

Three Major Laws (1)

Huygens' Principle: Every point on a wavefront can be considered a secondary source of spherical waves, and the position of the wavefront after a given time is the envelope of these secondary wavefronts.

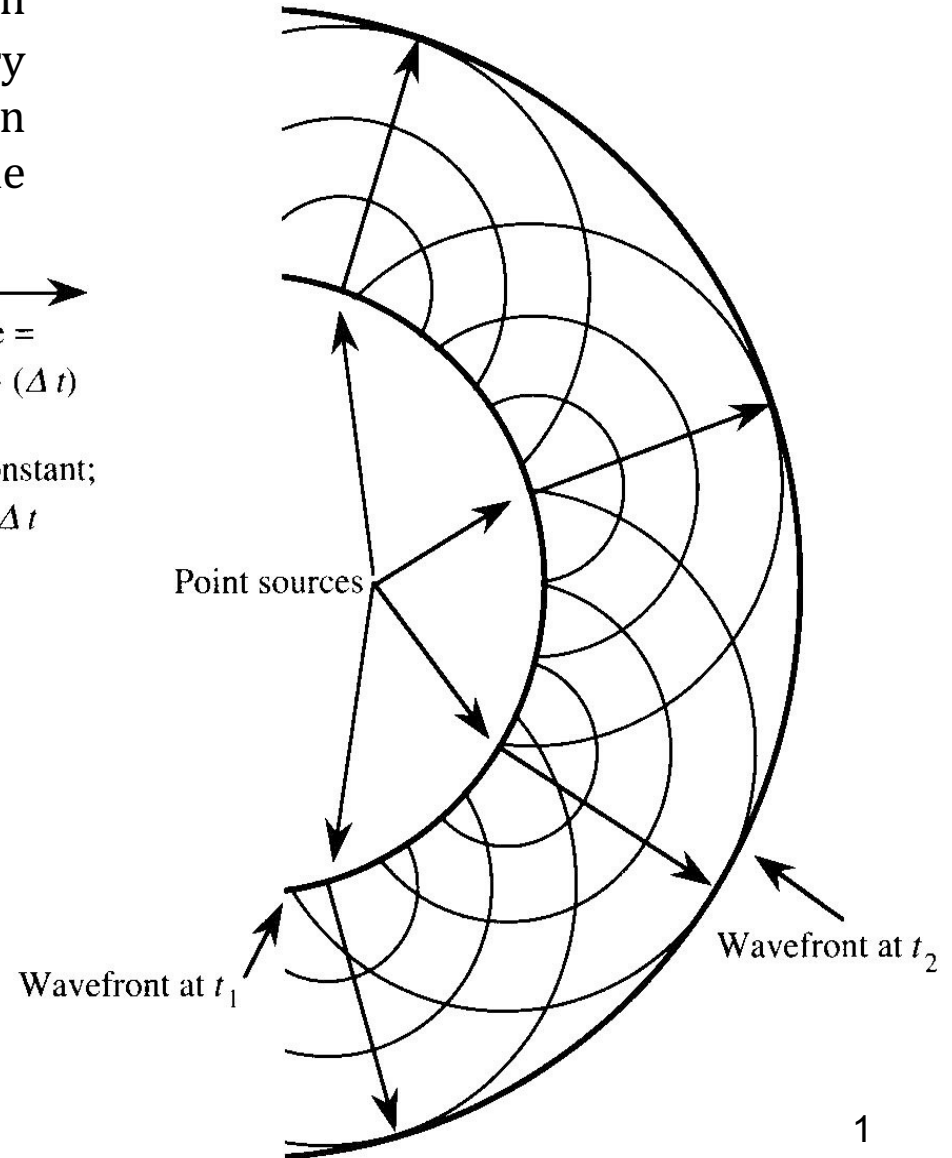


Christiaan Huygens (1629 – 1695)

$$\text{Distance} = (\text{velocity}) \cdot (\Delta t)$$

Velocity is constant;

$$t_2 = t_1 + \Delta t$$



Three Major Laws (2)



Pierre de Fermat (1601 – 1665)
(Wikipedia)

Fermat's principle explains the fuzziness. Hot air (i.e., low velocity zone) causes rays to bend such that light moves along the fastest route. **Same goes for seismic waves inside the Earth.**

Fermat's Principle: Fermat developed the *principle of least time*. The principle states that in the propagation of waves, the wave path between any two fixed points is that one along which the time of travel is the least of all possible paths.

Remark: Least time is **NOT** Least distance



Three Major Laws (3)

Reflection and refraction of seismic waves

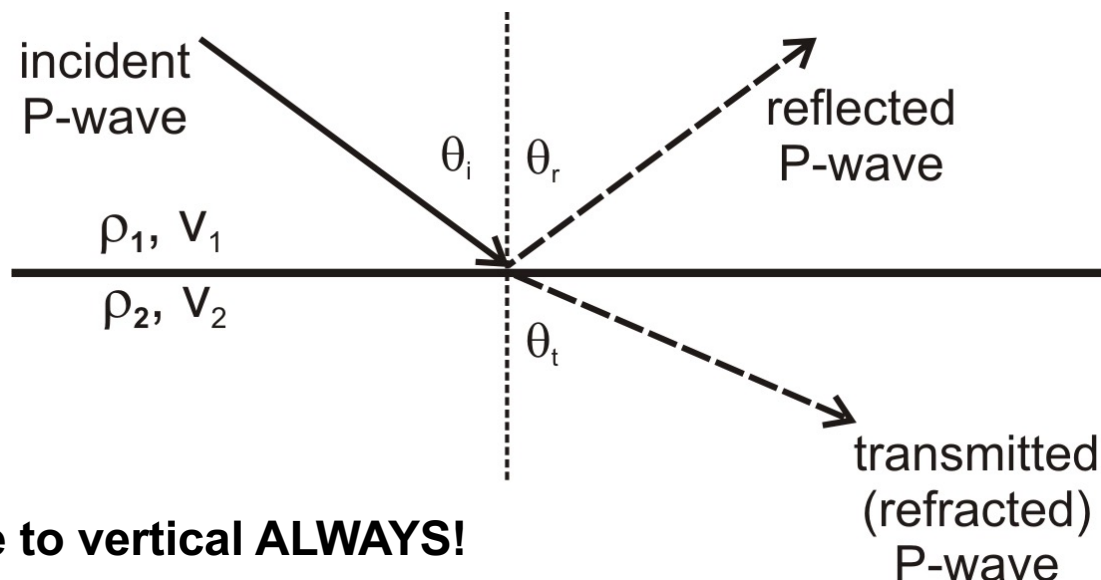
- seismic energy is partitioned at an interface: reflection and transmission

- each wave characterized by a **ray parameter**:

$$p = \frac{\sin \theta}{V}$$

- **Snell's Law:** ray parameter is the same for all waves at the interface

$$p = \frac{\sin \theta_i}{V_1} = \frac{\sin \theta_r}{V_1} = \frac{\sin \theta_t}{V_2}$$



θ is relative to vertical ALWAYS!

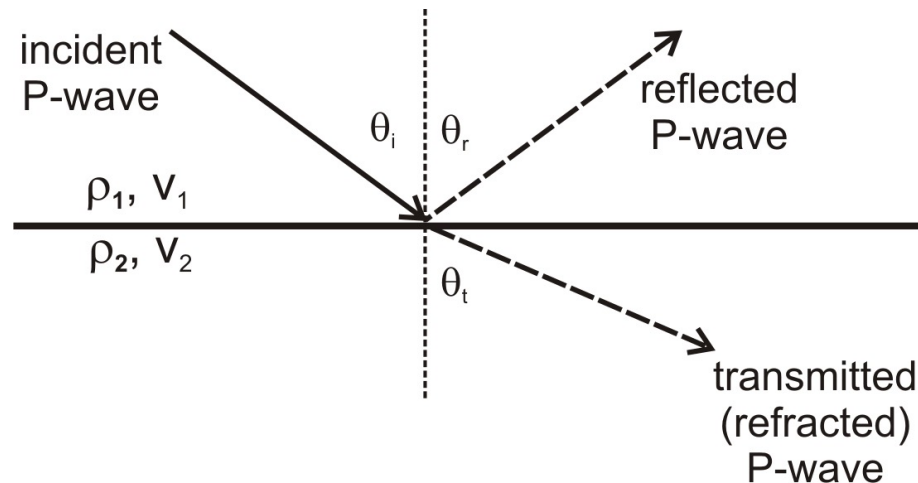
Reflection and refraction of seismic waves

Snell's Law:

$$p = \frac{\sin \theta_i}{V_1} = \frac{\sin \theta_r}{V_1} = \frac{\sin \theta_t}{V_2}$$

NOTE THAT:

- $\theta_i = \theta_r$
- a change in velocity across the interface results in a change in the direction of the wave that passes through the interface → the wave is **refracted** (also known as **'transmitted'**).
 $V_2 > V_1$: refracted wave bends **away from the normal** ($\theta_t > \theta_i$)
 $V_2 < V_1$: refracted wave bends **toward the normal** ($\theta_t < \theta_i$)



Reflection and Refraction of seismic waves

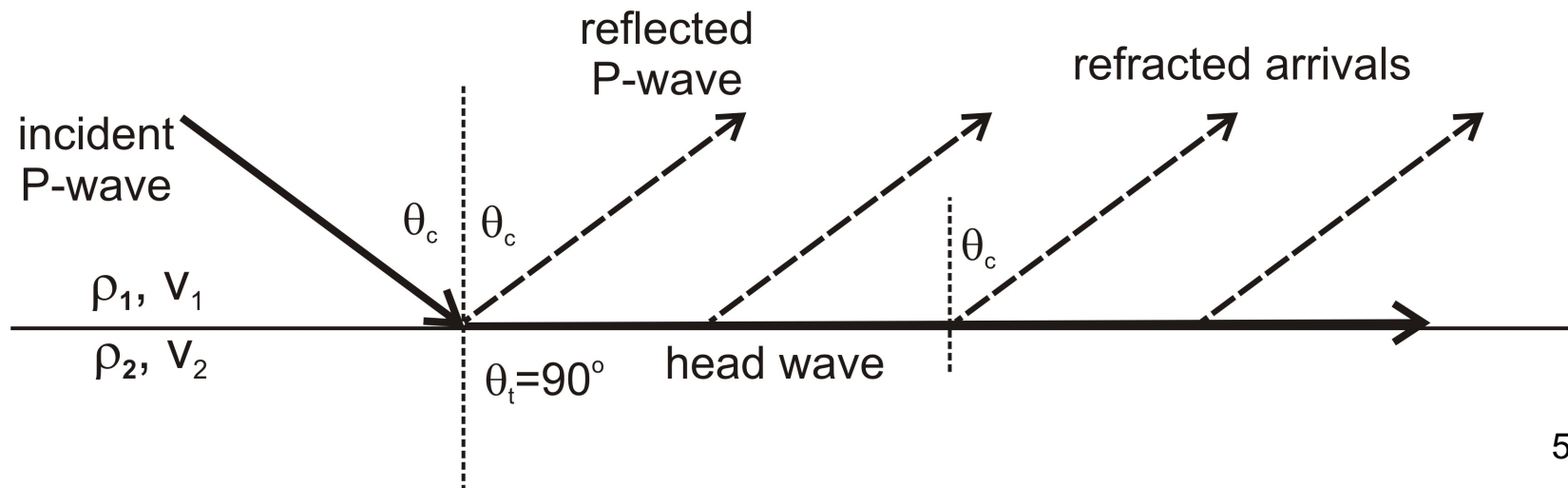
Critical angle: only for $v_2 > v_1$

→ angle of incidence that produces a refracted wave that travels along the interface ($\theta_t = 90^\circ$)

$$p = \frac{\sin \theta_i}{V_1} = \frac{\sin \theta_t}{V_2} \longrightarrow \frac{\sin \theta_c}{V_1} = \frac{\sin(90^\circ)}{V_2} = \frac{1}{V_2} \longrightarrow \boxed{\theta_c = \sin^{-1}\left(\frac{V_1}{V_2}\right)}$$

“head wave” – travels at v_2 , produces refracted arrivals at surface

if $\theta_i > \theta_c$: no refracted energy, **total internal reflection** (at angle θ_i)



‘Refracted Waves’ (or ‘Head Waves’)

Whispering Wall (Forbidden City)



From shutterstock.com

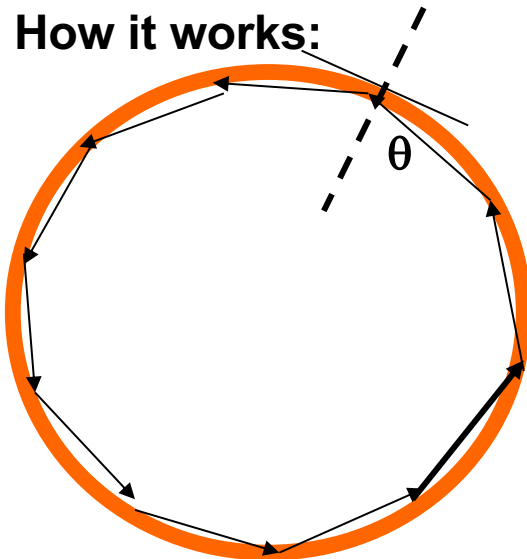
shutterstock.com - 25054621

Whispering Gallery, St Paul's Cathedral (England)



From Wikipedia

How it works:



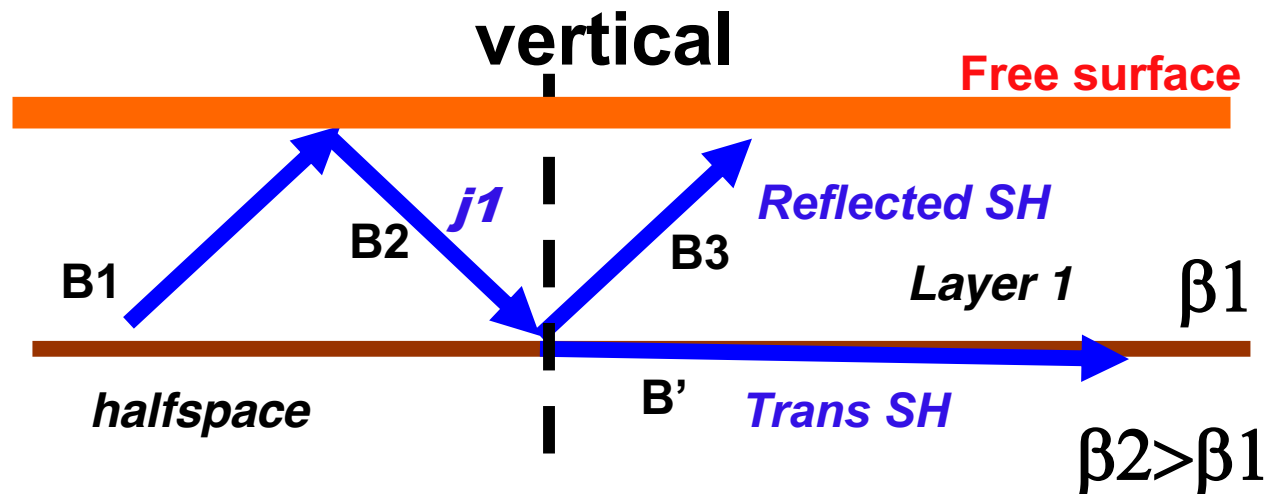
Nature of “whispering wall” or “whispering gallery”:

A sound wave is trapped in a carefully designed circular enclosure. A sound wave propagate at the critical angle (going through critical reflection) at each reflection point due to curved walls. The total internal reflection preserves the amplitude, which allows the wave to continue to be trapped without much decay.

This is actually similar to ‘surface wave’ (trapped wave with strong amplitudes)

Surface Wave 1 (related to Head wave)

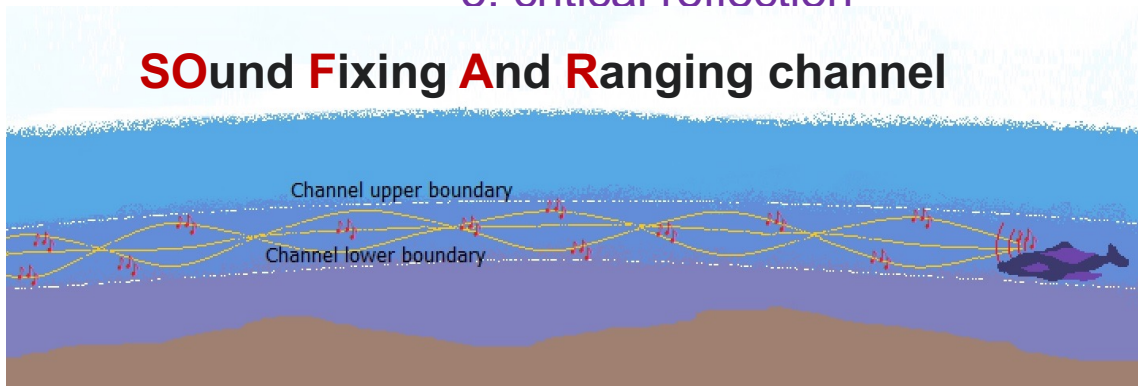
Love waves



The generation of Love wave (transverse particle motion) is essentially trapped SH polarized shear waves inside a lower velocity regime. This is also seen in 'SOFAR Channels' in the oceans.

Requirements:

1. velocity increase
2. presence of the free surface
3. critical reflection



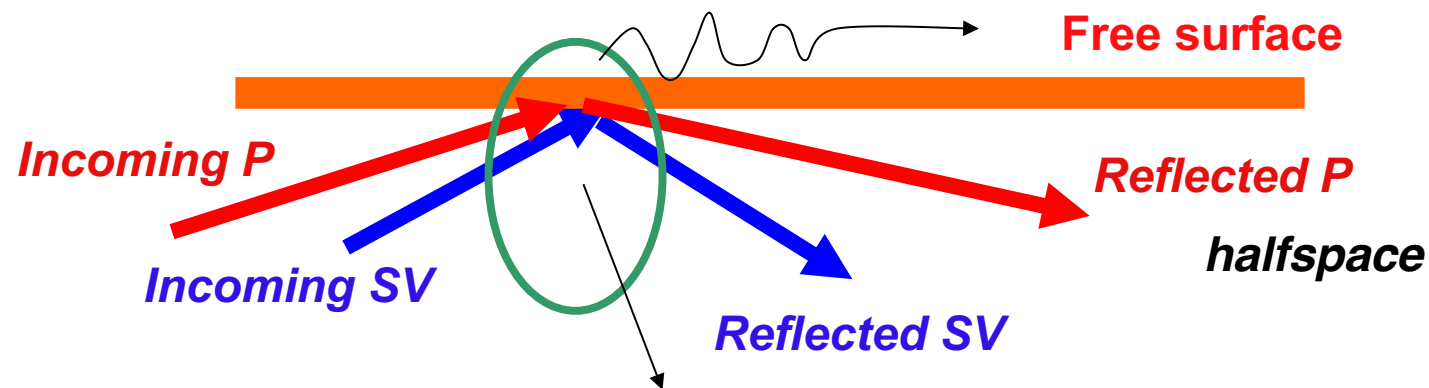
'SOFAR' channels:
Caused by echo inside a hot, low-velocity water layer. This becomes a waveguide that could propagate for thousands of kilometers. ⁷

Image from <https://oversoil.wordpress.com/2023/10/17/sofar/>

Surface wave 2 (Rayleigh waves, a true surface wave)

Definition: “Rayleigh waves are a combination of P and SV waves that can exist at the top of homogeneous half-space”

Half-space: space/area with uniform properties that is terminated by a boundary



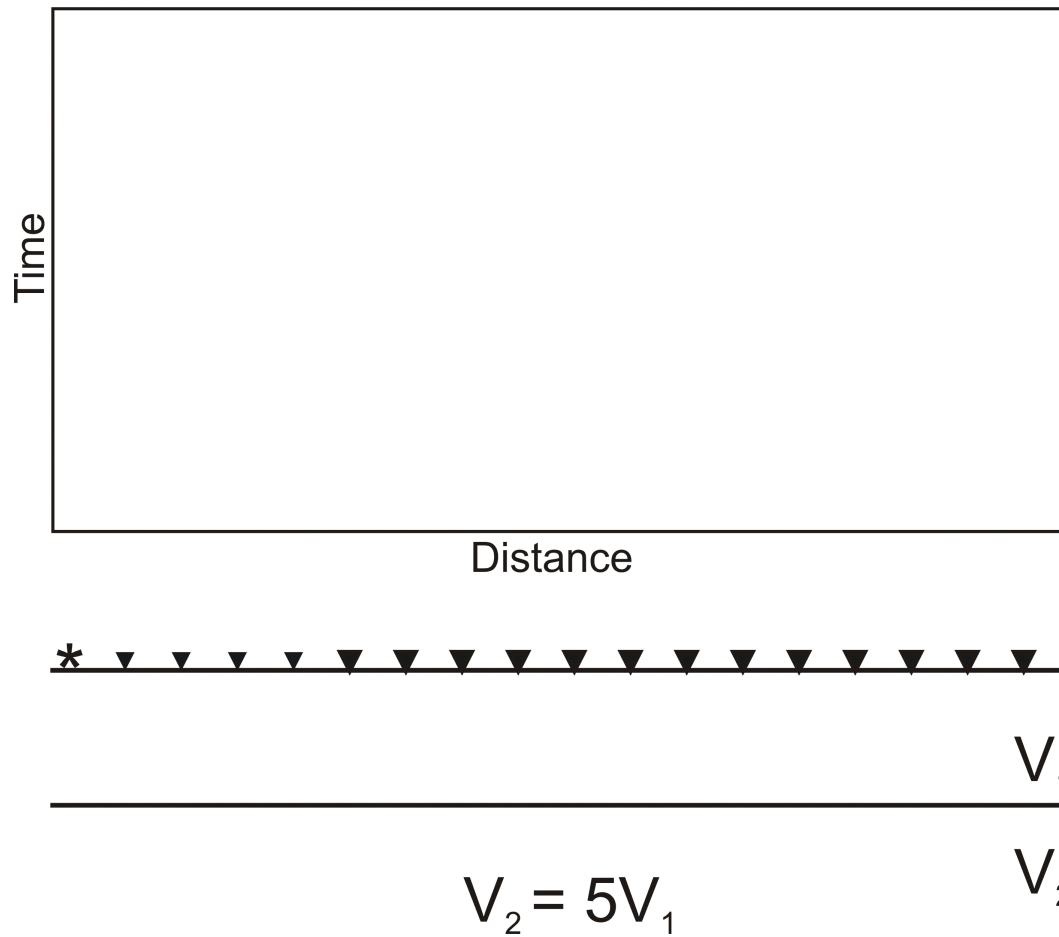
Assume a Poisson Solid (more or less Earth material), then $\lambda = \mu$, first, what are the speeds of V_s and V_p ?

Poisson Solid $\rightarrow V_R \sim 0.92 \beta$ (V_R = Rayleigh/horizontal speed)

Questions:

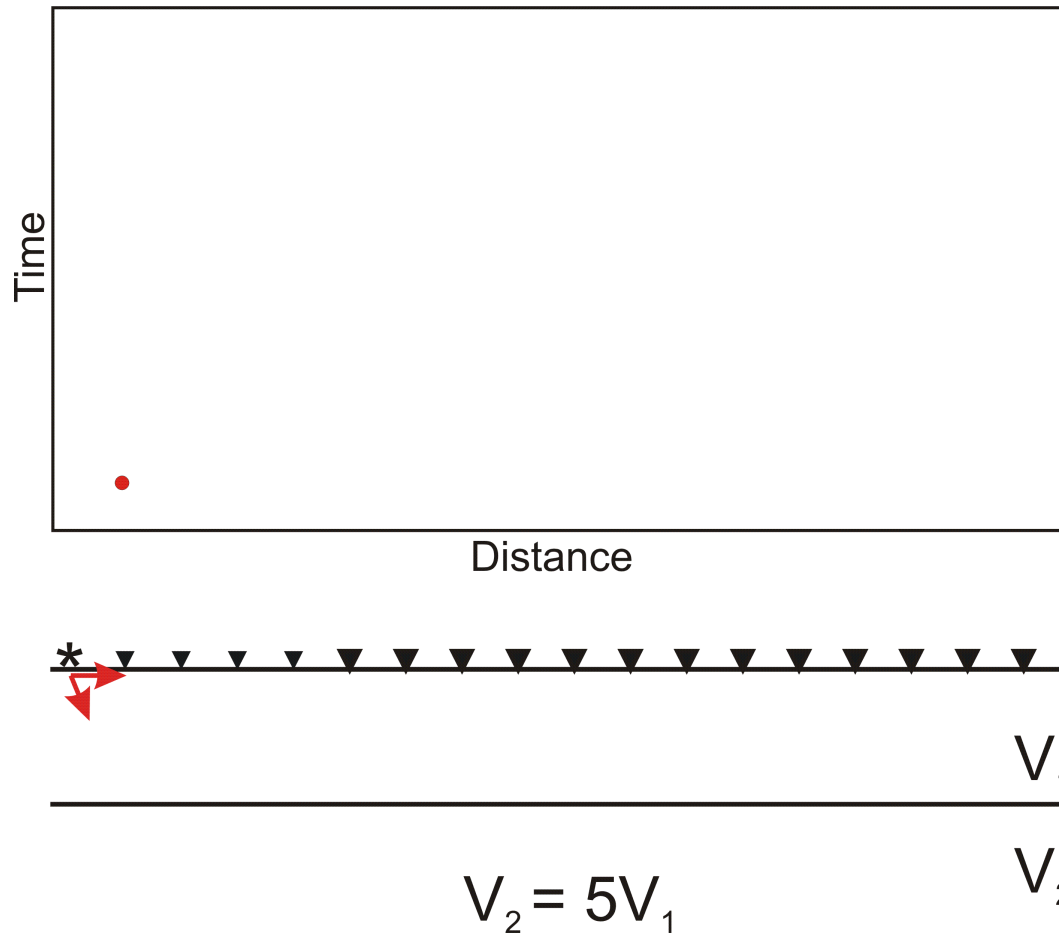
1. Which is usually faster, Rayleigh or Love??
2. Similar to P-SV body wave, which means it should be observed on which component?
3. Do Rayleigh and Love have the same depth sensitivity?

Seismic Reflections & Refractions



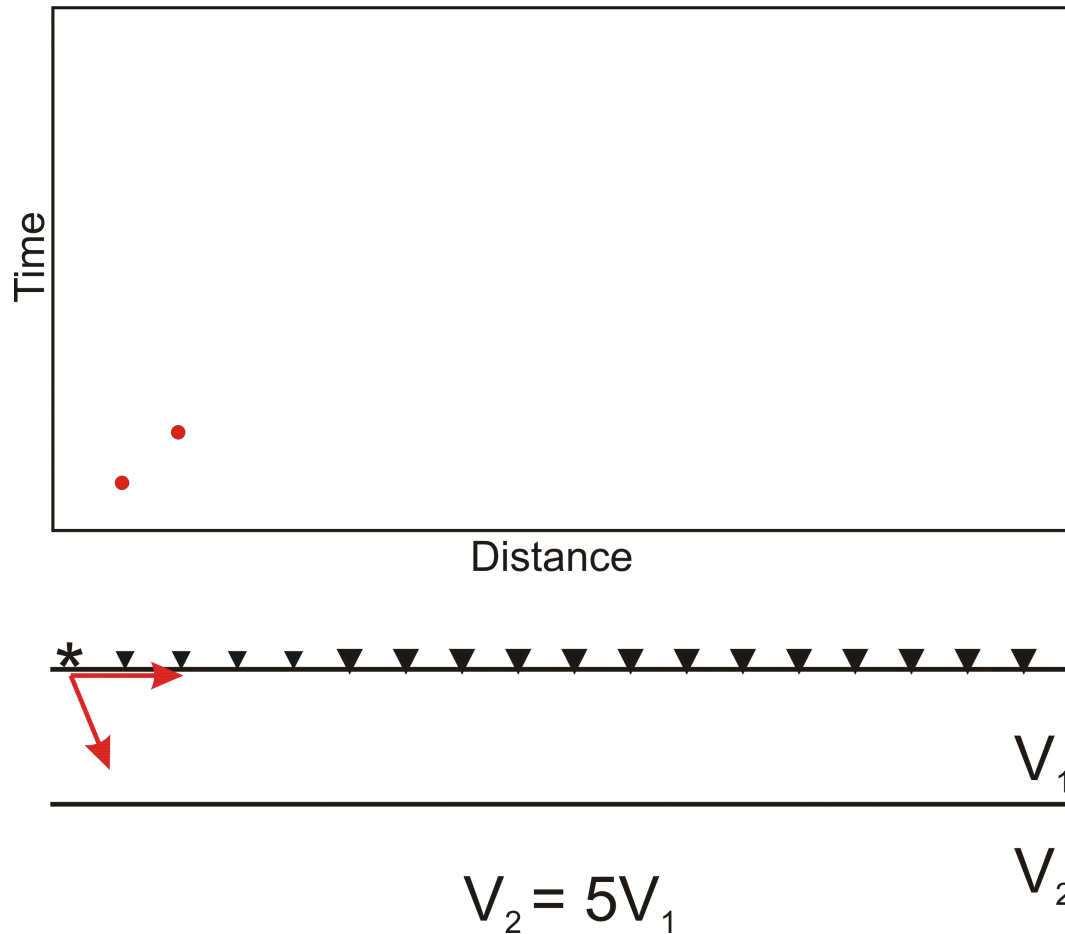
Craig Lippus (Seismic Products Geometrics Inc)

Using Seismic Refraction to Map the Subsurface



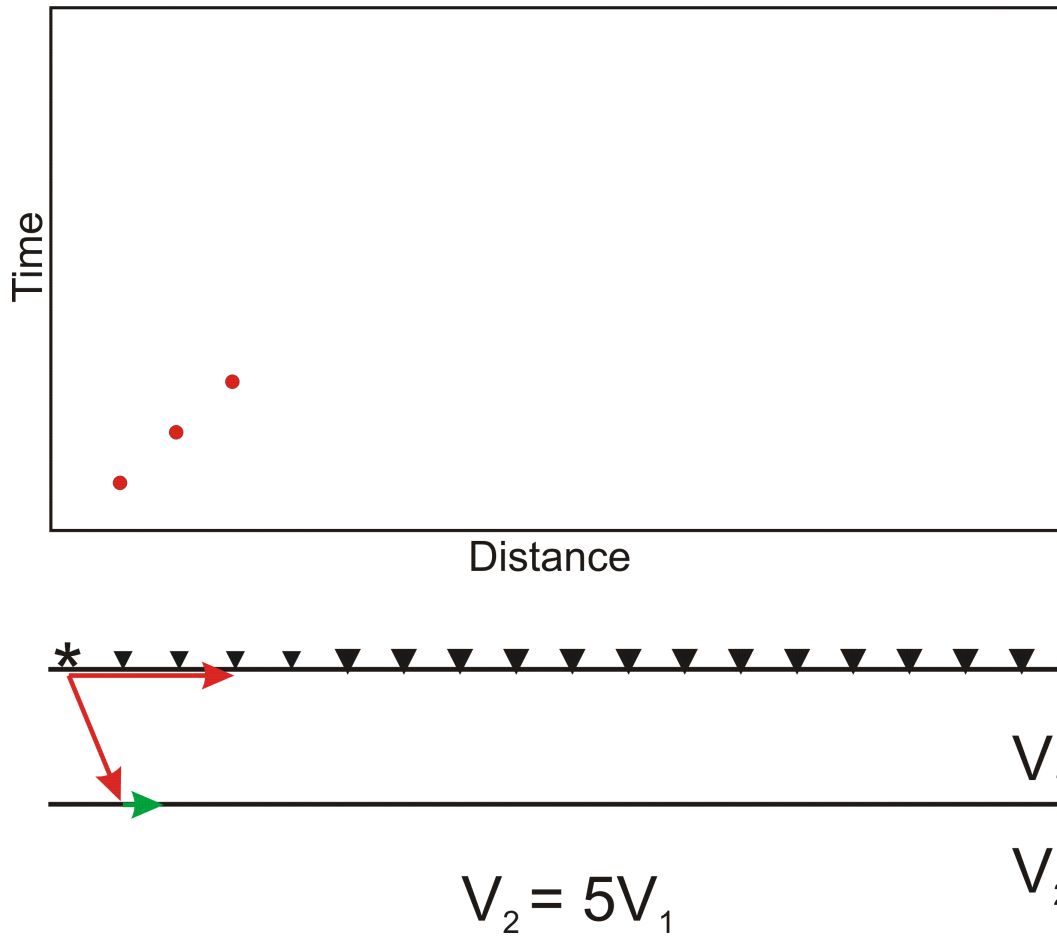
Horizontal red arrow = horizontally propagating P wave (not surface wave)

Using Seismic Refraction to Map the Subsurface

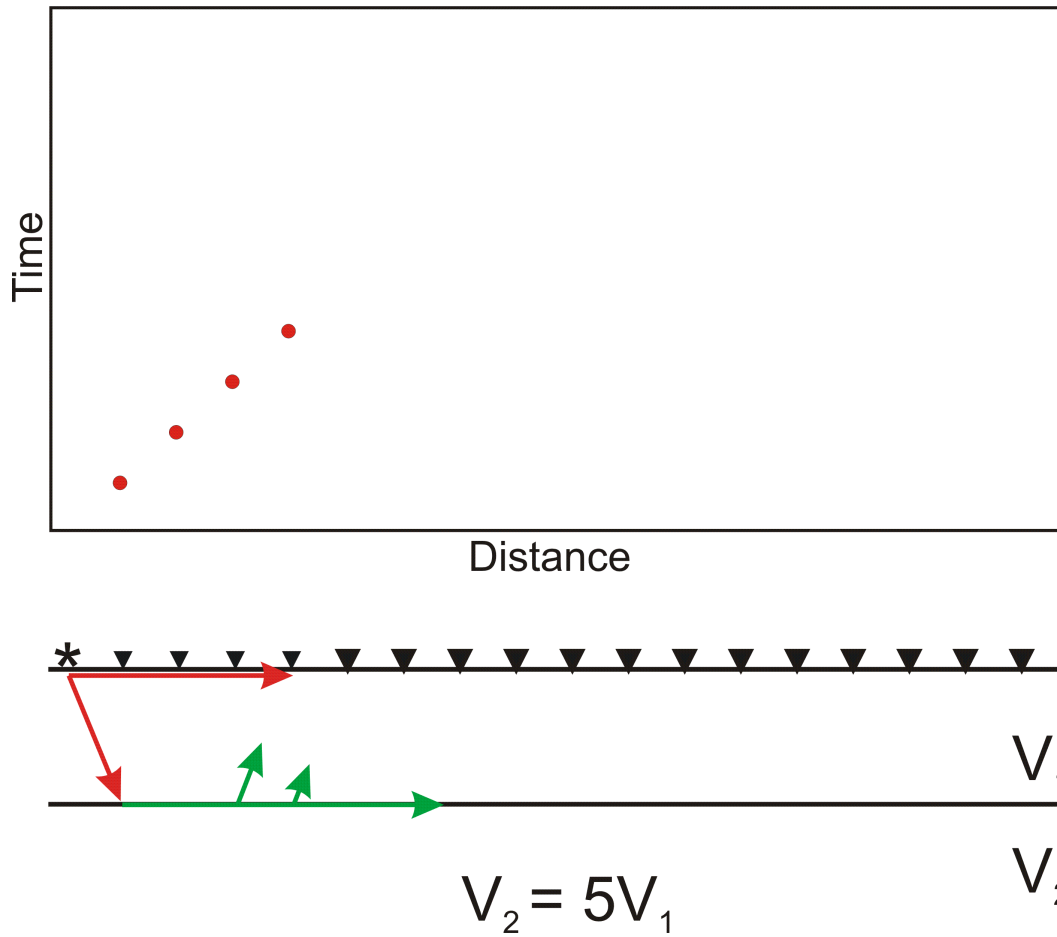


Horizontal red arrow = horizontally propagating P wave (not surface wave)

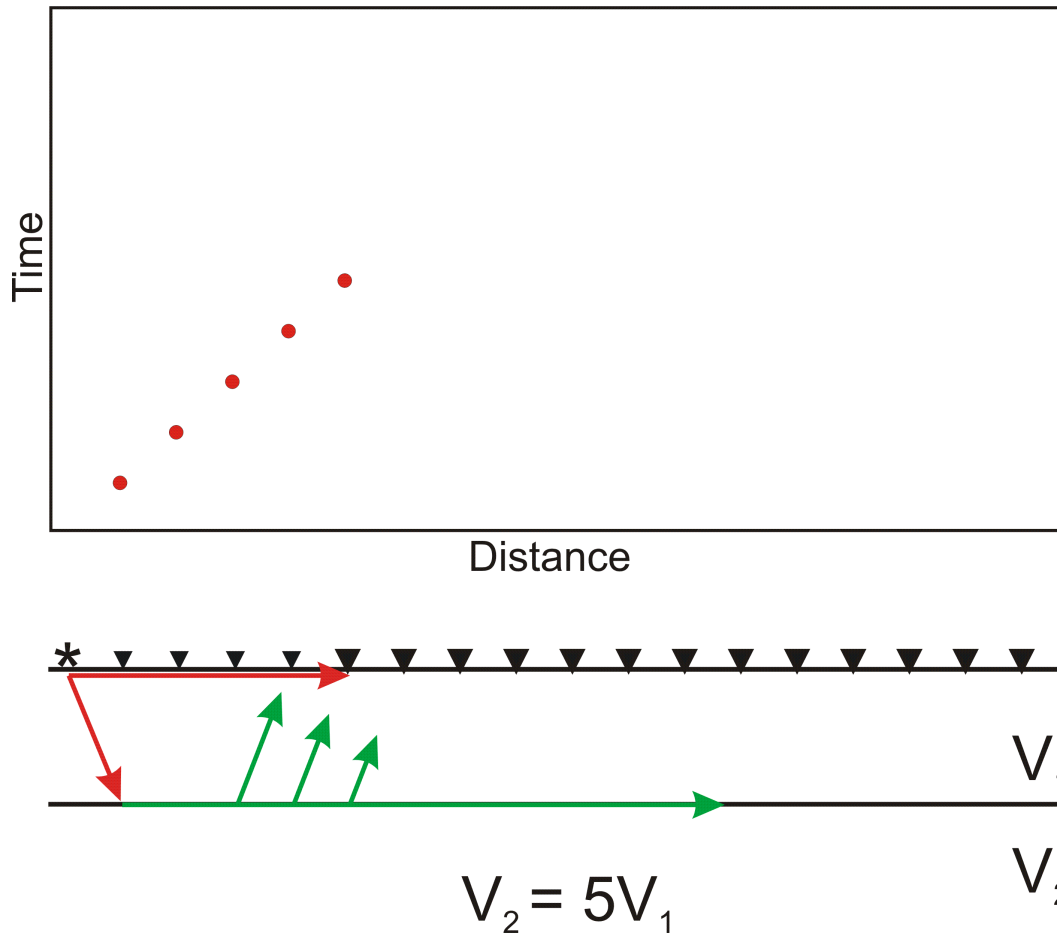
Using Seismic Refraction to Map the Subsurface



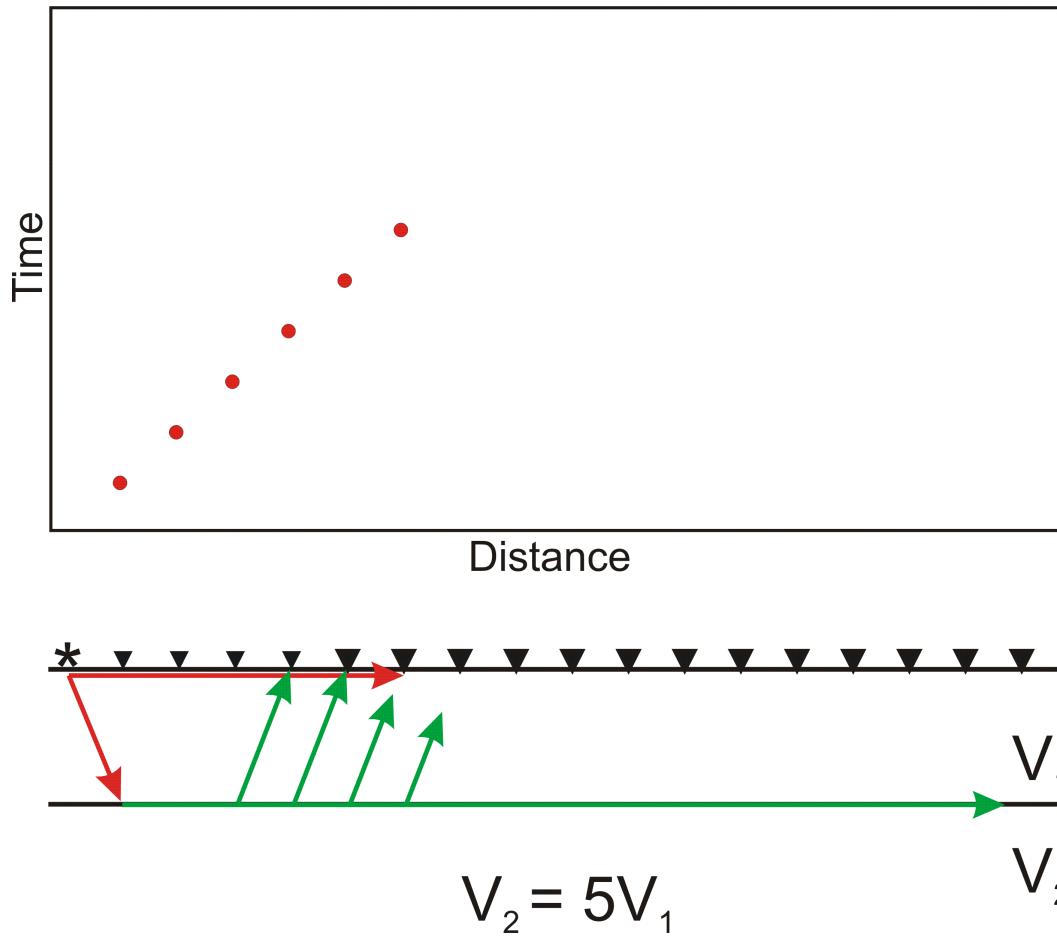
Using Seismic Refraction to Map the Subsurface



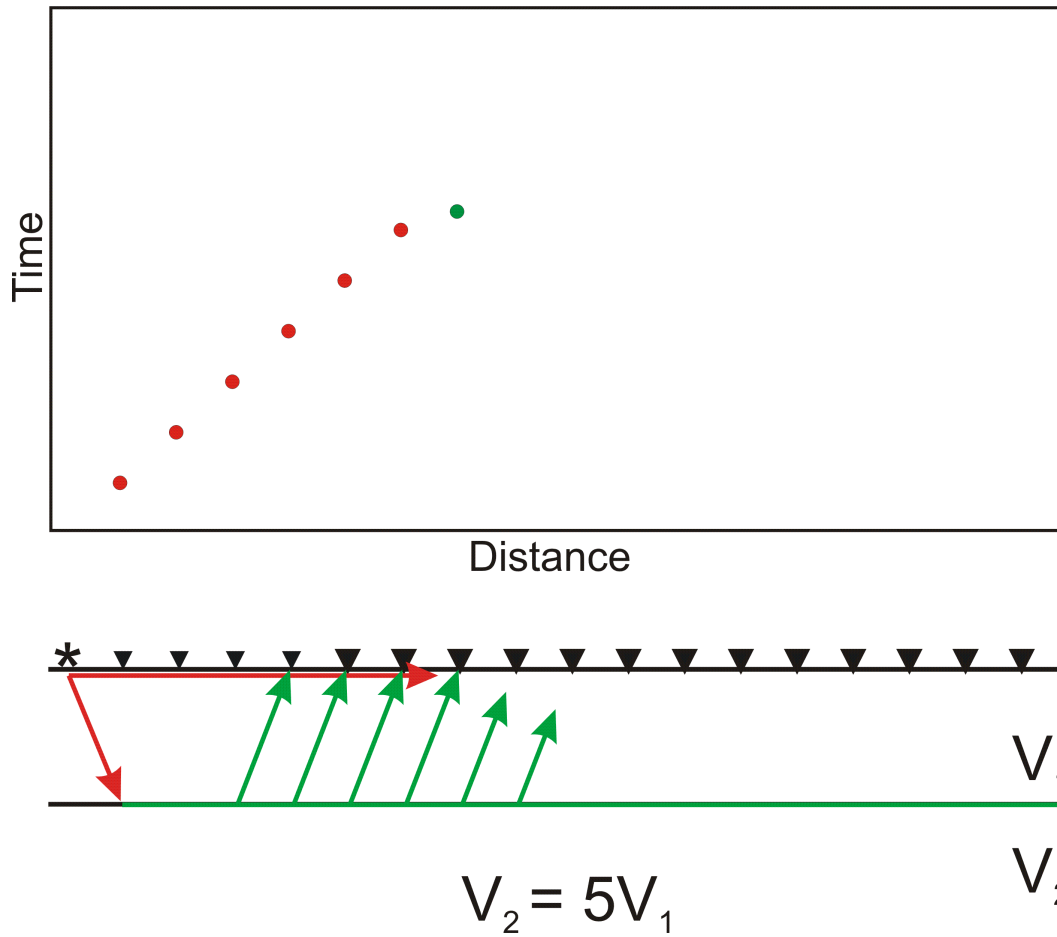
Using Seismic Refraction to Map the Subsurface



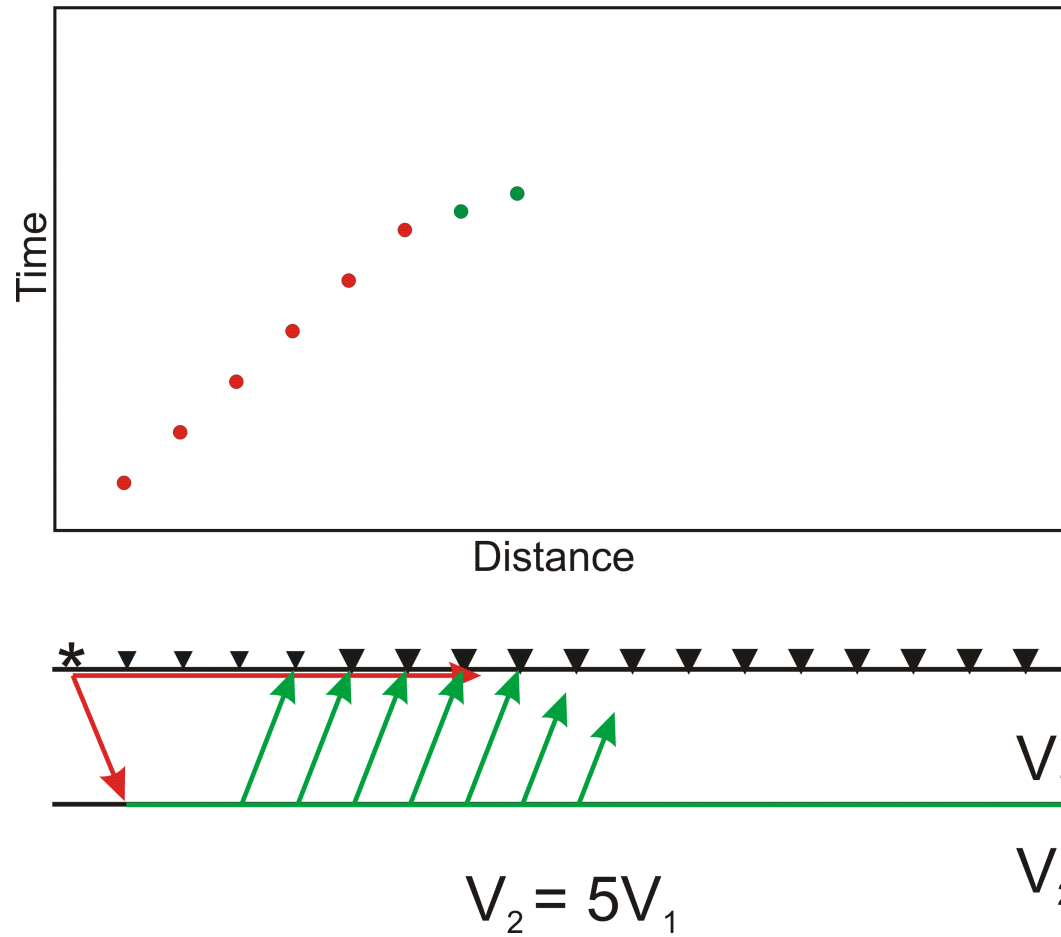
Using Seismic Refraction to Map the Subsurface



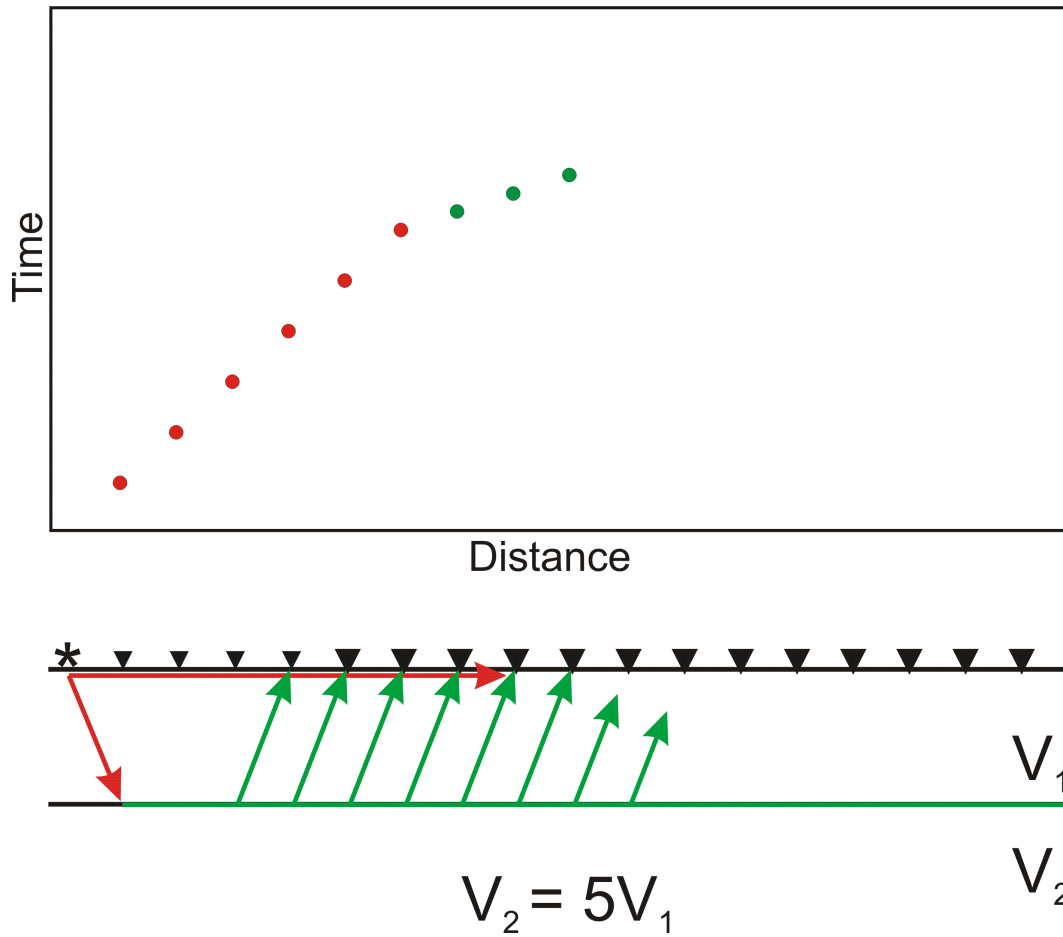
Using Seismic Refraction to Map the Subsurface



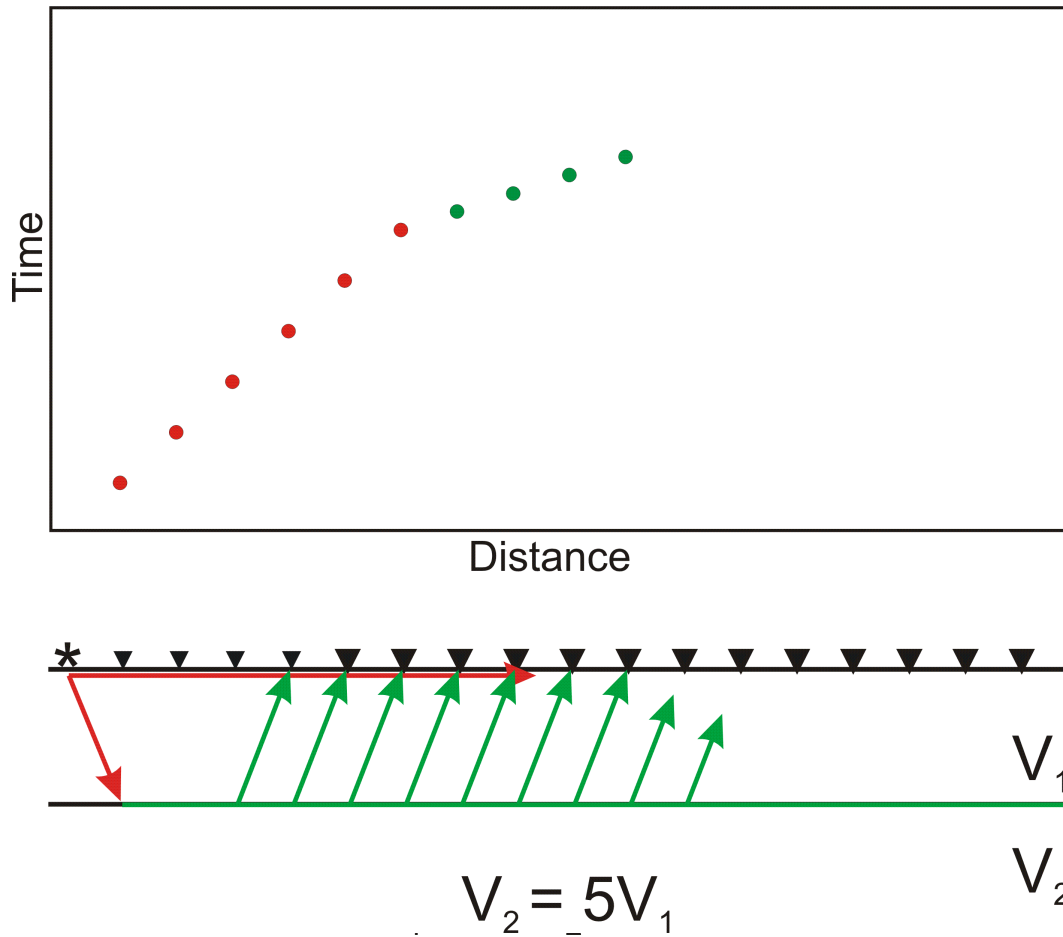
Using Seismic Refraction to Map the Subsurface



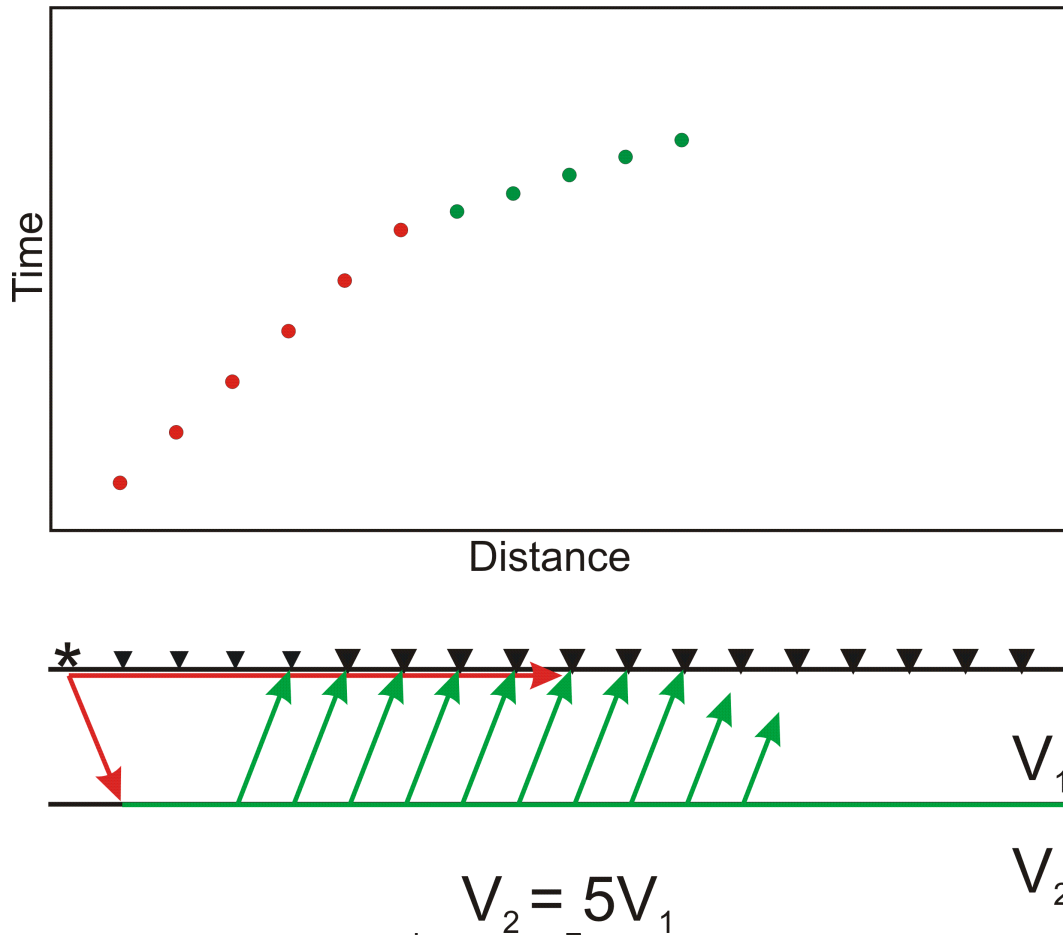
Using Seismic Refraction to Map the Subsurface



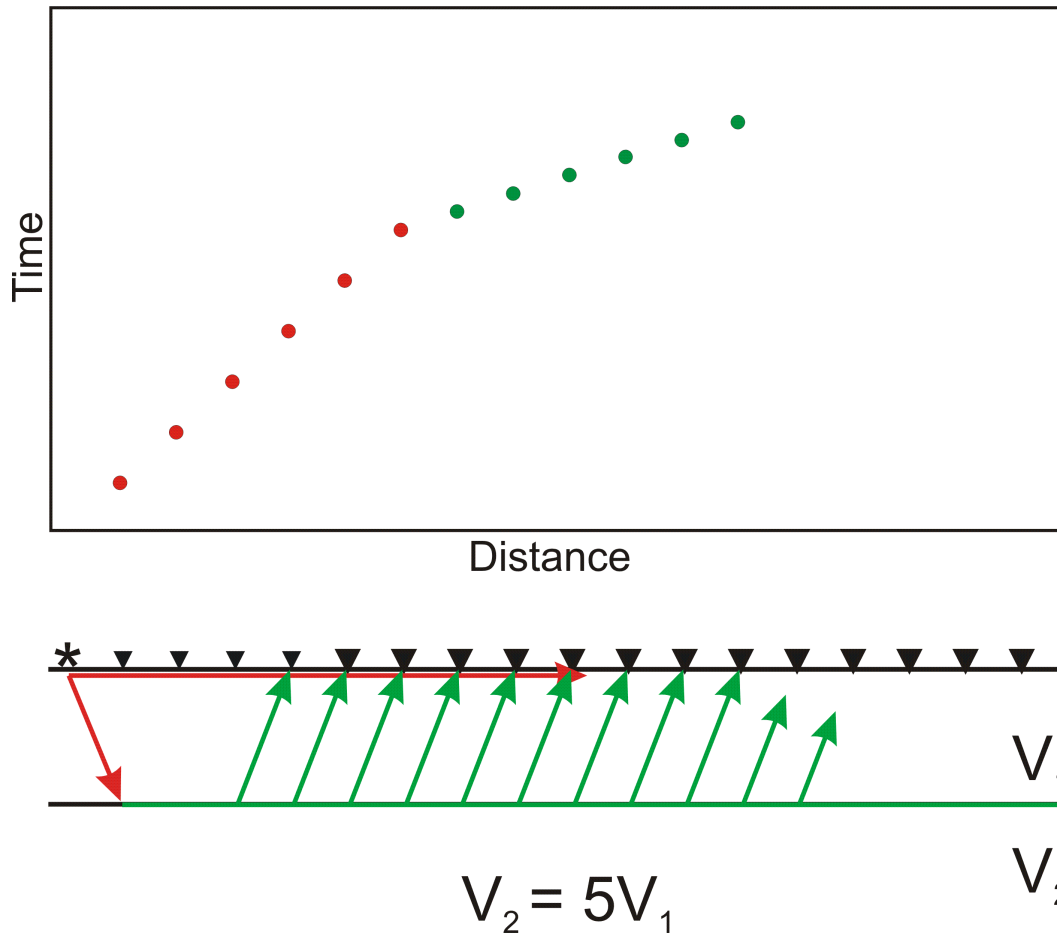
Using Seismic Refraction to Map the Subsurface



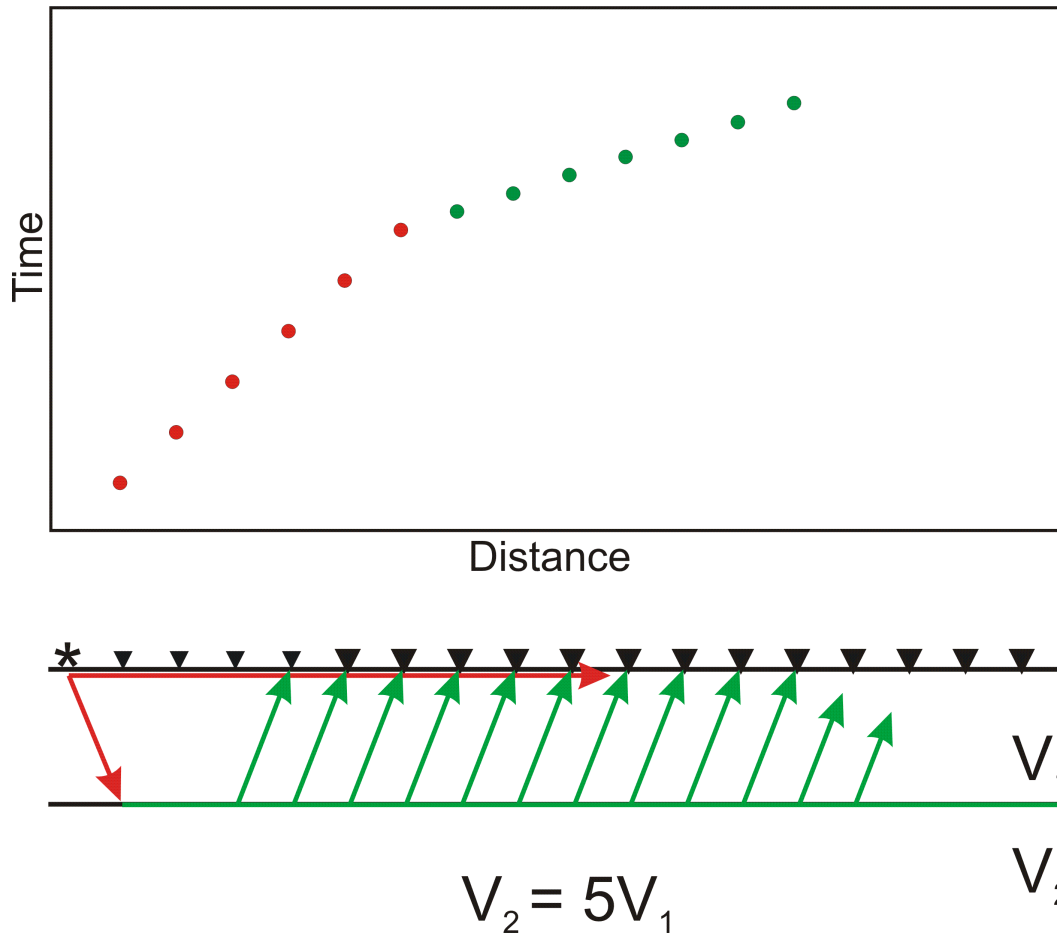
Using Seismic Refraction to Map the Subsurface



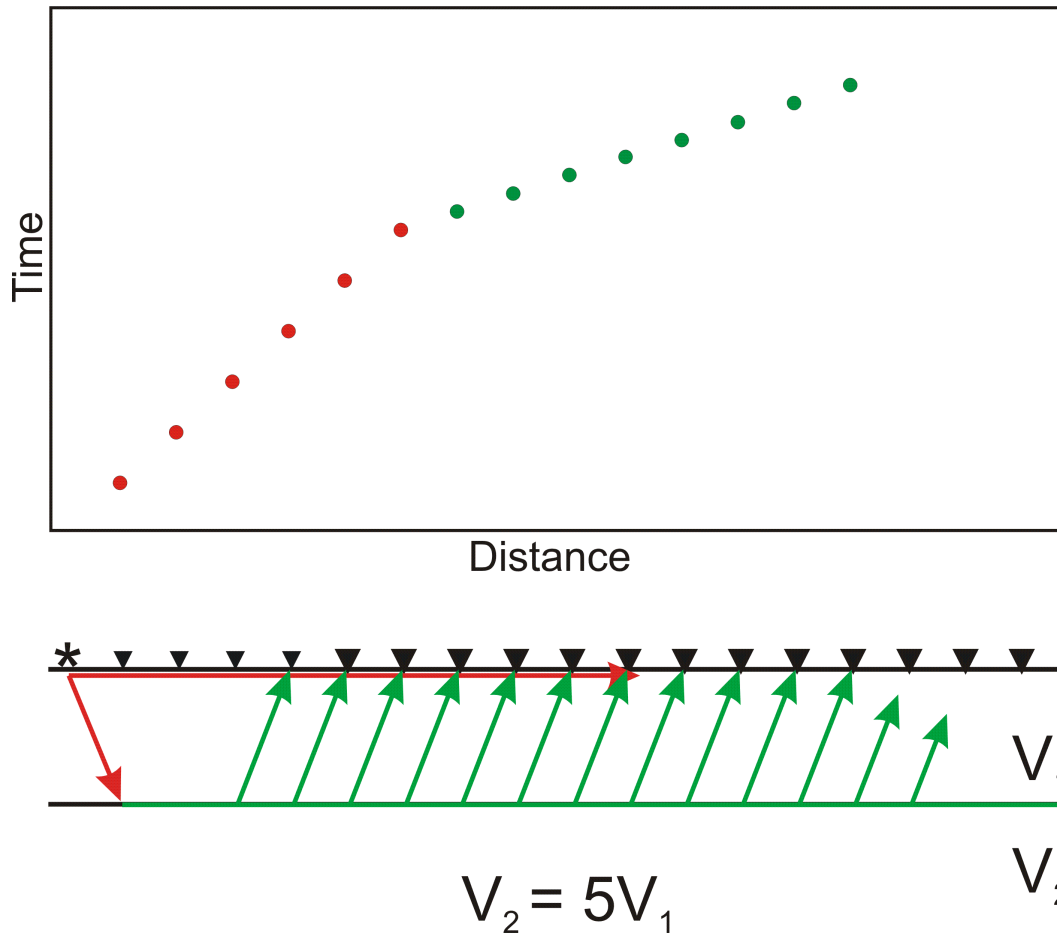
Using Seismic Refraction to Map the Subsurface



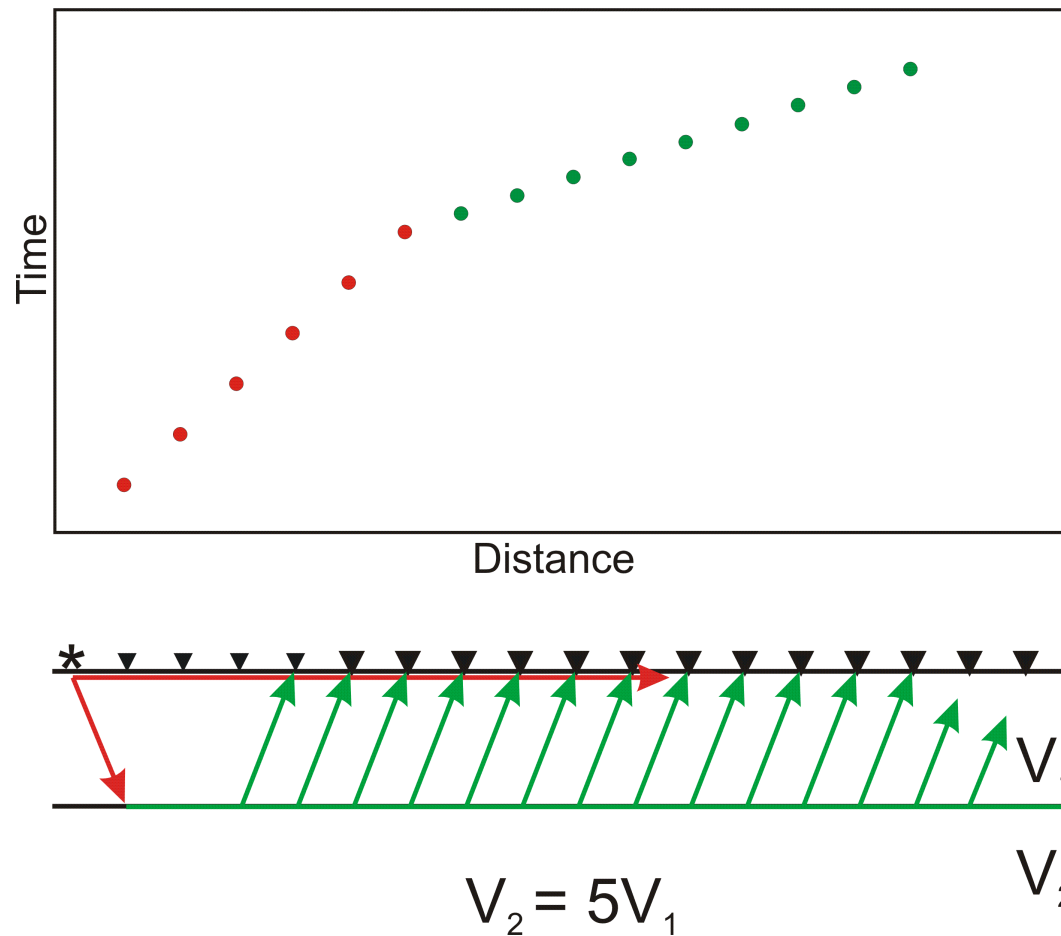
Using Seismic Refraction to Map the Subsurface



Using Seismic Refraction to Map the Subsurface

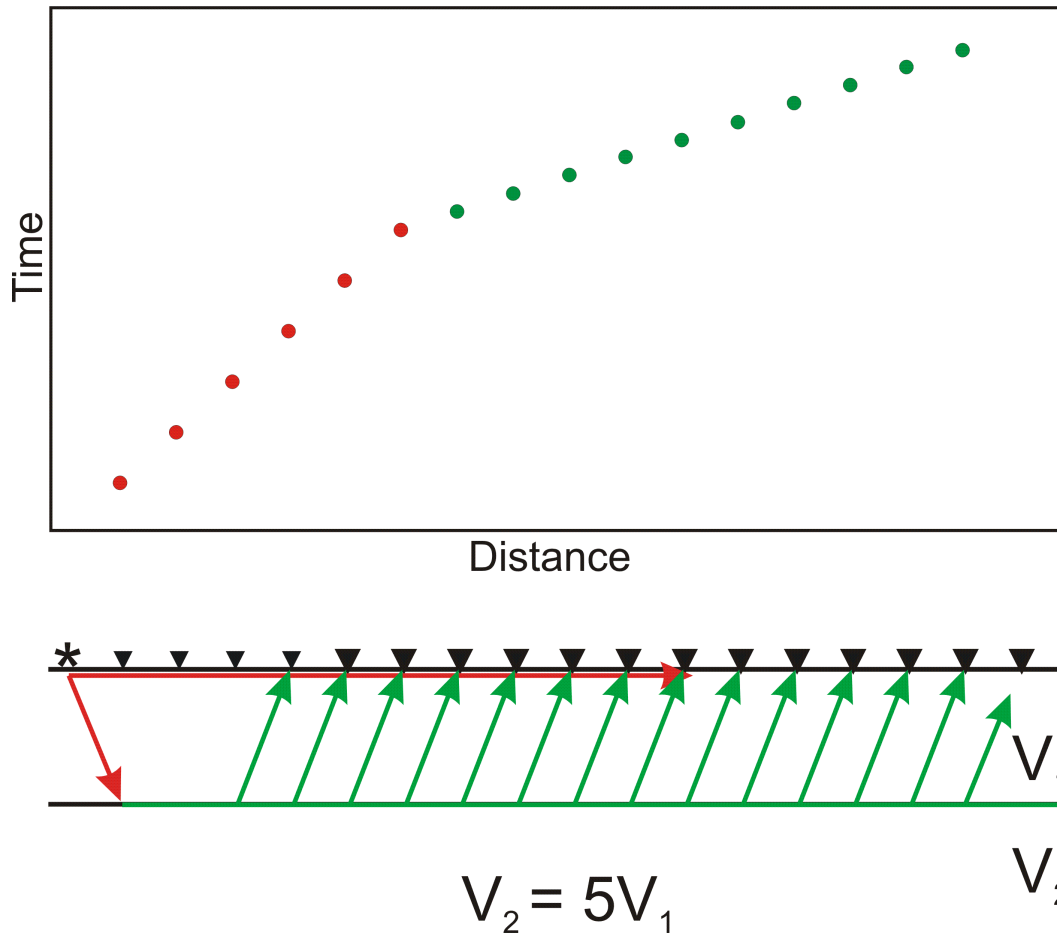


Using Seismic Refraction to Map the Subsurface

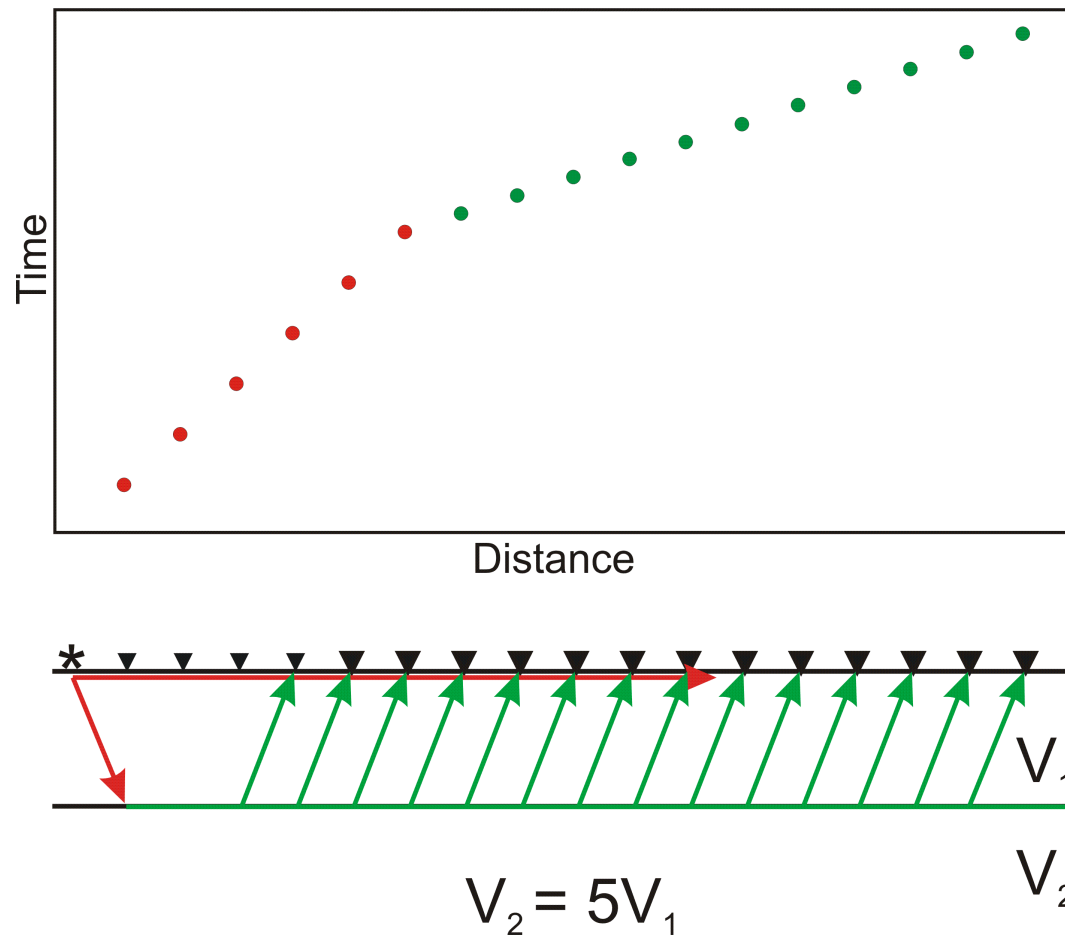


One advantage of refraction over reflection = first arrival

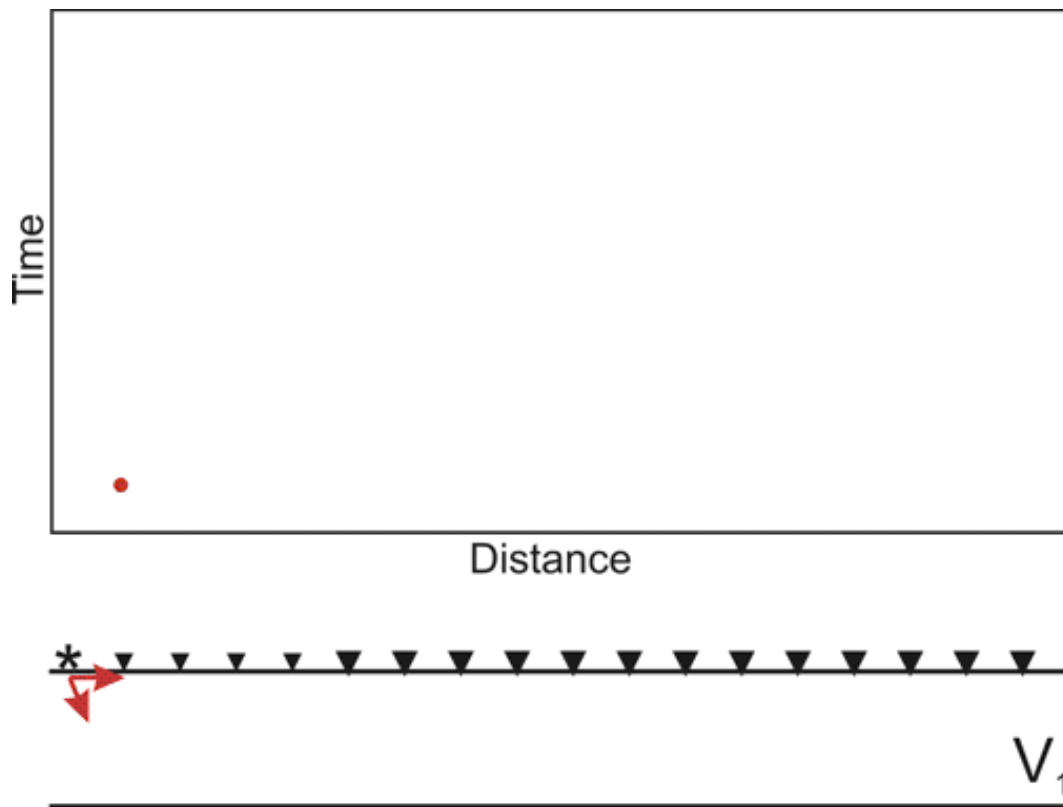
Using Seismic Refraction to Map the Subsurface



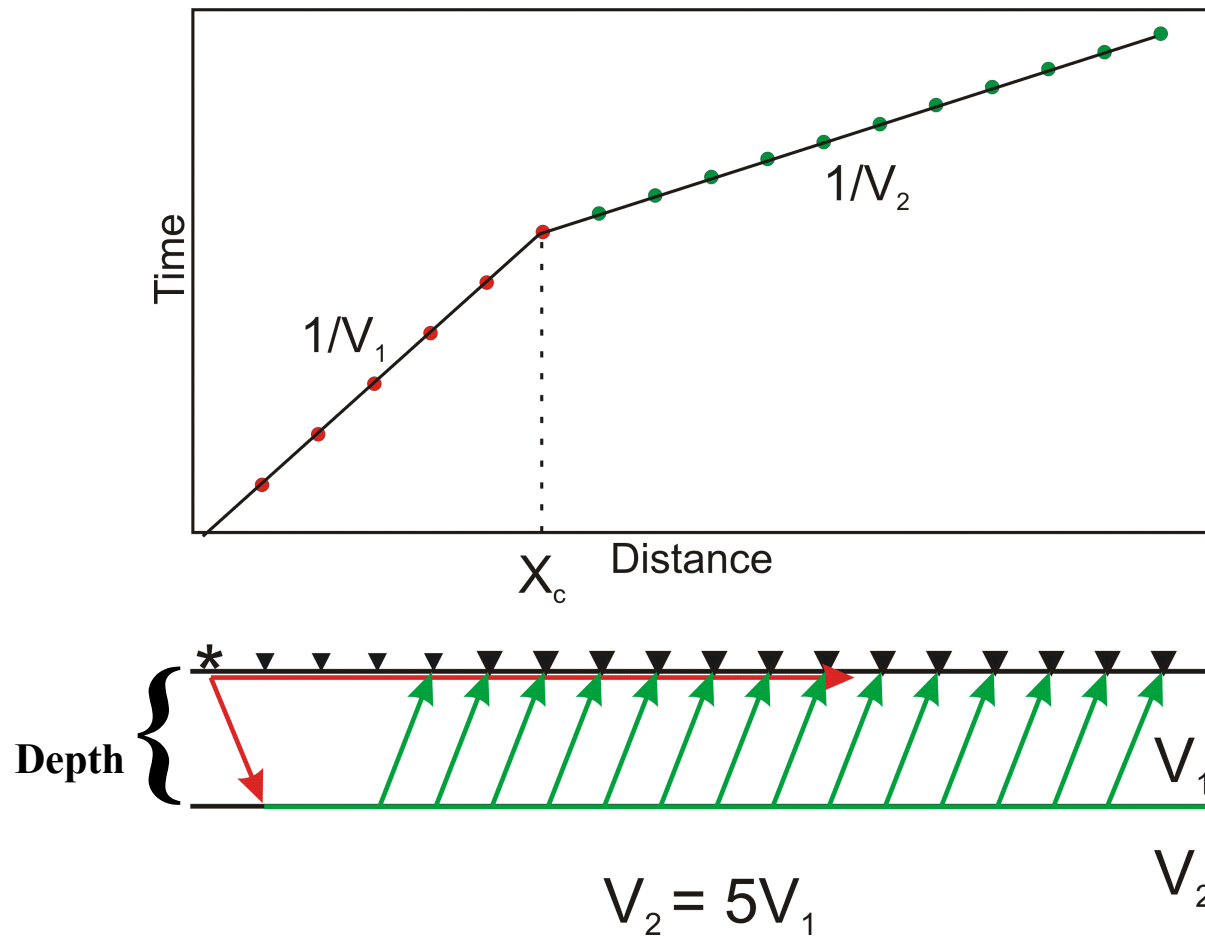
Using Seismic Refraction to Map the Subsurface



Using Seismic Refraction to Map the Subsurface

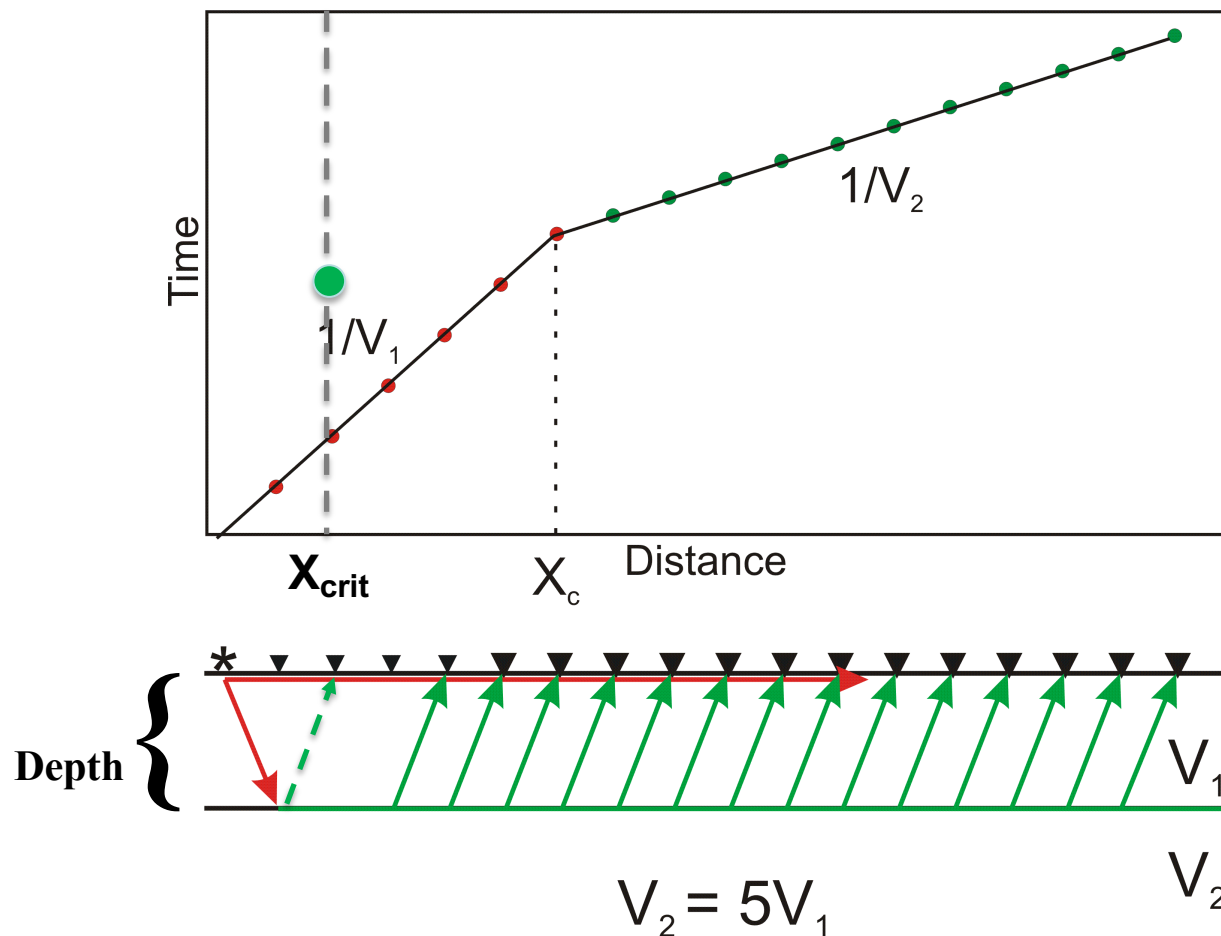


Using Seismic Refraction to Map the Subsurface



One advantage of refraction over reflection = first arrival

Using Seismic Refraction to Map the Subsurface



Critical distance X_{crit} : horizontal distance when refraction first appears

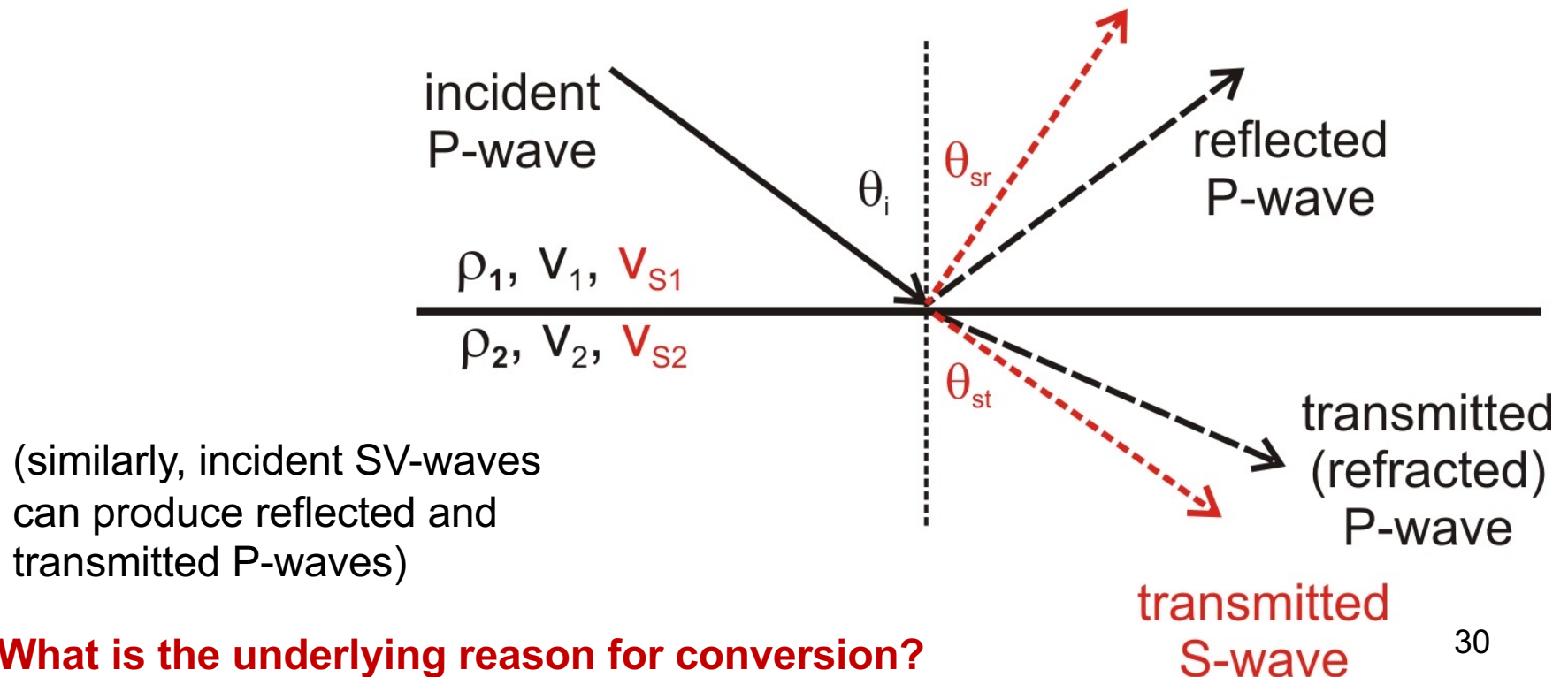
Crossover distance X_c : horizontal distance when refraction overtakes horizontal P

Reflection and refraction of seismic waves

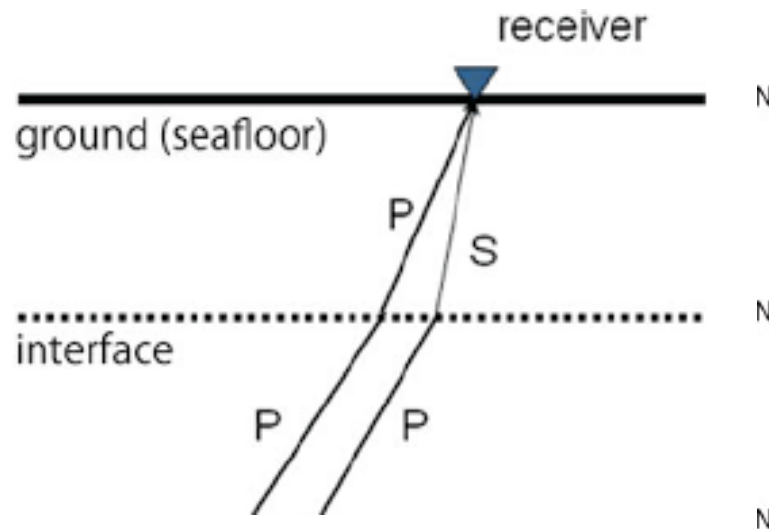
Mode conversion:

- P-waves at non-normal incidence will produce reflected and refracted S-waves (**SV-waves**)

$$p = \frac{\sin \theta_i}{V_1} = \frac{\sin \theta_{sr}}{V_{s1}} = \frac{\sin \theta_{st}}{V_{s2}}$$



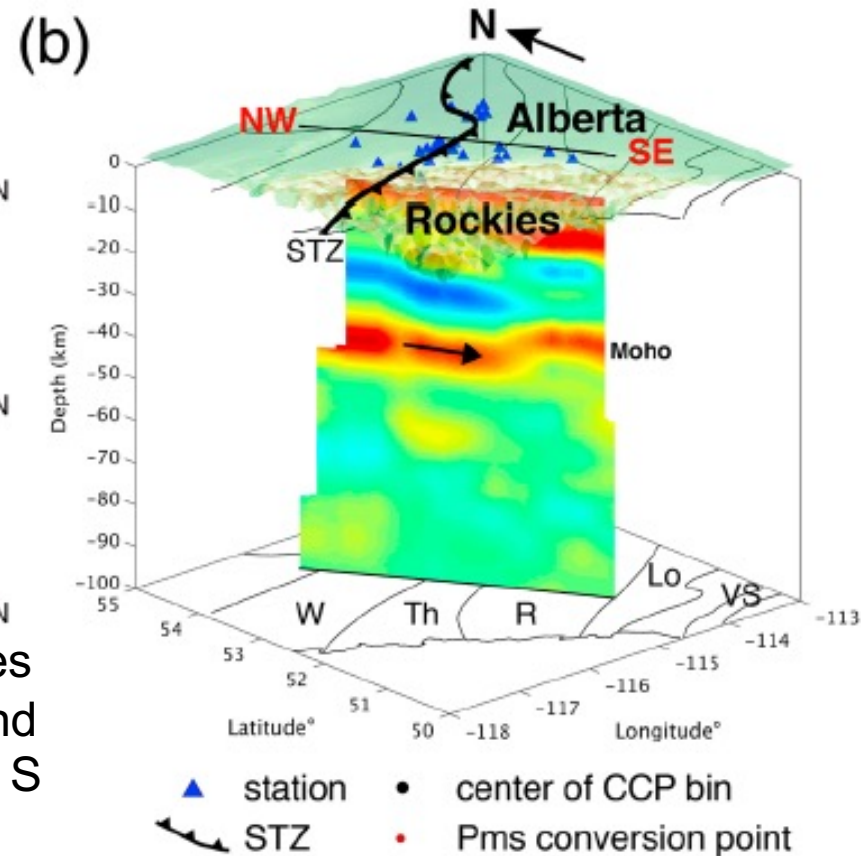
Converted Waves



This is one of the many converted waves being routinely used to image crustal and mantle interfaces. P waves convert to S upon entering a velocity gradient. The time difference of the two phases (P, and Ps) is a direct function of P and S waves traveling between interface and surface.

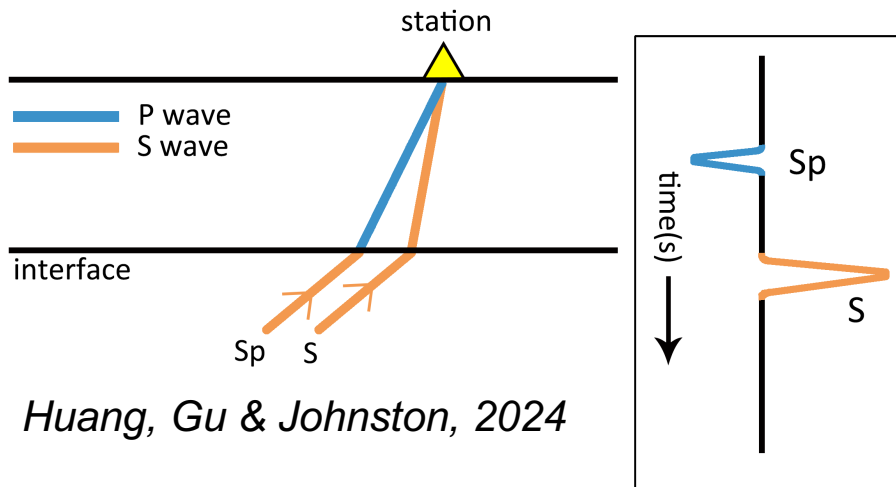
Assumptions:

1. Paths of P and Ps are similar
2. P wave and Ps waves are both present on Vertical & Radial components



The above figure (Gu et al., 2017) shows the result of P to S conversions at the Moho interface. In this instance, the Moho is deeper west of the Rocky mountains but shallows toward the Alberta Basin.

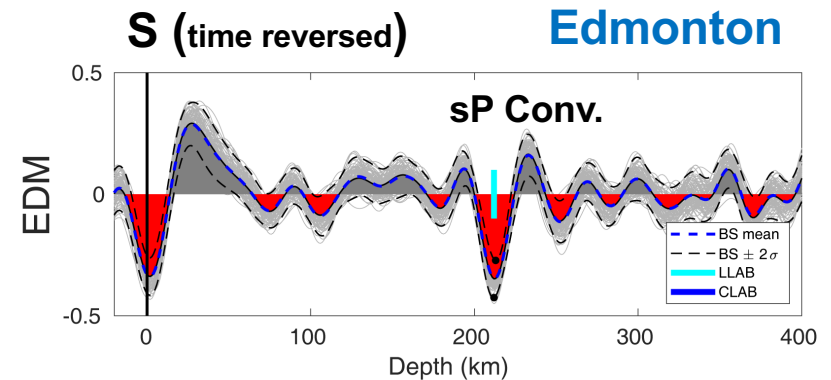
S-to-P converted waves



This is another converted waves being less frequently used to image crustal and mantle interfaces. **S waves converts to P** upon entering a velocity gradient. The time difference of the two phases (Sp, and S) is a direct function of **interface depth** and **velocity above the interface**.

Assumptions:

1. Paths of S and Sp are similar
2. Sp arrives before S (why?)
3. S wave and Sp waves are both present on Vertical & Radial components



The image above shows stacked sP converted waves at Edmonton station (in Leduc on UofA property). The time axis has been reversed to be more physical (i.e., greater times equals greater interface depth).

In this case, a negative conversion is obtained, that corresponds the depth of the mantle lithosphere (at a time that corresponds to ~210 km). This corresponds to fair deep roots of continent relative to oceanic lithosphere (150-180 km thick).

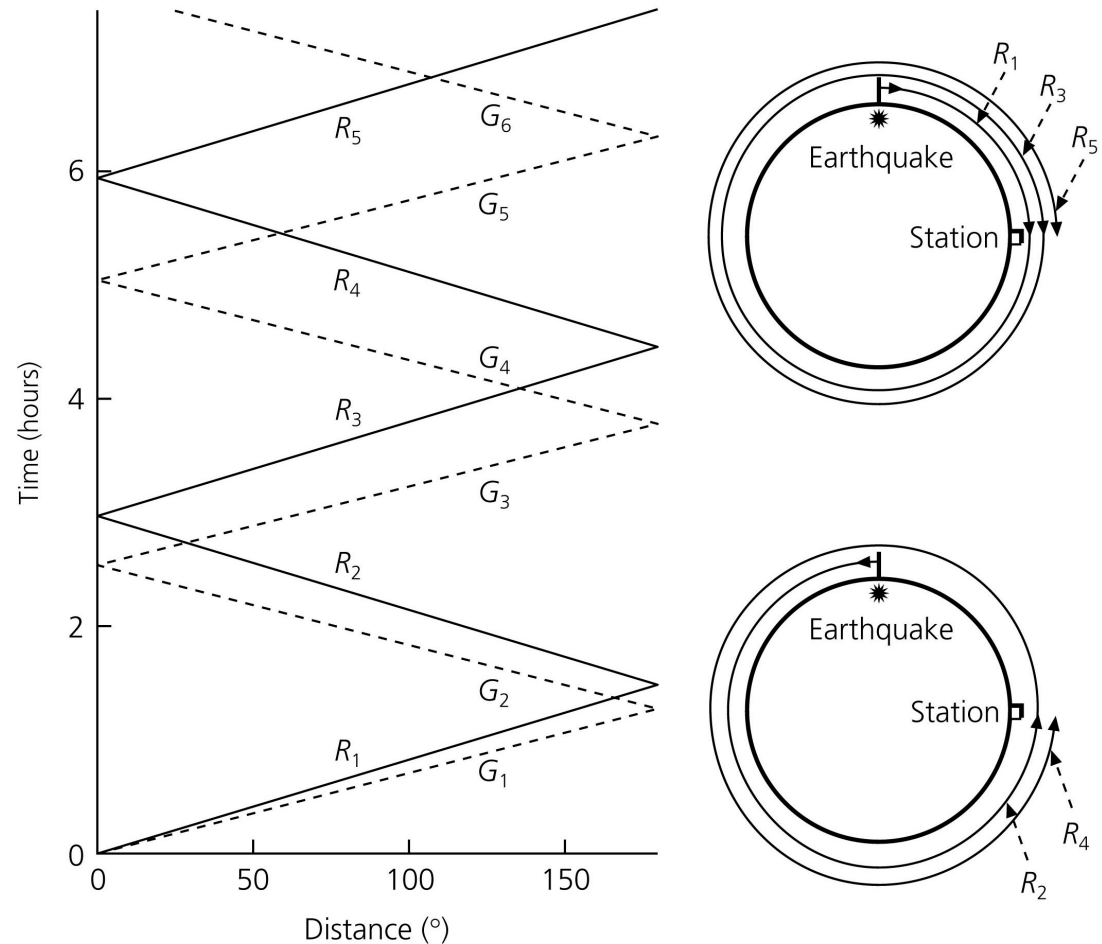
Surface Waves

Naming conventions:

1. G for *Love*, R for *Rayleigh*.
2. Odd numbers are *minor arcs*, even numbers are *major arcs* in the opposite direction.

At 180 degrees, we have an antipode, the surface wave amplitude is greatly amplified due to interactions of surface waves coming from all directions around the globe.

Figure 2.7-4: Six-hour stacked IDA record section.



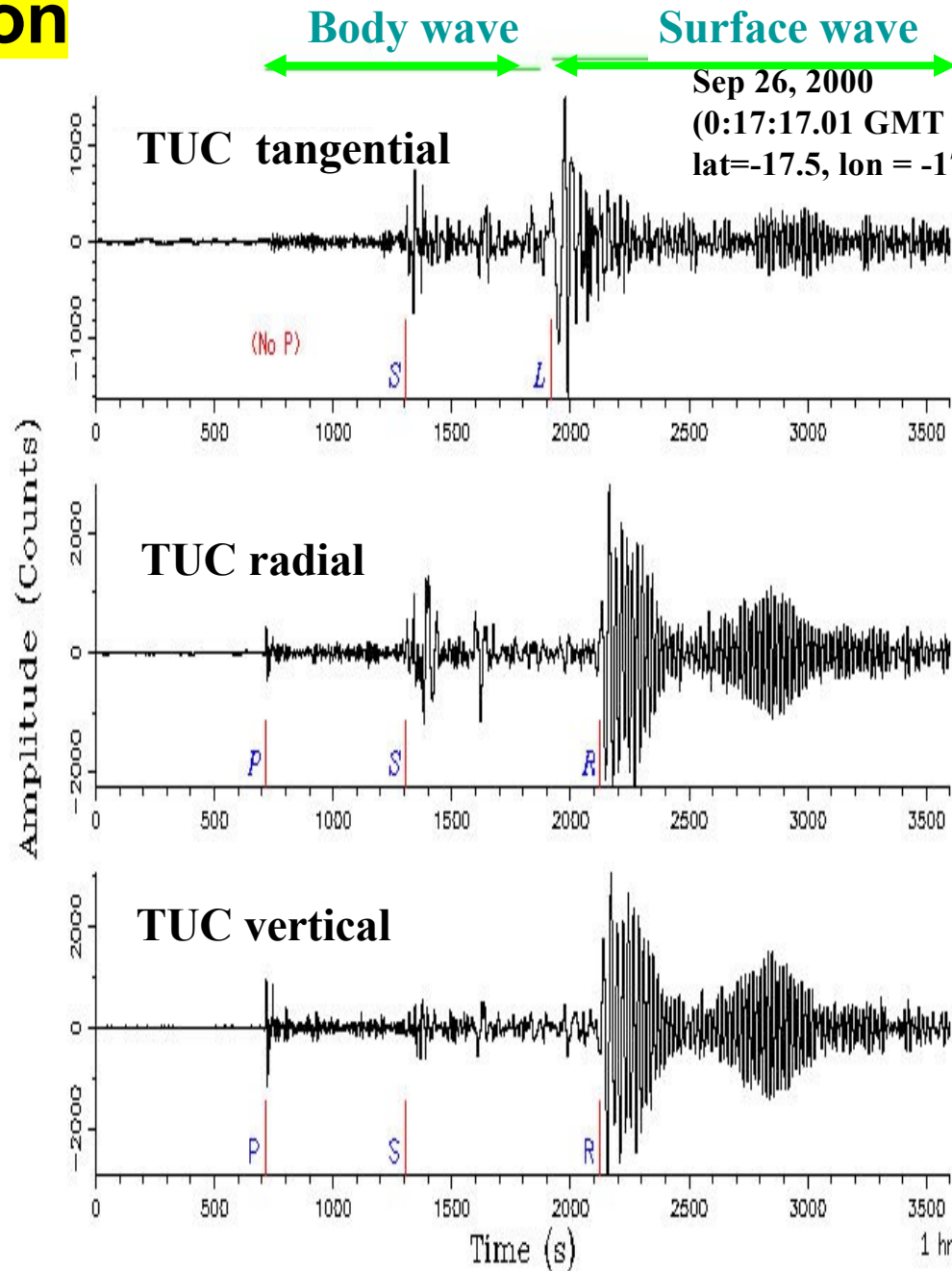
Propagation

Surface Waves:

Longer wave trains, larger amplitudes

Questions:

1. Why minimal 'P phase' on Tangential?
2. Why large vertical P amp.?
3. Why larger radial S phase?
4. Is 'phase' the same as 'wave' or 'wave type'?



Order:

1. P (P reflected, converted)
1. S (S reflected)
2. Love
3. Rayleigh

Amplitude:

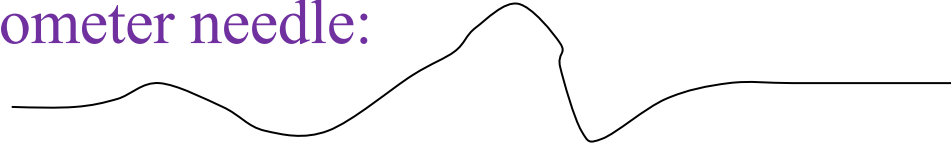
Depends on source types and mechanisms.

Earthquakes:

large S types of phases and surface waves (more shearing motion)

Components and Particle Motion

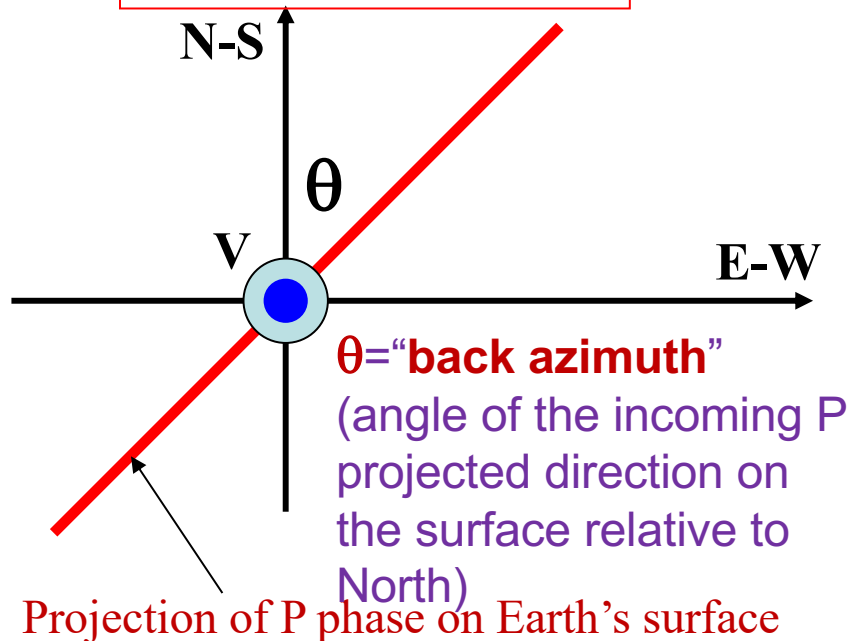
Imagine a seismometer needle:



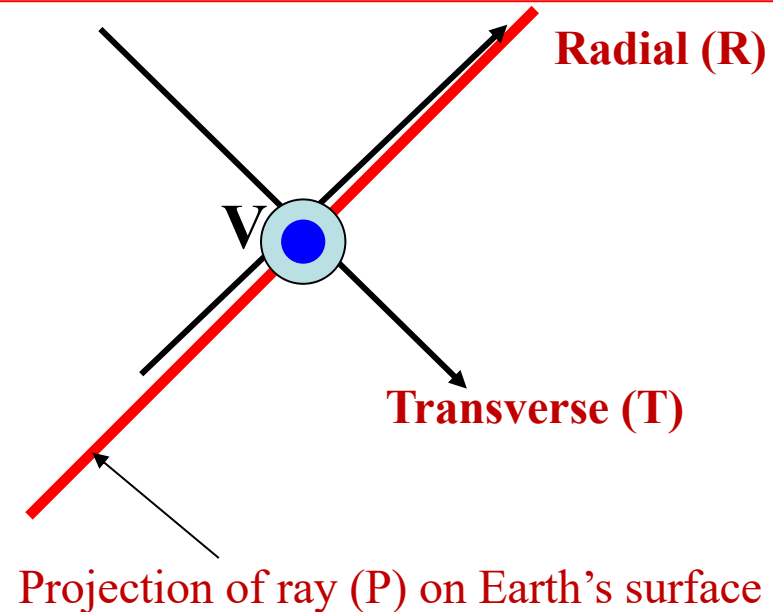
Suppose there is 3 cm displacement in east-west component, what does that really mean?

Answer: That means a particle positioned at the needle tip moves by 3 cm, i.e., particles on the ground/rock moves by 3 cm due to seismic wave. Seismometer is a motion recorder (meaning observing motion by sitting on a particle that moves).

**Map view of original
(EW-NS-V) system**



**Map view of rotated 'Great Circle' system
(R-T-V system)**



Polarization (also known as particle motion) plots

Why useful:

- (1) V-R (vertical-radial) plot give first motion + arrival angle + strength of vertical vs. radial components.
- (2) R-T (radial vs. transverse) plot gives presence of anisotropy (anisotropy means the same wave (e.g., S) travels at different speeds depending on direction)
- (3) E-N (eastwest vs. northsouth) gives back-azimuth!

What is being plotted:

Two recorded components of a given seismic phase, say P, or SS, etc.

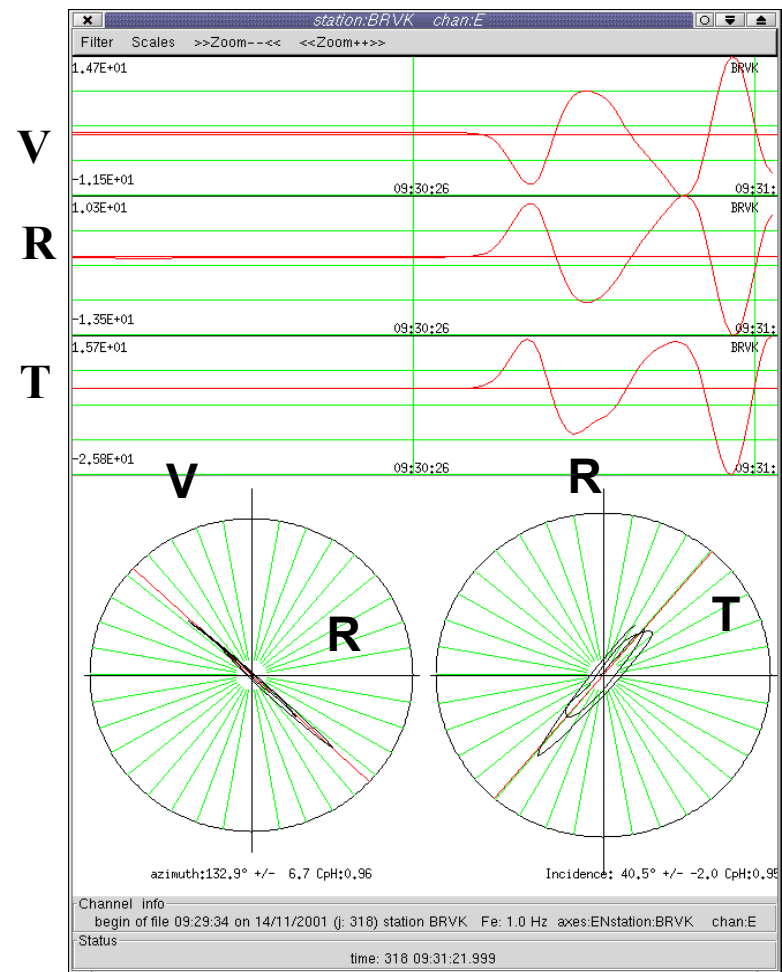
How to generate this plot:

1. Set up a blank plot of x-y axes, where origin is a point (0, 0).
2. Define a time window of interest, e.g., S phase shown here, zoom in and ignore other phases.
3. Suppose we want Radial (X) vs. Vertical (Y) particle motion plot:

3.1 Start with a time before the wave, measure the amplitudes (x0) of the Radial component at that time t0, this is the the x coordinate of the Particle Motion plot for t0 time. Similarly, measure the amplitude of the vertical component at that time, use it as the y coordinate (y0). Plot this point (x0, y0) on the Radial-Vertical polarization plot.

3.2. Continue this process for a later time point t1 in your window, measure the amplitudes of Radial (x1) and Vertical component at that time value, put the end result (x1,y1) on the polarization plot.

3.3. Do this for many more time points, which fills out the x-y polarization/particle motion plot. Examine the pattern after you have reached the end of your time window. If linear, try to fit a line to them and this line has different physical meanings.



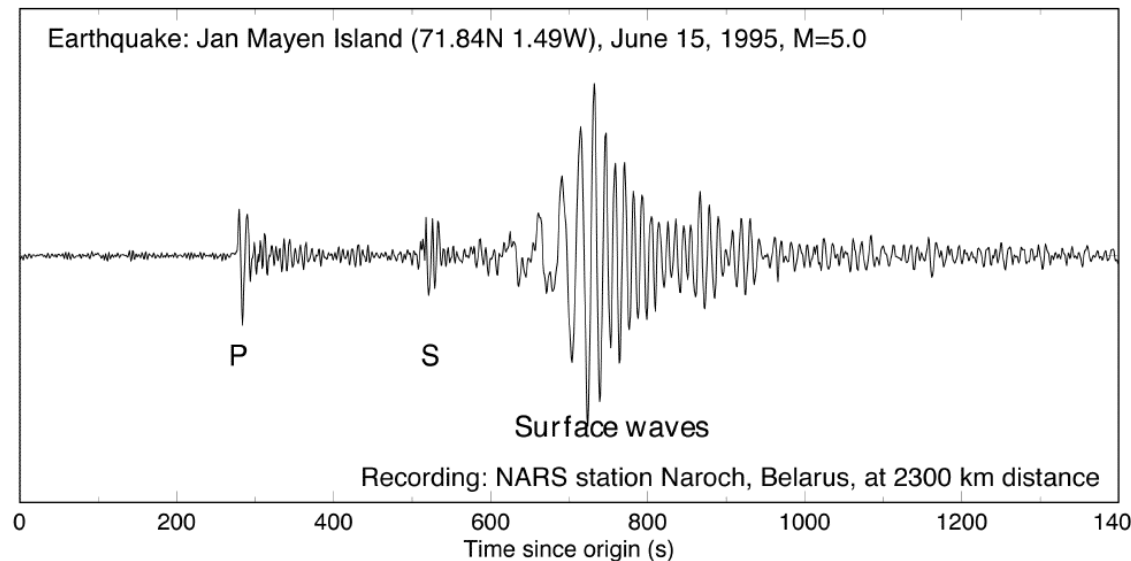
Seismic wave propagation & Amplitudes

In general, the amplitude of seismic waves **decreases** as the waves travel through the Earth.

1. Geometrical spreading
2. Attenuation
3. Scattering

ALSO: Variations in material properties (seismic velocity, density)

- partitioning of energy at an interface within the Earth
(e.g., Moho, CMB, lateral changes in geology)



(<http://www.uweb.ucsb.edu/~shao/links.html>)37

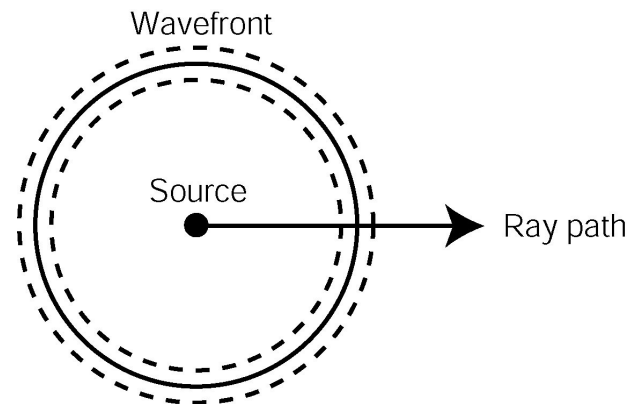
Factors that affect seismic wave amplitude

1. Geometrical Spreading

Seismic waves originate from a point source (e.g., earthquake, explosion) and carry energy away from the source.

Body waves

- wavefront is spherical
- radius increases over time

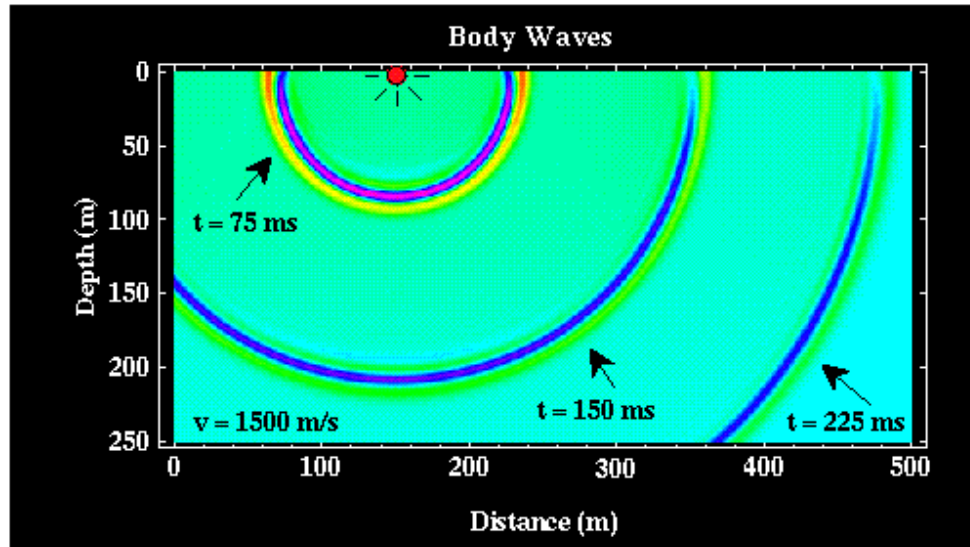


geometrical spreading / spherical divergence

- wavefront always contains a constant amount of energy (E_0)
- the energy at a point on the sphere surface is: $E(r) = E_0 / 4\pi r^2$
- amplitude of a seismic wave is related to energy: $E(r) \propto A^2$. (the alpha sign means 'proportional to'. This can be rewritten as $E(r) = c A^2$ where 'c' is a constant scalar.)
- since $E(r) \propto 1/r^2 \rightarrow A^2 \propto 1/r^2 \rightarrow A \propto 1/r$
 $\rightarrow$ BODY WAVE amplitude will decrease by $1/r$ (the distance from the source)

What about Surface Waves & what does it say about its amplitudes??

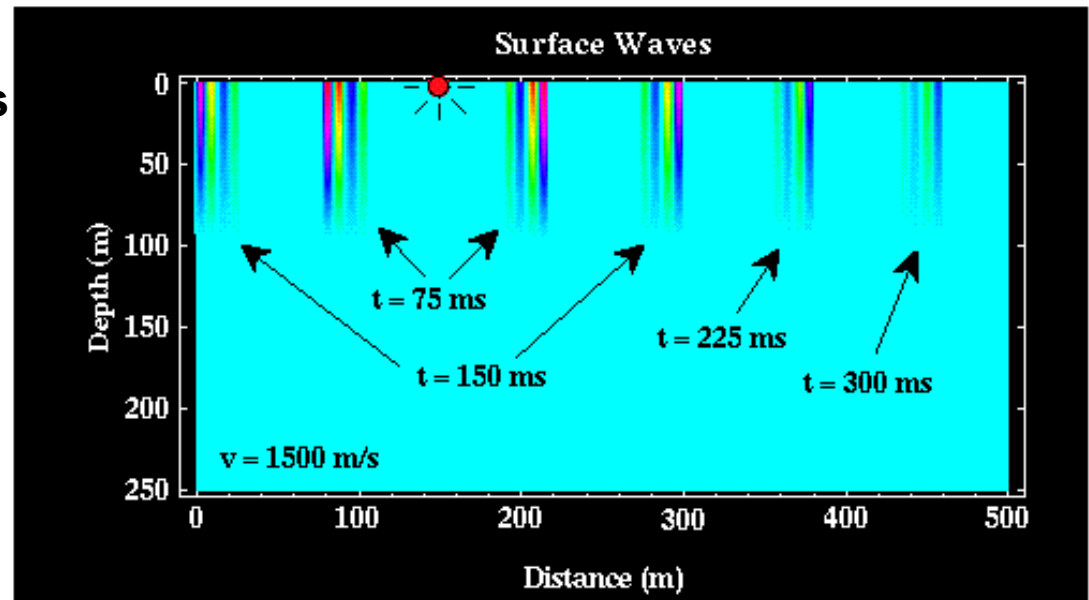
Body wave propagation



One person's noise is another person's signal. This is certainly true for what surface waves mean to an exploration geophysicist and to a global seismologist

Amplitude decay in surface waves (as a function of r) is less than that of body wave --- the main reason that we always find larger surface waves than body waves, especially at long distances.

Surface Wave Propagation



Travel time table

How to read: If you know the distance between source & receiver, find it on the x-axis but need to do conversion from km to degrees (say 60 deg, how?). Draw a vertical line, then find the intercepts between this line with the seismic phases (remember this term?). These times of intercepts are the predicted arrival times of a specific phase like P or PP, or ScS.

In this example:

At 60 degree distance (*how many km?*), you are expected to find

P: at precisely 10 minutes

PP: at 12 min

S: at ~18 min mark

SS: at ~ 24 min

Surface waves: 26 min mark

