tistical uncertainty of ± 2 and an estimated systematic uncertainty of ± 5, the Key Project's Type Ia supernova result is not seriously inconsistent with Sandage's independent estimate of 60 km/(s Mpc). "I'm pleased to see that we're beginning to converge," says Freedman. An independent Type 1a determination of the Hubble constant, by Saurabh Jha (Harvard-Smithsonian Center for Astrophysics) and collaborators,[5] has recently yielded $H_0 = 65 \pm 7$ km/(s Mpc).

Addressing the systematic errors of the individual techniques, and of the overall enterprise, has been a crucial issue for the Key Project team. What are the insidious effects, for example, of intervening dust or of varying galactic light-to-mass ratios? How far out does one have to look to get beyond non-Hubble streaming velocities toward local mass concentrations? How well, ultimately, is the underlying Cepheid period–luminosity relation itself calibrated?

Eventually we will learn more from new methods of determining H_0 that do not depend on the classical extragalactic distance scale. For example, the positions and amplitudes of the "acoustic peaks" of the power spectrum of fluctuations in the cosmic microwave background provide a measure of H_0. (See PHYSICS TODAY, November 1997, page 32.) So do time delays in gravitional lensing. One can also measure the Hubble constant by observing the Sunyaev–Zel'dovich effect—that is, the distortion of the cosmic microwave background in some directions by hot gas in intervening large clusters of galaxies.

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Model Suggests Deep-Mantle Topography Goes with the Flow

As geochemists, modelers, and seismologists try to make sense of data from Earth's mantle, a new model poses challenges to each group and suggests that progress in understanding the deepest regions of the mantle can occur only on a broad front.

In 1996 and 1997, when seismic tomography began producing much improved images of Earth's mantle, many researchers thought they were witnessing the resolution of the debate over whether mantle convection takes place across the entire mantle, or rather within—but not across—chemically distinct layers. The images revealed convincing evidence of slabs of subducted oceanic lithosphere penetrating through the boundary between the upper and lower mantle at a depth of 670 km. If slabs of oceanic crust, which formed, in part, from the upper mantle, could penetrate so easily into the lower mantle, it was difficult to see how the two regions could differ dramatically in composition. (See PHYSICS TODAY, August 1997, page 17.) High-pressure mineral physicists had already provided a suitable explanation for the discontinuity in seismic-wave speeds at the boundary: The boundary corresponded well to the pressure where the dominant phase in the mantle changes from spinel to perovskite—an isochemical, pressure-induced phase transformation.

Yet the idea of a layered, differentiated mantle has proved to have many lives. This is largely because different mantle-derived materials—that is, materials whose source is, at least in part, in the mantle—have very different trace-element signatures, making it very difficult to construct a self-consistent model of a homogeneous mantle that accounts for all the geochemical diversity. Measurements of element and isotope ratios in different mantle-derived materials seem to require at least four distinct reservoirs of material in the mantle. Although some of the diversity of materials can be accounted for by mixing recycled, subducted crust and lithosphere into the mantle, other measurements seem to favor a source of material that has remained isolated over long stretches of geologic time.

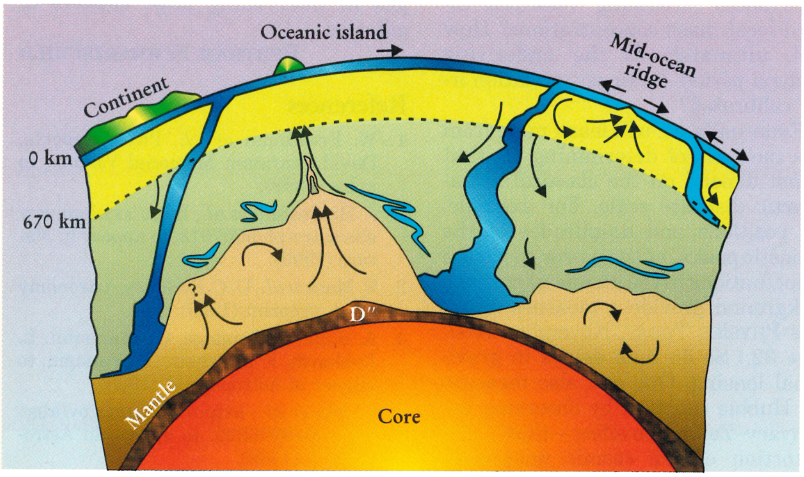
Recently, Robert van der Hilst, Hrafnkell Kárason, Bradford Hager (all at MIT), Louise Kellogg (University of California, Davis), and Francis Albarède (Ecole Normale Supérieure de Lyon in France) began developing a mantle model[1,2] that could explain some of the geochemical data and still be consistent with seismological evidence. The researchers suggest the existence of an isolated layer in the bottom 1000 km of the 2900 km thick mantle that is enriched in heavy elements compared to the upper and lower mantle, and therefore slightly denser. (See the figure on page 22.) Preliminary simulations of the model show that even slightly greater density of the deep layer relative to those above it would inhibit mixing and overturn of the layers.

The deep layer is distinguished from those above it by compositional differences, increased heating and thermal expansion, and perhaps even by phase changes. These effects compete and combine to determine the deep layer's density and elastic properties. Because seismic-wave speeds in a medium are determined by that medium's density and elastic properties, detecting the boundary between the deep layer and the lower mantle as a discontinuity in seismic-wave speeds could be quite difficult. Moreover, the nearly equal densities of the lower mantle and the deep mantle could result in a boundary with very complex topography. These complex topologies have prompted some researchers to refer to this model as the "Lava-lamp model," after the 1960s curiosity that gave many physicists a lasting interest in fluid mechanics.

Why a differentiated mantle?

Although the Lava-lamp model is an attempt to reconcile the compelling geochemical arguments for a chemically differentiated mantle with the seismological data, the motivation for the model extends beyond simply understanding mantle dynamics and structure. Understanding the mantle is key to understanding how the process of differentiation gave rise to Earth in its present form.

In the simplest view, the primordial Earth began as an undifferentiated mass. Early in its history, the iron and related siderophilic (literally, iron-loving) elements sank to the planet's center to form the core. Then, the light, lithophilic (stone-loving) elements floated up out of the mantle, or some portion thereof, to form the crust. The leftover middle region was the mantle—or, if the crust formed primarily from material in the upper portion, the mantle could be divided into an upper



THE LAVA-LAMP MODEL envisions a mantle with four tiers: the upper (yellow–green) and lower (gray–green) mantle, a deep layer (tan) and the thin D″ layer (brown) at the core–mantle boundary. The upper mantle is distinguished from the lower mantle by a pressure-induced isochemical phase change from spinel to perovskite at a more-or-less constant depth of 670 km. In contrast, the deep mantle layer is compositionally different than those above it, containing more heavy elements, such as iron and silicon, and more radioactive elements that heat this deep region from within. The resulting increased thermal expansion nearly nullifies the increased density from compositional changes, resulting in a nearly neutral-density boundary that deforms in response to descending slabs of oceanic crust (blue), ascending plumes, and other currents in the mantle. The mantle is also heated from below by the core (orange) and by D″. The basalts that characterize the mid-ocean ridge and ocean islands may contain trace element signatures of the upper and deep mantle regions. (Adapted from ref. 2.)

portion that was depleted in lithophilic elements, and a relatively undepleted abyssal, or deep, mantle. One question that geochemists try to answer is whether these two portions of the mantle could have persisted into the present or whether they would have eventually mixed. In looking at the composition of different materials derived from the mantle, geochemists see significant evidence for separate mantle reservoirs. (See the article by Don L. Anderson, PHYSICS TODAY, March 1989, page 38.)

Mid-ocean ridge basalts (or MORBs)—which form as portions of the upper mantle melt and rise to fill the void left when thin plates of oceanic lithosphere drift apart—probably provide the most direct samples of material from the upper mantle. Ocean-island basalts (OIBs), because of their association with plumes from deep in the mantle, might be thought to contain some signature of deep-mantle material. Indeed, measurements of rare-earth elements, noble gases, and other trace elements in MORB and OIB samples do show differences suggestive of expectations of depleted and undepleted mantle material, respectively. In particular, OIB samples seem to have a higher ratio of helium-3 (thought to be of primordial origin) to helium-4 (largely radiogenic, resulting from alpha decays). This may indicate that the primordial helium in the OIB source has remained deep enough in the mantle (at least a few tens of kilometers) that it was never lost to degassing. Similar arguments involving argon-40 have been advanced in favor of an undegassed deep-mantle reservoir.

Some of the arguments for differentiation of the mantle have important implications for Earth's evolution. Kellogg and her collaborators contend the upper mantle is so depleted of radioactive elements that accounting for Earth's current heat loss implies rapid planetary cooling or unrealistically high initial temperatures unless there is either a hidden reservoir of radioactive elements or some other source of heat.

Taken together, the geochemical evidence seems to argue for a differentiated mantle. However, the geochemical arguments for mantle differentiation are model dependent. The arguments based on mantle-derived materials assume that these materials bear signatures of their sources, but the process by which MORBs form is only beginning to be understood, and that of OIB formation is still murky. (See PHYSICS TODAY, July 1998, page 17.) Other arguments assume some initial composition for the primordial Earth (for example, based on chondrites left over from the era of terrestrial planetary formation). Yet others assume a model for how elements in the early Earth subsequently partitioned between core, crust, and portions of the mantle. Even with these caveats, it is difficult to see how a homogeneous mantle could account for all the observations, and if separate reservoirs exist in the mantle, the question is where.

A model fit for a mystery

Simulations show that reservoirs of different materials are unlikely to survive unmixed after eons of mantle convection unless they are physically isolated from each other. A layered mantle, with layers segregated by density and convection occurring within but not across layers, is a natural topology for achieving this end.

The choice of the bottom 1000 km of the mantle as a dividing line is not arbitrary. In their data sets, van der Hilst and Kárason see variations in the speeds of different types of seismic waves that collectively seem to indicate that, somewhere near a depth of 1700 km, the elastic properties—and therefore, perhaps the composition—begin to change. They also cite a previous study[3] that found evidence that the profusion of subducted slabs and other debris in the lower mantle seemed to become more sparse and diffuse at depths somewhere between 1500 and 1900 km. This observation is what one might expect if lighter slabs deformed and deflected as they began to penetrate a denser layer.

Moreover, although the bottom 1000 km represents less than 30% of the mantle's mass, this region is still sufficiently large to significantly affect the composition of both the mantle and Earth. If the deep layer contains sufficient uranium and thorium (in the model recently investigated by Kellogg and her collaborators, it contained about 3.6 times the uranium and 5.8 times the thorium of the upper mantle), it would generate sufficient radiogenic heat to make accounting for Earth's current heat loss much easier.

Additional radiogenic heating in the deep mantle would also result in thermal expansion, partially offsetting any density increase that would normally accompany changes in composition. In the model detailed by Kellogg, van der Hilst, and Hager, a composition change that would result in a 4% density change under conditions of constant temperature increases the density of the deep mantle by only 0.5% when thermal expansion is considered. Simulations performed by the researchers show that even such a small density difference would be sufficient to inhibit mixing of the mantle layers for billions of years, even in the presence of rising plumes and descending slabs.

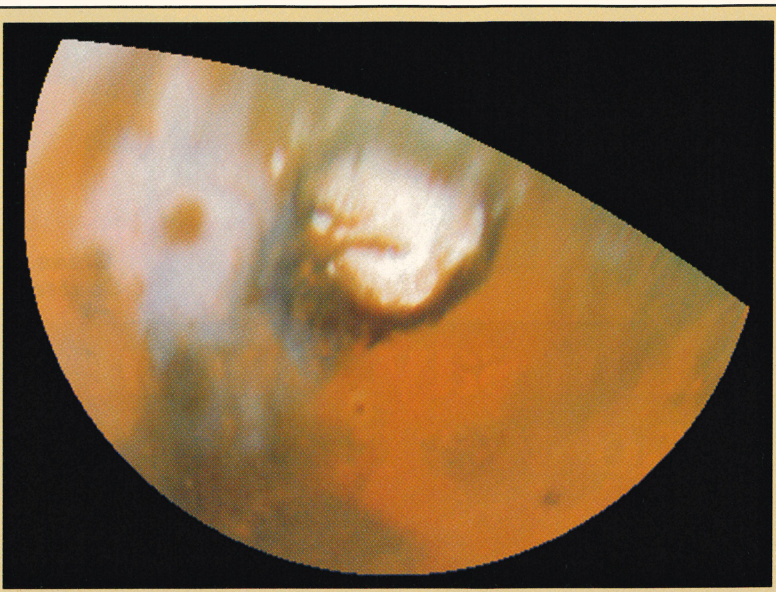
The resulting near-neutral density of the deep layer compared to that above it has the unintended consequence that the interface between layers is free to deform into arbitrarily complex topography in response to currents in the mantle, pressure from descending slabs, and so on. The complex topography would make the boundary between layers difficult to detect, especially given current resolutions of seismic tomography in the lower mantle. Further, Kellogg, Hager, and van der Hilst point out that the change observed in the seismic-wave velocity at the interface between the two regions depends not only on the additional density, but also on what elements are added. Adding iron to the deep region would result in a slower sound speed, while adding silicon could result in a faster sound speed, even while increasing the density of the medium.

An interesting challenge

With all the debate the Lava-lamp model has generated, one has to remember that the model is still in a preliminary state. Kellogg is busy responding to the wish lists of researchers for more realistic simulations. Peter Olson (Johns Hopkins University) stresses the importance of generalizing the model from two to three dimensions: "What works as a delicate balance in a two-dimensional box could change in an unconstrained three-dimensional environment." Recently, Anne Devaille (Institut de Physique du Globe de Paris) took a step in that direction,[4] demonstrating in analog experiments that such a two-layer model, heated from below, can be stable.

However, such analog experiments cannot address other concerns. Henry Pollack (University of Michigan) wonders how more realistic heating would affect the model. Because concentrations of radioactive elements decay exponentially, determining current concentrations of these elements from Earth's current heat loss requires knowing how long the heat takes to propagate through the mantle. Don Anderson (Caltech) would like the model to consider pressure effects in calculations of thermal expansion.

For their part, seismologists wonder whether the deep layer in the Lava-lamp model would be detectable at all, given the complex boundary topography and the interplay between thermal expansion and composition. Kárason's and van der Hilst's investigations seem to give some indication of structural and compositional variation in this region of the mantle. However, Guy Masters (University of California, San Diego) thinks that currently available seismic data sets for the lower mantle may be too noisy for such studies: "I don't think we are at the point where we can sort out temperature and compositional effects. Not all the data sets even show the vanishing of complexity at 1700 km that they [van der Hilst and Kárason] see." Masters, however, sees some hope of detecting the deep



An interplanetary weather forecast for Mars. Astronomers are used to seeing strange things when they turn their telescopes toward the Red Planet—some of them tantalizingly, and often deceptively, Earthlike. The image above, a stereographic projection centered on Mars's north pole, was returned by the Hubble Space Telescope Wide-Field Planetary Camera 2 on 27 April. It depicts a "spiral storm" 1600 km in diameter (the storm is a diffuse white spiral to the left of the bright ice cap) just south of the planet's northern polar ice cap. Although such storms were first observed over 20 years ago, April's tempest was three to four times the size of previously observed storms. So far detected only in Mars's northern hemisphere during its summer, the storms bear some resemblance to terrestrial polar cyclones.

On Earth, polar cyclones are driven by the temperature differences between the warm oceans and cooler atmosphere and amplified by the release of latent heat as evaporated water condenses at high altitudes. Mars's spiral storms are thought to be driven by a weaker engine—the temperature contrast between the cold, bright northern ice cap and the darker, warmer terrain to the south. Moreover, in the thin Martian atmosphere, a 200 mile-per-hour wind would pack the force of only a light terrestrial breeze. The relative weakness of the spiral storm in April is borne out by the fact that it swept up no detectable dust.

Martian storms are also short-lived, lasting only a few days. In the next Hubble image of the storm, taken six hours later, the ice clouds seemed to be sublimating in the Martian afternoon sun. Although subsequent images, taken a few days later by the Mars Global Surveyor (MGS), showed some evidence of mild continued disturbance, the striking cyclonelike structure was gone. Images of the spiral storm are available on the Space Telescope Science Institute's website at http://oposite.stsci.edu/pubinfo/1999/22/. A time-lapse sequence of the subsequent MGS images can be found on the MGS website at http://mars.jpl.nasa.gov/mgs/msss/camera/images/5_21_99_np_clouds/. The researchers who gathered and analyzed the Hubble images—James Bell (Cornell University), Michael Wolff and R. Todd Clancy (Space Science Institute, Boulder, Colorado), Steven Lee (University of Colorado, Boulder), Philip James (University of Toledo), and Michael Ravine (Malin Space Science Systems, San Diego)—are currently investigating the similarities and differences between Martian spiral storms and terrestrial polar storms.

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mantle layer, if it exists, in improved normal-mode data. The recent addition of high-resolution seismographic data from several deep-focus earthquakes offers researchers the opportunity to significantly improve resolution of density as a function of depth in the lower mantle. Masters hopes that by the end of the year, he and Adam Dziewonski (Harvard University) will be able to produce a new reference model for Earth with sufficient resolution to detect a 0.5% density increase in layers as thin as the bottom 300–400 km of the mantle. Even so, a negative result will not necessarily rule out the presence of a stable, dense layer deep in the mantle. According to Kellogg, the model in its current form seems to be stable for density differences as small as 0.25%.

If the Lava-lamp model's stability persists in more realistic calculations, then improved resolution of seismic models, by itself, would not necessarily verify or disprove the model, at least in the near term. For now, in addition to presenting the community with an interesting model, van der Hilst and his collaborators have shown that resolving the nature of the mantle, especially in its lower depths, will require progress on a broad front. Better radial and three-dimensional Earth models, constructed with ever-cleaner seismographic data, certainly will be important tools for such progress. Anderson would like to see new seismic techniques developed specifically to resolve complicated boundary layers: "We've gotten spoiled mapping the upper mantle. You can't detect complex boundaries simply by stacking seismograms."

Progress in geochemistry to reduce model dependence, and in high-pressure mineral physics to determine the phases likely to dominate the deep mantle, could help to constrain our understanding of the composition throughout the mantle. Masters agrees that seismology will need help resolving the nature of the mantle, saying, "Only when we start throwing enough different kinds of data at the problem will we begin to make real progress."

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