continuously moving laterally from west to east[8,10].

However, if the asymmetry of the inner core is induced by mantle structures, then the inner core should be locked into longitudinal alignment with the mantle, rather than consistently rotating faster. Or if the inner core does super-rotate, the rate of its rotation must be slow enough to allow a hemispheric dichotomy to develop. Yet at a rate of 0.3° yr^{-1}, it would take only 500 years to rotate the inner core by half a turn, whereas — assuming a typical growth rate of 0.3 mm yr^{-1} — it would take 150 million years (Myr) to grow a 50-km layer on top of the inner core. During this time, the inner core would have rotated 100,000 times about the mantle. Clearly, this should prevent the development of distinct hemispheres.

Waszek and colleagues[4] concentrate on the structure of the top 50–100 km of the inner core. In agreement with previous work[3], they detect faster seismic velocities in the eastern half. However, they also find that the longitudinal location of the boundaries between the two hemispheres is sharply defined — and displaced eastwards with depth (Fig. 1).

This eastward shift has important implications on the question of how super-rotation and a hemispheric dichotomy can be reconciled. Assuming that the asymmetry is imprinted at the time of crystallization, an eastward shift of the boundary is precisely what is expected from a very slow inner-core super-rotation: older, and thus deeper, inner-core material should have rotated slightly further eastwards compared with the longitude where it was formed. Assuming a typical growth rate, the observed eastward shift is consistent with a slow inner-core super-rotation between 0.1 and 1° Myr^{-1}.

This is much slower than the rotation rates suggested in previous seismic studies[3]. However, the results are not necessarily in conflict. All previous work was based on differences in seismic travel times over the past 40 years. Thus, they capture the present-day inner-core rotation, which may be much faster than the average rate of super-rotation over geological timescales that is measured by Waszek and colleagues. Indeed, a very slow super-rotation over which large fluctuations occur on decadal-to-centennial timescales is the scenario favoured by current numerical models of the geodynamo[11].

The seismic observations of Waszek and colleagues can thus be explained in terms of an east–west difference in crystallization rate combined with slow inner-core rotation. This interpretation is not unique: the shift in boundaries could instead reflect a gradual change of mantle structures over the 100-Myr timescale it took to form the top layer of the inner core. It is also unclear why viscous deformation, which should occur preferentially in the inner core's top layer, would not have destroyed the record of a moving dichotomy boundary — or whether it may, in fact, be responsible for it.

In any case, the study of Waszek *et al.*[4] provides a way of reconciling inner-core super-rotation with the hemispheric structure. At the same time, the analyses illustrate that although more-detailed inner-core structures provide further clues to the dynamics at the centre of the Earth, they also bring along new puzzles. ❐

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References

1. Song, X. & Richards, P. *Nature* **382,** 221–224 (1996).
2. Glatzmaier, G. & Roberts, P. *Science* **274,** 1887–1891 (1996).
3. Souriau, A. in *Treatise on Geophysics* Vol. 1 (eds Schubert, G., Romanowicz, B. & Dziewonski, A.) 655–693 (Elsevier, 2007).
4. Waszek, L., Irving, J. & Deuss, A. *Nature Geosci.* **4,** 264–267 (2011).
5. Buffett, B. A. *Geophys. J. Int.* **179,** 711–719 (2009).
6. Buffett, B. A. & Wenk, H. R. *Nature* **413,** 60–63 (2001).
7. Aubert, J., Amit, H., Hulot, G. & Olson, P. *Nature* **454,** 758–762 (2008).
8. Monnereau, M., Calvet, M., Margerin, L. & Souriau, A. *Science* **328,** 1014–1017 (2010).
9. Buffett, B. A. *Geophys. Res. Lett.* **23,** 2279–2282 (1996).
10. Alboussiere, T., Deguen, R. & Melzani, M. *Nature* **466,** 744–747 (2010).
11. Aubert, J. & Dumberry, M. *Geophys. J. Int.* **184,** 162–170 (2011).

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STRUCTURAL GEOLOGY

Natural fault lubricants

Motion along faults can occur in sudden earthquakes or through steady, aseismic creep. Rock samples retrieved by drilling deep into a creeping section of the San Andreas Fault show that clay minerals in fault rock promote creep behaviour.

Ben van der Pluijm

Active faults facilitate motion between blocks of crust. They can accommodate this motion through a range of behaviours. At one end of the range, earthquakes cause sudden and violent rupture; at the other end lies a steady creeping motion that does not generate significant seismic activity. The properties that govern these behaviours are central to fault rupture processes and their associated seismic hazard. The San Andreas Fault in California exhibits different types of slip behaviour in its various sections. For example, large damaging earthquakes have occurred on northern segments, in San Francisco in 1906 and Loma Prieta in 1989, whereas some of the central segments of the fault are creeping aseismically today. Two new papers, published in *Nature Geoscience* and *Nature* respectively[1,2], report that rocks taken directly from an actively creeping segment of the San Andreas Fault have low frictional strength, suggesting that the aseismic creep results from an inherent weakness in the fault rocks.

Faults are not simple planar surfaces marking the contact between two blocks of crust. Instead, they are complex and evolving structures, spread over some width and length. Crustal rocks form bounding walls on either side of the fault zone, which is often filled with fault rock. The strength of these fault rocks can be described using the friction coefficient — a measure of the rock's resistance to sliding against another rock when exposed to a shear stress — and governs motion on the fault.

Experiments on natural rocks have established that most rock types fail and slide at about the same level of stress[3]. Thus, faults are relatively strong, that is, resistant to slip, meaning that they require considerable stresses to allow displacement. However, some faults deviate from this pattern and exhibit weak behaviour. Furthermore, some fault surfaces may heal after rupture, which can cause the strength of faults to vary during the earthquake cycle.

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STEPHEN HICKMAN, USGS

Figure 1 | Fault rocks from the San Andreas Fault near Parkfield, California, at 3,197 m measured depth. Samples of clay-bearing fault rocks collected by the San Andreas Fault Observatory at Depth drilling programme (hole G, run 2, section 8)[12], show striated clay surfaces. Laboratory experiments on similar samples by Carpenter *et al.*[1] and Lockner *et al.*[2] support the hypothesis that clay-bearing fault rocks are inherently weak compared with the surrounding strong crust, and may cause segments of the fault in central California to fail by creep, rather than by sudden large earthquakes. Core diameter is 10 cm.

Weak fault behaviour could be caused either by the presence of fluids that create high fluid pressures, or by the presence of weak materials that act as lubricants. In particular, the presence of clay minerals containing smectite has been suggested to weaken faults significantly[4]. Even if smectitic clay did not previously exist in the fault rock, it can grow during faulting to form a fine coating over surfaces of rock that have been displaced[5]. These clays appear as striated surfaces in the fault rocks (Fig. 1) and act as a lubricant that facilitates steady slip. However, the precise reason for weak fault behaviour continues to be heavily debated[6]. The factors responsible for such behaviour can be tested in laboratory experiments on natural fault rocks, but rocks that are exhumed at Earth's surface are often affected by later weathering and alteration that mask the original mineralogy and rock texture. The San Andreas Fault Observatory at Depth[7], by drilling deep into the Earth's crust, provides access to rocks in the active fault zone and was set up with the aim of retrieving pristine samples of fault rock.

Carpenter *et al.*[1] analyse fault rock cuttings, taken from a vertical depth of about 2.7 km within the San Andreas Fault, and compare them with samples taken from the neighbouring wall rocks. In the laboratory, they test the frictional properties of the rocks by exposing them to various states of stress. The results show that fault rocks from the actively creeping segment of the fault, which are known to contain newly grown smectitic clays[5], have much lower friction coefficients and are thus significantly weaker than the neighbouring wall rocks. The experiments directly correlate frictional behaviour with the localized presence of smectitic clays and show that the fault rocks are inherently weak compared with the surrounding strong crust. Moreover, as the rocks are exposed to greater stresses, they increasingly resist rapid slip — and thus failure in the form of a sudden earthquake. Carpenter *et al.*[1] also find that the fault rock samples do not heal once they have been ruptured, and thus remain weak, further promoting creep behaviour.

Lockner *et al.*[2] analyse intact core samples of fault rocks from the same drill hole, rather than broken pieces of fault cuttings. Using a similar technique to assess the frictional strength of the material in laboratory experiments they arrive at even lower strengths for the rock samples taken from the creeping fault, further supporting the hypothesis that clay minerals control the behaviour of the San Andreas Fault in this creeping section.

Although fault creep can also be generated by high fluid pressures, these laboratory experiments on clay-bearing fault rocks indicate that mineralogy alone may be sufficient to explain why some segments of the San Andreas Fault slip slowly by stable creep, rather than generating large earthquakes. The results can also help explain the San Andreas Fault heat-flow paradox[8], where the friction between the sliding blocks of crust should generate significant heat close to the fault. However, elevated temperatures are not observed. The inherent weakness of the fault rocks and the lubrication provided by the smetitic clays explains why motion on the fault does not generate large amounts of frictional heat. Furthermore, the results may explain the unusual stress orientation observed for the San Andreas Fault. When faults are exposed to a horizontal stress, they characteristically slide at an intermediate angle compared with the direction of the imposed stress. However, the San Andreas Fault is oriented at a very high angle compared with the maximum horizontal stress acting on the Californian crust[9]. The presence of inherently weak rocks, now confirmed by the laboratory experiments, would facilitate motion at such a high angle.

Building on the success of the San Andreas Fault Observatory at Depth, more projects are underway at present to sample fault rocks, for example, from the Nankai seismogenic zone at the plate subduction interface near Japan[10] and at a fault similar to the San Andreas Fault, the Alpine Fault, in New Zealand[11]. By drilling directly into active faults, we can investigate pristine rocks that preserve a record of fault behaviour and the properties governing earthquake genesis.

The laboratory studies by Carpenter *et al.*[1] and Lockner *et al.*[2] on rocks drilled and sampled directly from the active San Andreas Fault clearly demonstrate the role of clay minerals in aiding weak fault behaviour and promoting aseismic creep**.** Clay is a mineral phase that can form at low temperatures and is commonly found in crustal fault rocks around the world, so direct observations and these laboratory results emphasize that localized clay mineralization offers a compelling explanation for weak fault behaviour, without necessarily requiring other mechanisms. ❐

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References

1. Carpenter, B. M., Marone, C. & Saffer, D. M. *Nature Geosci.* **4,** 251–254 (2011).
2. Lockner, D. A., Marrow, C., Moore, D. & Hickman, S. *Nature* doi:10.1038/nature09927 (2011).
3. Byerlee, J. D. *Pure Appl. Geophys.* **116,** 615–629 (1978).
4. Vrolijk, P. & van der Pluijm, B. A. *J. Struct. Geol.* **21,** 1039–1048 (1999).
5. Schleicher, A. M., van der Pluijm, B. A. & Warr, L. N. *Geology* **38,** 667–670 (2010).
6. Scholz, C. H. *Geology* **28,** 163–166 (2000).
7. Zoback, M., Hickman, S. & Ellsworth, W. *Eos* **91,** 197–199 (2010).
8. Lachenbruch, A. H. & Sass, J. H. *J. Geophys. Res.* **85,** 6185–6222 (1980).
9. Zoback, M. D. *et al. Science* **238,** 1105–1111 (1987).
10. www.jamstec.go.jp/chikyu/eng/Expedition/NantroSEIZE/index.html
11. www.gns.cri.nz/static/drillnz/nzcdp/dfdp/index.html
12. www.earthscope.org/es_doc/data/safod/Core Photo Atlas v4.pdf

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