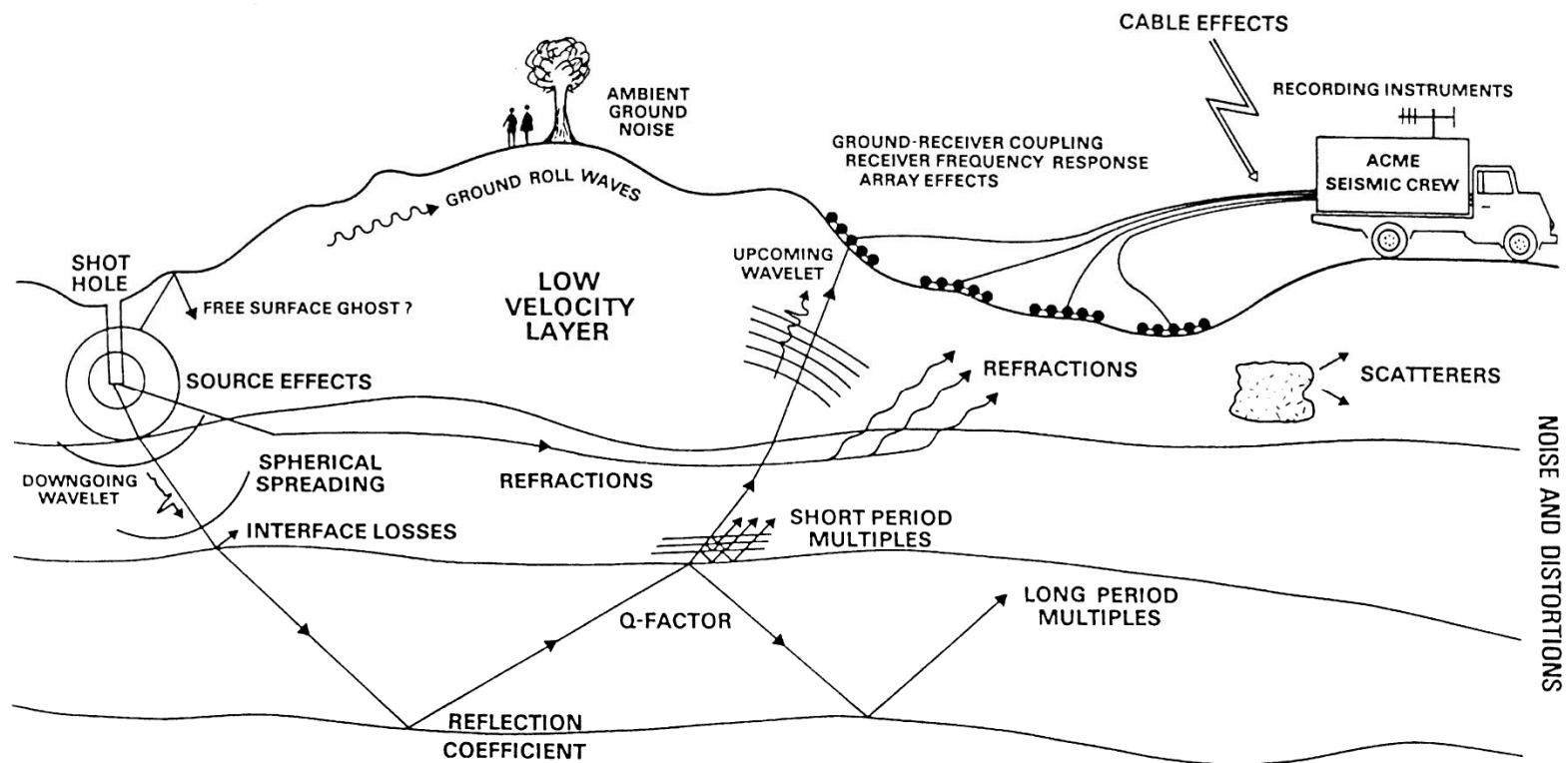


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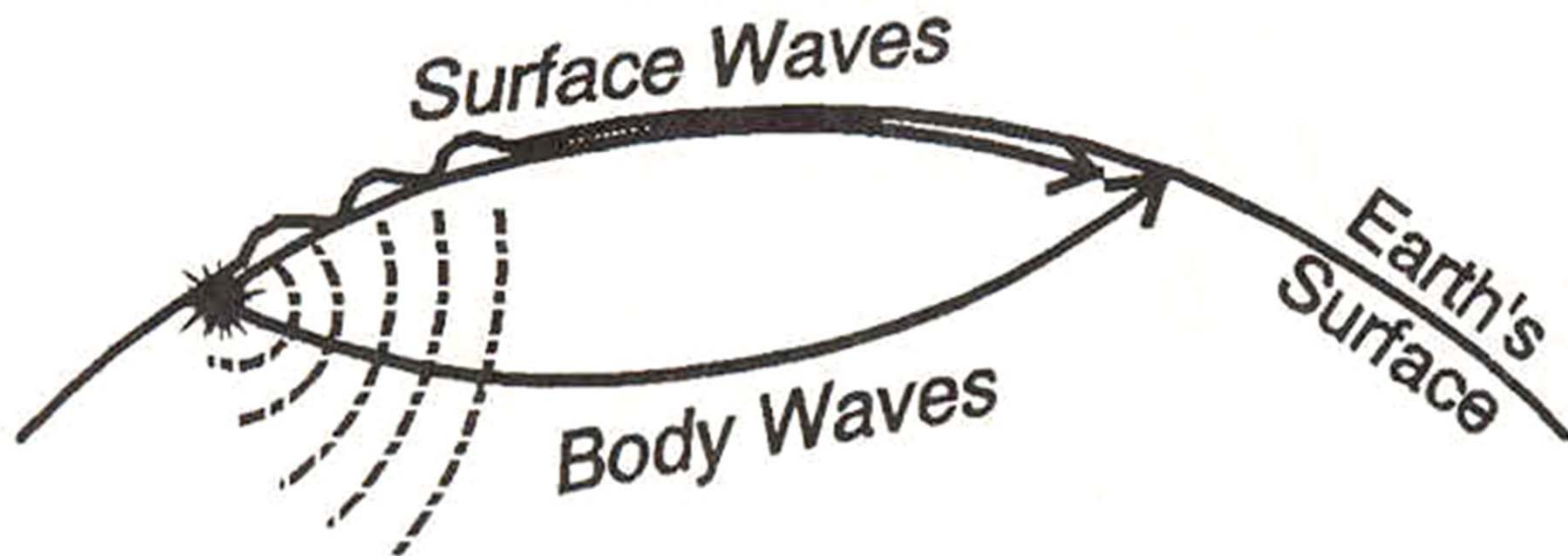
**GPH 301**

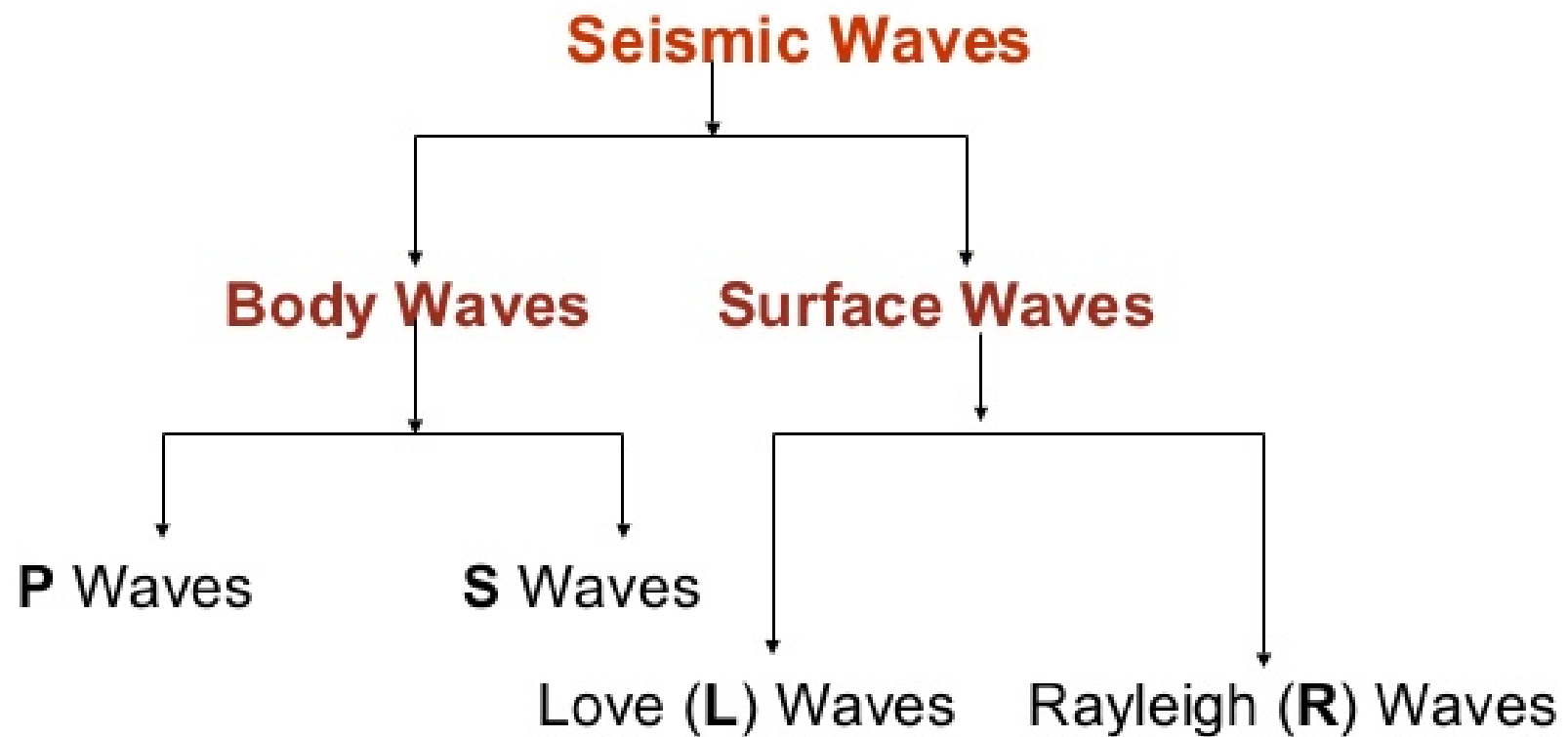
**Geophysical Exploration**

Dr. Sattam Abdulkareem Almadani



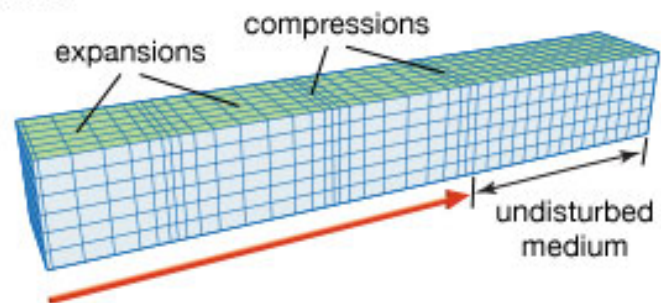
GPH 301 - Seismic Refraction Methods



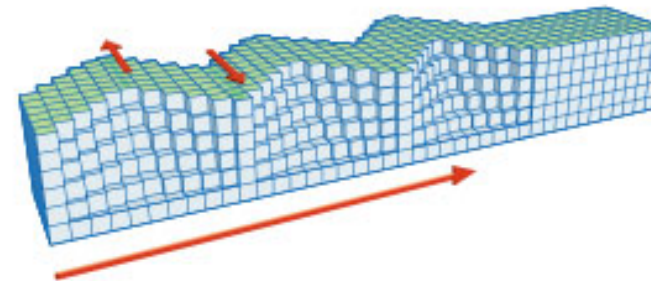


## Main types of seismic waves

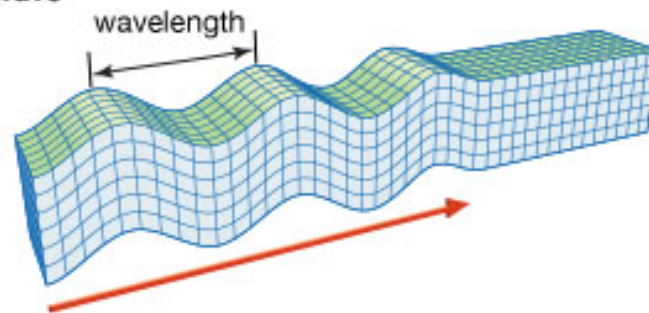
**P wave**



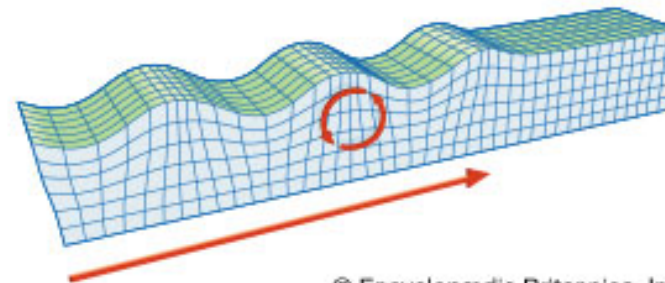
**Love wave**



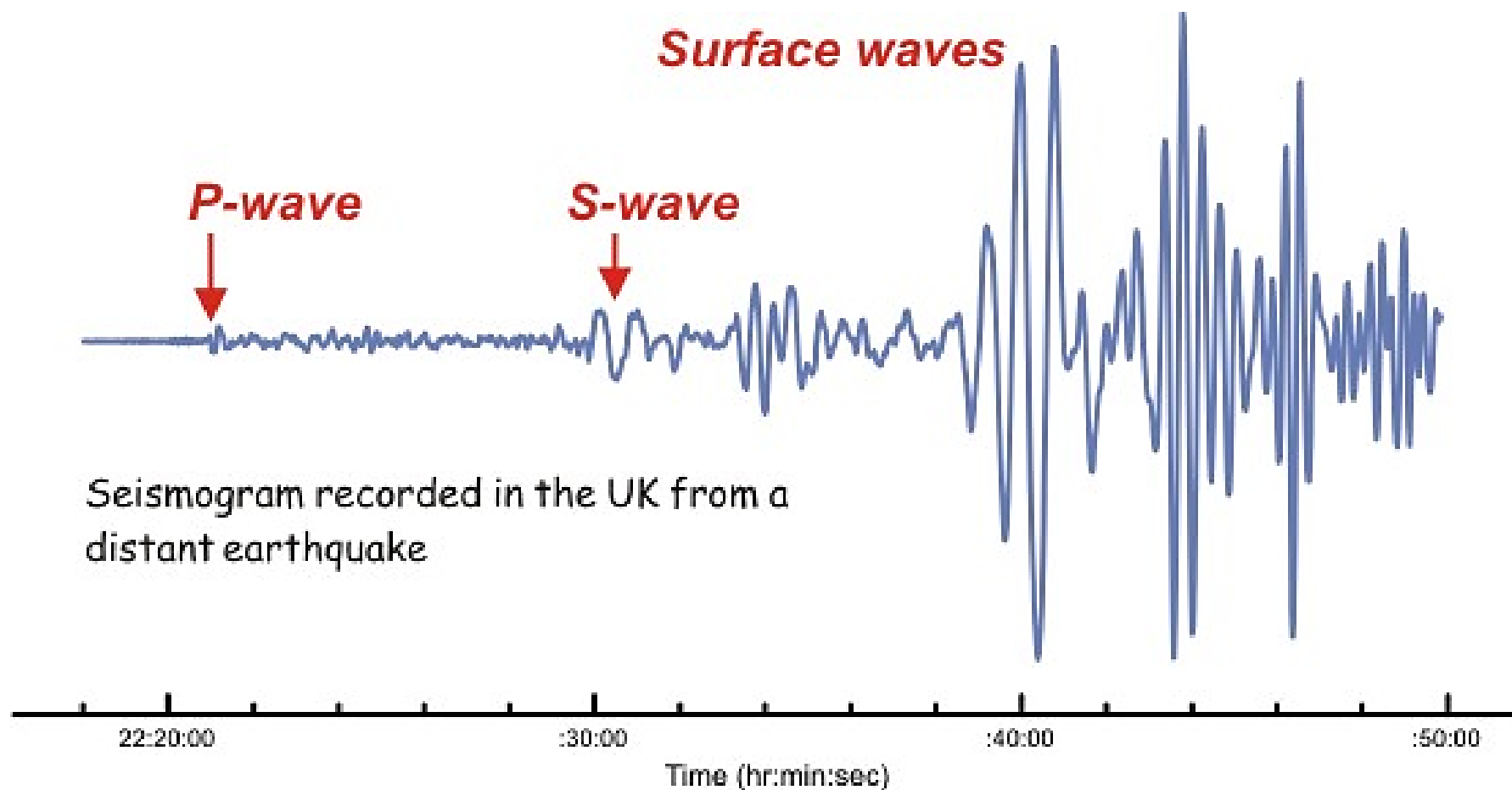
**S wave**



**Rayleigh wave**



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## Relationship between $V_p$ and $V_s$

### Compressional Waves

$$V_p = \sqrt{\frac{(\frac{4}{3}\mu + k)}{\rho}}$$

### Shear Waves

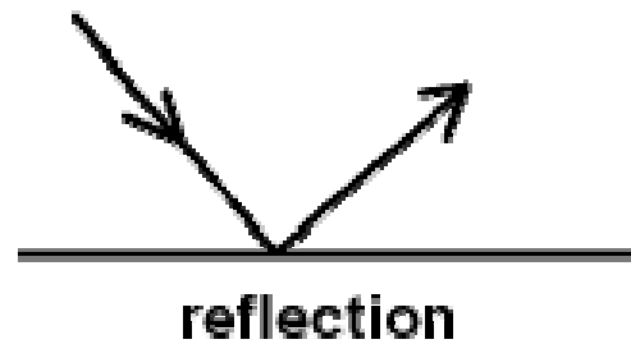
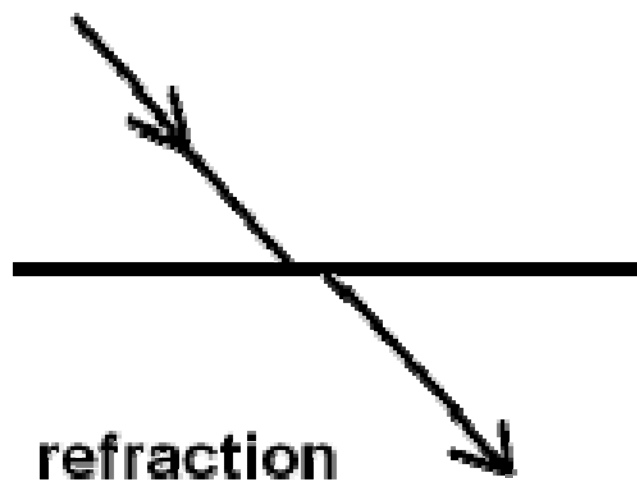
$$V_s = \sqrt{\frac{\mu}{\rho}}$$

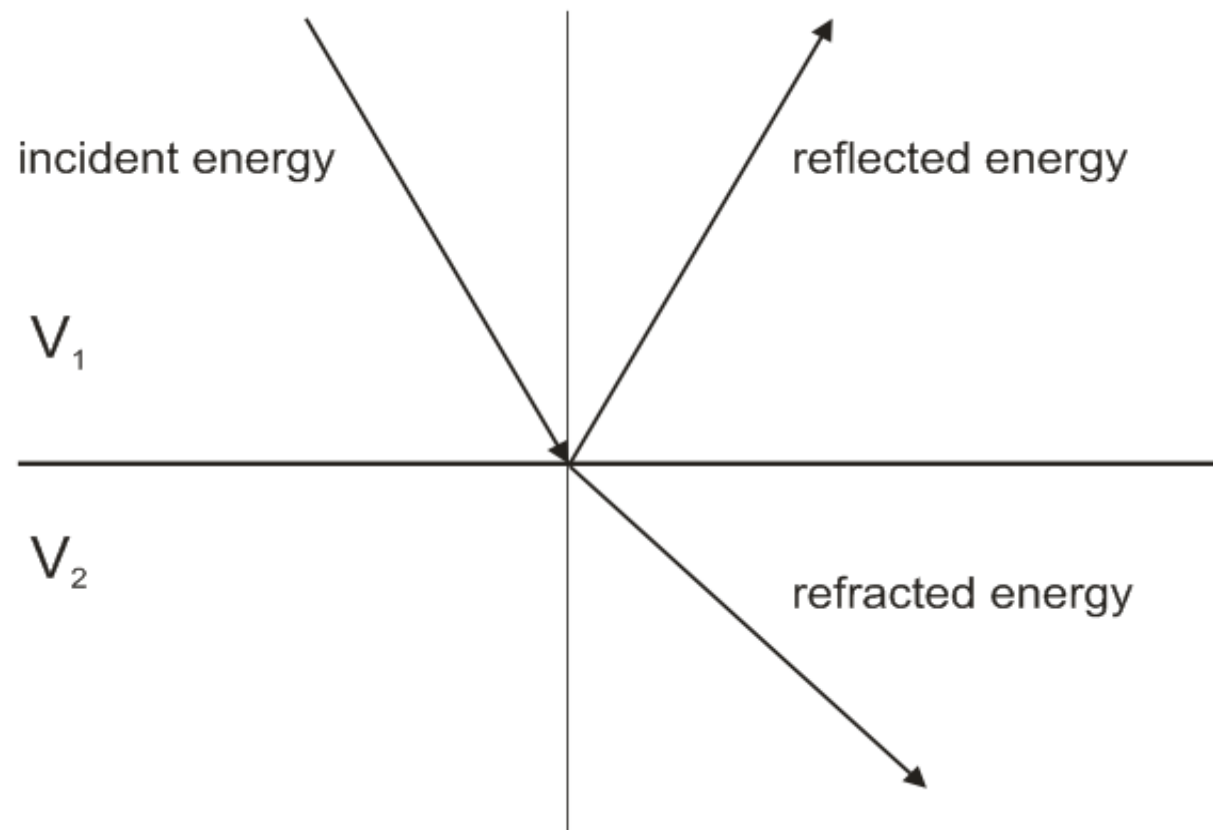
- Averaged  $V_p/V_s = 1.732$  for the crust
- For mafic rocks,  $V_p/V_s = 1.81$
- For felsic rocks,  $V_p/V_s = 1.70$

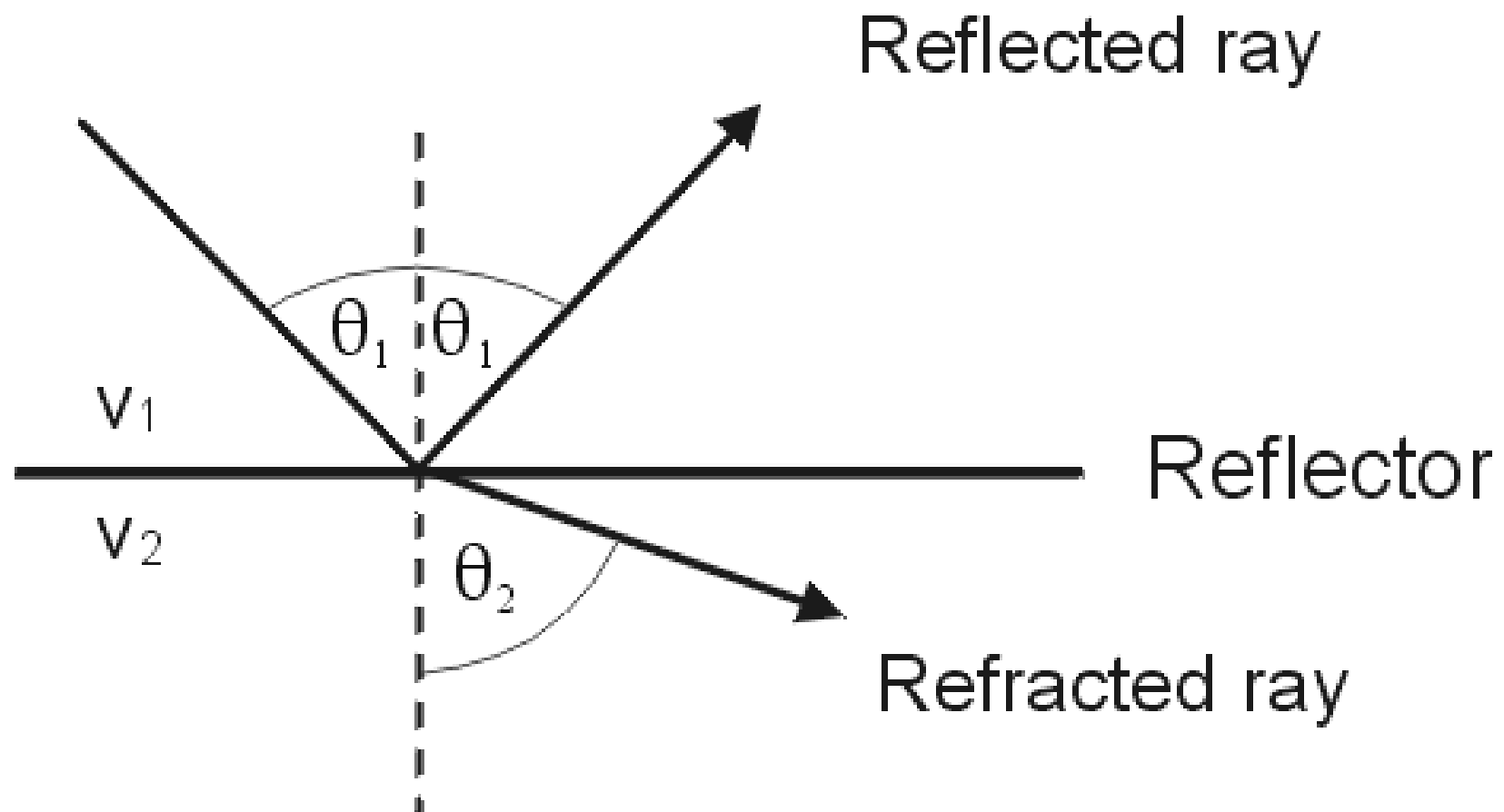
Q. What is the difference between refraction and reflection?



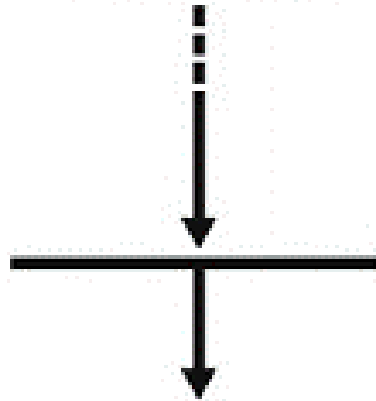
GPH 301 - Seismic Refraction Methods



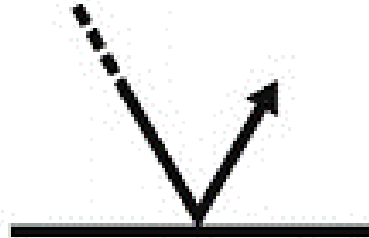




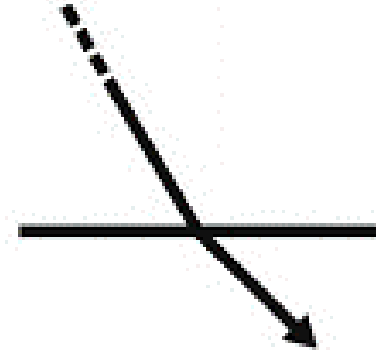
**Transmission**



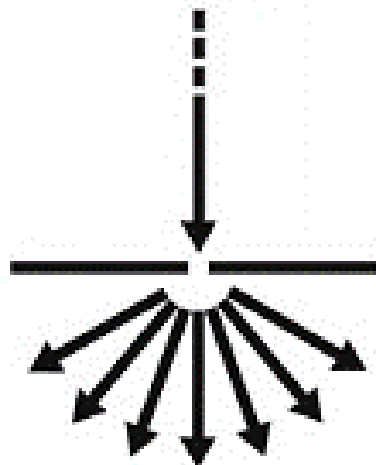
**Reflection**



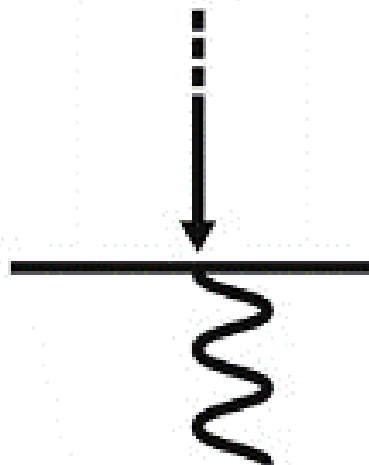
**Refraction**



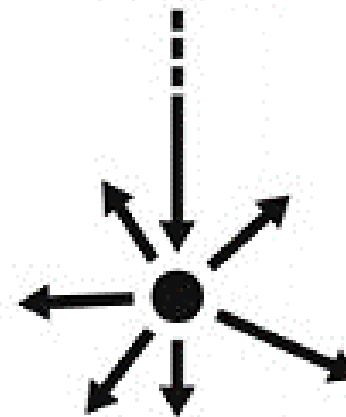
**Diffraction**



**Adsorption**

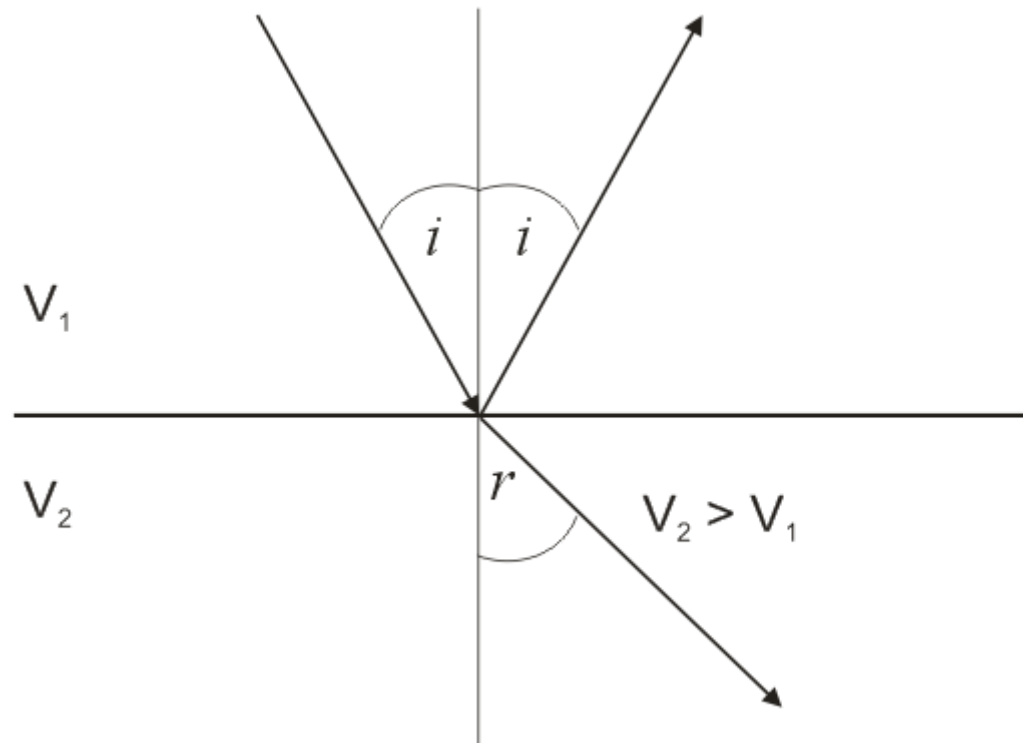


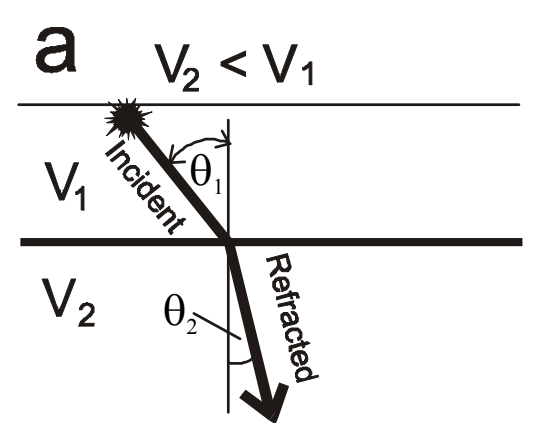
**Scattering**



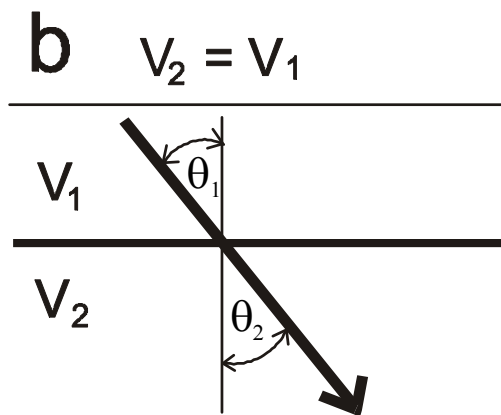
## Snell's Law

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2}$$

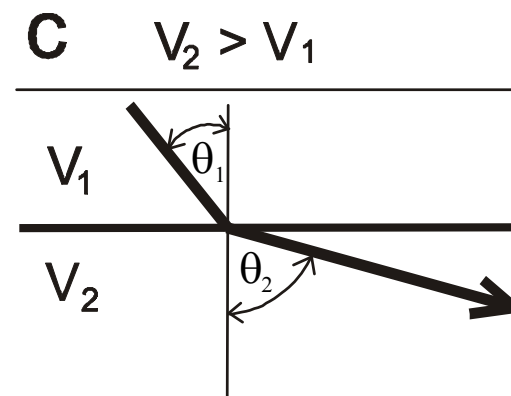




Refracted away from interface.



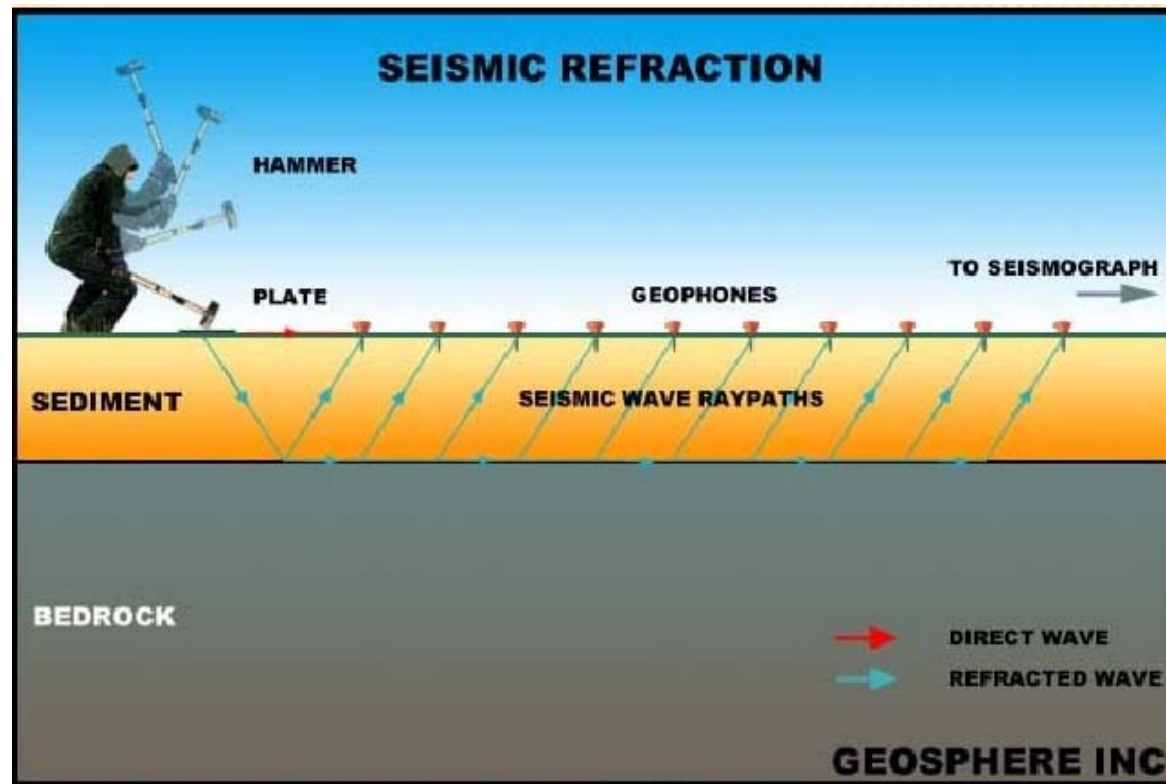
Ray not bent.



Refracted toward interface.

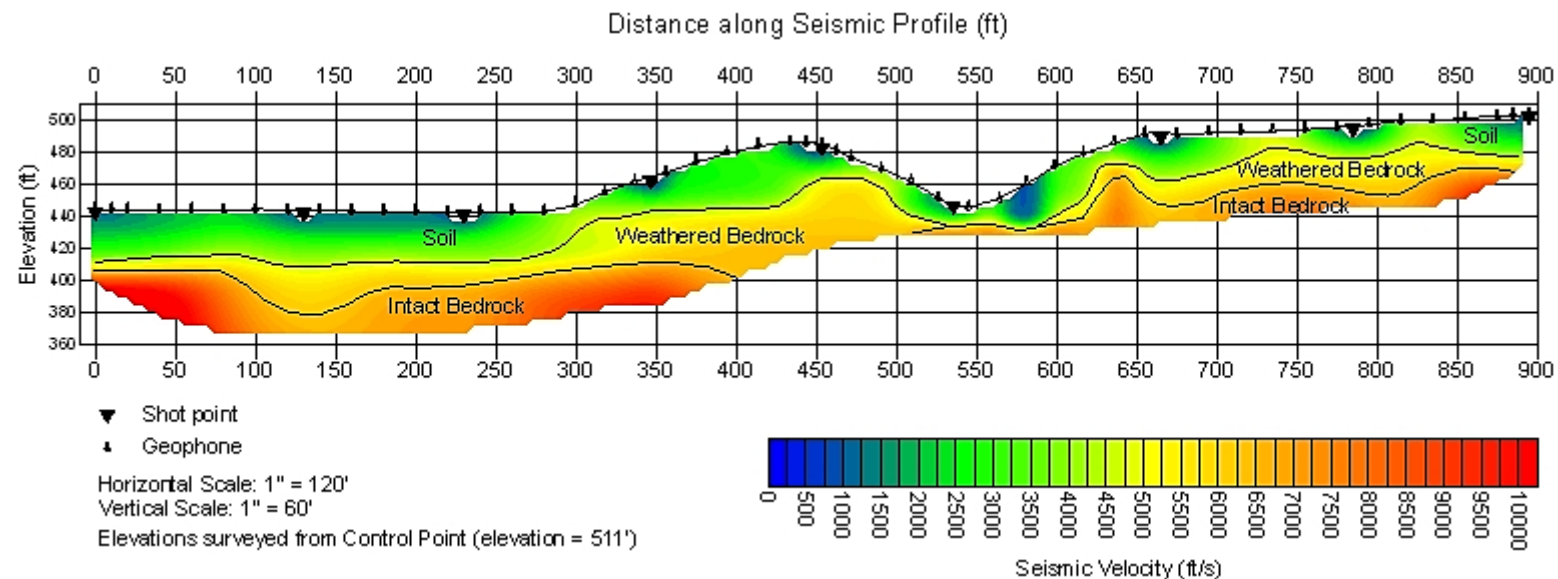
Q. What is seismic refraction?

Seismic Refraction: the signal returns to the surface by refraction at subsurface interfaces. And is recorded at distance much greater than depth of investigation.

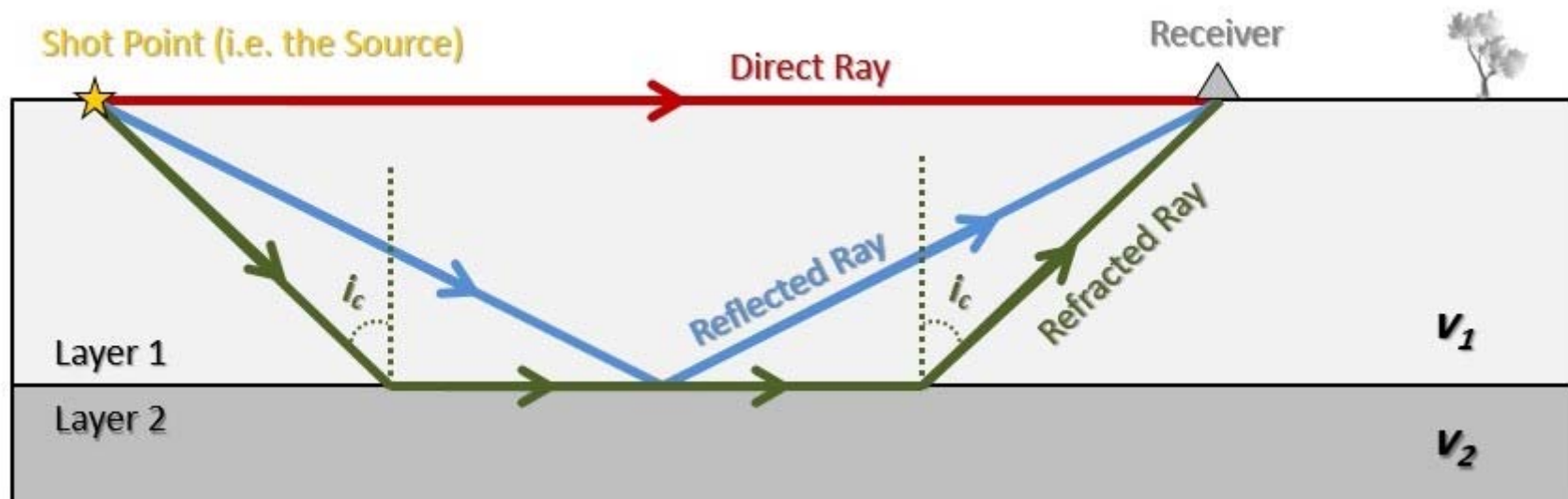


## Applications for seismic refraction:

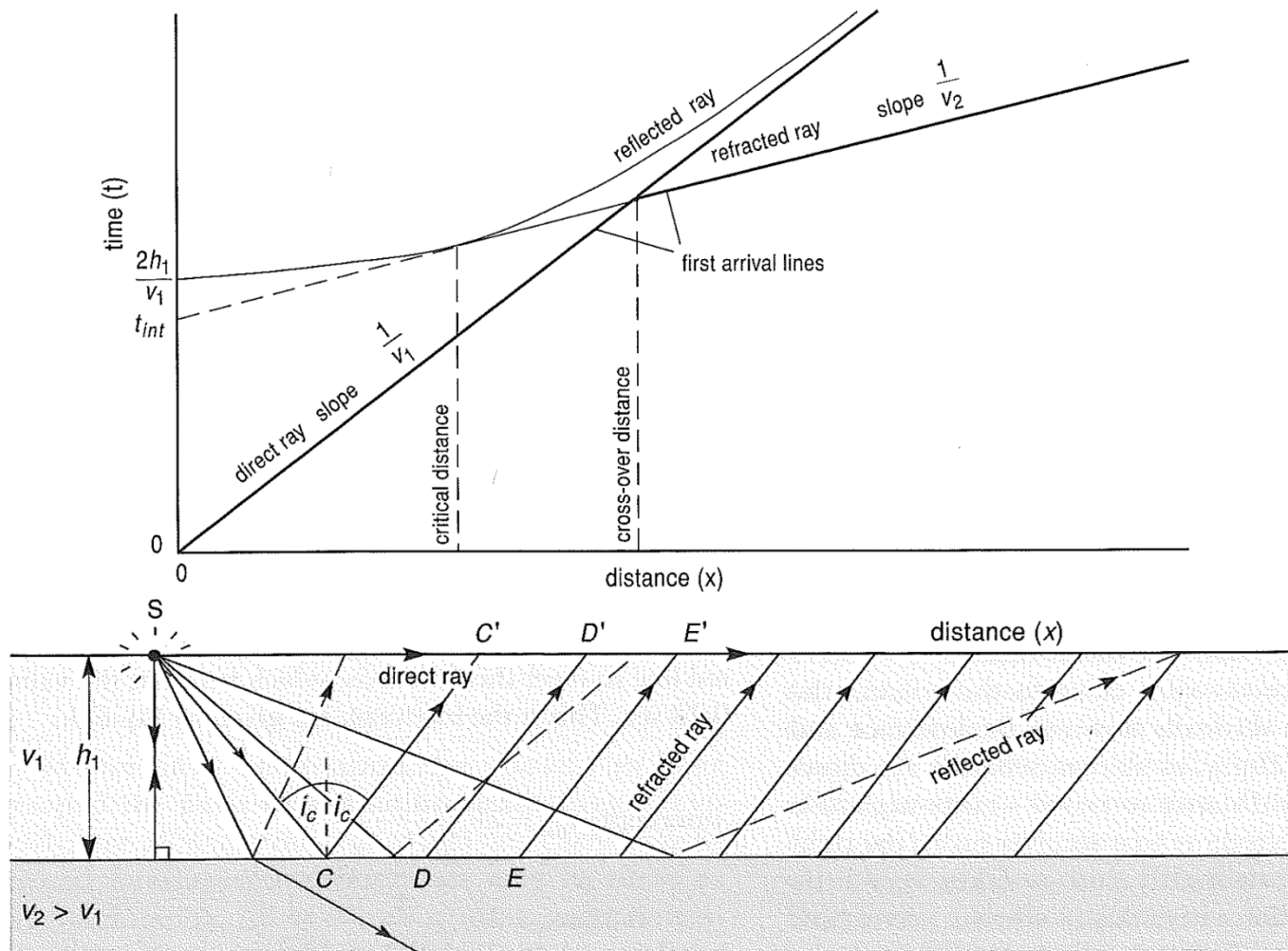
- Depth to bedrock.
- Groundwater exploration.
- Crustal structure and tectonics.



- When doing a seismic refraction survey, a recorded ray can come from three main paths:
  - The direct ray
  - The reflected ray
  - The refracted ray
- Because these rays travel different distances and at different speeds, they arrive at different times
- The direct ray and the refracted ray arrive in different order depending on distance from source and the velocity structure



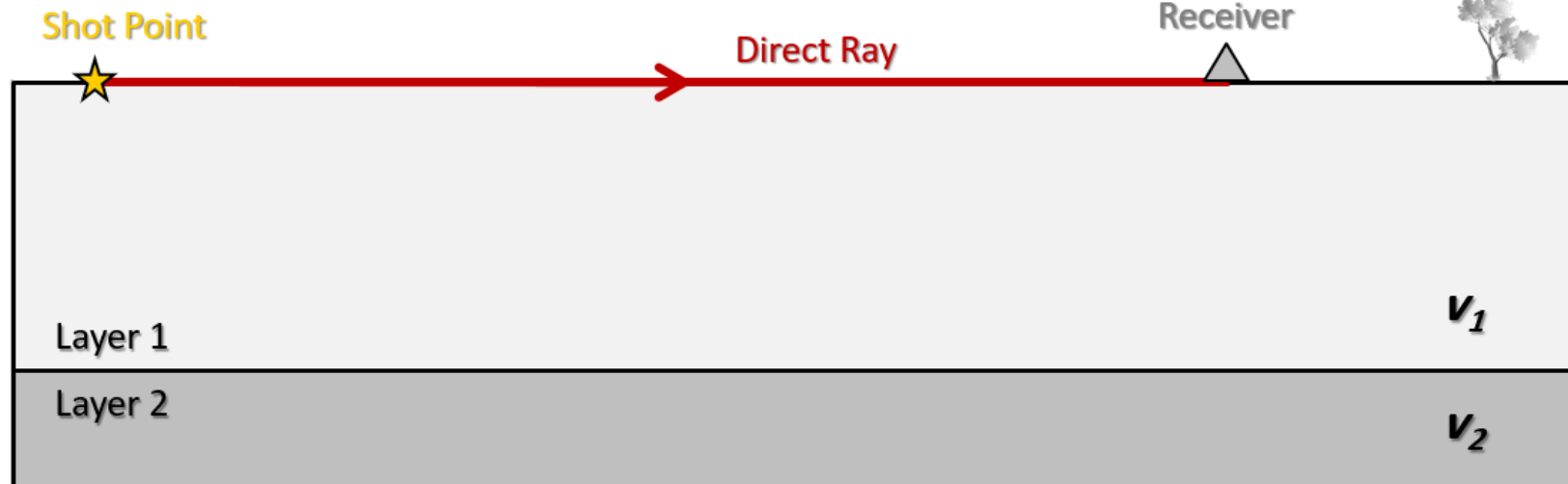
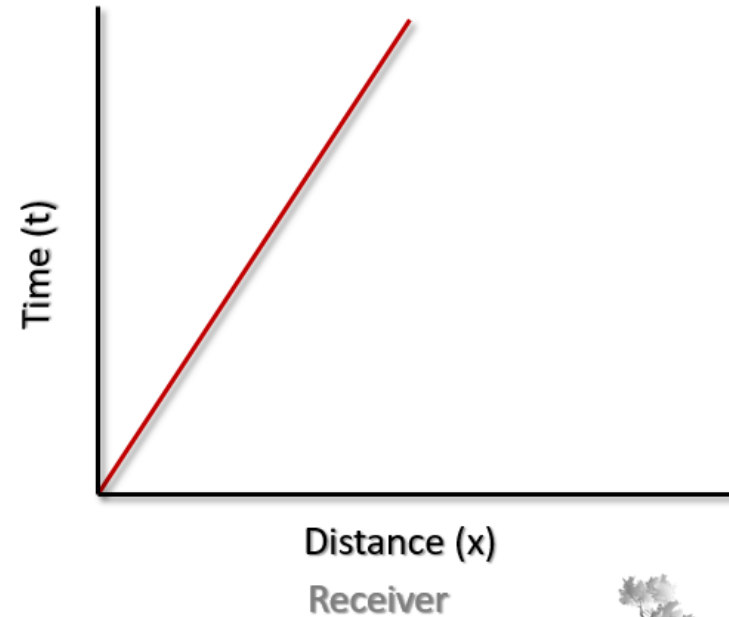
## The Time-Distance (t-x) Diagram



# The Direct Ray

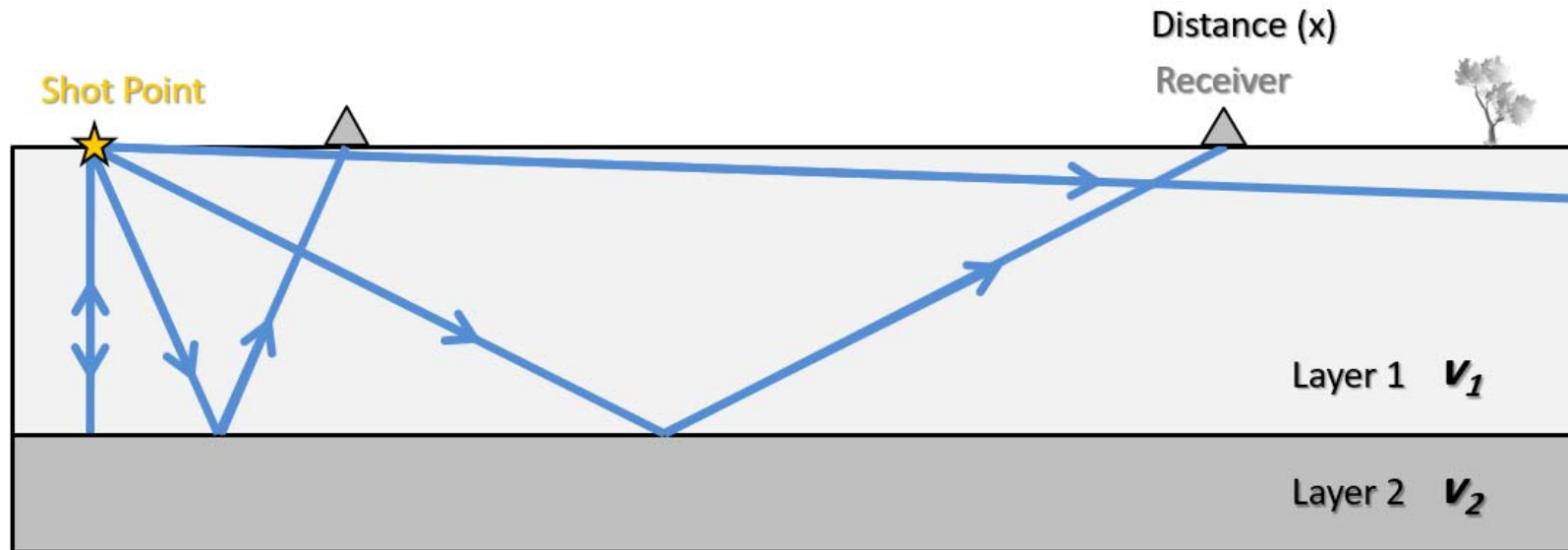
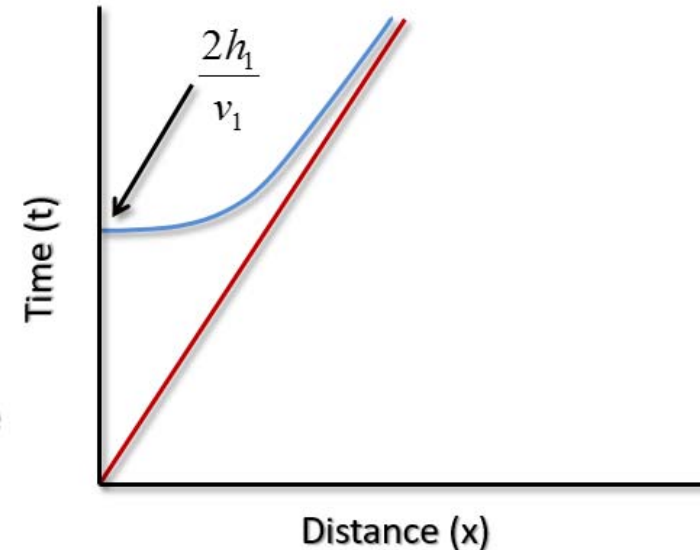
- The Direct Ray Arrival Time:
  - Simply a linear function of the seismic velocity and the shot point to receiver distance

$$t_{direct} = \frac{x}{v_1}$$



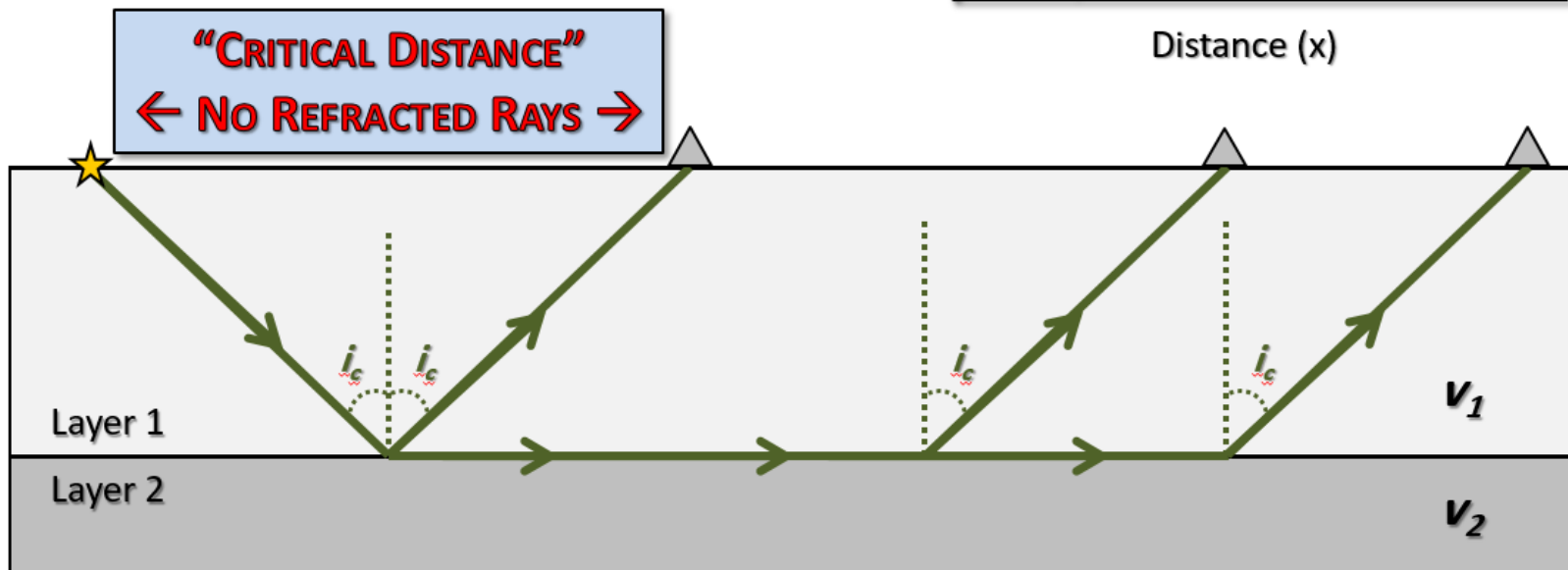
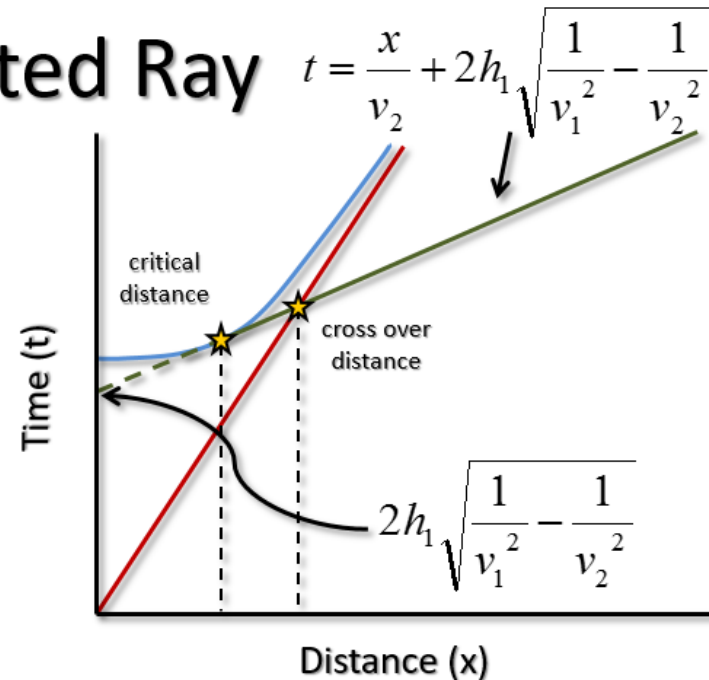
# The Reflected Ray

- The Reflected Ray Arrival Time:
  - is never a first arrival
  - Plots as a curved path on t-x diagram
  - Asymptotic with direct ray
  - Y-intercept (time) gives thickness
    - Why do we not use this to estimate layer thickness?



# The Refracted Ray

- The Refracted Ray Arrival Time:
  - Plots as a linear path on t-x diagram
    - Part travels in upper layer (constant)
    - Part travels in lower layer (function of x)
  - Only arrives after **critical distance**
  - Is first arrival only after **cross over distance**
    - Travels long enough in the faster layer

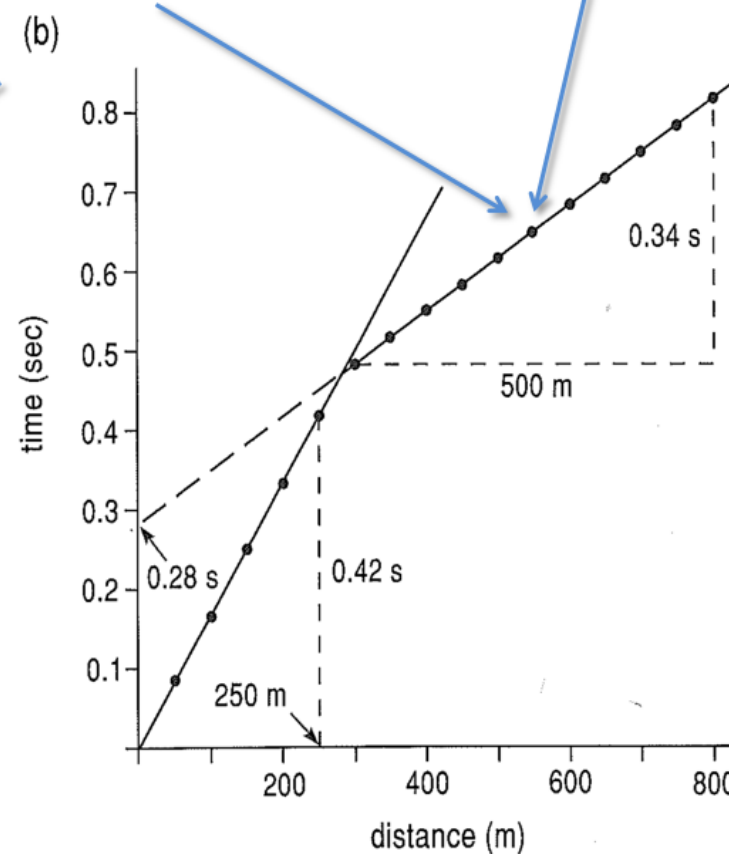
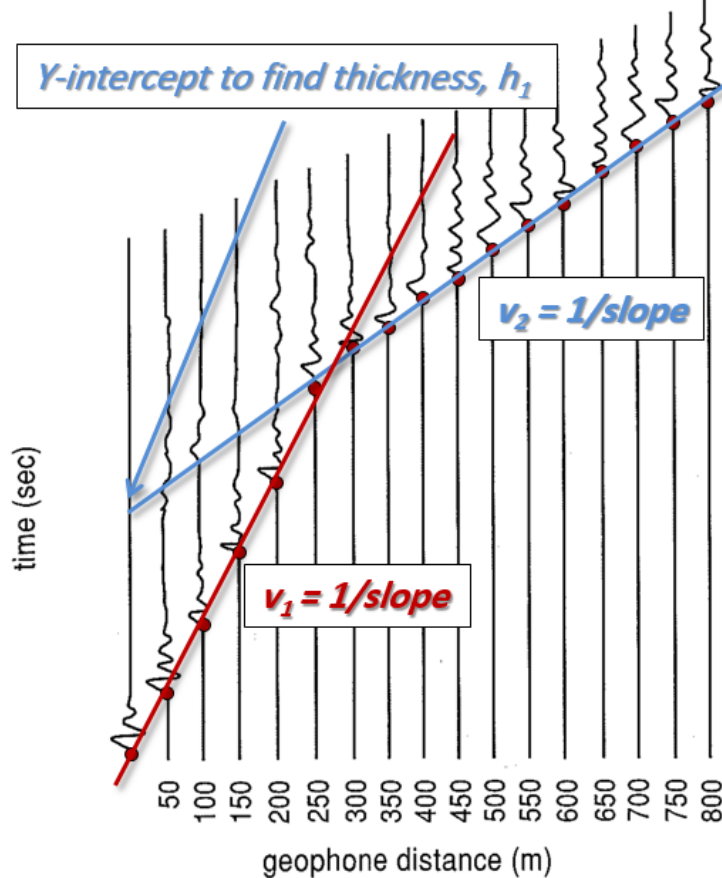


# Making a t-x Diagram

Refracted Ray Arrival Time,  $t$

$$t = \frac{x}{v_2} + 2h_1 \sqrt{\frac{1}{v_1^2} - \frac{1}{v_2^2}}$$

or 
$$t = \frac{x \sin i_c}{v_1} + \frac{2h_1 \cos i_c}{v_1}$$



# Refraction...What is it Good For?

- Seismic refraction surveys reveal two main pieces of information
  - Velocity structure
    - Used to infer rock type
  - Depth to interface
    - Lithology change
    - Water table

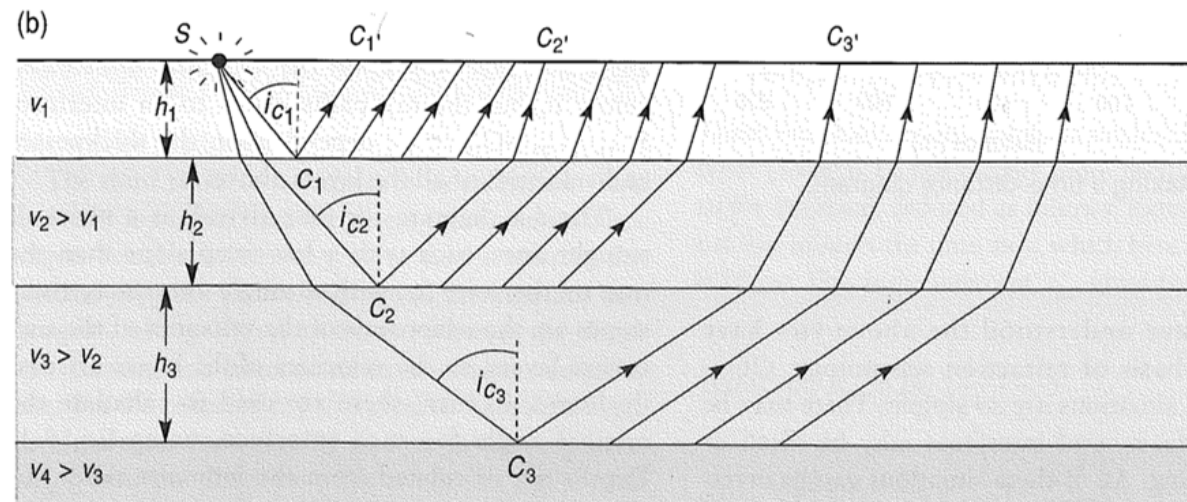
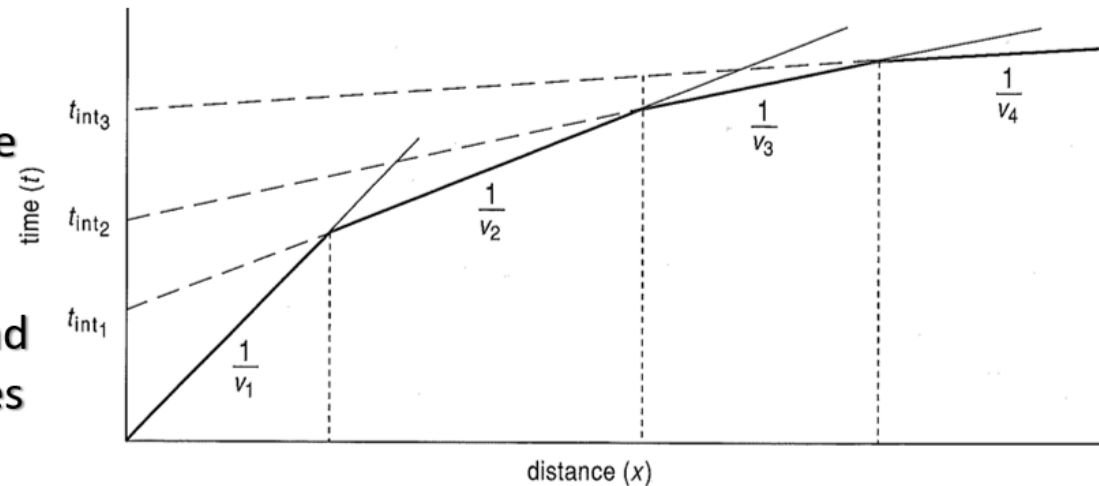
Table 6.1 Seismic velocities for rocks

Rock type	$v_p$ (km/sec)
<i>Unconsolidated sediments</i>	
clay	1.0–2.5
sand, dry	0.2–1.0
sand, saturated	1.5–2.0
<i>Sedimentary rocks</i>	
anhydrite	6.0
chalk	2.1–4.5
coal	1.7–3.4
dolomite	4.0–7.0
limestone	3.9–6.2
shale	2.0–5.5
salt	4.6
sandstone	2.0–5.0
<i>Igneous and metamorphic rocks</i>	
basalt	5.3–6.5
granite	4.7–6.0
gabbro	6.5–7.0
slate	3.5–4.4
ultramafic rocks	7.5–8.5
<i>Other</i>	
air	0.3
natural gas	0.43
ice	3.4
water	1.4–1.5
oil	1.3–1.4

Ranges of velocities, which are from a variety of sources, are approximate.

# Multiple Layers

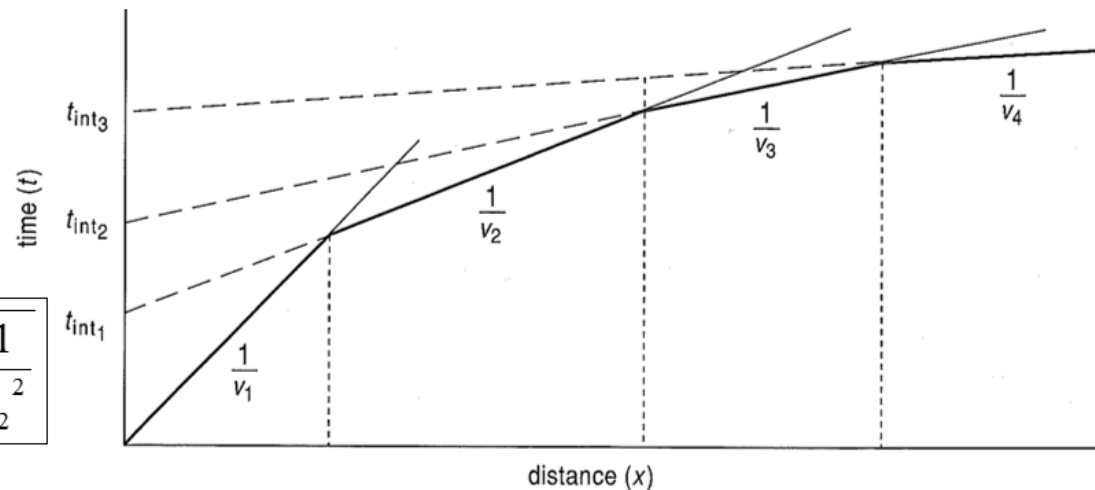
- Seismic refraction can detect multiple layers
- The velocities are easily found from the slopes on the t-x diagram



# Multiple Layers

- The layer thicknesses are not as easy to find
- Recall...

$$t = \frac{x}{v_2} + 2h_1 \sqrt{\frac{1}{v_1^2} - \frac{1}{v_2^2}}$$



$$t_{\text{int}_1} = 2h_1 \sqrt{\frac{1}{v_1^2} - \frac{1}{v_2^2}} \quad \text{Solve for } h_1 \rightarrow h_1 = \frac{t}{2 \sqrt{\frac{1}{v_1^2} - \frac{1}{v_2^2}}} = \frac{t}{2 \sqrt{\frac{v_2^2 - v_1^2}{v_1^2 v_2^2}}}$$

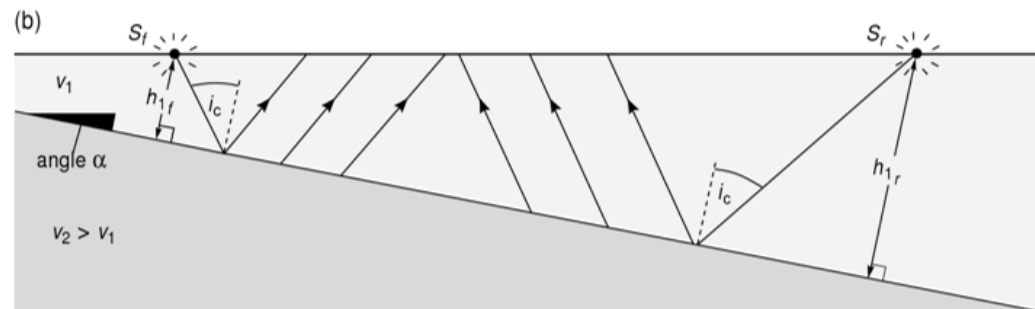
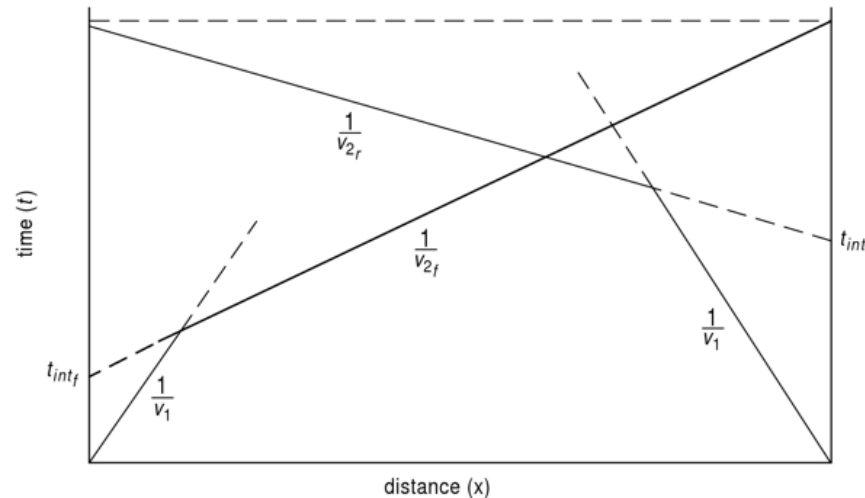
Now, plug in  $h_1$  and solve the remaining layers one at a time...

$$t_{\text{int}_2} = 2h_1 \sqrt{\frac{1}{v_1^2} - \frac{1}{v_2^2}} + 2h_2 \sqrt{\frac{1}{v_2^2} - \frac{1}{v_3^2}}$$

BEWARE!!!  $h_1, h_2$  are layer thicknesses, not depth to interfaces.  
So, depth to bottom of layer 3 / top of layer 4 =  $h_1 + h_2 + h_3$

# Dipping Interfaces

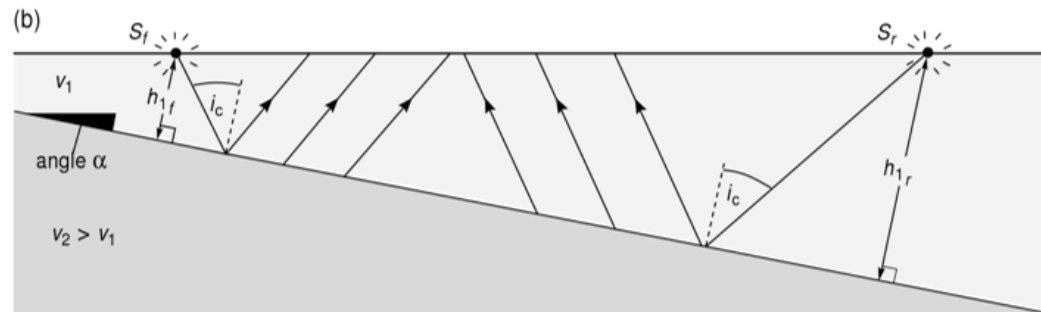
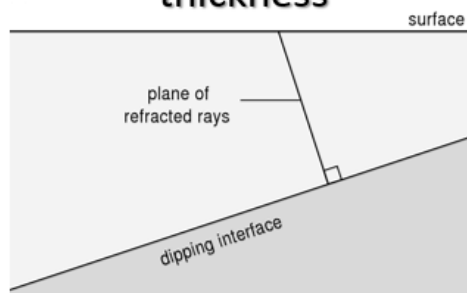
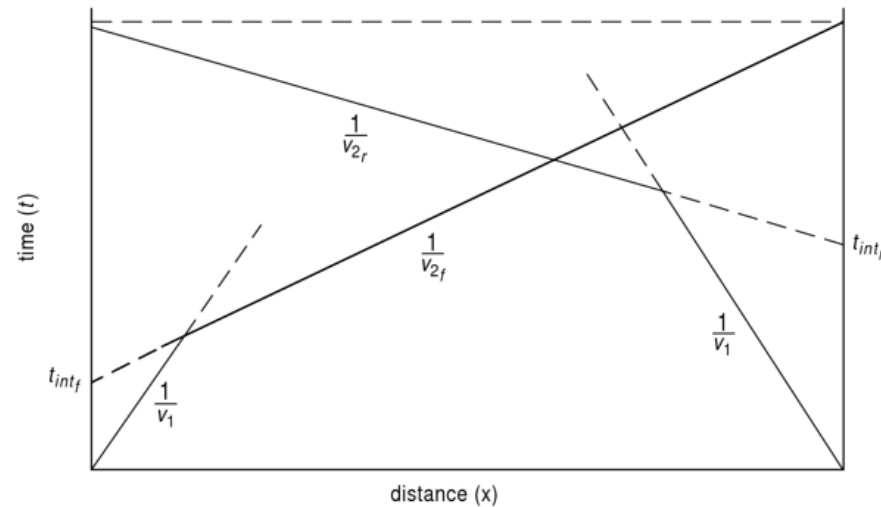
- What if the critically refracted interface is not horizontal?
- A dipping interface produces a pattern that looks just like a horizontal interface!
  - Velocities are called “apparent velocities”
- What do we do?



In this case, velocity of lower layer is underestimated

# Dipping Interfaces

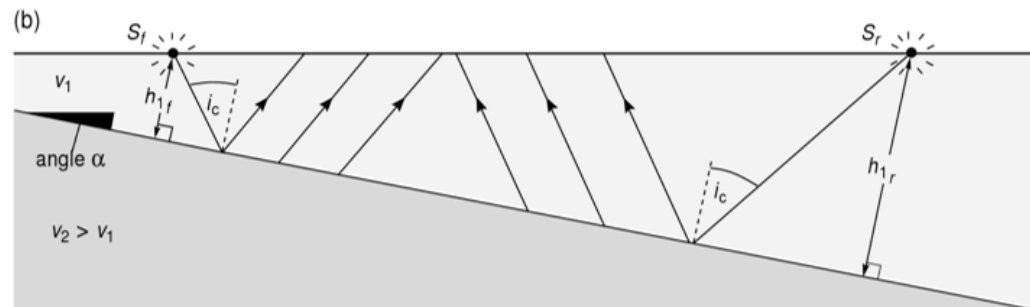
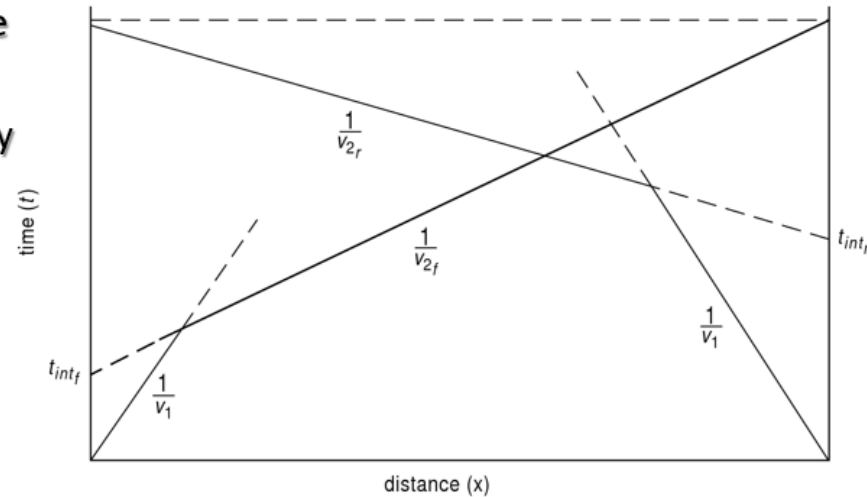
- To determine if interfaces are dipping...
- Shoot lines forward and reversed
- If dip is small ( $< 5^\circ$ ) you can take average slope
- The intercepts will be different at both ends
  - Implies different thickness



Beware: the calculated thicknesses will be perpendicular to the interface, not vertical

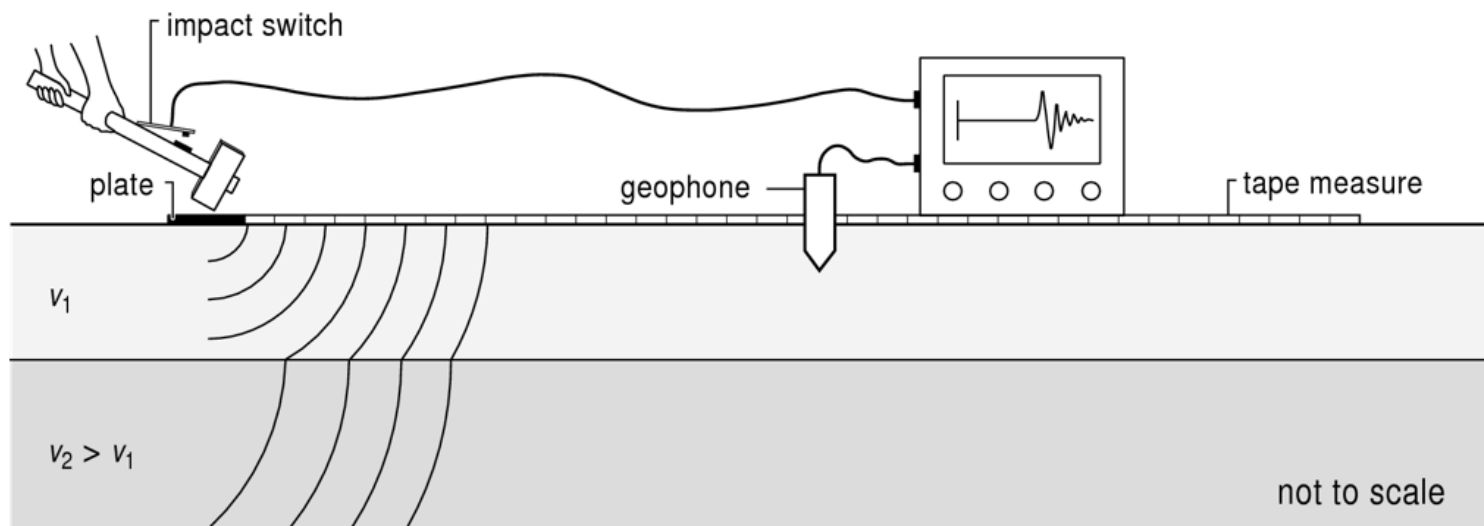
# Dipping Interfaces

- If you shoot down-dip
  - Slopes on t-x diagram are too steep
    - Underestimates velocity
  - May underestimate layer thickness
- Converse is true if you shoot up-dip
- In both cases the calculated direct ray velocity is the same.
- The intercepts  $t_{int}$  will also be different at both ends of survey



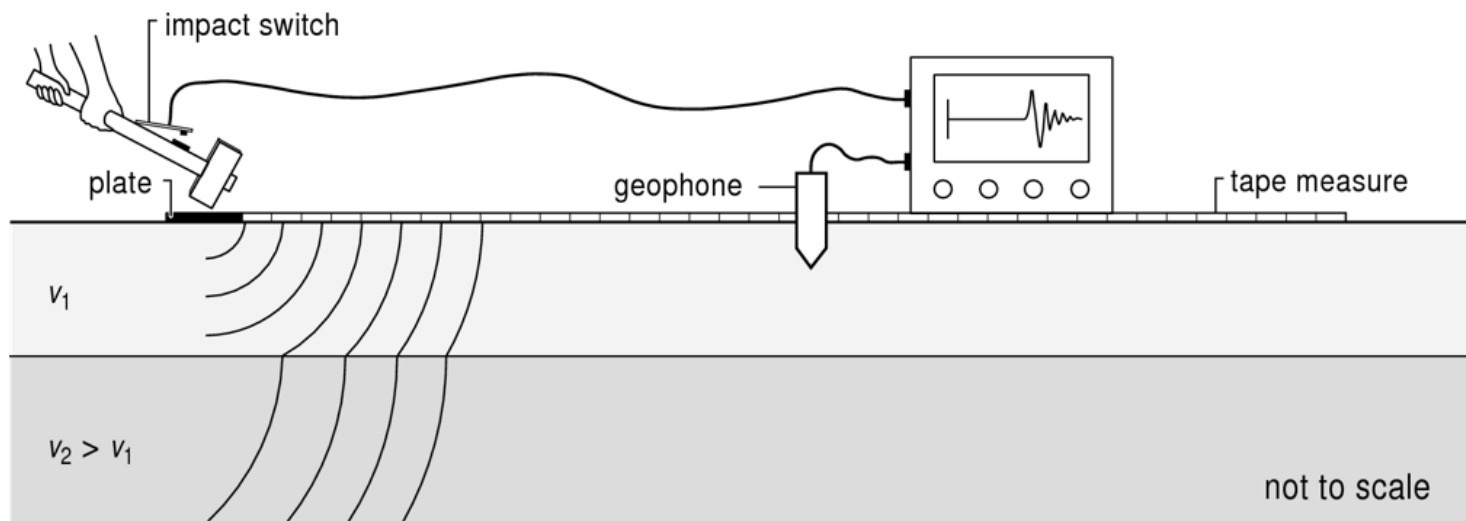
# Survey Types

- The simplest (and cheapest) type of survey is called a hammer seismic survey
  - A sledgehammer is whacked into a steel plate
  - Impact switch tells time=0
  - First arrivals are read digitally or inferred from seismogram
  - Because swinging a hammer is free, only one geophone is needed
    - More can be used, but single geophones must be along a linear transect



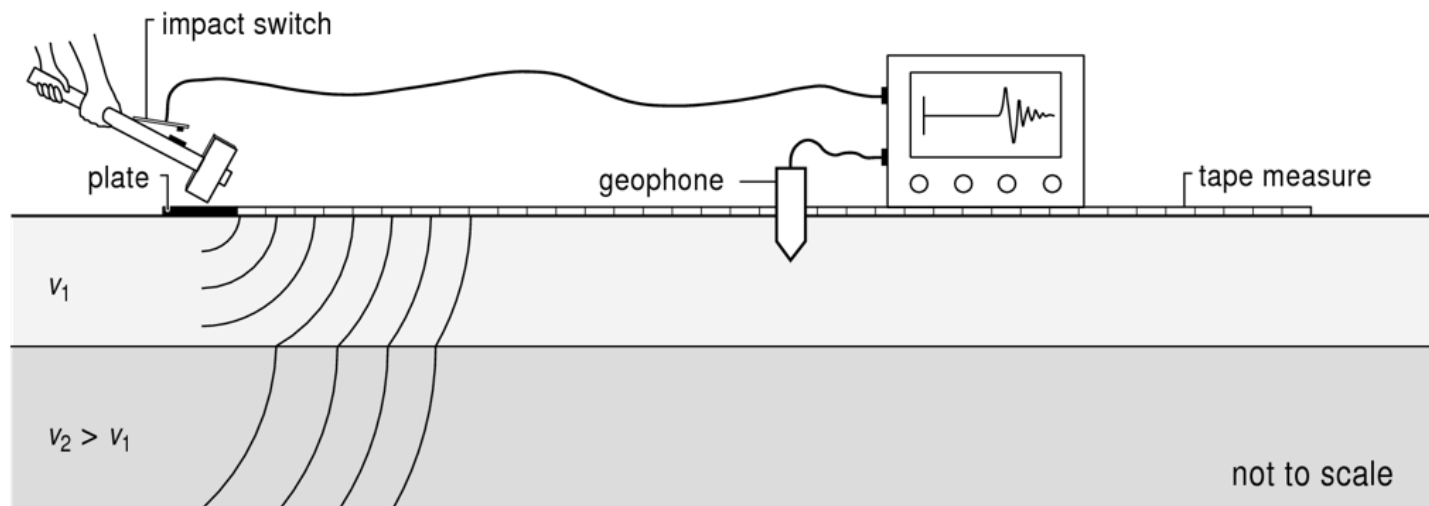
# Survey Types

- The maximum workable distance depends on:
  - The sensitivity of the system
  - The strength of the sledgehammer whacks
  - The amount of noise
    - Wind shakes trees, etc...
    - Cars, footsteps, HVAC, traffic, etc...
    - Surveys may be done at night to minimize noise



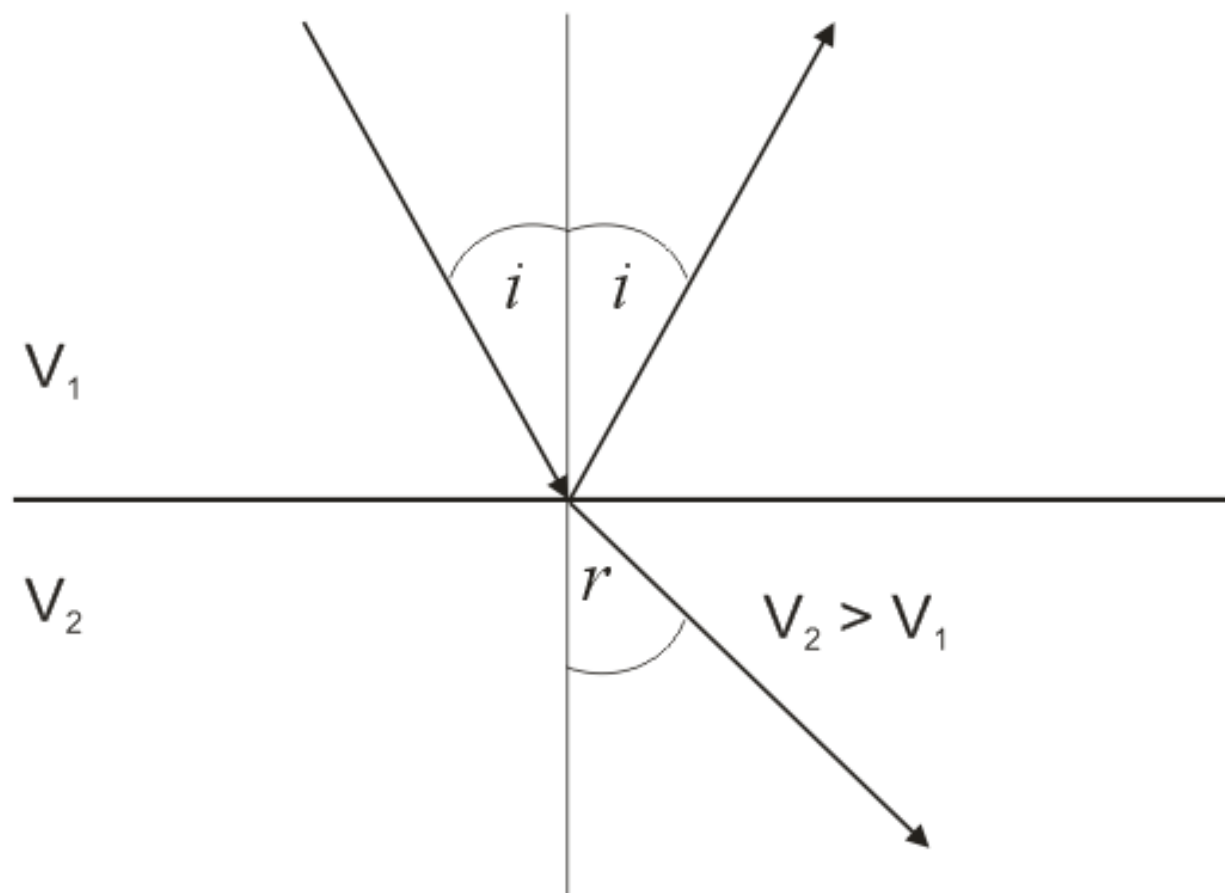
# Survey Types

- Often the signal to noise ratio is very poor:
  - Stacking is often used to help delineate first arrivals
- General rule of thumb:
  - Geophone array should be about 10x the depth to interface
  - 100 meters is the typical upper limit on length of hammer seismic transect
    - So hammer seismics are best for shallow interfaces (< 10 m)

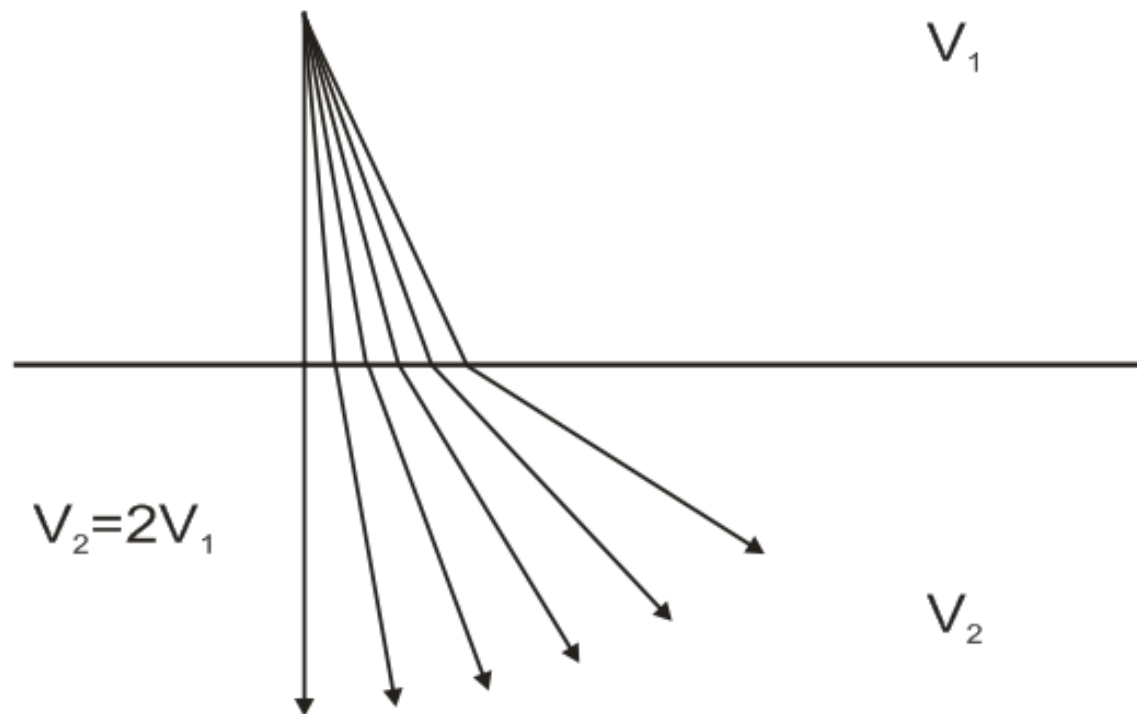


# Other Survey Types

- Explosion seismics
  - Offers a much stronger signal
    - Can detect deeper features
    - Often involves water explosions (much cheaper)
    - Geophones / Seismometers are often linked wirelessly (RF / radio waves)
- Marine Surveys
  - Sometimes use explosives, compressed air, high voltage charges, or many other types.
  - Usually use hydrophones
    - Respond to pressure changes (p-waves)
    - Surveying is often done while the ship is moving, so very long transects can be done at a lower cost



If  $V_2 > V_1$ , then as  $i$  increases,  $r$  increases faster



## Critical Refraction

At Critical Angle of incidence  $i_c$ , angle of refraction  $r = 90^\circ$

