PERSPECTIVES: GEOSCIENCE

Two Views of the Deep Mantle

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The core-mantle boundary (the interface between the liquid, metallic outer core and the solid, silica-rich mantle) exhibits the largest contrast in both seismic wave speeds and density in Earth's interior. Determining the properties of the mantle near this boundary is critical to our understanding of the evolution and present-day dynamics of Earth. At the moment, there are two views of the nature and cause of three-dimensional (3D) variations in wave speeds in the lowermost mantle. The first involves a sharp discontinuity in wave speed with substantial variations in topography located several hundred kilometers above the core-mantle boundary, whereas the second involves radial wave-speed gradients associated with large-scale heterogeneity in the lower mantle. The former point of view implies the existence of a chemical or phase boundary, whereas the latter indicates strong lateral and radial variations in temperature and composition.

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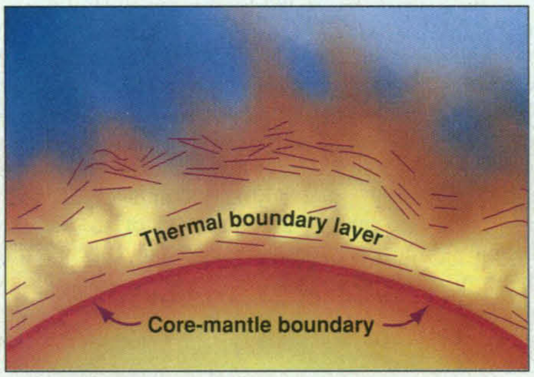
Fifteen years ago, Lay and Helmberger (*1*) detected a small seismic precursor to core-reflected shear waves, which they attributed to a discontinuity about 250 km above the core-mantle boundary. Such a discontinuity might be a sharp phase change or chemical boundary. Precursors to core-reflected shear (*ScS*) and compressional (*PcP*) waves have since been observed in numerous locations but are not observed globally. Frequently, *ScS* and *PcP* precursors are uncorrelated, implying that shear- and compressional-speed discontinuities may not coincide or that one may be present without the other. Thus, an image of Earth's lowermost mantle has emerged that includes uncorrelated discontinuities in shear and compressional speed with substantial topography (upper figure). A recent review article (*2*) discusses 15 years of core-mantle boundary research based on such local discontinuities in seismic impedance.

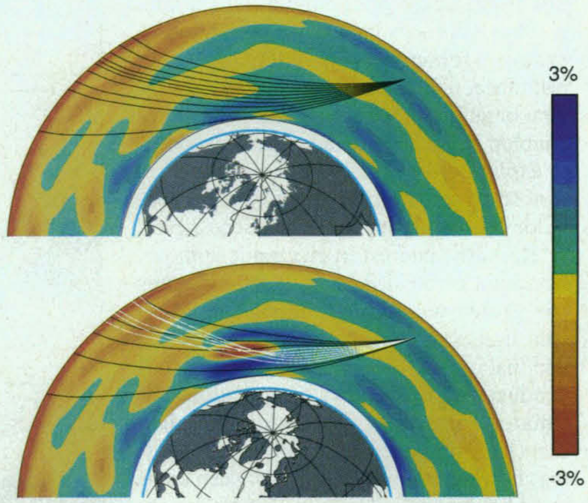
In contrast, tomographic maps of the lowermost mantle (*3–5*) show this region to be dominated by a long-wavelength component of lateral heterogeneity. Furthermore, the strongest anomalies at the core-mantle boundary extend some 500 to 1000 km into the mantle, thus spanning the proposed discontinuity. The images suggest thermal differences as the principal source of the anomalies, with some contributions from compositional heterogeneity. The data used in these inversions depend on the integrated properties of the medium along the ray path and are most sensitive to long-wavelength structure. According to the tomographic models, Earth's lowermost mantle exhibits variations in shear speed in excess of ±3% and variations in compressional speed roughly half this size (*6*). The top panel of the lower figure shows a cross section through a representative shear-speed model.



The inside story. Schematic diagram of Earth's lowermost mantle, the D″ region, with intermittent, uncorrelated discontinuities in shear and compressional speed and substantial topography (*16*).

Soon after the discovery of the *ScS* precursors, Cormier (*7*) investigated whether mantle heterogeneity or anisotropy might be responsible, and he suggested near-source slab effects as an alternative explanation for their origin (*8*). In the latter view, the *ScS* precursors originate close to the seismic source, rather than near the core-mantle boundary. Haddon and Buchbinder (*9*) suggested that large-scale 3D heterogeneity could be responsible, but, unfortunately, reasonable 3D images of the lowermost mantle were not yet available to validate this hypothesis. Therefore, they mimicked the effect of large-scale heterogeneity by sinusoidally perturbing the spherical Earth wavefront. In a subsequent paper (*10*), they suggested, alternatively, that the same scatterers that are needed to explain precursors to compressional (*PKP*) waves that traverse the core (*11*) could also be responsible for the *ScS* precursors. Most recent studies, however, invoke a lowermost mantle discontinuity to explain the precursors.

Motivated by the earlier work of Haddon and Buchbinder (*9*) and the availability of better 3D images of the lowermost mantle, Liu *et al.* (*12*) show that the precursors reported in (*1*) and later studies may be produced by gradients in shear-wave speed associated with large-scale heterogeneity in the lowermost mantle. They show that such gradients can fold the wavefront and produce a distinct arrival between the direct *S* wave and the *ScS* wave; when gradients are weak, no precursors are produced. Because variations in compressional-wave speed are smaller than those in shear-



Precursor pathways. (Top) The outer shell shows a cross section from Earth's surface to the core-mantle boundary through one shear-speed model (*5*) along the light blue great circle shown in the center map. The range of relative shear-speed perturbations is given by the color scale. Blue indicates faster than average wave speeds, whereas red indicates slower waves. Three-dimensional shear-wave rays (black) are projected onto the cross section. Rays start from a 502-km-deep event underneath the Sea of Okhotsk toward California. Wave-speed gradients in this model are not strong enough to fold the wavefront and produce the *ScS* precursor. **(Bottom)** Shear-wave ray geometry with enhanced gradients in the lowermost mantle underneath Alaska relative to the model shown at the top. The effect of these enhanced gradients is to fold the wavefront and thus to triplicate the travel-time curve. These triplicated *S* arrivals are responsible for the *ScS* precursors (white).

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wave speed, *PcP* precursors are rarer than *ScS* precursors. Furthermore, variations in compressional-wave speed are not necessarily correlated with variations in shear-wave speed, such that *PcP* precursors may be absent when *ScS* precursors exist, and vice versa, in accordance with the observations. To produce the precursors, Liu *et al.* need to locally enhance the wave-speed gradients, as illustrated in the bottom panel of the lower figure. This is justifiable, because existing tomographic models are the result of a damped least squares inversion that underestimates the amplitudes and gradients of heterogeneity.

Future tomographic inversions could use observations of precursors as additional constraints on lower mantle structure. Of course, the actual picture is more complex. For example, over relatively short epicentral distances, Schimmel and Paulssen (*13*) report precursors to *ScS* that cannot be explained by large-scale heterogeneity. Perhaps these precursors are produced by the same small-scale scatters that are needed to explain *PKP* precursors (*11*). Further complications involve the existence of thin (<50 km), ultra-low-velocity zones (*14*) and anisotropy (*15*) near the core-mantle boundary. These thin, slow regions at the base of the mantle are reminiscent of the heterogeneous crust on top of the mantle. Are they a result of differentiation of the mantle, like the crust, or are they produced by chemical interactions between the mantle and core?

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PERSPECTIVES: CONDENSED MATTER PHYSICS

Buried Spins in Slow Motion

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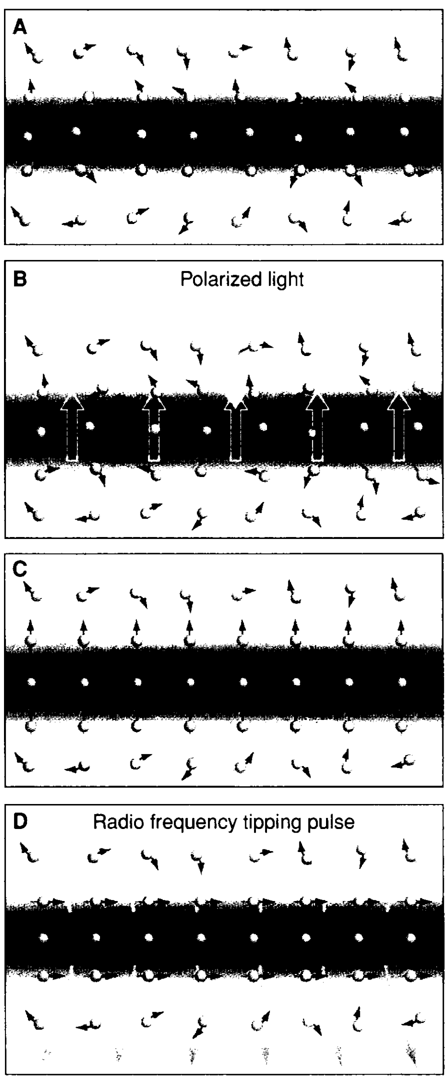
The past decade has seen tremendous refinement in nanofabrication, as semiconducting and metallic systems are now routinely made at the atomic level in ordered layers and clusters. This has fueled the advance of techniques for studying small-scale phenomena, and a vast number of probes have been introduced to examine topography, magnetization, capacitance, and chemistry. Near-contact interactions between sample and probe have enabled scanning surface spectroscopies to explore atomic-scale systems, but often nanostructures lie buried within a particular device, rendering them less accessible.

Recently, interest in electronic spin polarization embedded in solid-state systems has grown with a view toward creating spin transistors and spin memory devices and making use of spin coherence in semiconductors for quantum computation. Ultimately, the most demanding requirements are imposed by quantum computing, in which the interaction between spins must be dynamically controlled by the experimenter and yet, somewhat ironically, the spins must be largely isolated from their environment (*1*). In some cases, however, studying the virtues of a given spin system can be a tricky matter. On page 686 of this issue, Kuzma *et al.* use a clever method to study the spin polarization of a two-dimensional electron gas buried within a semiconductor heterostructure (*2*).

In these systems, a magnetic field applied perpendicular to the electron gas completely changes its spectrum of excitation modes. Electrons fall into quantized energy levels known as Landau levels, and the number of levels occupied by the electron gas as the temperature approaches absolute zero is known as the filling factor ν. Researchers have found that when ν is a fraction such as 1/3, charge carriers in these systems are best described not as simple electrons but rather as many-body excitations that, although constructed from electronic states, lose the electron's fermionic character (*3*). Their spin polarization is an important quantity that sheds light on this many-body system but until recently has been difficult to measure because the system must remain at millikelvin temperatures at which conventional optical probes can heat the electron gas. Using a site-selective nuclear magnetic resonance technique (*2*), Kuzma *et al.* discovered several unexpected properties of this exotic system.

The authors studied an electron gas that accumulates in the GaAs quantum well layers of an AlGaAs/GaAs semiconductor superlattice. Because there is a hyperfine interaction between conduction electron



Spin control. The sample is brought into the ν = 1/3 regime by lowering its temperature to as low as 300 mK and applying a perpendicular magnetic field. **(A)** A radio frequency pulse randomizes the nuclear spins, after which **(B)** the electronic polarization is optically pumped by circularly polarized light. The circular polarization of the light is converted into electron spin. **(C)** During this process, the hyperfine interaction polarizes nuclei that are in contact with the electron gas (shaded region), and after optical pumping these remain polarized. **(D)** The gas cools back down to its base temperature and regains its equilibrium properties, at which time a radio frequency tipping pulse is applied to the nuclear spins, initiating their precession.

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