EARTH'S INTERIOR STRUCTURE

To begin to understand planet Earth, one must understand what is below the earth's surface. Although much knowledge of the earth's interior structure is based on inference, seismological research has provided a detailed picture of the earth's layers and their physical and chemical characteristics.

PRINCIPAL TERMS

- **accretion:** the growth of a planet through gravitational attraction of matter in space; the process by which Earth and other large planetary bodies formed
- **asthenosphere:** the second layer (from the top) of the earth's interior; corresponds with part of the upper mantle (100 to 200 kilometers [62-125 miles] below the earth's surface)
- **differentiation:** the process of a planetary body's substances separating into distinct layers caused by different chemical and physical characteristics
- **discontinuity:** an area within the earth's surface in which seismic wave activity abruptly changes; in some cases, discontinuity corresponds with a border between two of the earth's layers
- **lithosphere:** the uppermost layer of the earth's interior; a hard, rigid, rocky layer that includes the crust and the very top of the mantle
- **mesosphere:** the third layer (from the top) of the earth's interior; a dense, rigid layer that corresponds with most of the mantle
- **rheology:** the study of the flow of matter; focuses on liquids and soft solids that behave like plastic
- **seismic wave:** a moving, energy-transferring disturbance that occurs because of an event, such as an earthquake, that releases low-frequency acoustic energy
- **silicate:** a compound with a negatively charged silicon ion; a main component of the earth's crust
- **wave velocity:** the rate of propagation of a wave; one factor in seismological research that can provide useful information about the structure of the earth's interior, which includes regions in which wave velocity markedly increases or decreases

Layers of the Earth's Interior: Chemical Divisions

The earth's interior is made up of three chemically distinct layers: the crust, the mantle, and the core. The mantle is further divided into the upper mantle and the lower mantle, and the core is divided into the outer core and the inner core.

The earth's solid crust spans from the surface to a depth of about 35 kilometers (22 miles), although the depth varies with location, sometimes reaching as far as 70 kilometers (43 miles). In general, the crust is thicker at continents and thinner at the ocean floor. Also, the continental crust is different from the oceanic crust in terms of composition: Continental crust is made of low-density rocks such as granite, whereas oceanic crust contains mainly high-density rocks such as basalt, a volcanic rock.

The crust is also described as having an upper layer called sial, which corresponds with the continental crust, and a lower level called sima, which corresponds with the oceanic crust. Sial is a reference to two of the main types of minerals found in the rocks of the continental crust: silicates and aluminum. Sima refers to the magnesium silicates in the oceanic crust.

The mantle stretches from a depth of about 35 to 2,890 kilometers (22 to 1,790 miles) below the earth's surface and is composed of silicates containing large amounts of magnesium and iron. Although the mantle is considered to be a solid layer, the layer's high temperature allows it to flow slowly over time (less so in the lower mantle, which is under more pressure). The mantle makes up about 84 percent of the earth's volume, and its plastic upper layer provides a slow-moving "sea" of rocks on which the earth's tectonic plates ride.

The lower mantle is more rigid and filled with denser materials, because of increased pressure and temperature. The lowest 200 kilometers (124 miles) of the mantle is referred to as the D" zone, an area in which the velocity of seismic waves decreases abruptly. This zone is also called the Gutenberg discontinuity, and it leads into the boundary between the mantle and the core.

The center of the earth is known as the core, and it is made up of two sections: a molten outer core and a solid inner core. The outer core starts 2,890 kilometers (1,790 miles) below the surface of the earth and is roughly 2,266 kilometers (1,408 miles) deep. Then, at about 5,150 kilometers (3,160 miles) below the surface, the inner core begins. The core's diameter is approximately twice the diameter of the moon.

Both sections of the core are composed mainly of iron and nickel, along with trace amounts of lighter elements. Substances behave differently under different amounts of pressure, which accounts for the inner core's solidity and the outer core's liquidity. The center of the core reaches a temperature of about 6,373 kelvins (6,100 degrees Celsius), which is roughly the same as the temperature at the sun's surface.

Layers of the Earth's Interior: Rheological Divisions

Whereas the crust, mantle, and core are considered chemical divisions, the earth's interior is also described rheologically, with layers divided by their physical characteristics and further defined by the flow and elasticity of matter, which behaves differently depending on temperature, pressure, and other variables. Rheology focuses on fluids as well as soft solids, in which solids behave like plastics under certain conditions. From the surface to the center, the earth's rheological layers are the lithosphere, asthenosphere, mesosphere, and the outer and inner cores (which correspond to the chemical core divisions).

The lithosphere—a hard, rigid, rocky layer—encompasses the crust and the very top of the mantle. Like the crust, the lithosphere has two distinct types—oceanic and continental—broken up into tectonic plates. These plates ride on top of the next layer, the asthenosphere, and play a major role in earthquakes and volcanic activity. The lithosphere is slow-moving and considered to behave elastically on a scale of thousands of years. The lithosphere plays a heat-conductive role atop the convecting mantle.

The boundary between the lithosphere and asthenosphere is evident based on response to pressure: The former is brittle while the latter is more viscous. The asthenosphere corresponds with part of the upper mantle, spanning a depth of about 100 to 200 kilometers (62-125 miles), although parts of the asthenosphere are thought to extend as deep as 700 kilometers (435 miles). This layer is characterized by low density, high viscosity, and mechanical weakness. (In fact, its name comes from the Greek word for "weak.") The asthenosphere flows on the order of millimeters per year (up to about one centimeter at most) and convects heat up from the inner layers of the earth.

The mesosphere (not to be confused with the atmospheric layer of the same name) encompasses the remainder of the mantle, spanning from about 600 kilometers (373 miles) deep to the core-mantle boundary, and it is denser and more rigid than the asthenosphere. Finally, the core divisions are the same chemically and rheologically.

Differentiation of Earth's Interior Layers

Before the earth's interior layers could differentiate, the earth itself had to form. The planet began as a solar nebula, a giant spinning cloud of helium, hydrogen, and other elements and debris from the big bang, which likely occurred 13.7 billion years ago. More than 9 billion years later, the nebula began to contract into a disc, causing it to spin faster. Nuclear fusion of the hydrogen and helium led to the formation of the sun in the center of the nebula, and other debris collided, forming asteroids and larger protoplanets; this growth by addition of matter is a process called accretion. One of these protoplanets became Earth.

As accretion continued, the earth's temperature increased until it reached a point in which the interior began to differentiate. Within 10 million years, the substances that made up the primitive earth's mostly homogeneous interior started separating into layers based on their physical and chemical properties.

An event called the iron catastrophe describes the formation of the earth's core, in a process that took tens of thousands of years, a relatively short time on the geologic time scale. During the iron catastrophe, NiFe (a dense alloy of nickel and iron) separated from its molten emulsion with other interior materials, particularly lighter silicates, and traveled toward the center of the earth. This process was driven by density differences between NiFe and the other materials, and it was facilitated by the earth's rising temperature, which allowed the once-homogeneous mix of materials to begin to melt. A primitive mantle, a layer that included what would eventually become the crust, also settled during the iron catastrophe.

Around 4.3 billion years ago, a crust formed with a basaltic composition similar to the oceanic crust. During this time, high temperatures in the mantle drove convection faster than it occurs in the present, and this initial crust likely did not last long. Four billion years ago, the continental crust as we know it began to form.

The upper mantle continues to differentiate through a process called plate tectonics. As mentioned, the lithosphere features tectonic plates, about seven or eight major ones and many more minor ones, that move about one centimeter per year and interact with each other at three types of boundaries: convergent, divergent, and transform faults. These interactions can result in earthquakes, volcanic activity, the formation of mountains, and the formation of trenches in oceans.

The movement of tectonic plates is influenced by a variety of factors, but the main driver is thought to be convection within the mantle, which exerts both gravitational and frictional forces on the plates. Mantle convection is the process of heat rising slowly from the interior of the earth through currents. To a lesser extent, gravitational forces not related to convection also help drive the plate movements. One such force relates to the creation of an oceanic lithosphere at spreading ridges: The new material adds on in a way that plates become thicker near the ridge, creating a lateral incline that results in a gravitational sliding effect. Other influences on plate movement include tidal drag from the moon's and the sun's gravitational pulls, the Coriolis effect, and minor wobbles created by the earth's rotation.

Boundaries Between Earth's Layers

Seismology, the study of seismic waves, provides a clear picture of the location and characteristics of the boundaries between the earth's interior layers. A seismic wave is a disturbance that carries energy through the earth from an event that releases low-frequency acoustic energy; an earthquake is a good example of one such event. While there are multiple types of seismic waves, one subtype, body waves, vastly contributed to seismological research of the earth's interior. Body waves travel through the interior (as opposed to the surface) of the earth and are divided into two classes: P waves ("primary" or "pressure" waves) and S waves ("shear" or "secondary" waves). P waves move faster, as their motion is direct. S waves, in contrast, involve motion that moves perpendicularly to the overall propagation of the wave. The viscosity of fluids is too low to support the perpendicular movement of S waves, but P waves can travel through both fluids and solids.

With an understanding of S waves and P waves, scientists have been able to use seismic data from earthquakes to map out discontinuities in the earth's interior; these discontinuities are areas of abrupt change of seismic activity, such as an increased or decreased P-wave velocity. Discontinuities are indicative of a compositional change and, therefore, help pinpoint the boundary between different layers of the earth.

Closest to the surface, the Mohorovičić discontinuity (often referred to as the Moho) indicates the border between the crust and the mantle. Because the crust has variable thickness, the Moho's relative depth varies: Although it can be found 5-10 kilometers (3-6 miles) under the ocean floor, it is much farther below continents, about 20-90 kilometers (10-60 miles) deep, at an average depth of 35 kilometers (22 miles). In the rheological division of layers, the Moho lies within the lithosphere except at mid-ocean ridges, where it indicates the boundary between the lithosphere and the asthenosphere.

The Moho was discovered by its namesake, Croatian seismologist Andrija Mohorovičić, in 1909. Mohorovičić had noticed that in seismograms of shallow earthquakes, there were actually two sets of P waves and S waves being recorded, not one as expected. One set moved directly from one point to another, fairly close to the surface, but the other set was refracted, much like a beam of light hitting a prism.

At a depth of about 220 kilometers (137 miles), within the upper mantle, lies another discontinuity. Called the Lehmann discontinuity, it was described in 1958 by Danish seismologist Inge Lehmann, who found that P-wave and S-wave velocities sharply increased upon reaching this depth. Later research showed conflicting results as to whether this discontinuity is present only under continents or only under the ocean floor. (Lehmann also is known for her discovery of the boundary between the earth's inner and outer cores, a boundary often called the Lehmann discontinuity.)

Farther into the mantle, in the deepest 200 kilometers (124 miles), which is referred to as the D" zone, there exists another discontinuity (the Gutenberg discontinuity), at the bottom of which is the core-mantle boundary. Named for German-born American seismologist Beno Gutenberg, this discontinuity is marked by decreased P-wave velocity and the disappearance of S waves, which cannot travel through fluid. This is the boundary between the solid mantle and the molten outer core. It is an uneven boundary, caused in part by convected heat from the core to the mantle and by turbulent eddies produced by the Coriolis effect within the liquid outer core.

Drilling to Earth's Center

Much of what is known about the interior structure of the earth is conjecture, based on the behavior of seismic waves. Because of the interior's extreme heat and pressure, sending humans or equipment far below the surface of the earth is impossible. Attempts have been made, however, to drill partway through the crust.

One of the largest-scale drilling attempts occurred in 1962. A Soviet research team began a project called the Kola Superdeep Borehole. The team's goal was to drill to the Mohorovičić discontinuity (at a depth of about 15 kilometers, or 9.3 miles) to learn more about the earth's interior. After three years of searching for a suitable location and after five years of constructing the drill and planning the operation, the drilling finally began in 1970 at the Kola Peninsula in the northwest region of the Soviet Union. Because the project aimed to go much deeper than ever before, the standard rotating drill shaft used in most deep-drilling projects would not work. Instead, the researchers built a drill in which the drill bit rotated independent of the drill pipe, greatly reducing the amount of friction resistance. The drill was powered by a pressurized lubricant that was pumped down the shaft.

The 9 inch borehole grew slowly, hitting the 12-kilometer (7.5-mile) mark twenty-four years later. It was here that the team had to give up. The temperature in the borehole was a sweltering 180 degrees Celsius (356 degrees Fahrenheit), much hotter than the team's initial estimate of 100 degrees Celsius (212 degrees Fahrenheit). This temperature was more than the drill could handle, because the heat at this level of the crust causes rocky material to behave like plastic, melting and blocking the drill's path. Had the drill made it to the 15-kilometer (9.3-mile) point, the temperature likely would have reached 300 degrees Celsius (572 degrees Fahrenheit).

Though the Kola project did not reach its depth goal, it was able to collect many core samples along the way, providing valuable insight into the earth's interior structure and geological history. The oldest samples were estimated to date from 2.7 billion years ago. Even fossils (twenty-four species of plankton) were found in the upper half of the borehole.

Researchers continue to attempt to learn more about the earth's interior. One group, the Integrated Ocean Drilling Program (IODP), is a collaboration of researchers from twenty-four countries seeking to advance this field of study. The program involves deep drilling through the oceanic crust, which is thinner than the continental crust. This drilling allows for the collection of ancient rock samples that tell a detailed story of the earth's geological history.

Deep-sea drilling has far-reaching research implications that go beyond understanding the earth's interior structure. One of the major objectives of the IODP, for example, is to monitor climate change, both on a small time scale and in larger cycles over time. The IODP builds on decades of work done by two older projects, which are now defunct: the Deep Sea Drilling Project and the Ocean Drilling Program.

Through seismology, drilling, and other research, scientists have moved well beyond the "hollow earth" hypotheses of the seventeenth and eighteenth centuries. Some of these hypotheses even included the idea of more suns and atmospheres inside the earth.

Rachel Leah Blumenthal

Further Reading

Blakey, Ronald C., Wolfgang Frisch, and Martin Meschede. *Plate Tectonics: Continental Drift and Mountain Building.* New York: Springer, 2011. With great relevance to the characteristics of the earth's crust, this book provides an introduction to plate tectonics, covering the earth's early history to the present day. Topics include subduction zones, mid-ocean ridges, and the formation of mountains.

Chilingar, George V., et al. *Evolution of Earth and Its Climate: Birth, Life, and Death of Earth.* Boston: Elsevier, 2011. This text provides ample information on the earth's formation, composition, and magnetic activity. It also explores the formation of the moon and its influence on the earth.

Dickey, John S. *On the Rocks: Earth Science for Everyone.* New York: Wiley, 1996. From stardust to Earth's and other planets' formation, this book is ideal for earth science novices. Easy to understand but comprehensive, *On the Rocks* is an enjoyable overview.

Lutgens, Frederick K., and Edward J. Tarbuck. *Earth Science*. 13th ed. Upper Saddle River, N.J.: Prentice Hall/Pearson, 2012. Originally published in 1976, *Earth Science* is an updated introductory textbook geared to undergraduates, including those without a science background. It covers geology and astronomy and other earth science topics.

Monroe, James S., and Reed Wicander. *The Changing Earth: Exploring Geology and Evolution*. 5th ed. Belmont, Calif.: Brooks/Cole, Cengage Learning, 2009. This textbook offers a solid introduction to geology in an easily readable format, supplemented with many relevant photographs, diagrams, and real-world examples.

Wu, Chun-Chieh. *Solid Earth*. Vol. 26 in *Advances in Geosciences*. London: World Scientific, 2011. This book discusses research papers in the fields of seismology, planetary exploration, the solar system, and other topics relevant to earth science.

See also: Continental Drift; Creep; Cross-Borehole Seismology; Deep-Earth Drilling; Discontinuities; Earthquake Magnitudes and Intensities; Earthquake Prediction; Earthquakes; Earth's Age; Earth's Core; Earth's Differentiation; Earth's Lithosphere; Earth's Magnetic Field; Earth's Mantle; Earth's Oldest Rocks; Geodynamics; Faults: Normal; Faults: Strike-Slip; Faults: Thrust; Faults: Transform; Heat Sources and Heat Flow; Lithospheric Plates; Magnetic Stratigraphy; Mantle Dynamics and Convection; Metamorphism and Crustal Thickening; Notable Earthquakes; Plate Motions; Plate Tectonics; Rock Magnetism; Seismic Wave Studies; Seismometers; Slow Earthquakes; Soil Liquefaction; Stress and Strain; Subduction and Orogeny; Tsunamis and Earthquakes; Volcanism.