Last Time: ***Seismic Reflection Travel-Time***

l

- ***Dipping Layer Problem:***

  → Using Δt^2 on x^2–t^2 plot: $\alpha = -\sin^{-1} \dfrac{V_1^2 \Delta t^2}{8 h_1 x}$ (works for 1-layer!)

  → Using T_{DMO} approximation on a T_{NMO} vs x plot:

  $$\alpha = \sin^{-1}\left(-\frac{V_{RMS}^n T_{DMO}}{2x} \right)$$ (works for n-layers!)

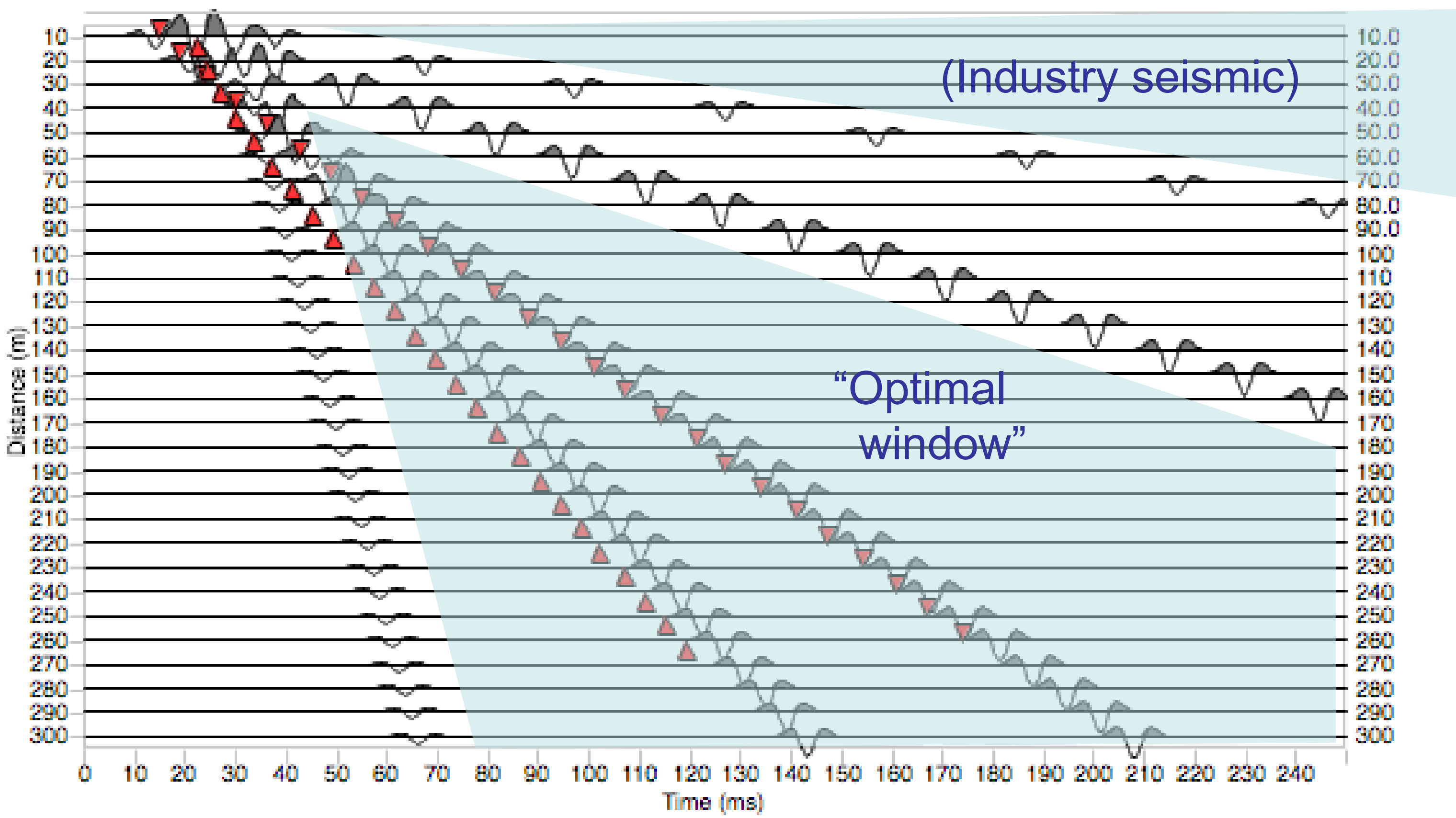
- ***Diffractions***: For a truncated layer boundary, travel-time of the diffraction has different moveout than reflection energy

  $$t = \frac{\sqrt{x_s^2 + h_1^2} + \sqrt{x_g^2 + h_1^2}}{V_1}$$

  → After migration, diffraction will remain as a "***smile***"(and in seismic section, shows up as a "***frown***")

Practicalities: Approximations valid for *small offsets only*; reflections visible in ***optimal window***, watch ***multiples***!

Optimal window: distances beyond interference from low-V waves, but also beyond direct & refracted wave interference to observe confidently

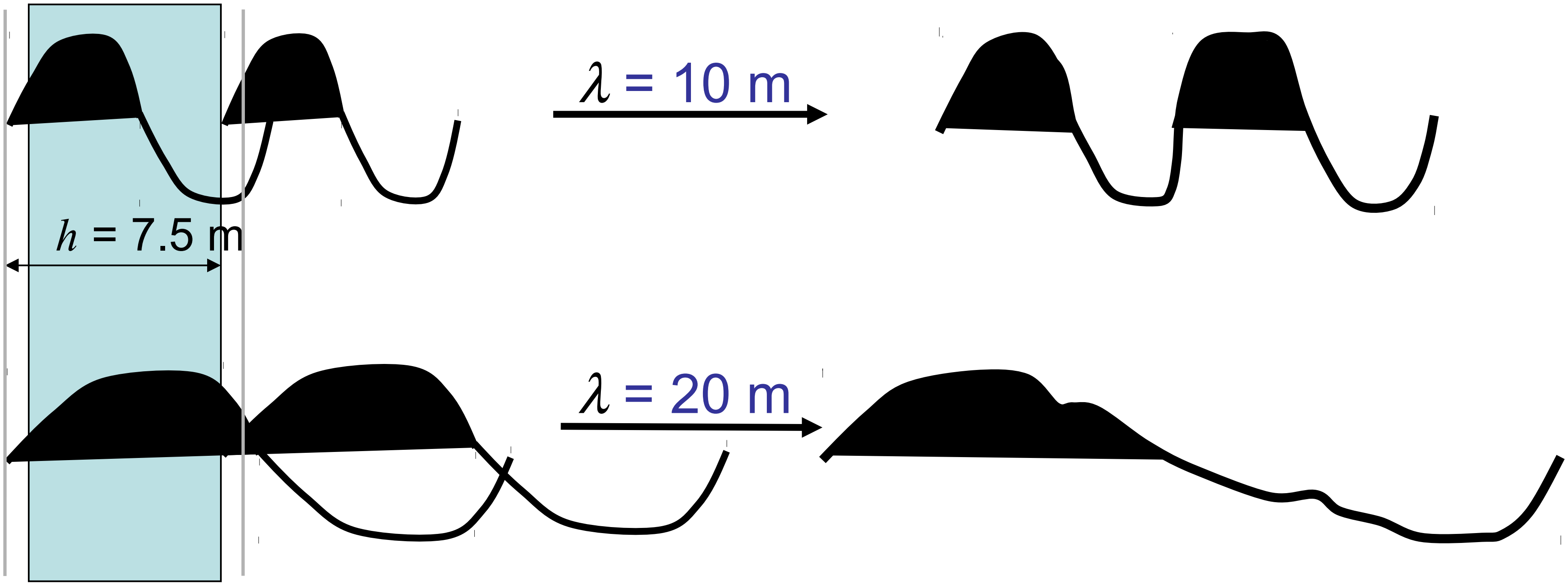


Model traces for direct, air, ground roll, first refracted, 2 reflected waves

More practical considerations:
(Burger §4.5-4.6)

- Emphasize high frequencies to better differentiate from low-f arrivals (e.g., surface waves) & improve ***resolution***

Vertical resolution: Recall $V = f\lambda$ (high frequency = short wavelength)

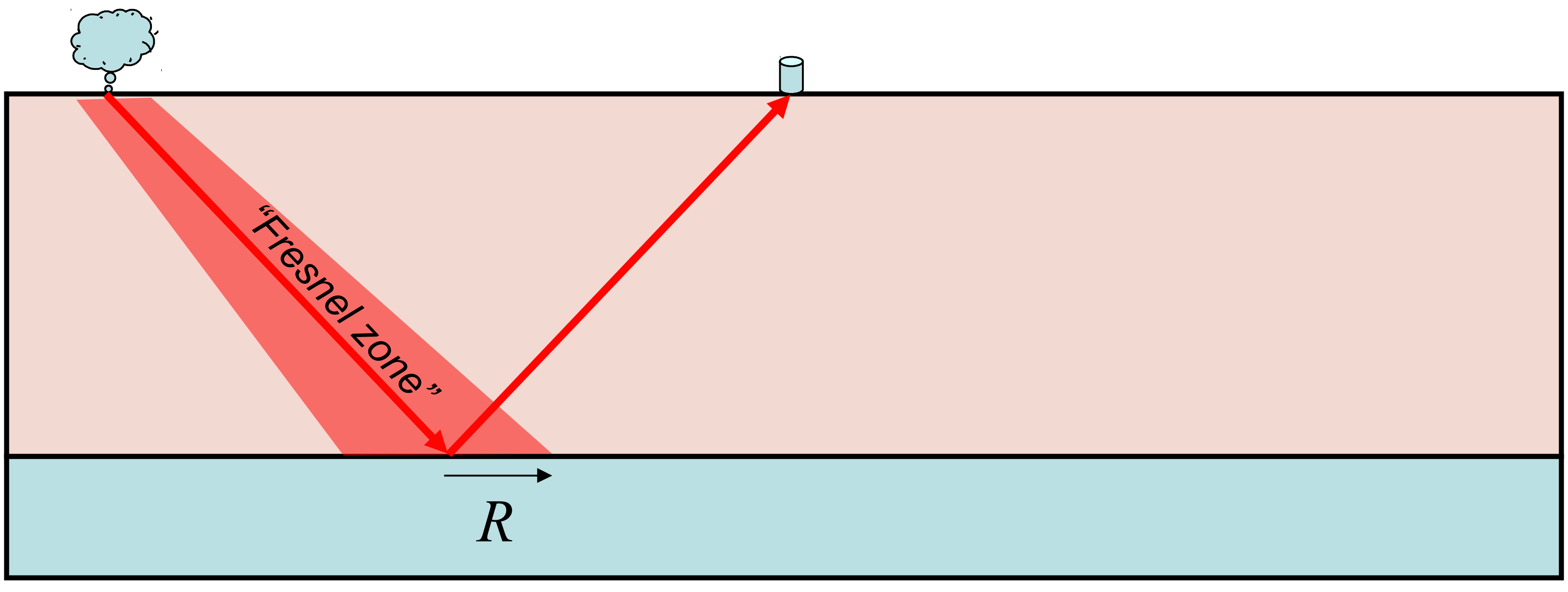


Theoretical limit of resolution for a thin bed is $h = \lambda/4$ (& in the practical limit, h will have to be $> \lambda/2$)

Frequency also determines ***horizontal resolution***:
The first ***Fresnel zone*** (approximate area of the reflector responsible for a signal) has radius

$$R = \frac{V}{2}\sqrt{\frac{t_0}{f}} = \sqrt{\frac{\lambda h}{2}}$$

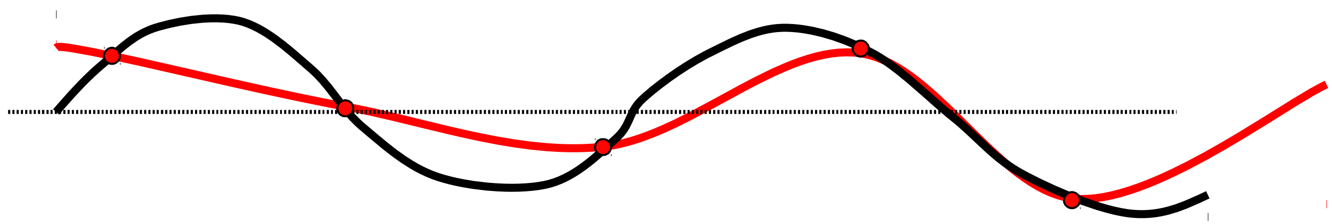
If $h_{min} = \lambda/2$, then $R_{min} = \lambda/2$!



For V = 1500 m/s, f = 150 Hz, h = 20 m ⇒ R = 10 m

To emphasize high frequencies we use:

- Geophones with high natural frequency ~ 100 Hz
- Filters to remove low-frequency arrivals
- High-rate sampling to avoid ***aliasing***



2000 Hz ⇒ 2000 samples per second

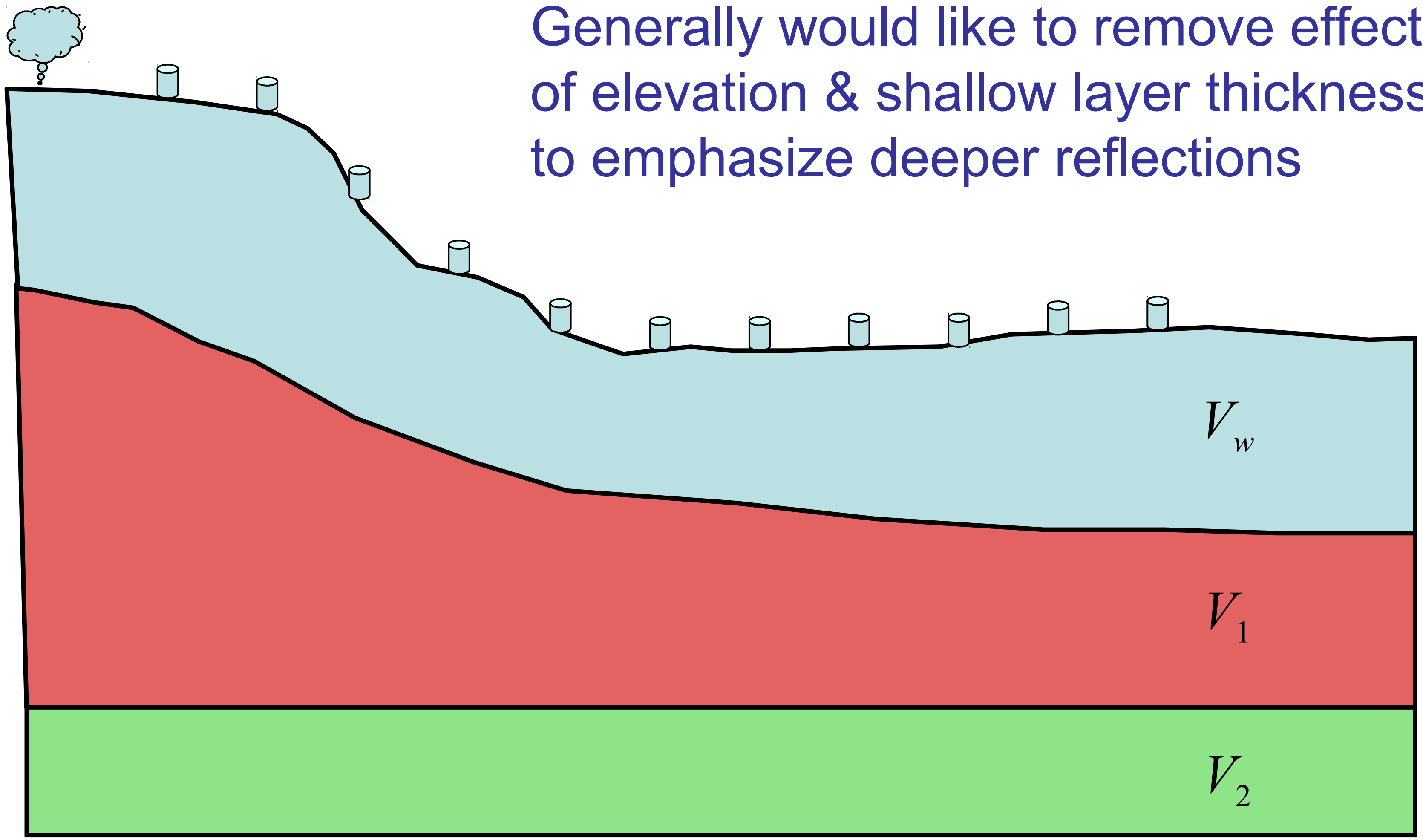
- High frequency source (e.g., dynamite, vibraseis)

To image with high resolution, must also avoid ***spatial aliasing*** (i.e., geophone sampling must be relatively close!)

Reflection Seismic Data Processing:

Step I: **Static Correction** for elevation, variable weathering &/or water table:

Generally would like to remove effects of elevation & shallow layer thickness to emphasize deeper reflections

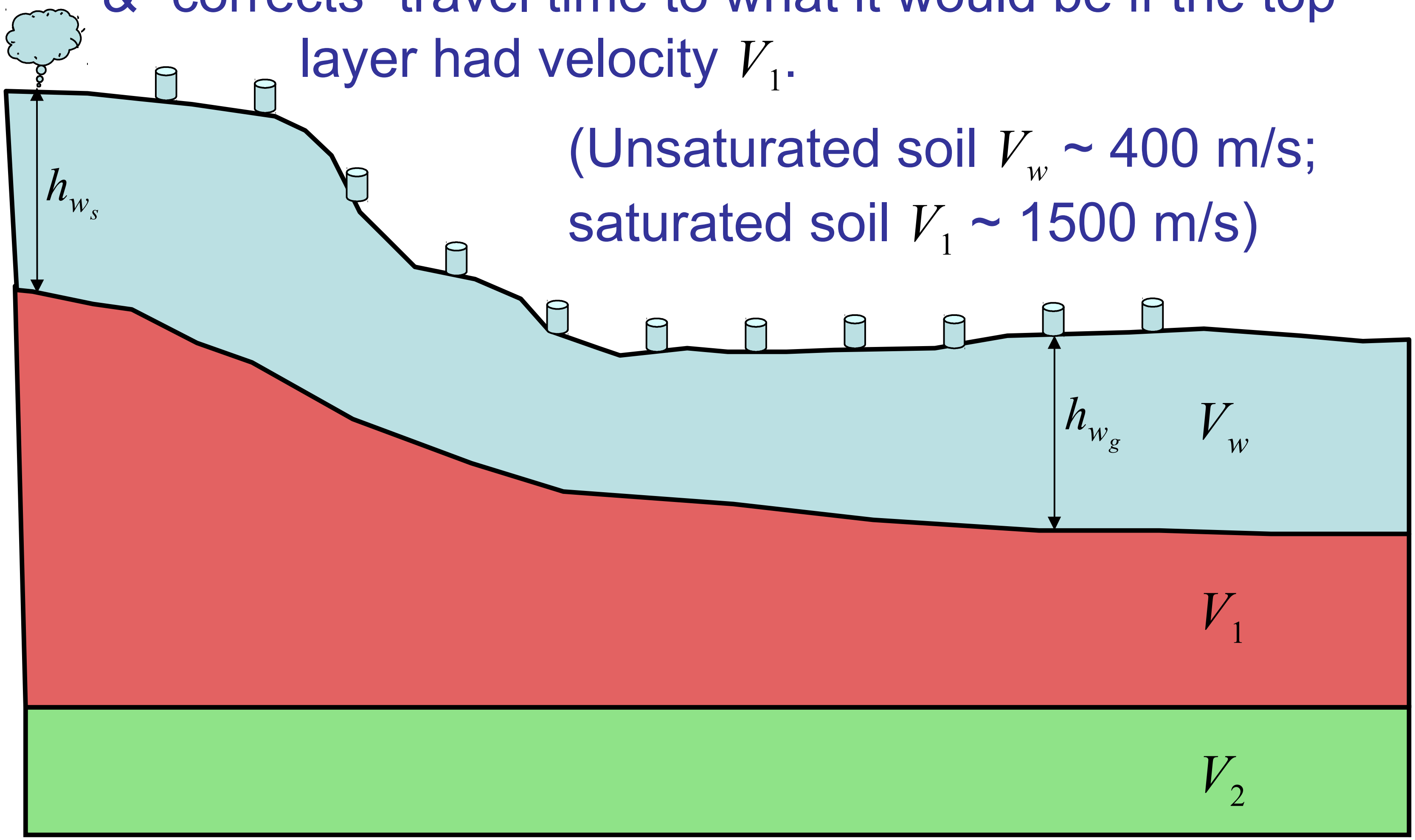


First subtract a correction for low-velocity layer thickness:

$$t_{corr} = t_{obs} - \frac{h_{w_s} + h_{w_g}}{V_w} + \frac{h_{w_s} + h_{w_g}}{V_1}$$

Assumes vertical rays, known thickness (***from refraction!***) & “corrects” travel time to what it would be if the top layer had velocity V_1.

(Unsaturated soil V_w ~ 400 m/s; saturated soil V_1 ~ 1500 m/s)

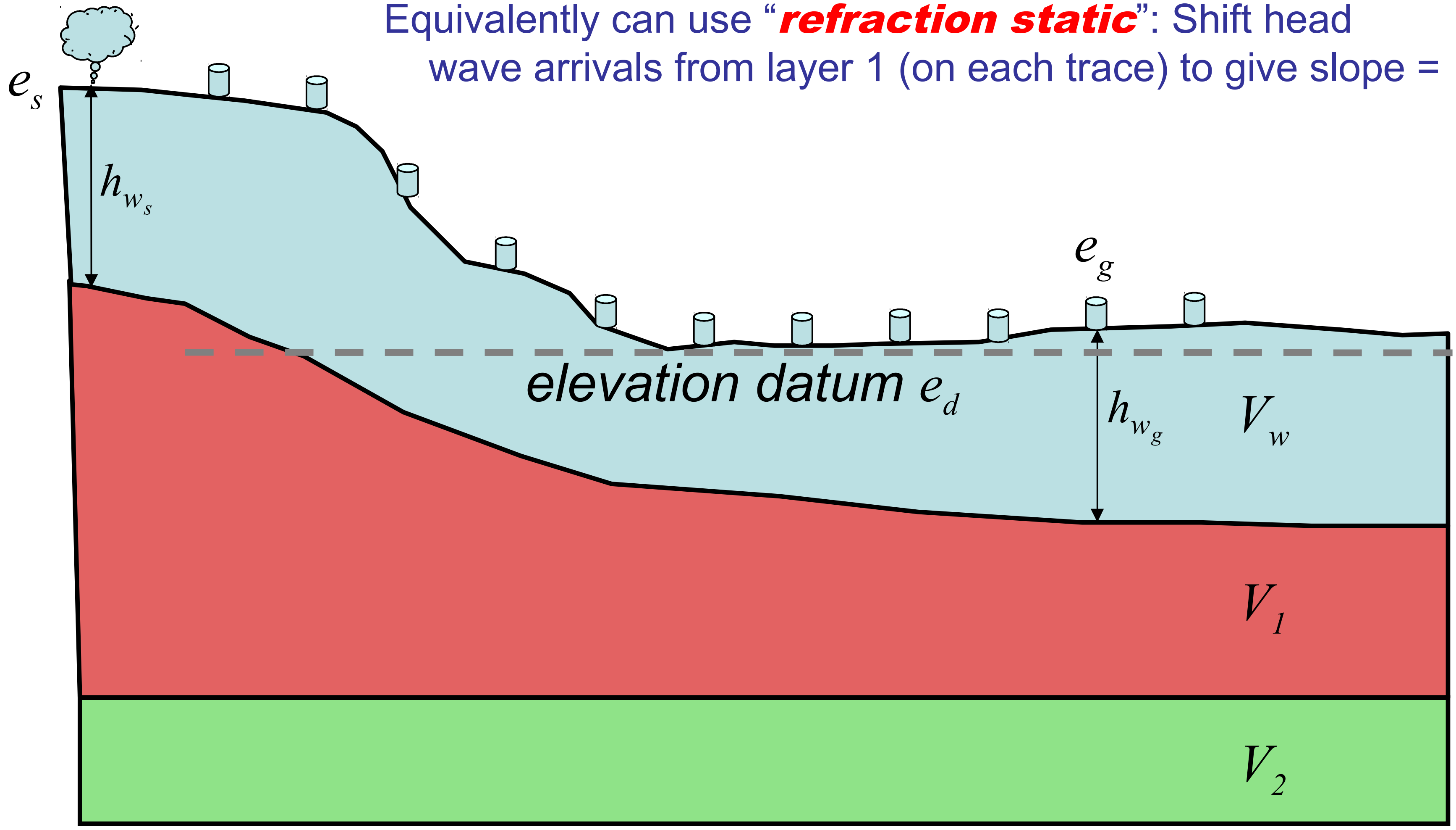


Then subtract a correction for elevation differences:

$$t_{corr} = t_{obs} - \frac{h_{w_s} + h_{w_g}}{V_w} + \frac{h_{w_s} + h_{w_g}}{V_1} - \frac{e_s + e_g - 2e_d}{V_1}$$

Typically choose elevation datum to be lowest point on the survey. Static correction is a time shift applied to the entire geophone trace!

Equivalently can use "***refraction static***": Shift head wave arrivals from layer 1 (on each trace) to give slope = $1/V_1$.



Static correction: Entire trace is shifted by a constant time
Dynamic correction: Different portions of the trace are shifted by different amounts of time

Reflection Seismic Data Processing Step II:

Correction for ***Normal Move-out (NMO)***:

If we want an ***image*** of the subsurface in two-way travel-time (or depth), called a ***seismic section***, we correct for NMO to move all reflections to where they would be at zero offset.

Could use Dix Eqns:

$$T_{NMO} = \frac{\sqrt{x^2 + 4h^2}}{V_{rms}} - \frac{2h}{V_{rms}}$$

but for lots of reflections, lots of shots this would involve lots of travel-time picks and lots of person-time…

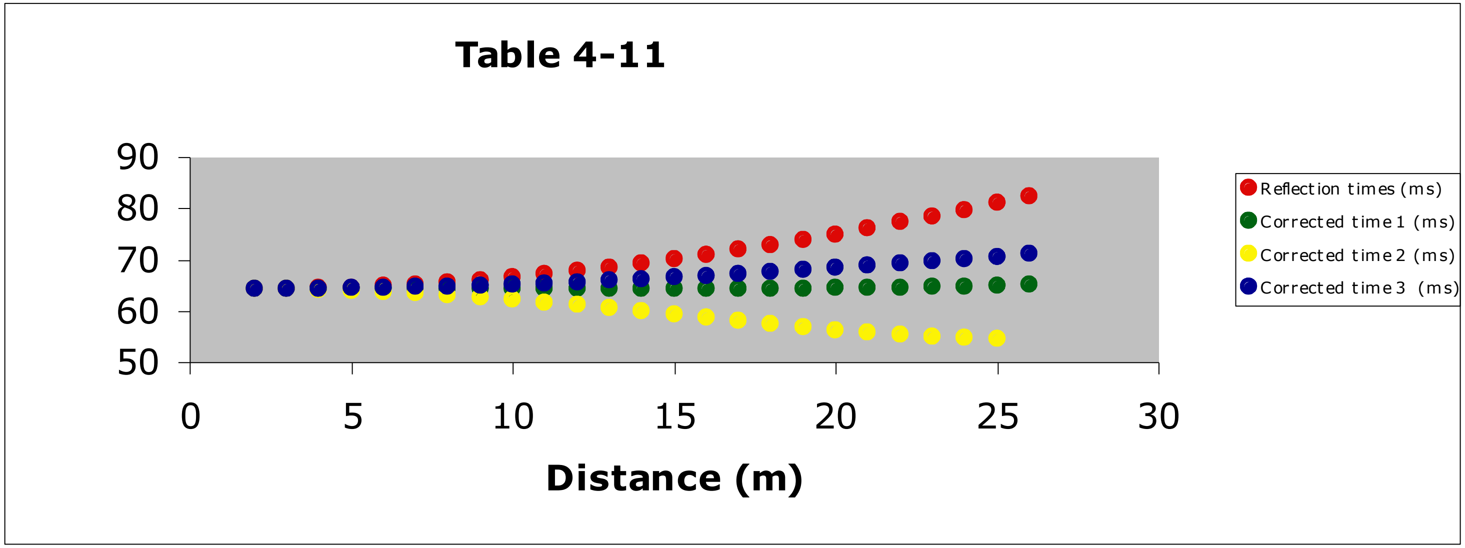
Instead we look for approaches that are easier to automate.

Approach A to Velocity Analysis:

Recall the second-order binomial series approximation to T_{NMO}:

$$T_{NMO} \doteq \frac{x^2}{2t_0V_s^2} - \frac{x^4}{8t_0^3V_s^4}$$

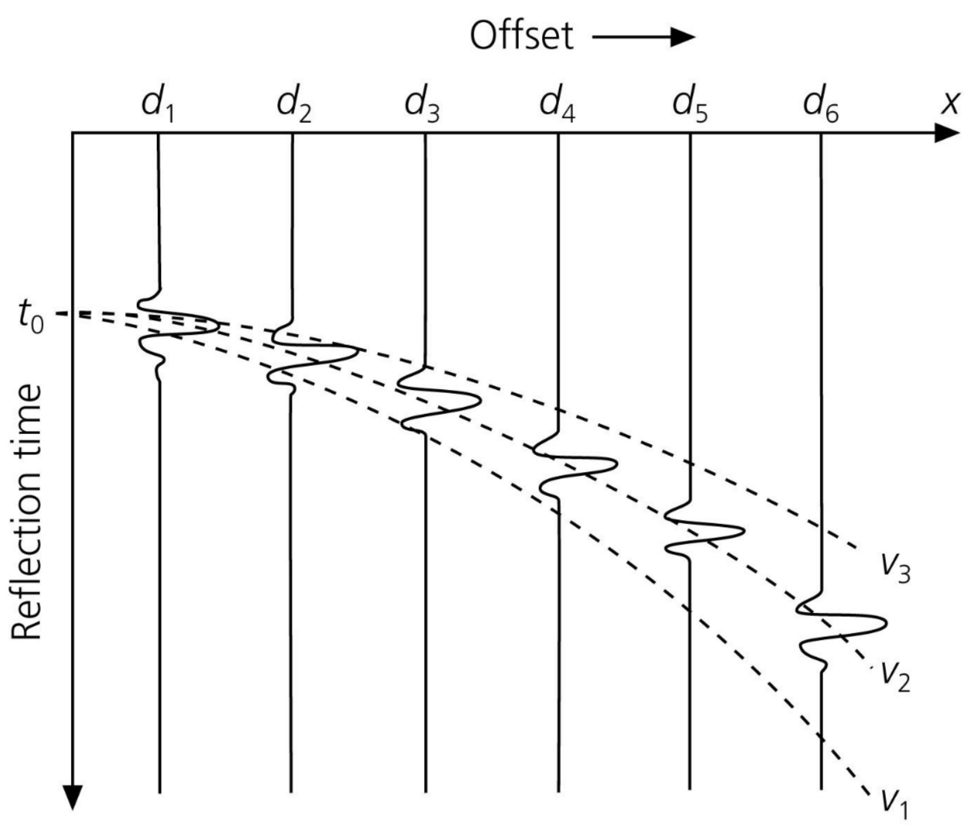
We know x but not t_0, V_s. One approach is to use trial-&-error: At every t_0, try lots of different "stacking velocities" V_s to find which best "flattens" the reflection arrival:

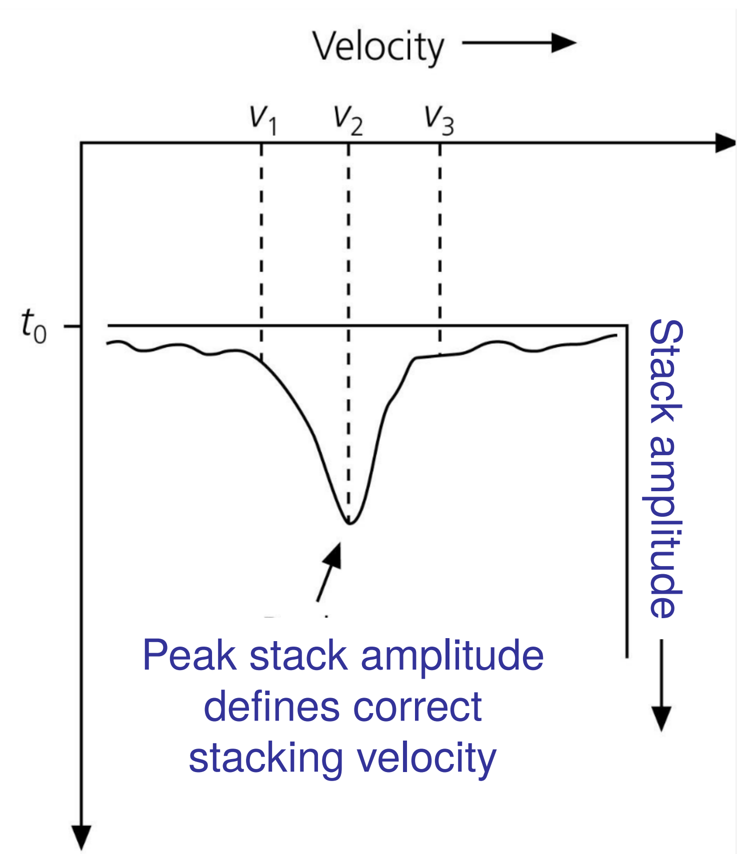


(Simple, but not fully automatic, and will not help to bring out weak reflections).

Approach B to Velocity Analysis:

Similar to Approach A, in that we try lots of t_0's and stacking velocities V_s… Difference is that for each trial we sum all of the trace amplitudes and find which correction produces the largest stacked amplitude at time t_0.





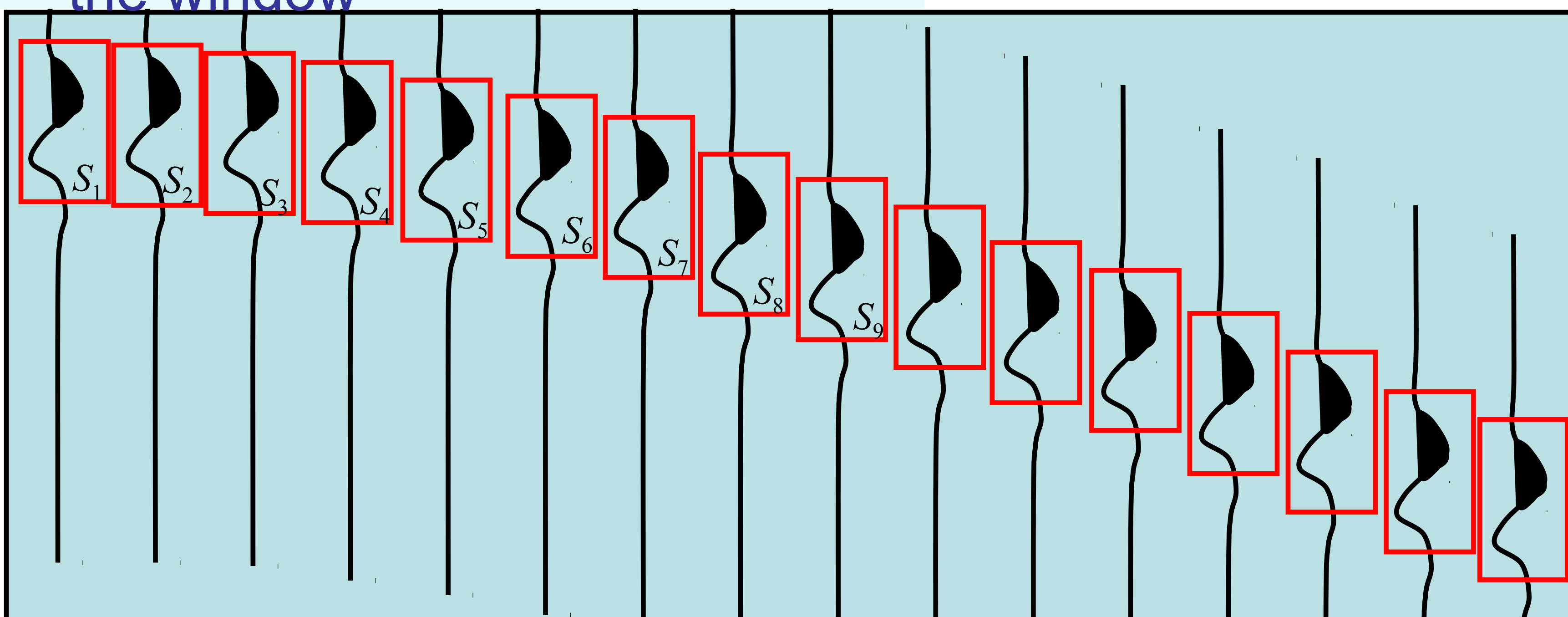
Approach C to Velocity Analysis:

- Assume every t_0 is the onset of a reflection.

$$T_{NMO} \doteq \frac{x^2}{2t_0V_s^2} - \frac{x^4}{8t_0^3V_s^4}$$

- ***Window*** every geophone trace at plus/minus a few ms and compare ("cross-correlate") all traces within the window

$$C_{ij} = \frac{N\sum S_iS_j - \sum S_i \sum S_j}{\sqrt{\left(N\sum S_i^2 - \left[\sum S_i\right]^2\right)\left(N\sum S_j^2 - \left[\sum S_j\right]^2\right)}}$$

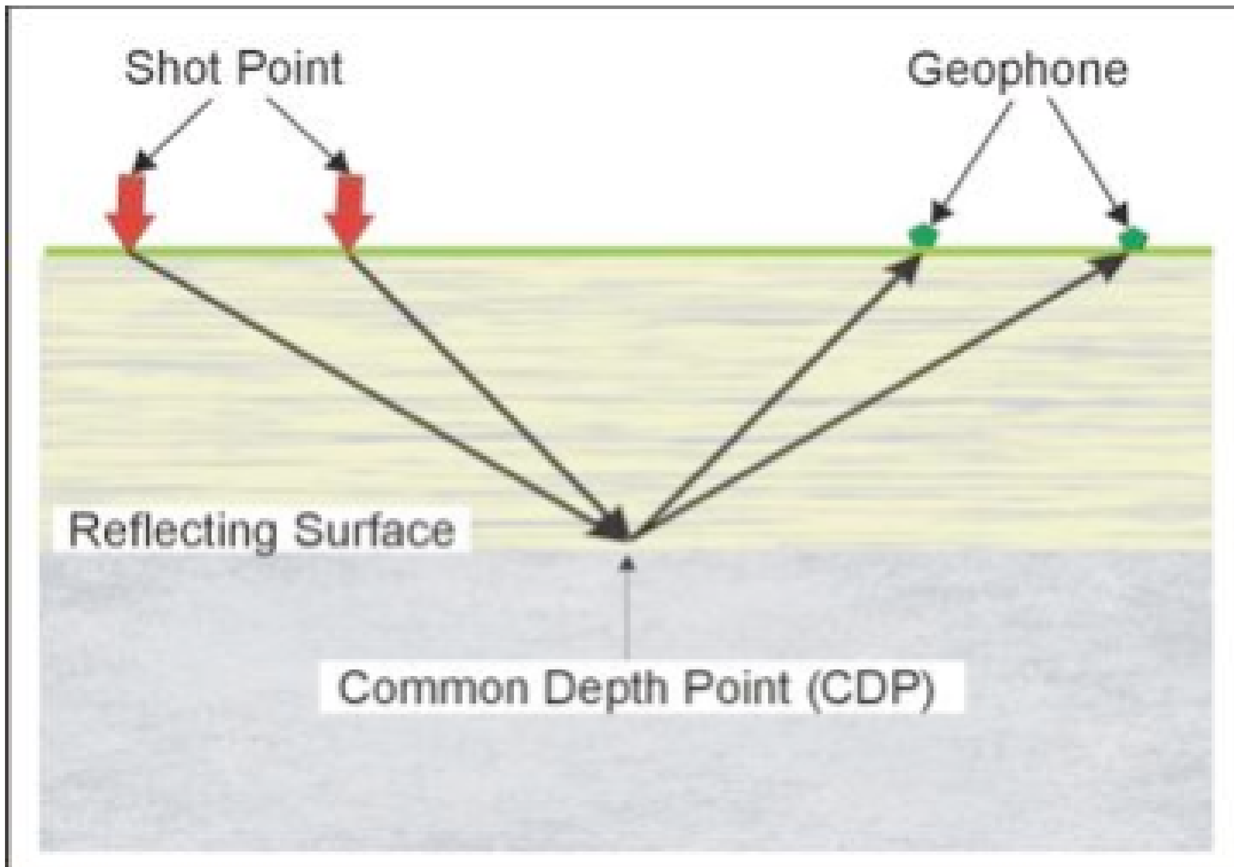


The stacking velocity V_s that yields the most similar waveform in all windows gives highest cross-corr & is used for that t_0.

Step III: Stacking Common Depth Point Gathers:

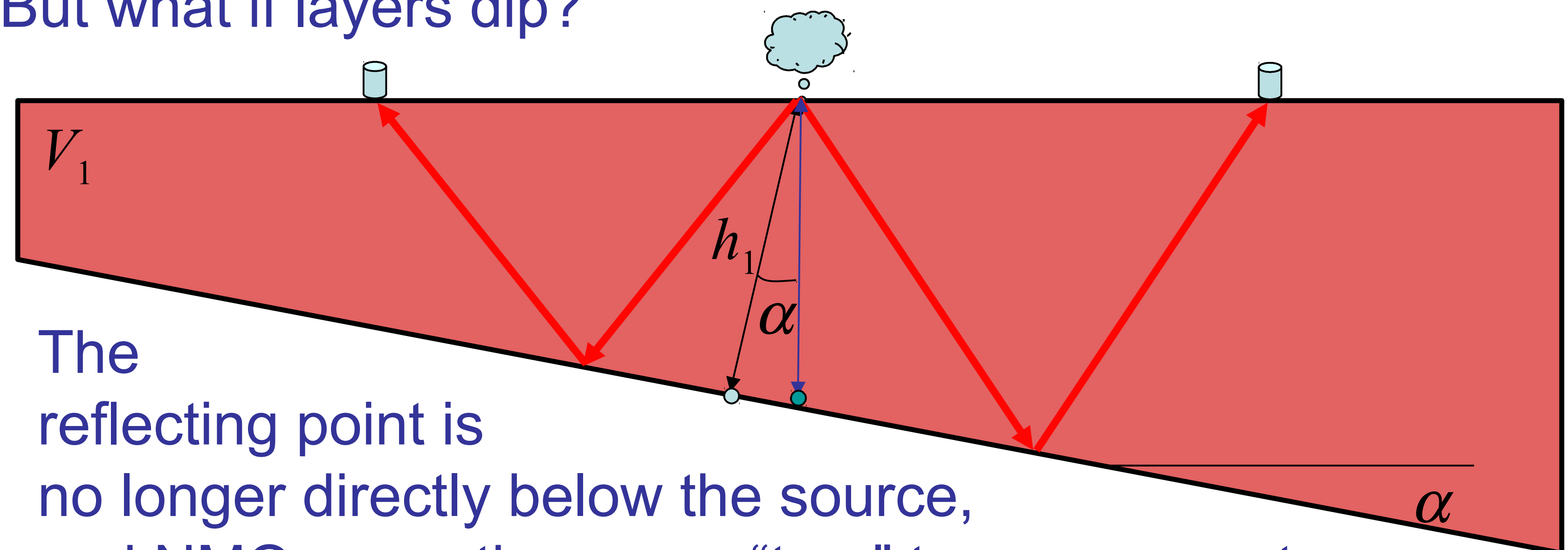
For industry seismic, usually have lots of shots & lots of receivers at every shot. Reflection signal is amplified and noise is attenuated by ***stacking***, i.e., summing traces from different source-receiver pairs in an optimal way. Most commonly use Common Depth Point (CDP) stacks:

First correct for NMO (after velocity analysis to determine best stack velocity V_s for each t_0), then sum all traces that have the same mid-point and place the summed traces at that point on the image.



After NMO correction and CDP stack, have a seismic section: horizontal layers all image correctly in two-way travel-time. If layers truly are ~ horizontal, processing can end here.

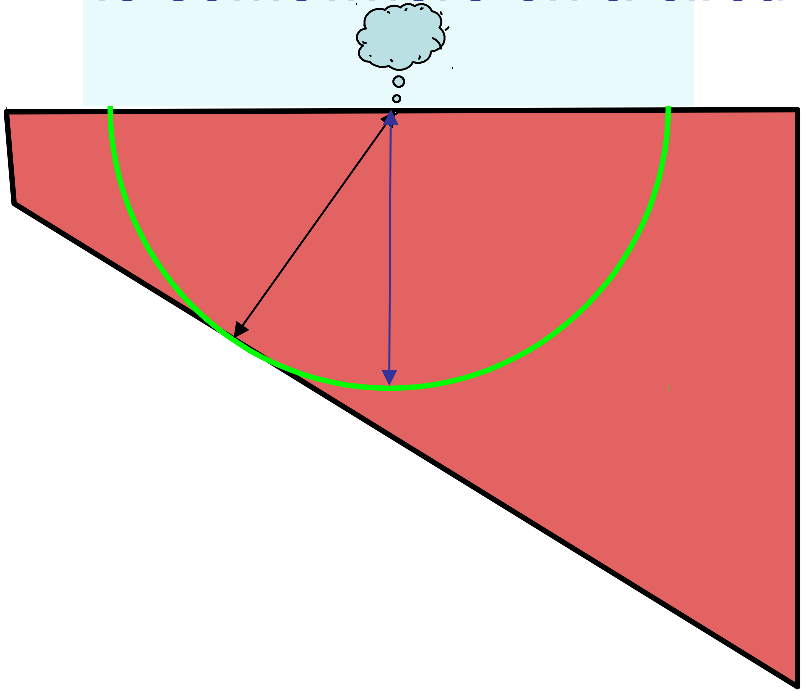
But what if layers dip?



The reflecting point is no longer directly below the source, and NMO correction maps “true” to an apparent reflecting point vertically beneath the source. For stacks from a multiple source-receiver array, this maps dipping reflectors to horizons that are shallower and may have shallower dip than the true horizons.

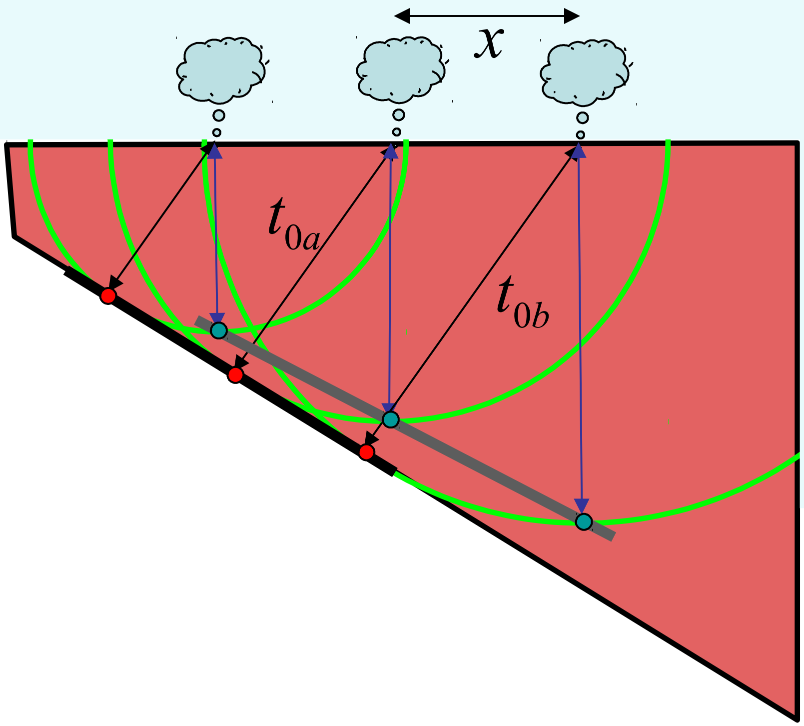
Step IV: ***Migration*** seeks to distribute reflection energy back to its correct position in two-way travel-time (& note some types of migration can correct for diffraction “frowns” as well as dip effects & “bow ties”).

Note that for a single dipping layer case with two-way travel time to the reflection t_0, the true reflecting point in twtt must lie somewhere on a circular arc of radius t_0:



So, if we have some sort of independent information relating to the medium (e.g., dip angle) we can map the reflections back to their true location in two-way travel-time.

Independent information comes from redundancy of the source-receiver midpoints! If one unique surface is responsible for a given set of reflection arrivals, that surface must pass through all of the circular arcs. The “true” reflecting surface is defined by a tangent passing through each of the arcs.

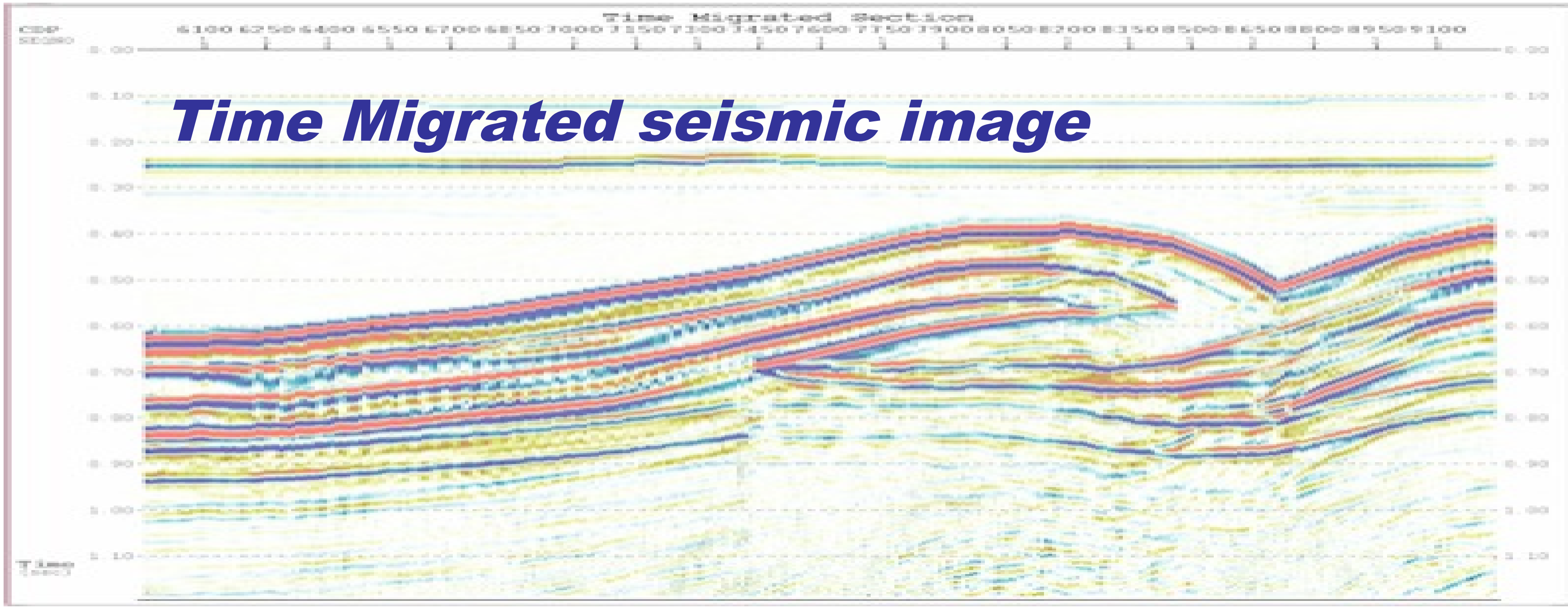


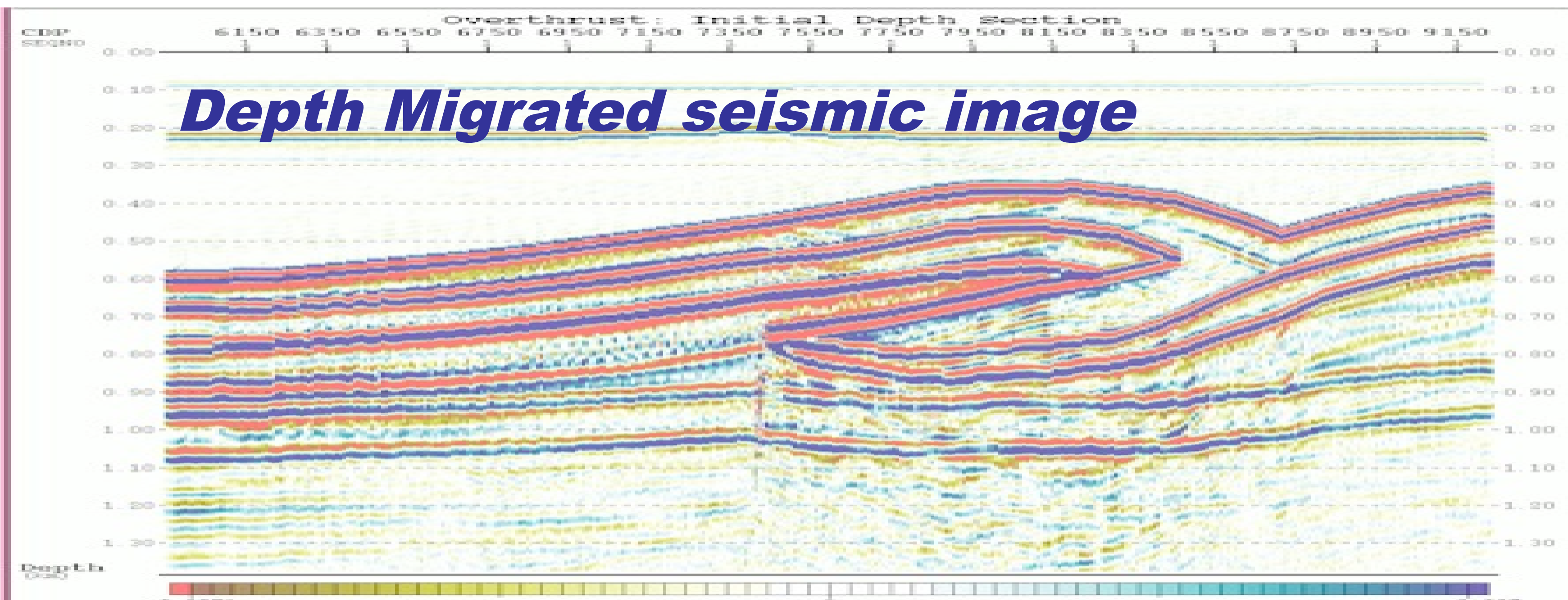
In the relatively simple case shown here of a uniformly dipping, single layer over a halfspace, can calculate dip of the reflector from any pair of two-way travel-times t_{0a}, t_{0b}:

$$\sin\alpha = \frac{V_1\left(t_{0b} - t_{0a}\right)}{2x}$$

Other processing steps may include:

- ***Amplitude adjustments***: Small changes in impedance contrast can change amplitudes significantly, make reflections visually hard to follow: Some software will normalize a reflection on one trace to that on the next.
- ***Frequency adjustments***: Filter to remove unwanted low-frequency info (e.g. ground roll) digitally after the fact instead of a priori (so information is preserved if needed!)
- ***Transmission adjustments***: "Inverse filtering" to upweight desired higher frequency (higher resolution) info that is attenuated more by the Earth medium; also filtering to remove effects of multiples
- Conversion of ***time section*** to ***depth section***, and ***depth migration***


Time Migrated Section
Time Migrated seismic image


Overthrust: Initial Depth Section
Depth Migrated seismic image