Refraction

Why do seismic waves travel a curving path through the Earth?

Background pages to accompany: **IRIS' Animations: Refraction**

Introduction

In high-school physics class, students learn that light waves bend when they travel from one material into another of different density abiding by **Snell's Law** (box below; see also how light waves differ from seismic waves on Page 3). Seismic waves follow the same law of refraction at compositional boundaries. If the seismic wave velocity in the rock below a boundary increases, the waves will be refracted upward and speed up relative to their original path. If it passes across a boundary to a lower velocity layer, the wave will be refracted downward and slow down. Because velocity generally increases with depth in the mantle, the wave paths get bent until they reach a critical angle at which point, the waves return to the surface following a curved path upward. Various **material properties** (i.e., **elastic moduli**) control the speed and **attenuation** of seismic waves.

HOT LINKS:

Interactive Flash page allows you to set the angle of incidence and the Index of Refraction and watch the angles change.
Reflection & Refraction: Air to Glass

High-school physics tutorial on the nature, properties, and behavior of waves. Refraction is covered in: **Lesson 3: Behavior of Waves, Boundary Behavior**

Video lecture on refraction of light (from *How Things Work*): **Elements of Physics: Refraction**

Seismic Waves and Earth's interior

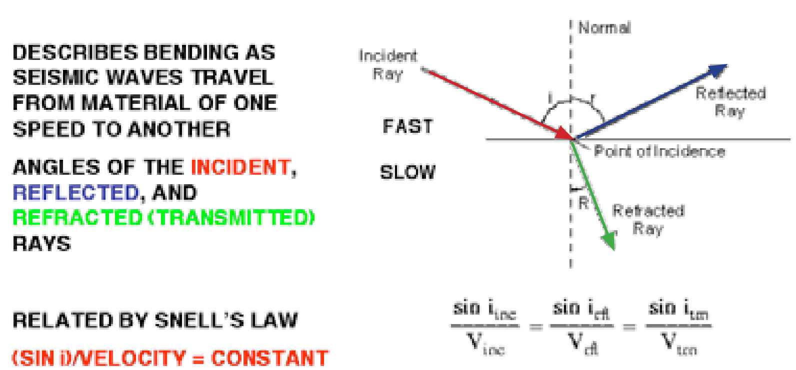
See page 2 (this document) for an extract from Chuck Ammon's excellent description of seismic waves behavior..

Snell's Law

A formula used to describe the relationship between the angles of incidence and refraction as they pass through a boundary between different media. Seismic waves can also be critically refracted at an interface when refraction reaches 90°.

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2}$$

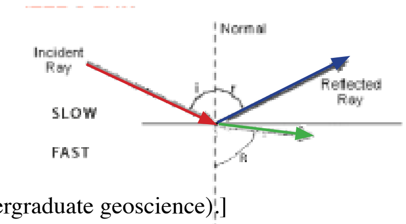
i = incoming ray angle measured from vertical
v_1 = velocity of that ray.
r = ray angle of the refracted ray
v_2 = velocity of that ray.



When an incident ray goes from:

1) faster to slower material, the refracted waves bend toward vertical (left)

2) slower to faster material, the refracted waves bend toward horizontal (below)



[graphic modified from **Seth Stein** (link to copious notes and slides on Earth's interior for undergraduate geoscience).]

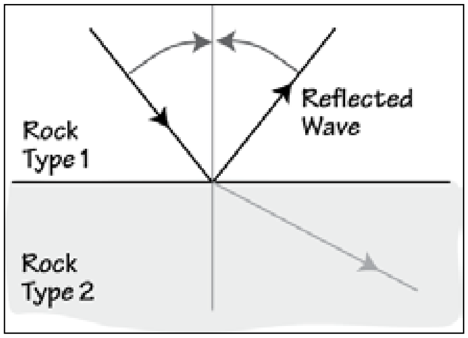
P-waves in Earth (extract from Seismic Waves and Earth's Interior)

by Charles J. Ammon, Penn State, used with permission.

The mathematics behind wave propagation is elegant and relatively simple, considering the fact that similar mathematical tools are useful for studying light, sound, and seismic waves. We can solve these equations or an appropriate approximation to them to compute the paths that seismic waves follow in Earth. Although seismic wave interactions are rich in both subtlety and complexity, two processes, reflection and refraction are common (and common to many other wave-systems such as light, sound, etc)

Reflection

A seismic reflection is generated when a wave impinges on a change in rock type (which usually is accompanied by a change in seismic wave speed). Part of the energy carried by the incident wave is transmitted through the material (that's the refracted wave described below) and part is reflected back into the medium that contained the incident wave.

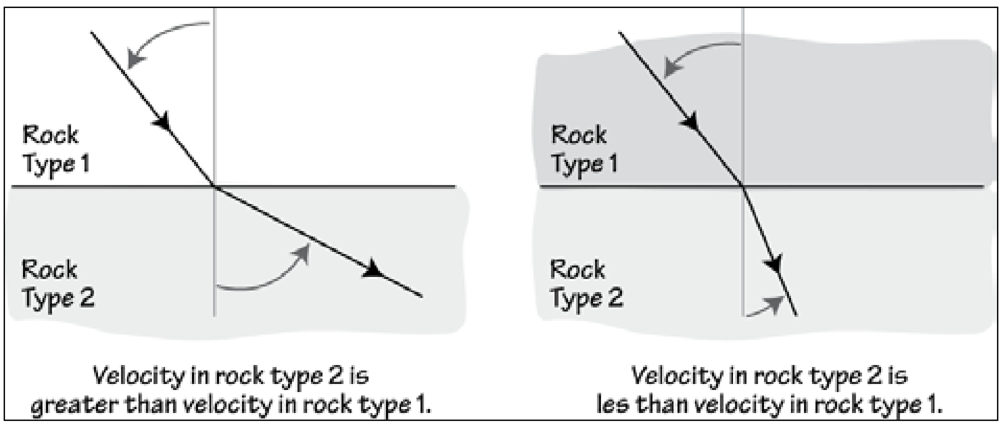


When a wave encounters a change in material properties (seismic velocities and or density) its energy is split into reflected and refracted waves.

The amplitude of the reflection depends strongly on the angle that the incidence wave makes with the boundary and the contrast in material properties across the boundary. For some angles all the energy can be returned into the medium containing the incident wave. Reflections are often used in the search for oil and natural gas, which have a large affect on the material properties, and thus generate distinguishable signatures in seismic reflections.

Refraction

As a wave travels through Earth, the path it takes depends on the velocity. Perhaps you recall from high school a principle called Snell's law, which is the mathematical expression that allows us to determine the path a wave takes as it is transmitted from one rock layer into another. The change in direction depends on the ratio of the wave velocities of the two different rocks.



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When waves reach a boundary between different rock types, part of the energy is transmitted across the boundary. The transmitted wave travels in a different direction which depends on the ratio of velocities of the two rock types. Part of the energy is also reflected backwards into the region with Rock Type 1, but I haven't shown that on this diagram (lower right).

Refraction has an important affect on waves that travel through Earth. In general, the seismic velocity in Earth increases with depth (there are some important exceptions to this trend) and refraction of waves causes the path followed by body waves to curve upward.

How are optical waves different from seismic waves?

Some care is needed when using the optical refraction analogy as the light velocities are *relative to density* while seismic velocities are not. The velocity of seismic waves increases with depth in the Earth. While density also increases with depth, density is not the controlling factor in the velocity increase. Consider the formula **F = ma**, an increase in density would actually slow the acceleration. However, the increase in the speed of seismic waves is a result of the rigidity (**m** = resistance to shearing) and incompressibility (**k** = resistance to compression) of the material increasing with depth faster than density. For example the velocity of a primary wave (**Vp**) is determined by **Vp = k+4/3m/r**. Density is in the denominator and actually slows the wave.

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Vocabulary

Attenuation—The gradual loss of intensity as a wave propagates through a medium. A seismic wave loses energy as it propagates through the earth.

Elastic moduli—Multiple mathematical descriptions of the various ways an object or material is deformed elastically when a force is applied.

Material properties —The bulk character of the rock, such as composition, density, elastic moduli, mineralogy, and phase (ex. the presence of melt). Seismic waves propagate through the earth with a velocity and manner that depend on the material properties of the earth.