Applied Seismic Methods - Key points

- Place of seismics among geophysical methods
- Principles of seismic method
- Frequency band and resolution
- Examples: Earth mantle, crust, exploration, environmental
- Seismic material properties
  - Wave velocities, elastic moduli, impedance
- Types of seismic data
- Basics of refraction and reflection data interpretation
- Surface-wave method (MASW)

- Reading:
  - Dentith and Mudge, Chapter 6

Place of seismic among other geophysical methods

- Look again into this table from "Introduction":

Method	*Property*	*Value Measured*
Gravity	Density	Spatial variations in natural gravity field
Magnetic	Magnetic susceptibility	Spatial variations in natural magnetic field
Radioactive	Abundance of radionucleides	Gamma radiation
Heat flow	Thermal conductivity, radioactive heat production	Heat flow
Electrical	Electrical conductivity	Apparent resistivity
Telluric current	Electrical conductivity	relative apparent resistivity
Spontaneous polarization	Oxidation potential, ion concentrations	Natural electrochemical potentials
Induced polarization	Electronic conductivity	Polarization voltages
Electromagnetic	Electrical conductivity+ magnetic susceptibility	Alternating electromagnetic field, phase and intensity
Seismic	Natural ground motion, velocity, heterogeneities	Ambient seismic noise, travel times, polarization
	Velocity, impedance contrasts	Seismic travel times, amplitudes, reflection patterns
Remote sensing	Natural radiation	Refraction intensity
	Reflectivity (albedo)	Reflected radiation
Borehole	Natural radioactivity	Natural voltages, natural gamma radiation
	Electrical conductivity, seismic velocity, nuclear reactions	Apparent resistivity, travel times, amplitudes, induced and back-scattered radiation

Among all other geophysical methods, seismic methods stand out specially:

1) Capable of non-invasive determination of the 1-D, 2-D, and 3-D subsurface structure;
2) Spatial resolution and detail is much greater than in most other methods.

However, this comes at a price of much larger data volumes and much more elaborate data processing

Yellow background in this table shows "controlled source" methods using artificial sources
The rest are "passive-source" methods using physical effects produced by natural phenomena or (for example) urban noise

Seismic method

- Seismic imaging uses waves in the elastic Earth to detect its heterogeneities and to measure its mechanical properties. In general terms, the method works like this:
- A strong local disturbance occurs naturally or is artificially created (earthquake, explosion, impact of a hammer). This disturbance represents the seismic source and can be of several types (radially expanding cavity for explosions, "double couple" for earthquakes)
  - The source is usually impulsive, but extended broad-band signals are also used, such as produced by a seismic vibrator
- The source disturbance produces waves spreading through the medium and deviating (refracting) or reflecting from heterogeneities (layers, crustal blocks, and other bodies)
  - The waves can be of multiple types discussed later
- These waves are recorded at multiple locations with precisely known coordinates (receivers)
- The travel times and waveforms of the recorded waves are inverted for wave velocities and target heterogeneities
  - Wave velocity values are related to the elastic moduli and density of the medium
  - The heterogeneities delineate the structure of the medium. and can be related to geological structure seen in boreholes and rock outcrops

Applications of seismic methods – Global and monitoring

- Earthquakes
  - Earthquake location and characterization
  - Mitigation of seismic hazard, earthquake engineering
- Study of the interior of the Earth
  - From as shallow as 1 m to as deep as 6400 km
  - Different types of waves:
    - Whole-Earth oscillations
    - Body and surface waves, P and S waves, P/S conversions
- Monitoring
  - Micro-earthquakes during mining or oil/gas production by fracking
  - Nuclear test monitoring
  - Tsunami early warning

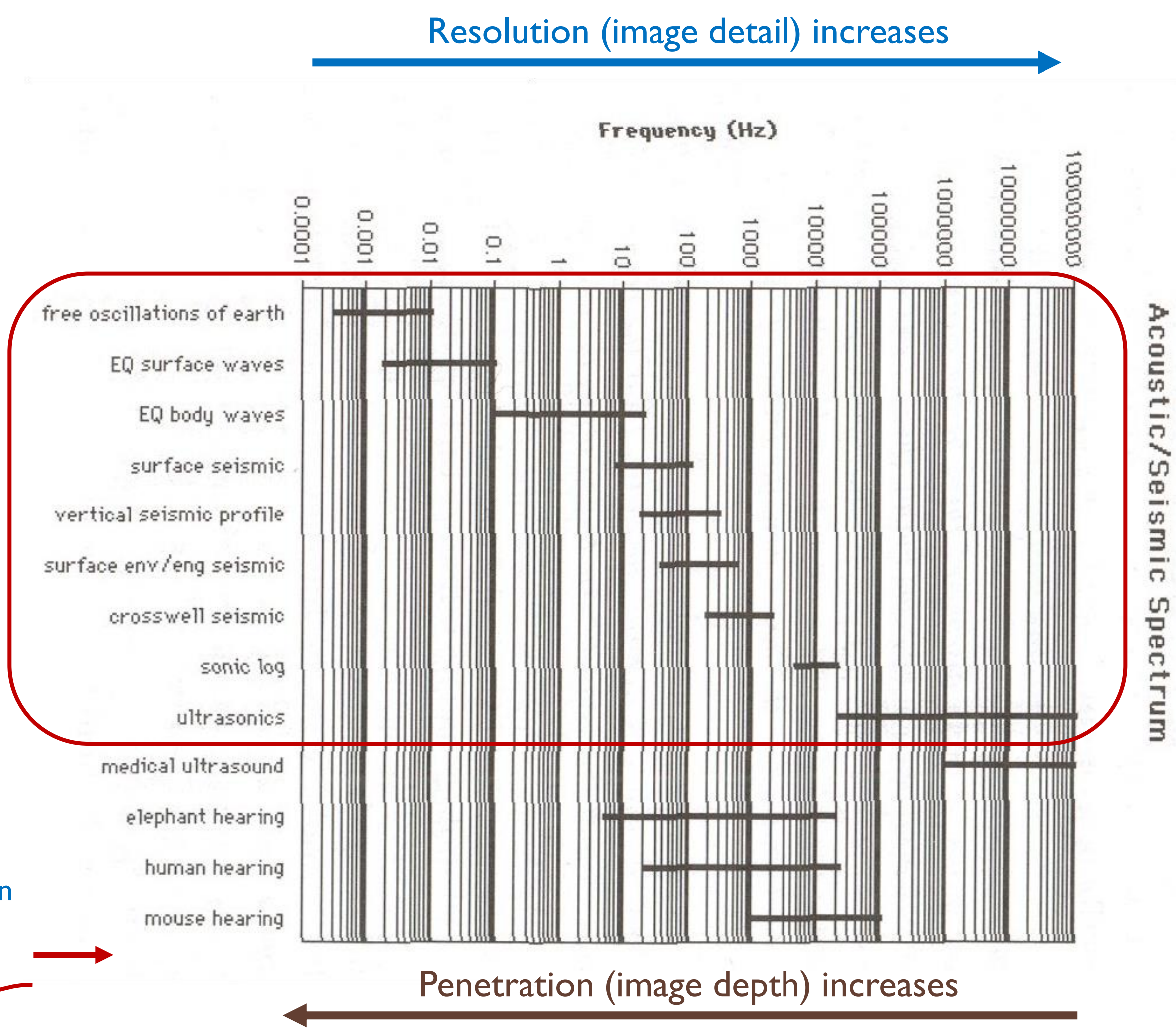
Applications of seismic methods – Exploration and Engineering

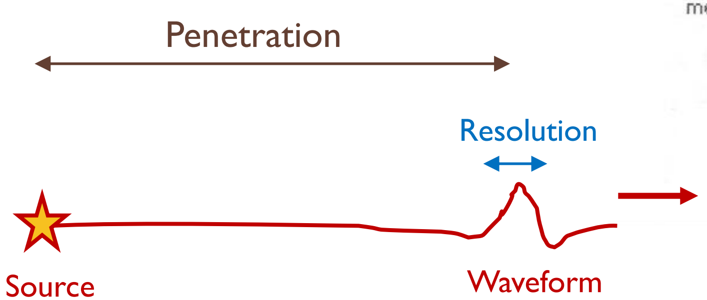
- Refraction seismics
  - Detect high-velocity formations
  - Depths to beds, velocities and gradients
- Reflection seismics
  - Geometrical types of structures
  - Maps of structures in 2-D and 3-D
  - Spatial relationships of various features
    - Geological history, unconformities;
    - Depositional environments.
  - Sediment velocities
  - Oil field monitoring and development; CO_2 sequestration
  - High-density ore bodies
- Surface-wave seismics
  - Environmental and engineering
- Laboratory
  - Characterization of rock properties for all applications

We discuss these applications in this lecture

Acoustic/seismic frequency band

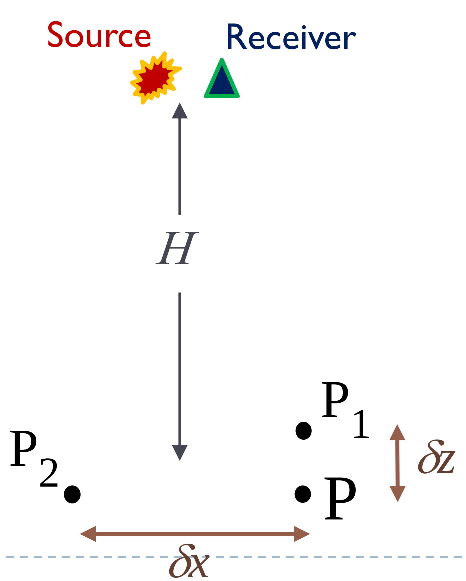
- Unlike all methods we studied before, seismology uses waves for imaging various structures
- Waves combine (often) deep penetration with (relatively) short wavelengths, which provide high resolution of details
- The wavelengths and imaging resolution are controlled by wave (i.e., source) frequency





Seismic resolution

- The ability of seismic measurements to identify small detail of targets at depth (shapes and edges of boundaries, fault drops, hydrocarbon traps, sizes of ore bodies, voids, etc.) is called "resolution"
- The resolution limit is determined by the length of the wave that is able to reach the target and be recorded. The general principle is that if two signals arrive within ½ of the dominant wave period (one peak of the waveform), they are considered unresolvable.
- The wavelength is inversely proportional to the frequency which we are able to record: $\lambda = \dfrac{V}{f}$
- For reflection imaging from the surface this principle gives:

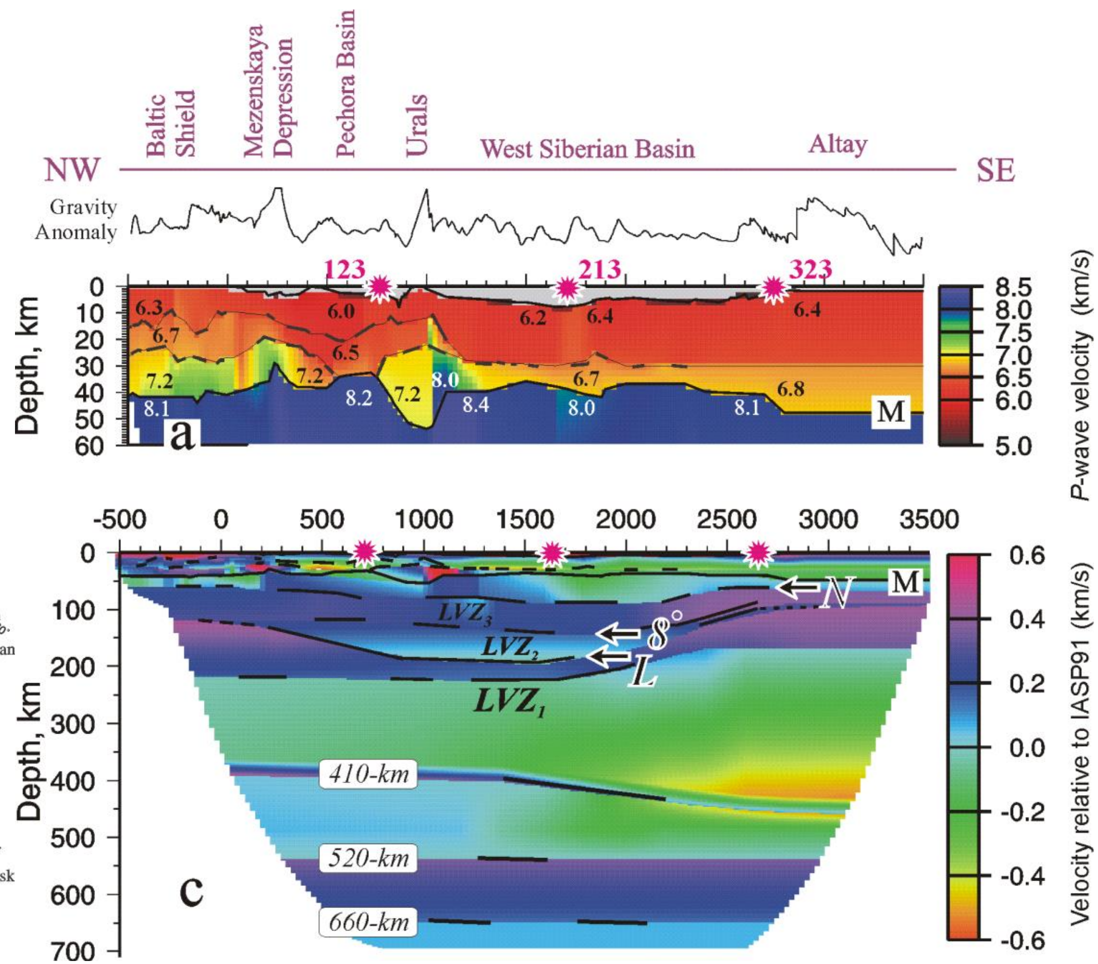


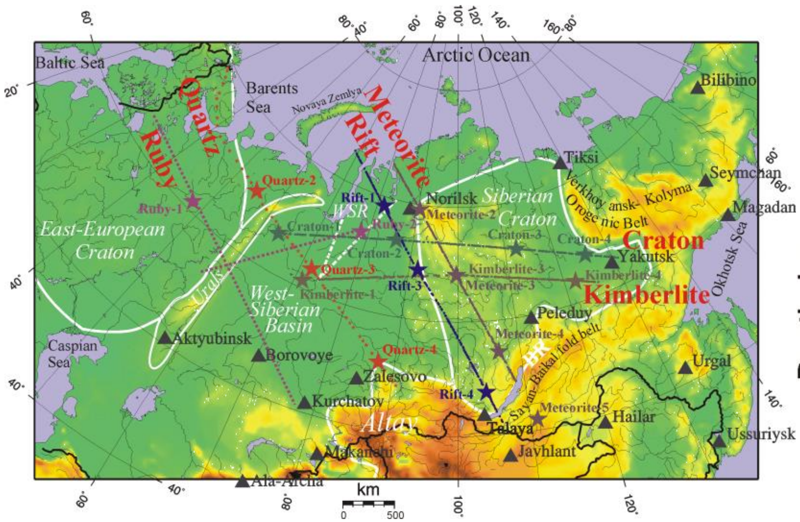
- The vertical resolution limit (thinnest layer resolvable) is: This is called the "quarter-wavelength" criterion $\delta z = PP_1 = \dfrac{\lambda}{4}$
- Horizontal resolution depends on λ weaker but quickly increases with the depth of imaging (H): $\delta x = PP_2 \approx \sqrt{\dfrac{1}{2} H \lambda}$

Example – Nuclear-explosion seismology

- There was time (1960's – 1980's) when nuclear explosions were available for seismology
- This gave images of the structure of the Earth's crust and upper mantle that are the most detailed so far

Structure along profile "QUARTZ" on the left

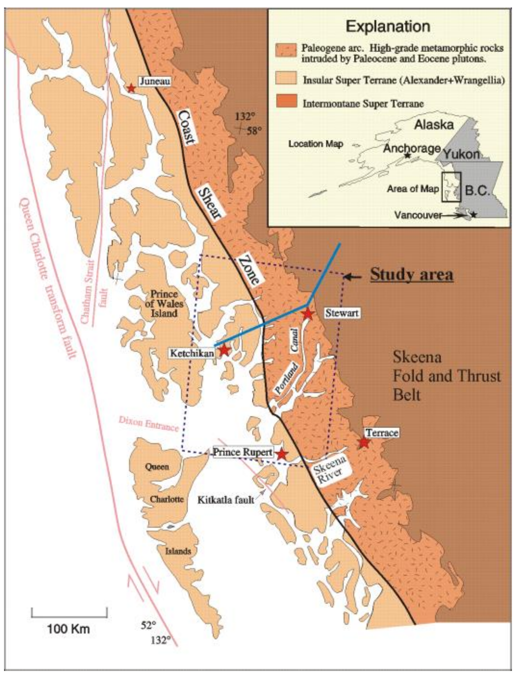


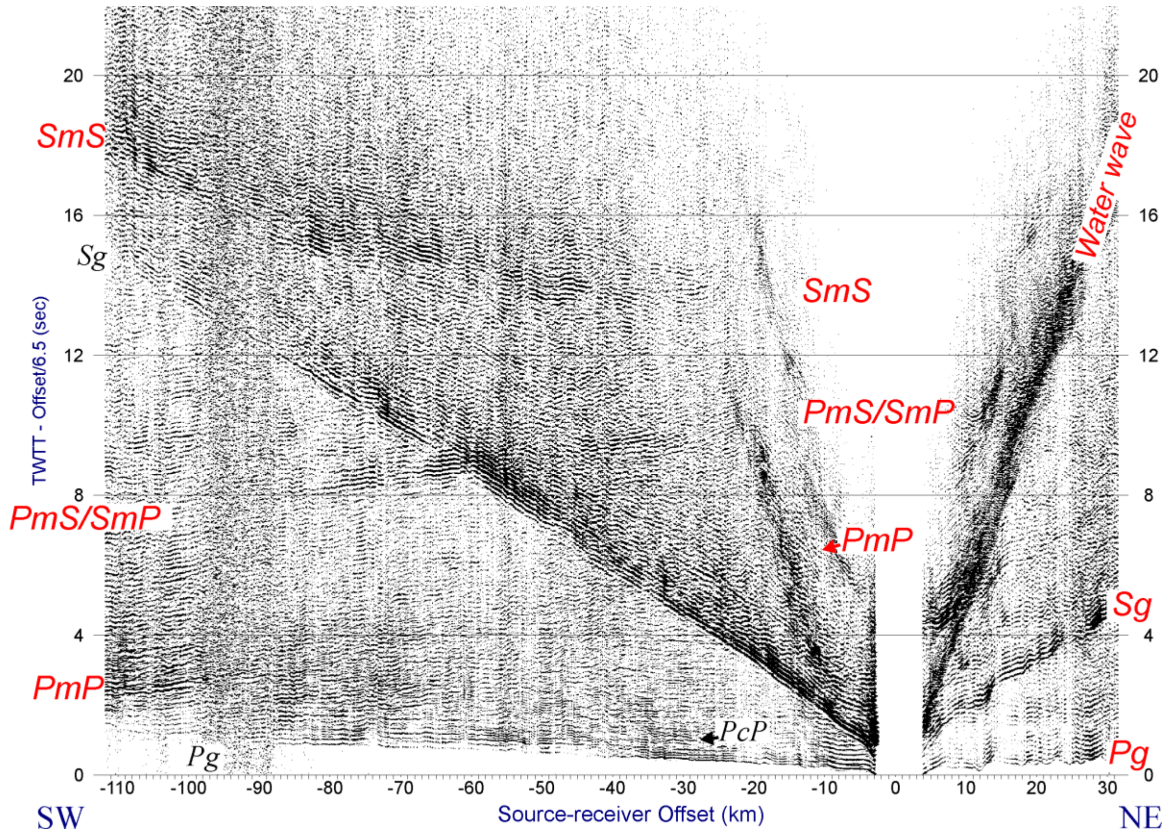


Example – Crustal-scale seismology

- Excellent imaging of the entire Earth's crust (base of the crust is at about 40-km depth)
- U.S. – Canadian border in British Columbia

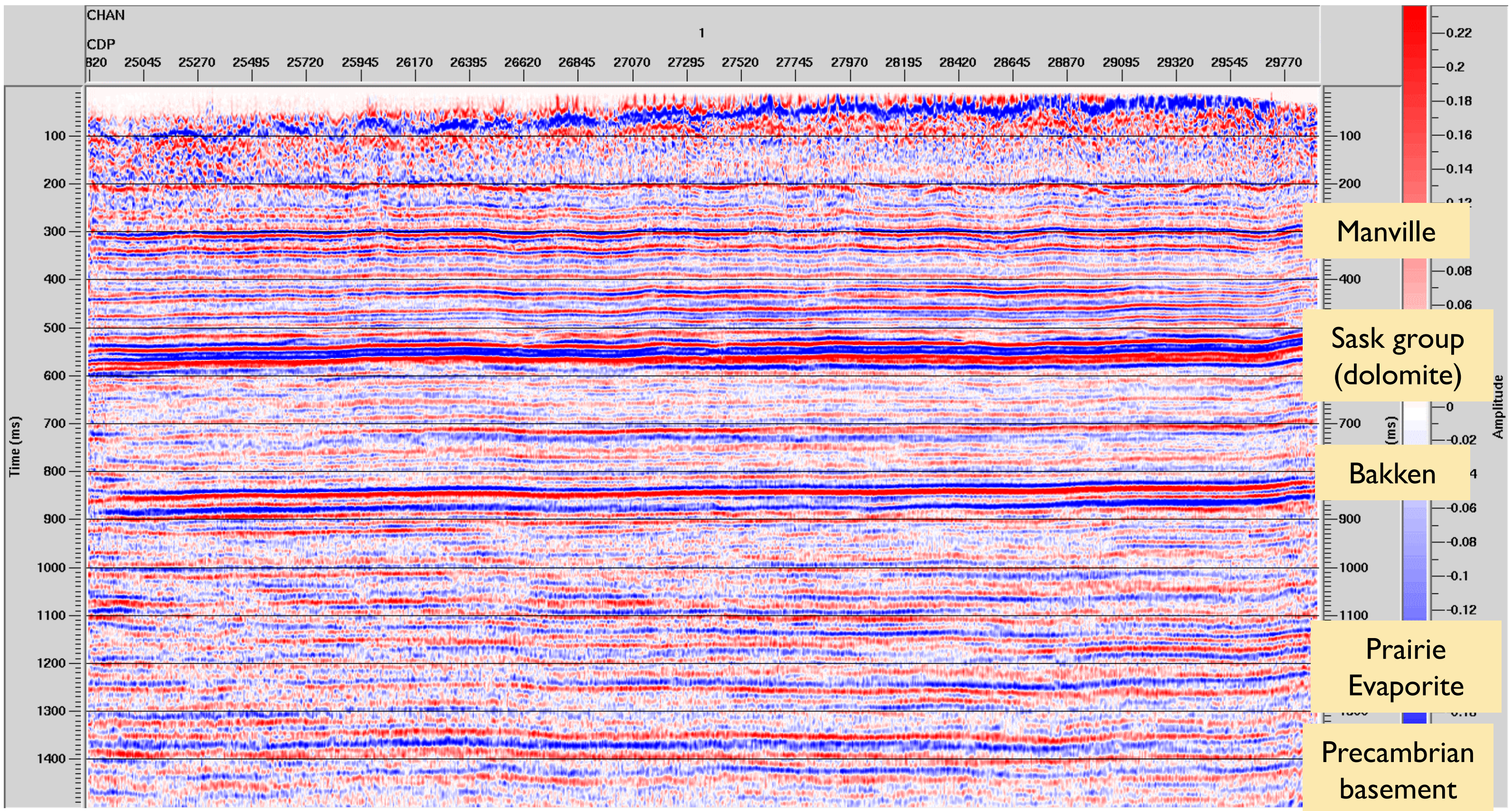
This is how "wide-angle" (recorded at large source-receiver distances) seismic records look like. Red labels indicate various direct and reflected wave arrivals





Example – Exploration seismology

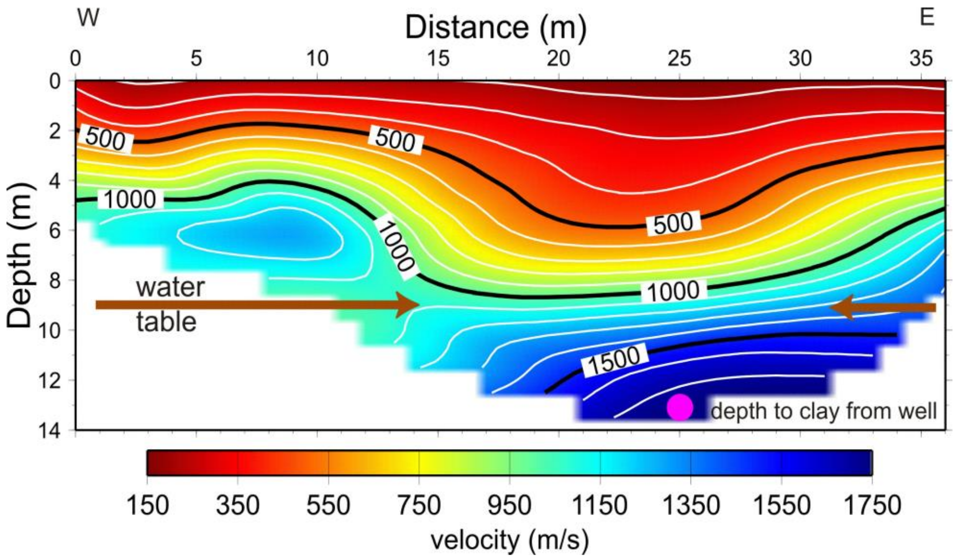
Stacked reflection section in southern Saskatchewan (TGI2 project)



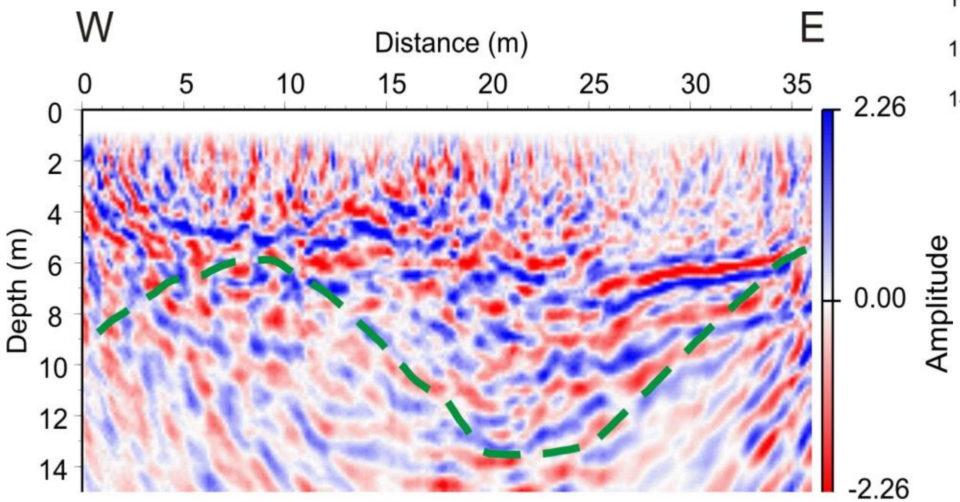
Example – Engineering/Environmental seismology

- Ultra-shallow refraction/reflection study using .22 caliber rifle shots as sources, ~600 receivers (3-D)
- Looking for the depth of the water table and shape of clay aquitard at ~ 8 meters
- Hill U.S. Air Force Base near Ogden, Utah

Tomographic seismic-wave velocity model from "refracted" arrivals



Reflection seismic image



Seismic properties

- What is measured by seismic methods?
- Velocities of various types:
  - Basic: P-wave (compressional) and S-wave (shear)
  - Surface wave (usually a mix of P and S deformations, traveling along the surface)
  - Guided waves (similar to surface but traveling within a low-velocity zone such as fault zone
  - Interval velocities from well logging
  - "Stacking velocities" inferred during processing reflection seismic data
- Reflection (P-wave, S-wave) and mode-conversion (P to S, S to P, P to surface wave, etc.) amplitudes
- Structure:
  - Depths to wave-velocity and density contrasts
  - Shapes of boundaries (folds, faults)
  - Layering, depositional sequences
- Amplitude decay rates ("attenuation")
- Frequencies of reverberations of the near surface
  - "Standing waves", important for engineering of seismic-hazard resistant structures

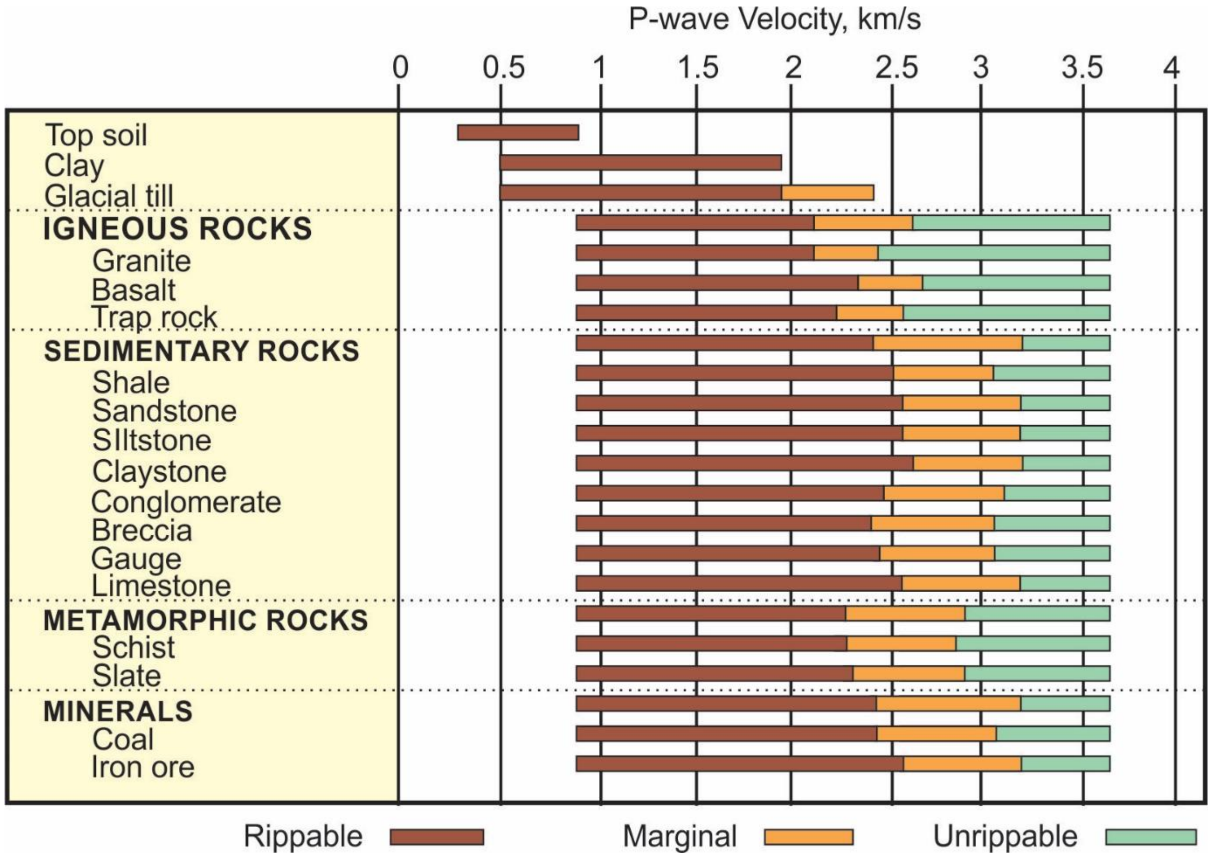
Seismic material properties

- Seismic velocities are generally related to rock lithology but also vary greatly due to physical conditions:
  - Generally increase with pressure, depth of burial
  - Decrease with temperature
  - Decrease with increasing fractures and porosity,
  - V_P increases but V_S decreases with pore-fluid saturation

Material	*Vp (m/s)*	*Vp (ft/s)*	*Vs (m/s)*	*Vs (ft/s)*	*ρ(g!cm³)*
Air	332	1090			0.0038
Water	1,400 - 1,600	4,600 - 5,250			1.0
Soil	300 - 900	980 - 2,950	120 - 360	390 - 1,180	1.7 - 2.4
Sandstone	2,000 - 4,300	6,560 - 14,100	700 - 2,800	2,300 - 9,190	2.1 - 2.4
Chalk	2,200 - 2,600	7,220 - 8,530	1,100 - 1,300	3,610 - 4,270	1.8 - 3.1
Limestone	3,500 - 6,100	11,490 - 20,000	2,000 - 3,300	6,560 - 10,830	2.4 - 2.7
Dolomite	3,500 - 6,500	11,490 - 21,330	1,900 - 3,600	6,240- 11,810	2.5 - 2.9
Salt	4,450 - 5,500	14,600 - 18,050	2,500 - 3,100	8,200 - 10,170	2.1 - 2.3
Granite	4,500 - 6,000	14,770 - 19,690	2,500 - 3,300	8,200 - 10,830	2.5 - 2.7
Basalt	5,000 - 6,400	16,400 - 21,000	2,800 - 3,400	9,190 - 11,160	2.7 - 3.1
Quartz	6,049	19,846	4,089	13,415	2.65
Calite	6,640	21,783	3,436	11,273	2.71

Rock rippability

- A popular application of seismology to exploration and engineering is for evaluating rock rippability by heavy machinery. Rippability is estimated from seismic velocities obtained from short and shallow seismic refraction surveys



The lower and upper velocity limits for rocks are selected arbitrarily in this diagram. See the preceding slide for specific velocity ranges.

Seismic material properties

- Seismic observations target mechanical properties of the medium:
  - S-wave velocity is sensitive to the shear elastic modulus (μ) and density (ρ):

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

Note that engineers often denote the shear modulus G

  - P-wave velocity is also sensitive to the bulk elastic modulus (K) (rigidity with respect to uniform pressure):

$$V_P = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}$$

$M = K + \frac{4}{3}\mu$ is called the "P-wave modulus"

  - Surface wave velocities are sensitive to all three parameters K, μ, and ρ. However, they are principally controlled by S-wave velocities (for example, $V_{\text{Rayleigh surface wave}} \approx 0.9\ V_S$)

- Therefore, if we obtain ρ from, for example, gravity or neutron logging, and V_P and V_S from seismic measurements, then the elastic moduli can be estimated:

$$\mu = \rho V_S^2 \quad , \quad K = \rho\left(V_P^2 - \frac{4}{3}V_S^2\right) \quad , \quad \lambda = K - \frac{2}{3}\mu = \rho\left(V_P^2 - 2V_S^2\right)$$

This combination of K and μ is called Lamè, or "incompressibility" modulus

Types of seismic data

- Travel times
  - This is the first and most important part of data analysis for almost any seismic record
  - The analysis starts by identifying arrivals of key waves (P and S) and measuring the times of their onsets.
  - Travel times from multiple source and receiver positions are inverted for the velocity structure. Mathematical procedure called seismic tomography (velocity, attenuation, or other) is often used for such inversion
- Waveforms
  - In a modern seismic survey, hundreds to thousands of source points are conducted. Each source is recorded by ~100 to ~30,000 channels (~1000 samples in each), and the complete records are stored and analysed
  - This is a lot more data than we have seen from other geophysical techniques. Processing of waveform data also utilizes a lot of software and computer power (~10,000-processor cluster systems)
- Cross-correlations of ground-vibration noise (produced by traffic, waves, mining and drilling machinery, etc.).
  - Cross-correlated noise waveforms recorded by two receivers often reveal waves traveling from one receiver to the other
  - This is one of the most actively growing seismic research areas in the recent years
- In laboratory studies with rock samples, stationary harmonic oscillations (somewhat analogous to frequency-domain EM in our labs) are often used to measure the dynamic (frequency-dependent) moduli of materials

Seismic travel times

- In surface recording, seismic records are unraveled by recognizing three types of "body-wave" paths (see figure). These paths are identified by their travel times as functions of the source-receiver distance x (usually called "offset")

- "Direct wave" (OF in the figure)

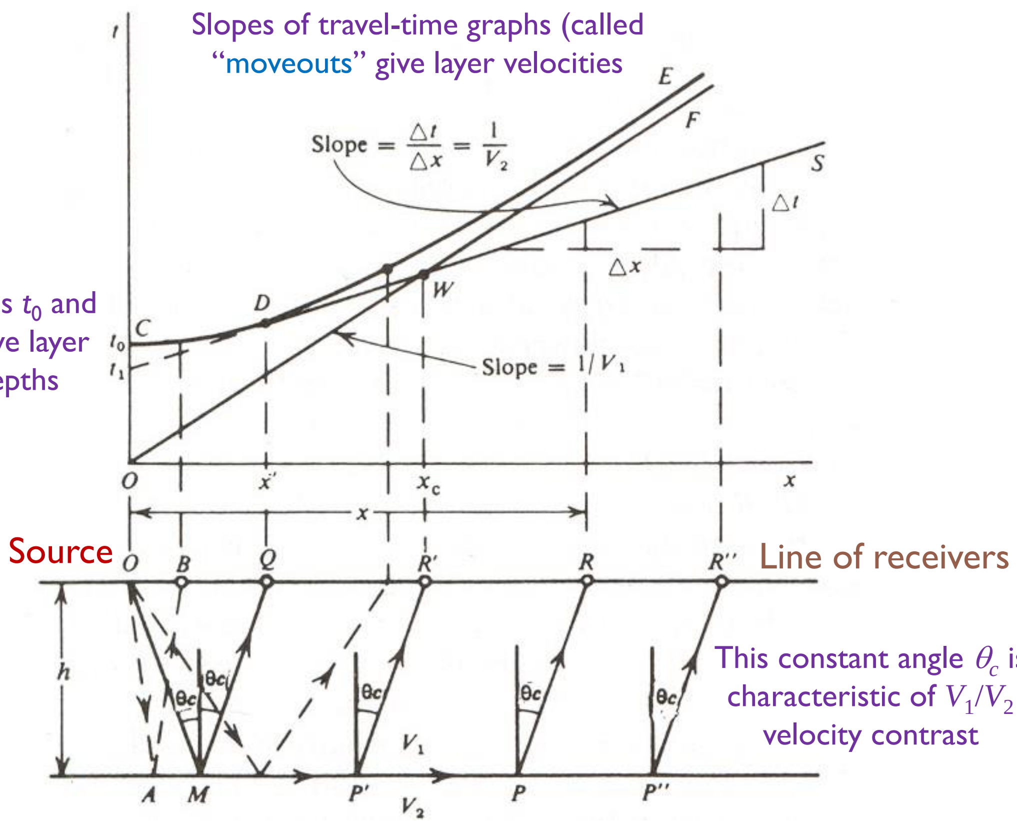
$$t(x) = \frac{x}{V_1}$$

- "Head wave" (DS in the figure)
  - Exists beyond " a critical point" D
  - Comes into first arrivals after a "crossover point" W

$$t(x) = t_1 + \frac{x}{V_2} \text{ , where } \quad t_1 = \frac{2h}{V_1}\cos\theta_c$$

- Reflected wave (CDE)
  - Always in the secondary arrivals, but often the strongest

$$t(x) = \sqrt{t_0^2 + \frac{x^2}{V_1^2}} \;, \qquad t_0 = \frac{2h}{V_1}$$



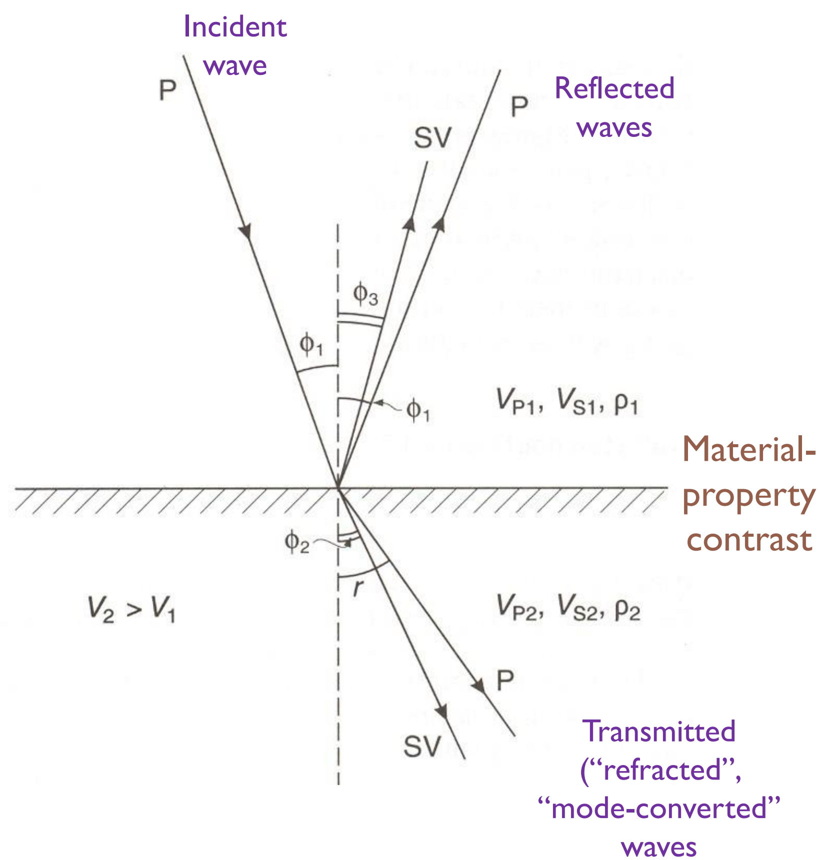
Head wave travels through fast "refractor" at $V_2 > V_1$

Wave refraction and reflection

- When a wave encounters a contrast in material properties V_P, V_S, and ρ, its propagation direction changes (this change is called "refraction") and amplitude is divided between several transmitted and reflected waves (figure)
- Refraction only depends on wave velocities and is insensitive to density
  - The relation governing refraction angles (ϕ and r in the figure) is called "Snell's law"
- At normal incidence (orthogonally to the boundary), the reflection coefficient is:

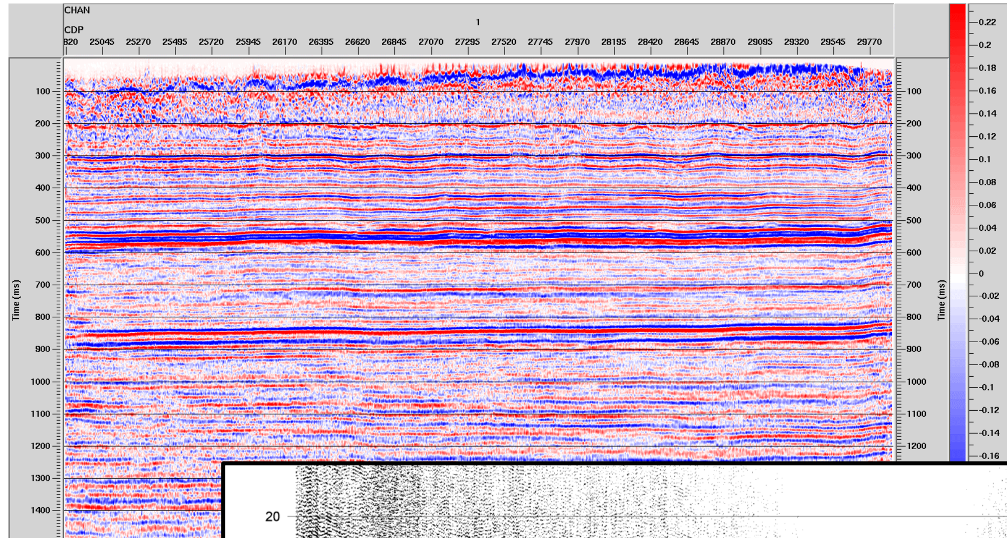
$$R = \frac{A_{\text{reflected wave}}}{A_{\text{incident wave}}} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

  where $Z = \rho V$ is called the acoustic impedance
  - This Z is analogous to the impedance for electro-magnetic waves (such as in MT and GPR)
- At oblique incidence, R depends on the incidence angle ϕ
  - This dependence is used to constrain the contrast in (V_P, V_S, ρ) by the "Amplitude Variation with Offset" (AVO) analysis

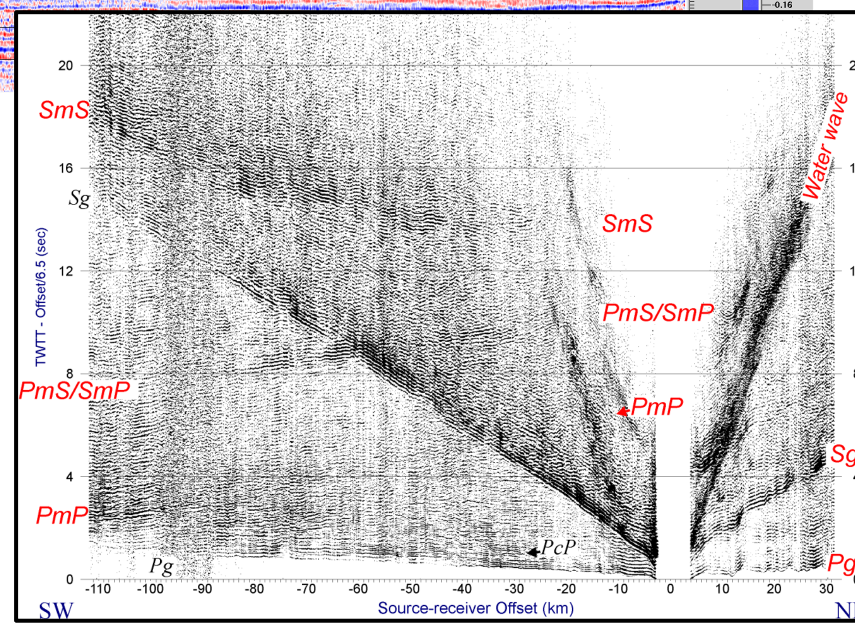


Reflection sections

- Thus, stacked and migrated seismic reflection sections like those shown before mostly represent layered variations of the product ρV:

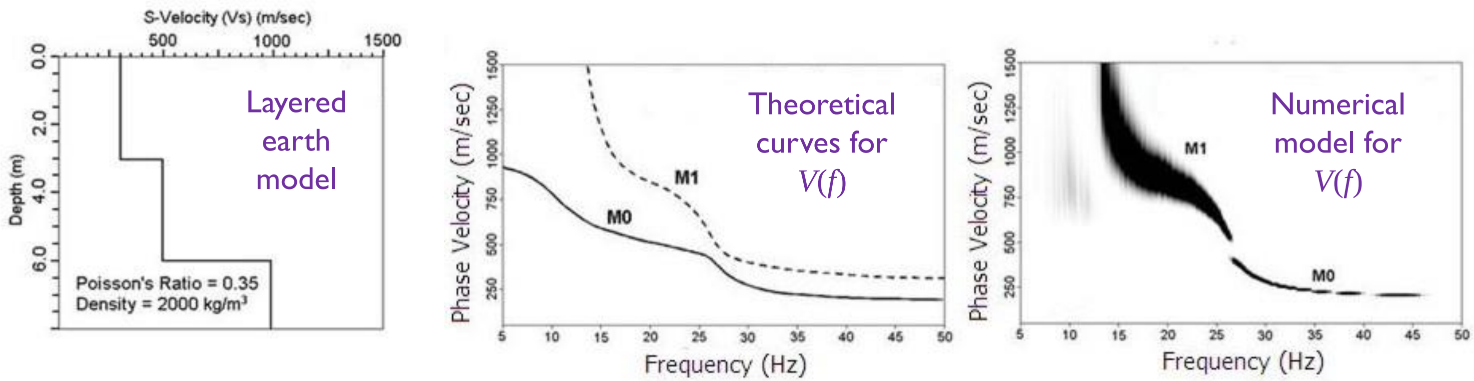


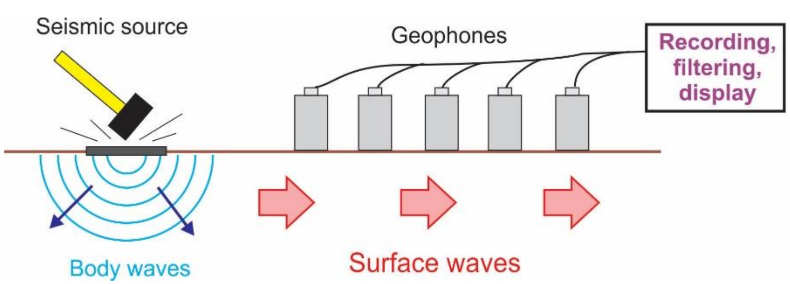
- However, unmigrated reflection sections like this wide-angle section are much less straightforward to interpret
  - This image also contains indications of ρV layering near the crust-mantle boundary (Moho), but it is much more difficult to decipher and prove



MASW (SASW) method

- Multichannel (or Spectral) Analysis of Surface Waves uses velocity dispersion measurements to invert for $V_S(z)$ and $\mu(z)$
- For surface waves, effects similar to skin depth in electromagnetics take place:
  - At higher frequencies, surface waves sample shallower depths, and their velocities are slower (plots below). This dependence $V(f)$ is called velocity dispersion.





- After velocity dispersion measurements are conducted at multiple locations, profiles $V_S(z)$ and $\mu(z)$ are combined in 2-D or 3-D maps