Scrambled Earth

Researchers look deep to learn how the planet cools its heart

By RICHARD MONASTERSKY

In the beginning, there was heaven and a sizzling chunk of rock called Earth. Asteroids bombarded the surface of the infant planet, while radioactive elements seethed below, building up so much heat that most of the globe eventually melted. From a distance, the world would have looked like a giant drop of liquid rock circling the sun.

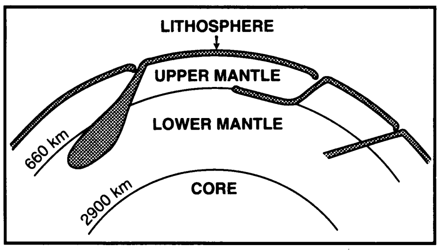
Since that time, Earth has slowly cooled, releasing much of its pent-up original heat. Even today, the quenching continues beneath our feet. The escaping energy pushes continents around the planet's surface through a process called plate tectonics. It causes the ground to quake and volcanoes to blow, killing thousands of people every year.

Yet for all its planet-wrenching consequences, this global cooling remains a mystery. For more than 2 decades, researchers have tried, with little success, to decipher exactly how Earth lets off steam.

The effort is beginning to pay off, however. Recent discoveries from several fields of research are now converging, allowing investigators to zero in on key issues. Tools as disparate as computer models and diamond-studded vises are bringing the planet's hidden interior into much sharper focus than ever before.

When reduced to its simplest form, the cooling question hinges on the mechanics of mixing. Like a pot of steaming soup, Earth loses heat through the stirring action of convective currents that draw hot material toward the surface, where it cools and then sinks. Much of this convection takes place within the mantle — the great rocky layer that surrounds the core and makes up 83 percent of the planet. Although the mantle is solid, the pressures are so intense that the deep stone actually flows, albeit at speeds of only a few centimeters per year.

Geophysicists can agree on that general picture, but arguments break out when they discuss how deep the mixing goes. Since the 1970s, scientists have debated two competing theories of convection. One camp, call them the lumpers, believes that convection currents stir the entire mantle, mixing both the upper and lower parts of this layer. Another group, call them the splitters, argues that the upper and lower mantle remain separate, each convecting on its own like the stacked pots of a double boiler. In this case, the upper mantle would act as a thermal blanket, insulating the lower mantle and slowing the escape of heat from the core.



The fate of plates: Scientists debate what happens to old lithosphere when it sinks. It could drop easily into the lower mantle (right), get trapped at the boundary between upper and lower mantle (center), or pool at the boundary and eventually break through (left).

The lumpers and splitters may both have it wrong, however. The newest findings suggest that Earth does not follow either of these simple patterns but might combine elements of both.

The current debate over mantle mixing extends an intellectual revolution that started nearly 30 years ago, when the theory of plate tectonics swept the geosciences. This powerful concept revealed that Earth's outer shell — the lithosphere — is broken into separate blocks that migrate around the globe like bumper cars in extra slow motion. Where two plates crash together, they build giant mountain ranges such as the Himalayas. When one plate slips beneath another, it creates a deep ocean chasm like the Mariana Trench. If two plates slip-slide past each other, they form quake-making faults like the San Andreas.

The theory of plate tectonics succeeded because it provided the intellectual framework to explain the planet's surface, the part that geologists can feel directly under their boot heels. But the theory only goes skin deep; it addresses just the top 100 kilometers of a planet that spans 6,370 km from surface to center. Even under the penetrating light of plate tectonics, the inner Earth has remained a terra incognita.

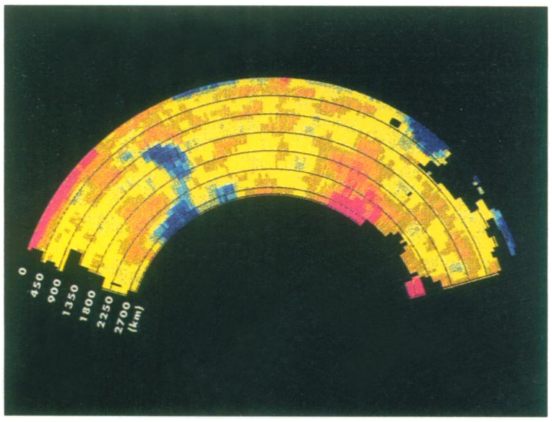
Scientists are therefore striving for deeper knowledge. "The new revolution is to project the global view of plate tectonics downward into the third dimension," says Raymond Jeanloz of the University of California, Berkeley.

Because researchers cannot reach into the lower mantle to measure its properties, experimental geophysicists such as Jeanloz turn the problem around, bringing the inner Earth into the laboratory. Aiding them in this quest is the diamond anvil cell (see sidebar on p.237), a brick-size instrument that allows researchers to recreate the hellish pressures and temperatures of the planet's center.

To address the convection debate, Jeanloz's group put the squeeze on a rock called periditite, which comes from the upper mantle. Although these rocks normally lie under Earth's surface crust, geologists find periditite exposed in places where interplate collisions have thrust part of the upper mantle above ground.

Jeanloz would like to work with actual material from the lower mantle, but no one knows what exists there. The rocks could contain the same ingredients as those of the upper mantle, or they could have a different composition.

As a test, Jeanloz used a diamond anvil to transport upper mantle periditite into a laboratory version of the lower mantle. The rationale vaguely resembles the Cinderella story. In that tale, if the prince can fit a foot into a glass slipper, he has found his princess. In Jeanloz's case, if the



Old and cold: Blue patch shows region where seismic velocities speed up, suggesting that subducting plate penetrated the lower mantle under Central America. The slab apparently reaches the top of the core and then spreads out. The tomographic image does not show the portion of the plate in the upper mantle.

Grand

squeezed periditite fits the expected qualities of lower mantle rock, then he has found the long-sought stone that might fill this hidden layer of Earth.

To measure the fit, Jeanloz uses X-ray diffraction to gauge the density of the compressed periditite. He knows the actual density of the lower mantle because seismologists have previously measured that value.

Periditite, it turns out, is no Cinderella. Even intense squeezing and heating couldn't shoehorn periditite into a proper fit. It has a density 3 to 5 percent lower than what scientists have measured for the deep mantle, Jeanloz says.

The Berkeley group first found hints of that discrepancy several years ago while conducting separate diamond anvil experiments with each of the minerals in periditite. But they wondered whether the whole rock might behave differently than the sum of its parts. The team recently confirmed their original findings with actual periditite, Jeanloz reported last December at a meeting of the American Geophysical Union.

Teams at the Carnegie Institution of Washington (D.C.) and the University of Tokyo obtained similar results, adding weight to the idea that the lower mantle and upper mantle have slightly different compositions.

If true, then the two regions must remain essentially separate, maintaining two distinct convecting systems, says Jeanloz. Material from the upper mantle could not sink into the lower mantle, otherwise that mixing would homogenize the two regions within a fraction of Earth's history — thus wiping out the density difference, he says.

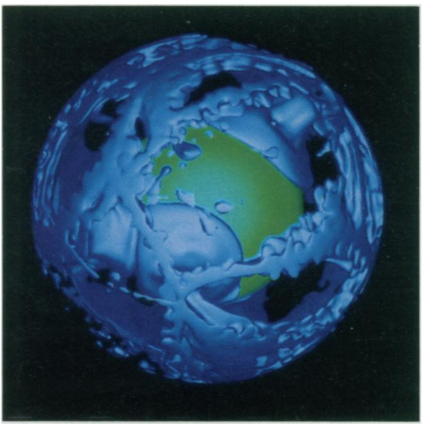
Chalk one up for the splitters.

Jeanloz acknowledges that these conclusions are controversial because the densities differ by only a few percent, keeping alive the debate over the lower mantle's composition. Yet he sees newer results tipping the balance in favor of the chemical layering theory. "Six years ago, we were sort of a lone voice in the wilderness," he says. "For better or worse, now a couple of other groups have joined in with us. It doesn't mean we're right. But at least that's the direction the pendulum is swinging."

Seismologists hear a different story when they eavesdrop on the murmurings of the inner Earth. These scientists study the mantle by analyzing the seismic waves that echo through the entire planet after earthquakes and nuclear explosions crack the crust.

The broad-brush picture from seismology reveals that the mantle has two parts: a thin upper shell surrounding a much thicker lower layer. The boundary between upper and lower mantle lies at a depth of between 650 and 670 kilometers.

Looking at an even finer level, seismologists can discern the edges of surface plates that are sliding into the mantle via ocean trenches. This process, called subduction, is Earth's own recycling system — a way to carry ancient lithosphere back into the mantle from which it formed. As the old lithosphere sinks, it makes room for new rock to grow at the youngest edge of the plate. Subduction also helps chill the inner Earth by carrying cool surface rocks into the torrid interior.



Computer simulation portrays cool, subducting rock as blue. In a few places, giant pools of rock cascade toward the core.

Tackley/NATURE

Because the mantle has a natural division, seismologists originally assumed that the two parts did not mix. Subducting plates could sink to the bottom of the upper mantle, but they would hit a barrier at a depth of 650 km that denies access into the lower mantle.

Thomas Jordan of the Massachusetts Institute of Technology challenged that view in the 1970s with seismic evidence that subducting plates did indeed penetrate the lower mantle. Jordan and his colleagues suggested that the mantle mixed from top to bottom, thus launching the debate between lumpers and splitters. One of Jordan's chief rivals in the debate is Don Anderson of the California Institute of Technology, who served as Jordan's graduate school mentor in the late 1960s.

The arguments have bounced back and forth for 2 decades, with little resolution. But a new picture of subduction is emerging from tomographic studies — a seismological technique that explores the inner Earth much the same way CT scanning resolves structures within the human body.

By analyzing millions of earthquake recordings from around the world, Rob van der Hilst of the Australian National University of Canberra has tracked the path of subducting plates. Yoshio Fukao of Nagoya University in Japan conducted a similar investigation. These tomographic studies can pick out sinking slabs of lithosphere because such rocks are relatively cool and thus slow down seismic waves.

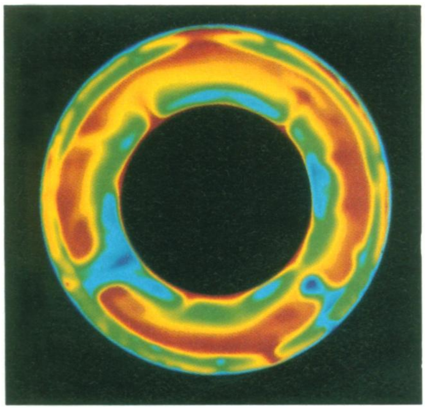
The work by van der Hilst and Fukao suggests that all plates were not created equal. Some slabs bend when they reach the 650 km boundary and remain in the upper mantle; others sink into the lower mantle. According to these studies, the boundary between the upper and lower mantle impedes the progress of sinking slabs, but it doesn't prevent all mixing.

Stephen P. Grand from the University of Texas at Austin has reached a somewhat similar conclusion through a different type of tomographic study. By concentrating on recordings from 180 earthquakes, he produced high-resolution maps of the mantle beneath the Americas.

Grand's maps support the lumpers' case by showing cool slabs reaching down into the lower mantle under South and North America. In fact, a patch of lithosphere under North America has apparently dropped all the way to the top of the core, he reports in a paper soon to appear in the JOURNAL OF GEOPHYSICAL RESEARCH.

But the slabs don't slide into the lower mantle easily. By reconstructing the position of the plates back in time, Grand reasons that the one beneath North America must be sinking at only one-fifth the speed that plates move when they first slip into the mantle. "Slabs encounter resistance at the 650 km depth but eventually they penetrate through that boundary and sink into the lower mantle at slow velocities," he says.

The idea that plates get held up before entering the lower mantle gains support from researchers who study artificial versions of Earth, created inside supercomputers. When used to simulate mantle convection, these three-dimensional numerical models show some surprising behavior.



A slice through computer-simulated mantle shows cool rock (green) sinking. The thin upper mantle has many downwellings, but only two (upper left and upper right) break into the lower mantle.

Tackley/NATURE

Two modeling teams — one led by Paul J. Tackley of the California Institute of Technology in Pasadena and another led by Satoru Honda of the University of Hiroshima in Japan — recently examined what happens to subducting slabs as they sink. For these experiments, the researchers assumed that the lower mantle contains the same basic ingredients as the upper mantle but that the rocks assume a more compact crystalline structure in the lower mantle. Geologists know that this type of phase transformation does indeed occur at a depth of 670 km.

In the models, subducting rock sinks to the boundary but cannot penetrate at first. Only after enough cool material accumulates atop the boundary does it finally break through to the lower mantle, according to two simulation studies reported last year (SN: 2/27/93, p.133).

Taken at face value, these results present a picture akin to that emerging from seismology. But many regard the models as too simplistic to offer much help in resolving the convection debate.

Modelers thus far have fudged their simulations by ignoring the stiffness of the lithospheric plates, a characteristic that, if included, would increase the cost of computing. According to some researchers, if the models represented the plates more realistically, these stiff slabs might break through the boundary instead of pooling above it. Tackley is currently trying to include the rigidity of plates in a three-dimensional simulation of mantle convection.

Despite the problems inherent in the models, Tackley believes the recent computer simulations, along with the seismic tomography results, have helped push the debate forward. He sees geophysicists now embracing the idea that the mantle does not mix as either one layer or two layers, but rather exhibits some intermediate type of flow.

"The debate is shifting to a question of the degree of the stratification in the mantle instead of whether the mantle convects as one layer or two," says Tackley, who sees some drift toward agreement between the opposing camps. "Even people who in the past have held extreme views are moving in favor of a compromise."

They may not admit it, however. Both Caltech's Anderson and MIT's Jordan regard their positions as unchanged.

Anderson thinks the debate has converged recently by shifting toward the idea that he has long championed — namely, that the mantle is stratified. The recent model results, he says, show at least partial layering within the mantle because sinking material gets delayed at the boundary. Anderson suggests that the models would produce even more complete stratification if they included differences in chemistry between the upper and lower mantle — a possibility supported by high-pressure experiments.

Jordan, not surprisingly, reads the situation differently. He contends that the new modeling studies don't contradict his original conclusion that plate material sinks all the way into the deep mantle. Whether the plates get delayed at the 650 km boundary is less important, he says. In fact, Jordan, Tackley, and others reported last year that seismic records do not show evidence of major pools of cold material sitting at the boundary. That study, he says, indicates that slabs cannot linger there for too long before breaking into the lower mantle.

Jordan agrees, however, that the layered mantle camp holds one wild card — the possibility of chemical differences between the upper and lower mantle. "Of all the arguments that were being erected [in the 1980s] in favor of mantle stratification, they've all fallen by the wayside except for the one that Jeanloz is discussing. The data that have come out recently support it, and it's a major fact that needs to be explained," says Jordan.

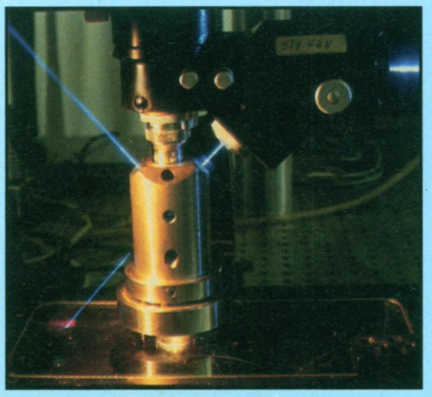
Don't expect an easy answer, though. With so many divergent ideas and observations seemingly contradicting each other, it may take a while to sort out the secrets of Earth's plumbing. "The pendulum seems to swing one way and then it swings the other," says Peter Shearer, a seismologist at the Scripps Institution of Oceanography in La Jolla, Calif. "It's not a problem that I expect to be resolved soon," he adds.

But rest assured that researchers will continue to battle it out. After all, the answer to the convection question ultimately determines how long Earth's inner fires will burn. Researchers have calculated that if the mantle mixes from top to bottom, it will become a cold corpse within a few billion years. "But with multiple-layer convection, it takes 5 to 10 times as long to cool the planet down," says Jeanloz. Earth remains geologically vigorous, active, young, and healthy for a much longer period of time." □

A tiny window into Earth

Forget what the song says: Diamonds are actually a high-pressure physicist's best friend. Taking advantage of the jewel's unrivaled strength, researchers can mimic the intense stresses present inside Earth and other planets.

Charles E. Weir and his coworkers from the National Bureau of Standards first introduced these gems into high-pressure studies in the 1950s, using diamonds that the U.S. Customs Service had confiscated from a smuggler. Now in wide use, the diamond anvil cell works like a vise, squeezing a sample between the pointed ends of two brilliant-cut diamonds typically about one-third of a carat in weight.



Laser beam enters anvil from right and splits after hitting diamonds inside.

H.K. Mao and R.J. Hemley/Carnegie Institution of Washington

Because the jewel points have facets that measure only a few hundredths of a millimeter wide, the diamond anvil can generate intense pressures with only the force of a hand-turned screw. Laboratories around the world routinely recreate pressures equal to those at the center of planet, 3.6 million times atmospheric pressure. Conditions like this would shatter materials weaker than diamond.

Strength is but one of the attributes that diamonds offer. Because the gems are transparent, researchers can heat a squeezed sample thousands of degrees by shining a laser beam directly through it. By hooking a microscope up, they can look directly through the diamond to monitor the material under pressure. Other techniques involve bombarding the sample with X rays, neutrons, or laser beams, which can reveal properties of the object in question. — R. Monastersky