



Probing the Geodynamo

Scientists have long wondered why the polarity of the earth's magnetic field occasionally reverses. Recent studies of our planet's churning interior are offering intriguing clues about how the next reversal may begin

BY GARY A. GLATZMAIER AND PETER OLSON

Most of us take it for granted that compasses point north.

Sailors have relied on the earth's magnetic field to navigate for thousands of years. Birds and other magnetically sensitive animals have done so for considerably longer. Strangely enough, however, the planet's magnetic poles have not always been oriented as they are today.

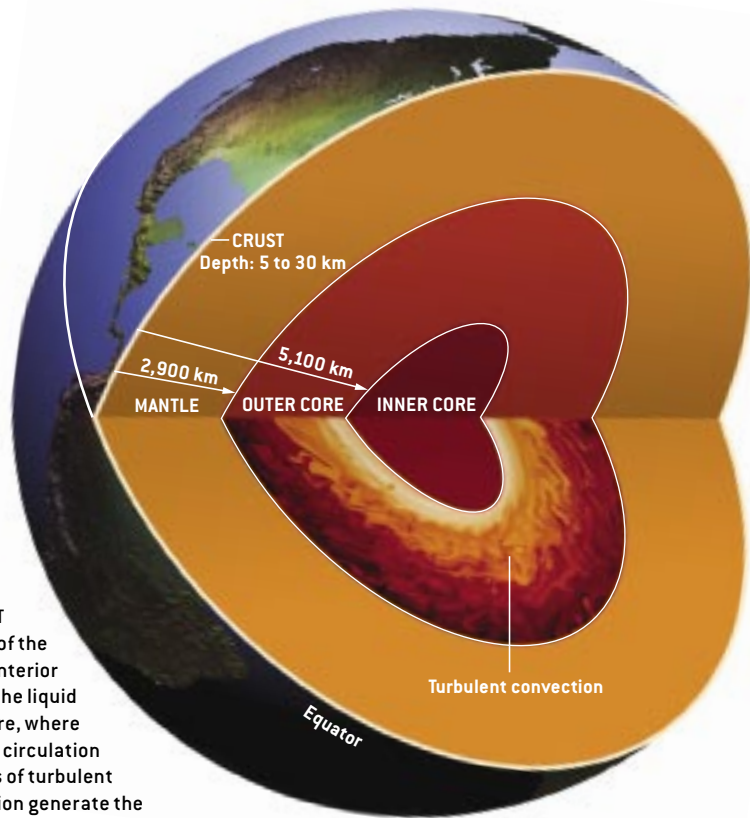
Minerals that record past orientations of the earth's magnetic field reveal that it has flipped from north to south and back again hundreds of times during the planet's 4.5-billion-year history. But a switch has not occurred for 780,000 years—considerably longer than the average time between reversals, about 250,000 years. What is more, the primary geomagnetic field has lessened by nearly 10 percent since it was first measured in the 1830s. That is about 20 times faster than the field would decline naturally were it to lose its power source. Could another reversal be on its way?

Geophysicists have long known that the source of the fluctuating magnetic field lies deep in the center of the earth. Our home planet, like several other bodies in the solar system, generates its own magnetic field through an internal dynamo. In principle, the earth's dynamo operates like the familiar electric generator, which creates electric and magnetic fields from the kinetic energy of its moving parts. In a generator, the moving parts are spinning coils of wire; in a planet or star, the motion occurs within an electrically conducting fluid. A vast sea of molten iron more than six times the volume of the moon circulates at the earth's core, constituting the so-called geodynamo.

Until recently, scientists relied primarily on simple theories to explain the geodynamo and its magnetic mysteries. In the past 10 years, however, researchers have developed new ways to explore the detailed workings of the geodynamo. Satellites are providing clear snapshots of the geomagnetic field at the earth's surface, while new strategies for simulating earthlike dynamos on supercomputers and creating physical models in the laboratory are elucidating those orbital observations. These efforts are providing an intriguing explanation for how polarity reversals occurred in the past and clues to how the next such event may begin.

GARY A. GLATZMAIER

MAGNETIC LINES OF FORCE from a computer simulation of the geodynamo illustrate how the earth's magnetic field is much simpler outside the planet than inside the core (*tangled tubes at center*). At the earth's surface, the main part of the field exits (*long yellow tubes*) near the South Pole and enters (*long blue tubes*) near the North Pole.



DISTINCT LAYERS of the earth's interior include the liquid outer core, where complex circulation patterns of turbulent convection generate the geomagnetic field.

Driving the Geodynamo

BEFORE WE EXPLORE how the magnetic field reverses, it helps to consider what drives the geodynamo. By the 1940s physicists had recognized that three basic conditions are necessary for generating any planet's magnetic field, and since then other findings have built on that knowledge. A large volume of electrically conducting fluid, the iron-rich liquid outer core of the earth, is the first of these conditions. This critical layer surrounds a solid inner core of nearly pure iron that underlies 2,900 kilometers

of solid rock that form the massive mantle and the ultrathin crust of continents and ocean floors. The overlying burden of the crust and mantle creates average pressures in the core two million times that at the planet's surface. Core temperatures are similarly extreme—about 5,000 degrees Celsius, similar to the temperature at the surface of the sun.

These extreme environmental conditions set the stage for the second requirement of planetary dynamos: a supply of energy to move the fluid. The energy driving the geodynamo is part thermal

and part chemical—both create buoyancy deep within the core. Like a pot of soup simmering on a burner, the core is hotter at the bottom than at the top. (The core's high temperatures are the result of heat that was trapped at the center of the earth during its formation.) That means the hotter, less dense iron in the lower core tends to rise upward like blobs of hot soup. When the fluid reaches the top of the core, it loses some of its heat in the overlying mantle. The liquid iron then cools, becoming denser than the surrounding medium, and sinks. This process of transferring heat from bottom to top through rising and sinking fluid is called thermal convection.

In the 1960s Stanislav Braginsky, now at the University of California at Los Angeles, suggested that heat escaping from the upper core also causes the solid inner core to grow larger, producing two extra sources of buoyancy to drive convection. As liquid iron solidifies into crystals onto the outside of the solid inner core, latent heat is released as a by-product. This heat contributes to thermal buoyancy. In addition, less dense chemical compounds, such as iron sulfide and iron oxide, are excluded from the inner core crystals and rise through the outer core, also enhancing convection.

For a self-sustaining magnetic field to materialize from a planet, a third factor is necessary: rotation. The earth's rotation, through the Coriolis effect, deflects rising fluids inside the earth's core the same way it twists ocean currents and tropical storms into the familiar spirals we see in weather satellite images. In the core, Coriolis forces deflect the upwelling fluid along corkscrewlike, or helical, paths, as though it were following the spiraling wire of a loose spring.

That the earth has an iron-rich liquid core, sufficient energy to drive convection and a Coriolis force to twist the convecting fluid are primary reasons why the geodynamo has sustained itself for billions of years. But scientists need additional evidence to answer the puzzling questions about the magnetic field that emerges—and why it would change polarity over time.

Overview/Turbulence Matters

- The geologic record reveals that the earth's primary magnetic field switches polarity every so often, and researchers have long wondered why.
- Recent computer models of fluid motion in the earth's molten core have simulated an earthlike magnetic field and associated polarity reversals. But because the fluid motion in these models is considerably simpler than the turbulent patterns thought to exist inside the earth, it is unclear how true to life these findings really are.
- Three-dimensional models capable of simulating turbulence, which are now under development, will one day resolve some of that uncertainty. In the meantime, satellite maps of the magnetic field and laboratory convection experiments are providing additional insight.

Magnetic Field Maps

A MAJOR DISCOVERY unfolded over the past five years as it became possible for scientists to compare accurate maps of the geomagnetic field taken 20 years apart. A satellite called Magsat measured the geomagnetic field above the earth's surface in 1980; a second satellite—Oersted—has been doing the same since 1999 [see illustration on page 55]. Investigators have mathematically projected these satellite measurements down to the top of the core using the assumption that the electric currents of the earth's mantle are negligible. The core-mantle boundary is the closest researchers can get to the much more intense and complicated magnetic field that exists within the core, where magnetic fluctuations actually originate; strong electric currents in the core prevent direct measurements of the magnetic field there. Despite the inherent limitations, several noteworthy observations came out of these efforts, including hints about the possible onset of a new polarity reversal.

One important finding was that most of the geomagnetic field originates at only four broad regions on the core-mantle boundary. Although the geodynamo produces a very intense magnetic field, only about 1 percent of the field's magnetic energy extends outside the core. When measured at the surface, the dominant structure of this field is called the dipole, which most of the time is roughly aligned with the earth's axis of rotation. Like a simple bar magnet, this field's primary magnetic flux is directed out from the core in the Southern Hemisphere and down toward the core in the Northern Hemisphere. (Compass needles point to the earth's north geographic pole because the dipole's south magnetic pole lies near it.) But the satellite missions revealed that the flux is not distributed evenly across the globe. Instead most of the dipole field's overall intensity originates beneath North America, Siberia and the coast of Antarctica.

Ulrich R. Christensen of the Max Planck Institute for Solar System Research in Katlenburg-Lindau, Germany, suspects that these large patches come

and go over thousands of years and stem from the ever evolving pattern of convection within the core. Might a similar phenomenon be the cause of dipole reversals? Evidence from the geologic record shows that past reversals occurred over relatively short periods, approximately 4,000 to 10,000 years. It would take the dipole nearly 100,000 years to disappear on its own if the geodynamo were to shut down. Such a quick transition implies that some kind of instability destroys the original polarity while generating the new polarity.

In the case of individual reversals, this mysterious instability is probably some kind of chaotic change in the structure of the flow that only occasionally succeeds in reversing the global dipole. But the frequency of reversals, which has been increasing steadily for the past 120 million years [see illustration on page 57], may have an external control. One possible candidate is a change in temperature at the bottom of the mantle, which could force the core to change its upwelling patterns.

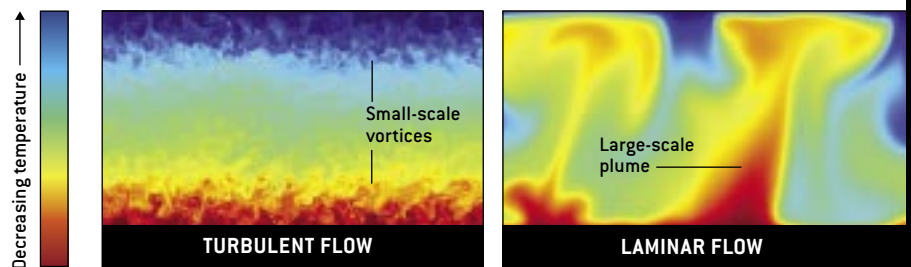
Symptoms of a possible reversal-inducing change came to light when another group analyzed the Magsat and Oersted satellite maps. Gauthier Hulot and his colleagues at the Geophysical Institute in Paris noticed that sustained variations of the geomagnetic field come from places on the core-mantle boundary where the direction of the flux is *opposite* of what is normal for that hemisphere. The largest of these so-called reversed flux patches stretches from under the southern tip of Africa westward to the southern tip of South America. In

this patch, the magnetic flux is inward, toward the core, whereas most of the flux in the Southern Hemisphere is outward.

Patch Production

ONE OF THE MOST significant conclusions that investigators drew by comparing the recent Oersted magnetic measurements with those from 1980 was that new reversed flux patches continue to form on the core-mantle boundary, under the east coast of North America and the Arctic, for example. What is more, the older patches have grown and moved slightly toward the poles. In the late 1980s David Gubbins of the University of Leeds in England—using cruder, older maps of the magnetic field—noticed that the proliferation, growth and poleward migration of these reversed flux patches account for the historical decline of the dipole.

Such observations can be explained physically by using the concept of magnetic lines of force (in actuality, the field is continuous in space). We can think of these lines of force as being “frozen” in the fluid iron core so that they tend to follow its motion, like a filament of dye swirling in a glass of water when stirred. In the earth's core, because of the Coriolis effect, eddies and vortices in the fluid twist magnetic lines of force into bundles that look somewhat like piles of spaghetti. Each twist packs more lines of force into the core, thereby increasing the energy in the magnetic field. (If this process were to go on unchecked, the magnetic field would grow stronger indefinitely. But electrical resistance tends to diffuse and smooth out the twists in the mag-



COMPLEX FLOW PATTERNS in the earth's molten outer core resemble two-dimensional computer simulations of turbulent convection (left). When running geodynamo simulations in three dimensions, however, scientists are limited to studying the larger plumes typical of laminar flow (right), which is akin to hot mineral oil rising through a lava lamp. Computers are so far incapable of resolving the much more complicated calculations associated with 3-D turbulent flow in the earth's core.

netic field lines enough to suppress runaway growth of the magnetic field without killing the dynamo.)

Patches of intense magnetic flux, both normal and reversed, form on the core-mantle boundary when eddies and

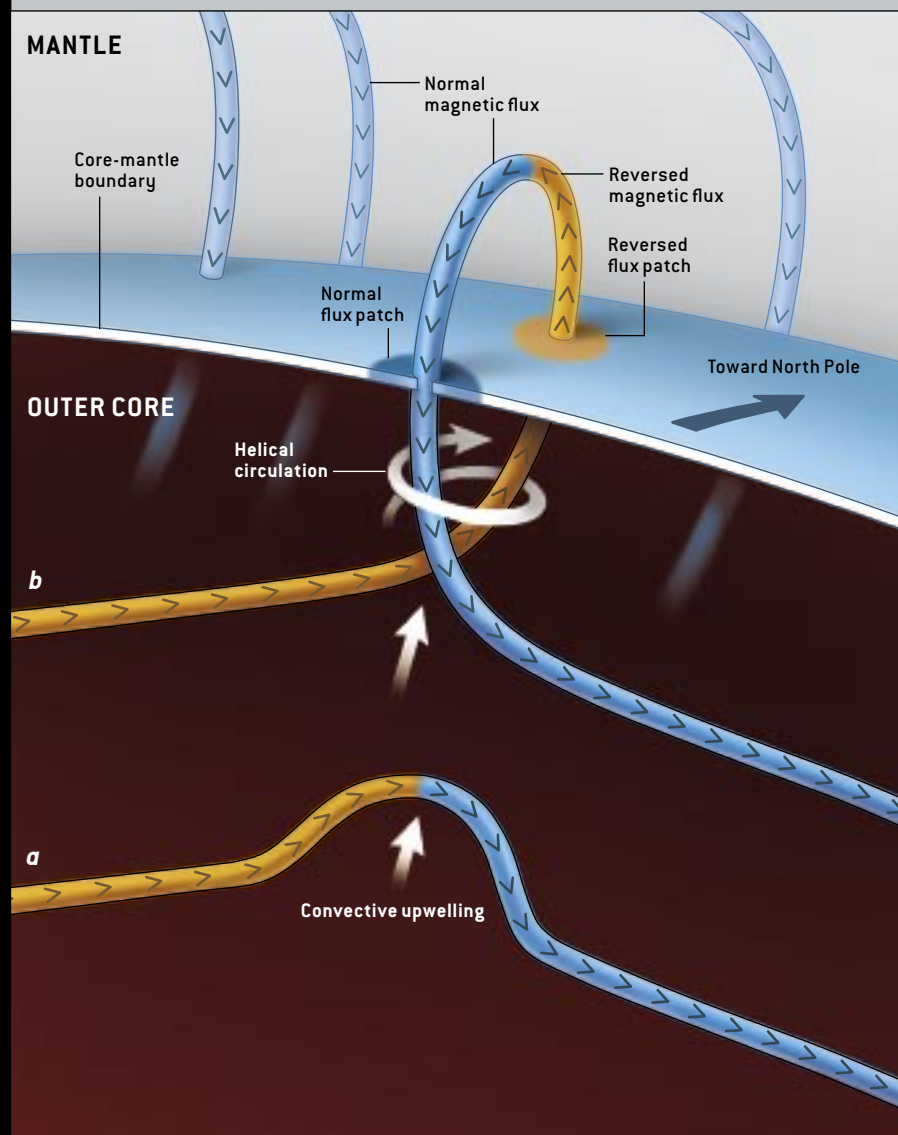
vortices interact with east-west-directed magnetic fields, described as toroidal, that are submerged within the core. These turbulent fluid motions can bend and twist the toroidal field lines into loops called poloidal fields, which have

a north-south orientation. Sometimes the bending is caused by the rising fluid in an upwelling. If the upwelling is strong enough, the top of the poloidal loop is expelled from the core [see box on this page]. This expulsion creates a pair of flux patches where the ends of the loop cross the core-mantle boundary. One of these patches has normally directed flux (in the same direction as the overall dipole field in that hemisphere); the other has the opposite, or reversed, flux.

When the twist causes the reversed flux patch to lie closer to the geographic pole than the normal flux patch, the result is a weakening of the dipole, which is most sensitive to changes near its poles. Indeed, this describes the current situation with the reversed flux patch below the southern tip of Africa. For an actual planetwide polarity reversal to occur, such a reversed flux patch would grow and engulf the entire polar region; at the same time, a similar change in overall regional magnetic polarity would take place near the other geographic pole.

REVERSED FLUX PATCHES

Regions where the direction of magnetic flux is opposite that for the rest of the hemisphere arise when twisted magnetic fields occasionally burst above the earth's core. These reversed flux patches can weaken the main part of the magnetic field at the earth's surface, called the dipole, and may even signal the onset of a global polarity reversal. Reversed flux patches originate as fluid rising through the molten outer core pushes upward on roughly horizontal magnetic field lines within the core. This convective upwelling sometimes bends a line until it bulges (a). The earth's rotation simultaneously drives helical circulation of the molten fluid that can twist the bulge into a loop (b). When the upwelling force is strong enough to expel the loop from the core, a pair of flux patches forms on the core-mantle boundary.



Supercomputer Simulations

TO FURTHER INVESTIGATE how reversed flux patches develop and how they may signal the onset of the next polarity reversal, researchers simulate the geodynamo on supercomputers and in laboratories. The modern era of computer dynamo simulations began in 1995, when three groups—Akira Kageyama of the University of Tokyo and his co-workers; Paul H. Roberts of U.C.L.A. and one of us (Glatzmaier); and Christopher A. Jones of the University of Exeter in England and his colleagues—independently developed numerical simulations that generated magnetic fields resembling the magnetic field at the earth's surface. Since then, simulations representing hundreds of thousands of years have demonstrated how convection can indeed produce patches of reversed magnetic flux on the core-mantle boundary—just like those seen in the satellite images. These patches often appear prior to a spontaneous magnetic dipole reversal, which some simulations can also reproduce.

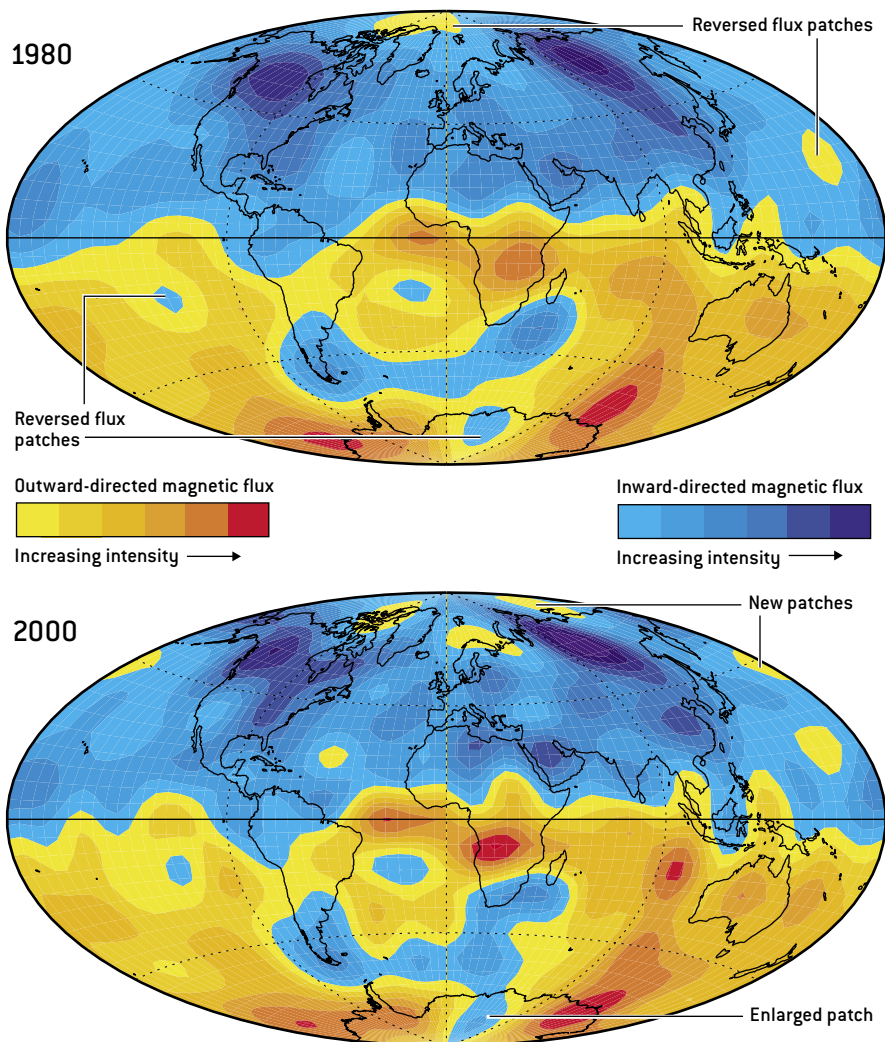
Computer-generated polarity reversals provided researchers with the first rudimentary glimpse of how such switches may originate and progress [see box on next page]. One three-dimensional simulation—which had to run for 12 hours a day every day for more than a year to simulate 300,000 years—depicted the onset of a reversal as a decrease in the intensity of the dipole field. Several patches of reversed magnetic flux, such as those now forming on the core-mantle boundary, then began to appear. But rather than extinguishing the magnetic field completely, the reversed flux patches created a weak field with a complex mix of polarities during the transition.

Viewed at the surface of the model earth, the reversal of the dipole occurred when the reversed flux patches begin to dominate the original polarity on the core-mantle boundary. In total, it took about 9,000 years for the old polarity to dissipate and for the new polarity to take hold throughout the core.

What Might Be Missing

BASED IN PART on these successes, computer dynamo models are proliferating rapidly. At last count, more than a dozen groups worldwide were using them to help understand magnetic fields that occur in objects throughout the solar system and beyond. But how well do the geodynamo models capture the dynamo as it actually exists in the earth? The truth is that no one knows for certain.

No computer dynamo model has yet simulated the broad spectrum of turbulence that exists in a planetary interior, primarily because massively parallel supercomputers are not yet fast enough to accurately simulate magnetic turbulence with realistic physical parameters in three dimensions. The smallest turbulent eddies and vortices in the earth's core that twist the magnetic field probably occur on a scale of meters to tens of meters, much less than what can be resolved with the current global geodynamo models on the current supercomputers. That means that all 3-D computer models of the geodynamo so far have



CONTOUR MAPS of the earth's magnetic field, extrapolated to the core-mantle boundary from satellite measurements, show that most of the magnetic flux is directed out from the core in the Southern Hemisphere and inward in the Northern Hemisphere. But in a few odd regions, the opposite is true. These so-called reversed flux patches proliferated and grew between 1980 and 2000; if they were to engulf both poles, a polarity reversal could ensue.

simulated the simple, large-scale flow of laminar convection, akin to the hot mineral oil rising through a lava lamp.

To approximate the effects of turbulent flow in laminar models, investiga-

tors can use unrealistically large values for certain properties of the fluid core that, in the real world, are too small to resolve numerically. To achieve realistic turbulence in a computer model, re-

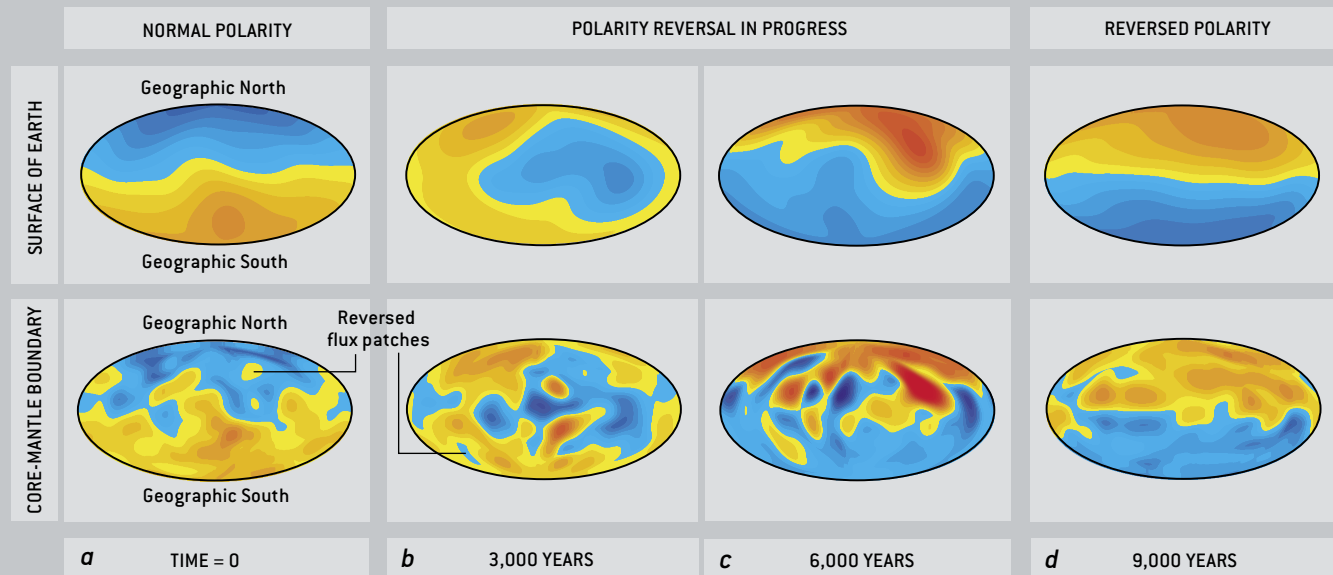
THE AUTHORS

GARY A. GLATZMAIER and **PETER OLSON** develop computer models to study the structure and dynamics of the interiors of planets and stars. In the mid-1990s Glatzmaier, then at Los Alamos National Laboratory (together with Paul H. Roberts of the University of California, Los Angeles), created the first geodynamo simulation that produced a spontaneous magnetic dipole reversal. Glatzmaier has been a professor in the department of earth sciences at the University of California, Santa Cruz, since 1998. Olson is particularly interested in how the earth's core and mantle interact to produce geomagnetic fields, plate tectonics and deep mantle plumes. He joined the department of earth and planetary sciences at Johns Hopkins University in 1978, recently completing a three-year service as departmental chair.

SIMULATED POLARITY REVERSALS

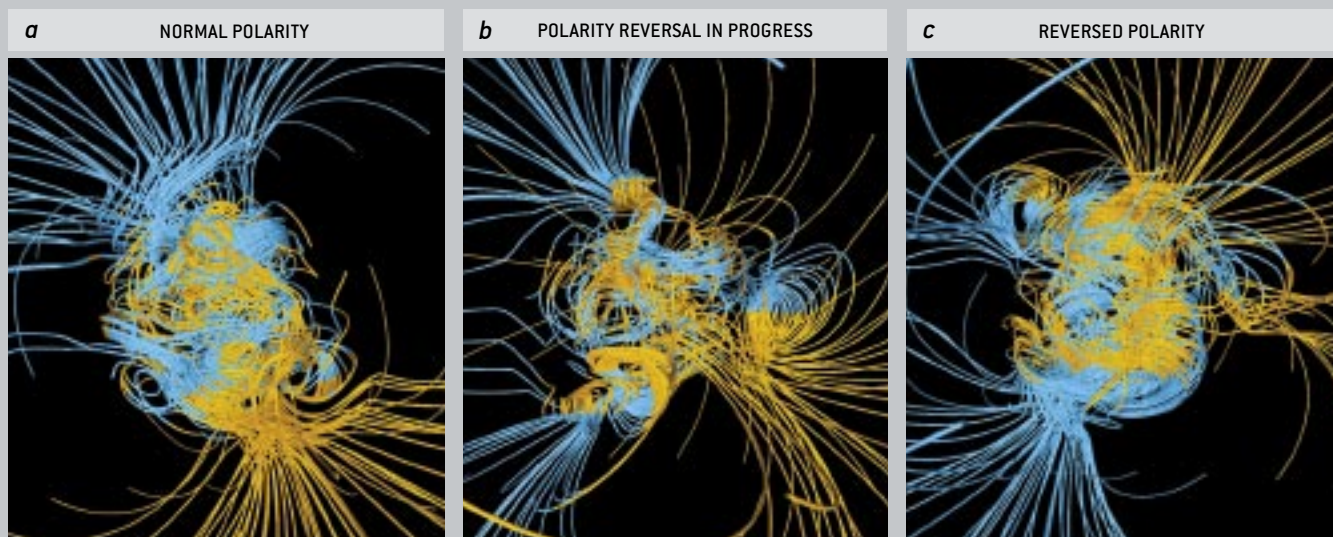
Three-dimensional computer simulations of the geodynamo are now capable of producing spontaneous reversals of the earth's magnetic dipole, offering scientists a way to study the origin of reversals preserved in the geologic record [see *timeline on opposite page*]. One simulated switch typical of a model co-

developed by one of us (Glatzmaier) occurred over a 9,000-year interval. This event is depicted as maps of the vertical part of the magnetic field at the earth's surface and at the core-mantle boundary, where the field is more complex. Models using magnetic field lines provide a third way to visualize a polarity reversal.



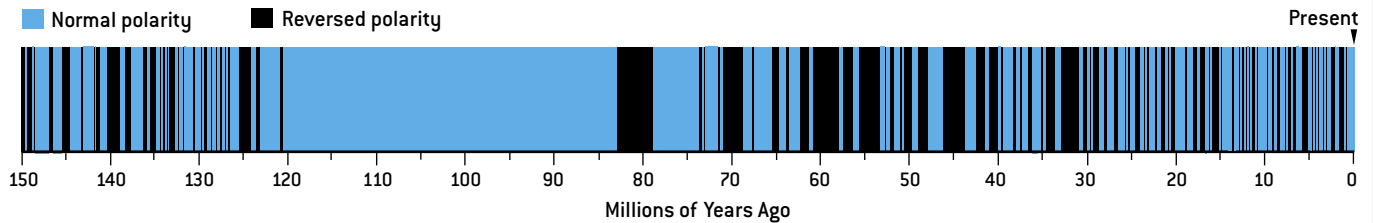
MAGNETIC FIELD MAPS start off with normal polarity, in which most of the overall magnetic flux points out from the core (yellow) in the Southern Hemisphere and in toward the core (blue) in the Northern Hemisphere (a). The onset of the reversal is marked by several areas of reversed magnetic flux (blue in the south and yellow in the north), reminiscent of the reversed flux patches now forming on the earth's core-mantle boundary. In about 3,000 years the reversed flux patches

have decreased the intensity of the dipole field until it is replaced by a weaker but complex transition field at the core-mantle boundary (b). The reversal is in full swing by 6,000 years, when the reversed flux patches begin to dominate over the original polarity on the core-mantle boundary (c). If viewed only at the surface, the reversal appears complete by this time. But it takes an additional 3,000 years for the dipole to fully reverse throughout the core (d).



MODEL illustrates the magnetic field within the core (tangled lines at center) and the emerging dipole (long curved lines) 500 years before

the middle of a magnetic dipole reversal (a), at the middle (b), and 500 years after that, when the reversal is nearly complete (c).



searchers must resort to a two-dimensional view. The trade-off is that 2-D flow cannot sustain a dynamo. These models do, however, suggest that the laminar flows seen in current geodynamo simulations are much smoother and simpler than the turbulent flows that most likely exist in the earth's core.

Probably the most significant difference is in the paths the fluid follows as it rises through the core. In simple laminar convection simulations, large plumes stretch all the way from the bottom of the core to the top. In the turbulent 2-D models, on the other hand, convection is marked by multiple small-scale plumes and vortices that detach near the upper and lower boundaries of the core and then interact within the main convection zone in-between.

Such differences in the patterns of fluid flow could have a huge influence on the structure of the earth's magnetic field and the time it takes various changes to occur. That is why investigators are diligently pursuing the next generation of 3-D models. Someday, maybe a decade from now, advances in computer processing speeds will make it possible to produce strongly turbulent dynamo simulations. Until then, we hope to learn more from laboratory dynamo experiments now under way.

Laboratory Dynamos

A GOOD WAY to improve understanding of the geodynamo would be to compare computer dynamos (which lack turbulence) with laboratory dynamos (which lack convection). Scientists had first demonstrated the feasibility of lab-scale dynamos in the 1960s, but the road to success was long. The vast difference in size between a laboratory apparatus and the actual core of a planet was a vital factor. A self-sustaining fluid dynamo requires that a certain dimen-

POLARITY REVERSALS have occurred hundreds of times at differing frequencies in the past 150 million years and probably long before that as well. Scientists discovered these reversals by studying magnetic minerals, which line up with the earth's magnetic field when a rock is heated. The minerals then retain the orientation of the field at the time the rock cools.

sionless parameter, called the magnetic Reynolds number, exceed a minimum numerical value, roughly 10.

The earth's core has a large magnetic Reynolds number, probably around 1,000, primarily because it has a large linear dimension (the radius of the core is about 3,485 kilometers). Simply put, it is exceedingly difficult to create a large magnetic Reynolds number in small volumes of fluid unless you can move the fluid at extremely high velocities.

The decades-old dream of generating a spontaneous magnetic field in a laboratory fluid dynamo was first realized in 2000, when two groups in Europe—one led by Agris Gailitis of the University of Latvia and one by Robert Stieglitz and Ulrich Müller of the Karlsruhe Research Center and Fritz Busse of the University of Bayreuth, both in Germany—indepen- dently achieved self-generation in large volumes of liquid sodium. (Liquid sodium was used because of its high electrical conductivity and low melting point.) Both groups found ways to achieve high-speed fluid flow in a system of one- to two-meter-long helical pipes, resulting in the critical magnetic Reynolds number of about 10.

These experimental results bear out theory, which gives us a measure of confidence when we apply our theoretic-

cal ideas about dynamos to the earth and other planets. Now many groups across the world are busy developing the next generation of lab dynamos. To better simulate earthlike geometry, these experiments will stir the liquid sodium inside massive spherical chambers—the largest nearly three meters in diameter.

Besides the ongoing plans for more realistic laboratory dynamos and 3-D computer simulations, the international satellite CHAMP (short for Challenging Minisatellite Payload) is charting the geomagnetic field with enough precision to directly measure its changes at the core-mantle boundary in real time. Investigators anticipate this satellite will provide a continuous image of the geomagnetic field over its five-year mission, allowing them to watch for continued growth of the reversed flux patches as well as other clues about how the dipole field is waning.

We anticipate that a synthesis of these three approaches—satellite observations, computer simulations and laboratory experiments—will occur in the next decade or two. With a more complete picture of the extraordinary geodynamo, we will learn whether our current ideas about the magnetic field and its reversals are on the right track. SA

MORE TO EXPLORE

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