lake data courtesy of Joseph Liddicoat and his colleagues at the University of California at Santa Cruz.

Based on observations of the present-day field, frozen-in flux appears to dominate short-term changes—changes that occur over a period of a few decades.

A successful theory of the geodynamo, and in particular the mechanism of polarity reversal, will rest in part on determining the relative importance of these two processes. Again the paleomagnetic data are beginning to yield a reasonably consistent picture. The reversing geodynamo appears to take a very active role at times and a rather passive role at other times. It is thought that during the rapid directional jumps unusually high accelerations in fluid flow drive the frozen-in flux into continuously changing patterns. In times when the field is relatively quiet, such as the hang-up periods, flux diffusion must play a larger role.

In some way that is not yet fully understood, gravity and the earth's rotation, acting on density differences within the core fluid, provide the driving forces behind the geodynamo and control this dichotomy of dynamo processes. The reversal phenomenon may be triggered when something disturbs the convection pattern of the core fluid, and with it the magnetic flux. Phillip L. McFadden of the Bureau of Mineral Resources, Geology and Geophysics in Australia and Ronald T. Merrill of the University of Washington suggest that the triggering process is intimately related to the way the outer core vents its heat into the mantle. For example, heat transfer could create hotter (rising) or cooler (descending) blobs of material from the inner and outer boundaries of the fluid core, thereby perturbing the main convection pattern.

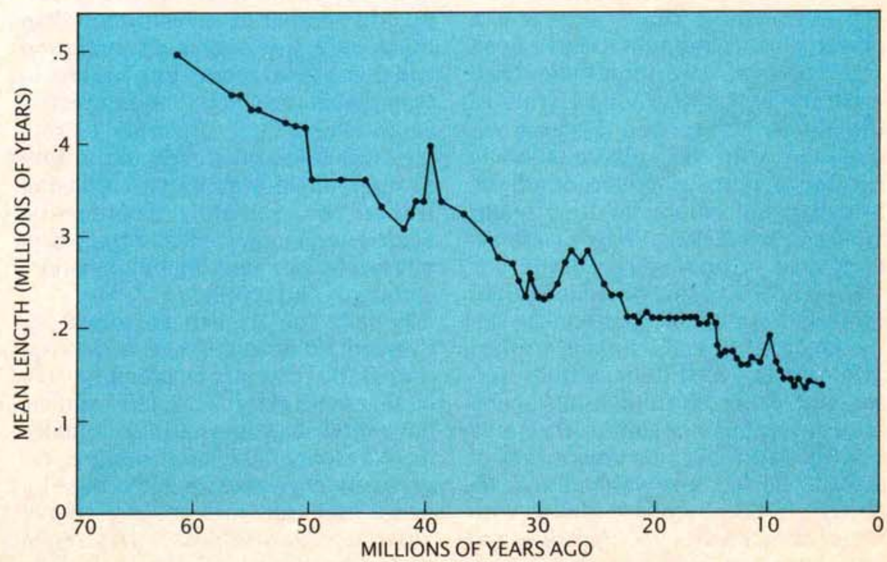
Among the more unorthodox and controversial theories is the "asteroid-impact hypothesis" proposed by Richard A. Muller and Donald E. Morris of the Lawrence Berkeley Laboratory. Their scenario begins with the impact of an asteroid or other extraterrestrial object large enough to send a great cloud of dust into the atmosphere. A kind of "nuclear winter" is seen as resulting, during which the polar ice caps would grow, abruptly altering the distribution of water on the earth's surface and with it the moment of inertia of the earth. The rotational acceleration of the mantle would then be increased to conserve angular momentum, causing friction and turbulence near the core-mantle boundary and initiating a reversal of the geomagnetic field.



FIELD LINES AND CORE FLUID can interact in two ways. Flux diffusion occurs when field lines (*red*) from regions of high field density spread to regions of low field density. This process accounts for field decays. Frozen-in flux occurs because the field lines are dragged along with the highly conductive core fluid and so can build up local fields.

How well do these two hypotheses account for such observations as the long-term increase in the frequency of reversal? In support of their model, Morris and Muller argue that the gradual cooling of the average ocean temperature would enable progressively smaller asteroid collisions (which occur more frequently) to induce ice-cap growth and reversals. But theories that depend on extraterrestrial intervention seem less convincing than theories such as the one offered by McFadden and Merrill, accounting for observed features of the geodynamo based solely on the thermodynamic state of the core and its effect on the deep mantle.

Geophysics today stands at a historic juncture. For the past three decades workers have combed the globe for the ghostly traces of ancient field reversals, correlated evidence from scattered sites, tried to sift reality from a less than ideal record and pieced together bit by bit a picture of the reversing field. Their results now challenge theorists to develop geodynamo models that can account for the observed behavior. As more paleomagnetic evidence is brought to light, it will play a critical role in determining which of these models are plausible and which ones are not.



DWINDLING length of the average polarity interval, when the earth's field is in the normal or the reversed state, reveals that polarity reversals have been taking place at an increasing rate. A complete geodynamo model will have to account for this trend.