The buoyancy of Earth’s deep mantle

The physical nature of two regions called large low-shear-velocity provinces at the base of Earth’s mantle is uncertain. A measurement of their density has implications for our understanding of mantle dynamics. See Article p.321

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Our planet’s surface is displaced by gravitational forces from the Moon and the Sun. The theoretical study of these displacements, known as solid tides, dates to the beginning of the twentieth century. Earth’s solid tides are sensitive to density variations in the mantle, but extracting this sensitivity had to await the development of an appropriate theoretical framework, high-quality geodetic data from the Global Positioning System and precise calculations to correct for various sources of background noise. Building on these advances, Lau et al. report on page 321 that two structures in the deep mantle called large low-shear-velocity provinces are denser than their surroundings. Their results reignite a long-standing debate over the role of these structures in global mantle dynamics.

The motion of Earth’s tectonic plates is driven by mantle circulation, whereby initially light material rises from the deep mantle, cools at the planet’s surface to form dense slabs, and then slowly sinks. Variations in the mantle’s density can also arise from differences in composition caused by melting processes near the surface and imperfect mixing of material over geological time. Accurate imaging of the mantle’s present-day density distribution is therefore essential to understand global mantle dynamics. But this has proved challenging.

Seismic tomography is a technique that uses seismic waves from earthquakes or explosions to image Earth’s internal structure. Over the past few decades, the technique has produced increasingly sharp images of the mantle’s elastic structure, which describes local variations in the propagation speed of two types of wave: shear and compressional.

As expected, tomographic images reflect plate tectonics in the upper part of the mantle. However, they also reveal two large low-shear-velocity provinces (LLSVPs), in which shear waves travel at lower-than-average speeds. The LLSVPs are situated above the boundary between Earth’s core and mantle, and are centred near the Equator, on opposite sides of the planet — beneath the Pacific Ocean and Africa (Fig. 1).

The nature of the LLSVPs and their role in global mantle dynamics are not well understood. Because of their lower-than-average shear velocities, it is generally assumed that they are the source of hot, buoyant material that rises from the deep mantle and cools at the surface. Each LLSVP is surrounded by a ring of material that has faster-than-average shear velocities. These rings are thought to be the graveyard of cold slabs that sink through the mantle.

There is evidence from the modelling of Earth’s seismic waves that the borders of the LLSVPs are sharp, which could indicate that these structures are compositionally distinct from the rest of the mantle. Their contributions to the planet’s moments of inertia (its adjustments to changes in its rate of rotation) and studies of giant volcanic deposits called large igneous provinces suggest that the LLSVPs might have been stable for at least 250 million years. If this is the case, they should be denser than their surroundings — otherwise, they would have rapidly dispersed. The LLSVPs could therefore serve as anchors for mantle circulation.

Almost 20 years ago, a study reported that the LLSVPs are indeed compositionally distinct from, and denser than, the surrounding mantle. The study combined constraints from Earth’s gravitational field and free oscillations — the planet’s natural vibrations. Whereas the seismic waves commonly used in tomography are sensitive to the mantle’s shear and compressional velocities, free oscillations are directly sensitive to its density.

However, this result has been met with scepticism because of inherent limitations in the associated data analysis. In the past few years, several studies have challenged the interpretation of the data and concluded that the LLSVPs have a lower-than-average density. Such studies either modelled the travel times of seismic waves under various assumptions about Earth’s mineralogy or considered Stoneley modes — free oscillations whose sensitivity to Earth’s structure is highest in the deep mantle.

Lau and colleagues’ work suggests that the pendulum might be swinging back the other way. The authors produced images of density variations in the deep mantle using a technique called tidal tomography. The technique is based on high-precision data on Earth’s solid tides that are derived from observations from the Global Positioning System. Using a probabilistic approach known as Monte Carlo forward modelling, they found that the tidal data favour the LLSVPs having a higher-than-average density.

How can we reconcile these seemingly contradictory results? The sensitivity of tidal data to density is highest at the core–mantle boundary, whereas the sensitivity
of Stoneley modes decreases in the deepest 100 kilometres of the mantle12,13. Furthermore, the seismic waves that were considered in ref. 12 sample the bulk of the deep mantle, but not the immediate vicinity of the core–mantle boundary3. Therefore, taken at face value, the results are not necessarily incompatible: the excess mass of the LLSVPs (with respect to their surroundings) could be concentrated in their deepest parts, extending not much higher than about 100 km above the core–mantle boundary.

To settle the debate, many factors that can bias results should be carefully considered. For example, it is difficult to independently constrain Earth’s density and elastic structure in studies that use tidal data or Stoneley modes, and uncertainties in the mantle’s deformation properties can affect the interpretation of tide measurements. Nevertheless, the combined results of these studies suggest that the conventional view of the LLSVPs as homogeneous, compact structures that extend into the mid-mantle needs to be revised.

Rather, the LLSVPs might consist of a bundle of distinct, well-separated ‘plumes’14, as tomographic images produced in the past few years seem to suggest15. The excess mass in the LLSVPs could be concentrated in a thin basal layer, and possibly focused in ultra-low-velocity zones — thin patches of extremely low seismic velocity and high density that reach no more than 40–50 km above the core–mantle boundary16,17. Current imaging studies do not have the sensitivity to detect such patches.

Future work should combine constraints from Earth’s free oscillations, solid tides, seismic waves and gravity — as well as constraints from newly accessible observables such as satellite-derived gravity gradients18. Doing so will help to resolve the fine-scale density structure of the deep mantle and enhance our understanding of past and present mantle flow.

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The effect of conservation spending

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Global biodiversity loss is occurring at a rate that is 1,000 times greater than the estimated background rate of species extinction1. The factors affecting the decline in biodiversity, and the actions and resources needed to arrest that decline, change over time and geographical region2. Without conservation interventions, the rate of species extinctions will continue to increase. For the interventions undertaken, how can the effectiveness of these attempts be assessed? On page 364, Waldron et al.3 use statistical analysis to provide evidence-based insights into the relationship between a country’s national investments to protect threatened species and the country’s rate of biodiversity decline.

The field of conservation science has been hampered by the limited evidence linking investments to conservation and measurable biodiversity outcomes4,5. Because a systematic approach for monitoring the impact of investment in biodiversity conservation is lacking, the absence of this type of assessment tool hinders progress towards achieving the global conservation targets specified in the United Nations Convention on Biodiversity plan (see go.nature.com/2xqKiv). These targets include preventing the extinction of threatened species and improving the conservation status of such species by 2020. Such a tool would also be a useful resource for achieving the United Nations Sustainable Development Goals.

One of the biggest differences when assessing the success of financial investments rather than conservation spending is that financial investors calculate the main benefit of their investment using a single metric: money. Because both investment and pay-off are measured by the same unit — a cash return bigger than the investment is a successful outcome — assessing financial investments is relatively simple.

In conservation, there are many measures of successful outcomes, including carbon sequestered, water quality improved, species secured, habitat structure improved and forest losses averted. Most conservation actions deliver several outcomes, each measured in a different way5. And even if one conservation objective is specified, such as saving species from extinction, it is still not clear how that can be measured. Would the desired outcome be to minimize extinctions, maximize the number of species that recover, or something else?

Figure 1 | Predicting the effect on biodiversity if extra national-level conservation investments had been made. Waldron et al.3 used statistical analysis of data on changes in the endangered-species status of birds and mammals between 1996 and 2008 in 109 countries to generate a model of the relationship between national-level conservation spending and changes in biodiversity in each country analysed. Their work provides evidence for a link between conservation spending and improvements in biodiversity, as assessed by decreases in the endangered status of species. This allowed them to estimate the effect that a further 5 million ‘international’ dollars of conservation spending would have had on biodiversity at a national level, and data are shown for a few of the countries analysed (international dollars represent a conversion from US dollars to account for differences in purchasing power in each country).

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