

Seismic Tomography—Using earthquakes to image Earth’s interior

Background to accompany the animations & videos on: [IRIS’ Animations](#)

[Link to Vocabulary \(Page 4\)](#)

Introduction

Seismic tomography is an imaging technique that uses seismic waves generated by earthquakes and explosions to create computer-generated, three-dimensional images of Earth’s interior. If the Earth were of uniform composition and density seismic rays would travel in straight lines as shown in Figure 1. But our planet is broadly layered causing seismic rays to be refracted and reflected across boundaries. Layers can be inferred by recording energy from earthquakes (seismic waves) of known locations, not too unlike doctors using CT scans (next page) to “see” into hidden parts of the human body.

How is this done with earthquakes? The time it takes for a seismic wave to arrive at a seismic station from an earthquake can be used to calculate the speed along the wave’s ray path. By using arrival times of different seismic waves scientists are able to define slower or faster regions deep in the Earth. Those that come sooner travel faster. Later waves are slowed down by something along the way. Various *material properties* control the speed and absorption of seismic waves. Careful study of the travel times and amplitudes can be used to infer the existence of features within the planet.

Seismic waves travel at speeds of several kilometers per second in the Earth, with the speed of compressional waves (P waves), being about 1.7 times faster than that of shear waves (S wave). Seismic wave speeds vary with change in rock type and density. [Learn more about P-wave behavior](#) in [Seismic Waves in Earth’s Interior](#).

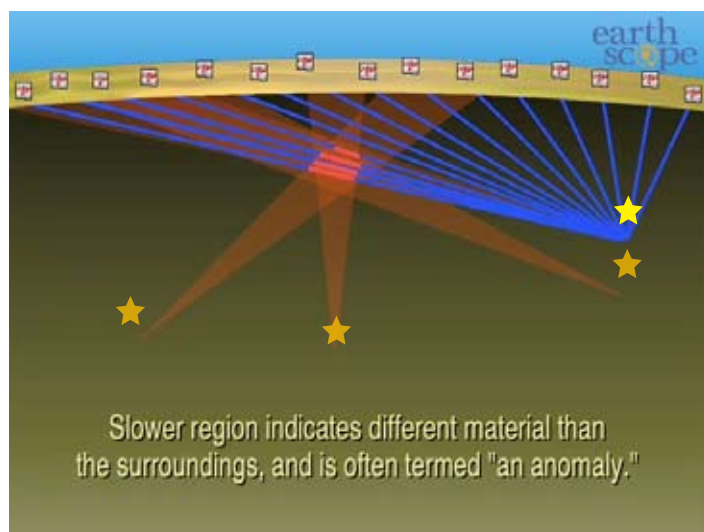


Figure 1: Image capture from animation depicts 15 seismic stations recording earthquakes from 4 earthquakes. An anomaly (red) is inferred by using data collected from stations that indicate slower wave speeds.

What variables yield the best resolution that allow seismologists to infer details at depth?

- 1) A high-density array of seismograph stations above and around the area being studied
- 2) Many earthquakes or explosions recorded by every station
- 3) Earthquake signals coming to stations from different parts of the world

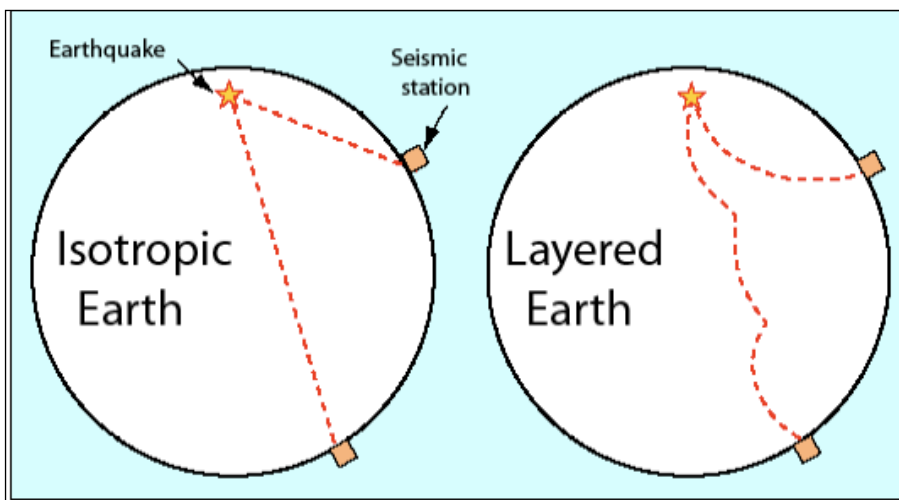


Figure 2: If the Earth had no changes with depth, pressure, or composition (isotropic) seismic waves would travel a straight path. Seismic imaging has revealed that the Earth has variation due to rock composition, elasticity, and temperature that cause the seismic waves to refract and bend when transmitted between different rock layers. [From [Seismic Waves and Earth’s Interior](#).]

For a series of animations that address “Why do seismic waves travel a curving path through the Earth?” see [Refraction](#) on IRIS’ Animations page.

CAT Scans & Seismic Tomography

For lack of a perfect analogy, seismic tomography is often compared to a CT scan (aka "Cat scan" for Computed Axial Tomography). The CT scan uses computers to generate a three-dimensional image from a lot of flat X-ray pictures.

The basic idea of a CT scan is this: The X-ray beam is the energy source, which sends its signal (electromagnetic radiation) to the receiver (computer), which then captures and stores the data. Images are collected from hundreds of angles and the computer analyzes the information to produce a 3-D image. X-rays are absorbed unequally by different materials, and computer-aided tomography consists of studying the attenuation (reduction in intensity and amplitude) of X-rays that pass through the body.

The weakness in this analogy is that the observed quantity in a CT scan is not a travel time, but rather the amount of X-ray absorption (attenuation). Seismic tomography uses the same principles, except travel-time difference, rather than their attenuation, is observed. In terms of wave behavior, ultrasound imaging is more analogous to P-wave tomography, where compressive waves are reflected and refracted off materials of different composition and density. We use the CT scan because it is commonly referred to without fully understanding how it works, plus it does provide an energy-receiver analogy.

Compared to CT scans, how does seismic tomography work?

First, for clarity, seismic tomography is much more difficult than X-ray tomography, because the ray paths are curved and initially unknown, and in some cases the locations of the earthquake sources are poorly known.

Seismic tomography uses the energy produced by thousands of local and global earthquakes (seismic waves) received by hundreds of receivers (seismographs) which record the data. Unlike an X-ray beam that shoots in one direction, the earthquake sends seismic waves in all directions, so instead of having to move the energy source around the Earth, scientists use multiple seismometers. One seismometer can only tell you that there has been an earthquake (as one X-ray can only tell you that you have bones). Many closely spaced seismometers yield 3-D information about features below Earth's surface.

To determine how features seen at Earth's surface correlate with structural and compositional differences deep within the planet, seismologists need denser networks of seismic stations so that they are recording seismic waves that propagate through finer and finer slices of the earth beneath them. It's important to understand that tomographic techniques give a very coarse look at the subsurface.

Complications of This Technique

Seismic tomography is a rapidly evolving discipline. Observed anomalies within the Earth are open to discussion and controversy, making it a dynamic science. Because of this, creating an animation is a moving target. Our aim is merely to give a generalized picture of the underlying principles.

Two main complications of this technique are:

- 1) seismic waves don't move in a straight trajectory away from an earthquake, but refract, or bend in response to changes in density; and
- 2) seismic waves can bounce off of sharp boundaries such as the core-mantle boundary as well as between the crust and the atmosphere.

Caveat emptor*

Several aspects of graphical presentation may make it difficult to interpret three-dimensional models in terms of Earth structure and processes:

- A model typically includes a huge amount of information, only a small fraction of which is shown, usually in the form of maps at various depths or vertical cross sections. The visual impression of the results given may be very sensitive to the precise position of the section. Wave speeds are usually displayed with colors, blue representing high wave speeds and red representing slow. It is natural to associate red colors with higher temperatures. However, many factors affect the wave speed, including composition, crystal orientation, mineralogy and phase (especially the presence of melt). Red anomalies may not really be hot, nor blue ones cold.
- The eye's sensitivity to color varies greatly across the spectrum, so inevitably some features are prominent while other, equally strong ones, are nearly invisible. For example, the transition from blue to yellow is much more noticeable than that from orange to red.
- If the color scale saturates, anomalies may look the same when they actually differ in strength by an order of magnitude. For example, lower-mantle anomalies are much weaker than upper mantle ones, but this is obscured in figures where the color scale saturates at the maximum lower-mantle anomaly. Because of these factors, the appearance of tomographic images may be highly variable, depending on graphical design choices made by seismologists.

[*from [Seismology: The hunt for plumes](#)]

Ongoing seismic-tomography experiments in the U.S. today

USArray, a component of EarthScope, is a fifteen-year program to place a dense network of permanent and portable seismographs across the continental United States (Figure 3). The thousands of seismograph locations on public and private lands across the continental United States record local, regional, and distant (teleseismic) earthquakes. Hundreds of earthquakes occur throughout the world every day. By analyzing the seismograms of these earthquakes, scientists can learn about Earth structure and dynamics, and the physical processes controlling earthquakes and volcanoes. ([Learn More about USArray.](#))

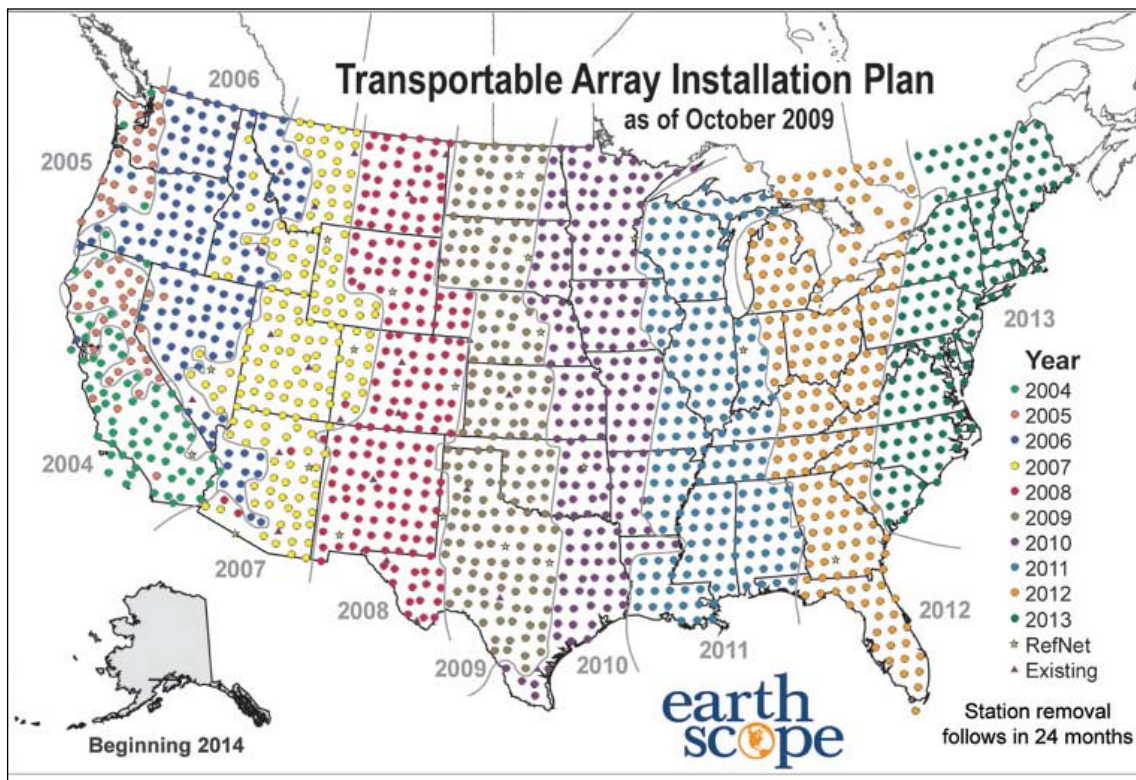


Figure 3: USArray's Transportable Array deployment plan. The Transportable Array is rolling across the country with roughly two-year deployments in each region. The spacing between each station is 70 km (~42 miles). Multiple deployments will cover all contiguous 48 states and Alaska over a ten-year period.

Vocabulary

Asthenosphere—the ductile part of the earth just below the lithosphere is about 180 km thick and is found 100–250 km (60–150 mi) below the Earth’s surface. The asthenosphere yields to persistent stresses more than the rigid crust or the core.

Body Waves—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.

Crust—the outermost major layer of the earth, ranging from about 10 to 65 km in thickness worldwide. The uppermost 15–35 km of crust is brittle enough to produce earthquakes. Oceanic crust is thinnest; continental crust is thickest.

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

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

Elastic Limit—the point at which any additional force to an object will permanently deform its shape.

Elastic Properties—the measure of an objects ability to change shape when a force is applied to it, and return to its original shape when the force on it is released.

Elastic Rebound—an objects ability to return to its original shape after being broken apart. See [Strike Slip](#) and [Subduction](#)

Elastic strain—Earthquakes are caused by the sudden release of energy within some limited region of the rocks of the Earth. The energy can be released by elastic strain, gravity, chemical reactions, or even the motion of massive bodies. Of all these the release of elastic strain is the most important cause, because this form of energy is the only kind...

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.

Frequency—the number of wave cycles per unit of time that pass a given point.

Hazard—a source of unpredictable, unplanned danger.

Intensity—The intensity is a number (written as a Roman numeral) describing the severity of an earthquake in terms of its effects on the earth’s surface and on humans and their structures. See *magnitude*.

Lithosphere—solid, rocky, outer part of the Earth, ~100 km thick (50 miles) comprised of the crust and the solid portion of the mantle. **The** thickness is age dependent with older lithosphere is thicker than younger oceanic lithosphere. The lithosphere below the crust is brittle enough at some locations to produce earthquakes by faulting, such as within a subducted oceanic plate.

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. When they occur in the Earth as the result of an earthquake or other disturbance, elastic waves are usually called seismic waves.*

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.

Seismic Wave— A seismic wave is 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—he geographic and historical distribution (the “where?” and “how often?”) of earthquakes.

Seismic Tomography— Seismic tomography is an imaging technique that uses seismic waves generated by earthquakes and explosions to create computer-generated, three-dimensional images of Earth's interior. See [Seismic Tomography](#)

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.

Seismic Wave— A seismic wave is 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.

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*.)