

## GEOPHYSICS

# Going with the mantle flow

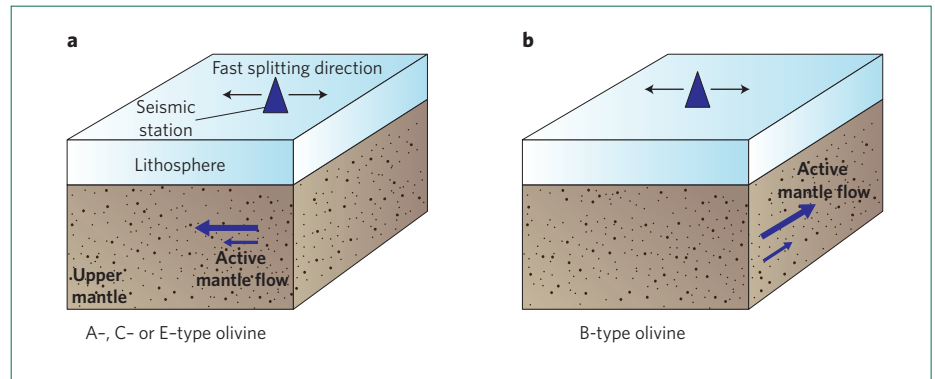
Measurements of directional travel speed of seismic waves constrain flow in the upper mantle. Laboratory experiments suggest that high pressure can change the mantle's mineral alignment, leading to a 90° offset in the direction of the fastest seismic waves.

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**B**elow the Earth's crust, the solid mantle moves in a slow and unseen dance, as cold slabs sink, hot upwellings rise, and convection slowly rids the Earth's interior of its primordial heat. Much of our knowledge of mantle flow patterns is indirect, inferred from geodynamical models or seismic tomography images. By contrast, observations of seismic anisotropy, the directional dependence of seismic wave speed, provide us with tantalizingly direct information about mantle flow direction: crystals of olivine, the most common upper-mantle mineral, tend to become aligned by the mantle flow, and seismic anisotropy is an indicator of this alignment. However, a set of laboratory experiments reported on page 73 of this issue by Jung and co-authors<sup>1</sup> suggests that the relationships between mantle flow and the resulting anisotropy might be more complicated than previously thought.

In the upper mantle, seismic anisotropy is a consequence of the lattice-preferred orientation of mantle minerals, known as the fabric. When olivine aggregates undergo deformation during mantle flow, individual crystals tend to align in preferred directions, resulting in seismic anisotropy. If the relationship between the flow direction and the resulting anisotropy is known, then a measurement of the 'fast' direction of anisotropy beneath a seismic station can provide information about the local flow geometry of the mantle.

The most straightforward indicators of upper-mantle anisotropy are obtained using a measurement known as shear-wave splitting. This technique measures the direction and time delay of the fast and slow waves that result when a polarized seismic shear wave passes through a seismically anisotropic medium. Shear-wave splitting is a powerful tool for inferring mantle flow, but it hinges on knowing the relationship between the fast splitting direction and the flow direction. Initial laboratory experiments<sup>2</sup> suggested that the fast axes of individual olivine crystals tended to align with the direction of shear, implying that fast splitting directions roughly correspond



**Figure 1** | Probing the mantle. **a**, Under the conventional assumption that olivine in the mantle beneath a seismic station is A-, C- or E-type fabric, observations of east-west direction in the fast wave component after shear-wave splitting are indicative of east-west mantle flow. **b**, If, instead, B-type fabric prevails beneath the overriding plate at depths greater than about 80–90 km, as suggested by the work of Jung and colleagues<sup>1</sup>, the same seismic observation would imply a north-south flow direction.

to the mantle flow direction. Subsequent work<sup>3</sup>, however, demonstrated that when water is incorporated into the crystal structure of olivine, the relationship between the fast splitting direction and the shear direction is completely different: now individual crystals tend to align so that the fast direction is 90° away from the flow direction, in a geometry known as B-type fabric.

Since then, a veritable alphabet soup of olivine fabric types has been discovered, including the original A-type as well as B-, C-, D- and E-types<sup>4</sup>, each associated with a specific set of physical conditions such as temperature, stress or water content. Fortunately for shear-wave splitting practitioners, it has turned out that the only fabric type that greatly changes the relationship between the fast splitting directions and the flow direction is the B-type. Laboratory experiments<sup>3,4</sup> have suggested that B-type fabric is restricted to regions of the upper mantle with significant water content, low temperatures and high stresses. These conditions may be found in the mantle wedge above subduction zones, where one tectonic plate sinks beneath another. Here, splitting observations have

been successfully explained with B-type fabric models<sup>5,6</sup>, but the regions of the upper mantle meeting the conditions for the occurrence of B-type fabric were thought to be limited.

Jung and co-authors<sup>1</sup>, however, report that the fabric transition of olivine from A-type to B-type can also be induced by high pressure, in addition to the previously tested parameters (water, temperature or stress). With a series of experiments on dry olivine, designed to mimic earlier work<sup>3</sup> but at higher pressures, they find evidence for a transition in fabric as pressure is increased to around 3 GPa, corresponding to depths of about 80–90 km. Such transitions have previously been reported<sup>7,8</sup>, but there has been controversy about whether the observed changes could have been due to stress or water content rather than pressure, and previous work had suggested a transition to C-type, not B-type, fabric.

Taken at face value, these experiments would suggest that the interpretation of shear-wave splitting measurements for mantle flow at depths below about 80–90 km should be different from the prevailing rule of thumb for A-type and similar fabrics. If the mantle at these

depths is dominated by B-type fabric, then the corresponding fast splitting direction should be perpendicular, not parallel, to the mantle flow direction (Fig. 1). Jung and co-workers highlight a particular example of this effect: beneath subducting plates, the fast splitting directions are often observed to be trench-parallel, which has been interpreted as evidence for trench-parallel mantle flow induced by the migration of trenches<sup>9</sup>. In view of the new results, the trench-parallel splitting direction may instead reflect entrained, trench-perpendicular flow in the sub-slab mantle.

But before seismologists revise the dominant paradigm for interpreting seismic anisotropy, some caution is warranted. As Jung *et al.* point out, their experiments cover only a limited range of experimental conditions, and extension to different temperatures and to 'wet' olivine is needed to characterize fully the region of the mantle where the inferred pressure transition might be applicable. The suggestion that the upper mantle may be dominated by B-type fabric below about 80 km is, at first sight, difficult to reconcile with some seismological observations. With the notable exception of the mantle wedge above subducting plates, geodynamical

models relying on the A-type (or similar) fabric paradigm have often been successful at explaining observations of seismic anisotropy from shear-wave splitting and other observables such as surface waves.

For example, measurements of seismic anisotropy interpreted in an A-type fabric framework are consistent with the expected mantle flow in the ocean basins, where flow is probably controlled by simple shear between the oceanic lithosphere and the underlying asthenosphere<sup>10,11</sup>. If the relationship between anisotropy and flow supports the presence of A-, C- or E-type fabric beneath the oceans, it may do so beneath subducting plates as well. Another challenge comes from the rock record: the overwhelming majority of mantle-derived peridotite rocks apparently show A-type fabric<sup>4</sup>. This observation seems difficult to reconcile with the prediction that most of the upper mantle should be dominated by B-type olivine, although there may be a sampling bias in the geological record.

The experiments by Jung *et al.*<sup>1</sup> represent another step forward in our understanding of how olivine fabrics form under upper mantle conditions, and provide evidence that the effect of pressure may be important. The extension of these experiments to still higher pressures and to

a range of water contents, temperatures and stresses will allow a fuller characterization of the olivine fabric 'phase diagram', which in turn will allow seismologists to relate their measurements of seismic anisotropy to flow directions — and, ultimately, to mantle processes. □

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#### References

1. Jung, H., Mo, W. & Green, H. W. *Nature Geosci.* **2**, 73–77 (2009).
2. Zhang, S. & Karato, S. *Nature* **375**, 774–777 (1995).
3. Jung, H. & Karato, S. *Science* **293**, 1460–1463 (2001).
4. Karato, S., Jung, H., Katayama, I. & Skemer, P. A. *Ann. Rev. Earth Planet. Sci.* **36**, 59–95 (2008).
5. Nakajima, J. & Hasegawa, A. *Earth Planet. Sci. Lett.* **225**, 365–377 (2004).
6. Kneller, E. A., Long, M. D. & van Keken, P. E. *Earth Planet. Sci. Lett.* **268**, 268–282 (2008).
7. Couvy, H. *et al. Eur. J. Mineral.* **16**, 877–889 (2004).
8. Mainprice, D., Tommasi, A., Couvy, H., Cordier, P. & Frost, D. J. *Nature* **433**, 731–733 (2005).
9. Long, M. D. & Silver, P. G. *Science* **319**, 315–319 (2008).
10. Conrad, C. P., Behn, M. D. & Silver, P. G. *J. Geophys. Res.* **112**, B07317 (2007).
11. Becker, T. W., Kellogg, J. B., Ekström, G. & O'Connell, R. J. *Geophys. J. Int.* **155**, 696–714 (2003).

## OCEAN SCIENCE

# Resetting the record

A substantial proportion of the carbon dioxide emitted into the atmosphere by human activities is sequestered in the oceans. Unfortunately, this sink is not without side effects: on entering the ocean, the carbon dioxide reacts with sea water to produce carbonic acid, decreasing the pH of the oceans and potentially threatening the stability of marine ecosystems.

Despite the severity of the implications — the livelihoods of large numbers of people depend on protein from the marine realm — empirical data documenting changes in ocean acidity over time are lacking, and current understanding relies heavily on model projections and laboratory studies. Temperate latitudes, where many of the world's most productive fisheries reside, are particularly under-sampled. J. Timothy Wootton, of the University of Chicago (*Proc. Natl Acad. Sci. USA* **105**, 18848–18853; 2008), and



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colleagues offer a glimpse from the coastal North Pacific Ocean. Using a high-resolution eight-year record they suggest that the rate of acidification at the sea surface may be greater than current models predict.

The team collected more than 24,000 measurements of surface water pH between 2000 and 2007 at the

uninhabited Tatoosh Island, off the coast of Washington State, United States. When they amalgamated the data, they found a decrease in ocean pH over the eight-year period. As expected, this was associated with a rise in atmospheric carbon dioxide concentrations. However, what they hadn't foreseen was the relatively fast rate of pH decline at this site.

The observed consequences for the ecosystem were complex: although some calcareous species such as the California mussel were hit hard, others, such as acorn barnacles, benefited from a lack of competition and increased in abundance.

The unexpected rate of change combined with the complexity of the ecosystem response highlights the need for ocean-based studies. The range of conditions and diversity of species found in the real world simply cannot be replicated in a laboratory.

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