

2.1 Seismic Waves

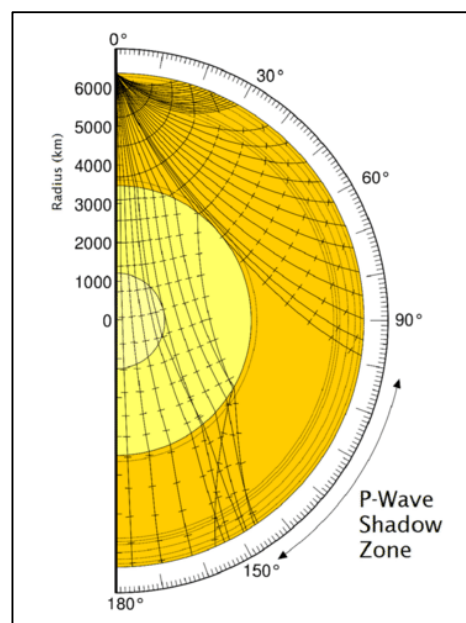
Most earthquakes happen when rock within the outer portion of the Earth suddenly breaks along a *fault* (a fracture on which slip occurs), and generates energy that travels through the surrounding rock outward from the break. Earthquake energy moves through rock and sediment in the form of vibrations. These movements are called seismic waves, or earthquake waves. When energy reaches the Earth's surface and causes it to vibrate (move up and down or back and forth). Geologists use the term earthquake for both the sudden movement that generates vibrations, and the ground shaking that results when these vibrations reach the Earth's surface. Seismologists distinguish among different types of seismic waves on the basis of where and how the waves move. Body waves pass through the interior of the Earth, whereas surface waves travel along the Earth's surface. Waves that cause particles of material to move back and forth parallel to the direction in which the wave itself moves are called **compressional waves**. As a compressional wave passes, the material first compresses (or squeezes together) and then dilates (or expands). To see this kind of motion in action, push on the end of a spring and watch as the little pulse, in which the coils become more closely spaced, moves along the length of the spring. Waves that cause particles of material to move back and forth perpendicular to the direction in which the wave itself moves are called **shear waves**. To see shear-wave motion, jerk the end of a rope up and down and watch how the undulation travels along the rope.

With these concepts in mind, four basic types of seismic waves can be defined:

- *P-waves* (*P* stands for primary) are compressional body waves, traveling at about 6 to 7 km per second. P-waves bend slightly when they travel from one layer into another. Seismic waves move faster through denser or more rigid material. As P-waves encounter the liquid outer core, which is less rigid than the mantle, they slow down. This makes the P-waves arrive later and further away than would be expected. The result is a P-wave shadow zone. No P-waves are picked up at seismographs 104° to 140° from the earthquakes focus.
- *S-waves* (*S* stands for secondary) are shear body waves, traveling at about 3.5 km per second, and arrive second at seismographs. Only solids resist a change in shape, so S-waves are only able to propagate through solids. S-waves cannot travel through liquid.
- *L-waves* (*L* stands for Love, the name of a seismologist) are surface waves that cause the ground to shift back and forth, producing a snake-like movement.
- *R-waves* (*R* stands for Rayleigh, the name of a physicist) are surface waves that cause the ground to ripple up and down.

The different types of seismic waves travel at different velocities. P-waves travel the fastest. S-waves travel more slowly, at about 60% of the speed of P-waves. Surface waves are the slowest of all.

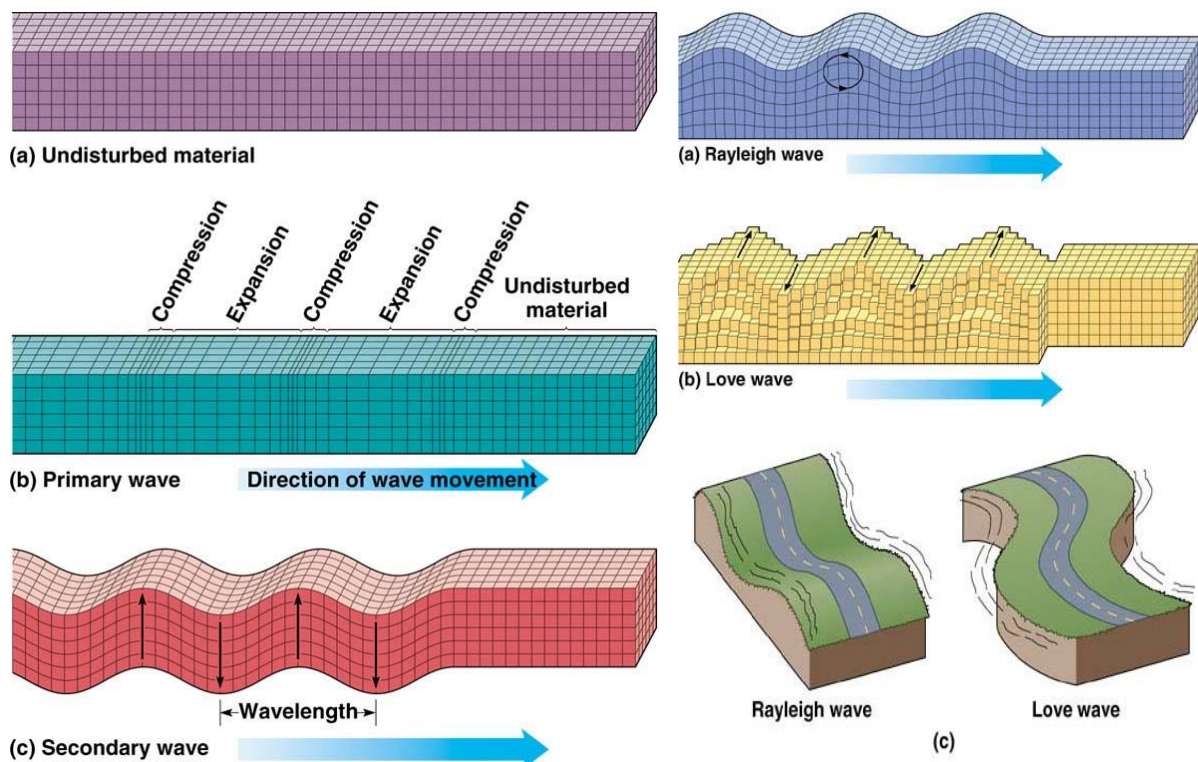
Where seismic waves speed up or slow down, they refract and change the direction in which they are traveling. Where seismic waves encounter an abrupt



boundary between two very layers with different properties, some of the seismic wave energy is reflected, bouncing back at the same angle it struck. The seismic wave reflections and refractions allow the layers and boundaries within the earth to be located and studied.

By tracing seismic waves, geoscientists have learned about the Earth's interior.

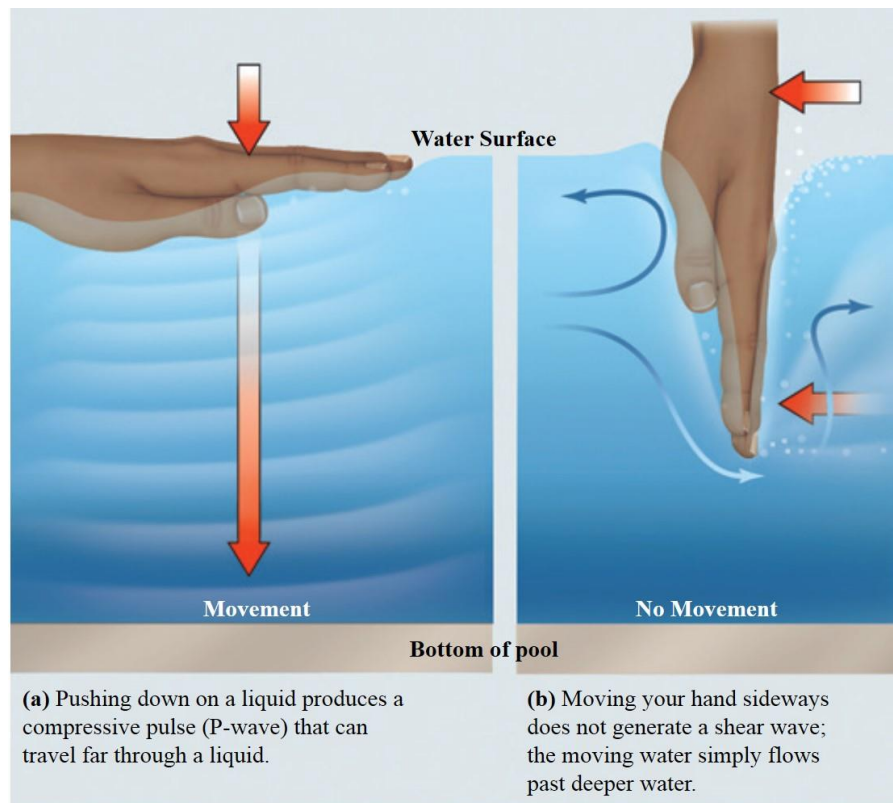
- *P-waves* slow down at the mantle core boundary, suggesting that the outer core is less rigid than the mantle.
- *S-waves* disappear at the mantle core boundary, indicating that the outer core is liquid.



The ability of a seismic wave to travel through a material, and the velocity at which it travels, depends on the character of the material. Factors such as *density* (mass per unit volume), *rigidity* (the stiffness of a material, meaning its resistance to shearing), and *compressibility* (how easily a material's volume changes in response to squashing) all affect seismic-wave velocity. As a result, seismic waves exhibit the following traits:

- Seismic waves travel at different velocities in different rock types. For example, P-waves travel at 3.5 km per second in sandstone (a porous sedimentary rock) but at 8 km per second in peridotite (an ultramafic igneous rock).
- The velocity of seismic waves can change when the waves pass from one rock type into another.
- In general, seismic waves travel faster in a solid than in a liquid. For example, seismic waves travel more slowly in molten iron alloy than in solid iron alloy.

- Both P-waves (compressional waves) and S-waves (shear waves) can travel through a solid, but only P-waves can travel through a liquid. To see why, picture what happens if you push down on the water surface in a pool—you send a pulse of compression to the bottom of the pool. Now move your hand sideways through the water. The water in front of your hand simply slides or flows past the water deeper down—your shearing motion has no effect on the water at the bottom of the pool.



The Earth's Internal Structure

Studies of seismic waves, meteorites that reach the Earth's surface, magnetic fields, and other physical properties show that the Earth's interior consists of a series of layers of different compositions and mechanical properties. The Earth is called a differentiated planet because of this separation into layers. How did the Earth become differentiated? First, recall that the density of liquid water is 1 g/cm^3 . The density of most rocks at the surface is about three times as great, just under 3 g/cm^3 . But the overall density of the Earth is about 5.5 g/cm^3 . Clearly, the Earth consists of internal layers of increasing density toward the center. The internal layers were produced as different materials rose or sank so that the least-dense materials were at the surface and the densest were in the center of the planet. Thus, gravity is the motive force behind the Earth's differentiated structure.

The Earth's Interior: Clues from the Study of Earthquakes

In 1889, a German physicist noticed that a pendulum in his lab appeared to begin rocking without having been touched. He reasoned that the pendulum was actually standing still while the Earth vibrated under it. A few days later, he read in a newspaper that a large earthquake had taken place in Japan about 12 minutes before the movement of his pendulum began. The physicist deduced that the energy generated by the earthquake had travelled all the way through the Earth from Japan and had slightly shaken his laboratory in Germany. Subsequent research revealed that earthquake energy moves through rock or along the Earth's surface in the form of waves, called seismic waves or earthquake waves.

Geoscientists immediately realized that the study of seismic waves traveling through the Earth could serve as a tool for exploring the Earth's interior, much as ultrasound today helps doctors study a patient's insides. That's because seismic waves travel at different velocities through different materials. So, by detecting depths at which seismic-wave velocities suddenly change, geoscientists can pinpoint the boundaries between layers and even recognize subtler boundaries within the main layers.

Internal Structure of the Earth based on Chemical Composition

The layers of the Earth are defined largely on the basis of chemical composition, viz. (1) the **crust**, which is subdivided into **continental** and **oceanic** crust, (2) the **mantle**, and (3) the **core**. Each of these layers has a distinct combination of chemical, mineral and rock compositions that distinguishes it from the others.

1. Oceanic crust, which underlies the seafloor, is only 7 to 10 km thick. The top portion of oceanic crust constitutes a blanket of sediment, generally less than 1 km thick, that consists of clay and tiny shells that settle like snow out of seawater. Beneath this blanket, the oceanic crust consists of a layer of basalt and, below that, a layer of gabbro.

Continental crust, in contrast to oceanic crust, varies in thickness from 25 to 70 km. The thinnest crust lies beneath regions called rifts, where the crust is being stretched apart and, therefore, has been thinned. Very thick continental crust occurs beneath mountain belts growing at locations where two continents are being squeezed together, causing the crust to shorten horizontally and thicken vertically. The broad plains found in the interiors of continents generally have a thickness of 35 to 50 km, about 4 to 6 times that of oceanic crust. Continental crust mostly contains granitic rock type, which make it less dense than oceanic crust.

In 1909, Andrija Mohorovičić, a researcher working in Zagreb, Croatia, discovered that the velocity of seismic waves suddenly increased at a depth of a few tens of kilometres beneath the surface of continents, and he suggested that this increase was caused by an abrupt change in the properties of rock. He proposed that this change in seismic velocity represents the crust-mantle boundary. Today we refer to this boundary as the Moho in Mohorovičić's honor.

2. The next major compositional layer of the Earth, the **mantle**, is a 2,820 to 2,890 km thick and surrounds the core and constitutes the great bulk of the Earth (82% of its volume and 68% of its mass). The mantle consists entirely of peridotite, a dark and dense ultramafic rock that's quite rare at the Earth's surface.

Geoscientists have found that the velocity of seismic waves changes markedly, in a step-like manner, in the portion of the mantle that lies between 410 and 660 km deep. Based on this observation, they divide the mantle into two sub-layers—the upper mantle, down to a depth of 660 km, and the lower mantle, from 660 km down to about 2,900 km. The portion of the upper mantle between 410 and 660 km, in which the steps in seismic velocity occur, is known as the transition zone.

3. The Earth's **core** consists primarily of iron alloy (~ 85%), with smaller, but significant amounts of nickel (~ 5%) and lighter elements (~ 8 – 10%) such as oxygen, sulfur and/or hydrogen. A dramatic decrease in P wave velocity and the termination of S wave propagation occurs at the 2900 km discontinuity (Gutenberg discontinuity or core – mantle boundary). Seismic studies led geoscientists to divide the core into two parts, the *outer core* (between

about 2,890 and 5,155 km deep) and the *inner core* (from 5,155 km down to the Earth's center at 6,371 km). Because S waves are not transmitted by non - rigid substances such as fluids, the outer core is inferred to be a liquid. Geophysical studies suggest that the Earth's outer core is a highly compressed liquid with a density of $\sim 10 - 12 \text{ g/cm}^3$. It can exist as a liquid because the temperature in the outer core rises so high that even the great pressures squeezing the region cannot keep atoms locked into a solid framework. Circulating molten iron alloy in the outer core is responsible for the production of most of the Earth's magnetic field.

Internal Structure of the Earth based on the physical (mechanical) properties

The mechanical (or physical) properties of a material tell us how it responds to force, how weak or strong it is, and whether it is solid or in molten state. The layers within the Earth defined principally on the basis of mechanical properties include:

1. The solid, strong, and rigid outer layer of a planet is the **lithosphere** (rock sphere). The lithosphere includes the crust and the uppermost part of the mantle. The Earth's lithosphere varies greatly in thickness, from as little as 10 km in some oceanic areas to an average depth of ~ 100 km that includes all of the crust and the upper part of the mantle.
2. Within the upper mantle, there is a major zone where temperature and pressure are just right so that part of the material melts, or nearly melts. Under these conditions, rocks lose much of their strength and become soft and plastic and flow slowly. This zone of easily deformed mantle is known as the **asthenosphere** (weak sphere) and extends to depths ranging from 100 to 660 km and including a transition zone from ~ 400 to 660 km. The boundary between the asthenosphere and the overlying lithosphere is mechanically distinct but does not correspond to a fundamental change in chemical composition. The boundary is simply a major change in the rock's mechanical properties.
3. The rock below the asthenosphere is stronger and more rigid than in the asthenosphere. It is so because the high pressure at this depth offsets the effect of high temperature, forcing the rock to be stronger than the overlying asthenosphere. The region between the asthenosphere and the core (from ~ 660 to 2900 km) is the **mesosphere** (middle sphere).
4. The Earth's core marks a change in both chemical composition and mechanical properties. On the basis of mechanical behavior alone, the core has two distinct parts: a solid **inner core** and a liquid **outer core**.

Source: Earth – Portrait of a Planet by Stephen Marshak
Earth Materials by Kevin Hefferan and John O'Brien
Earth's Dynamic Systems by Hamblin and Christiansen
Lumenlearning.com