Deeper understanding

Thomas S. Duffy

The boundary between the core and mantle is one of the most enigmatic regions of Earth's interior. Analyses of a newly discovered crystalline phase should yield a fuller understanding of this region.

The lowermost 250 km or so of Earth's mantle, known for historical reasons as D″, is comparatively small in volume but potentially holds the key to understanding a host of geophysical phenomena — among them the formation of plumes in the mantle, interactions between core and mantle, and the ultimate fate of subducting slabs of crust that are driven into the interior by tectonic forces. Investigations of this region largely depend on interpreting the behaviour of seismic waves, which have shown that it is highly complex. Until recently, however, studies of the region's mineral properties at high pressures and temperatures had been unable to provide satisfying explanations for much of this complexity. Part of the problem is that the extreme conditions in D″ — pressures up to 135 gigapascals and temperatures probably ranging between 2,000 K and 4,000 K — are difficult to reach in the laboratory. However, laboratory experiments and theory are finally coming together to bring this region into sharper focus.

Beginning on page 442 of this issue, papers by Iitaka *et al.*[1] and Oganov and Ono[2] provide insights that link the calculated physical properties of a newly discovered[3] high-pressure crystal structure with seismic observations of the deep lower mantle. Earth's mantle is composed mostly of dense silicate minerals containing magnesium, iron, calcium and aluminium. Experiments have shown that the lower mantle, extending from 660 km depth to the base of the mantle at about 2,900 km (Fig. 1), is mainly composed of $(Mg,Fe)SiO_3$ in a crystal structure known as perovskite. Although the properties of this material are compatible with most observations for the lower mantle, the abrupt change in properties near the mantle's base defied explanation in terms of perovskite behaviour.

Thus, Murakami and colleagues' experimental discovery[3] of a 'post-perovskite phase' in $MgSiO_3$, at conditions comparable to the D″ region, has stimulated considerable interest in the physical properties of the new phase. Given the difficulty of performing direct experiments under these conditions, first-principles quantum mechanical calculations of the type carried out by Iitaka *et al.*[1] and Oganov and Ono[2] are especially useful for studying the deep Earth. In contrast to the perovskite structure that is widely adopted by many compounds, the post-perovskite phase seems to be rather uncommon. In this structure, each silicon cation remains surrounded by six oxygen anions — producing the octahedral coordination that is characteristic of the lower mantle. But rather than forming a corner-linked, three-dimensional network as in perovskite, in the post-perovskite phase the silicon octahedra share edges and corners to form a sheet-like structure with alternating magnesium and silicon layers (see Fig. 1 of Iitaka and colleagues' paper on page 442).

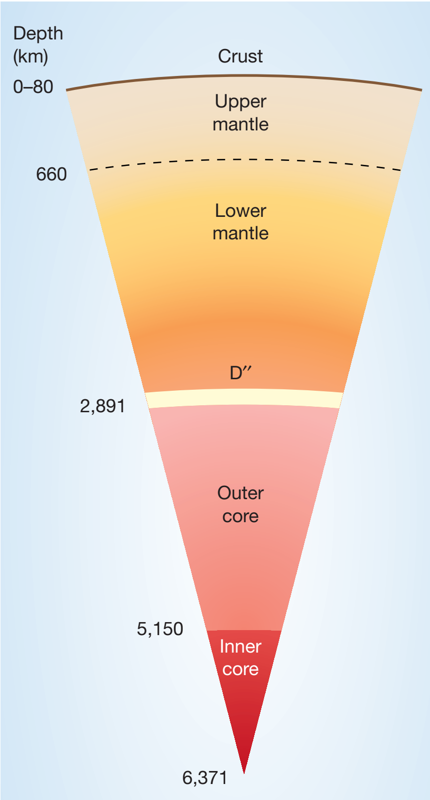

Figure 1 **The principal regions of Earth's interior. The latest interpretations of the lowermost mantle, the D″ layer, are shown in Fig. 2.**

This much could be demonstrated by laboratory experiment[3]. But theoretical calculations now shed light on several other properties of the post-perovskite phase. First, by taking account of thermodynamic considerations, Iitaka *et al.*[1] and Oganov and Ono[2] show that it is expected to be stable at pressures above about 100 GPa (at 0 K). Oganov and Ono[2] also include experimental observations of the new phase after heating at near 118 GPa. For experiments under these extreme conditions, reports of structural changes are all too frequently not verified. So multiple experimental observations of the post-perovskite phase[2–4], together with the theoretical predictions of its stability, mean that the implications of the new phase need to be seriously considered. Indeed, the two theoretical reports here[1,2] are also generally compatible with the findings from another study[5,6].

In conjunction with experimental findings, the theoretical results at 0 K indicate that the transition has a positive pressure–temperature slope. At mantle temperatures, the phase transition is then expected to occur about 200–300 km above the base of the mantle (Fig. 2, overleaf), consistent with evidence for a sudden change, or discontinuity, in the velocity of seismic waves there[7,8], possibly global in extent[9,10]. The positive slope of the phase boundary is even compatible with seismic-wave evidence[10] that the D″ discontinuity is elevated in seismically fast (and presumably cold) regions and depressed in seismically slow (hot) areas. The new phase is also found to be about 1–2% denser than perovskite at D″ conditions.

Calculations of the elastic properties confirm that the post-perovskite phase is anisotropic, being more compressible normal to layering than parallel to it. It also exhibits considerable anisotropy in seismic-wave velocities, especially for the type of waves known as shear waves. Given the nature of the structure, it is plausible that post-perovskite crystals will develop a lattice-preferred orientation under compression such that the direction normal to layering will tend to lie along the vertical. If the layering is imperfect, and taking into account the presence of other phases, the calculations show that a 2–3% seismic discontinuity consistent with deep-mantle observations[7–10] would result from this phase transition. The transition is expected to produce a larger discontinuity for shear waves than for compressional waves, the other main type of seismic wave.

This form of texturing will also result in horizontally polarized shear waves (of velocity v_{SH}) propagating faster than vertically polarized shear waves (v_{SV}). Seismic anisotropy in D″ is complex, but this sense of anisotropy has been well documented in certain regions[11]. Previously, this behaviour was difficult to reconcile with the known elastic

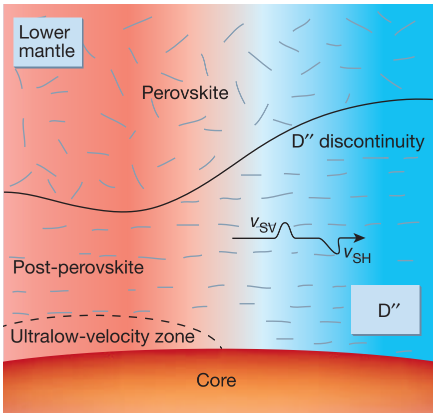

Figure 2 **New model for the mantle's base. The D″ discontinuity is now thought to be due to a transition from the perovskite to a post-perovskite structure in (Mg,Fe)SiO_3 about 200–300 km above the base of the mantle. The phase boundary is elevated in locally cooler regions (blue) and depressed in locally hotter regions (red). A tendency for the layers of the post-perovskite phase to align parallel to Earth's core can help to explain the faster propagation of horizontally polarized (v_{SH}) than vertically polarized (v_{SV}) shear waves. Ultralow-velocity zones are thin (5–40-km thick) regions, located directly above the core, where shear-wave velocities are strongly depressed.**

properties and deformation behaviour of perovskite and other lower-mantle minerals. Instead, it was proposed that the anisotropy resulted from aligned inclusions or layering of minerals with dissimilar seismic velocities. The discovery of the post-perovskite phase may provide a simpler explanation.

The proposed transition between perovskite and post-perovskite will not resolve all questions about the D″ region. But it clearly provides a new framework for studying the region and is sure to stimulate further geophysical observations, laboratory experiments and computer calculations. From a mineral-physics viewpoint, studies of texture development in the new phase, as well as constraints on the behaviour of more chemically complex systems, are clearly needed. Also, the elastic anisotropy has only been calculated at 0 K, yet in some cases temperature can drastically change the magnitude and even orientation of anisotropy. The theoretical studies[1,2,5,6] are in remarkably good agreement. But they all used similar techniques involving some degree of approximation, which will also necessitate further examination.

Nevertheless, a new era in the study of Earth's deepest mantle has begun. An explanation for both the D″ discontinuity and the onset of seismic anisotropy in the region may finally be within our grasp. ■

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Language

Children think before they speak

Paul Bloom

A linguistic contrast between English and Korean provides a telling test of different ideas about whether thought precedes the acquisition of language, or whether certain concepts are language-specific.

In his autobiography, written in the fourth century AD, Saint Augustine[1] described how he learned to talk: "By constantly hearing words, as they occurred in various sentences, I collected gradually for what they stood, and having broken in my mouth to these signs, I thereby gave utterance to my will." For Augustine, thought precedes language: language is a tool with which to express one's ideas and to understand the ideas of others. This is the view of many contemporary philosophers and psychologists[2–4], but it is not the only possibility. Many scholars would instead endorse the theory of linguistic relativity, and maintain that learning a language has a profound influence on a child's mental life. If so, then speakers of different languages might think in very different ways[5,6].

On page 453 of this issue, Hespos and Spelke[7] present data, from 5-month-old babies, that support Saint Augustine's view. They concentrate on a much-studied linguistic contrast. Korean, but not English, makes a distinction between 'tight-fitting contact' and 'loose-fitting contact'. For instance, Korean uses different verbs when describing placing a shoe in a large box, where it fits loosely, and when placing the shoe in a small box, where it is a tight fit — even young children who are just beginning to learn Korean honour this distinction when they speak[6]. Hespos and Spelke ask whether this distinction between two sorts of contact is universal, and exists before language-learning (in which case it should be present in babies), or whether it is the result of acquiring Korean (in which case it should be present only in children and adults who have some knowledge of that language).

They address this question by using a standard method in infant cognition. They show babies instances of a given category until they get bored (or habituated) and stop looking, and then see if the babies perk up — look for longer — at an instance from a

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Snug fit: in situations such as this, the Korean language makes a distinction between tight and loose contact.

new category. If so, it means that babies are sensitive to the categorical difference. Using this method, Hespos and Spelke find that 5-month-olds who are raised in an English-speaking community are sensitive to the Korean categories of meaning. If the babies are habituated to tight-fitting events, such as a cylinder placed within a narrow container or a ring-like object placed around a post, they will look for longer when later shown a loose-fitting event, such as a cylinder placed into a wide container (see Figs 1 and 2 of the paper, pages 453 and 454). The converse is also true. If habituated to loose-fitting events, babies will look for longer when shown a tight-fitting event. In this domain at least, the traditional view is right: thought precedes language.

Hespos and Spelke note the analogy here with phonology, in which there are also cross-