supply behind river dams upstream[6], and hydrological alterations and reclamation, such as the construction of levees that block river input to the delta plain[7]. If we are to manage deltas for the better, it is imperative to understand clearly how they form, how we have modified them, and what our realistic expectations for sustaining them should be.

Törnqvist and colleagues' contribution is to analyse deposits from more than 100 shallow boreholes in the Mississippi plain just over 100 kilometres to the west of New Orleans. These sediments show a clear transition, dated to around 1,500 years ago, from older wood-peat deposits to younger fluvial deposits. At that time, the area must have been a coastal swamp lying at, or just above, high-tide level.

By assessing the deformation of this transition line in relation to the thickness of the deposits above, the authors were able to assess the rate of compaction of the underlying peat in the time since the fluvial deposits began to be laid down. They could thus isolate the contribution of this compaction to the overall change of sea level relative to the land. The rates they establish — some 5 mm per year — suggest that the compaction of underlying peat is indeed highly significant, providing space to accommodate large quantities of fluvial sediment.

A central element of schemes to restore the Mississippi delta and others like it worldwide is the reintroduction, on various scales, of river water onto the delta plain. If Törnqvist and colleagues' estimation of the rate of compaction in the Mississippi delta is right — and, as they point out[1], there are reasons to believe that it is a conservative estimate — then any effective diversions will need to involve large amounts of fluvial sediments, similar to the quantities moved in natural processes such as the breaching of river banks (creating 'crevasses') and large floods. Because compaction is highly variable in space and time, depending on the underlying strata, the effectiveness of such diversions depends on a detailed understanding of sedimentary architecture underneath. A similar variability applies to other processes crucial to the preservation of deltas, such as sediment and water delivery, wetland development and maintenance, and the redistribution of coastal sediments. Future research should therefore focus on how this heterogeneity affects large-scale delta dynamics.

The effects of climate change — accelerated and possibly erratic sea-level rise, probably stronger and more frequent hurricanes, and alterations in the hydrological cycle affecting freshwater input into deltas — will also have to be taken into account when developing delta-management strategies. Against a backdrop of rising energy prices, restoration strategies should not depend on energy-intensive techniques such as the dredging and pumping of sediments over long distances for beach nourishment and marsh building. Rather, ecotechnological approaches that depend mainly on natural energies such as tides, waves and natural currents to disperse freshwater and sediments should be favoured[8]. The kind of detailed knowledge supplied by work such as that of Törnqvist *et al.* can only help us in making informed decisions.

References

1. Törnqvist, T. *et al. Nature Geosci.* **1,** 173–176 (2008).
2. Nittrouer, C. A. *et al.* (eds) *Continental-Margin Sedimentation: From Sediment Transport to Sequence Stratigraphy* (Wiley–Blackwell, 2007).
3. McKee, B. A, Aller, R. C., Allison, M. A., Bianchi, T. S. & Kineke, G. C. *Continent. Shelf Res.* **24,** 899–926 (2004).
4. Giosan, L. & Bhattacharya, J. P. (eds) *River Deltas — Concepts, Models and Examples* (SEPM, Tulsa, Oklahoma, 2005).
5. Costanza, R. *et al. Nature* **387,** 253–260 (1997).
6. Syvitski, J. P. M., Vörösmarty, C., Kettner, A. J. & Green, P. *Science* **308,** 376–380 (2005).
7. Day, J. *et al. Science* **315**, 229–250 (2007).
8. Mitsch, W. & Jorgensen, S. *Ecological Engineering and Ecosystem Restoration* (John Wiley, Hoboken, New Jersey, 2004).

GEODYNAMICS

Layer cake or plum pudding?

Whether convection in the Earth's mantle extends through its entire depth or if the mantle is layered has long been debated. Recent research suggests that spatially and temporally intermittent or partial layering is the most likely solution.

Paul J. Tackley

is at the Institute für Geophysik, ETH Zürich, Schafmattstrasse 30, 8093 Zürich, Switzerland.

e-mail: ptackley@ethz.ch

Since the late 1960s, when plate tectonics and slow, creeping convection of the rocky mantle became accepted, geoscientists have been debating whether convection extends from the surface to the core–mantle boundary, or whether the mantle is compositionally and dynamically layered. Geochemical observations appeared to support layering, whereas geophysical observations tended to support whole-mantle convection. The potential compositional boundary was typically put at 660 km depth, corresponding to the major seismic discontinuity that marks the boundary between the upper mantle and lower mantle. A range of possible reconciliations have been proposed, including leaky layering at 660 km, layering deeper in the mantle, or ubiquitous compositional heterogeneity like a 'plum pudding'. This debate continues, and was the focus of a special Union session "Whole or Layered Mantle Convection" at the AGU Fall Meeting held in December in San Francisco[1].

There are two geochemical observations that suggest there are distinct reservoirs in the Earth's mantle — a concept that is, at first sight, incompatible with whole-mantle mixing. First, the upper mantle is depleted in incompatible trace elements compared with what is expected from primitive planet-building material that the Earth should, on average, be composed of. The findings from the upper mantle therefore require there to be complementary enriched material somewhere else. Second, several isotopically distinct components can be traced in volcanic rocks, so these must exist in the mantle[2]. By contrast, geophysical observations, in particular from seismology, indicate that some subducted oceanic plates, known as slabs, sink all the way into the lower mantle (Fig. 1). This seems to rule out complete layering at 660 km.

In light of this controversy, geochemical observations have been interpreted to support different conceptual models: while some geochemists argue for 'leaky' layered convection (C. J. Allegre, Institut de Physique du Globe, Paris, France), others argue that

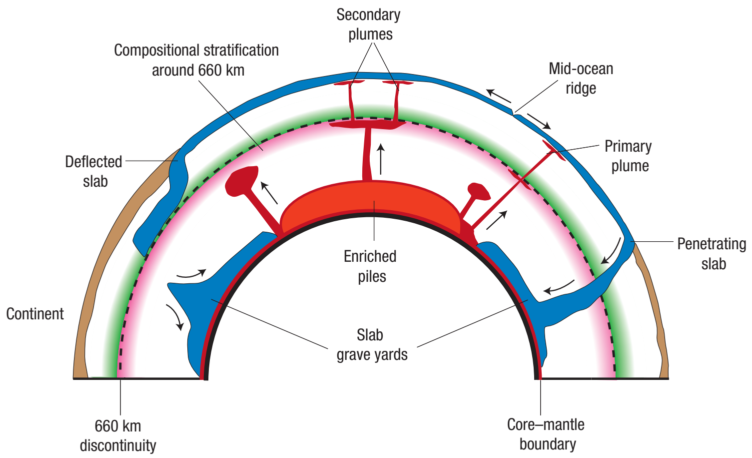

Figure 1 Leaky layers. The emerging model of mantle convection suggests that some relatively cool subducting slabs of oceanic plate (blue) are deflected at the 660 km discontinuity (dashed black line) whereas others penetrate all the way to the core–mantle boundary (solid black line), forming slab graveyards. Piles of material that are enriched in incompatible elements compared with the expected mantle average (orange) are pushed around at the core–mantle boundary by incoming slab material, and plumes form from their edges and tops (red). Some plumes penetrate below 660 km, whereas others are deflected and may produce secondary upper-mantle plumes. An average compositional stratification exists either side of 660 km.

most of the mantle could be similar to the depleted upper mantle, with only small volumes of enriched, hidden material (J. C. Lassiter, Univ. Texas, Austin, USA). This ambiguity might be reduced if we knew more about three-dimensional mantle structures and the dynamical behaviour of the mantle.

The 660 km discontinuity is key. Three-dimensional models of mantle structure obtained using seismic data[3,4] indicate that some subducted slabs penetrate the lower mantle, but many are deflected above 660 km (R. D. van der Hilst, Massachusetts Institute of Technology, USA). A dramatic change in the lateral spectrum of seismic heterogeneity can be seen at 660 km (a 'red' degree-2 dominated pattern above, and a 'white' spectrum below). This was interpreted as evidence for a strong inhibition of mass flux across this depth, suggesting that the observed slab penetration across the 660 km boundary must be episodic (A. M. Dziewonski, Harvard University, USA). Slab deflection at 660 km could be caused by a change in the crystal structure (phase) that produces a sharp density increase (lateral variations in the depth of this phase change, due to differences in temperature or composition, produce density anomalies that resist slab penetration), and/or an increase in viscosity. Both possibilities have been the subject of many numerical studies[5].

New calculations indicate a strong episodicity in mass flux across the 660 km depth when realistic mantle parameters are used (W. R. Peltier, Univ. Toronto, Canada), but in a time-averaged sense, this does not have much effect on the evolution of the mantle and core (S. L. Butler, Univ. Saskatchewan, Canada). Indeed, the mass transfer across 660 km is larger than the flux of slab material from above, despite the presence of a strong phase transition and a viscosity increase that are both expected to reduce this flux (S. D. King, Virginia Tech, USA).

The global average composition must change with depth in order to fit seismic data (L. Cobden, Imperial College London, UK), with the region above 660 km enriched in subducted crust, and the region below 660 km enriched in depleted harzburgite. Such stratification is predicted by dynamical calculations that take into account composition-dependent phase transitions (P. J. Tackley, ETH Zurich, Switzerland), and is consistent with the radial profile of seismic attenuation (F. Cammarano, Univ. California, Berkeley, USA).

Deeper in the mantle, compositional stratification has been proposed, either just above the core–mantle boundary as a thick undulating layer, or in isolated piles[6]. Slabs are compositionally stratified, producing seismic scattering that was used to track one slab sinking to the core–mantle boundary (B. Romanowicz, Univ. California, Berkeley, USA). If slabs reach the core–mantle boundary, do they stay there? One clue comes from seismic studies: there is growing evidence[7,8] for large-scale compositional anomalies in the deep mantle in regions away from downwellings (R. D. van der Hilst, Massachusetts Institute of Technology, USA), which might be slab material or 'primitive' material. Another clue comes from the trace-element composition of volcanic rocks at hotspots: in particular, osmium-isotope studies[9] show evidence for recycling of both parts of the slab — oceanic crust and melting-depleted harzburgite (J. Lassiter, Univ. Texas, Austin, USA). Hotspots are often thought to be caused by hot plumes rising from the core–mantle boundary. If true, this indicates that slab material accumulates above the core–mantle boundary.

The emerging hypothesis is thus a mixture of layered and whole-mantle convection. At 660 km, slabs penetrate intermittently in space and time and a globally averaged compositional stratification is maintained by the influence of phase transitions, while still allowing substantial mass exchange. The deepest mantle may contain piles of primitive material or subducted material that has gravitationally settled. The entire mantle is permeated by a mixture of compositionally distinct components, heterogeneous at all lengthscales. Two other recent proposals may also play a role: the effects of water may keep the transition zone enriched in trace elements[10], and a concentration of trace elements may exist in a 'magma ocean' that has always existed above the core–mantle boundary[11].

To resolve these issues, improved geochemical and geophysical data are essential, and so is quantitative testing of conceptual models. Direct numerical simulation of thermochemical mantle processes couples melting-induced differentiation and trace-element partitioning, convective mixing or segregation, and mineral physics information on rock physical properties and phase transitions. Such simulations, for example those presented at the meeting by P. E. van Keken, Univ. Michigan, USA, can generate synthetic geochemical and geophysical data for comparison with observations, and are a promising integrative approach to testing hypotheses and understanding the nature of the Earth's mantle.

References

1. http://www.agu.org/meetings/fm07/
2. Hofmann, A. W. in *Treatise on Geochemistry* (ed. Carlson, R. W.) 61–101 (Elsevier, Amsterdam, 2003).
3. Fukao, Y., Obayashi, M., Inoue, H. & Nenbai, M. *J. Geophys. Res.* **97,** 4809–4822 (1992).
4. Grand, S. P. *Phil. Trans. R. Soc. Lond. A* **360,** 2475–2491 (2002).
5. Schubert, G., Turcotte, D. L. & Olson, P. *Mantle Convection in the Earth and Planets* (Cambridge Univ. Press, Cambridge, 2000).
6. Tackley, P. J. in *Treatise on Geophysics Vol. 7: Mantle Dynamics* (eds Bercovici D. & Schubert, G.) 437–505 (Elsevier, Amsterdam, 2007).
7. Trampert, J., Deschamps, F., Resovsky, J. S. & Yuen, D. A. *Science* **306,** 853–856 (2004)
8. Ishii, M. & Tromp, J. *Science* **285,** 1231–1235 (1999).
9. Bizimis, M., Griselin, M., Lassiter, J. C. Salters, V. J. M. & Sen, G. *Earth Plan. Sci. Lett.* **257,** 259–293 (2007).
10. Bercovici, D. & Karato, S. *Nature* **425,** 39–44 (2003).
11. Labrosse, S., Hernlund J. & Coltice, N. *Nature* **450,** 866–869 (2007).