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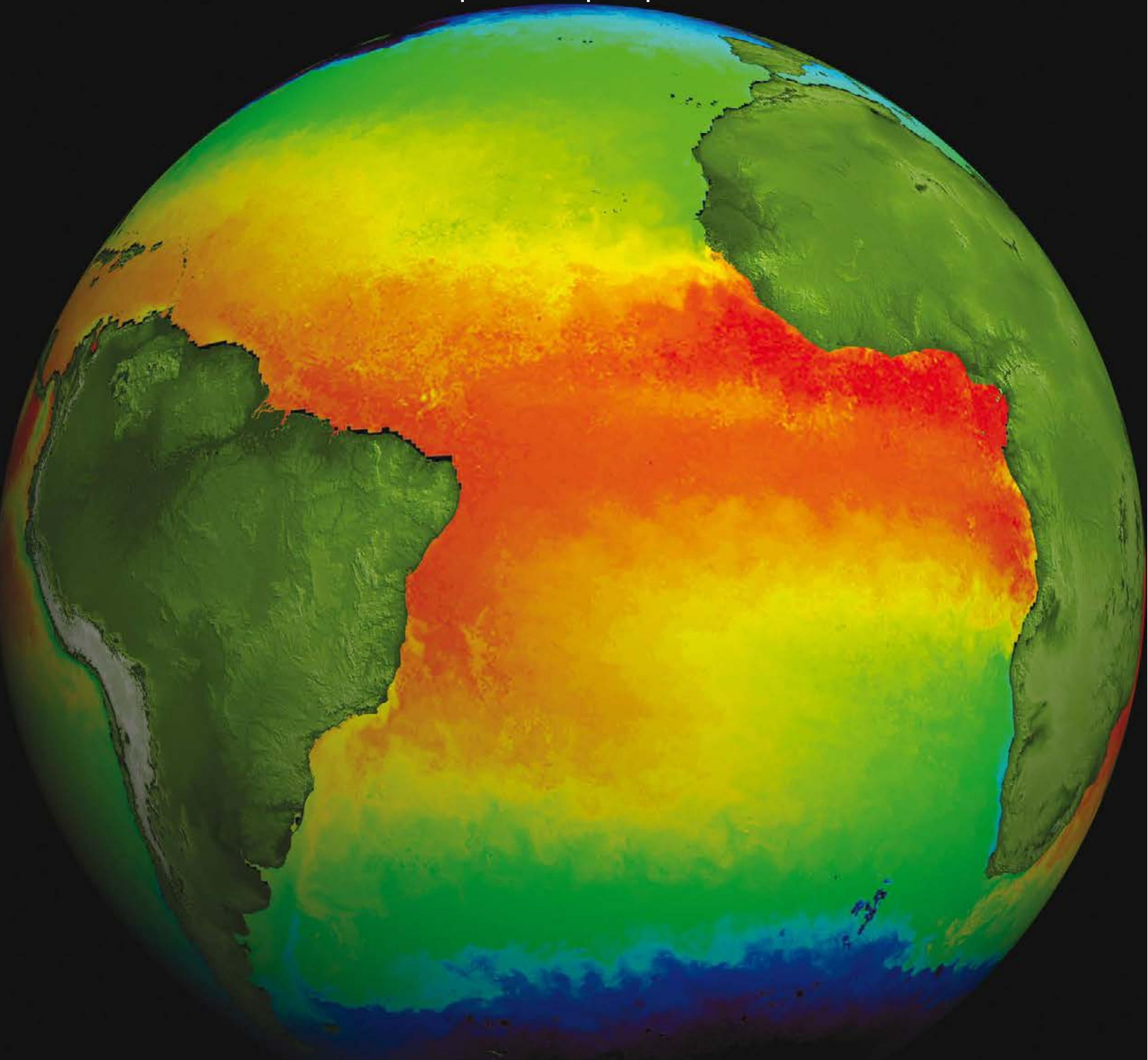
PHYSICS AND THE EARTH

Our planet in perspective



When north heads south

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The polarity of the Earth's magnetic field appears to have flipped randomly throughout history, with visual representations of these changes looking like product barcodes. But **François Pétrélis**, **Jean-Pierre Valet** and **Jean Besse** have a new insight that could explain a pattern in the rate of reversals

The Earth's magnetic field is becoming weaker. It has deteriorated by 10–15% over the last 150 years at a rate that has recently been speeding up. Doomsday enthusiasts, who believe some earthshattering event will destroy humankind in December this year, cite this weakening field as one of the possible apocalypse scenarios. They think that the poles might reverse, resulting in devastation across the world, possibly from a lack of shielding from cosmic rays.

However, there are many things wrong with this picture. First, a reversal takes several thousand years, not just one. Second, in a reversal the magnetic field does not disappear, because many poles form chaotically and so even though a compass would be useless, a magnetic field still exists. And third, a weakening field is not a sign of an impending reversal anyway – it is normal for the field strength to fluctuate in-between reversals.

But although there is a lot we do know about geomagnetic reversal – we are pretty sure we know how the field is generated and how it is able to change polarity – mystery still surrounds whether reversals are spontaneous or whether they are caused by some external trigger. Another enigma is that the reversal rate changes over time. During one 12-million-year period centred on 15 million years ago, for example, there were a staggering 51 reversals, while one 40-million-year period centred on 100 million years ago saw none.

The exact reason why such periods of reversal activity are so different is still unclear. But we have discovered one possible explanation that could hold the key. To build up a picture of what we speculate and why, we must first start with the basics – how the Earth's magnetic field is generated, and how it reverses.

Molten-metal magnet

Beneath the Earth's crust, the interior of the planet can be roughly described by three concentric layers (see figure on p39). The mantle, which lies between the crust and 2890 km deep, is pretty solid, but if you wait long enough, it acts as a slowly moving material. The mantle

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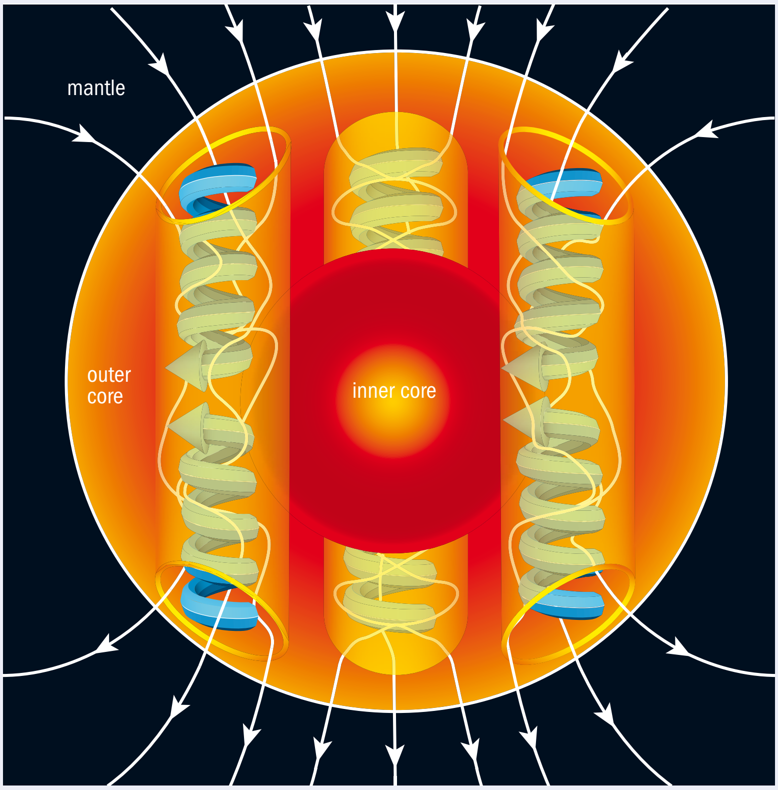
1 At the core of the matter



The Earth's magnetic field is produced by the movement of liquid metal in the Earth's outer core. Energy to power this movement comes from heat that is released as material from the outer core slowly freezes onto the solid inner core. This heat powers convection cells in the outer core, which keep liquid metal moving through the magnetic field, thus creating a bigger field in a feedback effect known as the geodynamo. The Earth's spinning motion causes the liquid to form spiralling eddies, the alignment of which allows the magnetic field produced in each to join together to make an even bigger field.

is also an insulator, which is great for allowing us to scrutinize the field pattern at the surface of the next layer down, the outer core. (For insulators, the magnetic field equation is simple, and so knowing the field at the mantle's surface lets you calculate what lies below.) The outer core is mostly molten iron and a few lighter elements, and lies 2890–5150 km below the surface. At these depths, where the temperature reaches 4000 K, this outer-core layer is a fluid and it moves rapidly (about a few kilometres per year). Finally, at the centre of the Earth is a solid-iron sphere, the inner core, which has a radius of 1228 km.

Scientists and engineers have discovered several ways to generate electric current and magnetic field from the mechanical energy of a moving electrically conducting solid. One way to do this is to use the "dynamo effect", in which a seed magnetic field is amplified by an instability to produce a larger field, and it is this phenomenon that also drives the magnetic field of the Earth. The liquid metal that makes up the outer core, which moves in convection cells powered by heat, passes through a small seed magnetic field, which induces an electric current to flow within it. This creates another magnetic field that is stronger than the pre-existing field and reinforces it. In turn, more current flows and the field increases, in a self-sustaining loop called the geodynamo. How the flow in the liquid core is organized is not clearly known but the Coriolis force is also expected to play a part. A common model is that the Earth's rotation causes the liquid metal of the outer core to form spiralling eddies aligned north–south, allowing the magnetic field generated by separate cells to join up (figure 1).

On the Earth's surface, the magnetic field appears very much like the dipole field that would be generated if a huge magnet existed inside the Earth, aligned along its axis of rotation. This is not exactly the case because the axis of the dipole is actually inclined by about 11° with respect to the rotation axis, which is why the poles of the dipole differ from the geographic poles. (When averaged over a few thousand years, however, the dipole axis is aligned along the rotation axis so that the geographic and the magnetic poles are at the same locations.) The reason for this discrepancy is that the magnetic field is not a perfect dipole aligned with the axis of rotation of the Earth, but has extra components that collectively cause the pole to wander. These extra components are responsible for the "secular variation" – changes in the strength and location of the field on a timescale on the order of 100 years that represent 10–20% of the total field.

Into reverse

The most dramatic and impressive consequences of secular variations are geomagnetic reversals. They were discovered by Bernard Brunhes at the beginning of the 20th century, when he noticed that the magnetization of some lava flows pointed the "wrong" way. This could be explained if the Earth's magnetic field had pointed in the opposite direction when the lava solidified. Since then it has been established that reversals are a permanent and dominant feature of the Earth's magnetic field. Their history has been deciphered using the magnetization of lava flows or from sequences of sediments that contain small magnetized particles that were oriented by the field when the rock was formed. The last magnetic-field reversal occurred about 780 000 years ago, and the detailed reversal timescale is very well known for the past 160 million years (myr) and with rather good confidence for the past 300 myr (see box, and blue curve in figure 3 on p55).

At first glance it seems as if the field has reversed in a random manner. But the "reversal frequency" – the number of reversals per million years – has varied markedly throughout history. Indeed, between 120 and 80 myr ago the average reversal frequency was zero, but since then it has been rising. These long periods without any reversals are called "superchrons" and the existence of several of these suggests that long intervals without reversals may have punctuated a large part of our geomagnetic history. The changing reversal frequency over time gives us reason to wonder whether it is influenced by some external factor that changes on a similar timescale. The timescale on which superchrons repeat therefore suggests that processes associated with geomagnetic-field reversals recur on a 200 myr timescale.

As humans have only ever penetrated a tiny fraction of the way through the crust, and seismic waves can only tell us so much about what lies beneath it, the Earth's insides remain pretty hidden from us. Our under-

Back and forth throughout history

This graph shows the polarity of Earth's magnetic field as far back as the Jurassic period some 160 million years (myr) ago. Purple denotes periods when the polarity of Earth's magnetic field was the same as it is today, and white denotes periods when the polarity was the opposite. So in purple times (like the present) compasses would have pointed north, but in white times they would have pointed south.

standing of what goes on there has therefore relied partly on laboratory and computer experiments that try to simulate what happens. To gauge whether such models are successful we can measure their behaviour and see whether it matches that of the Earth, such as having a magnetic field that flips over time.

In the lab

During the last 30 years, several computer simulations of the dynamo have attempted to recreate the processes involved in the generation of the Earth's magnetic field. But a major difficulty is that computers do not have enough processing power to accurately model an object as large as the Earth. The equations describing the dynamo must therefore be simplified before they can make any predictions. Yet although these models are not perfect representations, it is significant that they do produce fields with similar characteristics to the Earth.

In parallel, much information has been gained during the last 10 years from laboratory fluid-dynamo experiments that attempt to mimic the Earth's liquid outer core. In these experiments, moving parts create flow in a container of liquid metal – usually liquid sodium because of its good electrical conductivity and relatively low density. Properties including the magnetic field are measured and finally in 2001 the dynamo effect was seen in liquid sodium heated above 100 °C in two separate experiments by Robert Stieglitz and Ulrike Müller at the Karlsruhe Institute of Technology, Germany, and by a group led by Agris Gailitis at the University of Latvia. These experiments dealt with liquid flowing in a pipe or in an array of pipes.

A different approach was from an experiment that began in 1999 at the CEA research centre in Cadarache, France, in a collaboration with physicists at CEA Saclay, ENS Lyon and ENS Paris. What is known as the Von Kármán sodium (VKS) experiment involves a turbulent swirling flow of liquid sodium between two counter-rotating discs, aligned along the same axis, within a cylindrical container. A later version of the experiment produced not only the dynamo effect but also spontaneous reversals of the magnetic field. The reversals showed a remarkable degree of repeatability and appeared to be very similar to what is known about reversals of the Earth's magnetic field. Similar behaviour included a random field distribution, dipole collapse, rapid polarity change, and recovery of the dipole intensity. Interestingly, reversals were only observed when one of the discs rotated faster than the other.

A mechanism that explains why the magnetic field reverses in the experiment provides an interesting link to the reversals of the Earth's field (F Pétrélis, S Fauve, E Dormy, J-P Valet 2009 *Phys. Rev. Lett.* **102** 144503). We know that in both cases the dipolar field is not the only field of importance – if it were, the field would be stable – and that there is some non-dipolar contribution. In the VKS experiment a significant role is also played by a second mode, which is quadrupolar – roughly speaking this is like two dipoles facing each other. The coupling between the two modes provides a pathway for the dipole to flip from one polarity to the other: as the dipole field weakens, the quadrupole field grows, and then as the dipole grows in the opposite direction, the quadrupole field shrinks. If this coupling is strong enough, the magnetic field spontaneously oscillates between the two modes and their opposite polarities, yielding periodic field reversals. We believe that a similar process is involved in the case of the solar magnetic field, which oscillates with a period of 22 years.

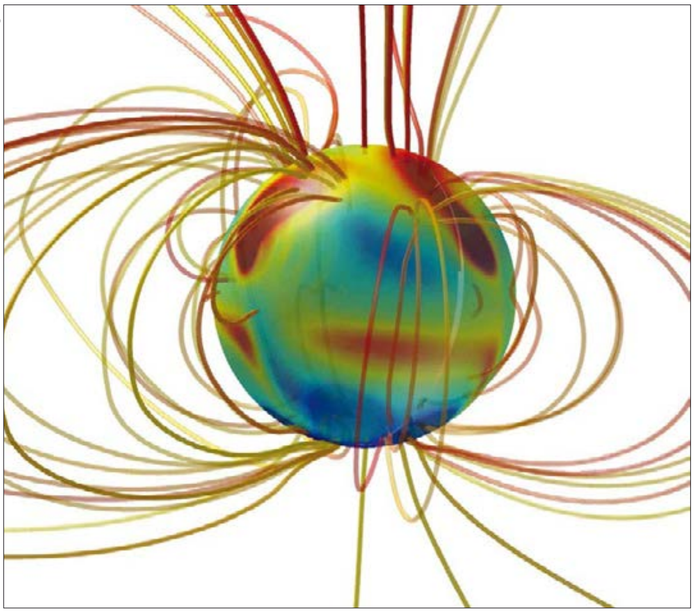
Unlike the Sun, though, the coupling between the dipole and other modes in the Earth is not strong enough to create a regular, periodic oscillation. To trigger a reversal, velocity fluctuations in the liquid core are also needed. For the Earth, a reversal involves two phases: a slow decrease of the dipole amplitude followed by a rapid recovery towards the opposite polarity. At the end of the first phase, the dipole–quadrupole interaction mechanism predicts that the magnetic field can either reverse, or increase back to the initial polarity, accomplishing what is called an excursion: a reversal that begins to take place but is then aborted.

If the dipole does reverse, however, the total field never actually goes to zero: at no point does it "switch off". In contrast, the dipolar field continuously changes shape during a reversal because the amplitude of other modes (including quadrupolar) continuously increases as the dipole decreases. Once the dipolar component has vanished, it is restored with the opposite polarity while the amplitudes of the other modes decrease. Paleomagnetic records of geomagnetic reversals show characteristics that are consistent with these predictions.

Experiments have therefore helped shed light on the

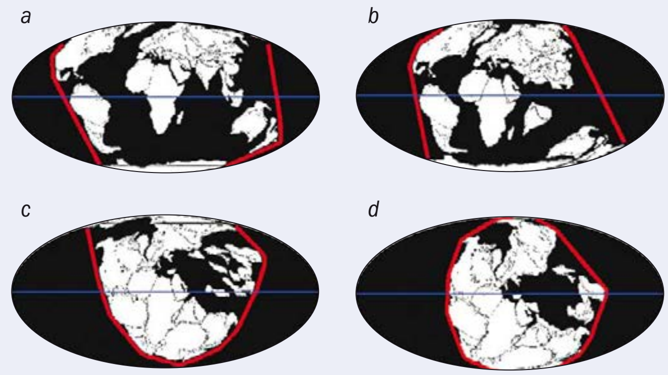
In the laboratory, reversals were only observed when one of the discs rotated faster than the other

C Gissinger



Pole position This computer simulation by C Gissinger shows the "dynamo effect" in the Earth's liquid outer core. This effect generates the Earth's magnetic field (shown here by looping lines). The radial component of the magnetic field is represented at the surface of the model, which corresponds to the core–mantle boundary.

2 Continents enclosed



The authors have found that the geographic distribution of the Earth's continents throughout history seems to be linked to the frequency at which the Earth's magnetic field reverses (see figure 3). These diagrams show how they defined the parameter they used to describe where the continents were. The continents were enclosed by their convex envelopes (red) and the distance from the equator of the centre of masses of these was measured. Examples here show the Earth's continents (*a*) at present, (*b*) 65 myr ago, (*c*) 200 myr ago and (*d*) 260 myr ago. In (*a*) and (*c*) there is a larger continental surface in the north and in (*b*) and (*d*) there is more in the south.

Earth's inner workings – both the mechanism by which the poles flip, and the intriguing fact that in the VKS experiment reversals were only observed when the discs rotated at different speeds.

Slow mover

As we have discussed, the Earth's magnetic field is caused by the dynamo effect in the liquid outer core, so for reversals we have to wonder what it is that perturbs the liquid flow to cause the magnetic-field change. One thing we know for sure is that the overall rate at which the Earth's magnetic field reverses varies on a timescale of about 200 myr. (Note that the poles themselves flip many times within this timescale: 200 myr is the time it takes for the reversal frequency to vary from zero – a superchron – to a maximum, and back again.)

It is difficult to link the change of reversal rate with turbulent flows within the Earth's liquid core as these have a characteristic timescale of the order of just a few centuries, which is much less than 200 myr. Conversely, the variations are too short to be accounted for by the extremely long-term growth of the inner core. Changes in the Earth's rotation are possible candidates, but they occur on timescales four orders of magnitude too short (20 000–100 000 years for Milankovitch cycles).

In the absence of any other mechanisms on this timescale, could mantle dynamics be related to long-term variations in reversal frequency? In other words, does the key lie in what happens at the core–mantle boundary, where the slow-moving solid mantle meets the faster-moving liquid-metal outer core? Indeed, flow velocity of the mantle does not exceed a few centimetres per year and the characteristic time for mantle convection is therefore on the order of 100 myr.

We should expect some link between reversal frequency and plate tectonics

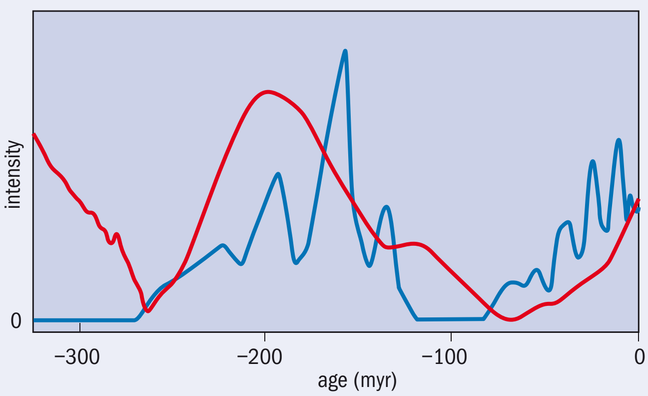
To understand how the mantle has behaved over the last 300 myr, a good tool is the study of plate tectonics. The large plates that make up the globe (currently eight major and many minor plates) have moved dramatically over the years. For example, 330 myr ago the continents as we know them were assembled as one supercontinent, Pangaea, which began to break up 200 myr ago with the opening of the central Atlantic. Tectonic plates can include continental crust or oceanic crust, and many plates contain both. Oceanic crust has a different composition to continental crust and is more dense. As a result of this density stratification, oceanic crust generally lies below sea level, while the continental crust corresponds to continents.

At certain plate boundaries, the oceanic crust can return down into the mantle in a region known as a subduction zone, where the oceanic crust then becomes known as oceanic slab. Seismic tomographic images have shown that many, but not all, slabs descend into the lower mantle. Some may be deflected at around 670 km deep and remain at the boundary between the upper and lower boundary, the lower mantle being of much higher viscosity. However, a large number of slabs do sink into the lower mantle, and can reach the core–mantle boundary in some 80–100 myr as part of huge mantle convection cells. It therefore becomes clear that what happens on the surface of the Earth – specifically the location of plates and subduction zones – could directly relate to the liquid outer core over a long enough timescale.

Thus, assuming that heat-flow conditions at the core–mantle boundary would control reversal frequency and also influence mantle convection, we should expect some link between reversal frequency and plate tectonics. As in the laboratory experiment where reversals only occur when the discs' velocities are different, we suggest that the reversal frequency of the Earth's magnetic field is constrained by a similar symmetry-breaking: some unevenness between the mantle flows of the Earth's northern and southern hemispheres.

We speculate that the long-term evolution in reversal

3 Reversal frequency meets its match



This graph shows the temporal evolution of geomagnetic reversal frequency (blue) and a parameter that shows the distance from the equator of the centre of mass of Earth's continents (red). The frequency at which the Earth's magnetic poles have flipped has changed throughout history. At some points in history – at around −300 and −100 myr on this graph, for example – no reversals took place for long periods of time. In-between these times the rate of reversals seems to rise and fall. The authors speculate that this long-term evolution in reversal frequency is linked to the equatorial symmetry of the geographic distribution of the continents. Curves were normalized, and shifted in the vertical direction, for comparison.

frequency is caused by changes at the core–mantle boundary, which are linked to the equatorial symmetry of the geographic distribution of the continents (2011 *Geophys. Res. Lett.* **38** L19303). To measure this, we considered the convex envelope of the continents back through history (figure 2) and measured the distance of its centre of mass from the equator. The centre of mass moved north and south of the equator over time, when the continents were top- or bottom-heavy.

When we compared this parameter with the geomagnetic reversal frequency, we found striking similarities (figure 3). The quantity varies on the same timescale as the reversal frequency and the two are strongly correlated. The similarities between the two curves suggest that a link exists between continental motion and the geodynamo processes that take place deep inside the Earth's liquid core.

A detailed description of this coupling is not currently possible because the evolution of mantle properties back in time is not yet well known. All we can suggest is that plate motions are indicators of motions deep inside the mantle, and that these motions are associated with changes in the boundary conditions at the core–mantle boundary. These changes modify the symmetry of the liquid flow within the outer core and change the reversal frequency. The mechanisms that drive this correlation are yet to be understood.

The current results suggest that plate tectonics – the visible motion of the plates together with the mantle motions that drive them – have exerted a significant control over geomagnetic reversal frequency for at least the past 300 myr. They thus bring additional evidence when assessing the importance of mantle dynamics in the mechanisms driving long-term dynamo processes. The next step is to further constrain the link between plate motions and the mantle, and ultimately to be able to relate this to the physical properties at the core–mantle boundary. ■