

The Evolution of the Earth's Magnetic Field

Molten iron flows through the outer core, creating conditions that generate the earth's magnetic field. Maps of magnetic activity at the core surface link fluid flow to the evolution of the field

by Jeremy Bloxham and David Gubbins

What is the weather like within the outer core, 1,200 kilometers from the earth's center? Temperatures there reach those of the sun's surface (5,800 degrees Celsius); pressures exceed a million atmospheres. The molten iron of the outer core churns around the solid inner core, acting as a dynamo that generates the earth's magnetic field. Magnetic tempests develop from surges in the liquid iron, which flows as readily as water and conducts electricity slightly better than does copper. Even at the earth's surface, 3,000 kilometers from the outer core, the tempests can be detected by the waxing and waning of the earth's magnetic field.

Clearly, geophysicists who seek to explain and forecast changes in the field must understand what happens in the outer core. Unlike meteorologists, they cannot rely on observations made in their own lifetime, however. Whereas atmospheric storms arise in a matter of hours and last for days, magnetic tempests develop over decades and persist for centuries. Fortunately workers have recorded changes

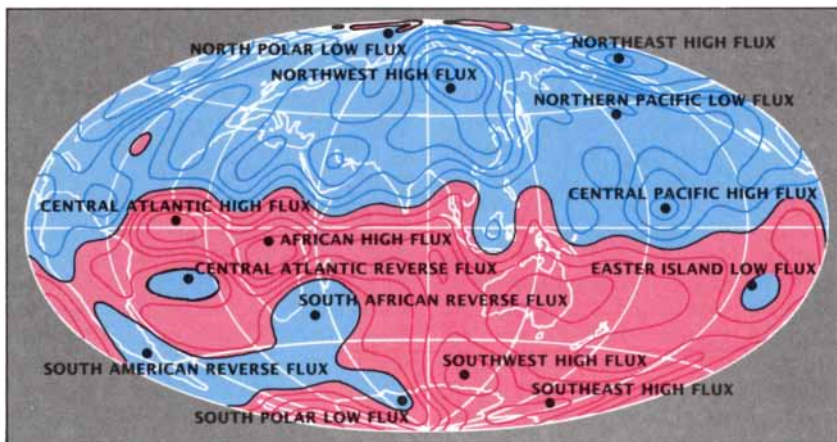
in the earth's magnetic field for more than 300 years.

During the past nine years our group, first at the University of Cambridge and then at Harvard University and the University of Leeds, has been working to extract more detail from the historical record. In 1983, by extrapolating from this data, the group succeeded in mapping the magnetic field at the boundary between the core and the mantle [see illustration on opposite page]. Since then these maps have revealed remarkable, unknown features of the earth's magnetic field and have elucidated the geodynamo, the process that maintains the field.

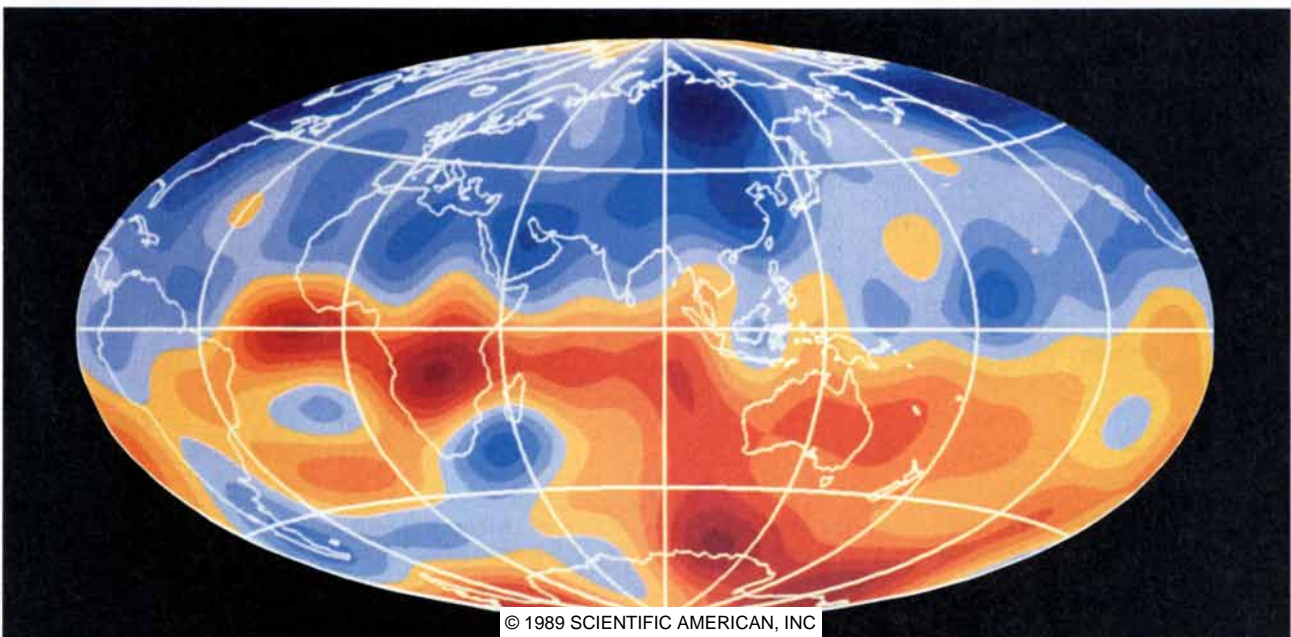
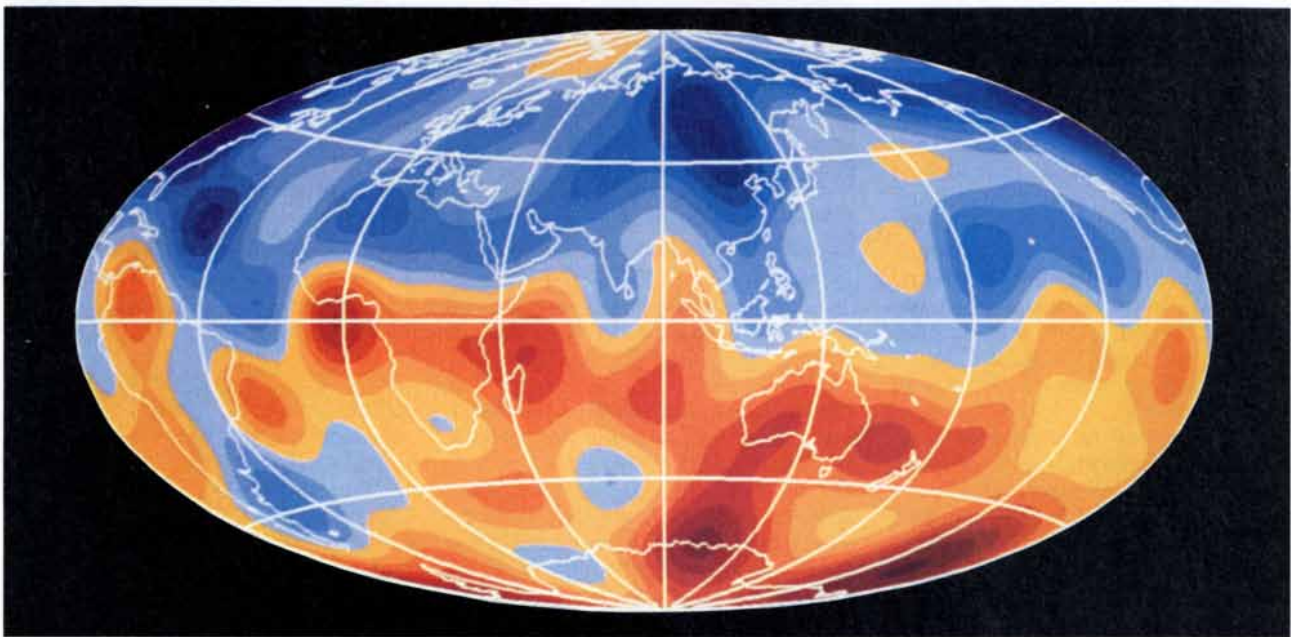
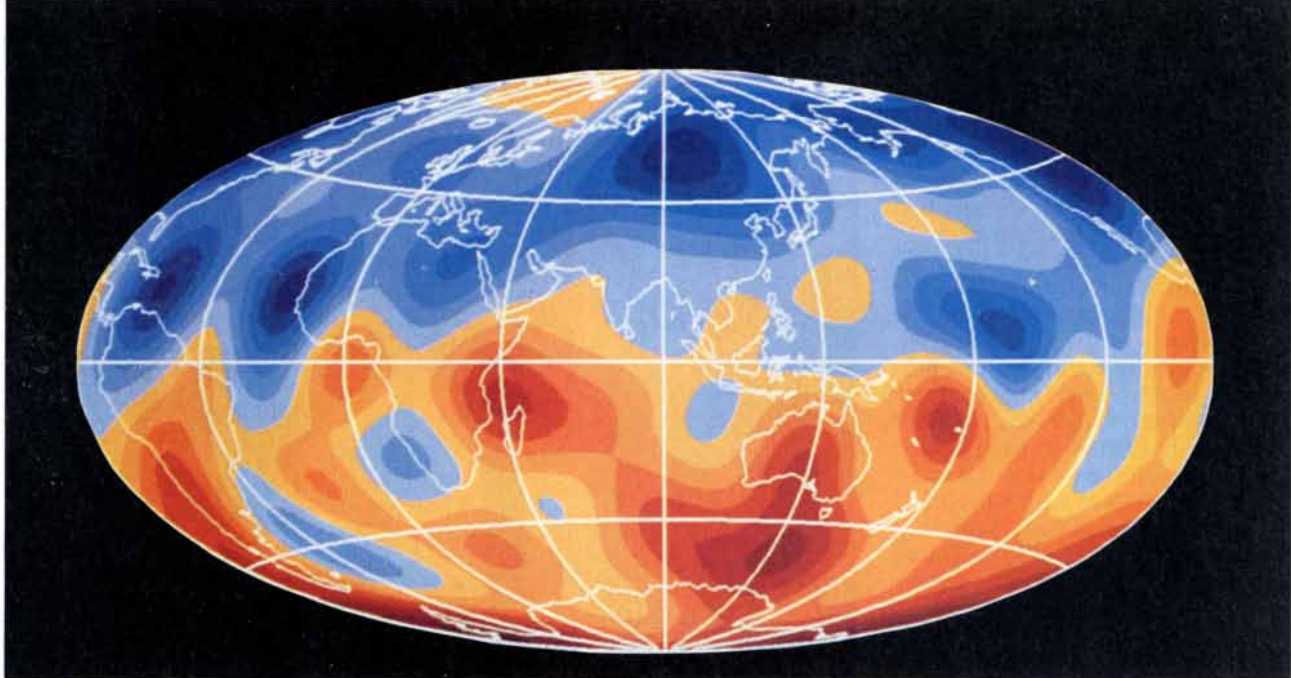
The basic characteristics of the geodynamo have been known since the

1950's. The influence of the earth's rotation and heat propels the molten iron in the outer core. As the conducting fluid flows through the outer core, it interacts with the earth's magnetic field, which has been present to some extent throughout geological time. The interaction generates an electric current, just as moving a wire across a magnet creates a current in the wire. Once the electric current is established, it too generates a magnetic field, which reinforces the earth's field. The geodynamo is self-perpetuating. So long as the forces that arise from both the earth's rotation and heat drive conducting fluid around the core, electric currents will materialize, and the magnetic field will develop.

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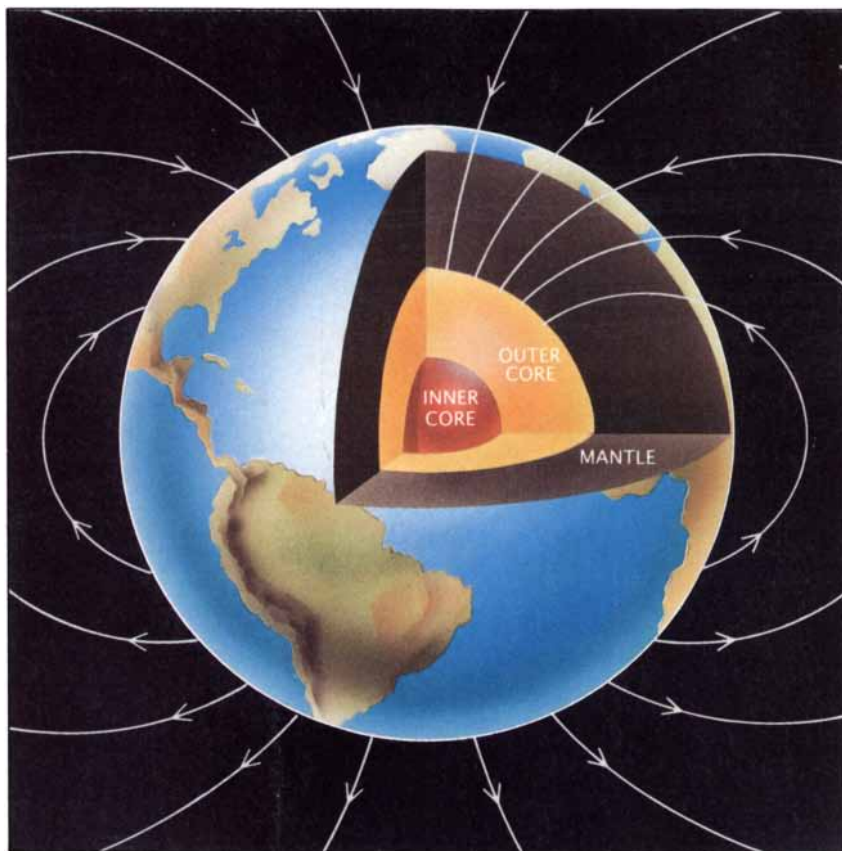
EARTH'S MAGNETIC FIELD at the boundary between the core and mantle (right) has been projected from measurements made at the earth's surface in 1777, 1882 and 1980 (from top to bottom). Intensity of color represents the intensity of magnetic flux perpendicular to the core surface: the number of lines of magnetic force that enter or exit the core surface. Blue tints represent inward flux; red and yellow tints show outward flux. Several "flux patches" are labeled above. During the past two centuries two high-flux patches near the north pole of the core and two near the south pole of the core have remained stationary. In the Southern Hemisphere three reverse-flux patches accompanied by high-flux patches have drifted to the west and south.



Although these simple ideas about the geodynamo provide an intuitive sense of how the field arises, it cannot explain many of the slow changes that workers have detected. For example, from decade to decade the field weakens by about 1 percent, and in some places its pattern rotates by about one degree relative to the earth's surface. Every million years or so, the field reverses polarity. During the past million years, for instance, the magnetic north pole has migrated from Antarctica to the Arctic [see "Ancient Magnetic Reversals: Clues to the Geodynamo," by Kenneth A. Hoffman; *SCIENTIFIC AMERICAN*, May, 1988]. Although many aspects of these phenomena remain inexplicable, the maps of the earth's magnetic field at the core-mantle boundary are evoking increasingly detailed theories of geomagnetism; the maps may also lead to a greater understanding of the magnetic fields generated by the other planets and the sun.

The first investigations of the earth's magnetic field date back to 1600, when William Gilbert published *De Magnete*. One century later, Edmund Halley crisscrossed the Atlantic Ocean in an extraordinary effort to chart magnetic declination (the angle between geographic and magnetic north). Other great explorers such as James Cook and James Ross also made detailed records of declination.

During the past two centuries workers have gradually improved the quality and quantity of measurements of the earth's field and have established geomagnetic observatories around the globe. Efforts to measure the field culminated in 1980 when the MAGSAT satellite was launched into space. The year-long project produced an abundance of high-quality data.

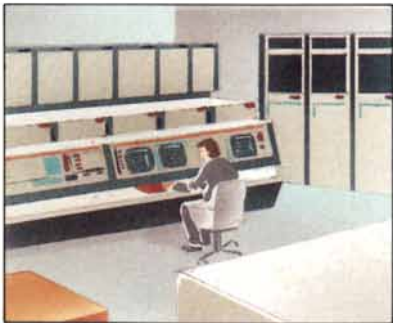




LINE OF MAGNETIC FORCE represent the field outside the core (*left*). A tangent to a field line indicates the direction of the magnetic force. The density of lines shows the

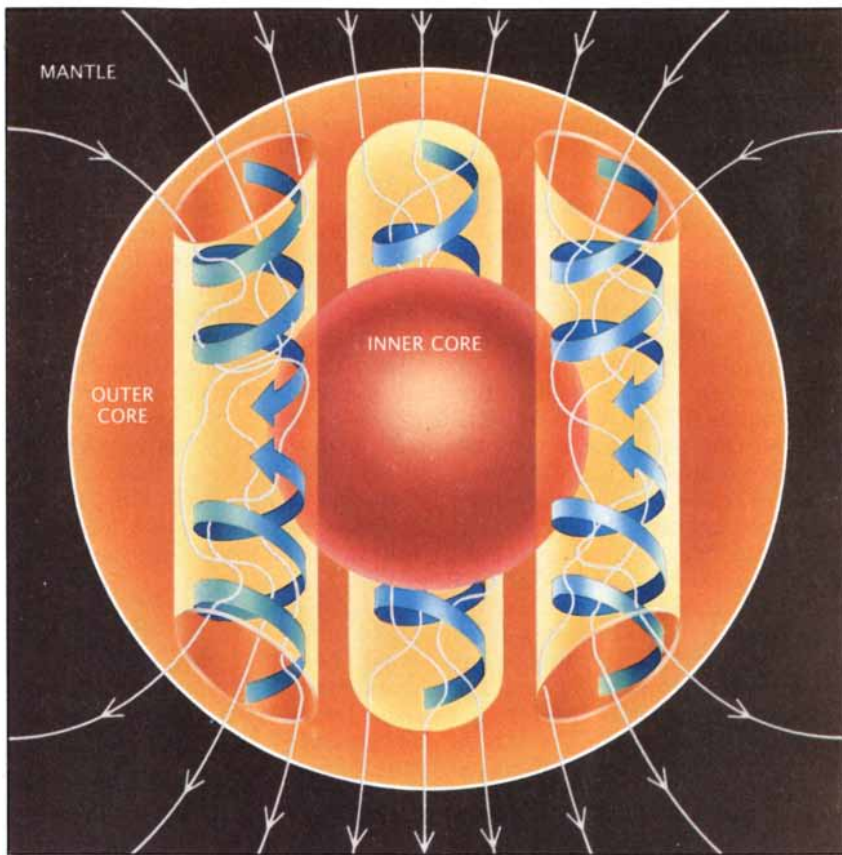
In the same year, one of us (Gubbins) began to collect and analyze records of the magnetic field from both historical and contemporary sources. Soon after, Kathy A. Whaler, Ken A. Hutcheson, Andrew Jackson and one of us (Bloxham) joined the project. David R. Barraclough of the British Geological Survey and Robert A. Langel of the National Aeronautics and Space Administration's Goddard Space Flight

Center gave invaluable advice on the data sources. The first stages of the project produced a 380-year record of the field at the earth's surface.

The maps revealed well-known characteristics and features of the surface field. The field looks similar to the field that would emerge from a giant bar magnet aligned with the earth's axis of rotation or, alternatively, from a huge loop of wire carrying current

GEOMAGNETIC JERKS YEARS	WESTWARD DRIFT HUNDREDS OF YEARS	CHANGES IN DIPOLE COMPONENT OF FIELD THOUSANDS OF YEARS
		
OBSERVATORIES	NAVIGATIONAL RECORDS	MAGNETIZED ARTIFACTS

VARIATIONS in the earth's magnetic field occur over different time scales. Each type of variation can be inferred from the sources of evidence shown at the bottom of the table. The mantle screens some electromagnetic signals that originate in



strength of the force. From maps of the magnetic field, the authors' group has deduced a possible configuration of fluid flow and magnetic field in the core (right).

around the Equator. Such a field has two poles where the strength of the field is greatest and hence is known as a dipole field.

The earth's magnetic field can be represented by lines of magnetic force. These lines trace curved paths, most of which exit near the South Pole and enter near the North Pole. A tangent to a field line indicates the direction of the magnetic force. The densi-

ty of the field lines represents the strength of the magnetic field.

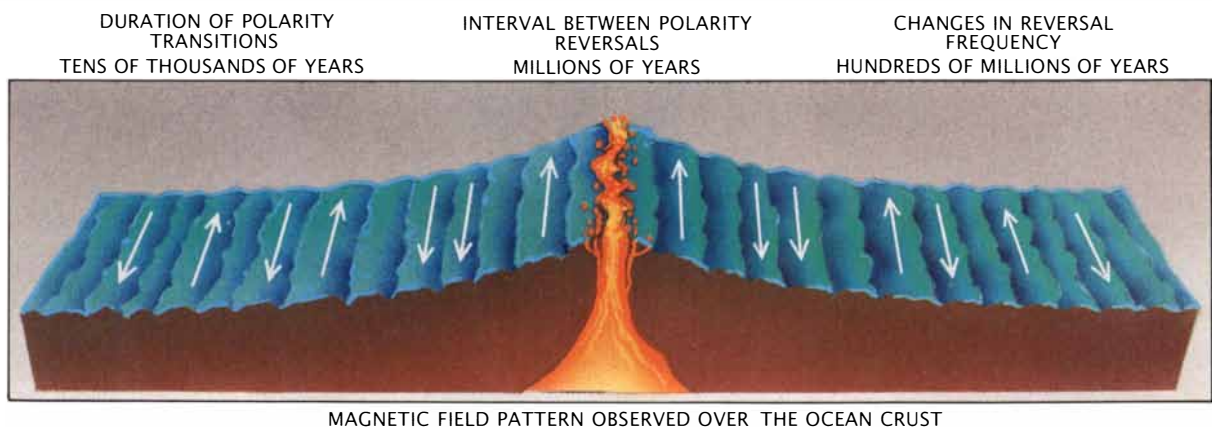
Maps that show the earth's magnetic field at the surface reveal the "secular variation," a term broadly applied to the changes in the earth's magnetic field that occur over periods of from decades to tens of thousands of years. Among the most striking changes are a decrease in the dipole component of the field and a westward drift of

part of the field pattern. The dipole component of the earth's field was considerably stronger 2,000 years ago than it is today. (Dipole decay is evident in Roman ceramic artifacts, which contain iron particles that are magnetized to a greater extent than are those in modern products.) In the next two millennia, if the present rate of decay is sustained, the dipole component of the field should reach zero. Westward drift was first observed by Halley in the Atlantic Ocean. There, the line of zero magnetic declination (the line along which the compass needle points directly at geographic north) has moved steadily westward during the course of several centuries.

To understand the origins of dipole decay and westward drift, one needs a picture of the magnetic field closer to its source, the outer core. The conducting fluid at the surface of the outer core masks the magnetic field in the interior. Yet one can deduce the magnetic field at the boundary between the core and the mantle.

Measurements of the field at the earth's surface can be projected to the core surface by applying mathematical methods devised in the early 19th century. Yet the projection has been performed reliably only in recent years. The complications did not stem from unknown physics: the crust and the mantle conduct electricity very poorly, and so for the most part they neither create nor screen magnetic fields. Instead difficulties arose because small-scale features of the field at the earth's surface, whether spurious or real, tend to blow up into large anomalies when the features are projected to the core.

Our group, in conjunction with Robert L. Parker, George E. Backus and



the outer core. Therefore, one cannot observe changes there that have a period of less than one year. During a period

of more than one year, one might measure a "geomagnetic jerk," a sudden change in the acceleration of the field pattern.

Loren Shure of the Scripps Institution of Oceanography, developed a mathematical method to find the least complicated core-surface map that could be projected from measurements at the earth's surface. In 1983 we first applied the method to the most recent observations because these presented the fewest difficulties. Since then the group has converted virtually all of the data from the past 380 years to create a series of maps of the field at the core-mantle boundary.

The maps show the number of field lines penetrating the core surface, that is, the flux going through the surface. We colored the maps with blue tints whose intensity represented the magnitude of the inward flow of field lines, or inward flux; the intensity of red tints represented the magnitude of outward flux.

If the magnetic field at the core were a simple dipole aligned with the earth's rotational axis, the map would become bluer toward the North Pole and redder toward the South Pole. Such a coloring would indicate that the most intense flux is at the geographic poles. In addition, the equator of the core surface would coincide with the boundary between red and blue shades, because the magnetic equator would coincide with the geographic equator. (The magnetic equator is the line along which the field exerts a force parallel to the surface

only. It is called a null-flux curve because no flux enters or exits through the portion of the surface marked by the curve.)

A map based on satellite measurements made in 1980 reveals that the geomagnetic field at the core surface shares some characteristics with a dipole field. The map is mostly blue in the Northern Hemisphere and mostly red in the Southern Hemisphere. Furthermore, the magnetic equator, or equatorial null-flux curve, lies close to the geographic equator.

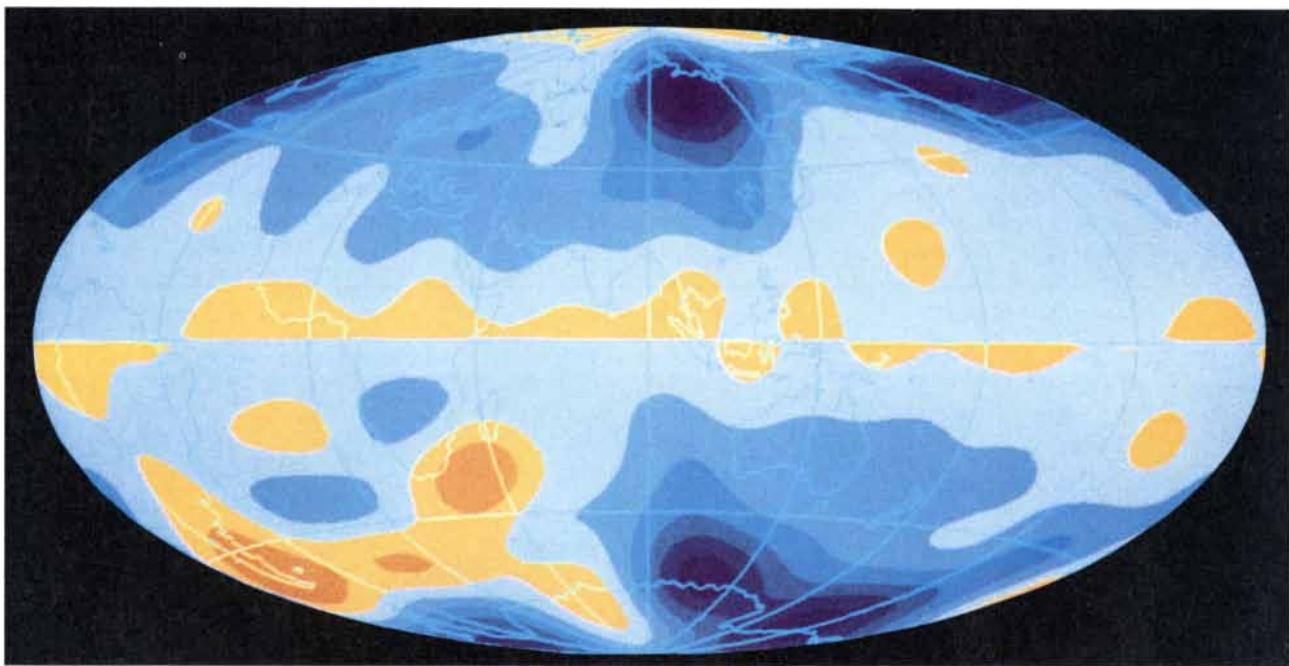
Yet the core-surface field differs from a dipole field in many respects. The 1980 map illustrates seven null-flux curves in addition to the magnetic equator. These curves appear on the map as borders between blue and red regions (boundaries between the inward and outward flux). A dark-blue patch on the map in a region below the South Atlantic Ocean indicates an intense inward flux. This patch is one example of a reverse-flux feature. The map also shows high- and low-flux features—regions where the flux is either more or less than that expected from a dipole field.

How do such observations of the core-surface field relate to observations at the earth's surface? The question is linked to three mysteries: the origin of the dipole component of the earth's magnetic field, the cause of dipole decay and the forces be-

hind secular variation (including westward drift). By exploring these questions and others, one can begin to understand how information about the core-surface field is shaping a new theory of the geodynamo.

Our group found that the greatest contribution to the dipole field comes from four patches on the core surface [see illustration below]. These patches are symmetrically displaced about the Equator. (Their centers lie at the intersection of the lines 60 degrees north, 60 degrees south, 120 degrees east and 120 degrees west.) The locations of the patches have not changed much throughout historical time, which suggests that they have a long-term role in shaping the earth's magnetic field.

The patches are near low-flux polar regions that contribute little to the dipole field. It is interesting to note that these polar regions have the same diameter as the projection of the inner core onto the surface of the outer core. This observation seems to agree with the work of Friedrich H. Busse and his colleagues at the University of California at Los Angeles. In 1973 they built a model that consisted of two spheres: one small sphere rotated inside a second, larger sphere that was filled with water. The workers found that the flow of fluid above and be-



DIPOLE COMPONENT of the field at the core surface is strongest in the regions colored in dark blue. In the Northern Hemisphere inward flux augments the dipole field; in the Southern

Hemisphere outward flux contributes to the dipole field. If the earth's field were a dipole field, the map would show areas of dark blue at the poles and would get lighter toward the Equator.

low the rotational poles of the inner sphere was weaker than the flow elsewhere. If the flow in the earth's outer core were similar to the flow in the model, one would expect the field to be weaker around the poles.

From Busse's work and our own, we inferred the general characteristics of the fluid flow inside the core. The four patches that contribute most strongly to the dipole field are, we think, the tops and bottoms of two columns of liquid. It seems likely that these columns (and perhaps a third) touch the inner core and run parallel to the earth's rotational axis [see top illustration on page 71]. We believe that fluid spirals down through the two columns and so creates a dynamo process that concentrates flux within the columns. If this theory proves true, we will be able to link the flow of fluid in the outer core directly to the field pattern at the core-mantle boundary.

Although promising, the theory is not complete. It does not explain the secular variation and in particular westward drift. During the past four decades two major explanations have been proposed. In 1950 Sir Edward C. Bullard and his colleagues at the University of Cambridge suggested that electromagnetic forces drive the core westward with respect to the crust and mantle.

The second theory, commonly at-

tributed to Raymond Hide of the United Kingdom Meteorological Office, posits that the westward drift arises from the wave motion of fluids in the core. Unlike the first theory, the wave theory could explain westward drift even if the core fluid did not rotate relative to the mantle. After all, a wave could form from the upwelling and downwelling of fluid, just as a wave can travel along a string even if the only motion is perpendicular to its length.

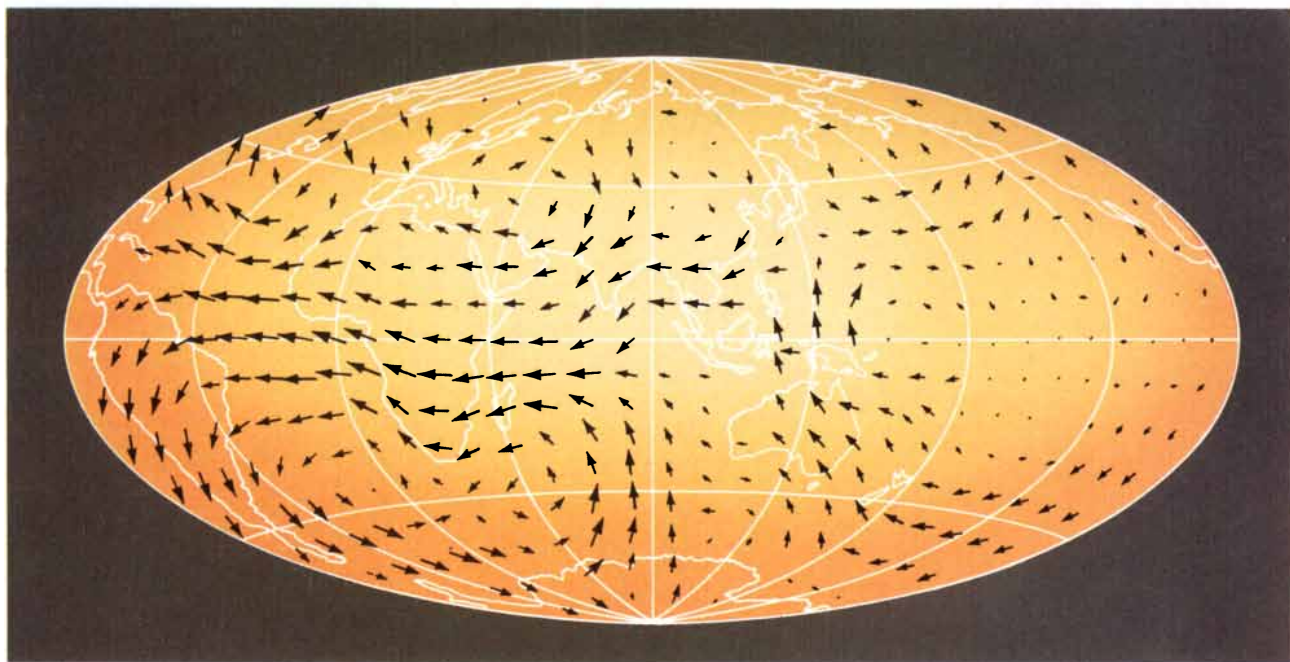
Maps of the field at the core surface seem to contradict Bullard's theory in toto and Hide's theory in part. Bullard's theory requires westward drift everywhere. Yet the historical record of the field at the core surface seems to indicate that westward drift is confined primarily to the Atlantic hemisphere (from 90 degrees west to 90 degrees east), where a few core features move west at rates of about 10 kilometers per year. Hide's theory might still be viable if an explanation can be given for why waves of iron fluid do not propagate in the Pacific hemisphere.

To understand the forces that drive westward drift and, more generally, secular variation, we tried to determine the direction of the fluid flow by tracing the movement of the magnetic field at the core surface. Magnetic field lines are "frozen" in the iron liquid of the core. As the fluid moves, the field

lines are carried along. If one could tag a field line, one could follow a parcel of fluid circulating around the surface of the core.

In our study we utilized a technique whose history extends back to 1965. Paul H. Roberts and S. Scott of the University of Newcastle upon Tyne had suggested a method to determine fluid flow directly from surface measurements of the field. Soon after, E. H. Vestine and his associates at the Rand Corporation applied the method to produce the earliest maps of fluid flow at the core surface. Roberts had realized, however, that the technique that he and Scott had proposed was ambiguous because in most cases individual magnetic field lines cannot be labeled. For example, the field lines that represent a uniform field cannot be distinguished from one another and cannot be traced from one moment to the next. Then in 1968 Backus at Scripps attempted to understand the ambiguity. He investigated the properties of curves where no flux penetrates the surface (so called null-flux curves). Backus noted that one could follow the passage of a null-flux curve over time and thereby determine fluid flow perpendicular to the curve (but not parallel to it).

Other workers have recently found additional situations that allow one to calculate fluid flow. Coerte V. Voorhies of the NASA Goddard Space Flight



FLUID at the core surface circulates rapidly in two regions: one below Europe, the other below the tip of Africa. (The arrows represent the direction and speed of the flow.) The two flows

could account for the westward drift of the magnetic field, as observed on the earth's surface. The flow pattern is consistent with the influence of the inner core and the earth's rotation.

Center showed that the flow can be determined if it remains steady over time. Jean-Louis Le Mouél and his colleagues at the Institut et Observatoire de Physique du Globe du Puy de Dôme in Clermont-Ferrand, France, have proved the flow can be found if it is driven by a balance of rotational and pressure forces. Whaler and David Lloyd at Cambridge showed the flow can be found in regions near the core surface where no upwelling or downwelling occurs. Today investigators are concentrating on combinations of all these plausible hypotheses.

We employed similar methods to determine fluid flow at the core surface. In the Atlantic hemisphere, we found two prominent circulations of fluid: one to the north of the Equator, the other to the south. Near the Equator the fluid from both the northern and southern circulations flows westward. The drift of core features to the west, which was observed in the historical record, appears therefore to be part of a great flow at the core surface.

Although the surface flow suggests the movement of the core features, it does not explain their origin. In 1958 Bullard first proposed a mechanism to explain the formation of core features [see illustration be-

low]. Bullard maintains that flux enters and exits the core as fluid circulates from deep in the core up to the core surface. In the process the upwelling fluid produces a high-flux feature and an intense reverse-flux feature—a combination known as a core spot because of its magnetic similarity to sunspots. Our maps of the field at the core-mantle boundary support Bullard's mechanism. We have investigated this mechanism further and find that it reasonably explains the formation and movement of core spots.

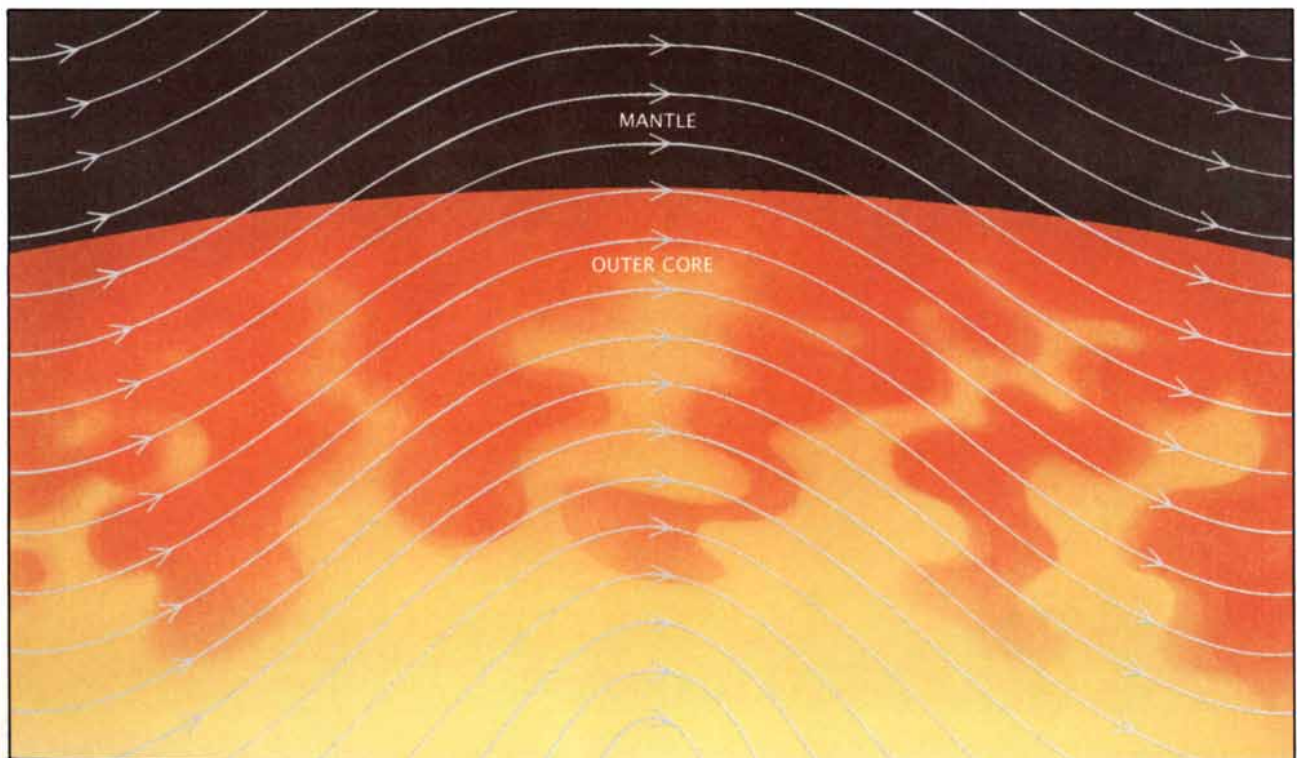
Some features of the field move and form at a rapid pace whereas others remain stationary. This phenomenon suggests some external influence. As long ago as 1967, Hide proposed that inverted mountains protruding from the mantle into the core could affect fluid flow at the core surface. Hence, the inverted mountains could influence the magnetic field in a manner similar to the way that mountains at the earth's surface affect the weather.

It is also possible that convection of heat through the mantle may cause the temperature at the core surface to vary, influencing fluid flow and the magnetic field. Adam M. Dziewonski and John H. Woodhouse of Harvard University and Robert W. Clayton and

his associates at the California Institute of Technology have mapped variations in temperature in the lower mantle. We have found some intriguing correlations between the core-field maps and the inferred lower-mantle temperature. For example, three of the four flux patches that contribute strongly to the dipole field lie under "cold zones," which suggests that the dynamo is "locked" to the mantle in some way. Core spots form below southern Africa, where the mantle is hot and might induce upwelling of core fluid. A low-flux feature in the Pacific Ocean also exists below a hot region of the mantle; possibly, slow upwelling has swept magnetic field lines away from the region. A cold ring around the Pacific Ocean may explain the lack of magnetic features there.

Evidence is mounting that the present dramatic fall in the dipole component of the field is caused by the growth and propagation of the reverse-flux features beneath Africa and the Atlantic Ocean. It seems that the present reduction in the dipole component of the field is caused by the growth of the African core spot and the southward movement of the Atlantic core spot.

The central Atlantic core spot ap-



UPWELLING FLUID crowds field lines up against the core surface. The lines associated with the upwelling fluid diffuse up and down through the boundary. The process creates an outward-flux patch (left side) and an inward-flux patch (right side).

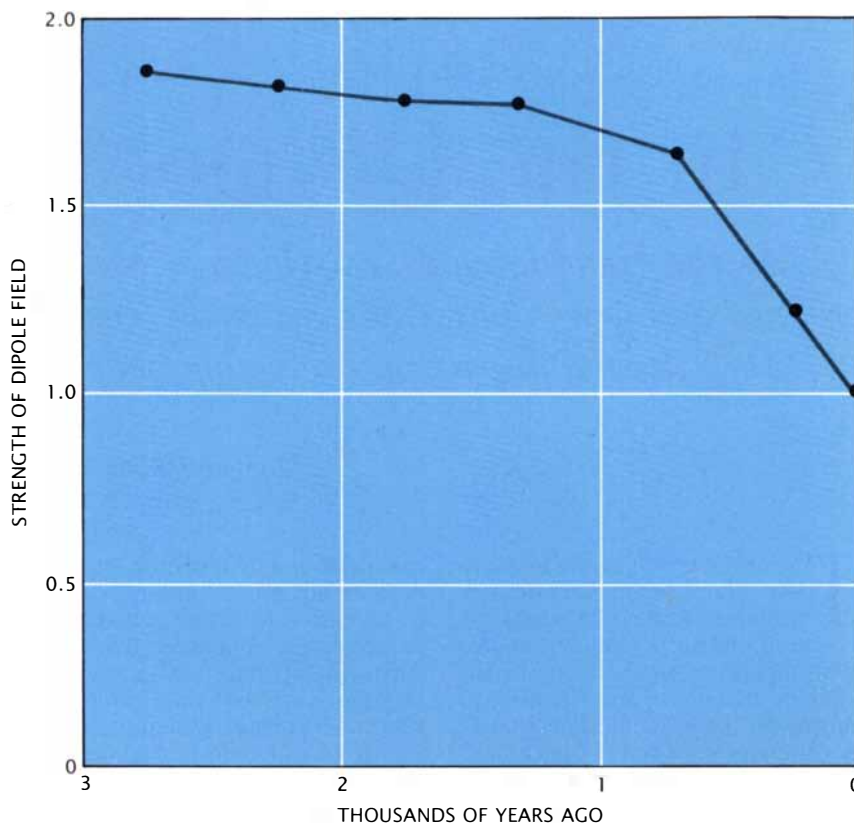
pears in our earliest core-field map, dated at 1650. Since then it has moved westward, and increasingly southward, at about .1 degree of longitude per year. The African core spot may have formed near Indonesia in the late 18th century but did not become prominent until the early 20th century. The African core spot has drifted westward rapidly, at about .3 degree of longitude per year.

The historical record is too short for a proper study of a cycle of these flux features, but we have tried to infer their movement. We suspect that core spots form near Indonesia and drift westward rapidly, at .3 degree per year. When they reach southern Africa, they intensify quickly. They then cross beneath the Atlantic Ocean at the slower rate of .1 degree per year and move increasingly southward. The present-day Atlantic core spot would then have formed 900 years ago and the African core spot some 200 years ago. This account is speculative, but it explains the long-term fall in the dipole component of the field observed in the archaeomagnetic record. As core spots move south, their reverse fluxes reduce the dipole field. If a new feature forms and drifts west, as the Atlantic and African core spots have done, the dipole component of the field will be further reduced and a complete reversal of the earth's magnetic field may occur.

Curiously, the historical record shows that reverse-flux features have formed and intensified but that none has decayed. Evidence suggests, however, that these features do decay during periods of dipole growth. During the past 10 million years the earth's magnetic field has reversed polarity once every 500,000 years or so. Yet the dipole field decays on a much shorter time scale. These facts suggest that the field does not reverse polarity after every period of dipole decay. In many cases a dipole field having the same polarity may emerge as reverse-flux features decline.

The late Allan V. Cox of Stanford University proposed a model to explain the random occurrence of reversals. He assumed that the strength of the dipole component of the field oscillates. On rare occasions, these oscillations would be so large that the polarity of the field would be reversed. We agree and add that the oscillations might originate from the movement of core spots.

Yet the formation of core spots cannot explain a puzzling aspect of field reversals. The magnetic field has reversed polarity at different inter-



DIPOLE PORTION of the earth's field has decayed rapidly over the past millennium. The graph shows the strength of the dipole component divided by its strength measured in 1980. Michael W. McElhinny and W. E. Senanyake of the Australian National University compiled the data from historical and archaeological sources.

vals during different geological periods. During the Cretaceous period 90 million years ago and the Permian period 170 million years ago, we know that no reversals occurred because the rocks that formed during those periods share the same polarity. During the past 90 million years reversals have steadily become more frequent. The core changes too rapidly to account easily for such long-term behavior. Changes in the solid mantle might be involved: they exhibit 100-million-year cycles. If the temperature increased in the deep mantle, particularly beneath southern Africa or Indonesia, the formation of the reverse-flux features could accelerate, thereby precipitating reversals.

Geophysicists are now in a position to construct more detailed theories of geomagnetism. Further study will require a continuous stream of observations. Data from the MAGSAT satellite has advanced our knowledge appreciably. Despite the tremendous success of that mission, no firm commitment has yet been made for future missions. Lack of funds also threatens to close impor-

tant magnetic observatories. Ironically, fewer observations are made today than were made 25 years ago.

We think data collection is now the overwhelming priority for the study of geomagnetism. It is essential that scientific agencies around the world maintain magnetic observatories and that they contribute to new facilities and satellite missions. It would be a shame indeed to miss the discovery of a new flux feature, the evolution of a magnetic tempest or the birth of a core spot.

FURTHER READING

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