speeding up of the seismic waves passing through it. These travel-time signals from the lower mantle have proved difficult to interpret because of overprinting by the larger variations in the uppermost 700 kilometres of the mantle. But Grand has carefully incorporated the seismic raypaths that turn in the upper mantle, which are usually omitted or treated in simpler ways. By this process, and the inclusion of waveform data from the numerous analog seismometers that operated in the 1960s and 1970s, he has been able to determine the three-dimensional upper-mantle structure, which is interesting in its own right, and to isolate the lower-mantle structure.

An extensive slab of rock that is seismically fast and therefore cold is seen sinking in the lower mantle beneath the subduction zones spanning the west coast of the Americas (see figure). The faster material is visible from the top of the lower mantle, near 800 km depth, to the base of the mantle. The subduction zones known to be present in the upper mantle are not clear, probably because they are masked by other mechanisms that cause strong velocity variation in the upper mantle, and also because the subducting slab is so narrow in the upper mantle.

The downwelling crosses the depth of 660 km, where there is a phase transition that was widely suspected to inhibit mantle flow[3,4]. There is no sign of cold material ponding at the base of the upper mantle over large areas (more than 1,000 km), as has been suggested from numerical simulations that are marked by episodic flushing of subducted material through the lower mantle[5,6]. The continuity of the descending sheet instead suggests steady flow in this region, although studies in the western Pacific[7,8] have found extensive volumes with fast seismic velocities beneath a few subduction zones, interpreted as ponding of slabs at the base of the upper mantle.

In Grand's work, the width and flow rate of the downwelling can be inferred to differ between the upper and lower mantles, whereas the initial seismic measurements that indicated slab penetration into the lower mantle[9] could not resolve such differences. The rate of sinking is inferred by comparing the depth of the lower edge of the sheet to the time at which subduction was initiated. Beneath the segment of the South American subduction zone where the rapid subduction commenced 50 million years ago, the sheet disappears at a depth of 1,300 km, so the rate of sinking in the lower mantle is about 1 cm per year. Beneath North America, subduction has been continuous and rapid throughout the past 150 million years, and the lower-mantle anomaly extends to the core. The subducting material sinks about five times more slowly and thus spreads to form a broader downwelling in the lower mantle than the upper mantle.

A similar result has come from modelling the geoid[10]. Ponding scenarios, on the other hand, would predict a much wider zone of seismically fast material concentrated near 660 km depth. The measured width of the downwelling under the Americas, 500 to 1,000 km, is in accord with previous local estimates[11]. The differences between upper- and lower-mantle downwelling have been linked to possible differences in the viscosity[12].

The extensive slab of descending material beneath the Americas implies that one convection cell spans the entire mantle, at least in this region. As the best image yet of lower-mantle structures on a scale of 300–1,000 km, this observation of large amounts of mass flux between the upper and lower mantle causes great difficulty for those who would argue that the mantle has not thoroughly mixed since its formation billions of years ago.

The debate is far from over. But Grand's model and interpretation of the fate of slabs descending into the lower mantle looks likely to guide our hypotheses for some years to come. ☐

John E. Vidale is in the Office of Earthquakes and Volcanoes, The United States Geological Survey, 345 Middlefield Road, Menlo Park, California 94025, USA.

ANIMAL BEHAVIOUR

Physics for macaques

IMAGE UNAVAILABLE FOR COPYRIGHT REASONS

Courtesy Academic Press / I. Tanaka

THIS is Tokei, a female Japanese macaque, at work retrieving an apple from the middle of a transparent tube by throwing a stone at it (*a*, Tokei throws stone; *b*, stone hits apple; *c*, Tokei moves to the other end of the tube and, *d*, collects the apple). During an investigation of macaque tool use at Jigokudani Monkey Park, Japan, Tokei emerged as a remarkable individual in her inventiveness in finding ways to extract the fruit from the tube. The study, described by E. Tokida *et al.* in *Animal Behaviour* (47, 1023–1030; 1994), started with the macaques being offered a pre-positioned hooked stick with which to pull out the apple. The retrieval options involving sticks were gradually increased in difficulty, culminating in Tokei's use of a natural shrub root she shortened for the purpose. At about the same time, the stone-throwing technique was discovered and eventually four macaques picked it up. The drawback was that the apple could be filched by a rival diner if the stone were thrown too hard. Tokida *et al.* found that Tokei threw stones with less force when other macaques were close to the other end of the tube — giving her more of a chance to see off the competition — than when they weren't; hence their inference that macaques have an appreciation of the principle of the conservation of momentum in collision. Their final observation lends itself to all manner of anthropomorphic speculation. Only Tokei brought her infants to the tube, pushed them in and got them to fetch the apple for her.

Tim Lincoln

---

1. Grand, S. P. *J. geophys. Res.* **99**, 11591–11621 (1994).
2. Lay, T. *A. Rev. Earth planet. Sci.* **22**, 33–61 (1994).
3. Christensen, U. *Geophys. J. R. astr. Soc.* **68**, 487–497 (1982).
4. Morgan, J. P. & Shearer, P. M. *Nature* **365**, 506–511 (1993).
5. Solheim, L. P. & Peltier, W. R. *J. geophys. Res.* **99**, 6997–7018 (1994).
6. Tackley, P. J., Stevenson, D. J., Glatzmaier, G. A. & Schubert, G. *Nature* **361**, 699–704 (1993).
7. van der Hilst, R., Engdahl, E. R., Spakman, W. & Nolet, G. *Nature* **353**, 37–43 (1991).
8. Fukao, Y., Obayoshi, M., Inoue, H. & Nenbai, M. *J. geophys. Res.* **97**, 4809–4822 (1992).
9. Creager, K. C. & Jordan, T. H. *J. geophys. Res.* **91**, 3573–3589 (1986).
10. Ricard, Y., Richards, M., Lithgow-Bertelloni, C. & Le Stunff, Y. *J. geophys. Res.* **98**, 21895–21910 (1993).
11. Jordan, T. H. & Lynn, W. S. *J. geophys. Res.* **79**, 2679–2685 (1974).
12. Gurnis, M. & Hager, B. H. *Nature* **335**, 317–321 (1988).