Global Graveyard

New images of Earth's interior reveal the fate of old ocean floor

By RICHARD MONASTERSKY

In their effort to unravel the secrets of Earth's interior, geoscientists have been stumbling about, a bit like Mr. Magoo, the notoriously near-sighted cartoon character. Researchers have spent decades trying different tricks for peering into the planet, but they have been unable to see clearly enough to resolve some of the most basic issues about this hidden realm.

One particularly vexing question is what happens to oceanic rock after a few hundred million years. The planet is 4.5 billion years old and new ocean floor forms continuously, but almost all of the ocean crust over 200 million years old has vanished, sinking into Earth's interior through a process called subduction.

Just where this rock ends up when it disappears from view has important implications, both for basic knowledge about the planet and for improved insight into the driving force behind earthquakes and volcanoes. "This is absolutely fundamental for our understanding of how the Earth works. It just changes your whole idea of Earth history," says Guy Masters, a seismologist at the Scripps Institution of Oceanography in La Jolla, Calif.

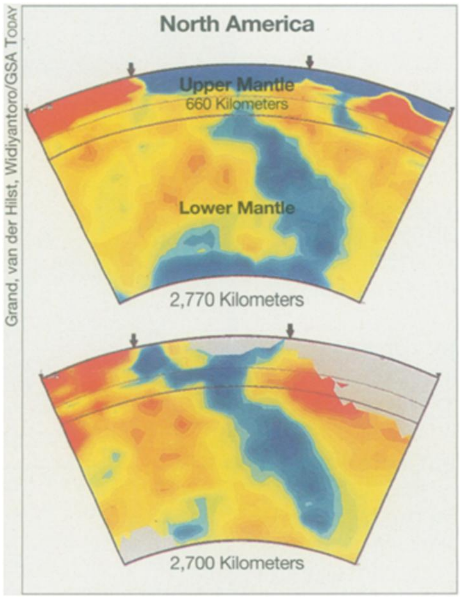
Masters first became interested in subduction while in graduate school in 1975. At the time, scientists were trying to decide whether the subducting ocean rock remained trapped near Earth's surface or sank all the way to the core. That same debate continues today. "It was a major controversy then, and it's a bit depressing that 22 years later, we're still arguing the same issue," he says.

His spirits are getting a lift, however, from two new studies poised to end the dispute. After spending years sifting through thousands of earthquake records, independent teams of seismologists have produced some of the most detailed images yet of the deep mantle, the great rocky layer between Earth's metallic core and its outer shell, called the lithosphere.

Their analyses have convinced many geoscientists that subducting ocean crust sinks extremely deep into the planet, thereby helping to mix the entire mantle, as if stirring a pot of soup. This process of mixing, or convection, provides the power for pushing Earth's surface plates around and bears ultimate responsibility for earthquakes and volcanic eruptions.

The mantle debate has persisted for so long because different lines of evidence have pushed scientists toward opposite conclusions. Previous studies of earthquake waves convinced many seismologists that the mantle mixes from top to bottom as one big layer.

Geochemists, however, came to believe in a two-layered mantle. They drew their conclusions from volcanic rocks, which have risen from Earth's upper mantle and provide a glimpse into what goes on inside the planet. The chemistry of these rocks suggests that the mantle segregates itself into almost completely separate upper and lower regions. The presumed dividing line lies at a depth of 660 kilometers, where descending seismic waves speed up, indicating a change in the character of the rock at that level.



Two visions of Earth: Similar pictures of the mantle beneath North America emerge from independent tomographic studies of secondary seismic waves (top) and primary seismic waves (bottom). These vertical slices through the planet show what appears to be cold ocean rock (blue) plunging toward the bottom of the lower mantle.

According to geochemists, ocean floor sinks only to the bottom of the upper mantle rather than dropping all the way to the base of the lower mantle, about 2,900 km below the surface.

In the split-level scheme of geochemists, the lower mantle remains essentially cut off from Earth's surface. This isolation has kept the deep rock in a pristine state, so it retains the primordial elements that Earth had in its infancy. In contrast, the upper mantle is like chewing gum that has lost its taste. The upper mantle is missing many of its primordial elements because rock from this region melted to form the crust early in its history, concentrating many of these elements at the surface.

Seismologists have tried to solve the mantle puzzle by using earthquake waves to produce images of the deep planet. Their technique is similar to computerized axial tomography, or CAT scanning, which uses X rays to make three-dimensional images of a person's internal anatomy.

In the past, pictures from seismic tomography were too fuzzy to reveal relatively thin features like subducting layers of ocean floor. The studies now emerging "give a much clearer image of Earth's interior than was previously possible," says Rob D. van der Hilst, a seismologist at the Massachusetts Institute of Technology. "On a few basic issues, I think we now have a definite answer."

In the April 10 NATURE, van der Hilst and his colleagues present seismic images showing slabs of subducting ocean floor diving down to the very bottom of the mantle—implying substantial mixing between the upper and lower portions of the mantle. Similar pictures appear in a separate study by Stephen P. Grand of the University of Texas in Austin, who discusses his research in the April GSA TODAY, a publication of the Geological Society of America.

"These are completely independent lines of research and completely different data sets, and they produce very similar images. The convergence of results is so convincing to everybody. By and large, we seem to reach a consensus that slabs do penetrate into the lower mantle," says van der Hilst, who collaborated with Sri Widiyantoro from the Australian National University in Canberra and E. Robert Engdahl of the U.S. Geological Survey in Denver.

To make their images, van der Hilst and his colleagues spent 5 years poring over records of 100,000 earthquakes from the last 3 decades. The scientists studied primary waves, or P-waves, which pulse through the planet vibrating molecules forward and backward, like sound speeding through air. These waves arrive at seismic stations before secondary waves, or S-waves, which shake molecules from side to side.

The researchers examined how long it took P-waves from individual earthquakes to reach stations around the world. Because they know, in general, how quickly P-waves travel through normal mantle rock, the scientists could detect unusual features in the mantle by looking for waves that took too long to arrive or arrived too quickly. Computers processed millions of these data points to create a three-dimensional image showing precisely where in the mantle the waves sped up or slowed down.

With this technique, van der Hilst's group found two unusually fast corridors of rock resembling broad ramps slicing into the planet. One is diving beneath North and South America, and the other is sinking under the southern margin of Asia and Europe. These fast regions, the scientists conclude, are slabs of ancient ocean floor subducting quite deep in the mantle, to at least about 1,300 km below the surface and in some cases much deeper. The ocean rock is colder than the surrounding mantle rock, so seismic waves speed up as they pass through the descending slabs.

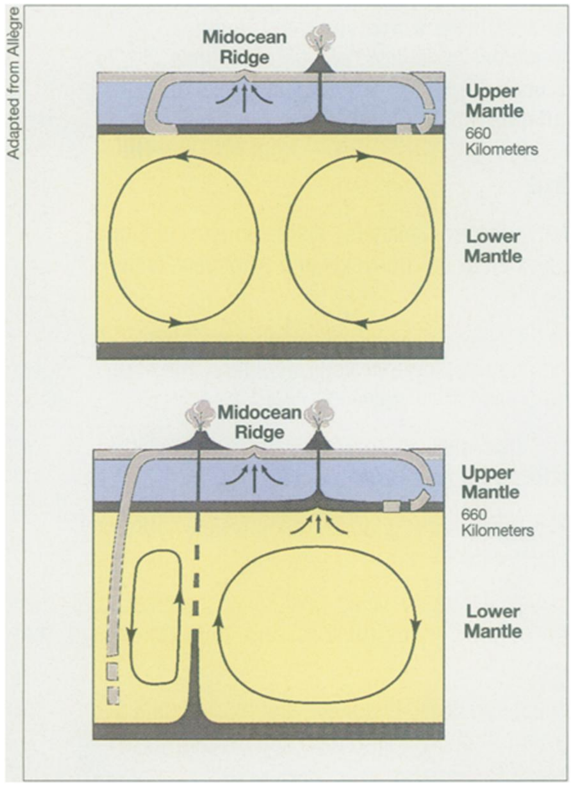
Grand took another approach, analyzing S-waves, which can echo off interior boundaries such as the junction between the core and the mantle or the mantle and the crust. He looked at only 250 earthquakes but analyzed each one in much more detail. Despite the different tactics, Grand found the same two long slabs descending beneath the Americas and beneath Europe and Asia.

The correspondence is striking, he says, because there has been little agreement in the past between tomographic studies relying on S-waves and those using P-waves.

Like fossils of extinct life, the cold slabs sitting deep in the planet are reminders of a period in Earth's history long past.

The feature beneath Europe and Asia, propose Grand and van der Hilst, is the floor of the Tethys, a sea that separated India and Africa from lands to the north. As continental movement closed the Tethys, the ocean floor disappeared into the mantle, forming the broad ramp visible in the seismic images. The Mediterranean, Black, Caspian, and Aral Seas are tiny remnants of the much larger Tethys.

The slab beneath the Americas represents a large section of the Pacific Ocean floor, called the Farallon plate, which once bordered western North and South America. Over the last 100 million years, much of the Farallon plate has slid eastward under the continents.



Geochemist Claude Allègre proposes that the mantle remained segregated into upper and lower sections (top figure) for most of Earth's history. In the last 500 million years (lower figure), the two-layer system has started breaking down, allowing mixing between the upper and lower mantles.

Strangely, neither of the new reports shows deep slabs where geophysicists most expected them: in the northwest Pacific. This hotbed of geologic activity is home to large earthquakes and major volcanic eruptions, all fueled by subducting ocean floor. From previous studies, geophysicists knew that the ocean slabs are sinking into the upper mantle beneath Japan, eastern Siberia, and the Aleutian Islands. The new tomographic studies, if accurate, show that these slabs do not venture from the upper mantle into the lower mantle.

The reason for this paradox may be that geoscientists are looking at the wrong moment in Earth's history. In the past, speculates van der Hilst, slabs in the western Pacific did sink all the way into the lower mantle. This process stopped temporarily about 40 million years ago, when movement of the Pacific seafloor plates changed direction, altering how the slabs descend and making it harder for them to break through the 660-km-deep barrier between upper and lower mantle, he says.

In support of this scenario, van der Hilst points to regions of cold rock sitting below Asia at a depth of 1,800 km. These lumps, he suggests, are remnants of the ancient Pacific floor that subducted into the lower mantle before the plate rearrangement occurred. Eventually, the oceanic plates of the northwest Pacific will resume their trip into the lower mantle, he suggests.

Geophysicists like van der Hilst and Grand acknowledge that they must refine their studies further to produce sharper tomographic images of the mantle. Even so, the new studies have won some converts among geochemists who formerly dismissed the fuzzy seismic pictures.

One such geochemist, Claude J. Allègre of the Institute for Physics of the Globe in Paris, has an idea that reconciles the volcanic rock studies with the new seismic images. Allègre explains that the two types of evidence need not agree, because they record different time periods. The rock geochemistry gives a picture of the entire history of mantle evolution over the last 4.5 billion years, whereas seismic images provide a snapshot of today and the last few hundred million years.

Linking the two lines of evidence, Allègre proposes that the pattern of mantle convection has changed during Earth's history. For the first 4 billion years, the mantle convected in two separate layers, thereby keeping the deep mantle relatively pristine. Over that time, though, Earth's interior cooled enough to alter the convection process. About 500 million years ago, the two-layer system started to break down, and it is now evolving toward a type of convection that mixes the mantle as one layer, he hypothesizes in the July 24 Earth and Planetary Science Letters.

Computer simulations support this concept, says Allègre, because they show that a two-layer convection system will switch over to a one-layer system as it cools.

"There is no conflict between the geochemistry and the geophysics," says Allègre, offering an olive branch.

It may take years, though, for the two opposing disciplines to break down old barriers and, like the mantle, blend into one. □