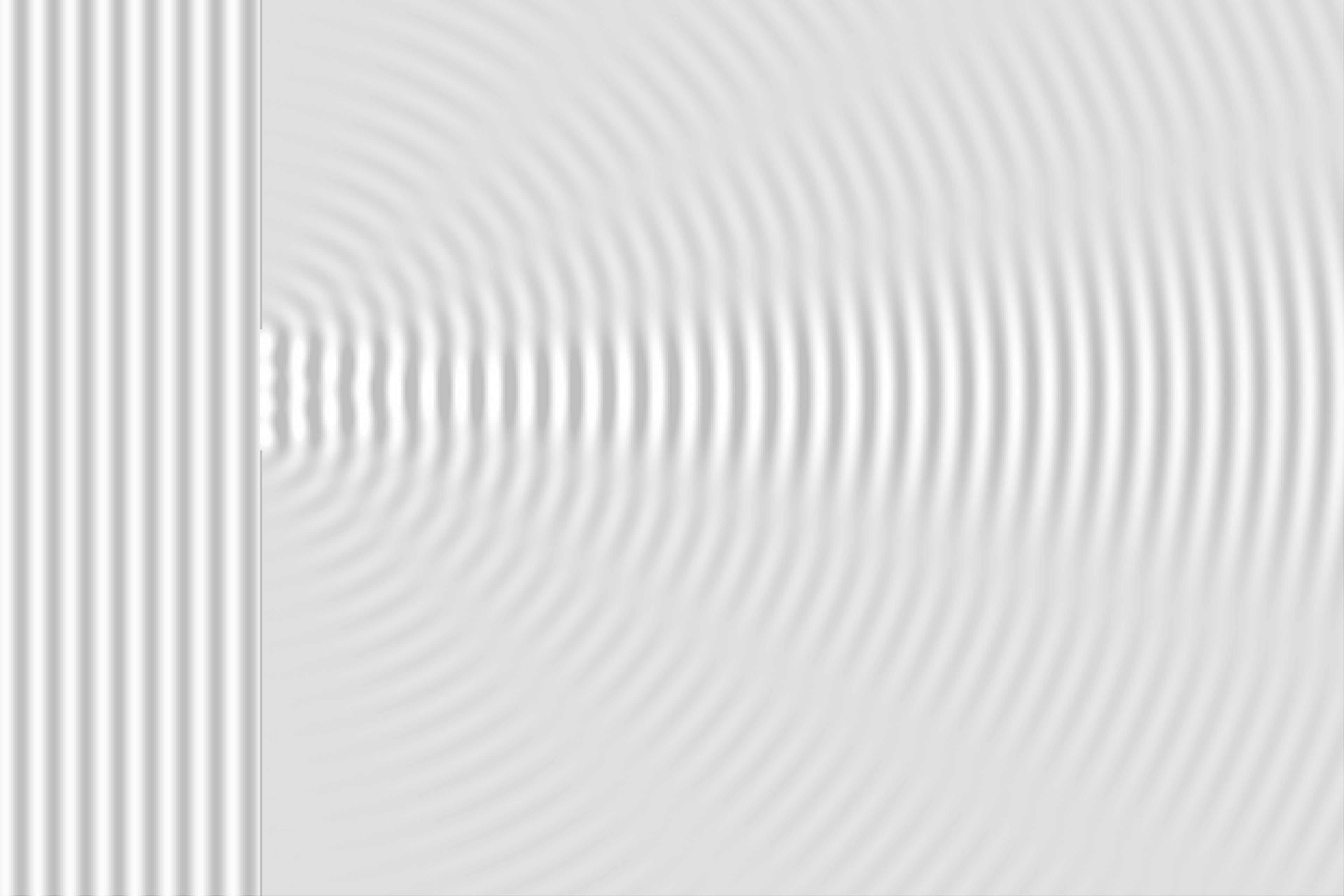
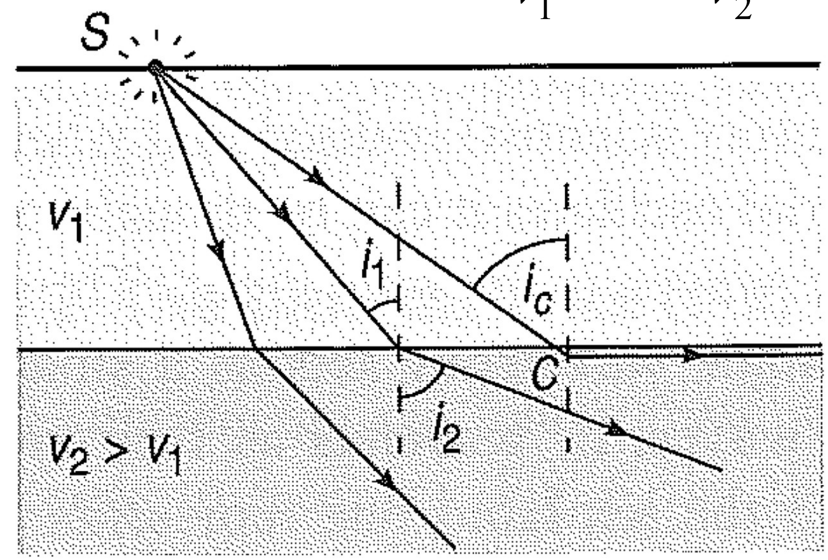
Refraction Seismology



Snell's Law & Critical Refraction

$$\frac{\sin i_1}{v_1} = \frac{\sin i_2}{v_2}$$

- Because seismic sources radiate waves in all directions
- Some ray must hit interface at exactly the critical angle, i_c
- This critically oriented ray will then travel along the interface between the two layers
- If more oblique than critical, all wave energy is reflected
  - The reflected energy is useful too!
    - E.g. Chapter 7



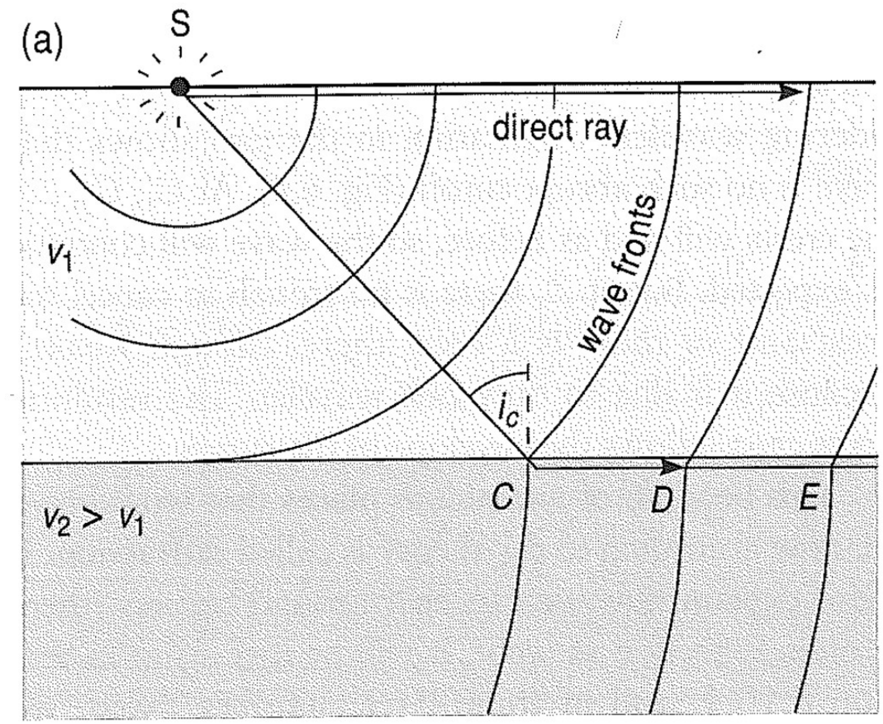
$$\frac{\sin i_c}{v_1} = \frac{\sin 90}{v_2}$$

$$\sin i_c = \frac{v_1}{v_2}$$

$$i_c = \arcsin\left(\frac{v_1}{v_2}\right)$$

Critical Refraction and Wave Fronts

- When a ray meets a new layer at the critical angle…
  - The ray travels along the interface
    - What layer is it in?
- Rays, aren't real, so consider the wave fronts…
  - Wave fronts travel in both layers
  - Wave front in top continues on the same trajectory
  - Wave front in Bottom has to be perpendicular to the ray
  - But the layers have different velocities
  - This sets up wavelets and head waves…

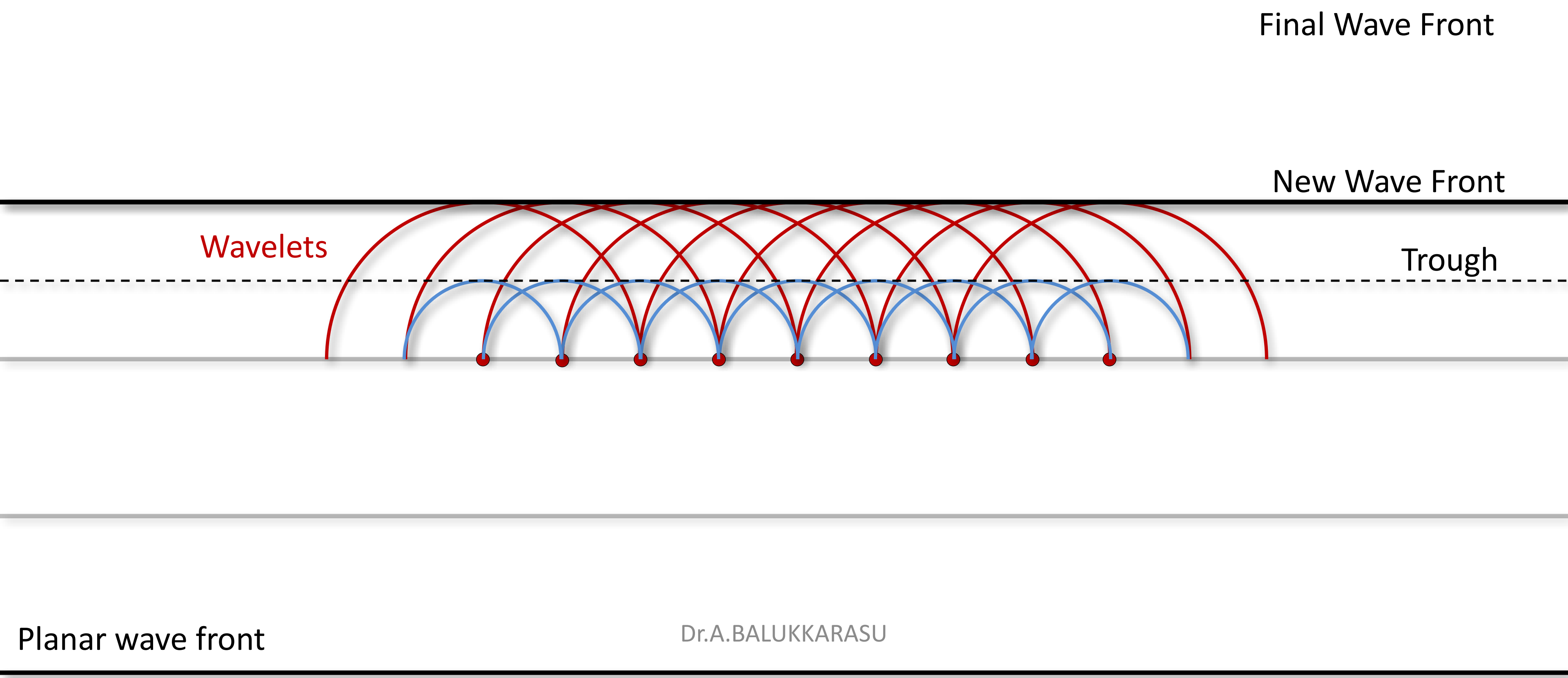


Huygens's Principle

- Recall that rays are not real
  - They are just an easy way to understand and quantify waves
- Wave fronts are what is really happening
  - But what causes wave fronts?
    - Huygens's wavelets explains…
      - Each point along a material is acts like a point source of waves
      - Like a pebble dropped into water

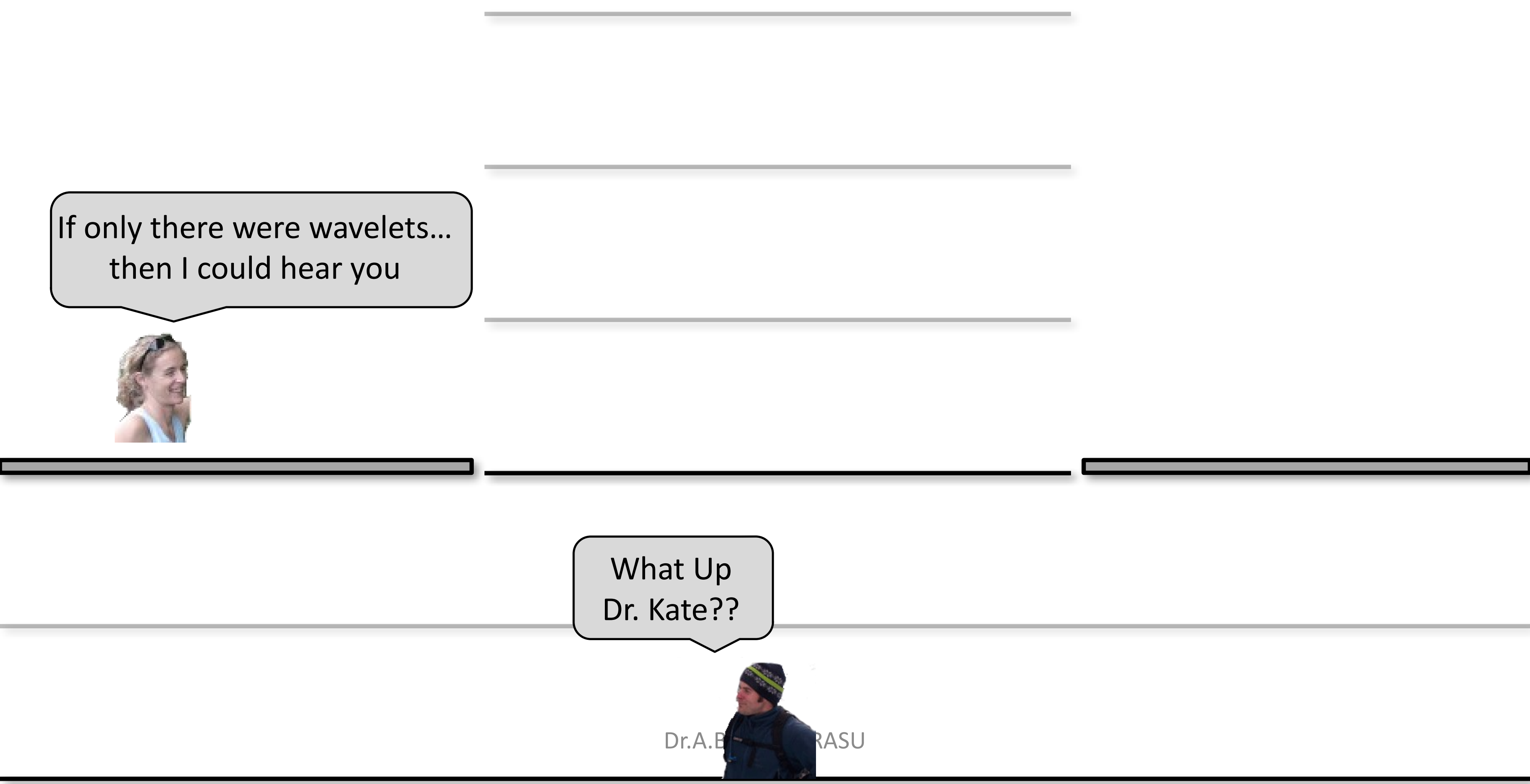
Huygens's Wavelets

- Huygens (a 17th century Dutch physicist) realized that:
  - When any particle oscillates it is a tiny source of waves
    - So, every point on a wave front acts as a small source that generates waves
    - The waves have circular (spherical) wave fronts and are called **wavelets**
    - Wavelets constructively interact (reinforcement) to produce the wave front
  - Has important implications for diffraction and critical refraction



Wavelets and Diffraction

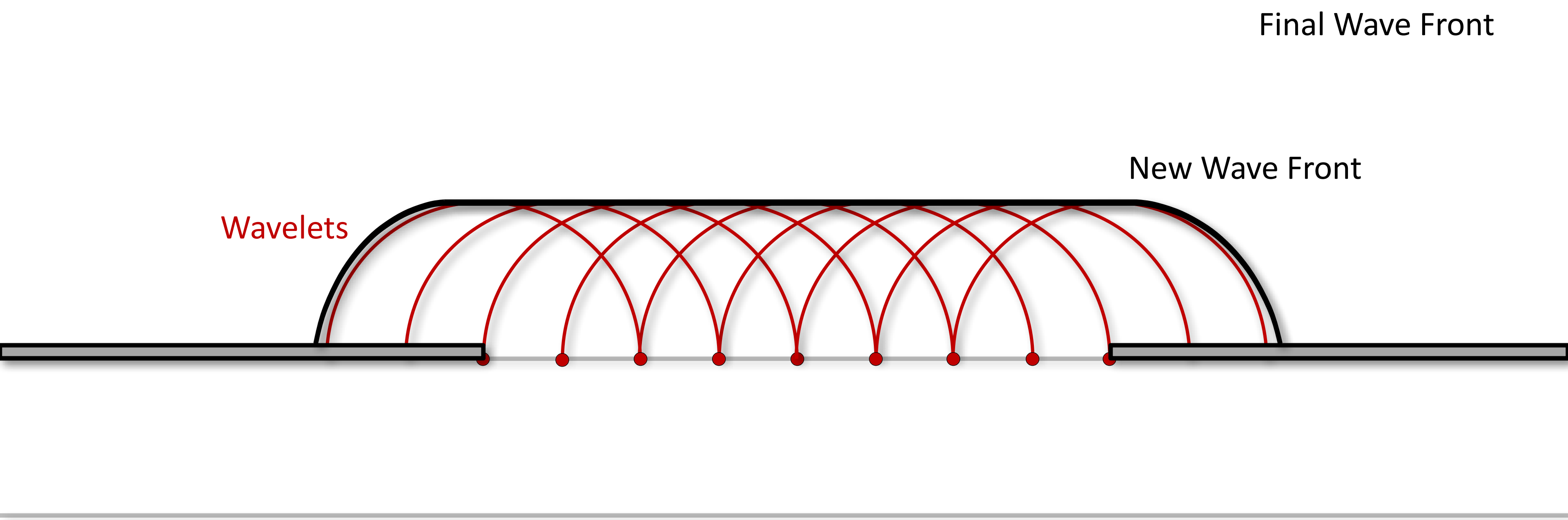
- If wavelets didn't occur, we wouldn't be able to hear around corners.
  - Light doesn't travel around corners very well because of its very high frequency



Wavelets and Diffraction

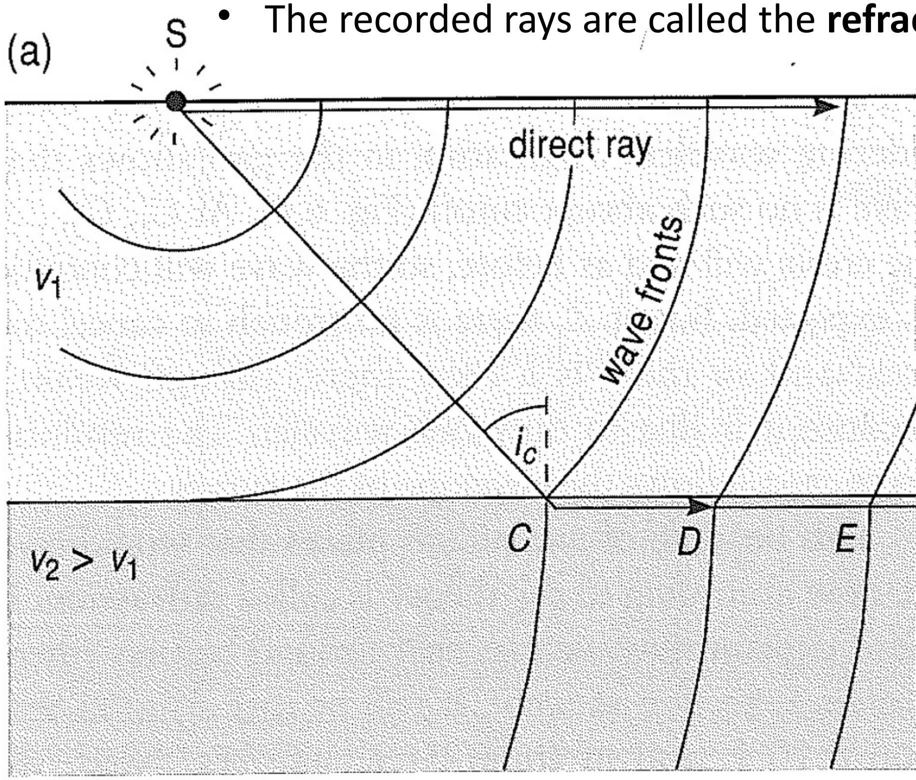
- Because of wavelets, a wave front that encounters an obstacle:
  - Will travel through the open space
  - The wave front after the barrier diffracts, or bends into an area that is predicted to be a shadow by ray theory.

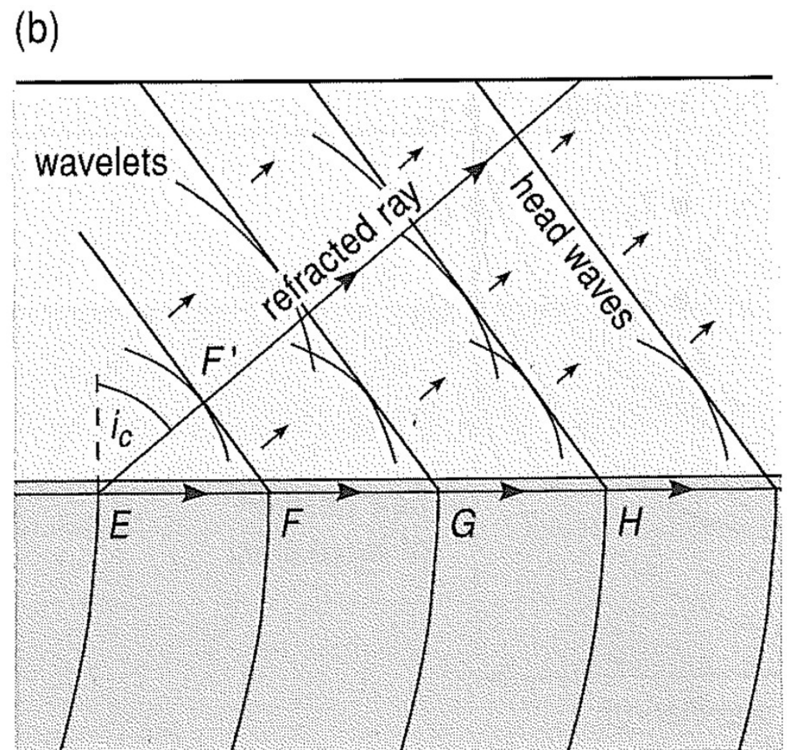
- But what about critical refraction?? *(java animation)*



Wavelets and Head Waves

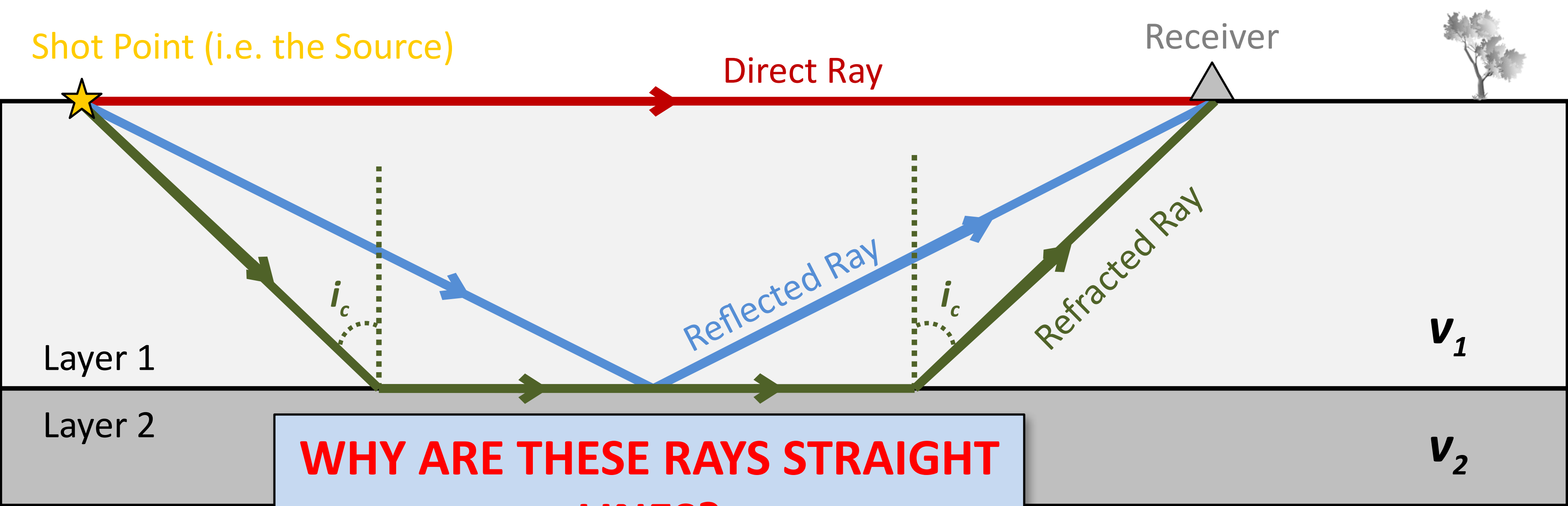
- The wave front just above the interface produces a continual stream of critically refracted rays
- The wave front just below the interface does the same
- These stream of critically refracted rays form **wavelets**
- The wavelets combine to form **head waves**
  - The head waves propagate up to the surface and can be recorded.
    - The recorded rays are called the **refracted rays**





Potential Paths in a Refraction Survey

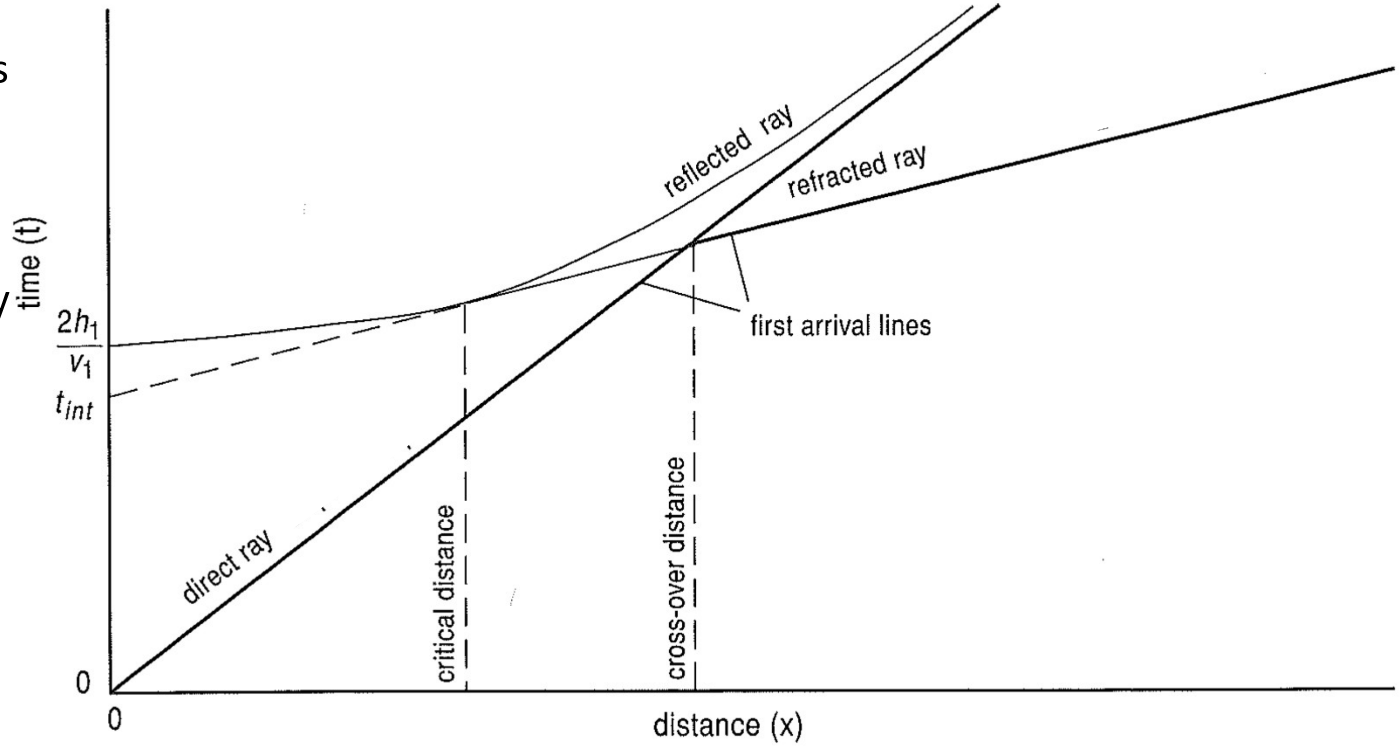
- When doing a seismic refraction survey, a recorded ray can come from three main paths
  - The direct ray
  - The reflected ray
  - The refracted ray
- Because these rays travel different distances and at different speeds, they arrive at different times
- The direct ray and the refracted ray arrive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

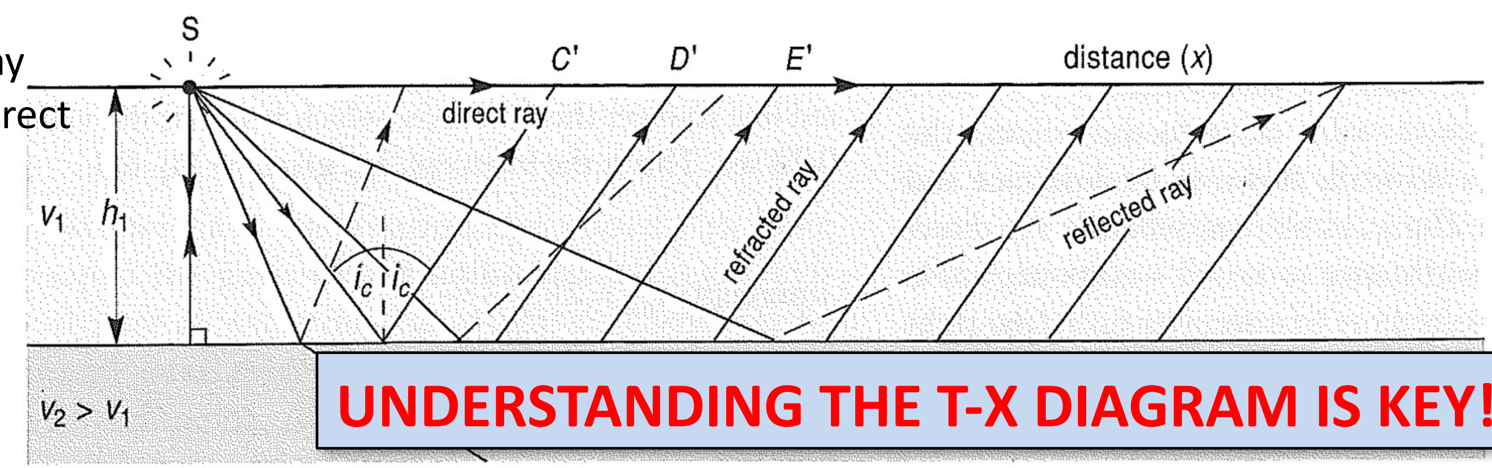


The Time-Distance (t-x) Diagram

Think about:

- What would a fast velocity look like on this plot?
- Why is direct ray a straight line?
- Why must the direct ray plot start at the origin (0,0)?
- Why is refracted ray straight line?
- Why does refracted ray not start at origin?
- Why does reflected ray start at origin?
- Why is reflected ray asymptotic with direct ray?



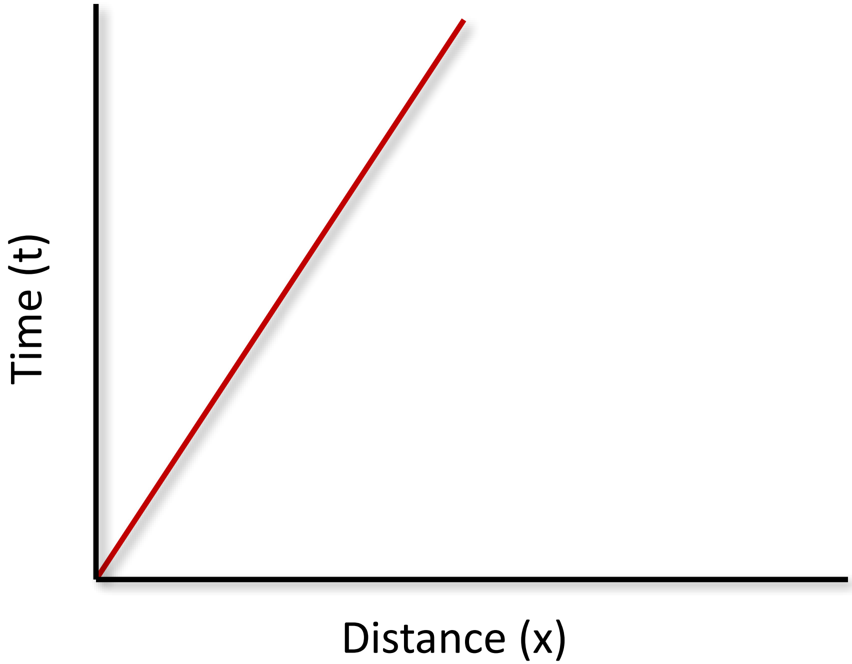


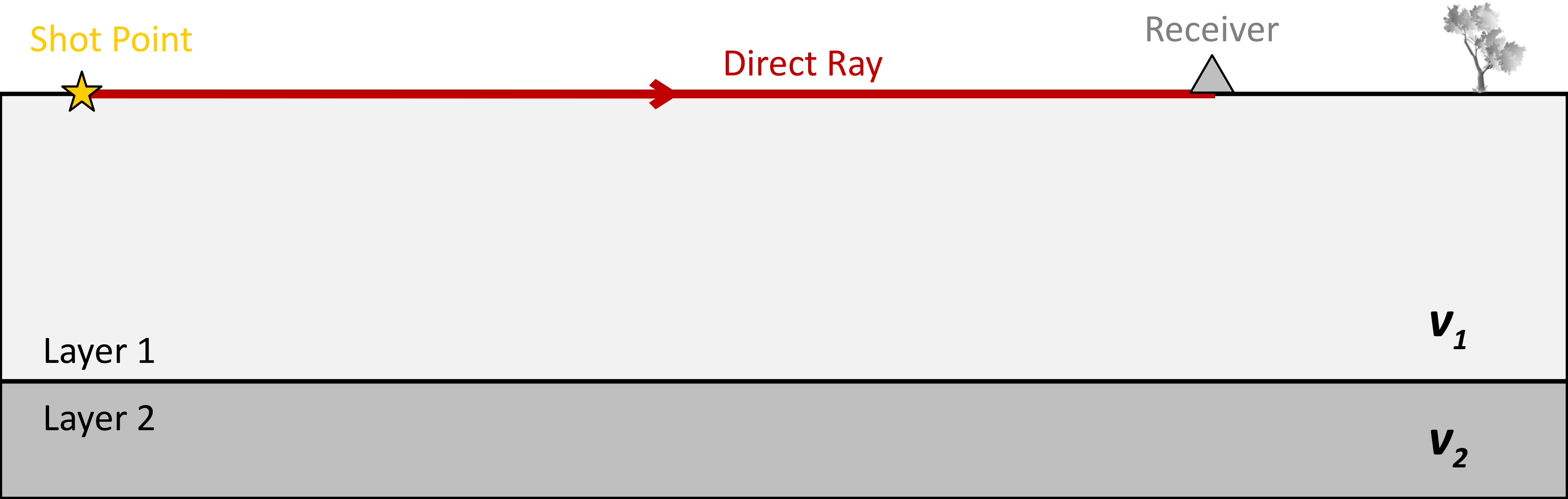
UNDERSTANDING THE T-X DIAGRAM IS KEY!

The Direct Ray

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

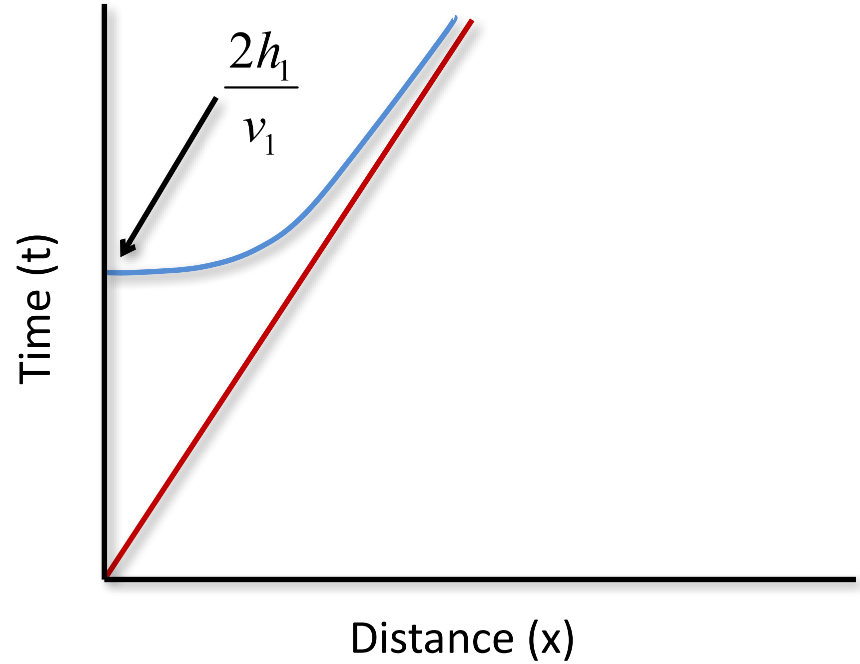
$$t_{direct} = \frac{x}{v_1}$$

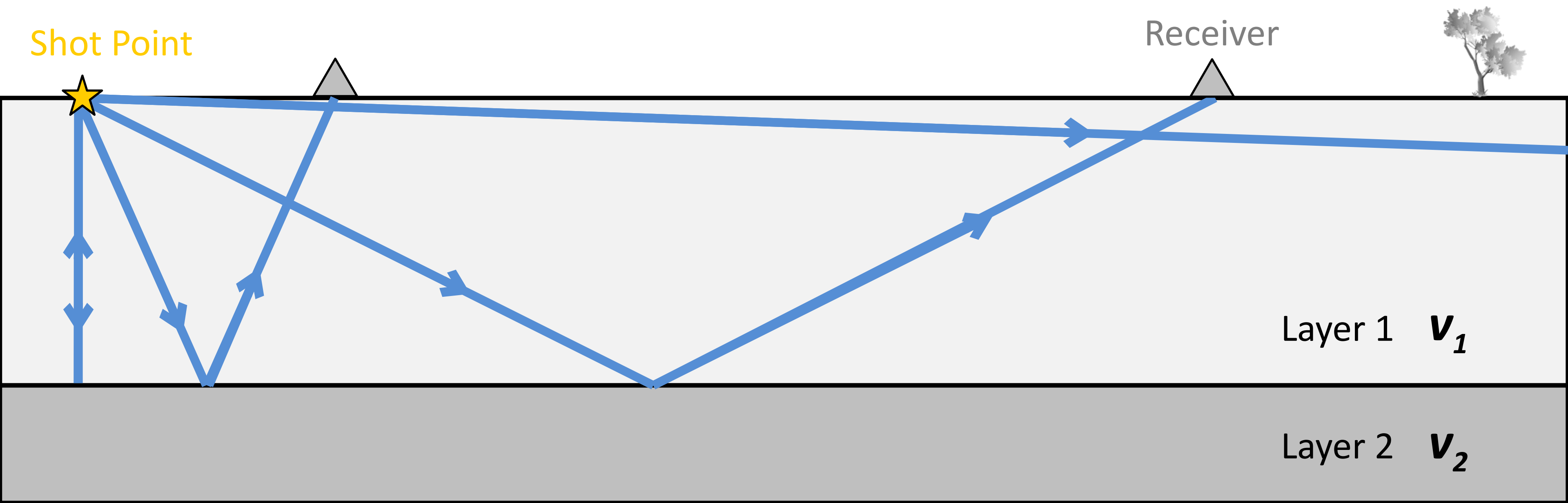




The Reflected Ray

- 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?

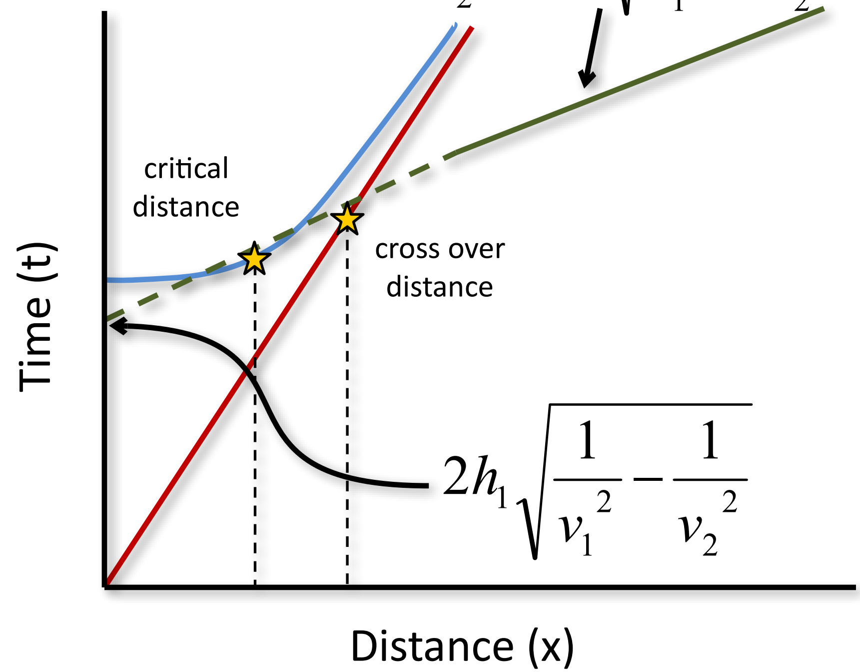


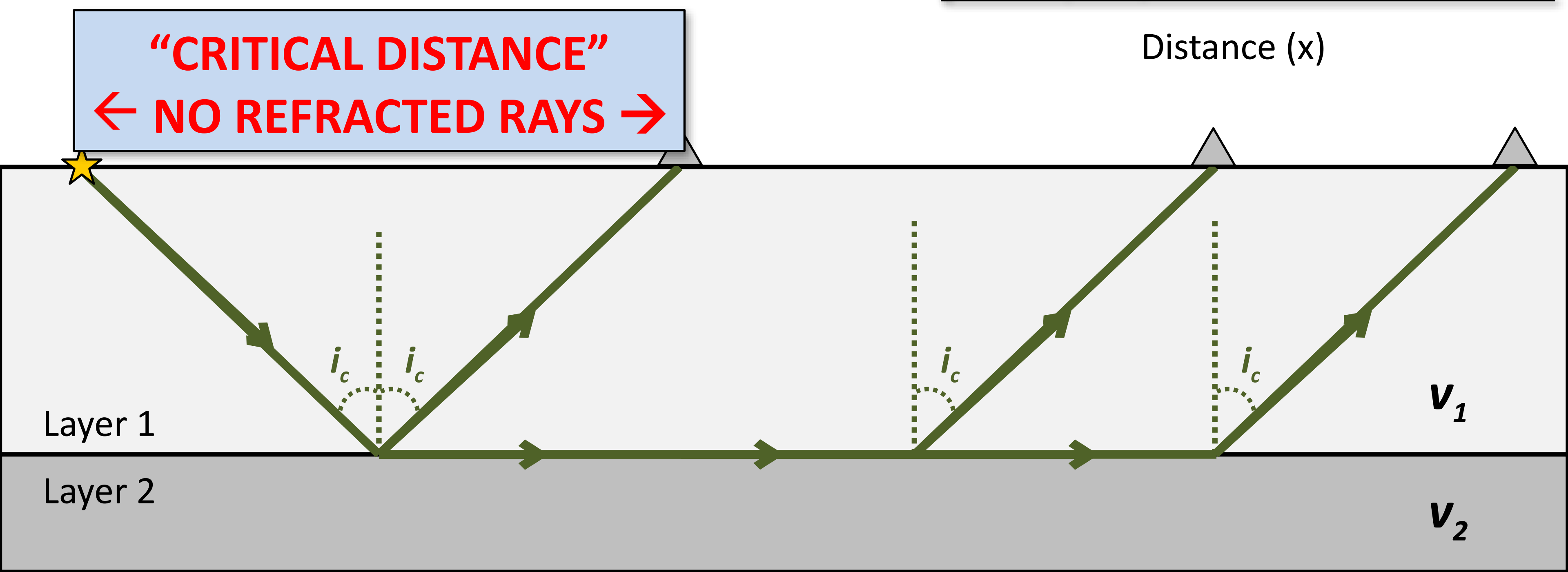


The Refracted Ray

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

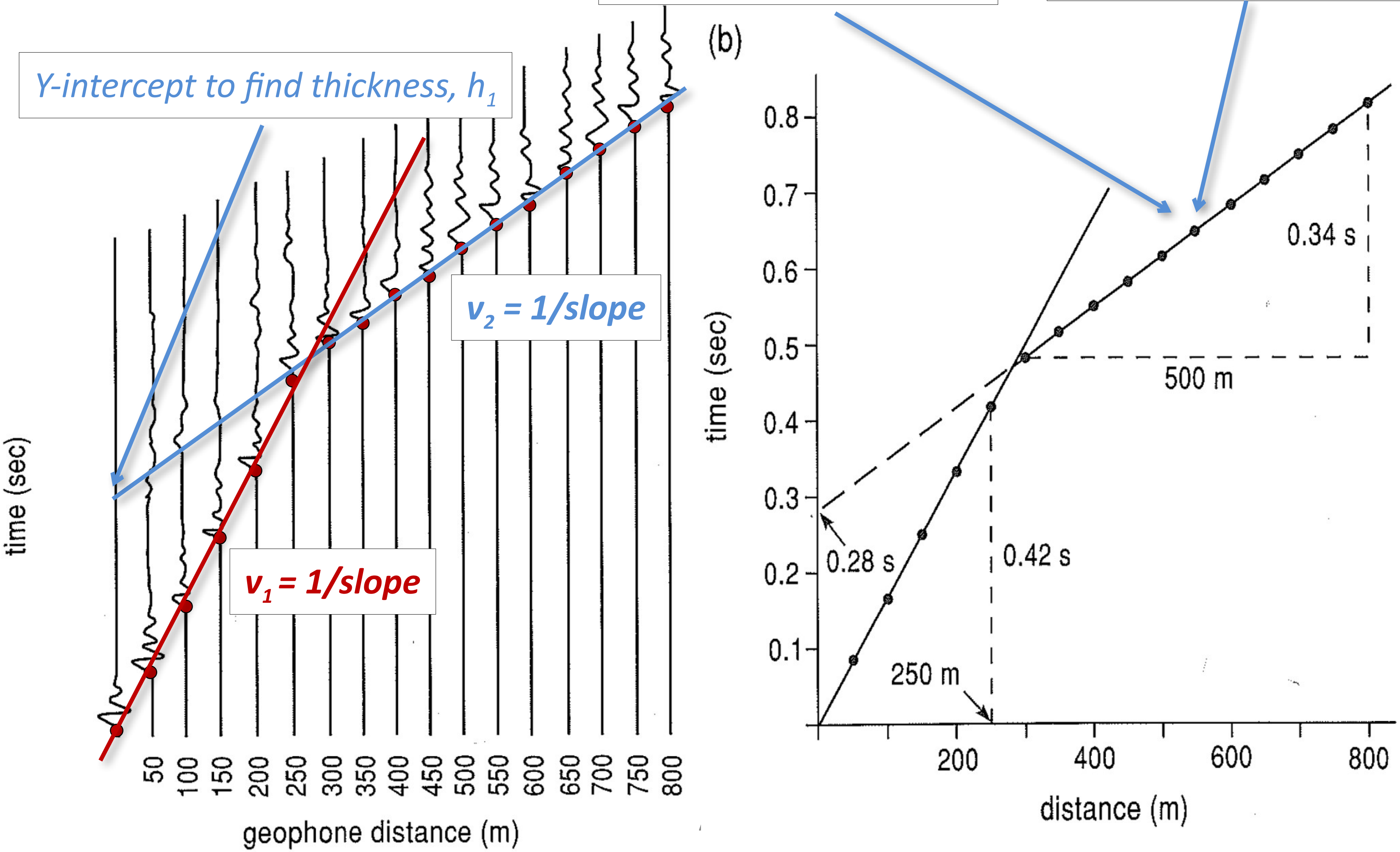
- The Refracted Ray Arrival Time:
  - Plots as a linear path on t-x diagram
    - Part travels in upper layer (constant)
    - Part travels in lower layer (function of x)
  - Only arrives after **critical distance**
  - Is first arrival only after **cross over distance**
    - Travels long enough in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

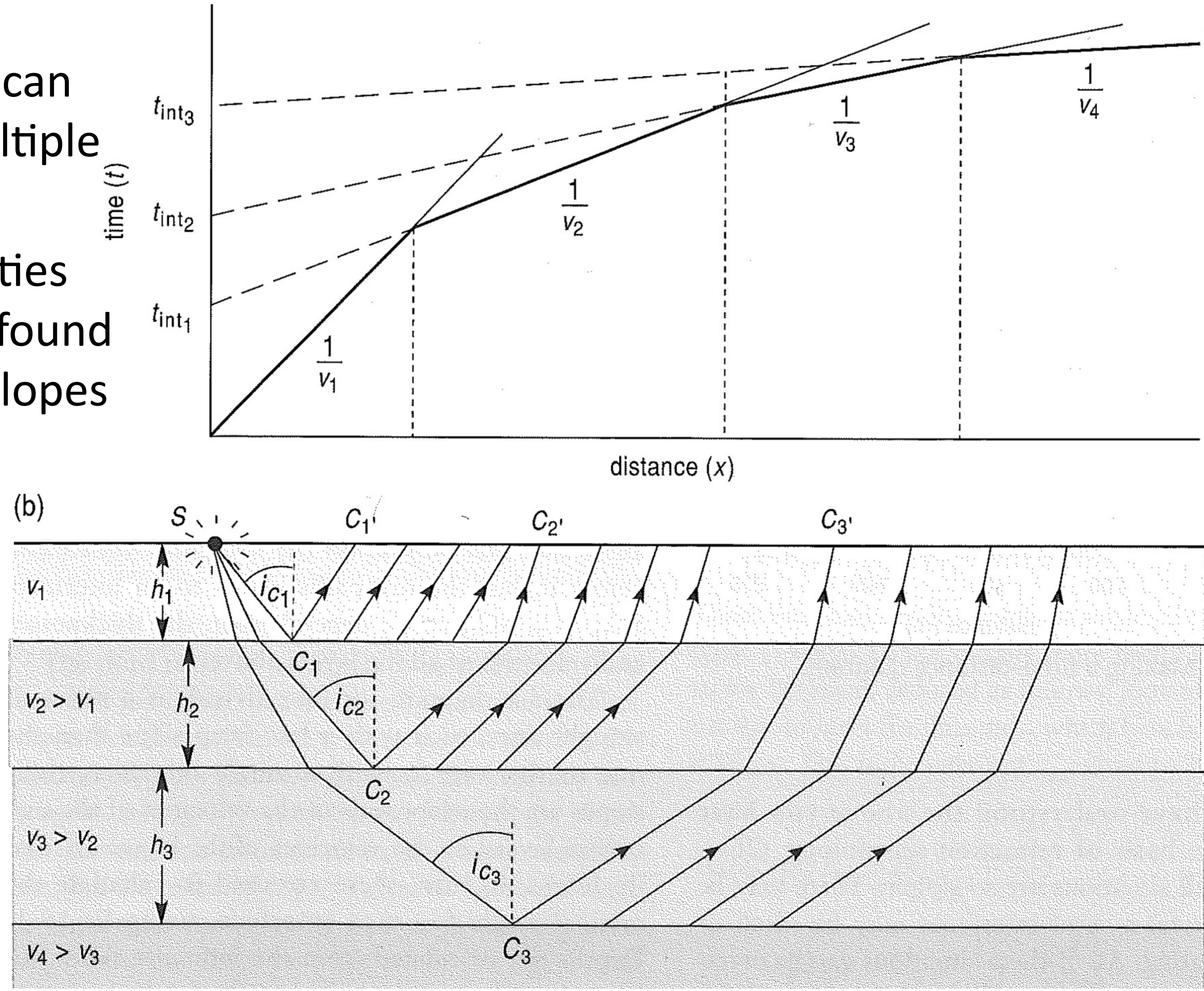
Table 6.1 Seismic velocities for rocks

Rock type	v_p (km/sec)
Unconsolidated sediments	
clay	1.0–2.5
sand, dry	0.2–1.0
sand, saturated	1.5–2.0
Sedimentary rocks	
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
Igneous and metamorphic rocks	
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
Other	
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.

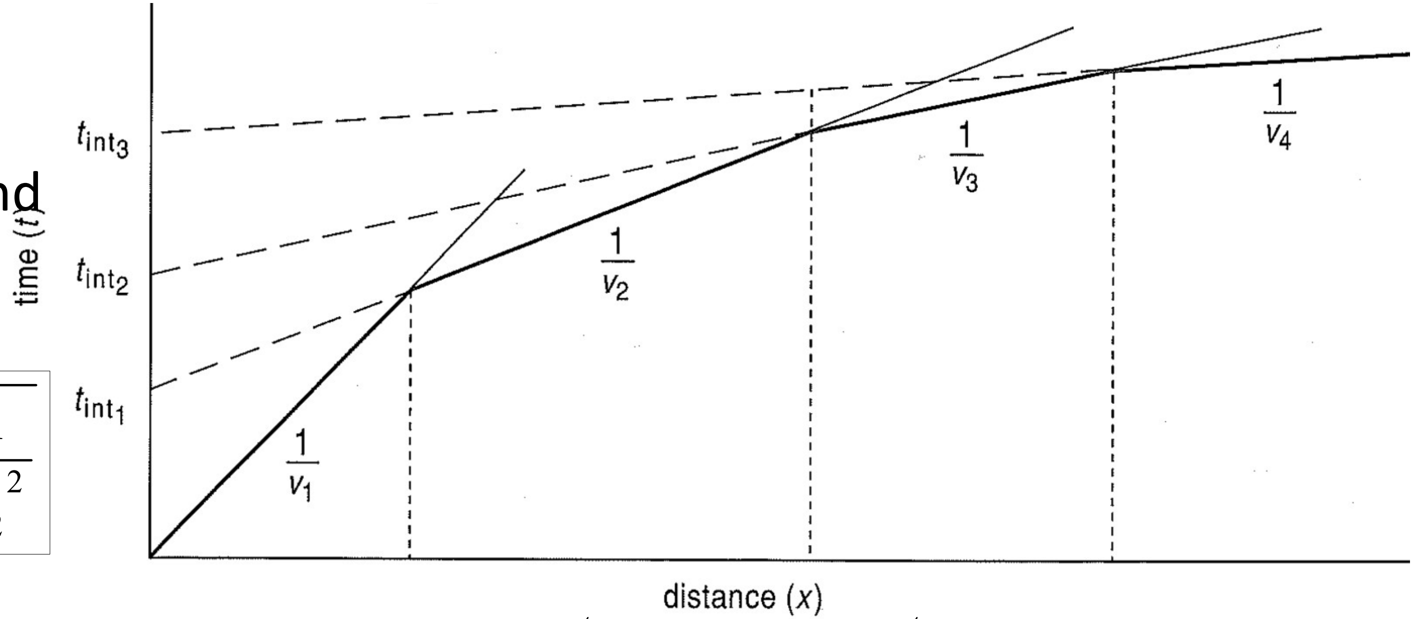
Multiple Layers

- 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…



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

$$t_{\mathrm{int}_1} = 2h_1\sqrt{\frac{1}{v_1^2} - \frac{1}{v_2^2}}$$

Solve for h_1…→ $$h_1 = \frac{t}{2\sqrt{\frac{1}{v_1^2} - \frac{1}{v_2^2}}} = \frac{t}{2\sqrt{\frac{v_2^2 - v_1^2}{v_1^2 v_2^2}}}$$

Now, plug in h1 and solve the remaining layers one at a time…

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

BEWARE!!! h_1, h_2, are layer thicknesses, not depth to interfaces.

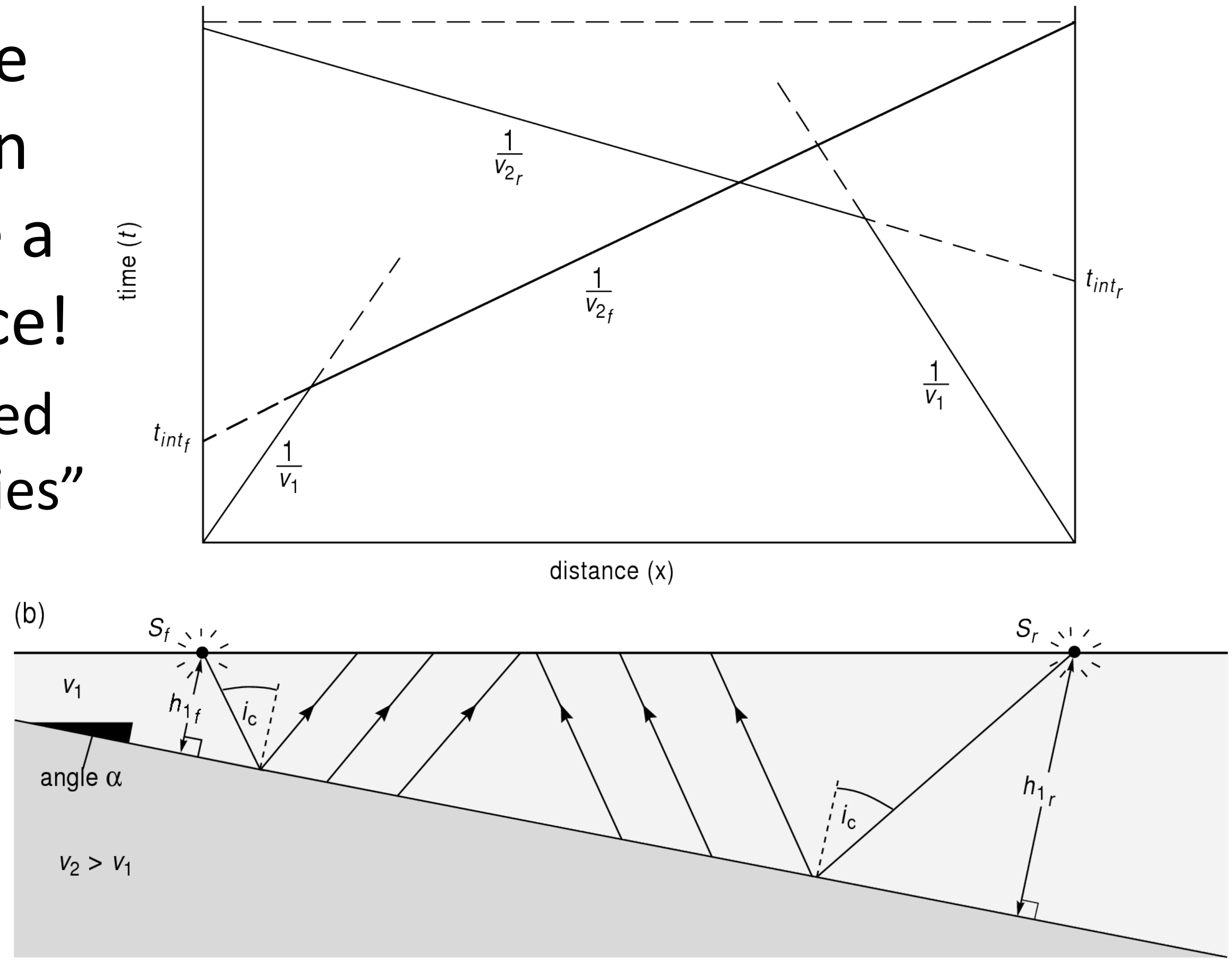
So, depth to bottom of layer 3 /top of layer 4 = $h_1 + h_2 + h_3$

Caveats of Refraction

- Only works if each successive layer has increasing velocity
  - Cannot detect a low velocity layer
- May not detect thin layers
- Requires multiple (survey) lines
  - Make certain interfaces are horizontal
  - Determine actual dip direction not just apparent dip

Dipping Interfaces

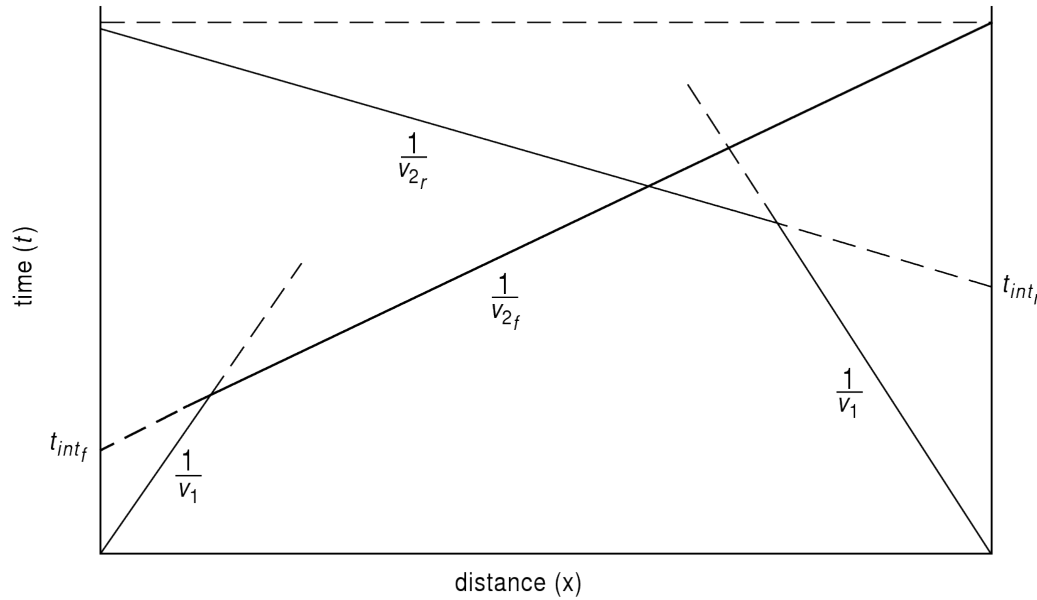
- What if the critically refracted interface is not horizontal?
- A dipping interface produces a pattern that looks just like a horizontal interface!
  - Velocities are called "apparent velocities"
- What do we do?

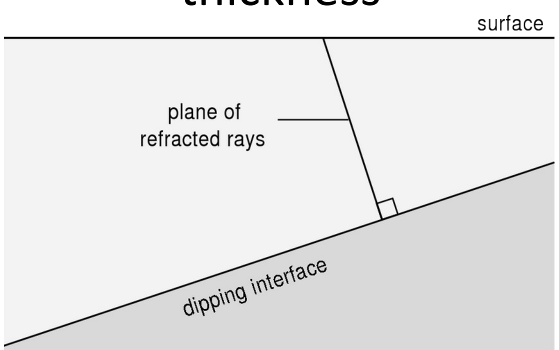


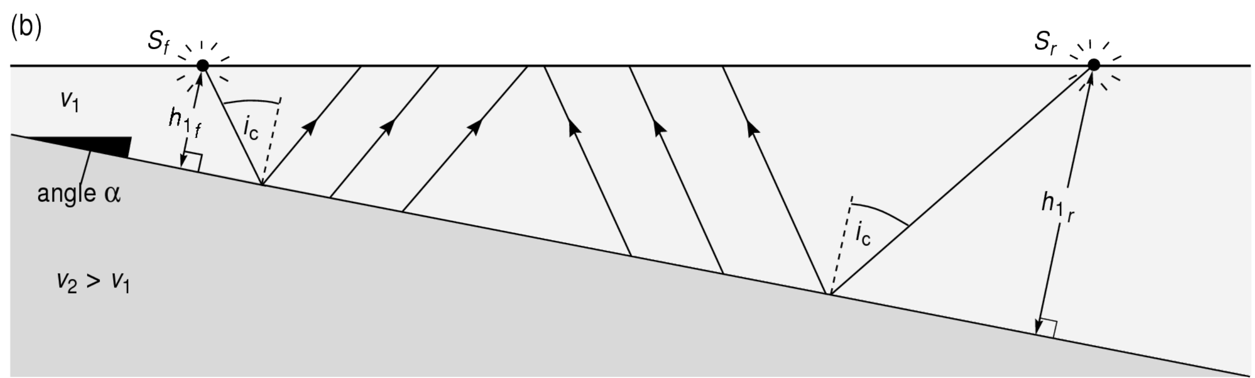
In this case, velocity of lower layer is underestimated

Dipping Interfaces

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



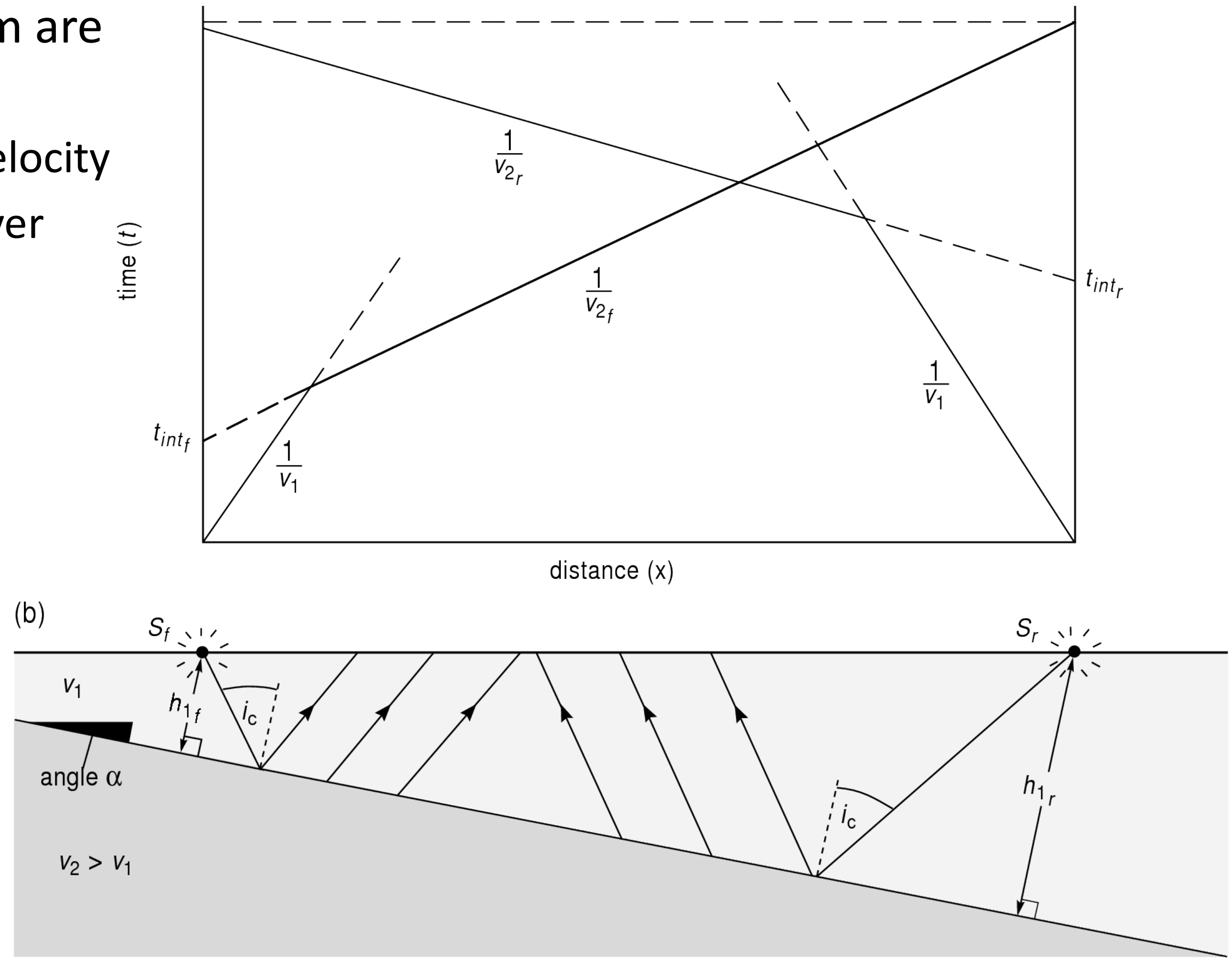




Beware: the calculated thicknesses will be perpendicular to the interface, not vertical

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



The Hidden Layer

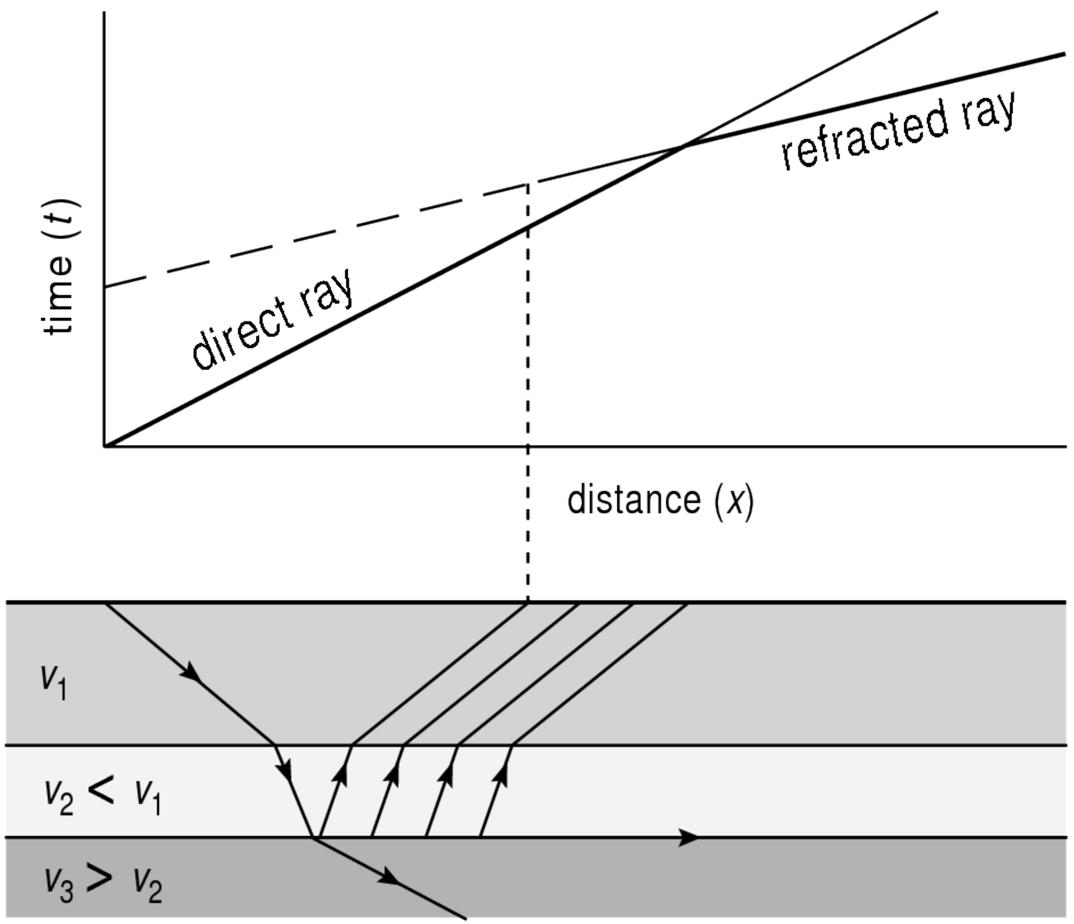
- There are two cases where a seismic interface will not be revealed by a refraction survey.

  - The Hidden Layer (book calls it “Hidden Layer Proper”)
  - The Low Velocity Layer

This one is straightforward, so we will look at it first.

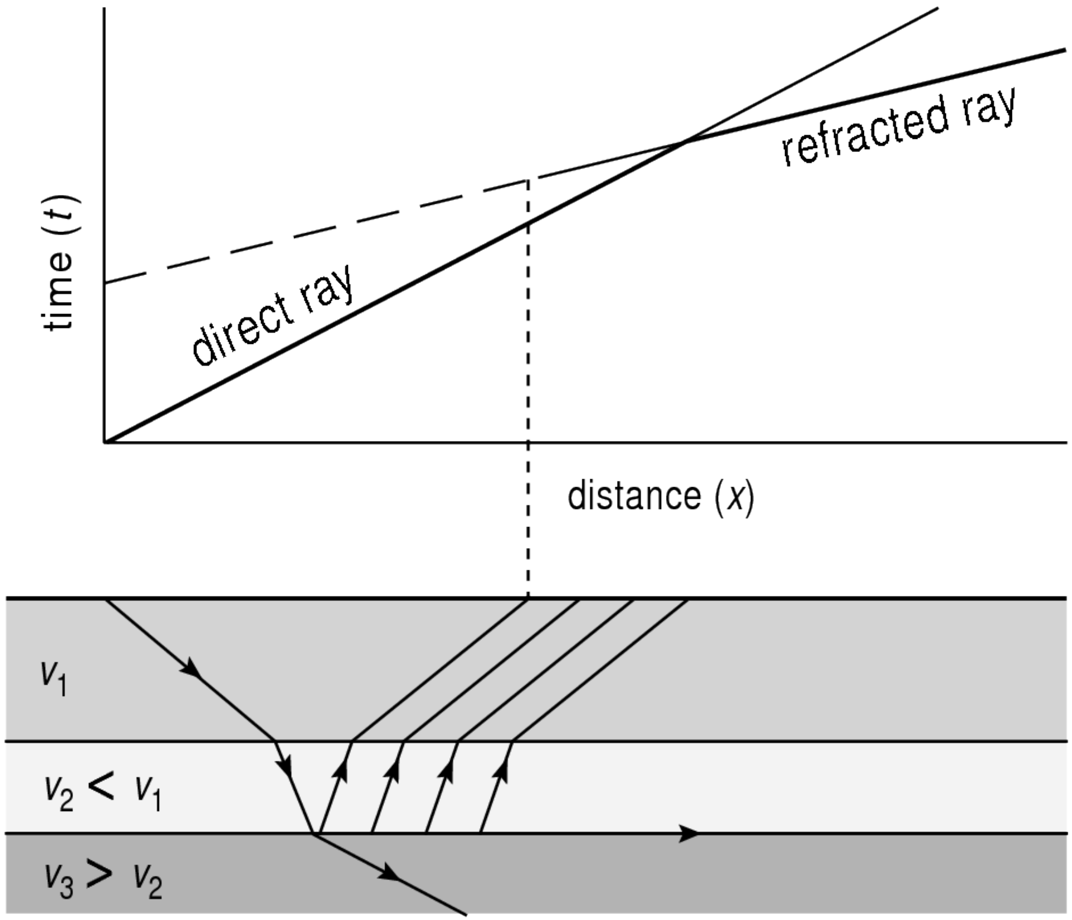
The Low Velocity Layer

- If a layer has a lower velocity than the one above…
  - There can be no critical refraction
    - The refracted rays are bent towards the normal
  - There will be no refracted segment on the t-x diagram
  - The t-x diagram to the right will be interpreted as
    - Two layers
    - Depth to layer 3 and Thickness of layer1 will be exaggerated



The Low Velocity Layer

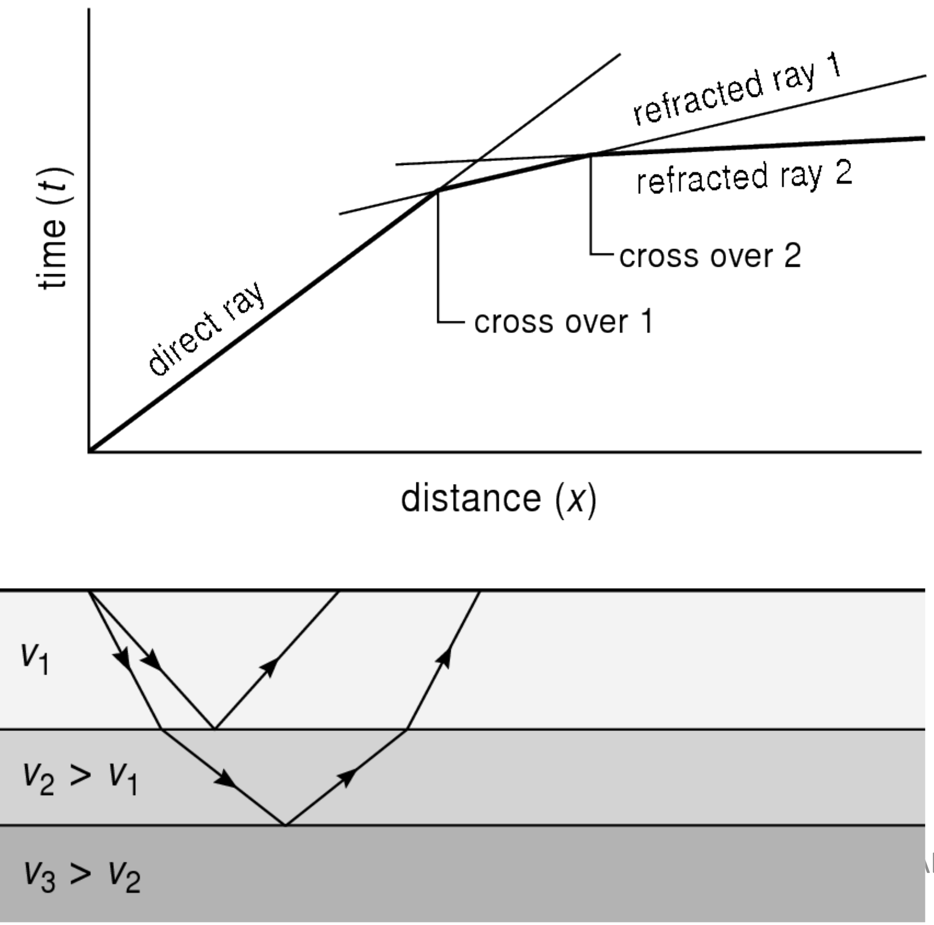
- Causes:
  - Sand below clay
  - Sedimentary rock below igneous rock
  - (sometimes) sandstone below limestone

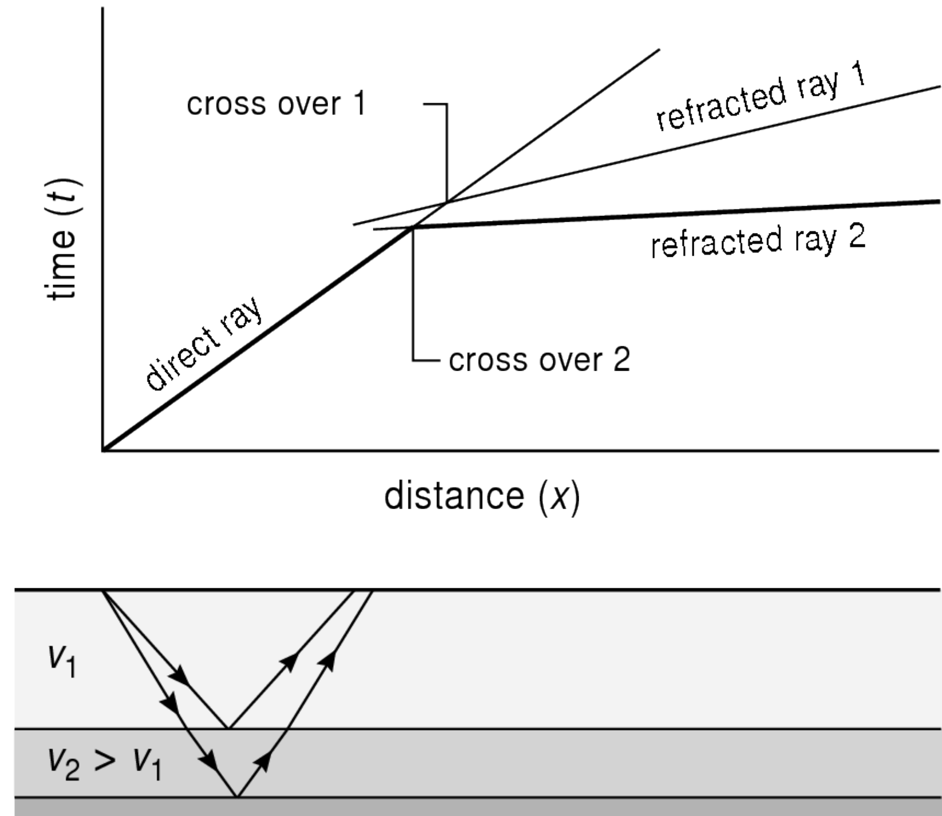


- How Can you Know?
  - Consult geologic data!
    - Boreholes / Logs
    - Geologic sections
    - Geologic maps

The Hidden Layer

- Recall that the refracted ray eventually overtakes the direct ray (cross over distance).
- The second refracted ray may overtake the direct ray first if:
  - The second layer is thin
  - The third layer has a much faster velocity



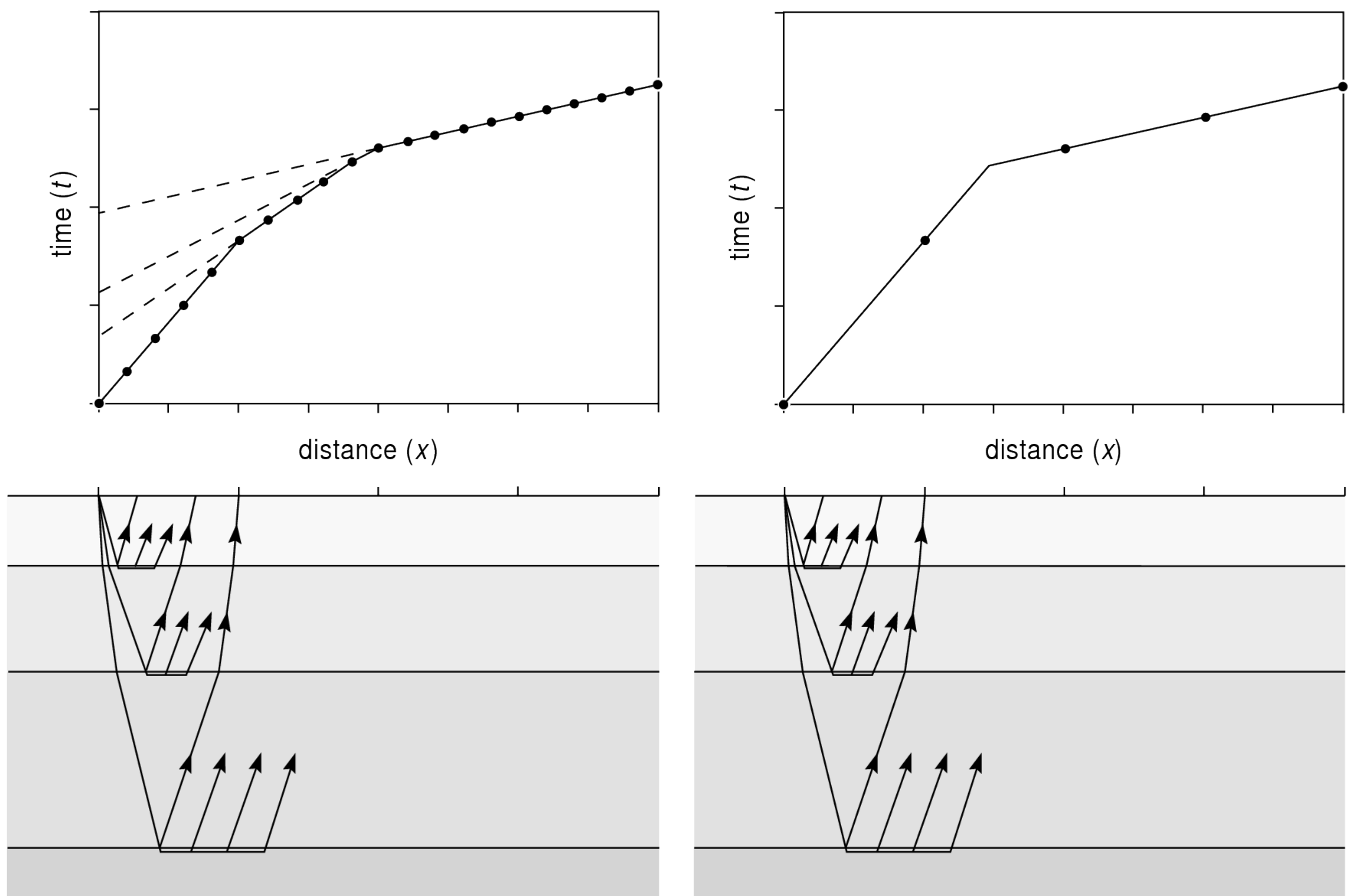


Show Maple Animations

Geophone Spacing / Resolution

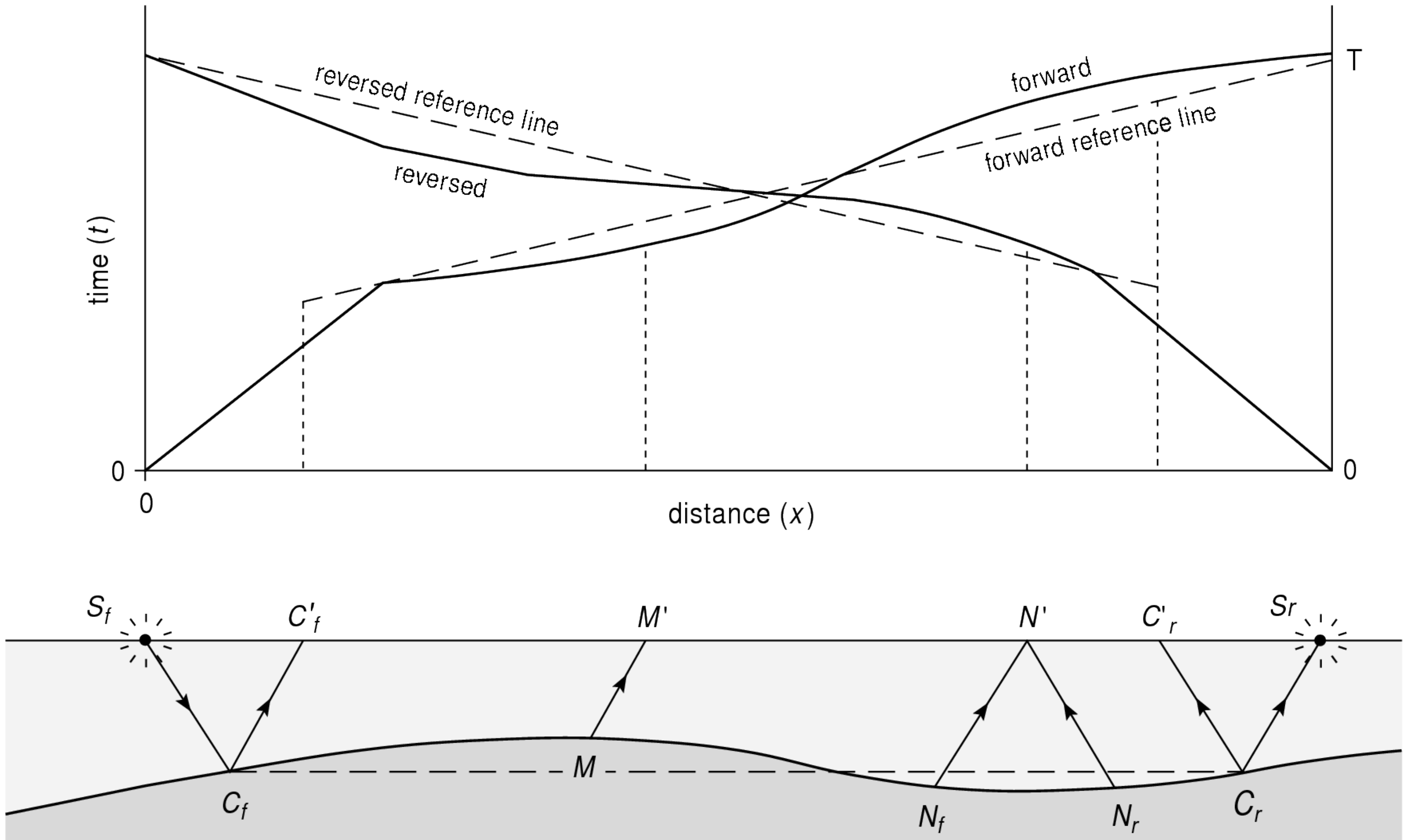
- Often near surface layers have very low velocities
  - E.g. soil, subsoil, weathered top layers of rock
  - These layers are likely of little interest
  - But due to low velocities, time spent in them may be significant

- To correctly interpret data these layers must be detected
- Decrease geophone spacing near source
- This problem is an example of…?



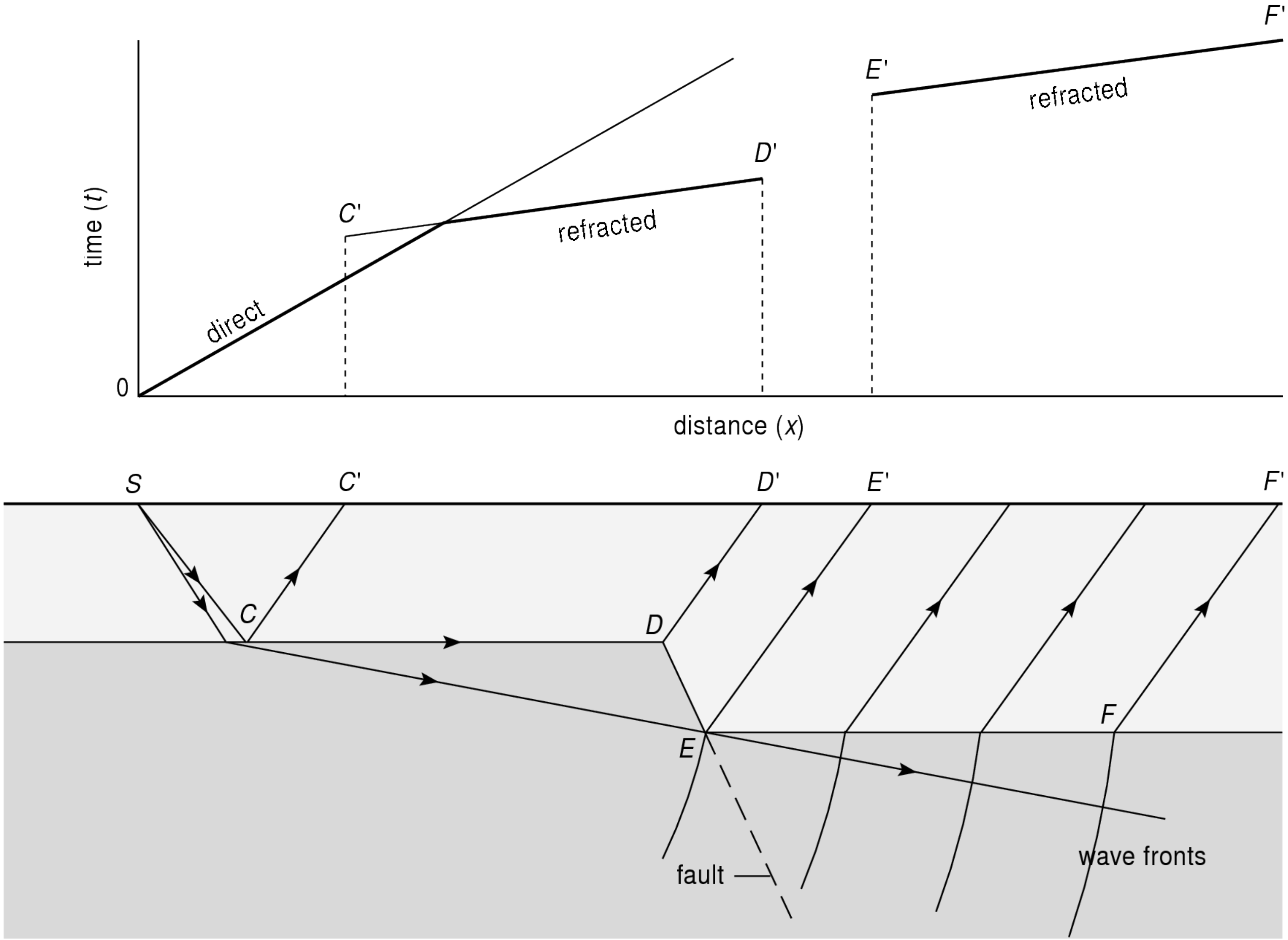
Undulating Interfaces

- Undulating interfaces produce non-linear t-x diagrams
- There are techniques that can deal with this
  - delay times & plus minus method
  - We won't cover these techniques…



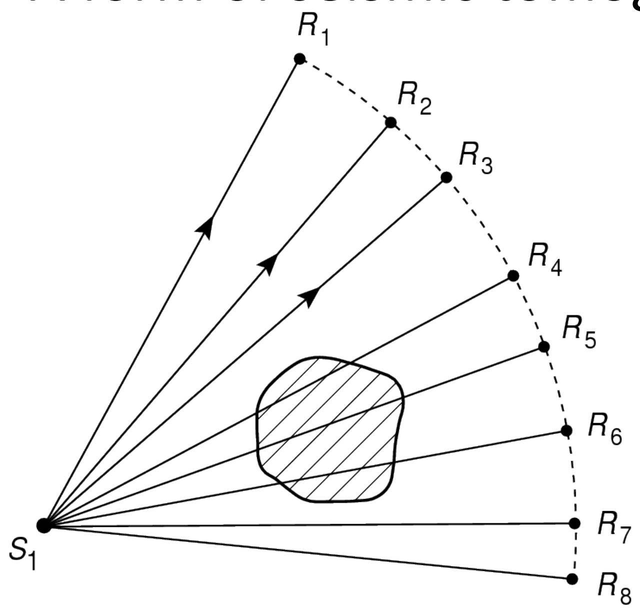
Detecting Offsets

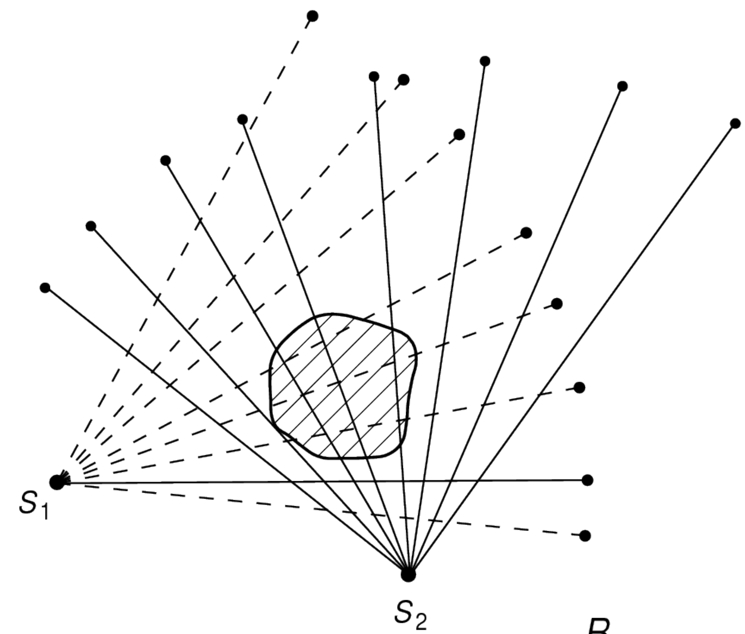
- Offsets are detected as discontinuities in the t-x diagram
  - Offset because the interface is deeper and D’E’ receives no refracted rays.

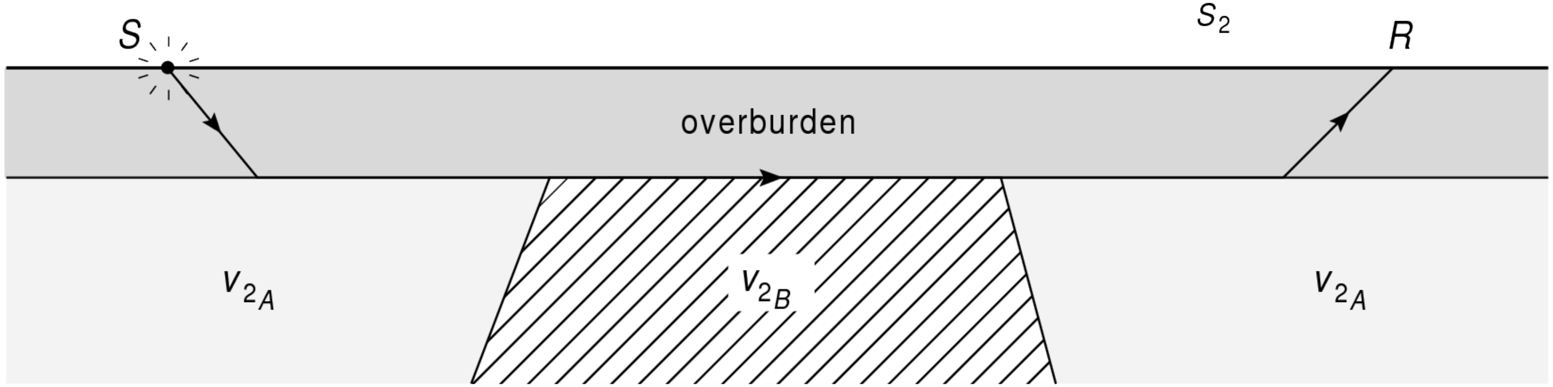


Fan Shooting

- Discontinuous targets can be mapped using radial transects: called “Fan Shooting”
  - A form of seismic tomography

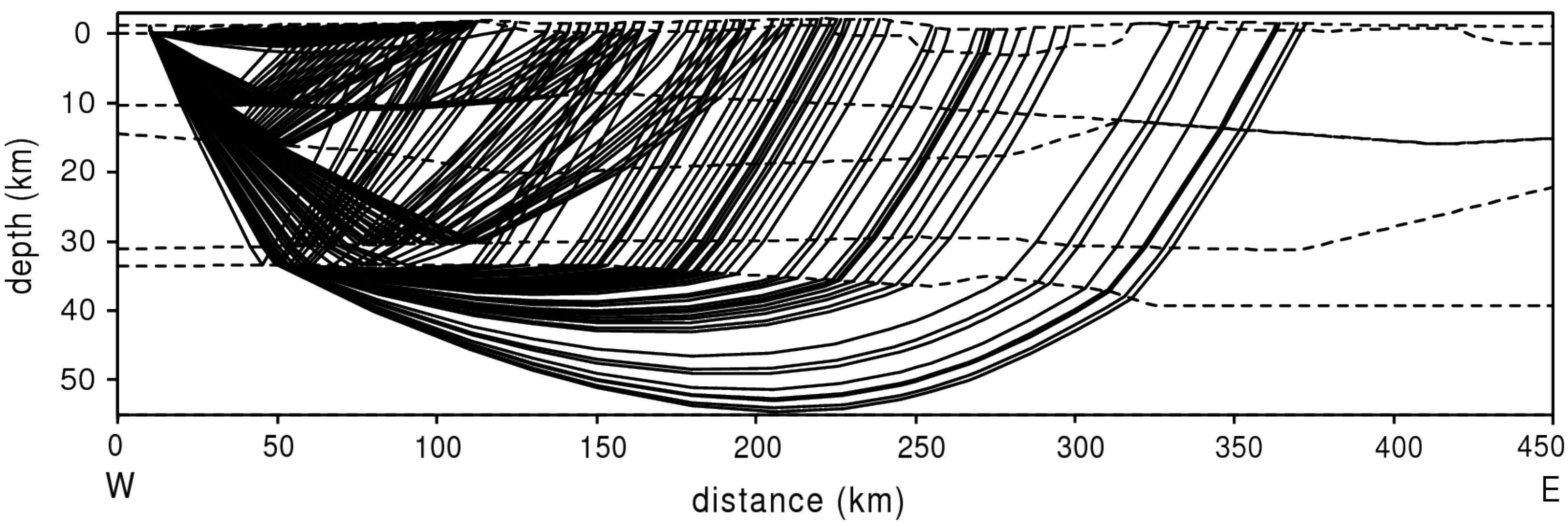






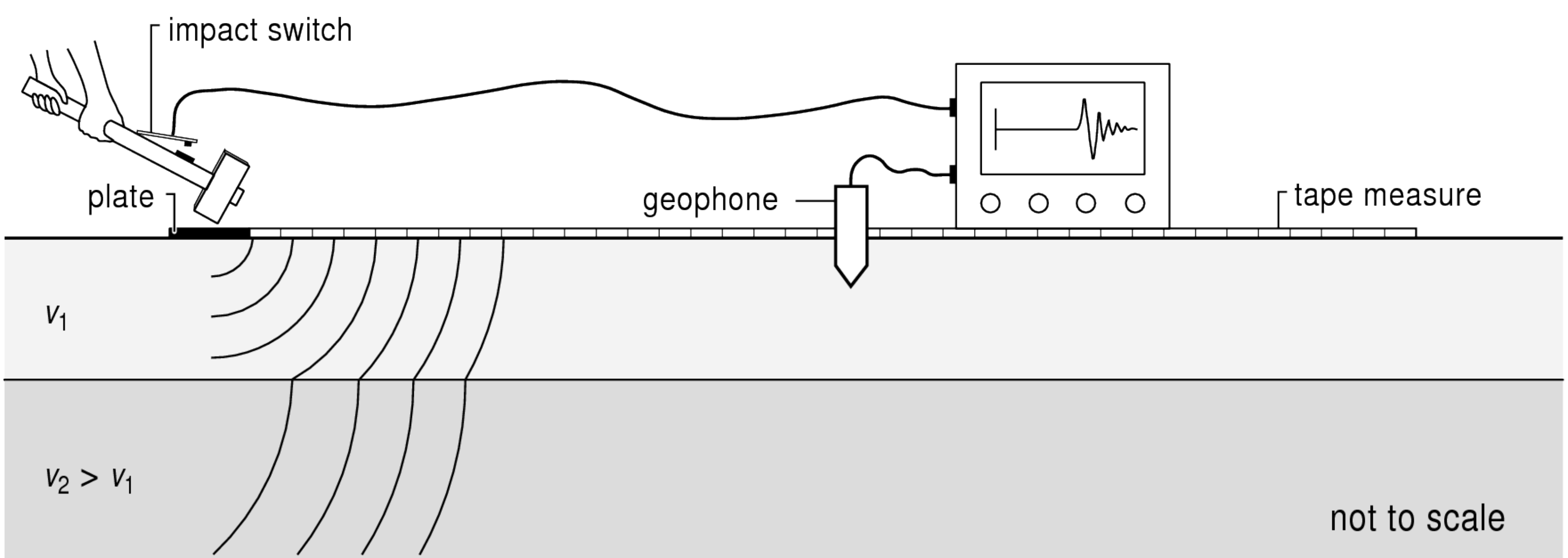
Ray Tracing

- All seismic refraction techniques discussed thus far are inverse methods
- One can also fit seismic data to forward models using Snell's law, geometry, and a computer
  - Initial structure is "guessed" and then the computer uses statistical versions of "guess and check" to fit the data.
  - Model generates synthetic seismograms, which are compared to the real seismograms



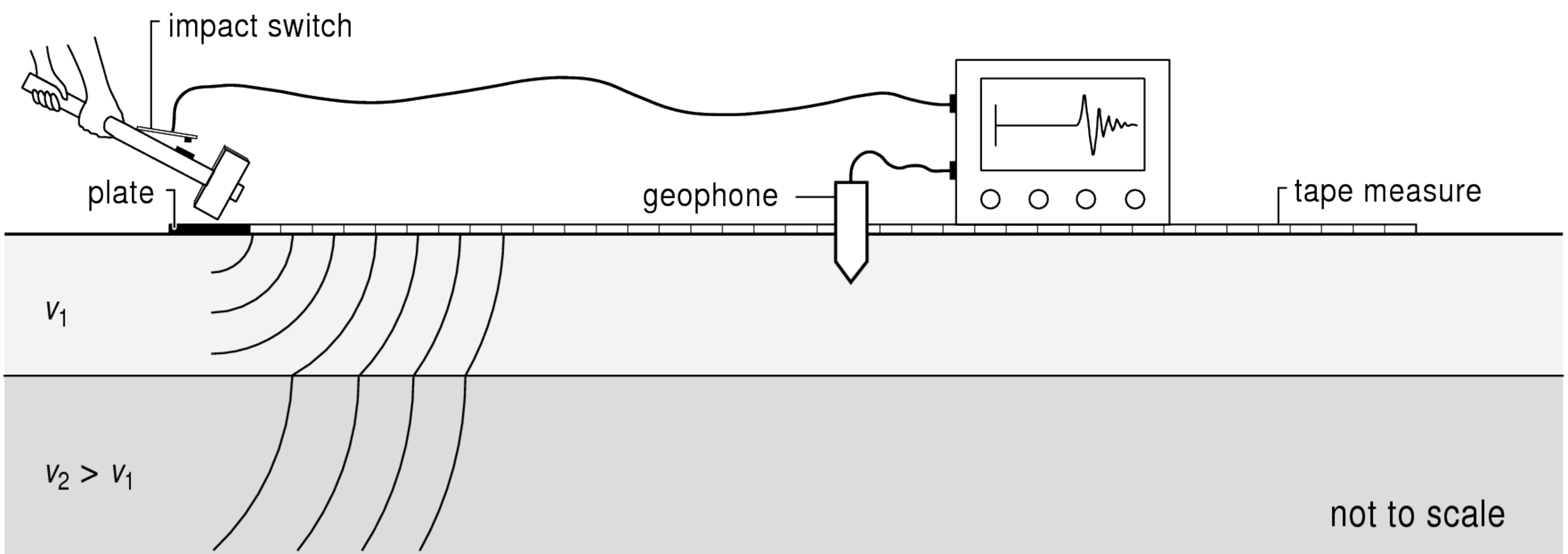
Survey Types

- 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



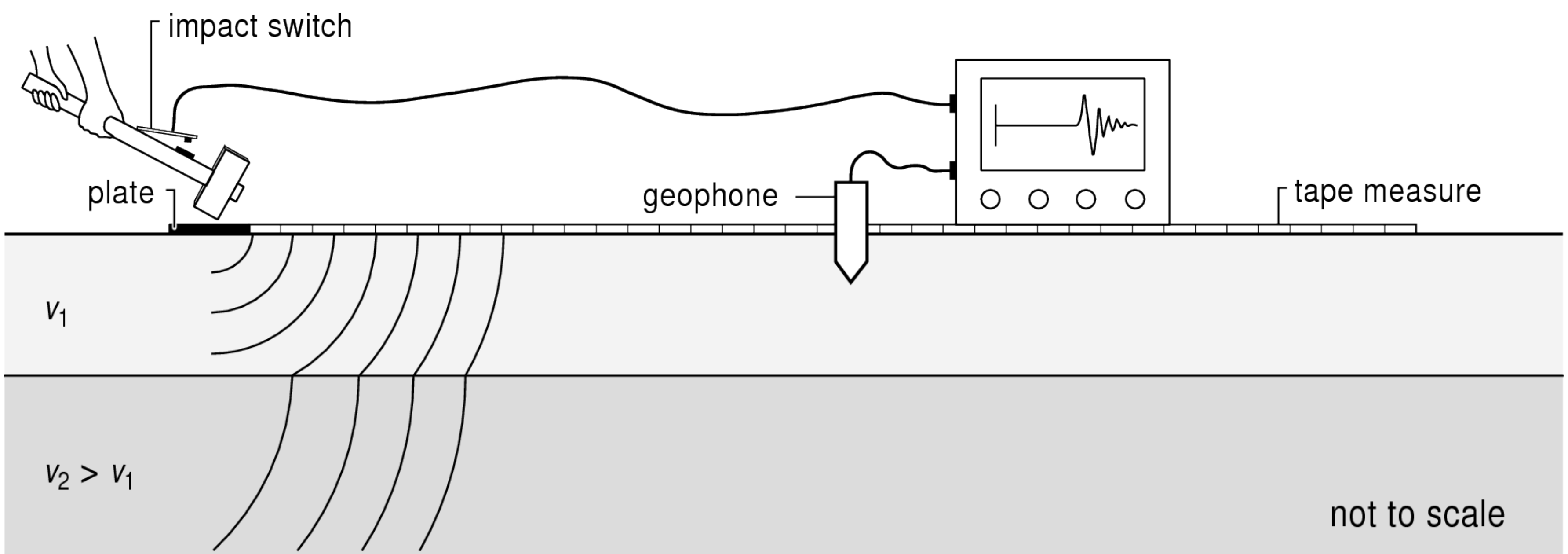
Survey Types

- 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