PALAEOMAGNETISM

In GAD we trust

Palaeomagnetists' basic assumption that Earth's magnetic field is a GAD, that is, a geocentric axial dipole, has been challenged by anomalous magnetic data from ancient Canadian basalts. At a closer look, fast continental drift could explain this anomaly.

Joseph G. Meert

Reconstructing the position of the land masses on the globe through deep time is like completing a blank puzzle. Palaeogeographers have only the known outlines of the continents and a few palaeomagnetic data to help them estimate past latitude and orientation of the land masses. To make matters worse, the palaeomagnetic data can be contradictory, and it can be difficult to unravel the many signals contained within a limited study. In the case of the 1.1-billion-year-old Keweenawan rocks of the Canadian shield, attempts to reconstruct the position of North America have been muddled, as the palaeomagnetic data have been controversially interpreted to reflect a deviation of Earth's magnetic field from the basic assumption of a geocentric axial dipole (GAD) model[1,2,3]. On page 713 of this issue, Swanson-Hysell and colleagues look at the rocks in higher resolution and neatly lay to rest the long-standing controversy over the nature of Earth's magnetic field 1.1 billion years ago[4].

Magnetic minerals in rocks — particularly those formed from molten rock — will align with the magnetic field. Rocks found today thus record the magnetic field direction at the time of their solidification. These palaeomagnetic data can aid the reconstruction of the movements of the continents, but only if the Earth's magnetic field is known sufficiently well. Palaeomagnetism therefore relies on the fundamental assumption that the Earth's magnetic field behaves as a GAD, that is, essentially as if there were a bar magnet centred in the Earth's core and aligned with the axis along which the Earth spins, giving rise to normal or reverse polarity (Fig. 1a,b). A more complex magnetic field and reversals (Fig. 1c) will introduce errors in palaeogeographic reconstructions. Evidence from the past few million years shows that the Earth's magnetic field is indistinguishable from the GAD model[5], but the structure of the field earlier in Earth's history is more controversial[4].

The Earth's magnetic field has periodically reversed polarity through time[6]. According to the GAD model, a shift from a normal (north-seeking) to a reverse (south-seeking) magnetic field will result in a change in the sign of the inclination, that is, the angle the magnetic field lines make with the surface of the globe; this angle varies with latitude from 0° at the Equator to 90° at the poles. Furthermore, the declination (the angle between the local magnetic north and geographic north) would be exactly 180° opposed. However, if more poles were present and remained stationary during reversal of the axial field, such as depicted in Fig. 1c, there would be large asymmetry in normal and reverse polarity directions, making it nearly impossible to produce reliable palaeogeographic maps.

Such reversal asymmetry has been suggested for the latter part of the Mesoproterozoic (~1.1 billion years ago)[1,2]. During this time, much of the continental crust was aggregating into a supercontinent

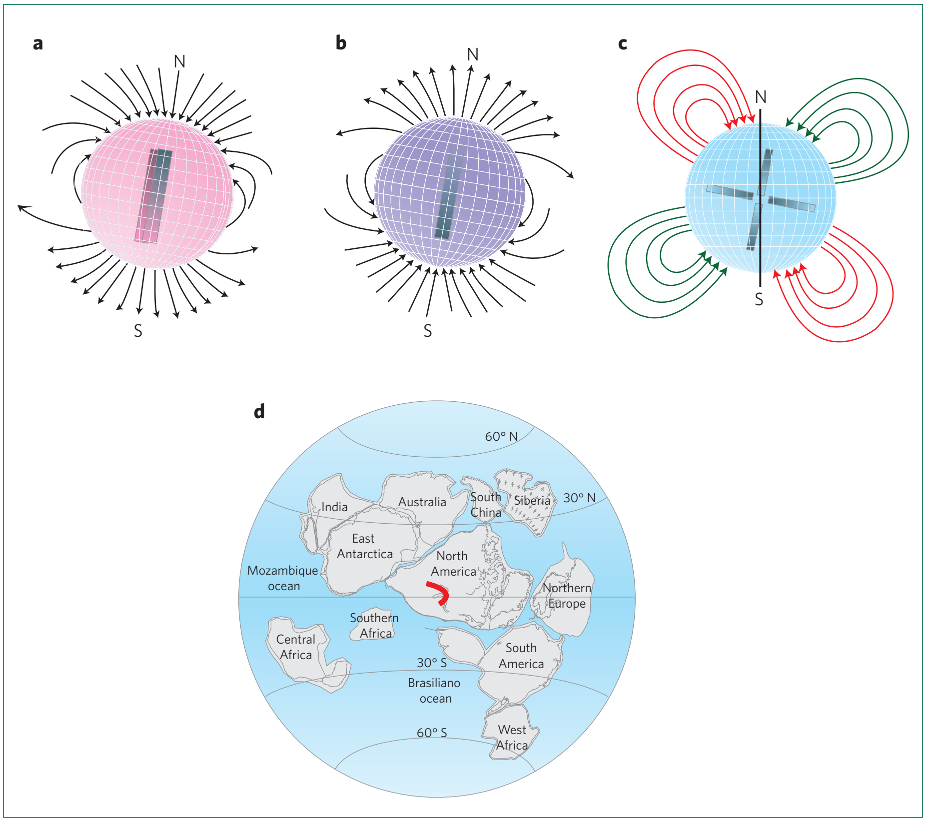

Figure 1 | Magnetic reversals and their records. **a**,**b**, Assuming a geocentric axial dipole magnetic field under normal (**a**) or reverse (**b**) polarity, the field behaves as if there were a bar magnet centred in the Earth and aligned with the spin axis. **c**, To explain the Keweenawan rocks of the Canadian shield, it has been proposed that the field can behave as a non-axial quadrupole field[5,6]. **d**, The supercontinent Rodinia formed about one billion years ago. Previous studies from the Keweenawan basalts (shown in red) suggested that reversals during this time had a non-axial quadrupole component (**c**). Swanson-Hysell and colleagues demonstrate[4] that the reversals recorded in the basalts were actually symmetric; the appearance of asymmetry in averaged normal and reverse directions arose from aliasing effects of recording the rapid motion of North America with low-resolution palaeomagnetic data.

known as Rodinia[7,8] (Fig. 1d). At the same time, a large volume of basaltic material erupted in the middle of the existing North American continent. Palaeomagnetic studies of these volcanic rocks, known as the Keweenawan basalts, have revealed a remarkable asymmetry between the inclinations observed in the average 'normal' polarity samples and the average 'reverse' polarity samples[1,2].

As the rocks were thought to have erupted over a relatively short time interval, the authors of those studies argued that this asymmetry indicates a significant deviation from the GAD model. They suggested that the structure of the Earth's magnetic field included a large contribution from a non-GAD field[1,2], which remained stationary while the GAD field underwent a symmetric reversal.

Swanson-Hysell and colleagues took a closer look at the reversal structure in the Keweenawan basalts at Mamainse Point near Lake Superior[4]. The lava pile at Mamainse is thick (~4,500 m) and contains several sequences of reverse and normal polarity magnetization. More importantly, the authors noted that each of the sequences of normal and reversed polarity were separated from the next by a time gap, when basalt was not flowing to the surface. Swanson-Hysell and colleagues obtained similar palaeomagnetic results to the earlier studies[1,2], but offer an alternative explanation for the asymmetry between the normal and reverse directions. They argue that the past studies, which simply averaged all normal and reverse directions, were flawed because North America underwent significant latitudinal motion, much of which was not recorded because of the gaps in volcanic activity. When averages of normal and reverse polarity directions are taken from lavas of the same age within the sequence, the directions perfectly fit the GAD model. According to these new observations, the apparent asymmetry is not due to any long-standing anomalous field behaviour, but instead to the rapid latitudinal motion of North America.

This conclusion explains the root cause of the asymmetry, but it requires unusually fast continental motion. Large continents generally move over the Earth at rates of less than 5 cm yr^{-1}. The rates proposed in this study are four to seven times higher. Swanson-Hysell and colleagues hint that this rapid motion was a response to mass instabilities in the mantle. In their model, the instability caused the entire crust and mantle to move rapidly to a dynamically stable configuration. This process, called true polar wander, repositions the excess mass (in this instance North America) towards the Equator.

The beauty of the true polar wander hypothesis is that it can be tested, as long as high-resolution data, similar to those reported here, exist for other continents. Indeed, there is some indication of true polar wander during the time interval in question from existing studies[4,7], although further work is needed to confirm this hypothesis.

Swanson-Hysell and colleagues have provided a new model[4] for explaining the magnetic field data from the Keweenawan rocks without the need for any non-GAD field contribution. If they are right, palaeomagnetists can henceforth conduct palaeogeographic reconstructions without worrying about a capricious magnetic field. ❐

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References

1. Pesonen, L. & Nevanlinna, H. *Nature* **294,** 436–439 (1981).
2. Nevanlinna, H. & Pesonen, L. *J. Geophys. Res.* **88,** 645–658 (1983).
3. Gallet, Y., Pavlov, V., Semikhatov, M. & Petrov, P. *J. Geophys. Res.* **105,** 16481–16499 (2000).
4. Swanson-Hysell, N. L., Maloof, A. C., Weiss, B. P. & Evans, D. A. D. *Nature Geosci.* **2,** 713–717 (2009).
5. McElhinny, M., McFadden, P. & Merrill, R. *J. Geophys. Res.* **101,** 25007–25027 (1996).
6. Opdyke, N. D. & Channell, J. E. T. *Magnetic Stratigraphy* (International Geophysics Series Vol. 64, Academic Press, 1996).
7. Meert, J. G. & Torsvik, T. H. *Tectonophysics* **375,** 261–288 (2003).
8. Li, Z. X. *et al. Precambrian Res.* **160,** 179–210 (2008).

BIOGEOCHEMISTRY

Fire's black legacy

Forest fires convert a small portion of burning vegetation into charred solid residues such as charcoal. A survey of Scandinavian forest soils reveals that charcoal has a highly patchy distribution, and a shorter-than-expected lifetime.

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Millions of hectares of boreal forest — coniferous forest in the high latitude Northern Hemisphere — are burnt each year, mostly in unmanaged sparsely populated regions[1]. The twentieth century has seen a rise in boreal forest fires, which in Canada has been linked to rising summer temperatures[2]. The risk of fire — together with the area burnt — is predicted to increase by at least twofold in Canada, Alaska and Russia by 2100 (refs 1,3,4), with potential ramifications for the global carbon cycle. A small portion of forest fuel is converted into solid charred residues[5,6] such as char, charcoal, soot and graphite — termed black carbon. These residues are considered to be highly resistant to decomposition, and are therefore thought to function as a long-term carbon sink. However, despite their significance, the distribution and turnover time of the pyrogenic carbon pool is poorly constrained. On page 692 of this issue, Ohlson and colleagues present results from an exhaustive survey of soil charcoal in Scandinavian forests, and show that the abundance and carbon content of charcoal varies through space and time[7].

Forest fires convert the majority of burning vegetation and soil organic matter into carbon dioxide, emitting around 250 Tg (1 Tg = 10^{12} g) of carbon per year in the pan-boreal forest alone[8]. However, approximately 1–3% of the burning organic matter gets converted into black carbon. Black carbon has a complex molecular structure, which is thought to increase its resistance to microbial decomposition — indeed, the lifetime of soil black carbon is known to extend to thousands of years[5,6,9].

However, recent research suggests that the amount of black carbon in boreal forest soils is lower than that predicted based on fire frequency and presumed lifetimes. Thus, the soil black-carbon pool may be less resistant to breakdown than previously thought. Equally uncertain is the size of the soil black-carbon sink: although black-carbon residues have been found in soils across the globe, the size of this