



The Engine that Drives the Earth

Peering into the mantle to reveal the inner workings of our planet

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Poets and philosophers have celebrated the timelessness of the land around us for eons, but the solid Earth is actually a very dynamic body. Great tectonic plates are in constant motion at Earth's surface.

Earthquakes and volcanic eruptions are manifestations of these movements on human time scales. But over millions of years, the movements of Earth's tectonic plate rearrange the face of the earth. They cause continents to rift and drift, creating entirely new ocean basins. Collisions between plates squeeze ancient oceans until they disappear and

produce majestic mountain ranges such as the Alps and Himalayas.

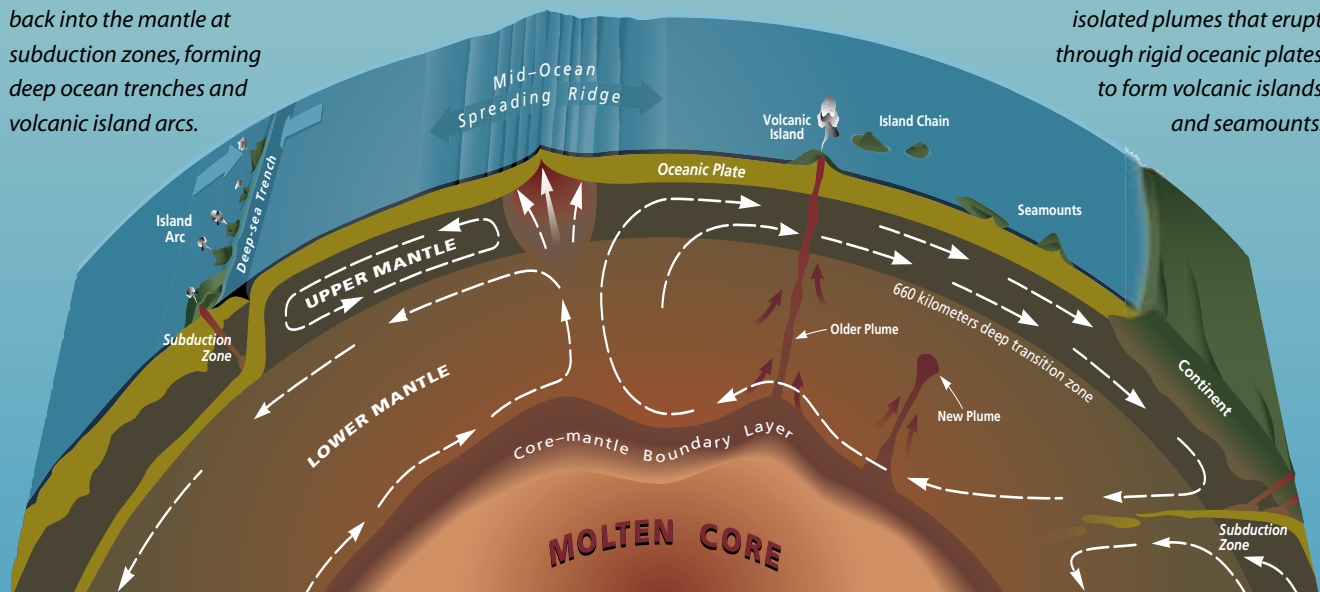
Like an auto mechanic who has to look "under the hood" to see the engine that powers your car, geologists need to look deep within Earth's interior to understand the tremendous underlying forces that build and shape Earth's surface. We are now beginning to comprehend and

Is the mantle one big pot or double-deckered?

Older, colder (and denser) oceanic plates collide with other plates and plunge back into the mantle at subduction zones, forming deep ocean trenches and volcanic island arcs.

At mid-ocean ridges, mantle rock rises, melts, and erupts to form new oceanic crust and volcanic mountain chains. Newly created seafloor crust spreads outward from the ridges.

In some seafloor regions, unusually hot areas of the mantle form narrow, isolated plumes that erupt through rigid oceanic plates to form volcanic islands and seamounts.



The underlying "flow" of materials in the mantle drives geological phenomena at Earth's surface, ranging from earthquakes and volcanoes to the creation of mountains and oceans. As any blacksmith knows, when a hard, brittle material like iron is heated to temperatures just below its melting point, it becomes malleable. Similarly, the high

temperatures and pressure within Earth's mantle deform rocks so that they can flow like a slowly moving liquid. Hot materials rise and cold materials sink in circular convection cells. Scientists are pursuing evidence to determine if the entire mantle convects (right side of diagram), or if the mantle is two-tiered (left side of diagram).

Jayne Doucette

describe the role that the Earth's mantle plays in driving changes on the planet we live on.

Hot, flowing rocks

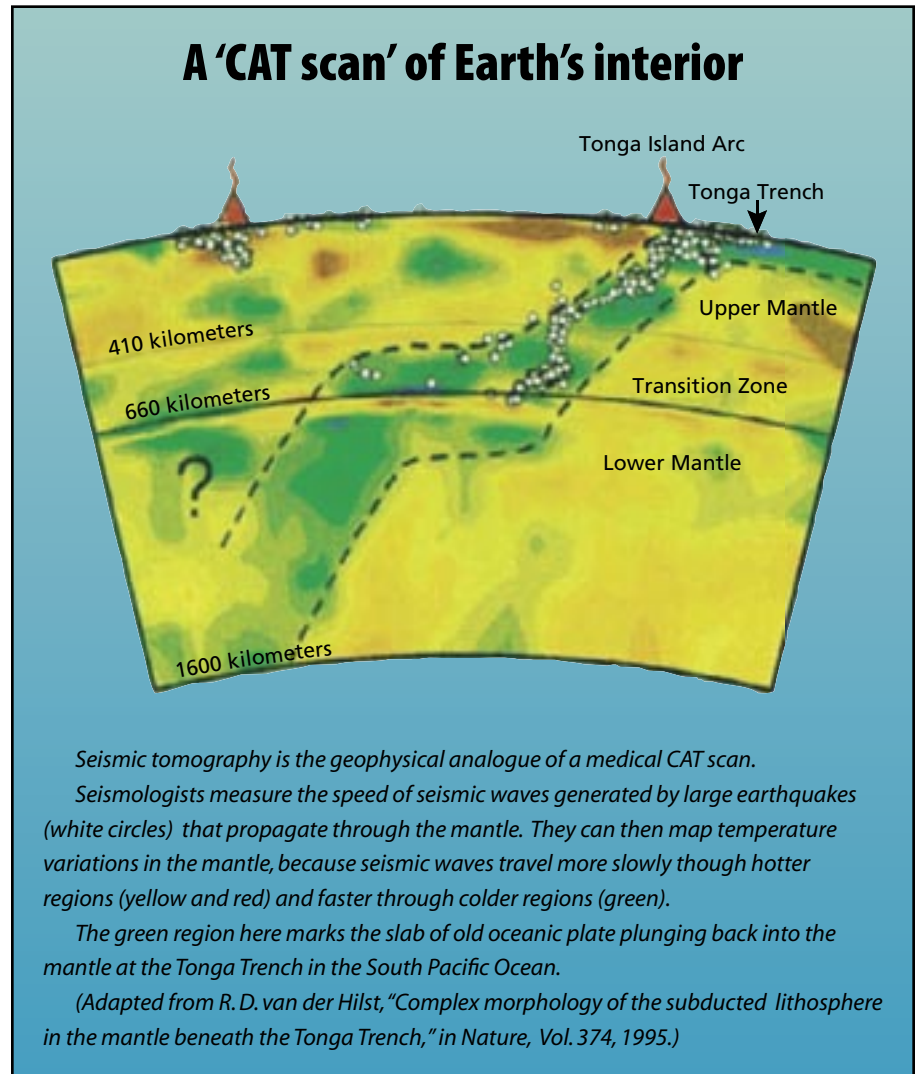
Earth's mantle is the solid, rocky interior of our planet that extends from the base of the crust all the way down to Earth's core, about 2,900 kilometers (1,800 miles) below the surface. Although they are solid, the rocks in Earth's mantle can deform and flow by viscous creep over long time periods. At first glance, this might seem odd; after all, the rocks we find on Earth's surface are cold and brittle, and they fracture or break if they are deformed. On a large scale, this same process causes earthquakes.

But as any blacksmith knows, when a hard, brittle material like iron is heated to a temperature just below its melting point, it becomes malleable. Similarly, given enough time, at the high temperatures and pressures found within Earth's interior, mantle rocks can deform and flow like a slowly moving fluid, even though they would appear solid to us. These movements are gradual in human terms (a few centimeters a year), but over a hundred million years, mantle rocks can move thousands of kilometers.

The energy that drives this movement is heat within the earth, which comes from two main sources. One is the residual heat left over from the formation of our planet 4.6 billion years ago. The radioactive decay of naturally occurring chemical elements in the earth—most notably uranium, thorium, and potassium—also releases energy in the form of heat. These two sources of heat warm Earth's mantle and cause it to rise and sink, much like soup in a pot on a stove. Material heated from below gets hotter and rises. It reaches the surface, releases its heat, becomes colder and denser, and sinks again.

Ocean trenches and ridges

The motion of tectonic plates, and all of their associated volcanic and earthquake activity, are believed to be the surface manifestation of similar thermal



convection occurring in Earth's mantle. The rigid outer layer of our planet, called the lithosphere, is the cold, top boundary of convection cells in the mantle. Two features of the ocean floor are the results of this active process.

At ocean trenches, old, cold, and dense lithosphere sinks back into the hotter mantle below, dragging surface plates along with it. The continents are carried along by these moving surface plates, producing the continental drift that, for instance, rifted and separated Africa and South America.

Beneath ocean spreading centers, two plates are moving apart. Hot, buoyant, solid mantle flows upward. It begins to melt as it reaches shallower areas where pressures are lower. That leads to volcanic

activity that forms new ocean crust along the great mid-ocean ridge system.

In addition to this plate-scale flow, plumes of hot material can rise at various places from within the convecting mantle to form ocean island volcanoes or "hot-spots" such as Hawaii. Indeed, convection currents in the mantle are responsible for most of the volcanic and tectonic processes that we see at Earth's surface.

A double-deckered mantle?

Mantle convection is the "engine" that drives our dynamic Earth. But since scientists cannot directly observe the workings of this engine, they have debated the exact mechanisms of this convection for more than half a century.

For example, does convection occur

over the entire mantle at once, creating a huge pot of essentially the same soup? Or is it layered—with separate convection cells occurring in an “upper mantle” (extending from near the surface to a depth of about 660 kilometers, or 410 miles) and in an underlying “lower mantle” (with denser rocks under higher pressure)?

This second scenario would result in two chemically distinct reservoirs in the mantle that almost never mix, like oil and water. The first model would seem to require a more compositionally uniform, well-mixed mantle. Two lines of evidence give contrasting answers to the question.

Lavas erupted at mid-ocean ridges and at oceanic islands have different compositions of trace elements and noble gases. (See “Conduits Into Earth’s Inaccessible Interior.” <http://oceanusmag.who.edu/v42n2/hart.html>) This strongly suggests that distinct geochemical reservoirs exist in the mantle, and seems to favor a layered convection model with different mantle compositions in the upper and lower mantle.

Geophysical ‘CAT scans’

In the mid-1990s, however, seismologists—studying how seismic waves generated by large earthquakes propagated in the mantle—made a startling discovery. Using a technique called seismic tomography—the geophysical analogue of a medical CAT scan—they were able to map variations in the speed of the seismic waves traveling through the mantle. We can infer temperature variations in the mantle from this, because seismic waves travel more slowly through hotter regions and faster through colder regions.

The seismic tomographic images showed that in some cases, cold tectonic plates sink only to depths of about 600 to

700 kilometers—near the base of the upper mantle. In other cases, they sink more than halfway into the lower mantle. These results clearly show that the density contrast (of lighter and denser rocks) at the base of the upper mantle is not a barrier to mixing between the upper and lower mantle.

How can we then explain the evidence for distinct reservoirs in the mantle? In other words, why isn’t our mantle soup well mixed?

This vexing question is unresolved. Some scientists have proposed that there are “unstirred” blobs of material floating in the mantle that have persisted throughout most of geologic history. Others have suggested that a dense, poorly mixed region exists in the lower 1,000 kilometers of the mantle. This region is chemically distinct and rich in heat-producing elements, and it generates flow into “hotspot” areas.

Other unanswered questions

There are other puzzling questions about how the mantle convection engine works. For example, seismic tomography studies of the shallow mantle beneath oceanic spreading centers reveal a broad region of slow seismic velocities. This suggests the presence of partially melted material across an area of several hundred kilometers. Yet volcanic activity at mid-ocean ridges occurs over remarkably narrow zones just a few kilometers wide. We don’t know how melting produced over such a broad region in the mantle can be focused into such a narrow zone of eruptive activity at the seafloor.

Another major debate centers around the origin of hotspot volcanic centers such as Hawaii and Iceland. Some researchers argue that hotspots are caused by rising plumes of hot mantle material originating

in the “unstirred” reservoir just above the earth’s core. Others think that processes occurring in the uppermost mantle cause some hotspots. Answering such questions will require the integration of data from seismology, geochemistry, and mineral physics with fluid-dynamical modeling of mantle convection.

New tools to look into the earth

This is a particularly exciting time for studies of the oceanic upper mantle. Advances in ocean-bottom seismic instrumentation now make it possible to record high-quality, seismic data from earthquakes at sites over the two-thirds of the planet covered by water. (See “Listening Closely to ‘See’ Into the Earth,” <http://oceanusmag.who.edu/v42n2/collins.html>)

Advances in geochemical and petrological studies over the past decade, including new analytical and sampling techniques, are defining important new limits on the mantle conditions that produce melting.

And in recent years we’ve seen tremendous increases in the affordability and speed of computer systems, improved numerical techniques, and a growing understanding of the complex processes of melting and viscous flow.

These advances are allowing the development of the first global-scale, self-consistent, three-dimensional models of mantle convection that can explain our surface observations of tectonic plate motions, gravity and topography. These studies will lead to much more complete understanding of mantle convection.

Like the auto mechanic at your local garage, we are finally “lifting the hood” to view Earth’s engine and the forces that drive changes on the face of the earth.