# Travel time curves

Background page to accompany the animations on the website: **IRIS Animations**

**Link to Vocabulary (Page 2)**

## Introduction

A travel-time curve is a graph of the time that it takes for seismic waves to travel from the epicenter of an earthquake (time and distance = zero) to seismograph stations varying distances away. The curves are the result of analyzing seismic waves from thousands of earthquakes, received by hundreds of seismic stations around the world. They are used by seismologists to quickly locate earthquakes. For introductory purposes, we animate only the direct P (red) and S (blue) waves that travel through the crust and mantle, plus the surface (yellow) waves that travel in the shallow crust. We ignore the reflected and refracted waves. By using what we know about the velocity of seismic waves through different materials, seismologists are able refine what we know about Earth's deep interior.

**Resources for background information on why seismic waves do what they do:**

- Exploring the Earth Using Seismology, P.3
- Refraction
- 3 Component Seismograph
- Multi-Station Seismograph Station

The animations show how we get from the "Exploring the Earth Using Seismology" on page 3 to the simple graph in Figure 1.

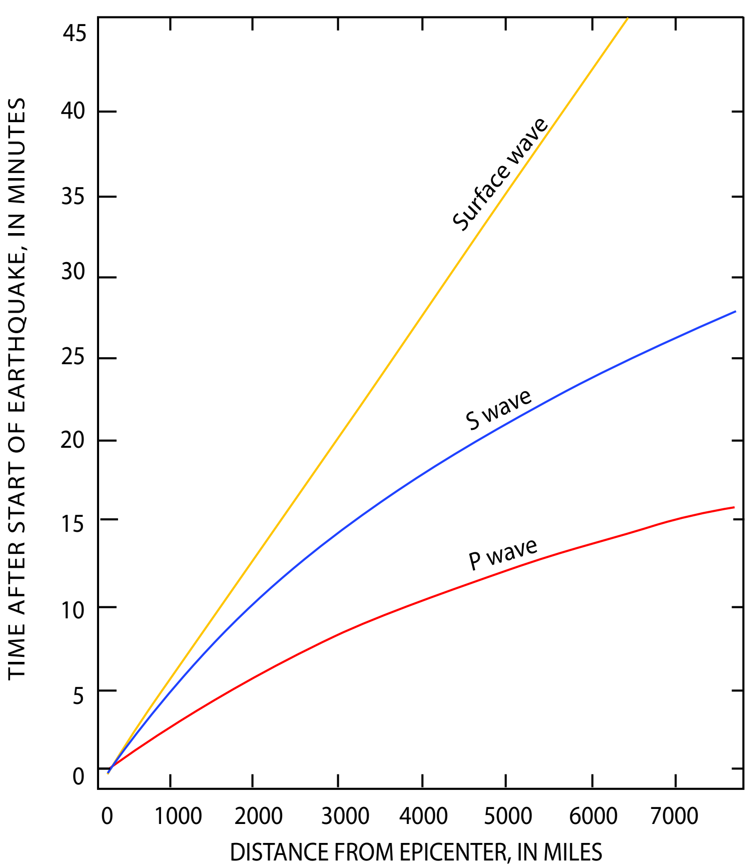



**Figure 1:** This is an example of a simplified travel-time curve showing the expected first arrival of P, S, and surface waves at a range of distances from the epicenter. It is important to notice that the difference between the S and the P times increases smoothly with distance. Therefore, a seismogram with a given S minus P arrival times will only match the travel time data at one specific distance.

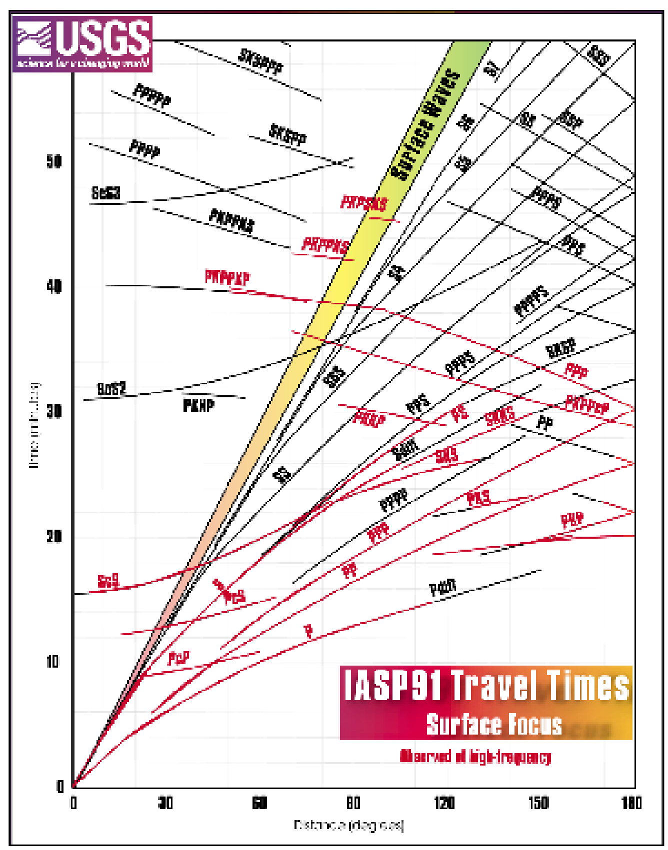



**Figure 2 :** This is an actual travel-time curve for body-wave phases (P and S) for an earthquake at the surface. For teaching purposes, just go with the first arrivals in Figure 1, but to get a sense of the complexity see next page. U.S.G.S. graph from: **Earthquake Travel Time Information and Calculator**

## It's Complicated

Although students may be familiar with the basic body-wave phases of P and S, the travel time curve in Figure 2 plots many additional body wave phases. These occur because the original P and S wave energy gets reflected and refracted as it travels through the Earth. Each time a reflection or refraction occurs another letter is added to the phase name (Figures 3 & 4).

The direct P arrival leaves the earthquake and travels directly through the mantle to the seismometer. The PP and pP arrivals, on the other hand, involve a reflection of energy from the surface of the Earth and arrive *after* the direct P wave arrival. The distinction between PP and pP is that for pP the seismic wave is initially upgoing from the focus for the surface reflection. Some of these are shown on the figure at lower left.

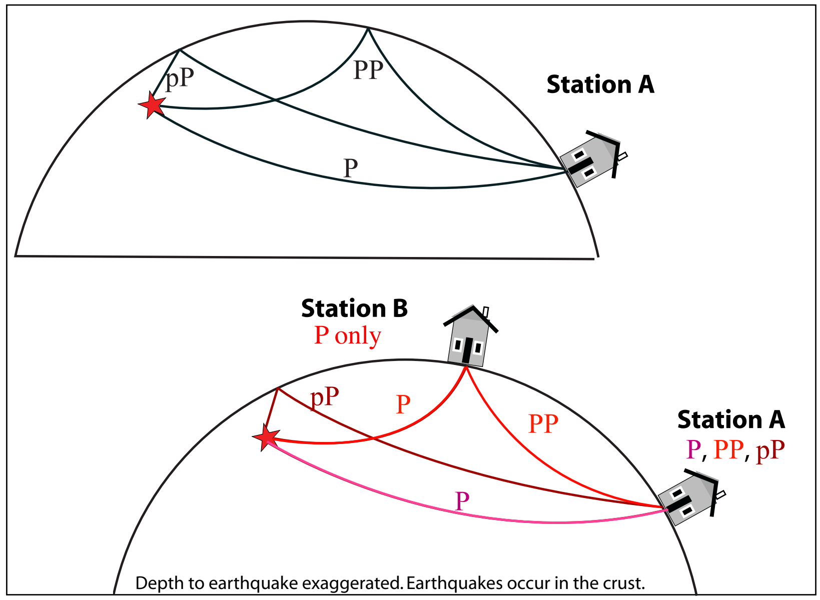



**Figure 3: Station A** receives *three* types of P waves. **Station B**, located half way between Station A and the epicenter, receives only the direct P wave in this three-path scenario. The PP refers to the entire path to **Station A** that gets reflected at the surface.

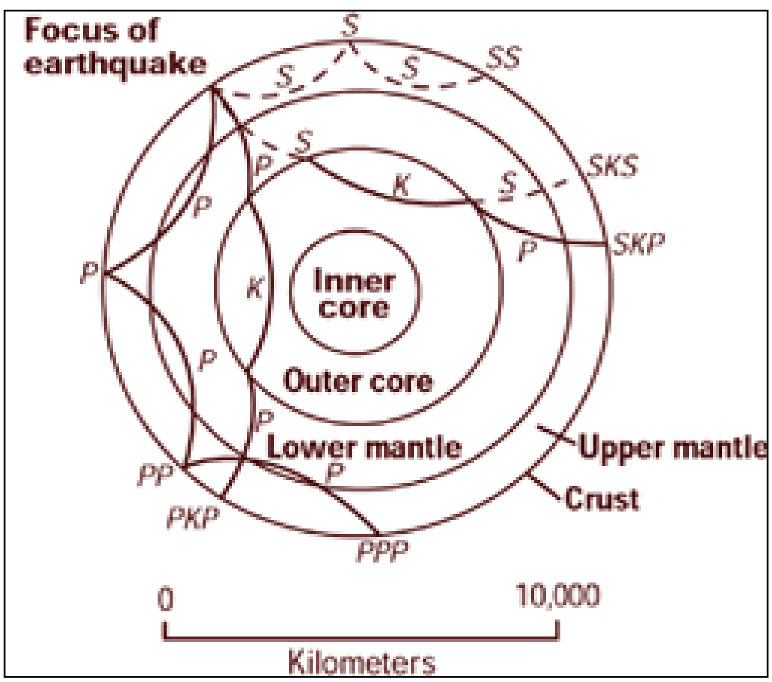



**Figure 4:** Cross section of the whole Earth, showing the complexity of paths of P waves (lower left) and S waves (upper right. (USGS image)

## Exploring the Earth Using Seismology

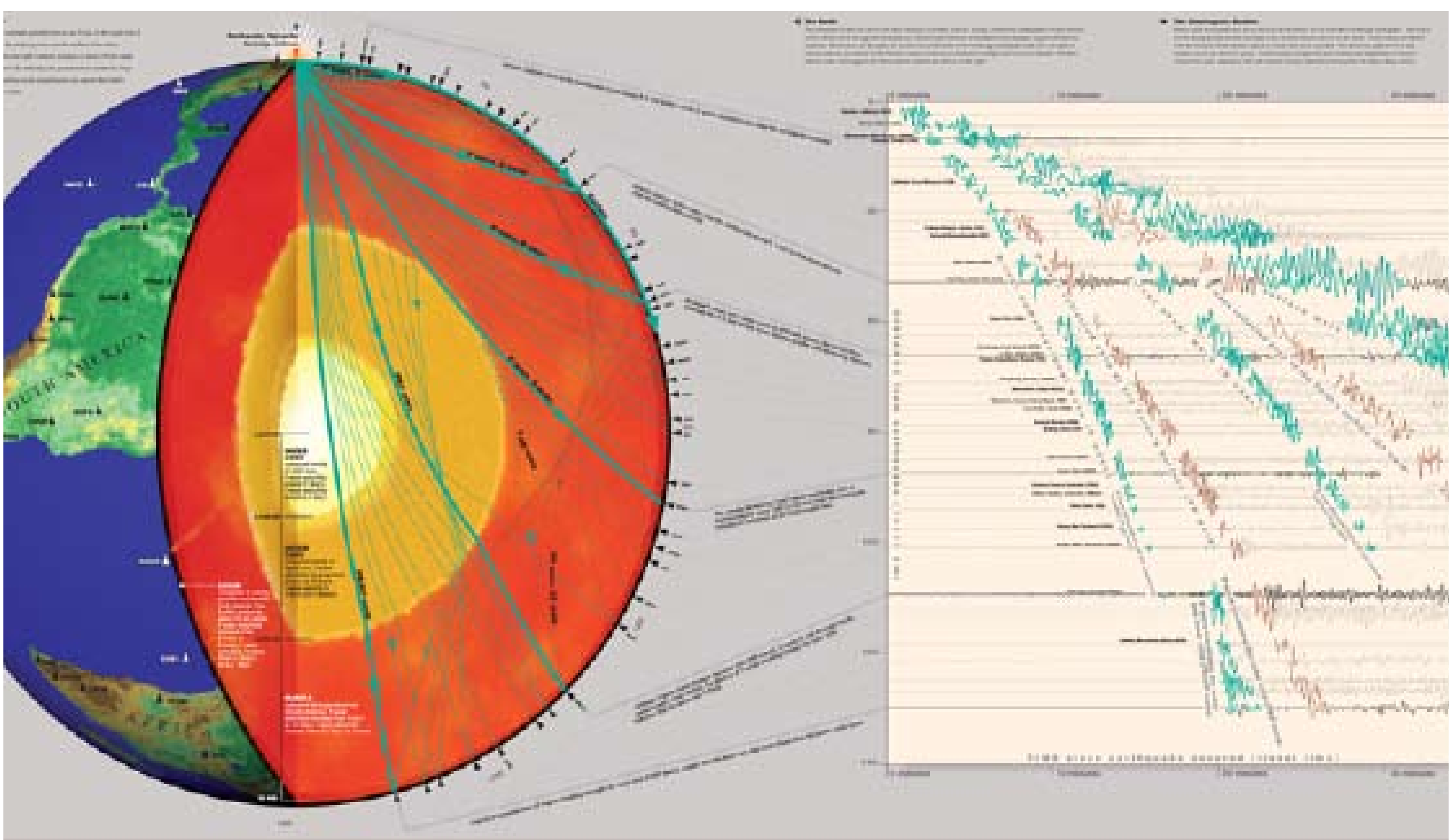
(This IRIS one-pager can be downloaded from above link.)

On January 17, 1994 a magnitude 6.9 earthquake near Northridge, California released energy equivalent to almost 2 billion kilograms of high explosive. The earthquake killed 51 people, caused over $20 billion in damage, and raised the Santa Susana Mountains north of Los Angeles by 70 centimeters. It also created seismic waves that ricocheted throughout the Earth's interior and were recorded at geophysical observatories around the world. The paths of some of those seismic waves and the ground motion that they caused are shown below.

On the right, the horizontal traces of ground motion (seismograms recorded at various locations around the world) show the arrival of the different seismic waves. Although the seismic waves are generated together, they travel at different speeds. Shear waves (S waves), for example, travel through the Earth at approximately one-half the speed of compressional waves (P waves). Stations close to the earthquake record strong P, S and Surface waves in quick succession just after the earthquake occurred. Stations farther away record the arrival of these waves after a few minutes, and the times between the arrivals are greater.

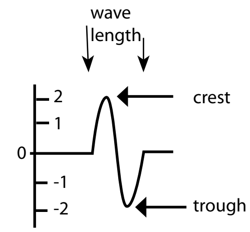
At about 100 degrees distance from the earthquake, the travel paths of the P and S waves start to touch the edge of the Earth's outer core. Beyond this distance, the first arriving wave — the P wave — decreases in size and then disappears. P waves that travel through the outer core are called the PKP waves. They start to appear beyond 140 degrees. The distance between 100 and 140 degrees is often referred to as the "shadow zone".

We do not see shear (S) waves passing through the outer core. Because liquids can not be sheared, we infer that the outer core is molten. We do, however, see waves that travel through the outer core as P waves, and then transform into S waves as they go through the inner core. Because the inner core does transmit shear energy, we assume it is solid.



# Vocabulary

To accompany Background files for **IRIS' Animation page**. (Definitions from **usgs.gov**; **nasa.gov**; **fema.gov**)




**Amplitude**—the maximum disturbance or distance from the constant point. On a seismogram the horizontal time line is flat until there is a ground disturbance which is recorded as wave, or *seismogram*. The amplitude of a seismic wave is the amount the ground moves up or down. Amplitude is one-half the distance between the crest and trough of one wave length. In drawing at right, maximum displacement is 2 + 2 = 4, so Amplitude = 0.5 * 4 = 2.

**Body Wave**s—waves that move within the Earth's interior or within a body of rock. P and S waves are body waves.

**Compression**—fractional decrease of volume due to pressure.

**Earthquake**—shaking or trembling of the earth that accompanies rock movements extending anywhere from the crust to 680 km below the Earth's surface. It is the release of stored elastic energy caused by sudden fracture and movement of rocks inside the Earth. Part of the energy released produces seismic waves, like P, S, and surface waves, that travel outward in all directions from the point of initial rupture. These waves shake the ground as they pass by. An earthquake is felt if the shaking is strong enough to cause ground accelerations exceeding approximately 1.0 centimeter/second squared. ***Types of earthquakes*** include:

A) **Tectonic Earthquake**: earthquake that occurs when the earth's crust breaks due to geological forces on rocks and adjoining plates that cause physical and chemical changes.
B) **Volcanic Earthquakes:** earthquakes that result from tectonic forces which occur in conjunction with volcanic activity.
C) **Collapse Earthquakes:** small earthquakes in underground caverns and mines that are caused by seismic waves produced from the explosion of rock on the surface.
D) **Explosion Earthquakes**: earthquakes which are the result of the detonation of nuclear and chemical devices

**Epicenter—**the point on the Earth's surface directly above the *focus* of an earthquake.

**Focus—**the point on the fault at which the first movement or break occurred. Directly beneath the *epicenter* at 1–50 km depth.

**Love Waves**—surface waves that move parallel to the Earth's surface and perpendicular to the direction of wave propagation..

**Magnitude**—The magnitude is a number that characterizes the relative size of an earthquake. Magnitude is based on measurement of the maximum motion recorded by a seismograph. Several scales have been defined, but the most commonly used are (1) local magnitude (ML), commonly referred to as "Richter magnitude," (2) surface-wave magnitude (Ms), (3) body-wave magnitude (Mb), and (4) moment magnitude (Mw). Scales 1-3 have limited range and applicability and do not satisfactorily measure the size of the largest earthquakes. The moment magnitude (Mw) scale, based on the concept of seismic moment, is uniformly applicable to all sizes of earthquakes but is more difficult to compute than the other types. All magnitude scales should yield approximately the same value for any given earthquake..

**Mantle**— the layer in Earth's interior between the crust and the metallic core.

**Material Properties of the Earth**—the bulk character of the rock, such as composition, density, elastic moduli, mineralogy, and phase (ex. the presence of melt). Elastic waves may propagate through the earth in a manner which depends on the material properties of the earth. The elasticity of the material provides the restoring force of the wave.

**Moment Magnitude**—the preferred measure of earthquake size (magnitude) in which the stiffness of the rock, the average slip on the rupture plane, and the area of the rupture plane are taken into account (the "moment" of the earthquake). See magnitude.

**P Wave**—the primary body wave; the first seismic wave detected by seismographs; able to move through both liquid and solid rock..Also called compressional or longitudinal waves, they compress and expand (oscillate) the ground back and forth in the direction of travel, like sound waves that move back and forth as the waves travel from source to receiver. P wave is the fastest wave.

**Rayleigh Waves**—surface waves that move in an elliptical motion, producing both a vertical and horizontal component of motion in the direction of wave propagation.

**Seismic Wave—** an elastic wave generated by an impulse such as an earthquake or an explosion. Seismic waves may travel either through the earth's interior (P and S waves; the fastest waves) or along or near the earth's surface (Rayleigh and Love waves). Seismic waves travel at speeds of several kilometers per second.

**Seismicity—**the geographic and historical distribution (the "where?" and "how often?") of earthquakes.

**Seismogram**—A real-time record of earthquake ground motion recorded by a *seismograph*. Seismograms are the records (paper copy or computer image) used to calculate the location and magnitude of an earthquake..

**Seismograph**—an instrument that records vibrations of the Earth, especially earthquakes. Seismograph generally refers to the *seismometer* and a recording device as a single unit.. See **IRIS' Seismographs.**

**Seismology**—science that deals with earthquakes and attendant phenomenon including the study of artificially produced elastic waves in the Earth's material.

**Seismometer—**a sensitive instrument that can detect waves emitted by even the smallest earthquakes. (See *seismograph*.)

**Shadow Zone**— The shadow zone is the area of the earth from angular distances of 104 to 140 degrees from a given earthquake that does not receive any direct P waves. This zone results from S waves being stopped entirely by the liquid core and P waves being bent (refracted) by the liquid core.

**Shear**—type of *strain* in which the shape of a material is displaced laterally with no corresponding change in volume.

**Surface Wave**—waves that move close to or on the outside surface of the Earth rather than through the deep interior like the faster P or S waves. Two principal types of surface waves, Love and Rayleigh waves, are generated during an earthquakes. Rayleigh waves cause both vertical and horizontal ground motion, and Love waves cause horizontal motion only. They both produce ground shaking at the Earth's surface but very little motion deep in the Earth. Because the amplitude of surface waves diminishes less rapidly with distance than the amplitude of P or S waves, surface waves are often the most important component of ground shaking far from the earthquake source.

**S Waves**—secondary body waves that oscillate the ground perpendicular to the direction of wave travel. They travel about 1.7 times slower than P waves. Because liquids will not sustain shear stresses, S waves will not travel through liquids like water, molten rock, or the Earth's outer core. S waves produce vertical and horizontal motion in the ground surface.

**Wave**—a disturbance that moves through a system. (See *seismic wave*.)

**Wave height**—the vertical distance from a wave's crest to its trough. (This measurement will be twice the amplitude measured for the same wave.)

**Wave crest**—the highest point a wave reaches. The lowest point is called its trough.

**Wavelength**—the horizontal distance between two successive crests, often measured in meters.