GEOL483
structure of this class

- The first about half is devoted to new material:
  - Tomography and location of earthquake sources
  - Surface waves
  - Rock physics and attenuation
  - Ray tracing and travel-time modelling
  - Amplitude variations with offset (AVO)
  - Vertical seismic profiling (VSP)
- In the second half of the class, we review the topics you have seen in GEOL335, with more detail and in-depth discussions of:
  - Refraction seismic method
  - Reflection method
  - Reflection data processing
- Additionally (time permitting), I have a couple “bonus” lectures that will not be included in the exam (attributes, Kirchhoff method)
- The GEOL483 labs consist of only three “projects”
  - Tomography and location
  - Surface waves
  - Seismic modeling
- In this term, we will conduct all labs and exams as take-home assignments

SEISMOLOGY

- Utilizes seismic (two types of sound) waves to make statements about the Earth's structure.
- By far the highest-resolution geophysical technique.
- As a *Geophysics* discipline, consists of:
  - Measurements ('data acquisition');
    - Emphasis on efficient acquisition techniques, vast volumes of data;
  - Data processing and analysis;
    - Very important and computer-based;
  - Interpretation in terms of models and geological concepts:
    - Forward (direct) modelling – predict seismic observations in a known subsurface structure;
    - Inverse modelling - Given the observed wavefield (travel times), determine the structure *and its uncertainty*.
      - Usually integrated with surface and borehole observations.
- <u>Reading:</u>
  - Telford *et al*., Chapter 1.
  - Shearer, Chapter 1

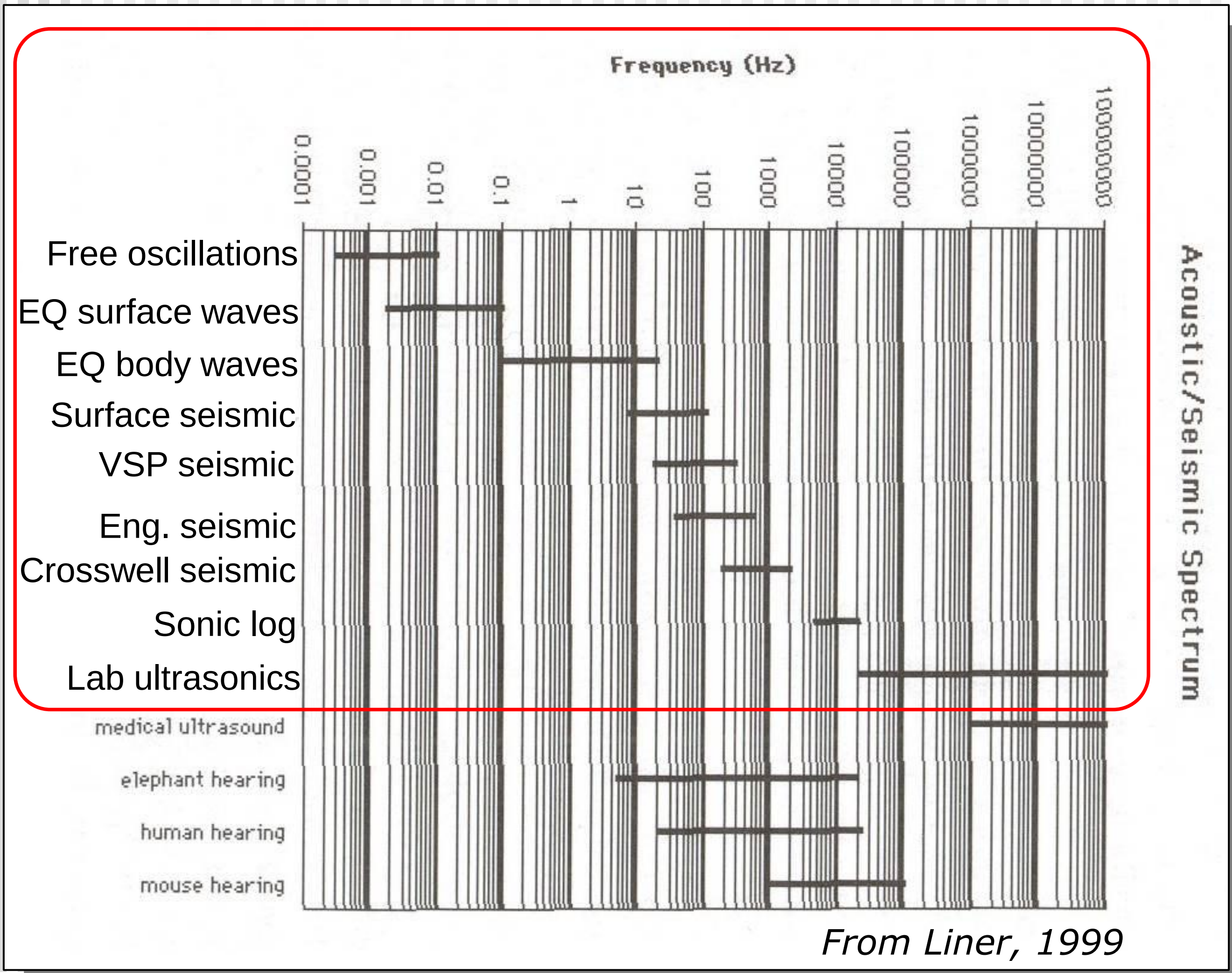
Seismic Methods

Their **Resolution**;
'Passive' and 'Active'

Method	***Property***	***Resolution***	***Value Measured***
Surface refraction	Velocities, velocity gradients	20 m-100 km	Travel times
Surface reflection	Impedance contrasts	0.5 – 20 m	Travel times, amplitudes, reflection patterns
Vertical seismic profiling	Velocities, reflectivity	0.2 – 5 m	Travel times, waveforms
Borehole acoustic logs	Velocities near the borehole, at ~10 – 50 kHz	0.1 m	Pulse time delays
Borehole cross-well	Velocity contrasts at ~10 - 50 kHz	~5 m	Travel-time delays
Laboratory ultrasonic	Velocities at ~100 kHz, anisotropy	1 – 5 cm	Travel times in samples
Surface waves	Velocity structure (primarily of S-waves)	10 m – 100 km	Phase spectra of waves from artificial and natural seismic sources; Dispersion curves
Monitoring	Location of creep within reservoirs and mines, natural earthquakes, weapons tests	100 m – 30 km	Travel times
Teleseismic	Location of earthquakes, velocity structures, reflecting and converting boundaries	30 – 100 km	Waveforms of body and surface waves (~1-1000 sec periods)
Normal modes	Whole-Earth oscillations	1000 km	Earth movements at > 1000 sec periods

Acoustic/Seismic Spectrum

- Key to *signal penetration* and *resolution*:
  - Resolution (the amount of resolvable detail) is typically *proportional* to frequency;
  - Signal penetration quickly *decreases* with increasing frequency.

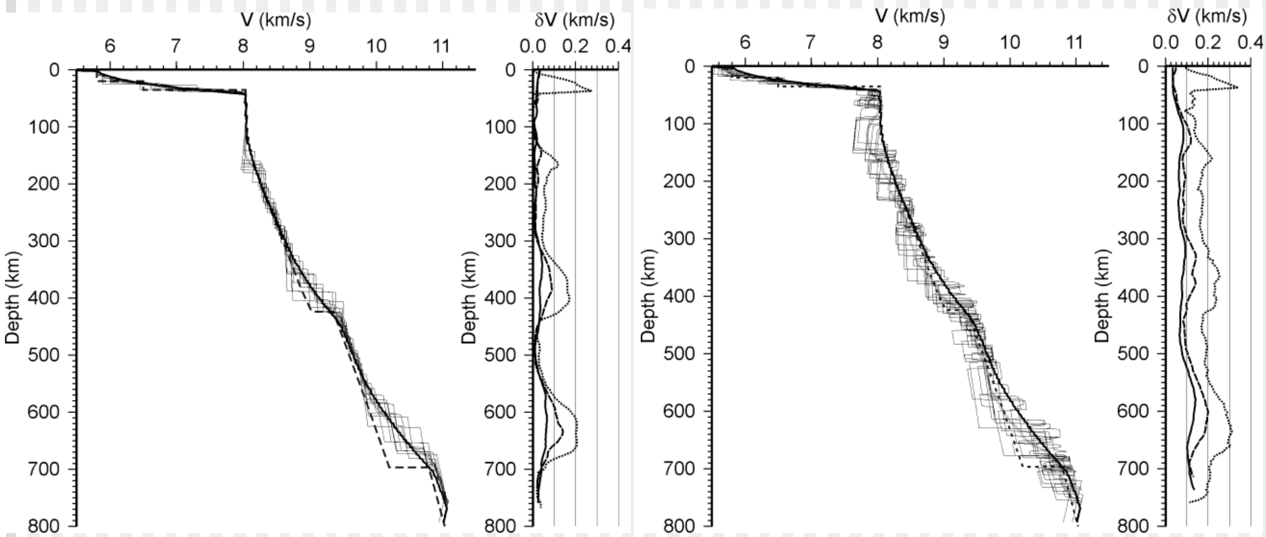


From Liner, 1999

Earth is complex

and so are the observations, but <u>models are always simplified</u>

- Observations are limited to the surface or a few boreholes.
- Different rocks often have similar seismic properties:
  - Seismic waves are sensitive to combinations of V_P, V_S, and density (we will study these combinations in this class)
  - Spatially-averaged and sample-derived properties are different;
  - Seismic properties are often *frequency-dependent*.
- Therefore, ambiguities in interpretations are common.
  - Solution – always keep an open mind and estimate the errors and use multiple methods to remove ambiguity.



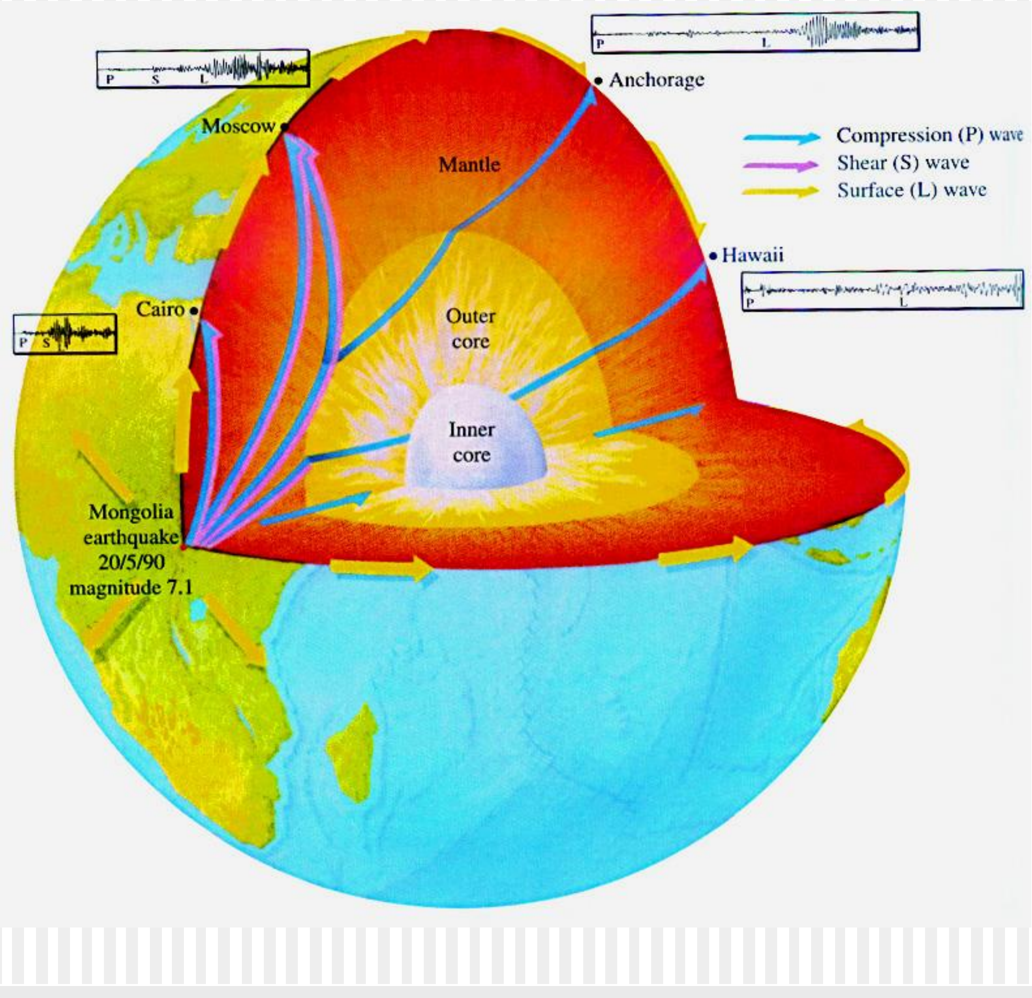
These plots show the uncertainty of velocity models (many thin lines) for the upper mantle from refraction models of nuclear explosions (explained later)

Examples of seismic work

- In the following slides, I show some examples of the most spectacular seismic work in which I happened to be involved

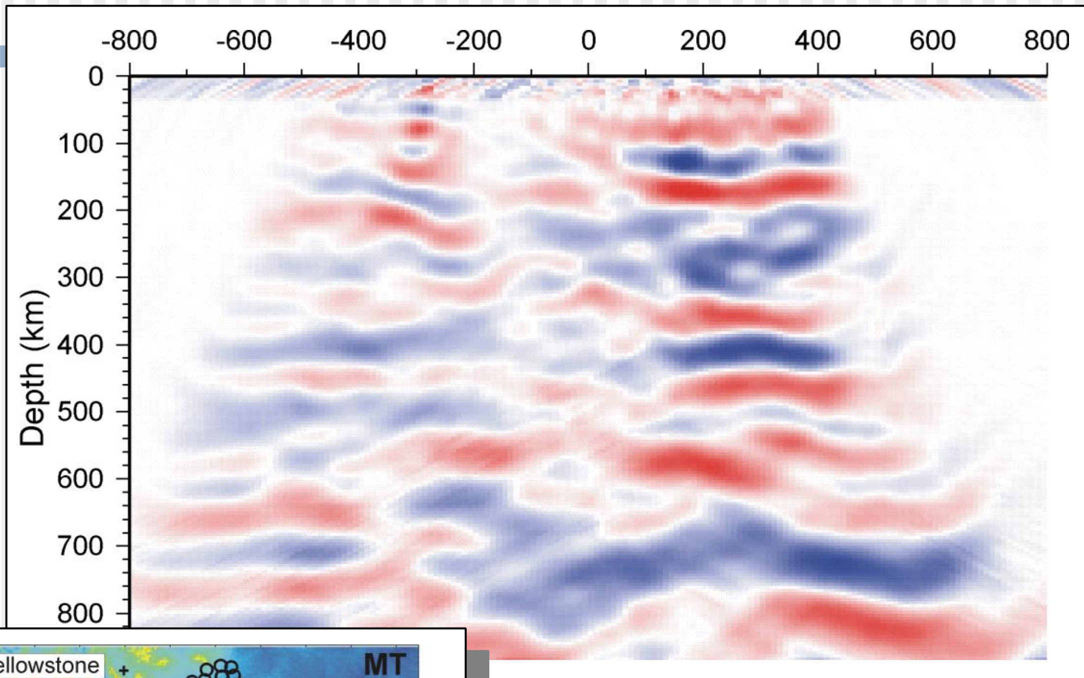
Earthquake seismology

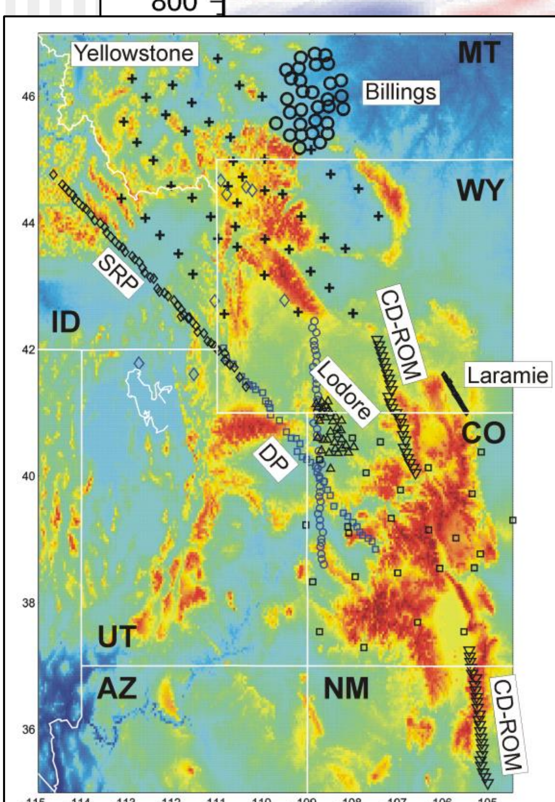
- This is not my work, just a cartoon showing how global-scale earthquake seismology works (deep structure, different types of waves, different sources, paths, recording locations and environments)



Teleseismic

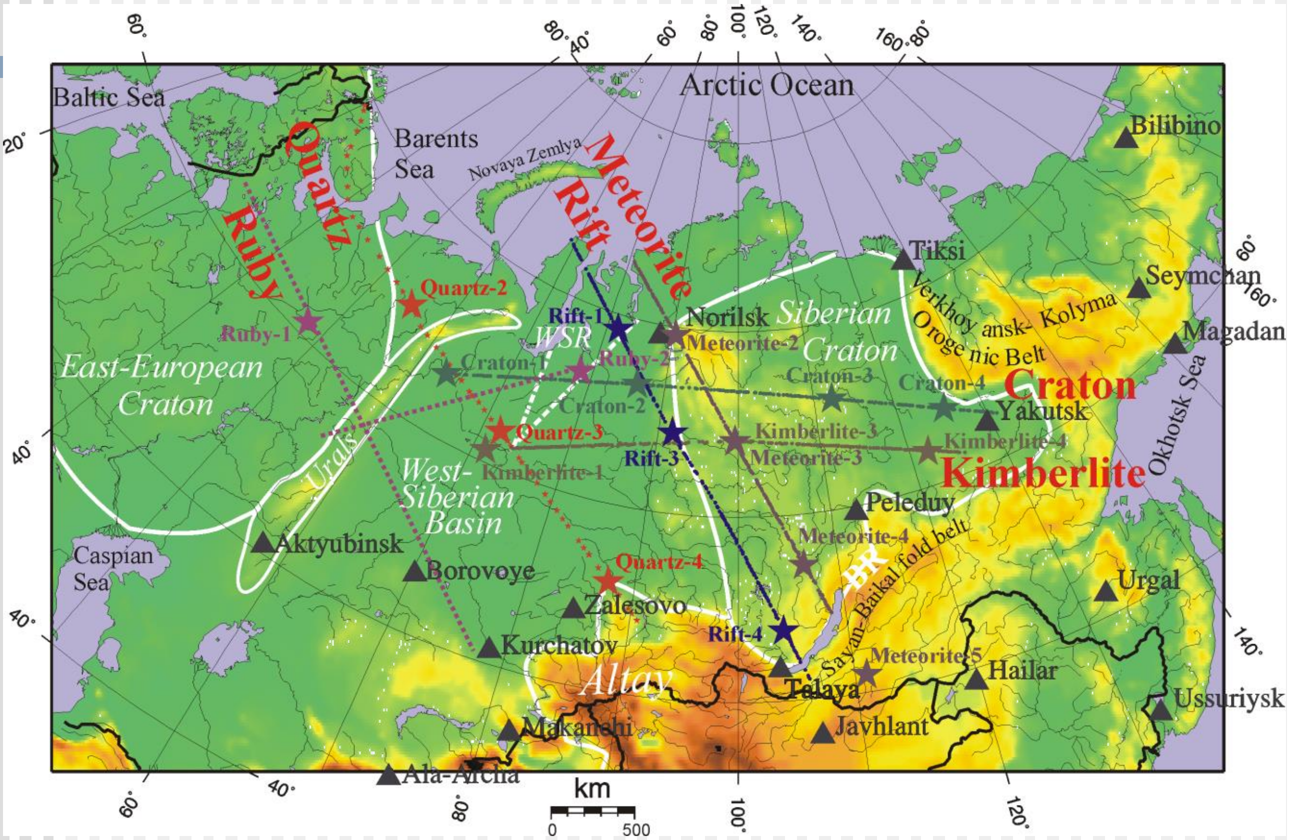
(Using signals from earthquakes beyond ~2500 km)





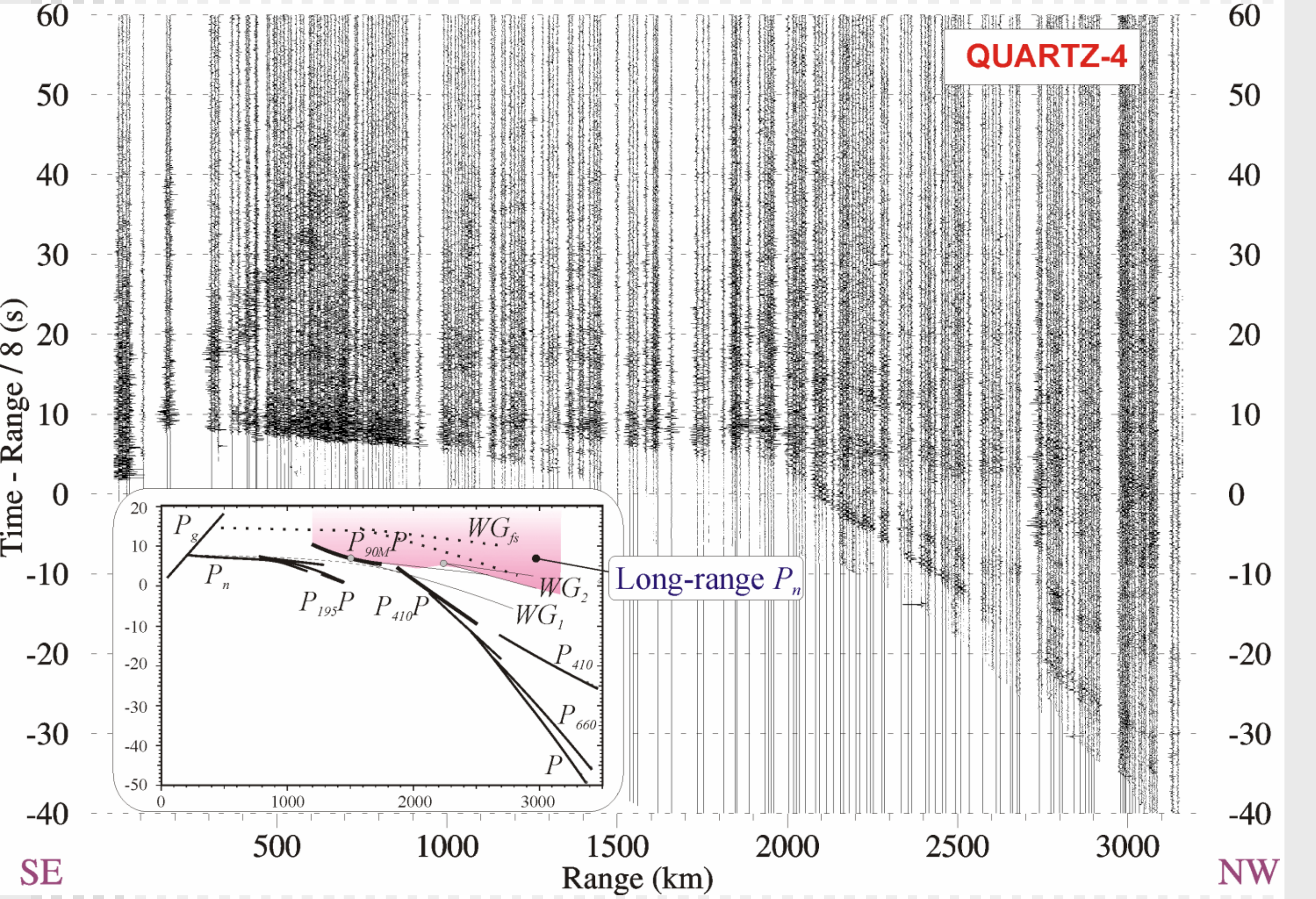
- This is a P/S “converted-wave” study of the upper mantle using teleseismic recordings (at > 1000 km from the earthquakes)
- A “passive” seismic array across three U.S. states (“CD-ROM” in the map)
- Reveals the base of the crust, velocity variations within the mantle;
- *P-S* 'converting' boundaries within the mantle.

Nuclear Explosions



- This is a megaproject in the Soviet Union in 1960-80’s which marked a unique era (unfortunately, gone) in deep-Earth science.
- 39 nuclear explosions were recorded in a quasi-3D grid of ultra-long range profiles using ~400 three-component recorders
- We looked at many of these profiles, and particularly profile Quartz extending from near Norway to Altay

Nuclear Explosions

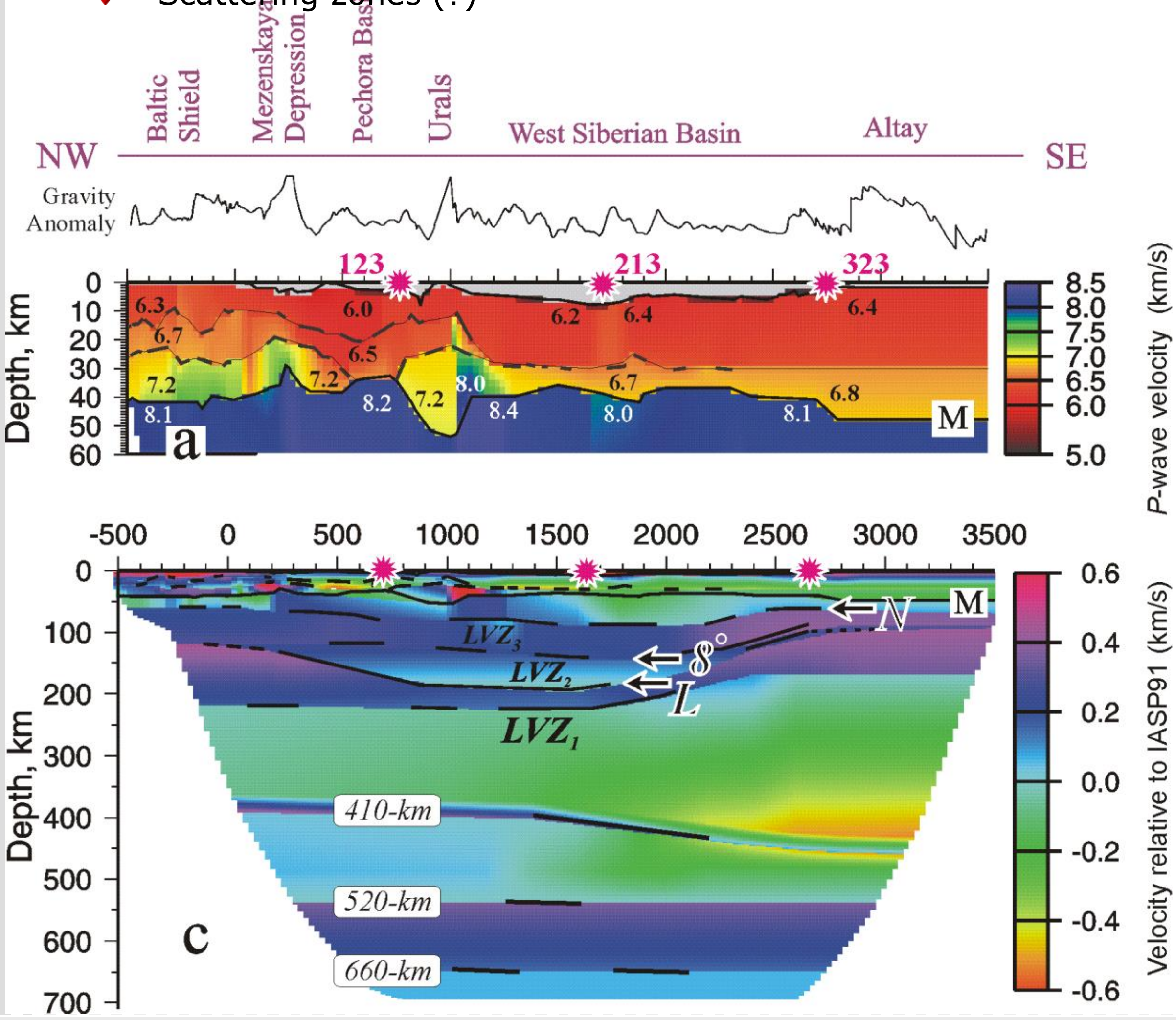


- Seismic records from the southern nuclear explosion of profile Quartz
- The inset shows a sketch of seismic waves identified in these records
- The meaning of the "long-range Pn" (highlighted with pink) was a subject of considerable debate at the end of 1990's
  - We say this is a "whispering-gallery" mode (multiple up-side reflections of a wave refracting through the upper mantle)
- This record also contains reflections from the Earth's core!

Deep structure

Interpreted from 3 PNE records like in the preceding slide + 55 large dynamite explosions in profile Quartz

- Note **a lot of structure** that cannot be seen in any other way:
  - Depths to ~700 km (some reflections from the outer core at 2900 km)
  - Velocity heterogeneity
  - Reflecting boundaries
  - Attenuating zones (partial melts?) within the mantle
  - Scattering zones (?)



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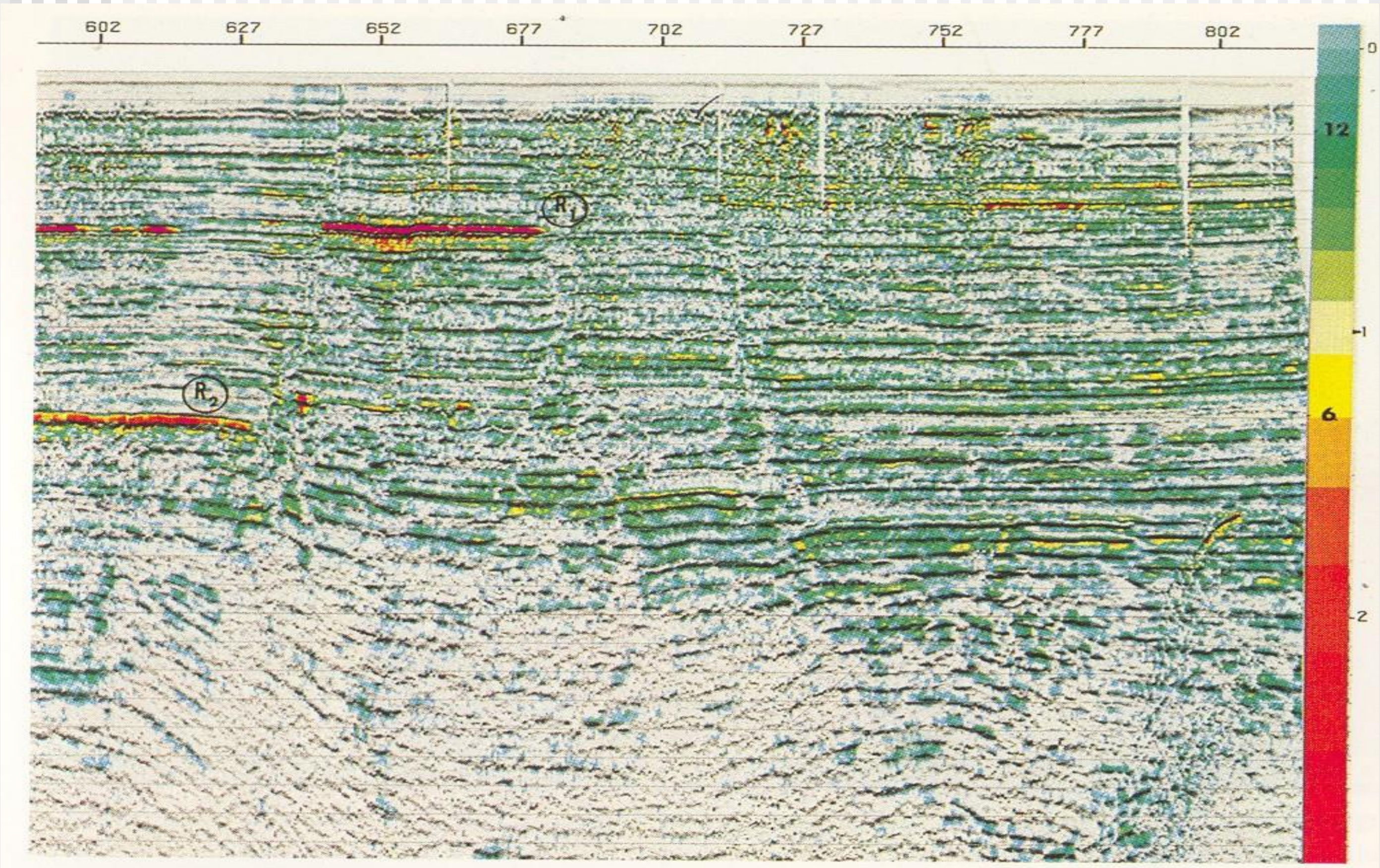
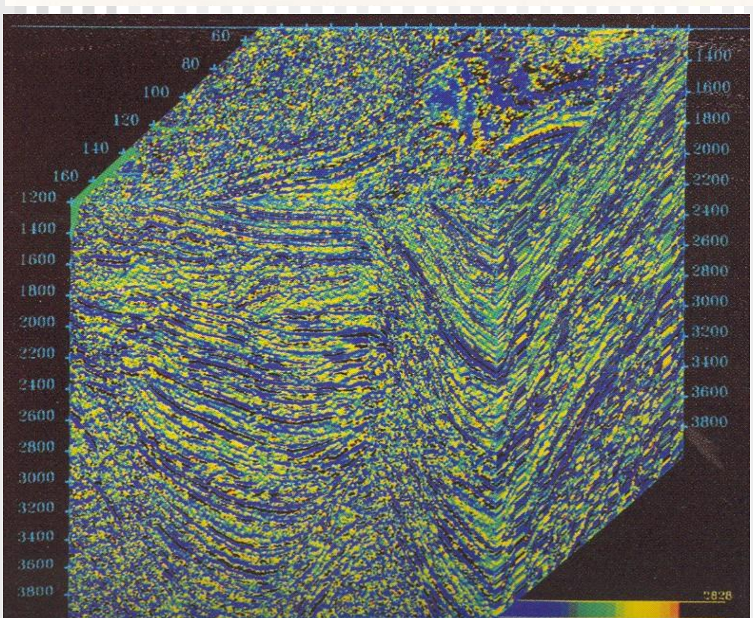
Oil/Gas exploration seismology

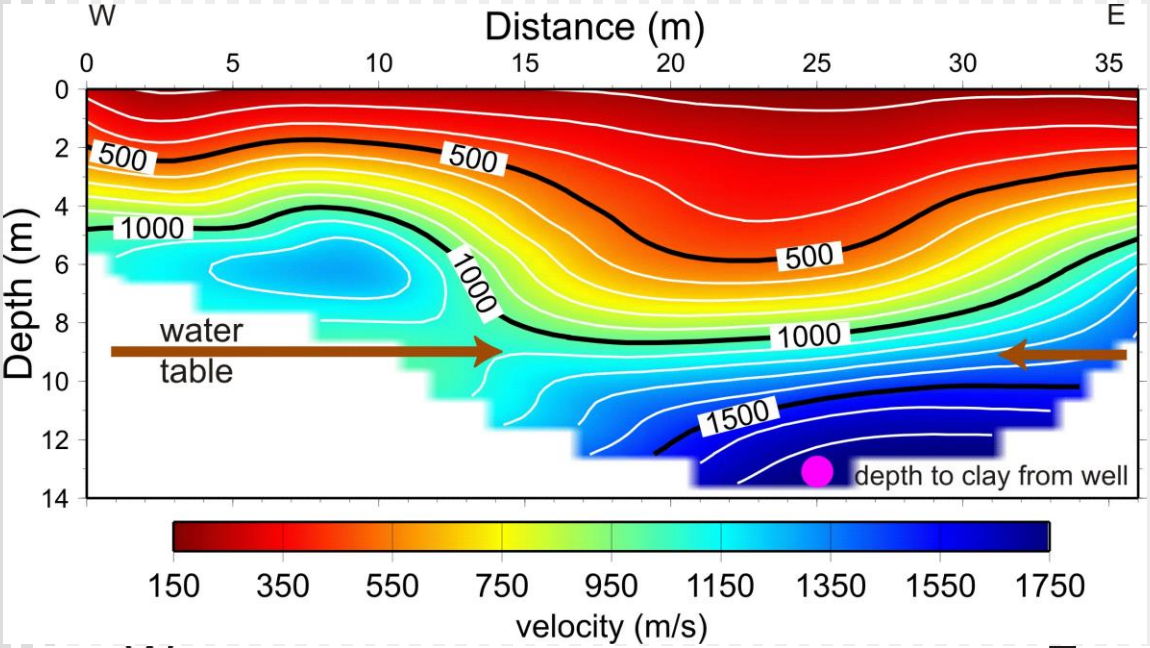


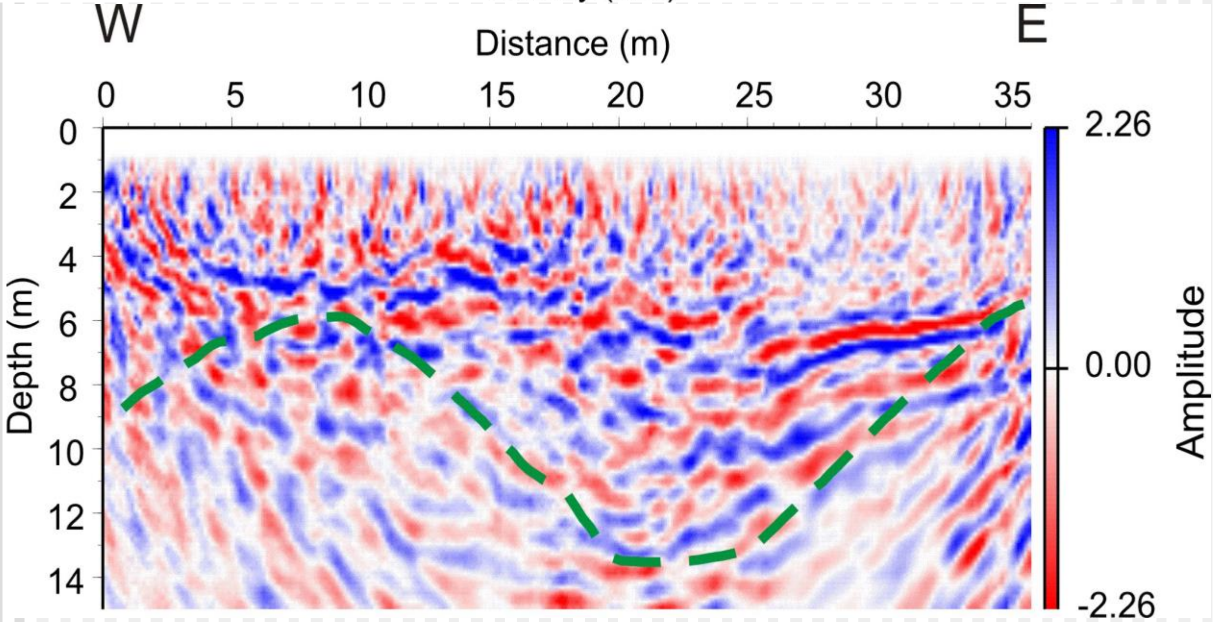


- Here is about how the data look in refection seismology:
  - Depths 1 to 5 km
  - Large volumes;
  - Great amount of detail (resolution);
  - High accuracy;
  - Multi-step and intricate processing
  - Using many ways to present and interpret

Shallow/engineering seismology

- The opposite end of depth range: 2 to 10-m depth reflection tomography (upper plot) and reflection image (bottom)





Key texts

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- Sheriff, R. E. (1991) *Encyclopedic dictionary of Exploration geophysics*, 3rd edition, Tulsa, OK, 384 pp.
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