Q&A

EARTH SCIENCE

Geomagnetic reversals

David Gubbins

Earth's magnetic field is unstable. Not only does it vary in intensity, but from time to time it flips, with the poles reversing sign. Much of this behaviour remains a mystery, but a combination of geomagnetic observations with theoretical studies has been providing enlightenment.

Has Earth always had a magnetic field?

Yes — or at least for a very long time. There are magnetized rocks of all geological ages, going back some 3 billion years. It also seems that the field has always been dipolar, with a north and a south pole (Fig. 1), except during reversal of the poles.

How is the field generated?

It is continually maintained by a dynamo acting in the liquid-iron outer core. It works in the same way as a car alternator. The liquid iron moves at speeds of about one millimetre per second, and when it cuts magnetic field lines it generates a voltage that reinforces the original magnetic field. The fluid motion is driven by buoyancy forces arising from density gradients caused by slow cooling of the whole Earth. The core solidifies from the centre outwards, with the lighter elements in the liquid separating and rising to help thermal currents drive convection. The solid inner core has grown to its present size over the past billion years or so. Earth's rotation affects the style of fluid motion, for example by aligning structures along the spin axis, but does not actually drive it.

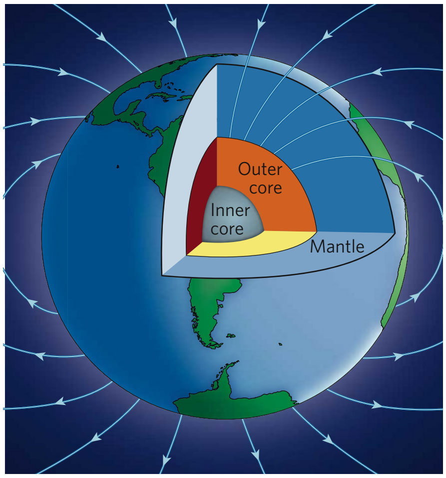

Figure 1 | Earth's magnetic field. The field looks like that of a bar magnet aligned with Earth's geographical axis, a so-called dipole structure. The non-dipole part of the field is significant, however, and accounts for why the compass rarely points exactly to true north. The field is generated in Earth's liquid outer core, some 3,000 kilometres below us; the rocky solid mantle is a fairly good electrical insulator and most of it is too hot to be magnetized, so it does not affect the field much.

What forms does the field take?

At Earth's surface the magnetic field closely resembles that of a bar magnet placed at Earth's centre and aligned approximately with the geographical axis. The geomagnetic poles are where the axis of this hypothetical bar magnet cuts Earth's surface (at present, the north magnetic pole is in the Canadian Arctic). When a measurement is available only from a single site, as is usually the case with palaeomagnetic data, a virtual geomagnetic pole (VGP) is determined by assuming a dipole form. The VGP can be a good approximation to the geomagnetic pole if the non-dipole field is small, but not during a polarity reversal. When surface observations are projected down to the core surface a more complicated structure appears (Fig. 2): the field still has the same average dipole structure and the geomagnetic poles are in the same place, but the non-dipole parts are now so strong that there are many places where the magnetic field is vertical ('dip poles'). The vertical field is strongest, not at the geomagnetic poles, but in two areas some 20° away from the geographical pole, the deep blue patches in Figure 2.

How do we know that Earth's polarity has flipped?

Rocks are magnetized and retain the direction of the magnetic field at the time of their formation. A good lava-flow sequence or sediment column can preserve the record of many reversals over a long period of time. There is also the evidence from magnetic stripes on the ocean floor.

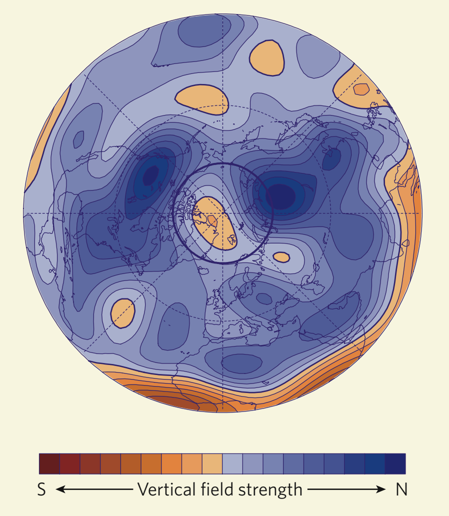

Figure 2 | Magnetic field at the surface of Earth's core. Only the Northern Hemisphere is shown in this projection of the surface of the outer core. The central circle denotes the position of the solid inner core. The magnetic field is stronger at this depth, 3,000 km below the surface, and the non-dipole part is more evident. Most surprisingly, the magnetic field is strongest (deepest blue) not over the North Pole, as one would expect from a dipole field, but in two blobs outside the central circle. The field within the circle is nearly zero (blue/orange boundary). This is the effect of the tangent cylinder, an imaginary cylinder around the inner core aligned with the geographical axis, that creates different dynamics in the polar regions. Mapping the field at the core surface was made possible by satellite data, and the discovery of a weak field over the poles marked the first real connection between observation and the dynamo theory.

How were these magnetic stripes produced?

Oceanic crust forms at ridges where two tectonic plates move apart. As the crust forms, it becomes magnetized by the magnetic field, leaving linear segments of new crust on each side of the ridge. When the magnetic field reverses, the new strip of crust is formed magnetized in the opposite direction, and this can be detected by a magnetometer towed behind a ship. When the magnetic anomalies are plotted they form a pattern of stripes; the rocks in any one stripe have the same mean age, which is how we know the age of the ocean floors so

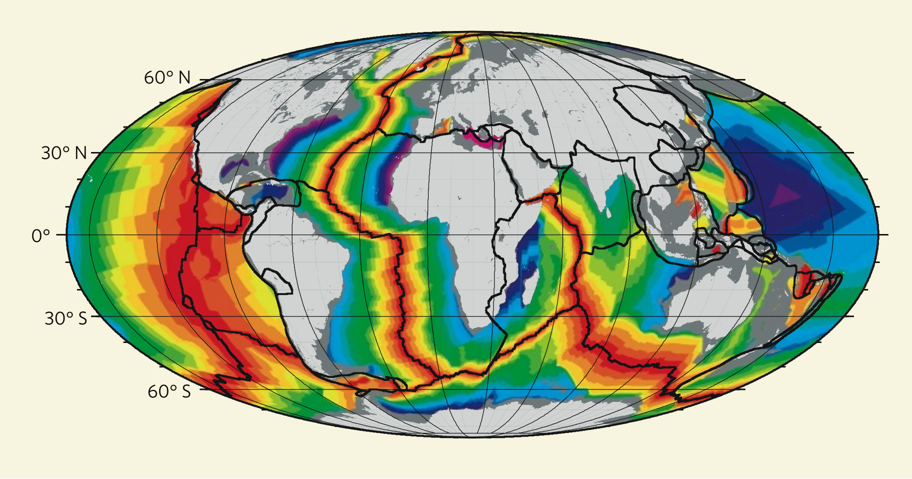

Figure 3 | Magnetic stripes on the ocean floor. The identification of these stripes meant that the corresponding rocks on the ocean floor could be dated rather precisely against the reversal timescale (see Fig. 4). The youngest floor (red) is close to the mid-ocean ridges where oceanic crust is formed, and the oldest (blue) is at the Atlantic coast and in the southwest Pacific. (Courtesy of R. D. Müller. See R. D. Müller *et al. Geochem. Geophys. Geosyst.* doi:10.1029/2007GC001743; 2008.)

well (Fig. 3). There are no stripes in the older parts of the Pacific Ocean, or at the edges of the Atlantic, because this crust was extruded at a time when there were no reversals.

Why does the magnetic field reverse?

Because it can: the forces involved and magnetic induction are the same regardless of the sign of the magnetic field. As the magnetic field varies all the time, it is a matter of chance whether a fall in the field ends up with it regrowing with the same or the opposite polarity. This suggests that a reversal is not just a flipping of the poles: on average, even the non-dipole parts must reverse.

And how does it reverse?

The basic dipole is not preserved during the reversal. Many observations suggest that the VGPs move around the rim of the Pacific, following one of two preferred longitudes, depending on the measurement site. If correct, this would imply that a magnetic field remains concentrated around the Pacific rim during the reversal (see below).

How long does the reversal take?

The magnetic field becomes progressively weaker, typically for several thousand years, before the direction changes, usually in a much shorter time. The reversed field then grows in strength over another few thousand years.

How frequent are reversals?

Recently (in geological terms), once every 300,000 years, on average (Fig. 4). The last time was 780,000 years ago, however, so we are somewhat overdue for another one. Since then, the polarity has started to change but flipped back straight away, in what is called an excursion, or aborted reversal. The field has done this at least ten times since the last full reversal.

Is there any pattern to the reversal timescale?

Much work has been done on the statistics of this timescale, with no convincing conclusion other than that it is random.

Has the magnetic field always reversed irregularly like this?

No, there are very long intervals of time, called superchrons, when there were no reversals. The last one, the Cretaceous normal superchron, was from about 124 million to 80 million years ago. There was probably an earlier one, the Kiaman, around 300 million years ago, which is much less well documented because there is no ocean floor of that age.

Why did reversals stop during superchrons?

Everyone is agreed that the timescale is too long for superchrons to be the consequence of a natural core process — the outer core turns over every 1,000 years and it is very unlikely to have changed of its own accord in the past 100 million years. It is probably an effect of the changing solid mantle. The dynamo is driven by cooling from the top of the outer core, and this cooling is controlled by plate tectonics and mantle convection, so a change in the cooling regime could spark a change in the behaviour of the dynamo. Either some dramatic event occurred that changed the rate at which the core lost heat, with the assumption that a dynamo will reverse only if driven hard; or the pattern of cooling on the core surface altered to change the nature of the fluid flow. The second option is more appealing to me, if less dramatic, because it is an inevitable consequence of mantle evolution.

Are the reversed and normal magnetic fields exactly the same?

Probably. This has been the subject of extensive studies of the data, and there are some claims of a difference. But it is most likely that the entire field reverses each time. Complete reversal is the only type allowed by theory; any normal–reversed differences are because the reversal is incomplete. How long complete reversal takes is again a subject of research, but theory suggests no longer than a few tens of thousands of years

Why do some reversals go through and others do not?

If the geomagnetic field is greatly disrupted it will grow again in either direction with equal probability. The field can reverse in the outer core by fluid motion moving the electric currents around, which takes only about 500 years. In the solid inner core things are different. In a solid the electric currents, and therefore the magnetic fields, can only change because of electrical resistance — a process that takes much longer, about 5,000 years, than induction by a moving conductor as in the liquid part of the core. The inner core may therefore impart some stability, or longer memory of the previous state. The field could remain reversed in the outer core for 5,000 years and still have a persistent normal direction in the inner core, encouraging the field to return to normal. This may be why there are many excursions between full reversals: nine times out of ten, the persistent inner-core field could

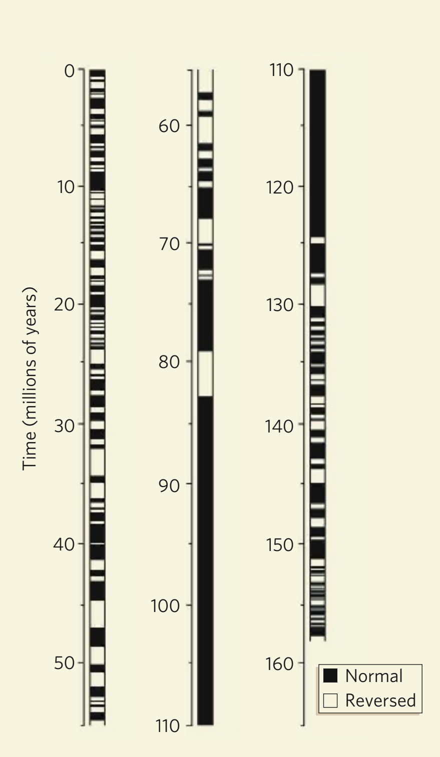

Figure 4 | Reversal timescale. Note the long black interval when the polarity was normal and there were no reversals, the so-called Cretaceous normal superchron (CNS). It may also be possible to discern an increase in the frequency of reversals since 80 million years ago, when the CNS ceased. (Revised from W. Lowrie *Fundamentals of Geophysics*; Cambridge Univ. Press, 1997.)

force the dynamo field back to its original polarity (Fig. 5).

Is there a connection between reversal behaviour and plate tectonics?

Possibly. Cooling drives the dynamo, and mantle convection means the heat lost from the core will vary from place to place. In particular, it seems that persistent subduction of tectonic plates around the Pacific for the past 150 million years has cooled off the whole of the lower mantle in a ring beneath the rim of the Pacific, and far more heat is drawn from the core in this location than elsewhere. When we use seismological data to set a boundary condition in numerical simulations of the geodynamo, we get downwelling of fluid in the outer core and concentration of magnetic flux beneath the cold regions. The magnetic-field concentrations coincide with those of the present-day field, as shown in Figure 6. This concentration of magnetic field can also explain why in some reversals the poles tend to follow the Pacific rim.

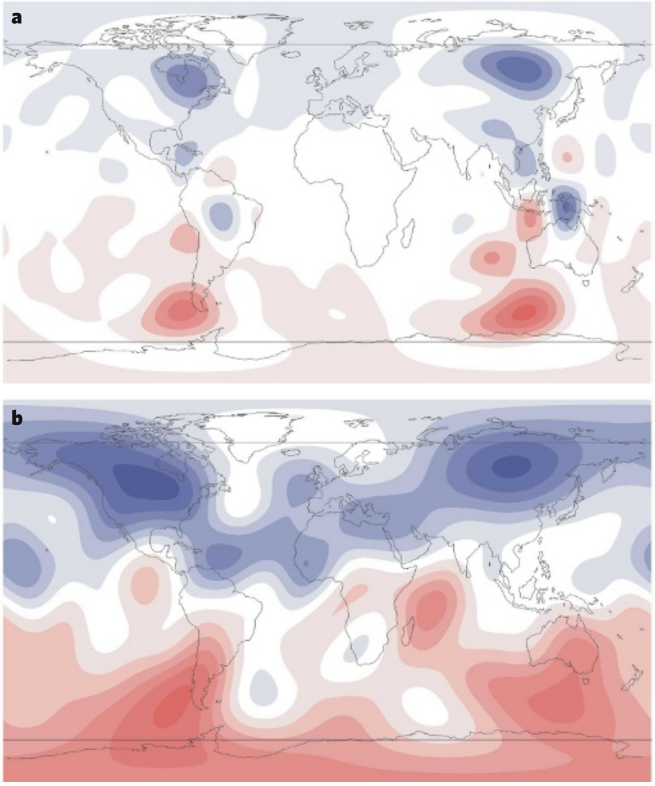

Figure 6 | Computer models of Earth's dynamo. a, The magnetic field generated by a dynamo model in which heat flow from the core surface matches that estimated from temperature in the solid mantle immediately above it. The four locations of strongest field lie very close to the corresponding locations in the modern Earth's magnetic field, shown in **b**. Cold mantle around the Pacific rim induces downwelling in the core, and this concentrates magnetic field lines. Generation is strongest around the tangent cylinder (Fig. 2), which explains the displacement of these lobes away from the geographical poles. (Reproduced from D. Gubbins *et al.*, 2007; see further reading.)

Are computer simulations of the dynamo informative?

Early attempts to understand the dynamo action of a liquid conductor were largely unsuccessful because only complicated fluid flows can produce the required regeneration of the magnetic field. It is now possible to model the magnetic-induction effects by supercomputer, but not the turbulence of flow in Earth's outer core nor Earth's rapid spin rate. Perhaps surprisingly, computer models using greatly simplified assumptions do reproduce aspects of the geomagnetic field such as the dipole, somewhat unrealistic reversals, and parts of the present non-dipole field (Fig. 6). Some theoreticians think the next generation of supercomputers will be powerful enough to answer some of the remaining questions.

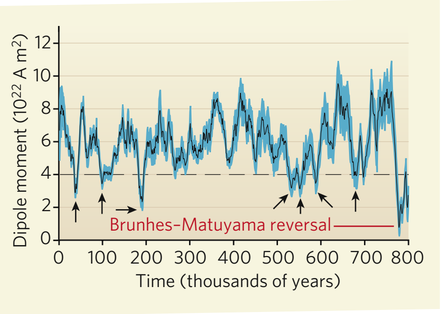

Figure 5 | Excursions. Compilation of records of magnetic intensity (dipole moment) for the past 800,000 years; the present value is about 8 on this scale. The last reversal, between the present Brunhes chron and previous reversed Matuyama chron, is marked by a dramatic low in intensity 780,000 years ago. Excursions, indicated with arrows and as measured by quite different data indicating the wayward direction of the magnetic field, occur when the field strength falls below about 4 (dotted line). These data showed, for the first time, the highly erratic behaviour of Earth's magnetic field even during times of stable polarity. (Redrawn from Y. Guyodo and J.-P. Valet *Nature* 399, 249–252; 1999.)

And laboratory experiments?

There are ambitious attempts to study dynamo action in the lab using large containers of liquid metal — sodium, gallium and mercury have all been used. Experiments can reach higher spin rates than computers, but the problem is the great size required to produce a large enough induction to regenerate a magnetic field: the inductive effect depends on the product of the electrical conductivity, size and fluid-flow speed. Reducing the size from the radius of Earth's core to lab scale means the fluid must flow fast to compensate. We are likely to learn a great deal about the nature of fluid flow and turbulence from experiments, but not so much about the dynamo action.

Is it true that we're heading for another reversal?

It could be. The dipole has been weakening by about 5% per century since at least 1850, and archaeological artefacts show it to have been much stronger in Rome 2,000 years ago. The present fall is associated with activity in Earth's core beneath the South Atlantic and Indian oceans, where the field is reversing locally in a process similar to that in sunspots during the Sun's 11-year cycle of magnetic reversal. This could be the start of a reversal, but we have not yet reached the point of no return. If the dipole does fail, it is more likely to be an excursion than a full reversal, because many such dramatic falls have occurred in the past without a full reversal (Fig. 5).

Should we be worried about a reversal?

A weaker magnetic field means more cosmic radiation reaching Earth's surface because of the lessened shielding effect of the magnetosphere — the local region of space dominated by the field. We can also expect more auroral activity. In the past, species that use the magnetic field for navigation have become extinct during reversals (but mostly single-cell organisms that presumably use the magnetic field to tell up from down). Increased atmospheric geomagnetic activity means more disruption to electronic communication and power distribution, but we know little about the way in which the magnetosphere would react to a different geomagnetic field. Whether a reversal would present a health risk to humans is less clear: even a weak field may have a shielding effect. The human race has survived many excursions and a few reversals already: so we are likely to come through the next one unscathed. ■

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