

SEARCH AND DISCOVERY

Earth's Upper Mantle: How Low Can It Flow?

For years, a debate has raged among Earth scientists about the convection within our planet's thick mantle. Most researchers agree that the 3000 km thick mantle is divided into an upper region and a lower region by an interface at a depth of about 660 km where the mantle materials undergo an isochemical phase change. But they differ as to whether this seismic discontinuity is a barrier to convection.

Over the years, many geochemists have pointed to evidence that different regions of the mantle have different chemical compositions and assume that these different regions are the upper and lower mantles. If so, the upper and lower mantles must have isolated convection cells, with virtually no mixing between them; the slabs of the rigid upper crust (the lithosphere) that sink below the surface at the edge of tectonic plates should stay within the upper mantle, their material being recycled there. On the other hand, a number of geophysicists have long maintained that the convection involves the whole mantle. These researchers display pictures based on seismic data that seem to show lithospheric slabs sinking nearly to the core-mantle boundary.

The publication of two new seismic studies with greatly improved resolution now signals the end to this particular debate. Not that everyone suddenly believes in whole-mantle convection. Rather, each side is finally convinced that the evidence on the other side can no longer be ignored. Instead of continuing the standoff between simplistic models, Earth scientists are starting to join forces to formulate a new, more complex explanation that will account for all the data.

The new results come from global seismic tomography (three-dimensional mapping of seismic speeds in Earth's mantle) performed by different researchers on different types of data: Stephen Grand of the University of Texas at Austin analyzed the arrival times of S-waves, or shear waves,¹ while Rob van der Hilst of MIT, Sri Widiyantoro of the Australian National University and Robert Engdahl of the US Geological Survey in Denver,² looked at the arrival times of P-waves, or compressional waves. With unprecedented resolution for the lower

Does material in Earth's mantle circulate within the upper and lower regions separately, never mixing, or is the entire mantle stirred as one? The latest evidence indicates that convection involves at least some deep mixing of the upper mantle.

mantle, each study provides strong evidence that the lithosphere is sinking well into the lower mantle. Moreover, the correlation between the two independent analyses is so striking³ that the results have won over a number of skeptics.

"CAT" scan of Earth

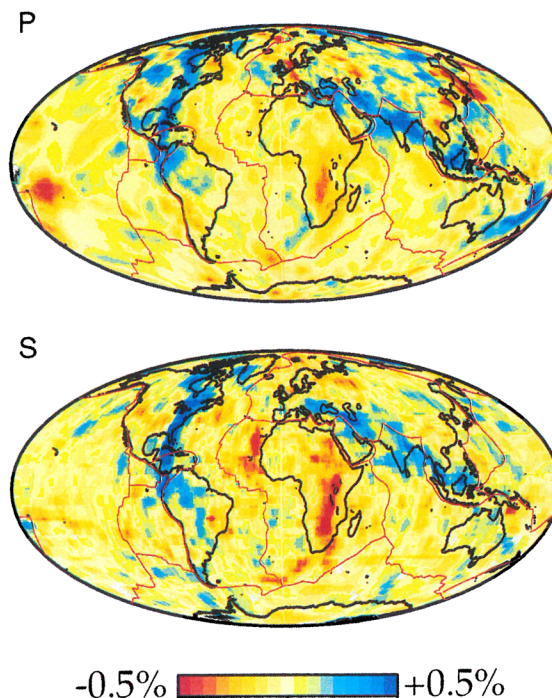
The global seismic studies start with the arrival times of waves from many earthquakes around the globe over the past decades; these waves crisscross the mantle in all different directions, sampling it along innumerable paths. By inverting the data, analysts can extract the speed with which the seismic waves were traveling at each point within the mantle (these "points" are typically blocks that measure 100–200 km on a side). In principle, the pro-

cedure, known as global seismic tomography, is similar to computerized axial tomography (CAT), which traces x rays through, say, a person's head, to take a picture of the brain. One can display the data by taking slices through the Earth, such as vertical cross sections through its depth or spherical shells below its surface.

The map of wave speed turns out to be a rough indication of the temperature distribution: Waves travel faster in regions that are colder. In plots of what geophysicists call velocity anomalies (the deviations of speeds from the average value), researchers often color the higher speeds blue and the lower ones red to suggest the colder (blue) and warmer (red) regions of the mantle.

Descending slabs?

The figure below shows the anomalies at a depth of 1350 km in the P-wave speeds according to one model, compared to the S-wave velocity anomalies in an independent model. Both models show a fairly continuous, narrow region of above-average speeds (blue) extending more than 10 000 km across most of North America and partly into



ANOMALIES IN WAVE VELOCITIES from seismic disturbances essentially map temperature regions, with areas of above-average speeds reflecting colder (blue) material and below-average speeds signaling warmer (red) material. Similar patterns are seen in these independent models of P-wave (top) and S-wave (bottom) speeds at a depth of 1350 km. Note the long narrow features extending the length of the Americas and stretching across Eurasia, which may indicate deep convection. (Adapted from ref. 2.)

Quantum State Reconstruction of Squeezed Light

These five images are probability distributions for quantum states of light, as measured by a group at the University of Konstanz in Germany.¹ The top distribution is a coherent state and the other four are a variety of squeezed states.

"Squeezed" refers to the reduction of some of the innate uncertainty required by quantum mechanics. In particular, a state ψ is squeezed in an observable x if the uncertainty Δx is less for ψ than it is for the vacuum state. The Heisenberg uncertainty relation is still satisfied because squeezing in x must always entail a corresponding increase in uncertainty of the complementary observable p .

For about a decade now, squeezed states have been produced using lasers and nonlinear optical media, but detailed mapping of such states has been achieved only in the past few years. The Konstanz researchers, Gerd Breitenbach, Stephan Schiller and Jürgen Mlynek, apply a technique called optical homodyne tomography. This uses an electro-optic modulator, piezoelectrically controlled phase delays and a homodyne detector in such a way that the detector's output is essentially a measurement of the instantaneous electric field of the light at a certain phase θ of the light's oscillation. The statistics of these measurements are plotted in the five images.

The quadrature amplitude x_θ is proportional to the electric field measured at the phase θ . The vertical axis of each plot shows the probability of measuring the specified value of x_θ at phase θ . The variation with phase from 0 to 2π can be interpreted as time evolution through one oscillation period of the light.

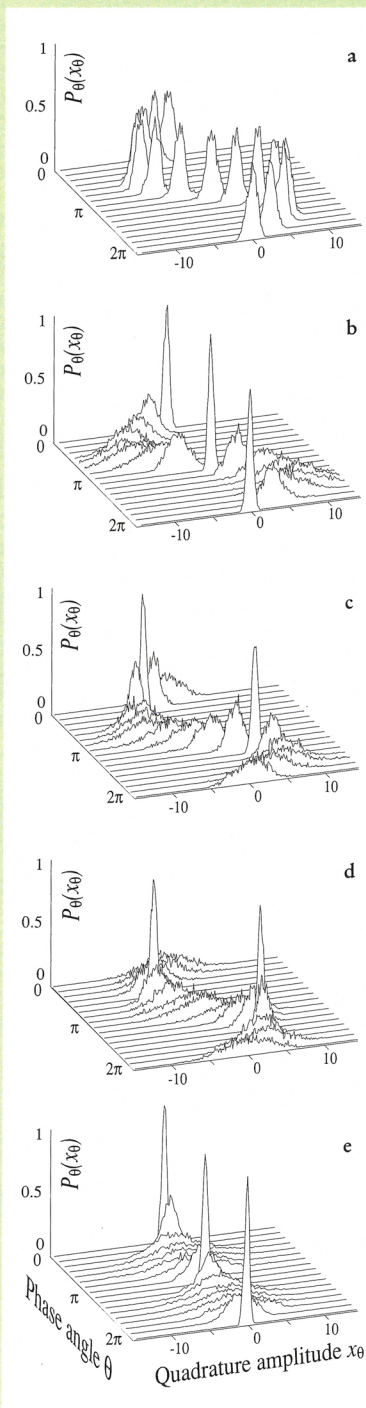
Part (a) shows a coherent state and can be interpreted as time evolution of the wavepacket of this pure state. (See Daniel Kleppner's Reference Frame on page 11 for more about coherent states.) The other states are mixtures and therefore cannot be described by a single wavepacket. State (b) is phase squeezed and state (d) is squeezed in the complementary quadrature: amplitude. The uncertainty of the amplitude of the light in state (d) is smaller than the fluctuations of electric field of a vacuum state! State (c) demonstrates the group's ability to squeeze a state in an arbitrary quadrature: It is squeezed in the 48° quadrature (where 0° corresponds to phase squeezed and 90° corresponds to amplitude squeezed). The final part, (e), shows a squeezed vacuum state.

For each state, the Konstanz group uses the quadrature probability distribution to reconstruct the state's Wigner function and density matrix. Either of these fully characterizes the quantum state of the light in much the same way that a wavefunction fully characterizes a pure quantum state.

Reference

1. G. Breitenbach, S. Schiller, J. Mlynek, *Nature* **387**, 471 (1997).

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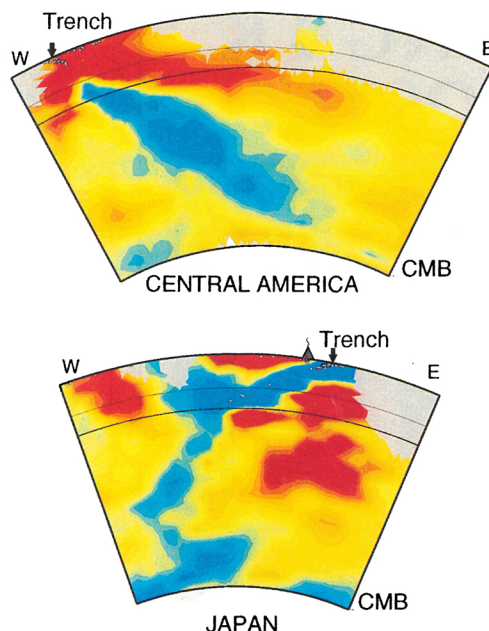
South America. A similar line of high-speed anomalies, at least as long, stretches between Europe and Indonesia, across southern Asia. In both cases, the structures persist at many depths. The figure on page 19 shows the P-wave velocity anomalies in vertical cross sections centered on Central America and Japan, respectively. The cold regions appear to be continuous as a function of depth, suggesting the descent of slabs of oceanic lithosphere at the edge of tectonic plates: Indeed, the features both in the Americas and South Asia coincide with regions that have a long history of subduction (the descent of a continental plate). Unfortunately, the data coverage is not uniform, so the resolution is not as good in other regions of the globe as it is in the Americas and Eurasia.

The data used in these studies are not new. For the S-wave study, Grand has analyzed thousands of individual seismograms from the World Wide Standardized Seismograph Network and the Global Digital Seismograph Network, ending up with high-quality data. The data used in the P-wave study come from the database published by the International Seismological Center and, for recent years, the USGS's National Earthquake Information Center, but Engdahl, Van der Hilst and Ray Buland (USGS in Denver) have carefully reprocessed it, narrowing the constraints on the focal depth of the earthquakes and placing stricter selection criteria on the events.

Geochemical data

Earth may be the ultimate black box, whose internal workings can be deduced only by measuring what goes in and what comes out. Whereas geophysicists record the vibrations sent forth from rumblings within the mantle, geochemists look at the materials—primarily the radioisotopes and trace elements—that Earth spews from erupting volcanoes or squeezes out at mid-ocean ridges.⁴ Many geochemists assume that when Earth formed, its composition was largely homogeneous, with the relative proportion of heavy elements similar to that found today in the Sun or in meteorites. As Earth has evolved over the past 4.5 billion years, its composition has become more heterogeneous, although the geochemists assume that the lower mantle has remained fairly pristine. (A contrasting theory is that the material melted and degassed soon after the planet was accreted and while it was still hot, so that little primordial material is left.)

One class of elements that seems to have been significantly redistributed are the "incompatible" elements—those that do not fit easily into the



A VERTICAL SLICE through

Earth's crust indicates colder material (blue), suggesting tectonic plates that have descended continuously through the mantle for perhaps 40–50 million years. Figures show the cross section of P-wave anomalies through two regions of the world, with blue coding regions where seismic waves travel anomalously fast. CMB is the core-mantle boundary. (Figure courtesy of Rob van der Hilst, MIT.)

crystal structures of the minerals in the mantle. Wherever the mantle rock melts, such elements readily escape into the melt and are carried with it to the surface. Geochemists then expect that the upper mantle, where melts are more likely to develop, is more depleted in these incompatible elements than the lower mantle. Indeed, basalts from mid-ocean ridges, which are assumed to well up from the upper mantle, contain smaller percentages of the incompatible elements than either the continental crust or some ocean island basalts, which are thought to stem from plumes from the lower mantle. Mixing between upper and lower mantles, so the reasoning goes, would not allow such heterogeneities.

By measuring the concentration of an incompatible element in the continental crust, one can estimate the amount by which the mantle must have been depleted. In the case of neodymium, estimates of the depleted volume of the mantle range from 25–50% of

Accelerator Magnet with Brittle Superconductor Sets a Record

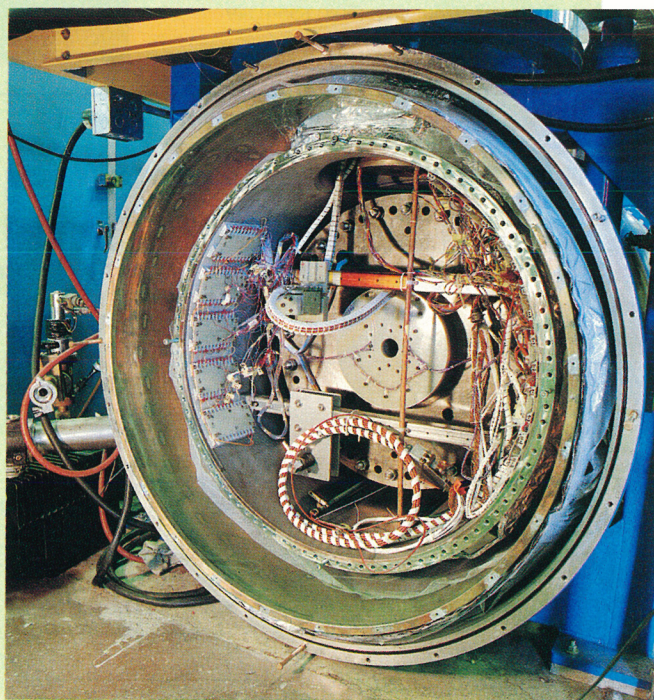
At the Lawrence Berkeley National Laboratory, Ron Scanlan and colleagues are investigating the use of brittle superconducting cable to create accelerator bending magnets significantly stronger than those designed for the abandoned Superconducting Super Collider (SSC) and CERN's much-anticipated Large Hadron Collider (LHC). With the 1-meter-long prototype dipole magnet shown here end-on, the group recently achieved a record bending field of 13.5 tesla in the 5 cm beam aperture visible at the center.

The coil that creates this unprecedented dipole field is made of Nb_3Sn , an intermetallic compound whose great virtue is that the critical magnetic field at which it loses its superconductivity is considerably higher than that of the Nb–Ti alloy of the SSC and LHC magnet designs. A Nb–Ti wire cannot support any supercurrent in a field exceeding 11 T. But at least it is a malleable, ductile metal that can be extruded and wound into magnet coils.

Nb_3Sn , by contrast, is a ceramic-like compound as brittle as glass. Therefore the LBNL group had to extrude and wind the cable before the ultrathin niobium filaments were made to react chemically with the tin in the surrounding matrix by baking the wound coil at 650°C for ten days. When subsequently cooled to liquid-helium temperatures, the intermetallic compound becomes a high-current superconductor. The successive cryogenic walls seen in the photo are for an outer liquid-nitrogen shield and then the inner liquid-helium vessel.

After a series of 40 “training quenches,” the record 13.5 T dipole field was achieved at 1.8 K, a temperature at which the helium is superfluid. So far, the enormous Lorentz-force stresses on the coils do not appear to have degraded the current-carrying capacity of the Nb_3Sn .

The LHC magnets, which will also be bathed in superfluid helium, are expected to operate at a field strength of only 8.4 T, limited as they are by the critical field of Nb–Ti. The energy of the protons that can be stored in an accelerator ring is proportional to the bending-magnet field strength times the ring's circumference. Therefore if one could, some day, fill the 27 km LHC ring with 13.5 T Nb_3Sn bending magnets, one could increase the collider's beam energy from 7 TeV, the present design goal, to 11 TeV. Conversely, one could fit a



7 TeV beam into a ring only 17 km in circumference. Prototype SSC magnets, designed to operate at 6.6 T in liquid helium at 4.4 K, did in fact reach 10 T when tested at 1.8 K.

Manufacturing thousands of full-length Nb_3Sn bending magnets for a next-generation proton collider is still very much in the future. Making these ceramic superconducting coils is, as yet, very expensive and time consuming. But they are also of great interest to those who are thinking about the next generation of magnetic-confinement fusion devices.

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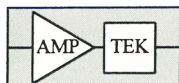
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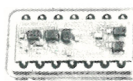
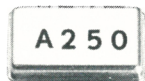
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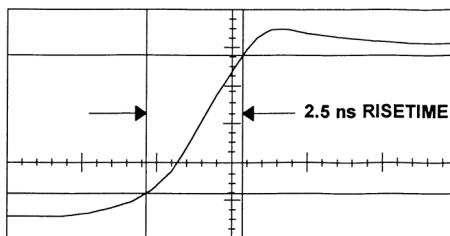
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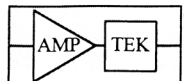
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the total. A percentage of 25% just corresponds to the upper mantle volume, inferring that the lower mantle is nearly pristine. The implication of a higher percentage is not as clear.

Other arguments for an isolated lower mantle are based on analyses of the noble gases derived from radioactive decay of Earth's primordial elements. For example, estimates of the quantity of primordial radioactive potassium-40 suggest how much of the daughter, argon-40, should have been produced. Some mass-balance calculations⁵ find that about half of the expected amount of argon-40 currently resides in the atmosphere or continental crust. The remainder is likely still to be in the mantle. The survival of a lot of argon-40 would suggest that it must have been stored in a fairly isolated lower mantle: If there had been appreciable mixing, more of the argon would have leaked out to the surface.

Reconciling points of view

Already, Earth scientists are formulating models that are compromises between the whole-mantle and isolated-mantle pictures of convection. The main requirement of the geochemical evidence is that there be chemically distinct reservoirs; they do not have to be totally identified with the lower mantle. Thus, one might imagine a model of the mantle with isolated, discontinuous volumes dispersed throughout the mantle. Another possibility is that the mass transport does not occur in a steady state but rather intermittently.⁶ Or, some think, slabs lose geochemically monitored elements in the upper mantle as they sink to lower depths.

Guy Masters of the Scripps Institution of Oceanography feels that many in the Earth science community are ready to accept the idea of mass transfer within the mantle and start asking specific questions such as "How much is there?" and "What impact does it have?"

BARBARA GOSS LEVI

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