THE EARTH'S LAYERS

THE INSIDE STORY

What are the **major layers** of the Earth?

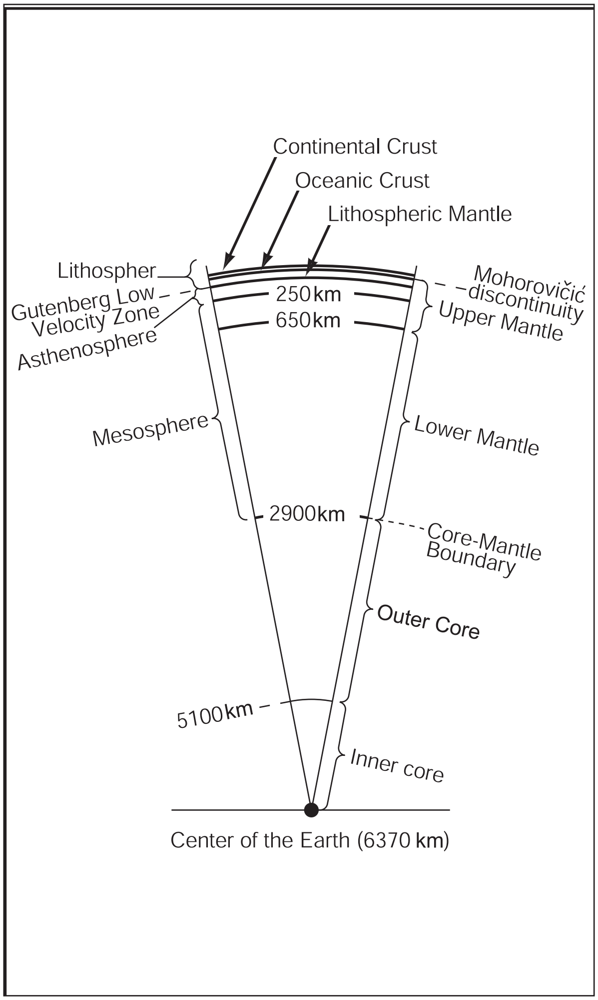
The Earth is generally divided into four major layers: the crust, mantle, inner core, and outer core. The following defines each division. (Note: numbers representing the thickness and depth of these layers differ depending on the reference; thus, the numbers here should be taken as approximations):

Crust—The Earth's crust is the outermost layer and is the most familiar, since people live on the outer skin of the crust. It is rigid, brittle, and thin compared to the mantle, inner core, and outer core. Because of its varying characteristics, this outer layer is divided into the continental and oceanic crusts.

Mantle—In general, the Earth's mantle lies beneath the crust and above the outer core, averaging about 1,802 miles (2,900 kilometers) thick and representing 68.3 percent of the Earth's mass. A transition zone divides this layer into the upper and lower mantles.

Outer core—The liquid outer core is a layer between 1,793 and 3,762 miles (2,885 and 5,155 kilometers) deep in the Earth's interior. It is thought to move by convection (the transfer of heat through the circulating motion of particles—in this case, the material that makes up the outer core), with the movement possibly contributing to the Earth's magnetic field. The outer core represents about 29.3 percent of the Earth's total mass.

Inner core—The inner core is thought to be roughly the size of the Earth's Moon. It lies at a depth of 3,762 to 3,958 miles (5,150 to 6,370 kilometers) beneath the Earth's surface and generates heat close to temperatures on the sun's surface. It represents about 1.7 percent of the Earth's mass and is thought to be composed of



The Earth's cross section, illustrating the cores, mantle, crust, and other divisions.

a solid iron-nickel alloy suspended within the molten outer core.

What **percent** of the Earth's volume **constitutes the crust, mantle, and core**?

Although the core and mantle are about equal in thickness, the core actually forms only 15 percent of the Earth's volume, while the mantle comprises 84 percent. The crust makes up the remaining 1 percent.

Do geologists **subdivide the Earth** in any other way?

Yes, geologists have another way of looking at the Earth's interior layers. The following list refers to this view:

Lithosphere—The lithosphere (*lithos* is Greek for "stone") averages about 50 miles (80 kilometers) thick and is composed of both the crust and part of the upper mantle. Overall, it is more rigid than deep, yet more molten mantle and cool enough to be tough and elastic. It is thinner under the oceans and in volcanically active continental regions, such as the Cascades in the western United States. The lithosphere is physically broken up into the brittle, moving plates containing the world's continents and oceans. These lithospheric plates appear to "float" and move around on the more ductile asthenosphere. (For more on plate tectonics, see below).

Asthenosphere—A relatively narrow, moving zone in the upper mantle, the asthenosphere (*asthenes* is Greek for "weak") is generally located between 45 to 155 miles (72 to 250 kilometers) beneath the Earth's surface. It is composed of a hot, semi-solid material that is soft and flowing after being subjected to high temperatures and pressures; the material is thought to be chemically similar to the mantle. The asthenosphere boundary is closer to the surface—within a few miles—under oceans and near mid-ocean ridges than it is beneath landmasses. The upper section of the asthenosphere is thought to be the area in which the lithospheric plates move, "carrying" the continental and oceanic plates across our planet. The existence of the asthenosphere was theorized as early as 1926, but it was not confirmed until scientists studied seismic waves from the Chilean earthquake of May 22, 1960.

What is the difference between **compositional and mechanical layering** of the Earth?

When scientists talk about the Earth's crust (oceanic or continental), mantle, and cores, they are discussing layers with distinct chemical compositions; thus, it is referred to as compositional layering. The lithosphere and asthenosphere differ in terms of their mechanical properties (for example, the lithosphere moves as a rigid shell while the asthenosphere behaves like a thick, viscous fluid) rather than their composition, so this is why the term mechanical layering applies.

Who gave the first **scientific explanation** of the **Earth's interior**?

Empedocles, a philosopher who lived during the 400s B.C.E., was one of the first to formulate a scientific description of the Earth's interior. He believed the inside of the Earth was composed of a hot liquid. In fact, Empedocles was close to the truth. Modern scientists realize that the Earth's interior does not hold mythical beings but megatons of rock and molten matter.

What is **isostatic rebound**?

Scientists know the lithosphere can "bend," usually thanks to a heavy load on the crust. For example, a large ice cap, glacial lake, or mountain range can bend the lithosphere into the asthenosphere, causing the lower layer to flow out of the way. The load will then sink until it reaches its buoyancy point; then it is supported by the asthenosphere. If anything changes the load, the lithosphere will rise back up over geologic time—usually measured in thousands of years—in a process called isostatic rebound. One recent example is the Northern Hemisphere regions that sat under the miles-thick glacial ice sheets during the last ice ages. Many, such as the Adirondack Mountains in northern New York, are now experiencing isostatic rebound, often resulting in small earthquakes as the land rebounds.

Why is it so **important to study** the Earth's **internal structure**?

The Earth's internal structure is important because of its many influences on our planet's past, present, and future geology. For example, the mantle and crust are

Is there any folklore about the Earth's interior?

Because of the lack of knowledge about the Earth's interior, many ancient cultures had strong beliefs and superstitions associated with the underworld. One familiar to many is the concept of Hell or Hades, a place ruled by a "devil" or "Satan." Some cultures believe that wicked people who die are punished in Hell in the afterlife. Another example of a myth about the Earth's interior comes from the Mayas of the Yucatan. They believed in the Mitlan, the icy cold underworlds presided over by Ah Puch, or the Lord of Death. When Peru and Chile were ruled by the Incas, they also had an underground god of death, Supai. The god of the Earth, Pachacamce, was also able to cause underground rumblings, usually when he was angry.

Ancient myths and folklore have also brought us tales of trolls, goblins, giants, elves, and dragons living in the deep subterranean caves in the Earth's interior. Still other ancient cultures spoke of a hollow Earth, where other civilizations existed deep inside our planet. Such lore has long since been interpreted as entertainment—in the guise of science fiction and fantasy—by such great writers as Jules Verne in his *A Journey to the Center of the Earth*.

directly involved in plate tectonics, or how our planet's landmasses and ocean floor move around the planet. Convection in the Earth's mantle generates and recycles the planet's crust at the plate boundaries over time. And the inner and outer cores appear to be directly related to the generation of the Earth's magnetic field.

CRUST, MANTLE, AND CORES

How do the **oceanic and continental crusts** differ?

The Earth's crust varies in thickness and composition beneath the oceans and continents. The oceanic crust measures from 3 to 6 miles (5 to 10 kilometers), averaging about 4 miles (7 kilometers) in thickness; the continental crust measures between 16 to 62 miles (25 to 100 kilometers), averaging about 19 miles (30 kilometers) thick. The thickest continental crust regions exist mostly under large mountain ranges such as the Sierra Nevada, Alps, and Himalayas, where it can be as thick as 62 miles (100 kilometers).

The oceanic and continental crusts also differ in composition and density. The oceanic crust is composed of dark, iron-rich rock similar to basalt. It is high in silica and magnesium (sometimes referred to as SIMA); it is often distinguished from the next layer (the mantle) by having more silica. The continental crust's composition is more complex. In general, continental rocks are light-colored, with an average composition between diorite (mostly hornblende and plagioclase feldspar with a little quartz) and granodiorite (the same composition as diorite, but with more quartz present). These are rocks high in silica and aluminum and are often referred to as SIAL. The continental crust's distinguishing compositional difference from oceanic crust is its higher amount of silica, with many regions having relatively high concentrations of quartz. This is mechanically crucial because—particularly in the presence of minor amounts of water—quartz-rich rock becomes relatively flexible at mid-crustal temperatures and pressures. Density differs, too: The oceanic crust has a density of 233 pounds per cubic foot (3,000 kilograms per cubic meter); the continental crust has a lower density of only 195 pounds per cubic foot (2,500 kilograms per cubic meter).

Beside the fact that both crusts lie on the mantle, there is one similarity between the two: Both have a temperature range of between 1,148 to 32°F (700 to 0°C). (For more information about the rocks mentioned above, see "Rock Families.")

What are the **major minerals** that make up the **Earth's crust**?

Although the oceanic and continental crusts differ in mineral composition, the overall Earth's crust is abundant in two major mineral groups: silica (around 12 percent) and orthoclase feldspar (just over 50 percent). (For more information about these and other minerals, see "All about Minerals.").

What is the **Mohorovičić discontinuity**?

The boundary between the crust and mantle is named in honor of the man who first proposed its existence, Croatian geologist Andrija Mohorovičić. In 1909, Mohorovičić analyzed data from a Croatian earthquake, calculating a jump in seismic wave velocity at a depth of about 34 miles (54 kilometers). This turned out to be the mantle boundary underneath the continental crust, a division now called the Moho or the Mohorovičić discontinuity.

Scientists believe the change is compositional, the rock type changing from the crust (with a seismic velocity of around 4 miles [6 kilometers] per second) to the denser mantle (with a seismic velocity around 5 miles [8 kilometers] per second). Like most interior layers, the Moho varies in depth. Beneath the continents, the Moho averages around 22 miles (35 kilometers) but overall it ranges from around 12 miles (20 kilometers) to 44 or 56 miles (70 or 90 kilometers) in depth. Beneath the oceans, the Moho averages about 4 miles (7 kilometers) below the ocean floor.

What are the **upper and lower mantles**?

The mantle is divided into the upper and lower mantle, represented by seismic and chemical changes in the layer. The upper mantle falls between 12 miles (20 kilometers) to 44 miles (70 kilometers) beneath the continental crust, and about 3 miles (5

Have scientists collected samples of the Earth's mantle?

No, since they would have to physically drill into the mantle no such samples have been collected to date. The depths involved are too great for today's drilling technology. But that doesn't mean scientists haven't tried. In 1956, the Moho Project was developed to drill through the Earth's crust to the Mohorovičić discontinuity, the division between the crust and the mantle. The plan was to drill to the Moho through the seafloor, where the Earth's crust is thinnest. Lack of funding and other problems—both scientific and engineering—caused the program to shut down in 1966.

The Moho Project eventually developed into the Deep-Sea Drilling Project and the Ocean Drilling Project. Though the drilled holes are relatively shallow (seldom more than 33,000 feet [1,000 meters]), which is not even close to the Moho, the data gathered have given scientists a better understanding of oceanic sediments and volcanism.

kilometers) beneath the oceanic crust. It begins to transition to the lower mantle at about 255 miles (410 kilometers) deep. Past the transition zone, the lower mantle starts about 416 miles (670 kilometers) to about 1,793 miles (2,885 kilometers) deep.

Are there many **discontinuities** in the Earth's **mantle**?

As technology improves, scientists uncover more about our planet. This includes the discoveries of the many "boundaries" (discontinuities) within the Earth's mantle created by seismic or chemical changes. For example, the Hales discontinuity is found in the upper mantle at depths of about 37 to 56 miles (60 to 90 kilometers), a region in which seismic velocities change. Other seismic discontinuities include the Gutenberg and Lehmann discontinuities. (For more information about these boundaries, see below.)

Other discontinuities occur in the mantle at about 255, 323, and 416 miles deep (410, 520, and 670 kilometers). Each is either a chemical (416-mile [670-kilometer]) or seismic (255- and 323-mile [410- and 520-kilometer]) change, the entire range representing the gradual transition between the upper and lower mantles. At the lowest depth, and with accompanying high pressures, the crystalline structure of the material gets tighter, changing the rock type.

Have any **upper mantle rocks** been discovered?

It was once thought that rocks found deep underground, such as kimberlites and lamproites (ancient rocks that also yield most of the world's diamonds), would give scientists a good idea of the composition of mantle rock, but even the deepest mine in the world, a gold mine in South Africa that reaches about 2,225 feet (3,581 meters), doesn't come close to reaching the mantle. One might think, too, that molten rock brought up from the mantle—by way of volcanoes and hot spots—might yield some information. However, that is still not a good representative sampling because as volcanic rocks rise to the surface they are contaminated by other minerals.

But many scientists believe we do not have to drill to get to the mantle. They have found older, deep crustal and mantle rock thrust up in what are called ophiolite belts. Such rocks are found in the Bay Islands of western Newfoundland and in Oman, an area that contains the world's largest fragment of ancient oceanic lithosphere exposed on the Earth's surface. (The so-called Oman United Arab Emirates ophiolite belt contains 2-billion-year-old rock and is part of a large ophiolite belt running from Spain to the Himalayas.) In fact, certain Oman ophiolite rocks called boninites are thought to represent melted material formed by partial fusion of the hot, shallow mantle.

What **major minerals** may make up the **Earth's lower mantle**?

The Earth's lower mantle appears to contain three important minerals: just less than 80 percent perovskite $(MgFe)SiO_3$; about 20 percent magnesio-wüstite—$(MgFe)O$; and a small trace of stishovite, SiO_2, a mineral synthesized by Russian mineralogist Sergei Stishov (1937–) in the late 1950s and first found at Meteor Crater, Arizona, in the 1960s. To some scientists this implies that perovskite is the most abundant mineral in the Earth, though this has not yet been proven.

What is the **Gutenberg discontinuity**?

In 1913, German geophysicist Beno Gutenberg (1889–1960) was the first to discover the approximate location of the mantle-outer core boundary, a transition zone now known as the Gutenberg discontinuity. This is where seismic waves slow down, indicating a zone between the semi-rigid inner mantle and the molten, iron-nickel outer core. (Gutenberg also published many papers on seismic waves with Charles Richter, who developed the Richter scale that measures earthquake intensity. For more information about earthquakes and seismic waves, see "Examining Earthquakes.")

Who first **discovered the Earth's core**?

In 1906, R. D. Oldham, the first to use seismic data to determine the interior of the Earth, postulated the existence of a fluid core. In 1915, Beno Gutenberg published a measurement of the core's radius.

Who **discovered the solid inner core**?

In 1936, Danish seismologist Inge Lehmann (1888–1993) presented a paper titled, "P'" (or P-prime, after the seismic waves), which announced the discovery of Earth's inner core. The division between the inner and outer core is now called the Lehmann discontinuity. (Lehmann later became an authority on the structure of the upper mantle.)

The size of this core within a core was not calculated until the early 1960s, when an underground nuclear test was conducted in Nevada. Because the precise location and time of the explosion was known, echoes from seismic waves bounced off the inner core provided an accurate means of determining its size. These data revealed a radius of about 756 miles (1,216 kilometers). The seismic P-waves passing though the inner core move faster than those going through the outer core—good evidence that the inner core is solid. The presence of high-density iron thought to make up the inner core also explains the high density of the Earth's interior, which is about 13.5 times that of water.

What is the **importance of the outer core** to the Earth's **magnetic field**?

Some scientists believe the molten, iron outer core has a powerful effect on the Earth: Acting as a geodynamo, it might create the magnetic field. Others point to the differences in the inner and outer core flow rates. This could create what is called a hydromagnetic dynamo that would explain the Earth's magnetic field.

Either way, such a planetary-scale dynamo would be similar to how an electric motor generates a magnetic field, one that acts like a giant bar magnet with a north and south pole. The basic physics of electromagnetism fits here: Iron, whether liquid or solid, conducts electricity; when you move a flowing electric current, you generate a magnetic field at a right angle to the electric current direction.

The molten outer core of our planet releases heat by convection, which then displaces the flowing electrical currents. This generates the magnetic field that is oriented around the axis of rotation of the Earth, mainly due to the rotational effects on the moving fluid. Thus, invisible geomagnetic lines stretch from one pole, curve far out into space, then go back to the opposite pole. The curved lines are further shaped by the electrically charged particles of the solar wind into a teardrop shape called the magnetosphere.

Paleomagnetic records indicate this magnetic field has been around for at least 3 billion years. Scientists know that without some mechanism—such as the core's interactions deep within the Earth—the field would only last about 20,000 years, mainly because the Earth's inner temperatures are too high to maintain any permanent magnetism. And without this magnetic field, all organisms—including humans—would be exposed to the extremely damaging effects of solar wind radiation.

Has the Earth's **magnetic field** ever **reversed polarity**?

Yes. Based on data from ancient (and not-so-ancient) rock, scientists know the Earth's north and south magnetic fields have reversed polarity many times. The switching from north to south (an individual reversal event) seems to take only a

What are "core-rigidity zones" and why are they important?

Scientists have long believed the outer core is liquid, but they recently discovered the existence of core-rigidity zones, or small patches of rigid material within the fluid outer core that seem to congregate at the core-mantle boundary. They believe these patches might influence many phenomena, such as the behavior of the Earth's magnetic field; the formation of volcanic hot spots, such as the Hawaiian Island chain; and even why the Earth wobbles on its axis as it rotates (called nutation).

Some scientists suggest that these chunks of material form as the Earth cools and heat flows out of the core, allowing the molten outer core to solidify into the inner core. This causes an increase in the lighter elements in the outer core. Because they are lighter than iron, they can "float to the top" of the outer core, collecting as solid material at the core-mantle boundary. Of course, the reality of how this works is probably much more complex.

couple thousand years to complete; once the reversal takes place, periods of stability seem to average about 200,000 years. No one really knows why the poles reverse, but theories range from the changes in lower mantle temperatures to the imbalance of landmasses on our world (most of the continental landmass is in the Northern Hemisphere).

Interestingly enough, the last magnetic reversal was 780,000 years ago, giving us our current northern and southern magnetic poles. Scientists believe our magnetic field is slowing weakening, so we might be heading for a long-overdue magnetic reversal. They also know that reversals tend to occur when there is a wide divergence between the magnetic poles and their geographic equivalent, as is currently the case. No one really knows when or if a reversal will occur, but it will probably not be during our lifetimes. Researchers know our ancestors did survive the last few magnetic reversals to continue our species. In fact, as one scientist mentioned, the only consequence of a reversal might just be the purchase of a new compass.

SEISMOGRAPHY AND EARTHQUAKES

How do scientists use **earthquake waves** to study the **Earth's interior**?

All knowledge about what happens in the mantle and cores of the Earth has been derived from circumstantial evidence—mostly the analysis of seismic data. Scientists use earthquake waves, or waves generated by the seismic shaking from earthquakes, to better understand the Earth's interior. (For more information about earthquakes

Who first used seismic data to study the Earth's interior?

When the great Assam earthquake occurred on June 12, 1897, R. D. Oldham, who was then heading the Geological Survey of India, used the records to become the first person to clearly identify the S wave. He was also first to prepare the travel time tables for seismic P- and S-waves and to use the seismological data to infer the internal structure of the Earth.

and earthquake waves, see "Examining Earthquakes.") When a quake occurs, the Earth reverberates like a ringing bell, generating seismic waves with speeds that range between 1.9 to 9.4 miles (3 to 15 kilometers) per second.

The two major seimic waves are called Love and Rayleigh (also seen erroneously as Raleigh) waves. Both are surface waves that are more likely than P- or S-waves to make tall buildings sway. Love waves, named after the English mathematician A. E. H. Love (1863–1940), move in a side-to-side direction at about 2.7 miles (4.4 kilometers) per second, perpendicular to the earthquake direction and parallel to the surface. Rayleigh waves travel at about 2.3 miles (3.7 kilometers) per second and cause the most damage. Named after English physicist Lord John William Strutt Rayleigh (1842–1919), they are similar to waves caused by throwing a rock into a pond, with the waves moving outwards in all directions from the center.

Two other seismic waves—P- (primary) and S- (secondary or shear) waves—go all the way through to the Earth's interior, moving at different velocities through various geologic materials. Similar to sound waves, P-waves compress and dilate the matter they travel through (rock or liquid) and can move twice as fast as S-waves. On the other hand, S-waves move through rock but can't travel through liquids. In general, both waves slow down as they move through hotter materials and refract or reflect as they travel through layers with varying physical properties.

Why are these factors important? The differences in speeds and direction of the waves helped researchers determine the various liquid and solid layers—along with discontinuities—within the Earth's interior. By mapping the travel time and dividing the distance traveled by that time, researchers were able to determine the velocity of the seismic waves. (These changes in speed occur because parts of the mantle and core are made of different materials.) Once scientists were able to pinpoint these velocity changes, earthquake data became a way of "seeing" inside the Earth's interior.

Do **P- and S-waves** travel through the **crust**?

Yes, even though scientists use P- and S-waves mostly to study the Earth's mantle and cores, the waves also can be used to interpret information about the crust. In general, it is known that P-waves travel about 4 miles (7 kilometers) per second through oceanic crust (similar to their speed through the rocks basalt and gabbro), and through the continental crust at about 3.7 miles (6 kilometers) per second (similar to their speed through the rocks granite and gneiss).

Can **P- and S-waves be detected everywhere** they occur during an earthquake?

No, not all places on Earth can detect P- and S-waves during certain earthquake events. Some areas do not receive these seismic waves because of the way the core and mantle interact with the waves. For example, P-waves are bent at the core-mantle boundary, creating an arc called the P-wave shadow zone, which is about 105-142 degrees from the earthquake's epicenter. Because of this, P-waves are not received at seismic stations along the shadow zone. S-waves also have an S-wave shadow zone, which is a much larger arc of about 105 to 180 degrees. Scientists also believe the S-waves can't go through the Earth's outer core, which is why they believe the outer core must be liquid.

Was **seismic data** used to determine the **lithosphere and asthenosphere**?

Yes, earthquake waves were used to determine the boundaries of the lithosphere and asthenosphere in a way similar to how the crust, mantle, and core were discovered. At a depth of about 62 miles (100 kilometers), both P- and S-waves decrease in velocity. This boundary marks the base of the lithosphere and the top of the asthenosphere, called the low-velocity zone (LVZ).

Are there **problems with determining the Earth's interior** using earthquake waves?

Like any study in science, understanding the Earth's interior using earthquake waves is not perfect. For example, seismic waves do not travel in a straight line, but will bend, refract, and reflect if they run past, through, or bounce off an irregularity (usually a difference in rock density). Also, most seismic stations are located on the continents in the Northern Hemisphere, leaving huge gaps in data elsewhere around the world (although scientists are working to build up the network of seismic stations).

What is **seismic tomography**?

Seismic tomography is a relatively new technique that looks into the Earth's interior. This method is similar to medical ultrasound, in which doctors use high frequency sound through a mother's belly to map out the various densities within the womb, using the changing velocities of the ultrasound waves. The image, in the form of a tomograph, is actually a cross section of the mother and child, with the various density readings interpreted as the baby's bones, skin, and organs.

Seismic tomography, first invented by Adam Dziewonski of Harvard University in the 1970s, depends on a somewhat similar procedure. Instead of using ultrasound, this tomography looks at seismic waves generated by numerous earthquakes, with the travel time of the seismic waves compared to a reference model. By combining the data from many earthquakes, subtle changes in wave speed can be identified. (In general, if the waves move quickly, it usually indicates cooler or denser rock; slower waves indicate warmer or less-dense rock.) Scientists then use computers to construct three-dimensional density images of the Earth's interior, including upwelling and downwelling of molten rock in the mantle.

MOVING CONTINENTS AND PLATE TECTONICS

Who **initially proposed** the idea of **moving continents**?

The idea of the continents moving around our planet was mentioned as early as 1587 by the Flemish map maker (with German origins) Abraham Ortelius (1527–1598) in his work *Thesaurus geographicus*. In 1620, Francis Bacon (1561–1626) also mentioned the idea, noting the fit of the coastlines on both sides of the Atlantic Ocean. By the 1880s, many other scientists were mentioning the connection. For example, in 1885, Australian geologist Edward Seuss proposed that the southern continents had once been a huge landmass that he called Gondwanaland.

But it was German scientist Alfred Wegener (1880–1930) who first formally published the idea of continental displacement (or drift) in his 1915 book, *The Origins of Continents and Oceans*. He believed the continents were once joined together into one supercontinent, a place he named Pangaea (also spelled Pangea, meaning "all land") that was surrounded by a superocean called Panthalassa. He also suggested that the massive continent divided about 200 million years ago, with Laurasia moving to the north and Gondwana (or Gondwanaland) to the south. Wegener based his ideas of continental motion on numerous observations: The continental distribution of fossil ferns called *Glossopteris* (from studies by Seuss); the discovery of coal in Antarctica by Sir Ernest Henry Shackleton (1874–1922); similar glacial erosion seen in the tropical areas of India, South Africa, and Australia; the apparent fit of the South America and west African continental shorelines; and, although it may only be legend, by watching ice floes drifting on the sea.

Although Wegener is now considered "the man who started a revolution" in geology, his ideas were hotly debated by scientists of his time. Not only was he a meteorologist in a community of geologists, but he could offer no logical mechanism for the movement of the landmasses. It wasn't until the 1960s, long after his tragic death in Greenland (he died at the age of 50 while on a rescue mission), before Wegener was vindicated. By then, scientific measurements, observations, and technology had

A man looks at the rubble of a building destroyed in Bumerdes, Algeria, after an earthquake struck the region on May 21, 2003. It was estimated that more than 1,500 people died and more than 7,200 people were injured in this quake, which registered 6.7 on the open-ended Richter scale. *AP/Wide World Photos.*

advanced enough to prove that, indeed, the continents are moving around the planet on giant lithospheric plates. Wegener's theory of continental displacement was replaced by the new field of plate tectonics, which is the basis for modern geology.

What **physical evidence** shows that the **continents move**?

Scientists have gathered plenty of evidence that shows the continents move over time. For example, the shape of the continents and their fit was determined by Sir Edward Bullard in 1965. He did not site the usual continental shapes we see, but he measured the "real" edge of the continents: the continental slope, an area that shows a much better fit at the 6,560 foot (2,000 meter) depth contour than at the shorelines of continents.

Other scientists matched the continental geology on either side of an ocean. For example, the mountain belts of the Appalachians and the Caledonides are relatively similar geologically, as are the sedimentary basins of South Africa and Argentina.

Another way to prove that continents move over time includes paleontology, in which similarities or differences of fossils on certain continents indicate a match. For example, there are similar Mesozoic Era reptiles in North America and Europe, a time when scientists believe those two continents were joined together; similar Carboniferous and Permian flora and fauna are found in South America, Africa, Antarctica, Australia, and India. In contrast—no doubt after the continents were well separated—there is a wide diversity of organisms in the Cenozoic Era.

Can magnetism in rocks determine continental movements over geologic time?

Yes, paleomagnetism, or the record of a rock's magnetism based on the polarity of magnetic minerals within, can be used to determine continental movements throughout the geologic record. Taking paleomagnetic data from all over the world, scientists discovered that the geomagnetic poles (not the geographic poles) wandered over time. The data also revealed that the magnetic poles have never been more than 20 degrees from the geographic poles.

Taking this data one step further, researchers knew there can be only one north pole and one south pole at any time. They discovered that ancient rocks vary in magnetic orientation and direction. Scientists determined that the magnetic poles did not wobble in different orientations for each continent, but that the continents moved and the poles stayed in relatively the same locations. Thus, scientists were able to reconstruct the location of continents over the Earth's long history based on the polarity changes in rocks from all over the world.

What is **plate tectonics**?

The Earth's crust and lithosphere are broken into over a dozen thin, rigid shells, or plates, that move around the planet over the plastic aesthenosphere in the upper mantle. The interaction between these plates is called tectonics, from the Greek *tekon* for "builder"; plate tectonics describes the deformation of the Earth's surface as these plates collide, pass by, go over, or go under each other. In other words, plate tectonics describes how these plates move, but not why.

Overall, plate tectonics combines Wegener's theory of continental displacement (or drift) and Hess's discovery of seafloor spreading (see below). The theory has truly revolutionized the study of the Earth's crust and deep interior. It allows scientists to study and understand the formation of such features as mountains, volcanoes, ocean basins, mid-ocean ridges, and deep-sea trenches, and to understand earthquakes and volcano formation. It also gives clues as to how the continents and oceans looked in the geologic past, and even how the climate and life forms evolved.

Who contributed to **early work in plate tectonics**?

There were several key scientists who contributed to the study of plate tectonics as it became more favored in the late 1960s. One of the most popular scientists to discover evidence for plate tectonics was J. Tuzo Wilson (1908–1993). By 1965, he described the origin of the San Andreas fault, the large crack in the Earth's surface near San Francisco, California, as a transform fault (or strike-slip)—one of the major plate bound-

What was the shrinking Earth theory?

Before the idea of plate tectonics took over modern geologic thinking, some scientists believed in the shrinking Earth theory. They believed that the Earth started as a molten ball of rock; as it cooled, a skin of crust formed. As the rest of the molten ball cooled, the Earth shrunk, causing the crust to buckle, much like how an apple shrinks and wrinkles as it dries in the sun. The large wrinkles became the continents and ocean basins, while the small wrinkles turned into the long mountain belts.

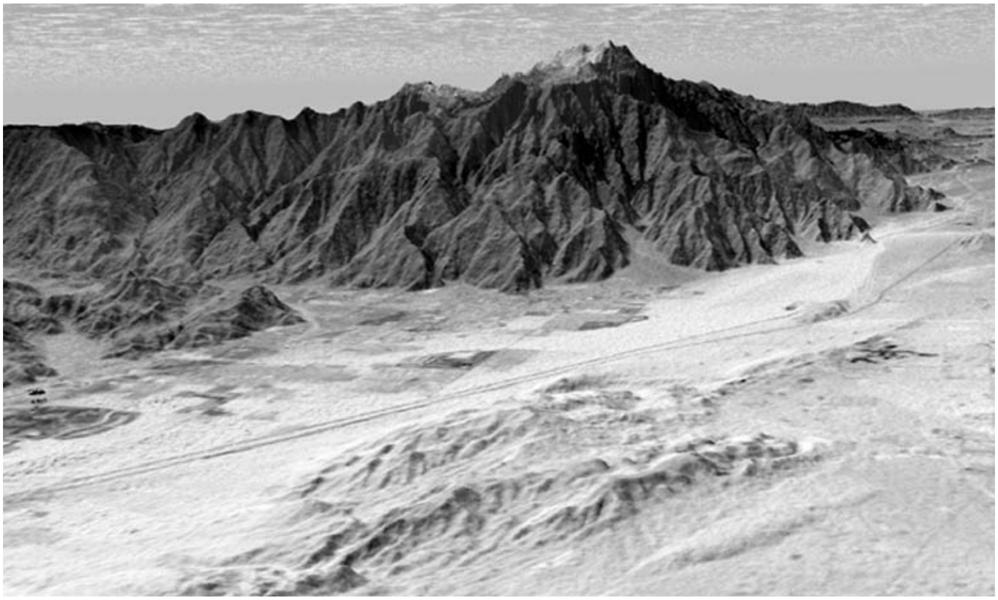
But there were problems with this theory. For example, the shrinking Earth theory predicts that mountain ranges continually rise from the shrinking of the globe, but in reality mountains rise and are worn down over geologic time. The theory also has a difficult time accounting for the movement of the continents around the world. It can't explain the presence of fossils in high places, such as the Alps. The theory also predicts that volcanoes and mountain ranges occur randomly worldwide, an idea that we now know is false. (Mountain ranges are found in narrow belts, such as the Alps and Appalachian Mountains, and most volcanoes occur along plate boundaries or above areas known as hot spots.) And of course, all these events and features are better explained by plate tectonics.

aries. In 1968, Xavier LePichon (1937–) participated in the definition of the overall "plate tectonics" model and published the first model quantitatively describing the motion of six main plates at the Earth's surface; in 1973, he wrote the first textbook on the subject.

Other geologists have made major contributions to the development of the plate tectonics theory: William Jason Morgan published a landmark paper in 1968 explaining the many tectonic plates and their movements; he also recognized the importance of mid-plate volcanic hot spots that create island chains such as the Hawaiian Islands. Walter Pitman III was instrumental in interpreting the pattern of marine magnetic anomalies detected around mid-ocean ridges, an indicator of active seafloor spreading and evidence of plate tectonics. And Lynn R. Sykes used seismology to refine plate tectonics, and he noted the connection between transform faults at the mid-ocean ridges and plate motion. He also coauthored *Seismology and the New Global Tectonics* in 1968, which relates how existing seismic data could be explained in terms of plate tectonics.

What is the connection between **earthquakes and plate tectonics**?

Only the lithosphere has the strength and brittle behavior to fracture in an earthquake. And as lithospheric plate boundaries push, pull apart, or grind against each other, earthquakes occur. In 1969, scientists published the locations of all earthquakes



The city of Palm Springs nestles at the base of Mount San Jacinto in this computer-generated perspective. The San Andreas Fault passes through the middle of the sandy Indio Hills in the foreground. This 3-D perspective view was generated using topographic data from the Shuttle Radar Topography Mission (SRTM) and an enhanced color Landsat 5 satellite image. *AP/Wide World Photos.*

that occurred from 1961 to 1967. They discovered most earthquakes (and volcanoes, too, they later learned) occurred in narrow belts around the world. Thus, it is now known that areas with frequent earthquakes and volcanoes help define the plate boundaries. (For more information about earthquakes, see “Examining Earthquakes,” and for volcanoes, see “Volcanic Eruptions”.)

What did the **continents** look like **in the past**?

Because of the movement of the lithospheric plates, the continents’ positions have changed over time. For example, some scientists believe that about 700 million years ago a huge continent called Rodinia formed around the equator; about 500 million years ago, the continent broke apart, forming Laurasia (today’s North America and Eurasia) and Gondwana (or Gondwanaland; today’s South America, Africa, Antarctica, Australia, and India). Then, about 250 million years ago, the continents were once again together in one massive supercontinent called Pangea (or Pangaea, translated as “all land”). Eventually, the huge continent began to break up, forming Laurasia and Gondwana again.

What are the **four types of lithospheric plate boundaries**?

There are just over a dozen major lithospheric plates, and all include continental and oceanic crust, plus part of the mantle. As each one moves continuously over the face

Can plate tectonics help in earthquake prediction?

In an indirect way, plate tectonics can help in earthquake prediction, but only to a point. Scientists know that earthquakes along plate boundaries are some of the strongest. Thus, they can predict the general areas where larger earthquakes will occur in the future. In fact, based on past earthquake data, scientists estimate that about 140 earthquakes of magnitude 6 or greater will occur on the lithospheric plate boundaries each year. Unfortunately, we do not have the technology or knowledge to pinpoint when or where such events will occur.

of the Earth, they interact along their boundaries. There are four major types of plate boundaries: divergent, convergent, transform, and plate boundary zones. The following lists and defines each boundary:

Divergent—Divergent (or constructional) plate boundaries are where the plates pull away from each other, creating new crust; seafloor spreading takes place at divergent boundaries (see below). Earthquakes that occur along these boundaries are usually shallow, and such boundaries are usually very young, geologically speaking. Overall, the spreading rates of divergent plate boundaries seems to range from fractions of an inch to just over 3 inches (1 to 8 centimeters) annually. For example, the Mid-Atlantic Ridge is a divergent plate boundary in which the Eurasian plate is pulling away from the North American Plate.

Convergent—Convergent (or destructional) boundaries are often thought of as trench boundaries. An example is the Marianas Trench in the Pacific Ocean, which is the world's deepest trench and is where the Pacific plate converges with the Philippine plate. These boundaries also mark subduction zones, an area where the oceanic plate subducts into the mantle. At convergent plate boundaries, plates are destroyed by subduction. For example, in addition to the Mariana Trench, the Andes Mountains of South America's west coast sit on a convergent boundary (the Nazca plate is pushing into and being subducted under the South American plate). Earthquakes that occur along these boundaries are shallow to deep, and the crust is much older than at divergent boundaries. There are three subtypes of convergent plate boundaries: ocean-ocean, in which a volcanic island arc forms above the downgoing slab, such as in the Mariana Trench; ocean-continent, in which a volcanic arc forms along the edge of a continent (continental crust is too buoyant to subduct), such as with the Andes of South America; and the continent-continent, in which a collision between the boundaries produces a continental crust up to twice as thick as normal, such as with the Himalayas, created by the collision of the Indian and Eurasian plates.

Transform—Transform boundaries are plates that slide by one another but do not destroy or create new material. For example, the San Andreas fault in California is a transform boundary, in which the North American plate slides by the Pacific plate.

Plate boundary zones—For the want of a better name, scientists consider those broad belts as undefined boundaries; the effects of plate interaction are unclear at plate boundary zones. For example, the Mediterranean-Alpine region between the African and Eurasian plates is not well defined, as it contains several smaller fragmented plates (called microplates) in between the major plates. Because of this, the geological structure of the area—and even the earthquake patterns—are very complex.

What is **seafloor spreading**?

Seafloor spreading is one of the processes that helps move the lithospheric plates around the world. The process is slow but continuous: Like a hot, bubbling stew on the stove, the even hotter asthenospheric mantle rises to the surface and spreads laterally, transporting oceans and continents as if they were on a slow conveyor belt. This area is usually called a mid-ocean ridge, such as the Mid-Atlantic Ridge system in the Atlantic Ocean.

The newly created lithosphere eventually cools as it gets farther from the spreading center. (This is why the oceanic lithosphere is youngest at the mid-ocean ridges and gets progressively older farther away.) As it cools, it becomes more dense. Because of this, it rides lower in the underlying asthenosphere, which is why the oceans are deepest away from the spreading centers and more shallow at the mid-ocean ridges. After thousands to millions of years, the cooled area reaches another plate boundary, either subducting, colliding, or rubbing past another plate. If part of the plate subducts, it will eventually be heated and recycled back into the mantle, rising again in millions of years at another or the same spreading center.

How was **seafloor spreading discovered**?

In the 1950s, scientists realized that as igneous rocks cool and solidify (crystallize), magnetic minerals align with the Earth's magnetic field like tiny compass needles, essentially locking the magnetic field into the rock. In other words, rocks with magnetic minerals act like fossils of the magnetic field, allowing scientists to "read" the rock and determine the magnetic field from the geologic past. This is called paleomagnetism (see above).

The idea was proposed by Harry Hess (1906–1969), a Princeton University geologist and U.S. Naval Reserve rear admiral, and independently by Robert Deitz, a scientist with the U.S. Coast and Geodetic Survey, both of whom published similar theories

If the ocean floor is always reforming, how old are the rocks?

The age of the ocean floor varies from the Jurassic Period (200 million years ago) to modern time at the major mid-ocean ridges. For example, the continually forming Mid-Atlantic Ridge between the South American and African plates is a range of some of the youngest "mountains" on the planet.

that became known as seafloor spreading. In 1962, Hess proposed the idea of seafloor spreading, but had no proof. As Hess formulated his hypothesis, Dietz independently proposed a similar model, which differed by noting the sliding surface was at the base of the lithosphere, not at the base of the crust.

Support for Hess's and Dietz's theories came only one year later: British geologists Frederick Vine and Drummond Matthews discovered the periodic magnetic reversals in the Earth's crust. Taking data from around mid-ocean ridges (seafloor spreading areas), Vine noted the magnetic fields of magnetic minerals showed reversed polarity. (The Earth's magnetic field has reversed its polarity around 170 times in the last 80 million years.) From the spreading center outward, there was a pattern of alternating magnetic polarity on the ocean floor—swaths of opposing polarity on each side of the ridge. As the spreading center continues to grow, new swaths develop, pushing away material on either side of the ridge. Thus, these strips of magnetism were used as evidence of lithospheric plate movement and of seafloor spreading.

How **fast** does the **seafloor spread**?

Today, the rates of seafloor spreading vary from about 1 inch (2.54 centimeters) per year in the mid-Atlantic ridge area to about 6 inches (15 centimeters) in the mid-Pacific Ocean. Scientists believe seafloor spreading rates have varied over time. For example, during the Cretaceous Period (between 146 to 65 million years ago) seafloor spreading was extremely rapid. Some researchers believe this quick movement of the lithospheric plates may have also contributed to the demise of the dinosaurs: As the continents changed places over time, so did the climate. In addition, more plate movements might have meant more volcanic activity, releasing dust, ash, and gases into the upper atmosphere and contributing to more climate variation. This change in climate and vegetation may have cause several species of dinosaurs to die out or become diseased, contributing to the dinosaurs' extinction.

How **fast** are the **lithospheric plates moving**?

The speed of the lithospheric plates around the world depends on which plate you are observing. For example, the fastest is the Australian plate, which is moving northward

Will California ever fall into the ocean?

No, California will *not* fall into the ocean, but the part of California on the Pacific plate (moving northwest) will move along the North American plate boundary (moving southeast), changing part of the state. Over the last 20 million years, the Pacific plate has slid about 200 miles (322 kilometers) northwest at an average rate of about 2 inches (5 centimeters) per year.

at about 6.5 inches (17 centimeters) per year. The Atlantic Ocean, with plates such as the Eurasian to the east and North American to the west, is moving about 0.5 to 1 inch (1 to 2.54 centimeters) per year on each side. This is a more typical number for the majority of the major plates. In fact, the Atlantic Ocean has opened more than 33 feet (10 meters) since Columbus sailed across in 1492.

Why is the **Mariana Trench** so famous?

The Mariana Trench is the deepest point on the Earth's crust, measuring at a depth of 35,840 feet (10,924 meters) on the Pacific Ocean floor, or about 8 miles (13 kilometers) deep. If you sank the Earth's highest surface mountain (Mt. Everest, which stands at 29,022 feet [8,848 meters] high) into the trench it would still be covered with more than 5,000 feet (around 2,000 meters) of water.

What **mountains** have been formed by **plate collisions**?

There are a number of beautiful mountain ranges built by plate collisions. Some of the more famous ones are the Rocky Mountains in North America, the Alps in Europe, the Pontic Mountains in Turkey, the Zagros Mountains in Iran, and the Himalayas in central Asia. All these mountain ranges were formed by plates slamming into one another, creating the uplift of the land.

What is the **Wadati-Benioff zone**?

The Wadati-Benioff zone is named in honor of seismologists Kiyoo Wadati and Hugo Benioff. At a convergent plate boundary, the downgoing slab (or subducting chunk of a boundary) is defined by a zone of earthquakes known as the Wadati-Benioff zone, an area that reaches to a depth of about 435 miles (700 kilometers) from the Earth's surface.

What are **rifts**?

There are numerous deep rifts on the Earth's surface. Many associated with powerful tensional tectonic forces that are constantly trying to rip or split apart parts of the

Earth's crust. Over thousands of years, the movements of the rifts' associated plates will open many of these cracks even wider, while moving continents into new positions. We will not see these changes in our lifetimes because it takes thousands to millions of years to notice such great movements. Right now, we can only measure plate motion a few inches per year, not miles.

What is the **African Rift System**?

The African Rift System (or Afro-Arabian Rift System) is a group of rifts or cracks in the Earth's crust. In general, this system has three "arms" of rifts, or what geologists call a triple junction structure:

Red Sea Rift—This rift separates Arabia from Egypt and Ethiopia. (It extends northward into Israel to the Dead Sea, Jordan River, and Sea of Galilee Rift Valley; from there it becomes less distinct as it continues north into Lebanon and Turkey.) It is up to 167 miles (270 kilometers) across and increases about 1 inch (2.5 centimeters) per year; it currently has a maximum depth of up to 4,921 feet (1.5 kilometers).

Gulf of Aden Rift—This separates southern Arabia from Somalia. Its width is similar to the Red Sea Rift at the western edge; as it reaches the Indian Ocean, the width increases to over 205 miles (330 kilometers).

East African Rift Valley—This cuts through Eastern Africa in a southwest direction and is about 2,423 miles (3,900 kilometers) in length; its width in Kenya varies from 25 miles (40 kilometers) in the south to about 62 miles (100 kilometers) toward the north. In Ethiopia, its width varies from about 19 to 81 miles (30 to 130 kilometers); at the junction with the Red Sea and Gulf of Aden Rifts, the width reaches about 186 miles (300 kilometers).

What **mechanism** makes the **lithospheric plates move**?

Even though the idea of moving lithospheric plates has been accepted by most scientists, no one can agree on the mechanism(s) that cause them to move over time. But there are plenty of theories. One of the most commonly acknowledged theories was proposed in 1928, when geologist Arthur Holmes suggested that, like a pot of bubbling water on the stove, convection in the mantle was the driving force behind continental drift. He also suggested that the crust was recycled by divergence and subduction, but he had no proof at that time.

Today, most scientists believe in a modified version of Holmes's idea: they theorize that a dozen or so rigid plates slide around on the partially molten asthenosphere, with the continents embedded in the plates. In addition, because basalt is more dense than granite, the oceanic crust "sags" lower as it "floats" on the asthenosphere. As for the driving forces behind plate motion, they are probably some combination of mid-ocean ridge pushing and plates being pulled deep into the mantle (subduction), all the result of a fluid mantle in motion.

Can the **middle of a lithospheric plate** experience **earthquakes and volcanoes**?

Yes, the middle of a lithospheric plate can experience plate boundary events in the form of earthquakes and volcanoes, but it does not happen very often. Called intraplate ocean tectonics, it involves something scientists often refer to as hot spots: rising molten rock from the mantle that breaches the mid-plate surface, forming volcanoes. If the plate is moving in one direction, the volcanoes line up in one direction in a youngest-to-oldest fashion. One of the most famous hot spot areas is the Hawaiian Islands chain, which is located in the "middle" of the Pacific lithospheric plate. (For more information about the Hawaiian Islands, see "Volcanic Eruptions.")

There are also unexplained movements in the middle of lithospheric plates. For example, the strongest earthquakes ever recorded in the United States (1811–1812) occurred along what scientists call the New Madrid fault line, which is an area near New Madrid, Missouri, located at the "middle" of the North American plate. Another occurred in 1886 at Charleston, South Carolina. Both these areas seem to be strange places for such earthquakes, and scientists still can't explain why. (For more information about these and other earthquakes, see "Explaining Earthquakes.")