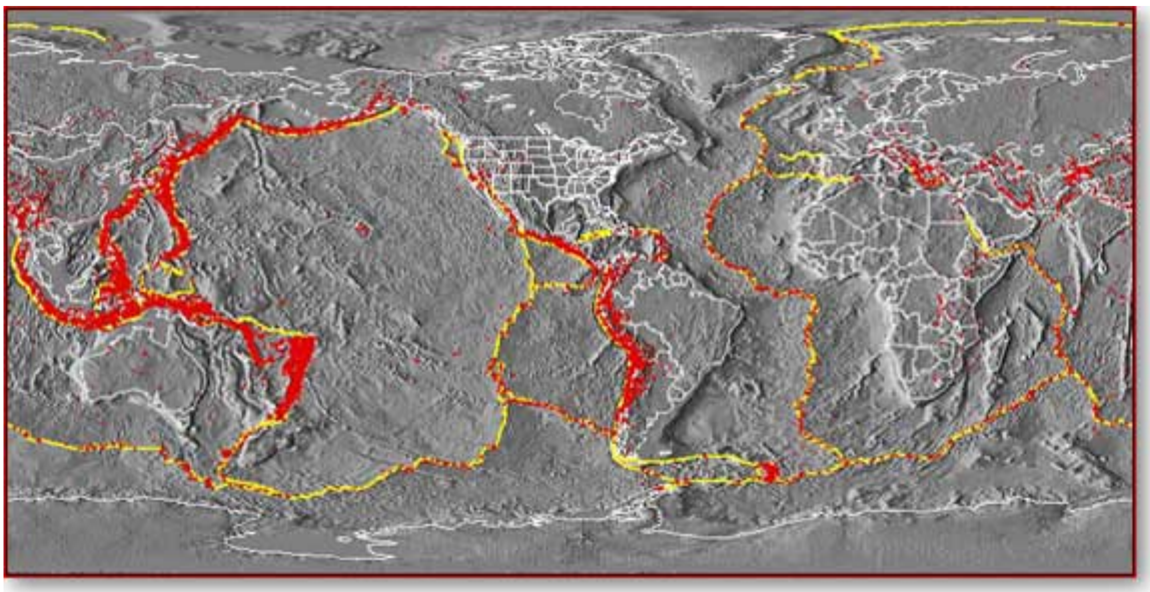
Lab 5 : Earthquakes -- I: Locating an Earthquake

Introduction

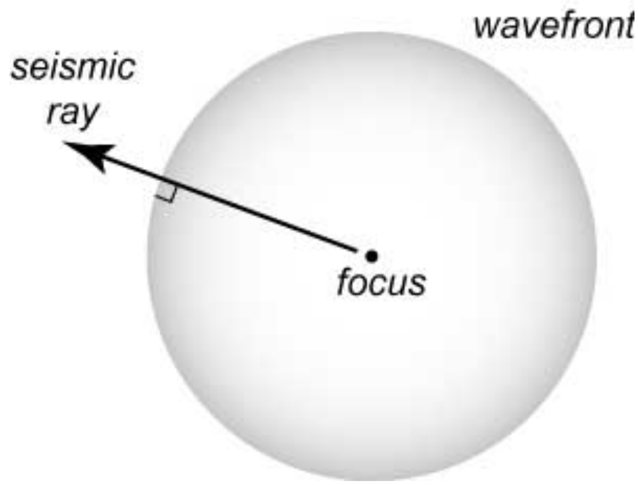
Earthquakes have had a profound impact on nearly all human societies. In the past, earthquake activity was explained by myths and legends and often ascribed to human causes, e.g. wickedness or failing to follow god's wishes. Modern scientific research has shown that the vast majority of seismic events is concentrated in narrow seismic belts (see map below). These events are recorded by a worldwide seismic network using seismographs. Using the characteristics of the seismic waves recorded on a seismogram, the locations and magnitudes of the individual earthquakes are readily determined and logged.



Epicenter distribution. Deep earthquakes are indicated in red whereas shallows ones are shown in yellow.

Seismic Waves

When an earthquake occurs, the strain energy stored in the rocks adjacent to a fault is released through brittle failure and movement. This energy radiates outward from the focus as a series of wavefronts.



These wavefronts are a series of concentric spheres that expand outward from the focus. An individual ray path is perpendicular to the wavefront.

There are two classes of seismic waves:

Body waves are produced at the point of the earthquake within the Earth (i.e. the focus) and pass through the Earth's interior. They propagate outward from the focus as an expanding sphere, the **wavefront**. Because the area occupied by the wavefront is continually expanding, the amount of energy at any given point on the wavefront, decreases with increasing distance from the focus. Body waves may penetrate deep into the Earth and even pass all the way through it.

Surface waves do not form until a body wave strikes the Earth's surface directly above the focus (epicenter). They radiate out from the epicenter and travel along the surface of the Earth. These waves need a free surface, i.e. the Earth's surface, to propagate. The closer the earthquake focus to the surface, the greater the amount of energy transferred from the body waves to the surface waves.

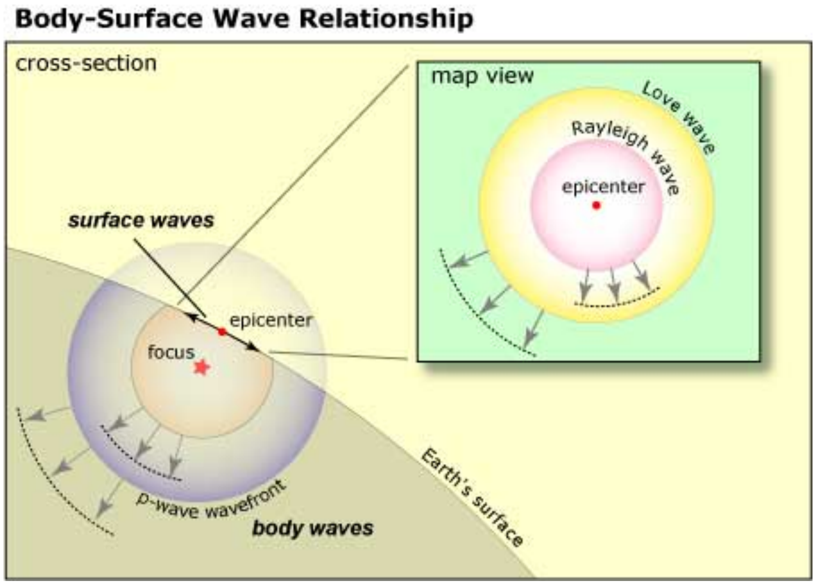
Body waves consist of two types:

- p-waves, primary or compression waves
- s-waves, secondary or shear waves

There are two types of surface waves:

- **Rayleigh waves**: surface wave that moves close to solid's surface. Its amplitude decreases exponentially with depth. Rayleigh waves have velocities that are approximately nine tenths of s-waves, e.g. $V_r = 0.9\ V_s$.
- **Love waves**: these waves are produced if seismic velocity increases with depth. Particle motion is at right angles to the wave direction and parallel the Earth's surface, i.e. horizontal for the Earth. Love waves are slightly slower than Rayleigh waves.

Surface waves do not form until a body wave strikes the Earth's surface directly above the focus (epicenter). The closer the earthquake to the surface, the greater the energy transferred to the surface waves.



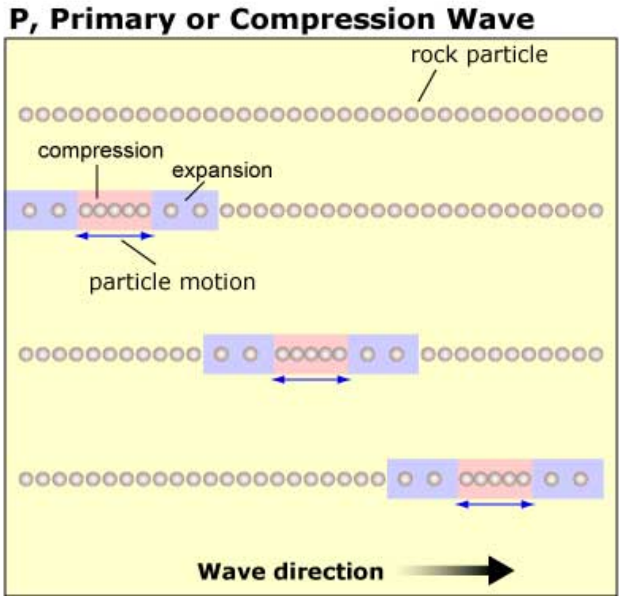
Body waves

Body waves are seismic waves that past through the interior, i.e. "body", of the Earth. These waves are useful for determining the internal structure of the Earth as well as locating an earthquake's focus and epicenter. They generally have little effect on surface structures and hence are not ones that engineers consider when they design earthquake resistant structures.

There are two main types of body waves, each traveling by different processes with different velocities. The types of materials they can pass through differs also. The two types of body waves are:

- **p-waves**, primary or compression waves
- **s-waves**, secondary or shear waves

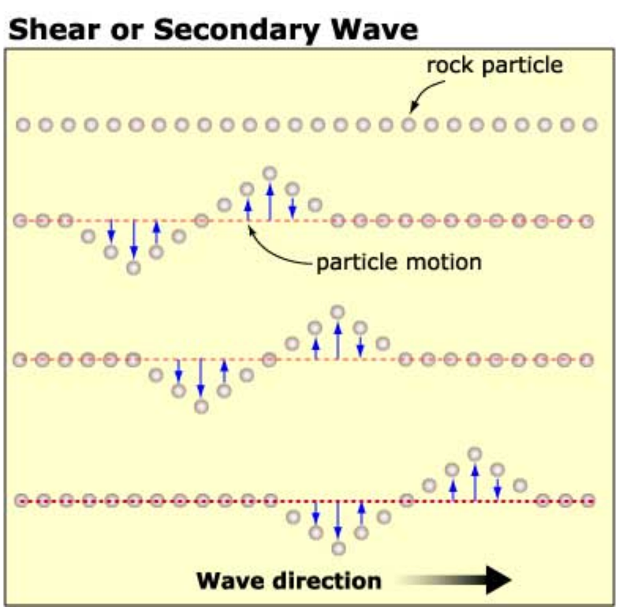
P-waves or **primary waves** arrive at a seismographic station first after an earthquake. Thus, their name primary. These waves are also known as compression or pressure waves because of the associated particle motion. As a p-wave passes through a rock, the rock particles move back and forth in same direction, i.e. longitudinal, as wave is traveling. Thus, the rock undergoes alternating compression and expansion as the particles vibrate around an equilibrium positions. There is, however, no rotation of the particles.



P-waves have the following characteristics:

- very fast (4-7 km/s in crust and 8 km/s in mantle)
- velocity drops to 1.5 km/s in water
- pass through all types of materials, e.g. solid, liquid, gas (when reach atmosphere create waves we hear as a low, thunderous roar

Secondary or **s-waves** are slower than p-waves so they arrive later at a seismographic station. They are also called **shear waves** because of the rock particle's unique motion. As an s-wave passes, rock particles move iat right angles to the wave direction. Material is rotated and sheared by an s-wave but there is no volume change.



S-waves have the following characteristics:

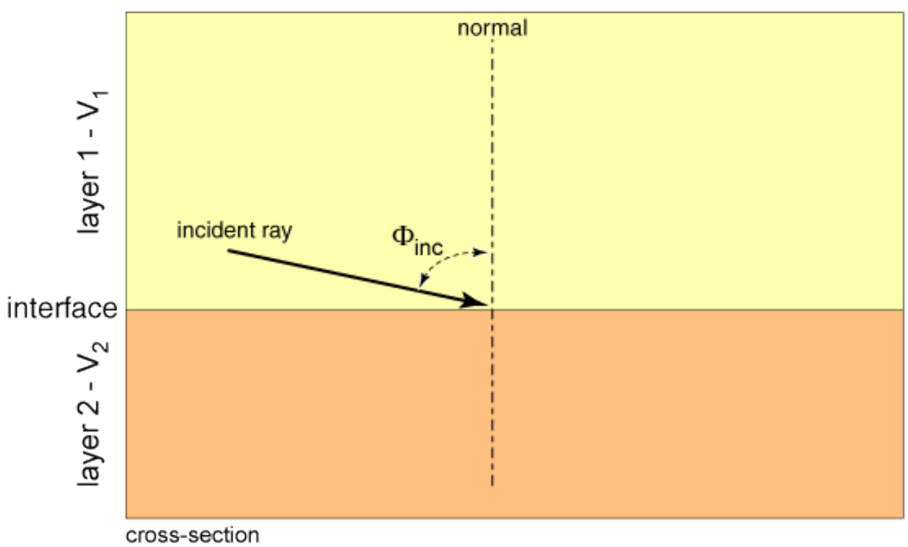
- in the crust, they have velocities of 3-4 km/s
- shear is transmitted from a rock particle to its next neighbor
- s-waves cannot pass through liquids or gases
- two components:
    - horizontally polarized motion: SH
    - vertically polarized motion: SV

Reflection & Refraction

As seismic rays travel through the Earth, they encounter layers (shells in three dimensions) of differing composition and physical properties. When they hit the interfaces between these shells, the waves are, depending upon a variety of conditions, transmitted, reflected and/or refracted. The fate of the incident ray is a function of the angle of incidence and the physical properties of the two layers. Although this behavior results in very complex seismic ray behavior, it also provides a wealth of clues about the interior of the Earth. This information can be used to construct models of the Earth's interior as well as locate the position of earthquakes. Thus, the study of seismic ray transmission, reflection and refraction is extremely important both for scientific as well as practical reasons.

Incidence

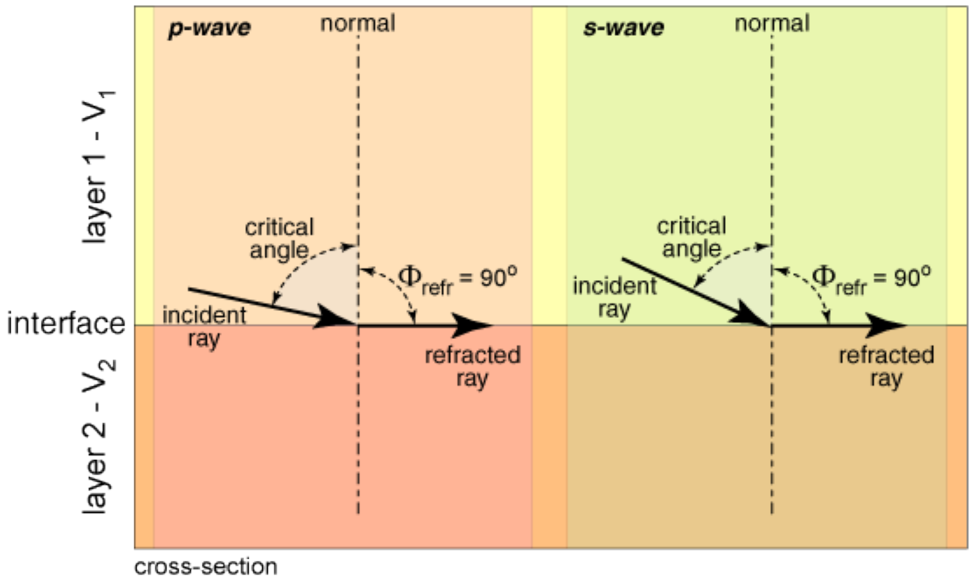
A critical factor in determining how an incident seismic ray behaves is the angle at which the ray strikes the interface. This angle is measure not from the interface surface, but from the normal to the interface, i.e. a line drawn at right angles to the interface. The normal is anchored at the point where the seismic ray strikes the interface.



The angle of an incident ray is measured from the normal to the interface to the ray path.

Critical Angle

The behavior of the incident seismic ray largely depends upon the relation of the incidence angle to the **critical angle**. At the critical angle, the incident ray is refracted along the interface between the two layers. Seismic rays incident to the interface at angles greater or less than the critical angle behave very differently.



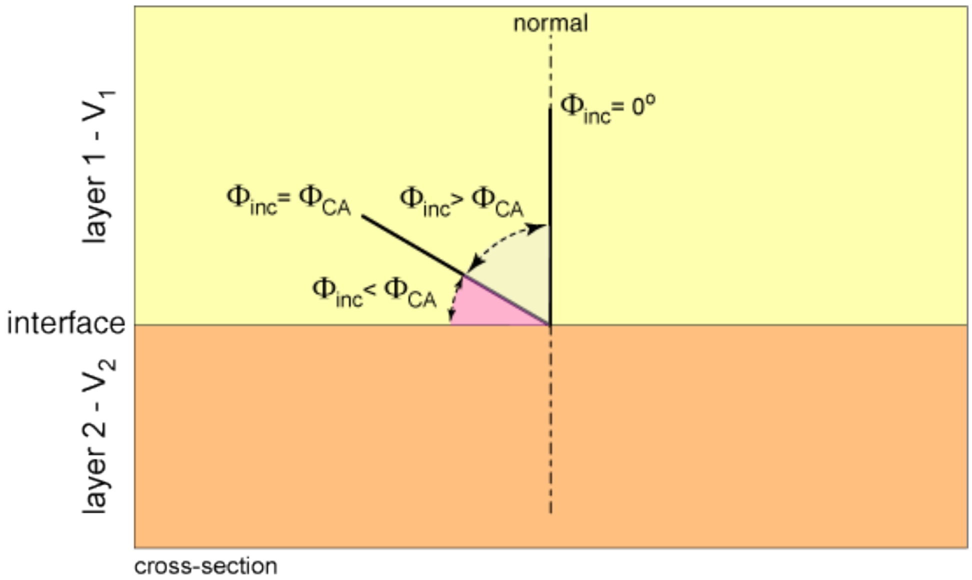
The critical angle defines how the incident ray behaves and is different for s- and p-waves.

The critical angle varies with the seismic velocities of the two adjacent layers. Because they have different velocities, s- and p-waves traveling through the same layers will have different critical angles.

Fate

The fate of a seismic ray when it encounters a layer of different physical characteristics depends upon the angle of incidence. Based on the relation of this angle to the critical angle, there are four possible fates for the incident ray. These are:

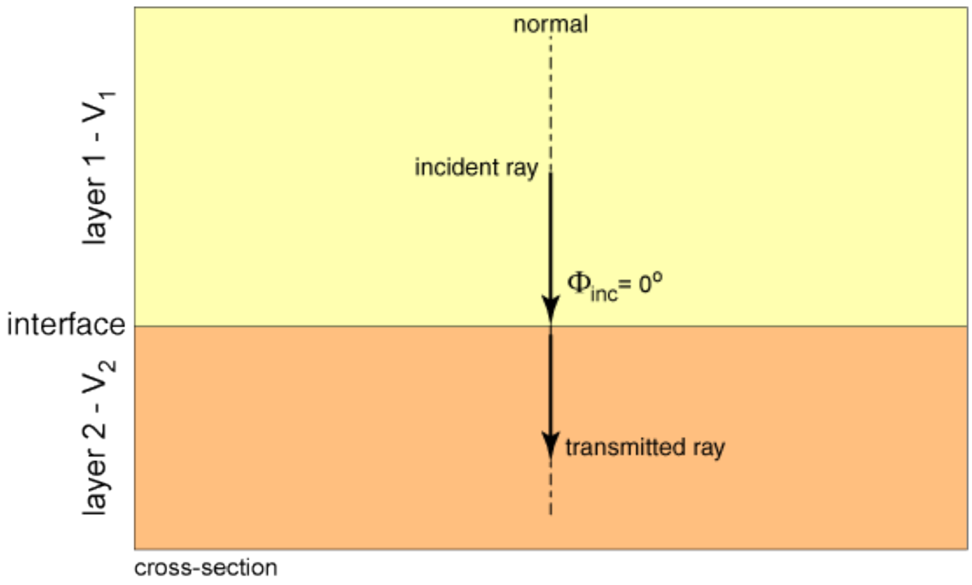
- **0^o (at right angles to interface)**: ray is transmitted into lower layer with no change in direction
- **less than critical angle**: wave split into two reflected rays that stay in original layer and refracted ray that enters the lower layer
- **equal to critical angle**: ray refracted along layer interface
- **greater than critical angle**: two rays reflected back into upper layer



The angle of an incident wave to the interface it strikes is measured relative to the normal to the interface.

Transmitted

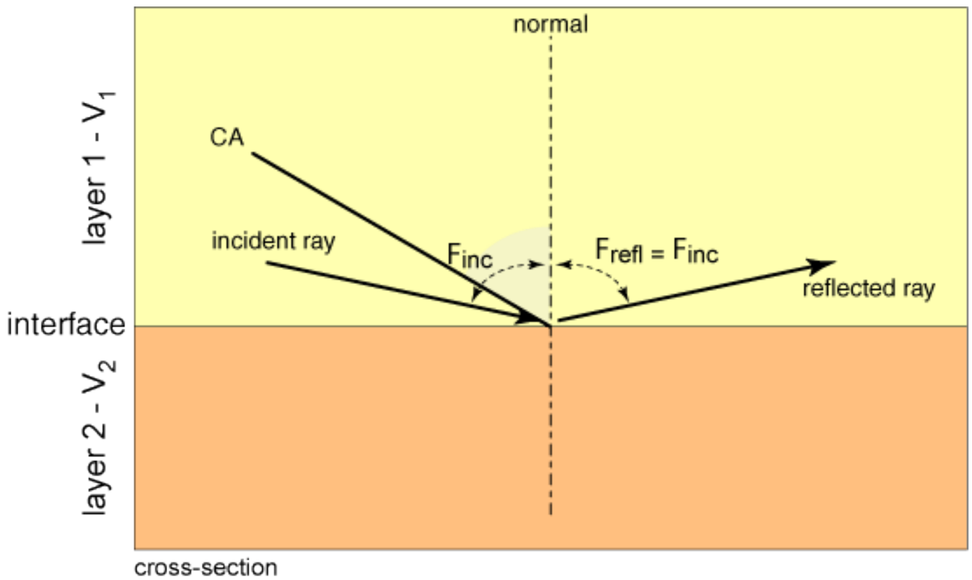
A **transmitted ray** is produced when a seismic ray strikes an interface at right angles, i.e. an incident angle of 0. The ray proceeds into the lower layer in the same direction as the original ray. There is a change in ray velocity as it moves from one layer to another.



Right angle incidence produces a ray that is transmitted into the lower layer.

Reflected

A **reflected ray** is one that bounces off the layer interface back into the original medium. This process is similar to light hitting a mirror and being reflected back to the observer. A reflected ray is produced when the angle of incidence is greater than the critical angle.



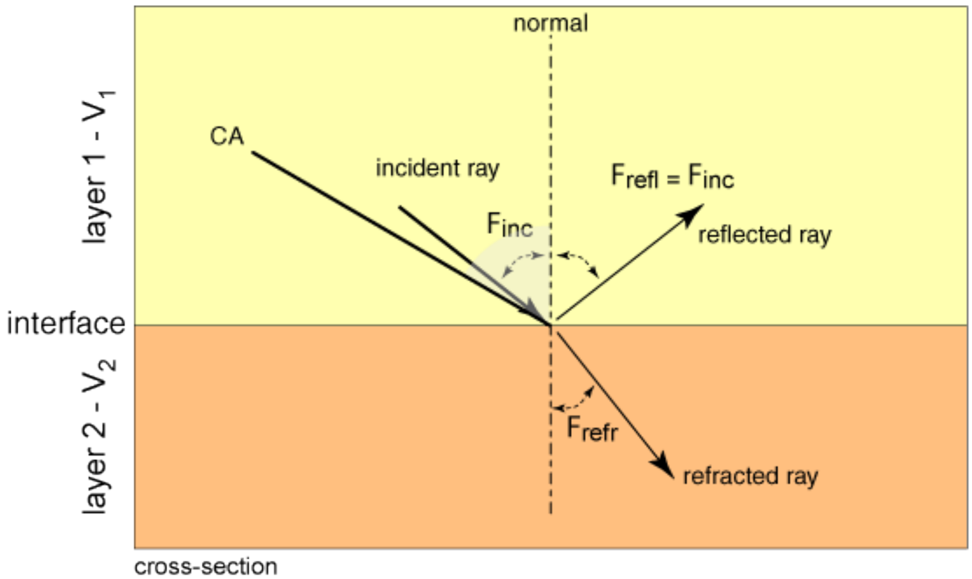
The angle of the reflected ray equals that of the incident ray.

The angle at which the ray is reflected is equal to the angle of the incident ray. Thus, as the incident angle decreases, the angle of the reflected ray also decreases. In addition, the energy of a reflected ray is similar to that of the incident ray as required by the law of conservation of energy.

Refracted

At incident angles less than the critical angle, an incident ray generates a **refracted ray** along with a reflected ray. This wave is propagated into the lower layer at an angle determined by the angle of incidence and the seismic velocities of the two mediums. This process is the one that makes a pencil placed in water appear bent at the air/water interface. The angle of the reflected ray equals that of the incident ray.

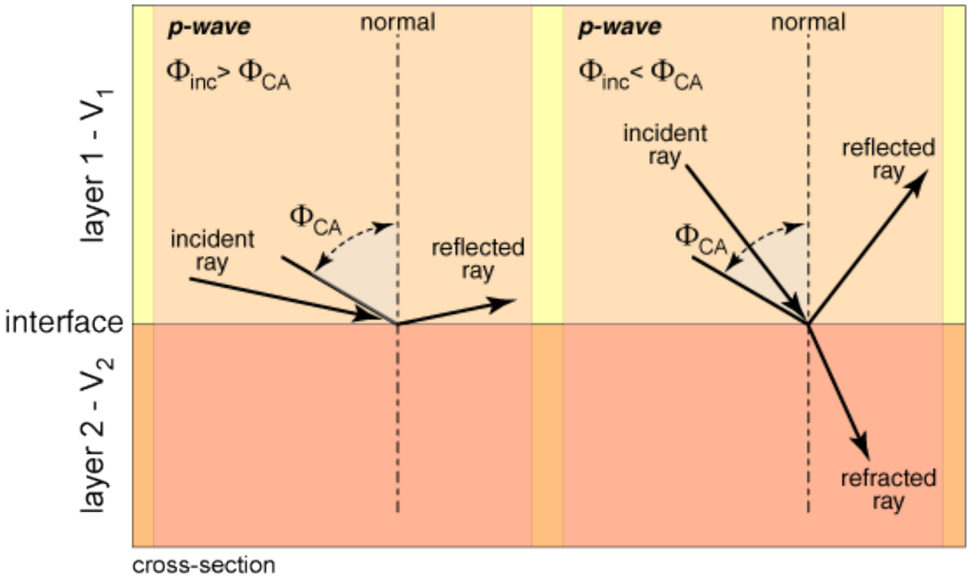
Under these conditions, the initial energy of the incident ray is split between the reflected and refracted rays. Since the energy of the incident ray is now divided between the refracted and reflected rays, both waves will have less energy than the original incident wave. The sum of the energies of the two rays will, however, equal that of the original incident ray.



A refracted ray is also produced at low angles of incidence.

Snell's law

The fate of an incident seismic ray depends upon the angle that it strikes the interface between layers of different physical properties. If it is above the critical angle, the rays is simply reflected. However, when it strikes the interface at an angle less than the critical angle, both reflected and refracted rays are produced.



The behavior of an incident ray is determined by the characteristics of the layers.

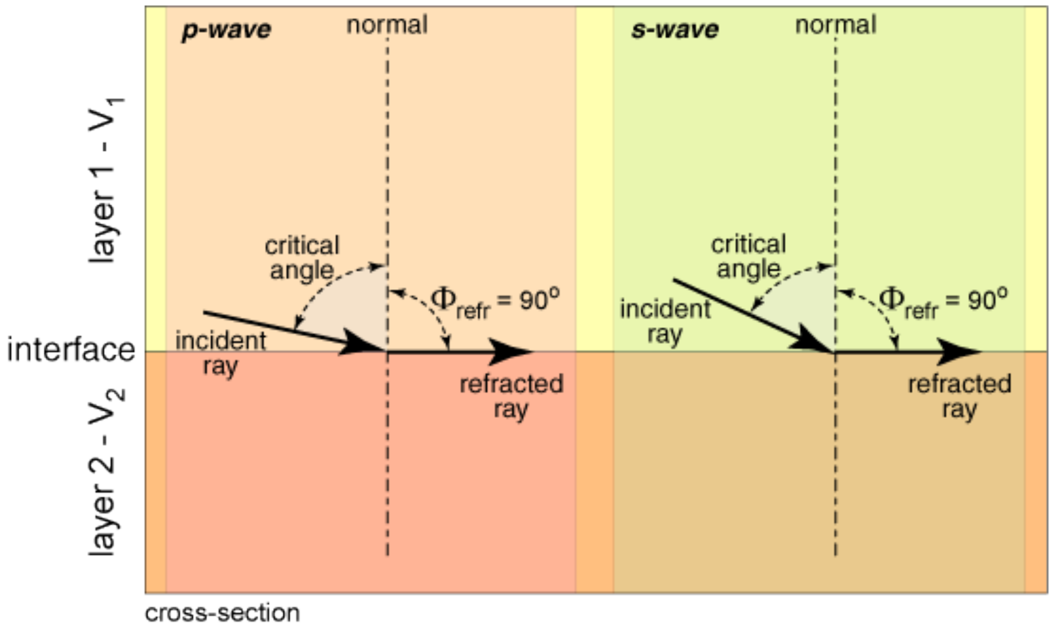
The behavior of the incident rays and the value of the critical angle is a function of the seismic velocities in the two adjacent layers. The relationship between the angles and the seismic velocities is described by **Snell's Law**, a relatively simple mathematical expression but very important.

Snell's law relates incident angle, refracted/reflected angle and layer seismic velocities by the following expression.

$$\frac{\sin(\Phi_{inc})}{\sin(\Phi_{refr})} = \frac{V_1}{V_2}$$

Critical Angle

The behavior of the incident seismic ray largely depends upon the relation of the incidence angle to the **critical angle**. At the critical angle, the incident ray is refracted along the interface between the two layers. Seismic rays incident to the interface at angles greater or less than the critical angle behave very differently.



The critical angle defines how the incident ray behaves and is different for s- and p-waves.

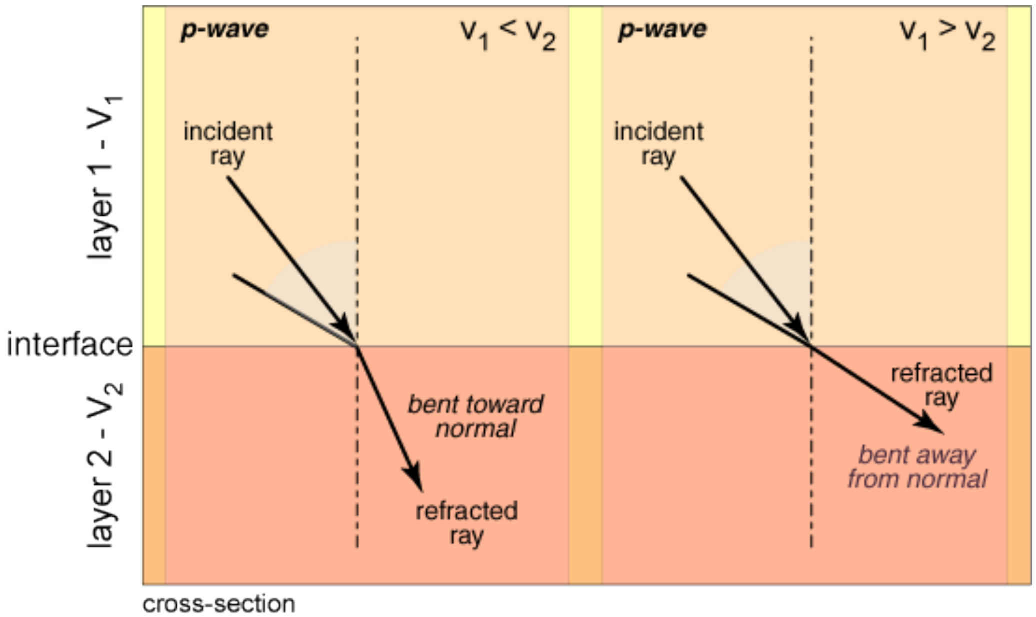
The critical angle varies with the seismic velocities of the two adjacent layers. Because they have different velocities, s- and p-waves traveling through the same layers will have different critical angles. This angle can be calculated using Snell's law by setting angle of refraction equal to 90o, i.e. the angle a ray will be refracted along the layer interface.

$$\frac{\sin(\Phi_{inc})}{\sin(\Phi_{refr})} = \frac{\sin(\Phi_{inc}^{CA})}{\sin(90^\circ)} = \frac{\sin(\Phi_{inc}^{CA})}{1} = \frac{V_1}{V_2}$$

$$\sin(\Phi_{inc}^{CA}) = \frac{V_1}{V_2}$$

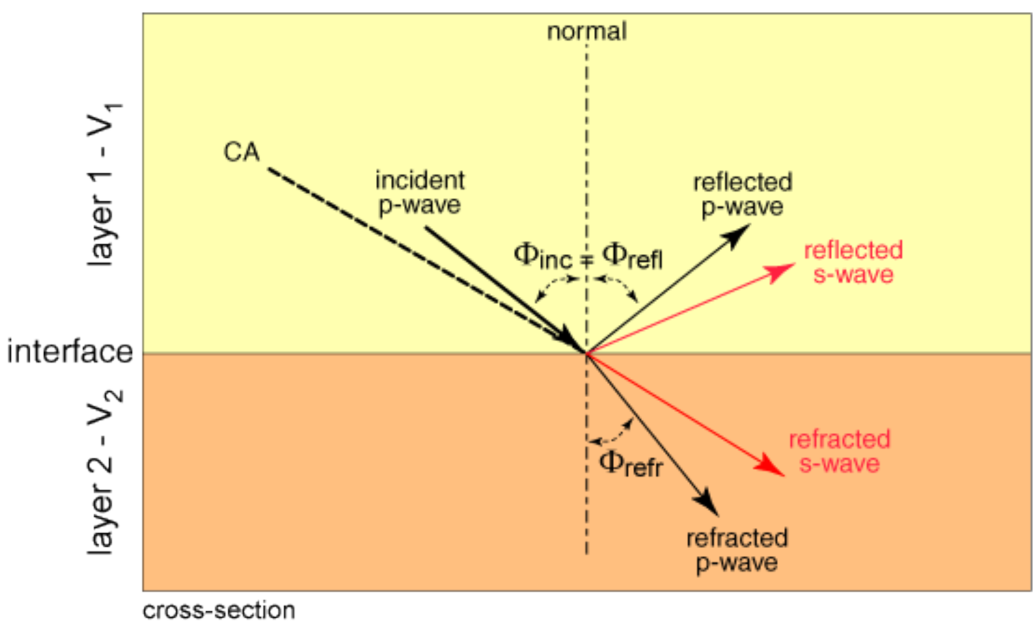
Behavior

How a incident wave is refracted in the lower medium is determined by the relative seismic velocities of the two layers. When the velocity in the upper layer is less than in the lower layer, the wave is refracted toward the normal. The opposite behavior, i.e. bending away from the normal, when the velocity is greater in the upper layer.



Conversions

When an incident ray strikes the interface between two layers at an angle less than the critical angle, four waves are produced. Two are reflected waves in the original layer and two are refracted waves in the lower layer. Each set of waves consist of both a p- and s-wave.



The behavior of the waves is dependent the relative velocities in the two layers. Specifically, the amplitudes of the reflected and refracted waves are a function of the densities and seismic velocities of the two layers.

Complete

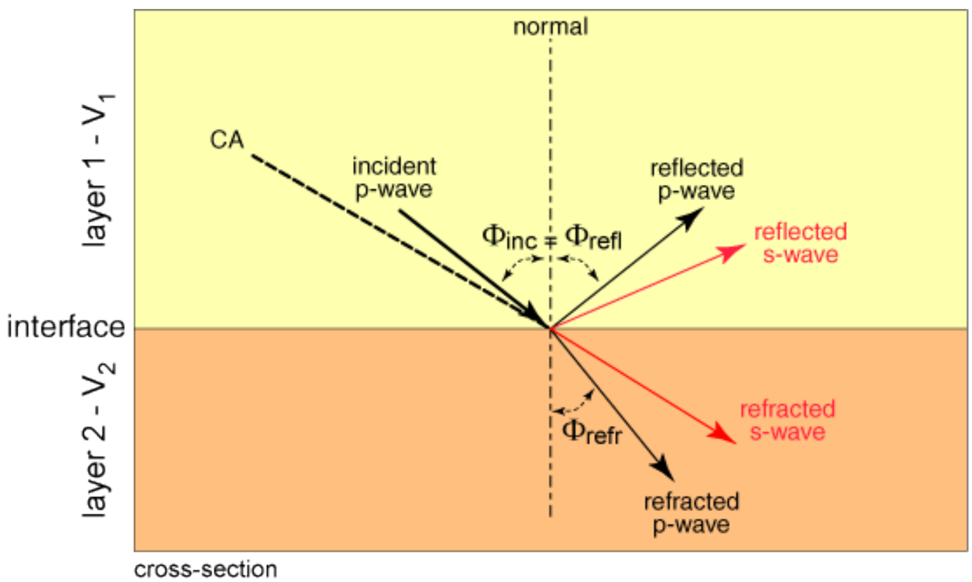
Because both p and s-waves are generated upon incidence, Snell's law is more complex if it is written to describe all generated waves. Considering both reflected and refracted waves as well as both p- and s-waves, the complete form of Snell's law is:

$$\frac{\sin(\Phi_i)}{\left(V^1_{s\ or\ p}\right)} = \underbrace{\frac{\sin\left((\Phi_{refl})^1_p\right)}{V^1_p} = \frac{\sin\left((\Phi_{refl})^1_s\right)}{V^1_s}}_{\text{reflected waves}} = \underbrace{\frac{\sin\left((\Phi_{refr})^2_p\right)}{V^2_p} = \frac{\sin\left((\Phi_{refr})^2_s\right)}{V^2_s}}_{\text{refracted waves}}$$

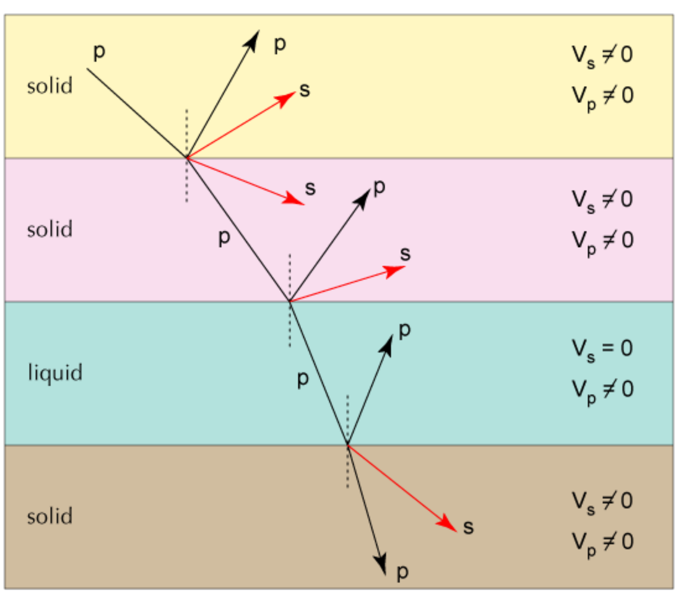
Body Wave Ray Behavior

Because the Earth's interior consists of a number of shells of differing densities and therefore seismic velocities, the path a seismic ray takes through the Earth can be very complex. Depending upon the angle of incidence and the nature of the new medium, a ray may reflected, refracted or converted to another type when it strikes an interface between two different shells. Thus, a large number of rays can be generated from a single ray emanating from an earthquake focus. To describe a ray's path through the Earth, seismologists have devised a naming scheme that identifies the shells a particular ray has traversed.

Propagaton



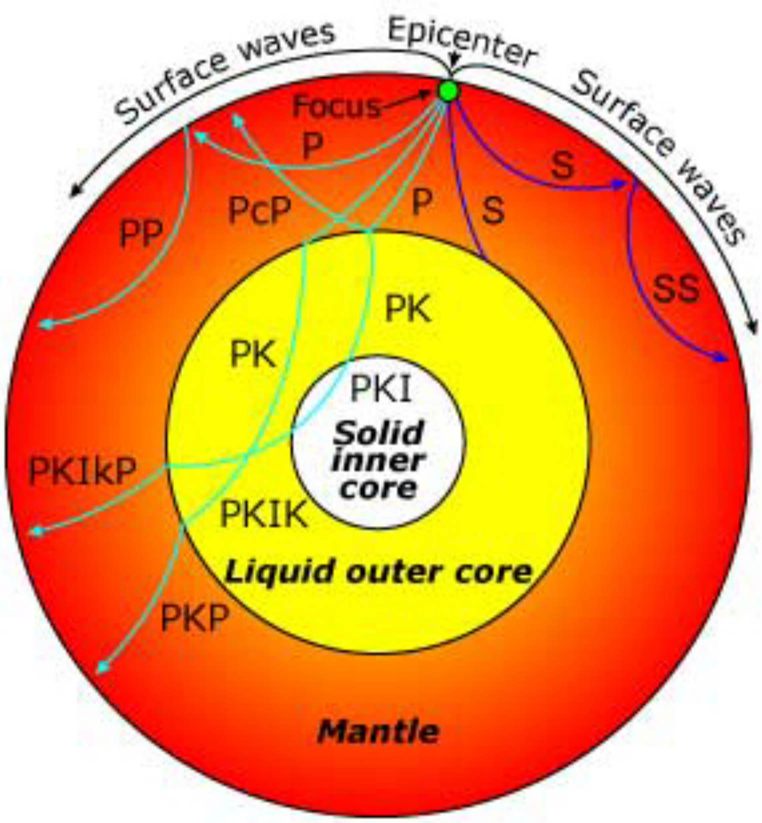
Layers



Naming

The following conventions are used to identify the segments of a seismic ray.

- P-waves
  - **P** - traveled through the mantle
  - **p** - reflected from Earth's surface close
  - **K** - traveled through the outer core
  - **I** - traveled through the inner core
- S-waves
  - **S** - traveled through the mantle
  - **s** - reflected from the Earth's surface close
  - **J** - traveled through the inner core
- reflection
  - **c** - at the mantle-outer core boundary
  - **i** - at the outer core-inner core boundary



Locating an Earthquake's Epicenter

One of the first steps a seismographic station takes after detecting an earthquake is to locate its **epicenter**, i.e. the point on the Earth's surface directly above the earthquake focus. This procedure involves utilizing the observation that s and p body travel at different velocities. Thus, the time difference between the arrival of these two body waves for the same seismic event will be at different stations. The difference in time of arrival is, in large part, a function of distance from the epicenter to the station. That is, the farther the station is from the earthquake, the greater the time lag between the p and s wave arrival. This difference in arrival time can be used to locate an earthquake's epicenter.

Locating an earthquake's epicenter is important for planning responses to the event. For example, trains traveling in remote areas such as this area of Alaska could be warned to watch for damage to tracks and bridges along their routes.

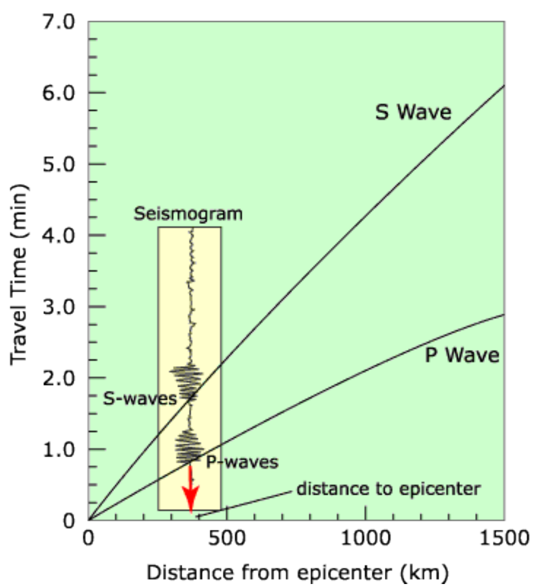
Using the arrival times of seismic waves for locating earthquakes was first proposed by John Mitchell, an astronomer studying the Great Lisbon earthquake of 1755. Unfortunately, the instrumentation necessary to put his suggestion into practical operation would not arrive for another 150 years.

Wave Travel

Primary or p waves travel through the Earth by compression whereas secondary or s waves move by shear. Thus, p waves travel through solid, liquid and gas, but s-waves can only pass through solid material. In addition, p-waves are faster than s-waves (see table below), thus they arrive at a seismographic station after an earthquake first.

Material	P-Wave Velocity (km/sec)	S-Wave Velocity (km/sec)
Crust	3 - 6	2 - 3.5
Mantle	7.5 - 13	5 - 7
Outer Core	7.5 - 10	0
Inner Core	12	3

Time Travel



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