Seismology

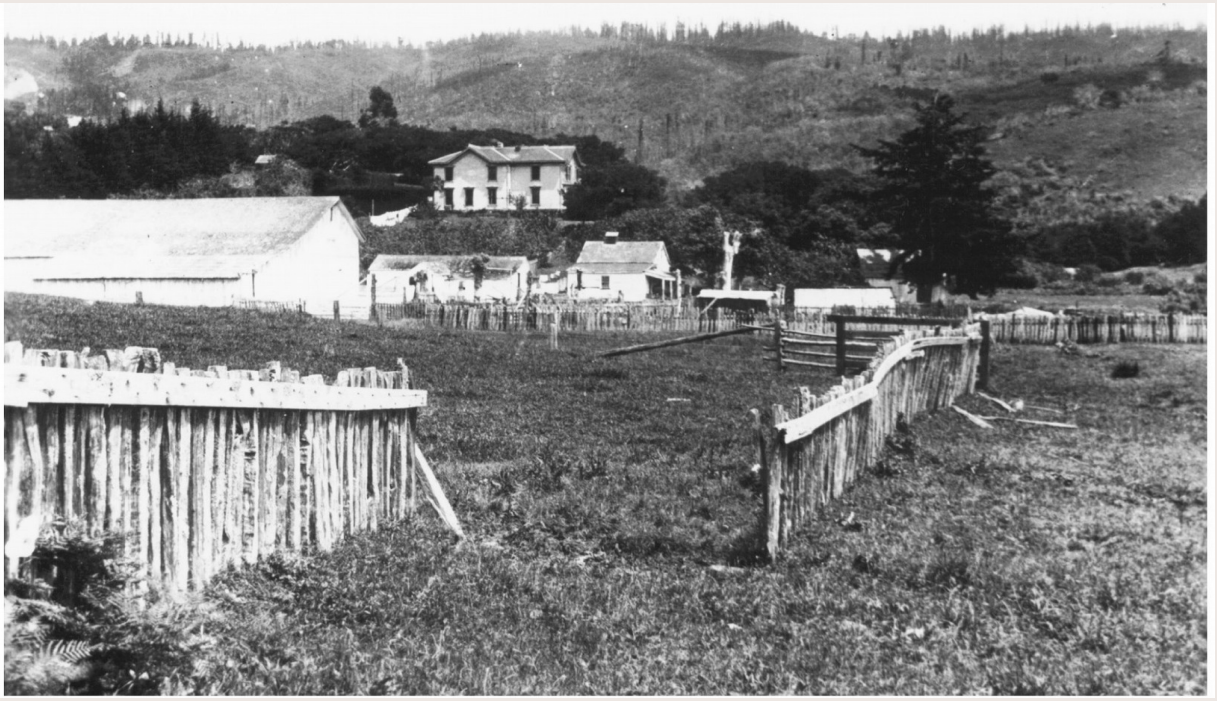
as a part of Geophysics

- Use of elastic waves to learning, understanding of the Earth and other planetary bodies.
- Involves determination of various properties of the Earth via the application of physical theories and experimental techniques.
- Consists of:
  - Measurements ('data acquisition');
  - Data processing;
  - Interpretation in terms of models and geological concepts:
    - Forward modelling - given a cause (plus a theory!), determine the effect;
    - Inverse modelling - Given an observation (plus, maybe several theories!), determine the cause.
- <u>Reading:</u>
  - Reynolds, Chapter 1.
  - Shearer, Chapter 1
  - Telford *et al.*, Chapter 1.

Motivation for studying seismology

- By far the best-resolution non-invasive subsurface imaging method
  - Key tool in oil/gas exploration
  - Shallow and environmental imaging
- Understanding and mitigation of natural hazards
  - Mining
  - Earthquakes
  - Tsunamis
  - Nuclear tests
- **Key source of knowledge about the Earth**

Seismic Hazards



Fence offset by the San Francisco 1906 earthquake

Normal faults pulling crust apart (Iceland)

Earth is a complex body (and so are the observations)

- Different geologic conditions yield similar distributions of physical properties.
- Observations are mostly limited to the surface.
- Therefore, uncertainties in interpretation are common.
- Solution - integrated interpretation using multiple methods to remove ambiguity.

Geophysical Methods

- Rely on *contrasts in physical properties* associated with rock or mineral bodies:
  - Look for 'anomalies' (departures from some 'regular behaviour').
- Geophysicist needs specialized methods and tools to solve different problems:
  - *i.e.*, different methods measure different properties;
  - The results are combined during interpretation.

Geophysical Tools Available

'Passive' and 'Active'

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

- 'Active' methods (involving an artificial disturbance) are highlighted in yellow.

Geophysical Methods

- Geodesy (shape of the Earth) and gravity measurements
  - Initial, reconnaissance work;
  - Shape of the Earth;
  - Plate motion;
  - Basin shapes and extents;
  - Structural trends, fault locations;
  - Location of local changes (anomalies) suggesting economic ore deposits.
- Magnetic methods
  - Plate motions;
  - Limits of basins;
  - Depth to basement;
  - Basement lineations;
  - Ores associated with magnetic minerals.

Geophysical Methods

- Seismology
  - Highest-resolution;
  - Earthquakes;
  - Whole-Earth oscillations;
  - Surface waves;
  - Study of the interior of the Earth
    - From as shallow as 1 m to as deep as 6400 km.
  - Refraction seismics
    - Detect high-velocity formations;
    - Depth to beds, velocities and gradients.
  - Reflection seismics
    - Types of structures;
    - Maps structures in 2D and 3D;
    - Spatial relationships of various features:
      - Geological history, unconformities;
      - Depositional environments.
    - Sediment velocities;
    - Oil field monitoring and development.

Most Important !

Geophysical Methods

- Radioactive methods
  - Location of radioactive materials;
  - Rock type distribution;
  - Age of rocks.
- Electrical Methods
  - Variation of resistivity (conductivity) with depth;
  - Location of conductive/resistive mineral deposits.
- Borehole Logging
  - Most detailed in vertical dimension;
  - Nature of sedimentary rocks;
  - Reservoir rock properties;
  - Location of minerals.
- Lab methods
  - Physical properties;
  - Calibration of field results.

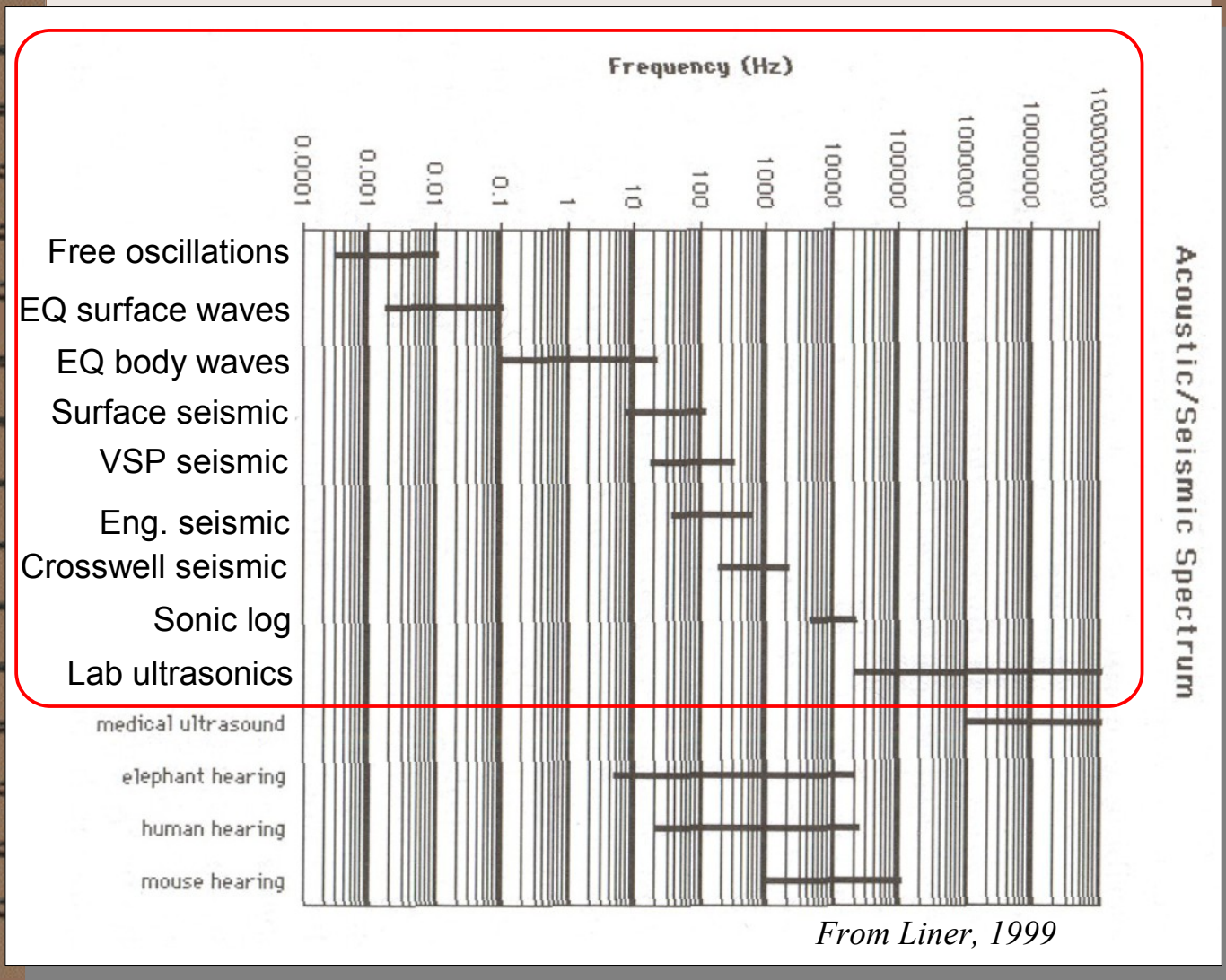
Worldwide Costs

Petroleum Exploration in 1991

- Land:
  - Seismic: $\$10^9$;
  - Gravity: $\$3 \cdot 10^6$;
  - Magnetic: $<\$10^5$.
- Marine:
  - Seismic: $\$10^9$;
  - Gravity: $\$10^6$;
  - Magnetic: $<\$5 \cdot 10^5$.
- Airborne:
  - Gravity: $\$2 \cdot 10^6$;
  - Magnetic: $<\$4 \cdot 10^6$.
- Development:
  - Seismic, land: $\$30 \cdot 10^6$;
  - Seismic, marine: $\$50 \cdot 10^6$.

Acoustic/Seismic Spectrum

- The key issues are *signal penetration* and *resolution*:
  - Resolution (the degree of resolvable detail) is typically *proportional* to frequency;
  - Signal penetration quickly *decreases* with increasing frequency.



From Liner, 1999

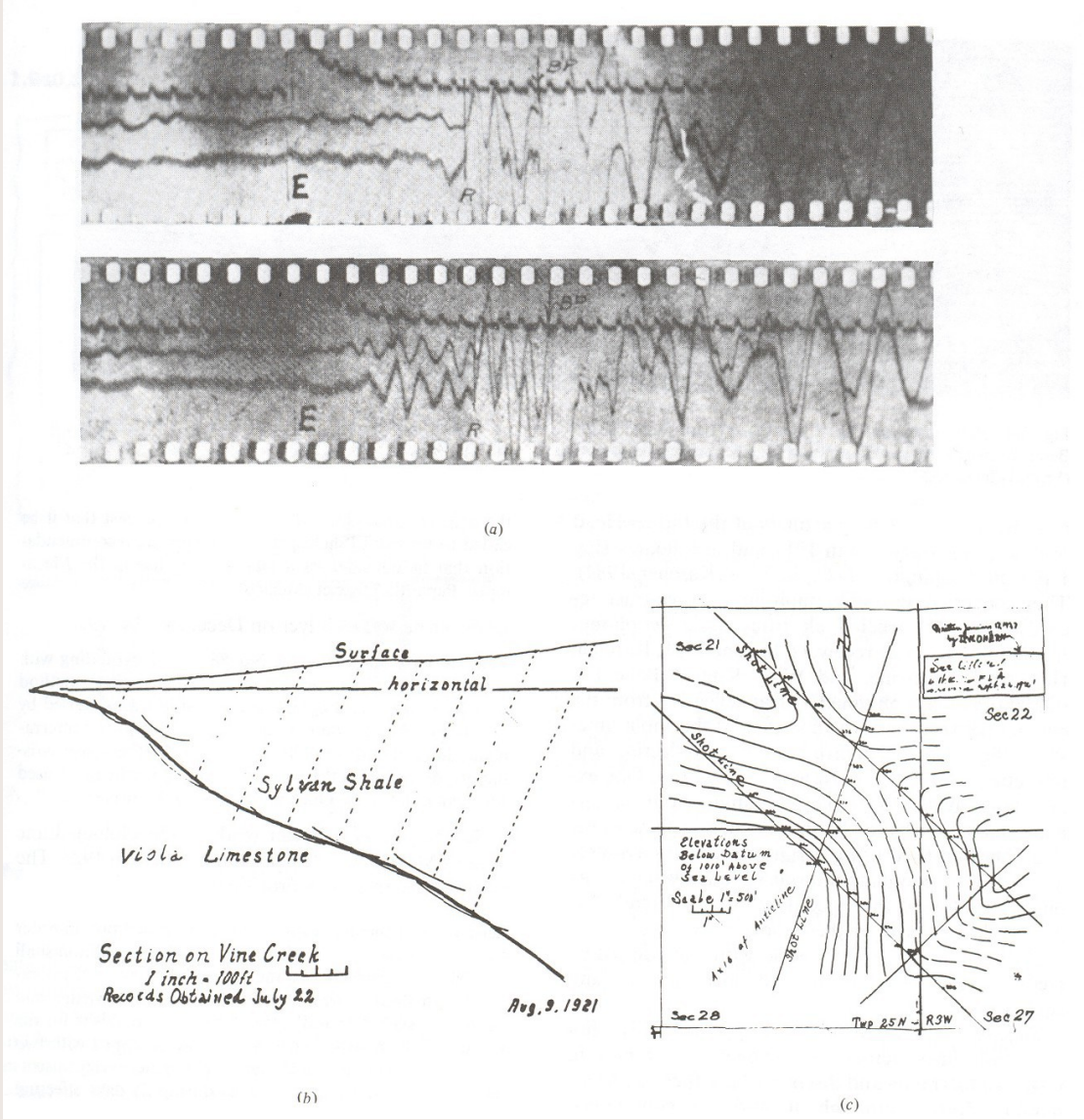
Brief History of Exploration Geophysics (Oil/Gas)

Pre-Digital Computer (before 1960)

- 1899-1907: Theory of seismic reflection and refraction (Knott, Wiechert, Zoeppritz);
- 1906: Golitzine invented electromechanical seismograph;
- 1915: successful gravity survey by Eõstvõs (Hungary) to delineate an oilfield in Czechoslovakia;
- 1917: Schweider used gravity to detail a known salt dome in Germany; later confirmed by drilling;
- 1920: Discovery of Nash Salt dome in Texas (De Goyer);
- 1914-1918: World War I. Developed seismic-based techniques to locate heavy enemy artillery (Mintrop);
- 1918-1920: Mintrop and Karcher (U.S.) pioneered seismic techniques for salt dome exploration;
- 1930: Society of Exploration Geophysicists founded. 'Geophysics'.
- 1953: Magnetic tape became commercially available. Birth of playback processing.
- 1953: Vibroseis method developed (Conoco) but not applied extensively until ~1970's.
- 1956: The Common-Midpoint (CMP) method patented.

First seismic records

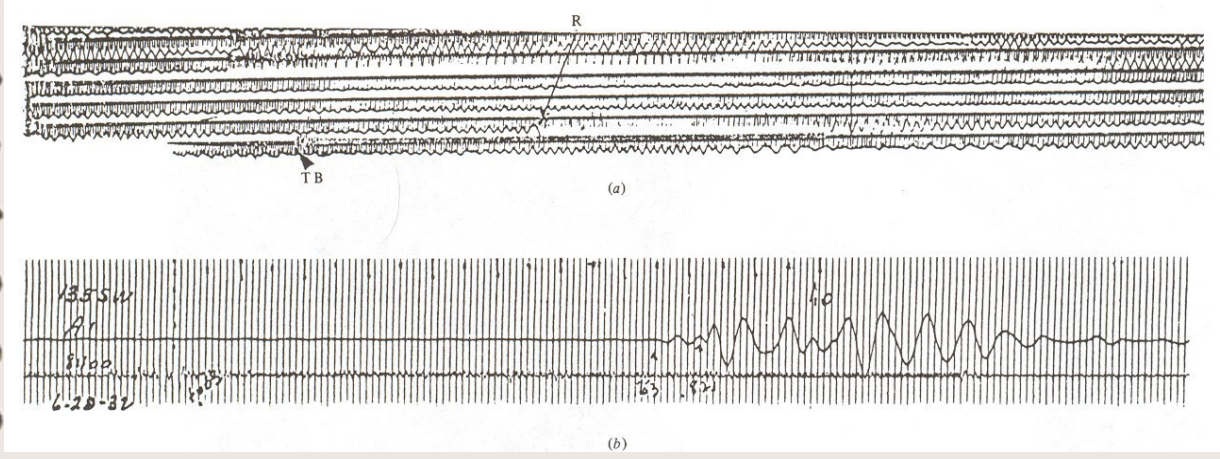
Reflection (1921, Karcher et al., Oklahoma City)



From Schriver, 1952

First seismic records

Refraction (1924-25, 1932, Marland Oil, Texas)

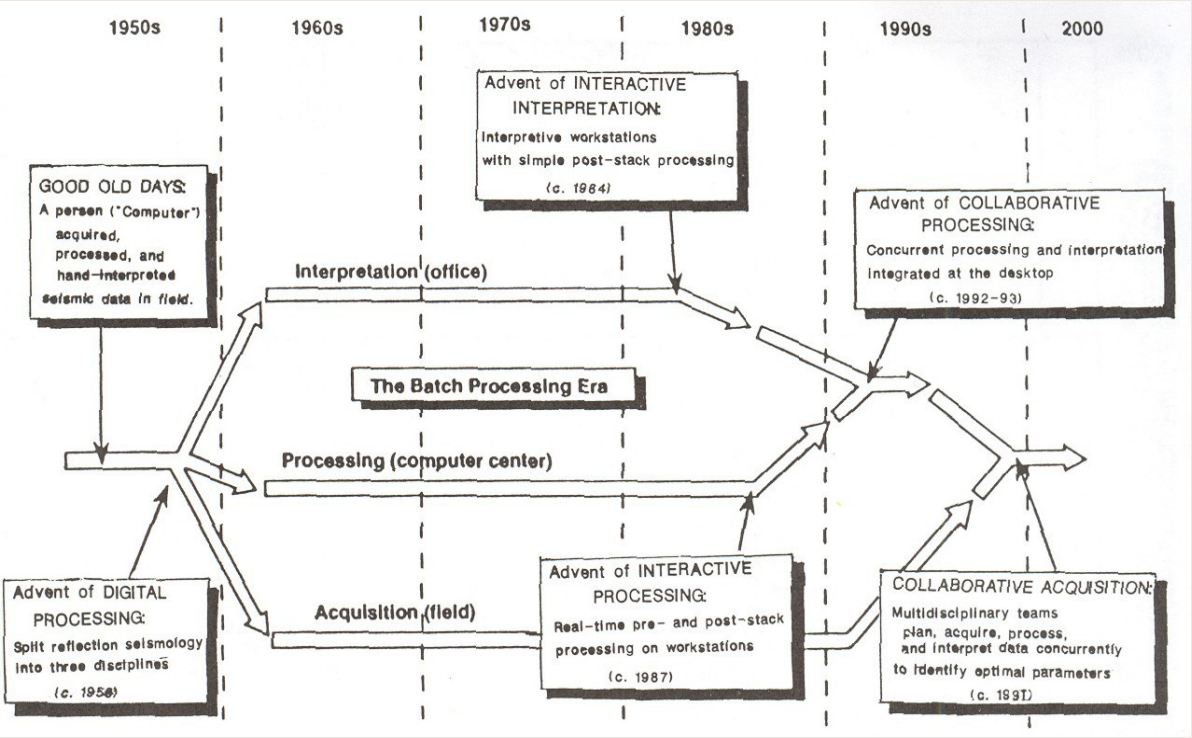


From Scheriff and Geldart, 1995

Brief History of Exploration Geophysics (Oil/Gas)

- Digital Computer Era (after 1960):
  - Birth of modern Data Processing industry;
  - Affected every field and method in geophysics
    - Computer to a geophysicist is like microscope to biologist, or telescope for astronomer.
  - 2-D, 3-D, 4-D (time-lapse) seismic;
  - mid-70's: production-related seismics;
  - PC clusters
    - 1000's of computers working on one task.
- 2000's:
  - 10's of thousands of *solid-state* recording channels on the ground;
  - Routine 3-component recording;
  - Graphics Processing Units
    - 100's of processors on a single board;

The Digital Era



Mainframes

UNIX workstations, PC's

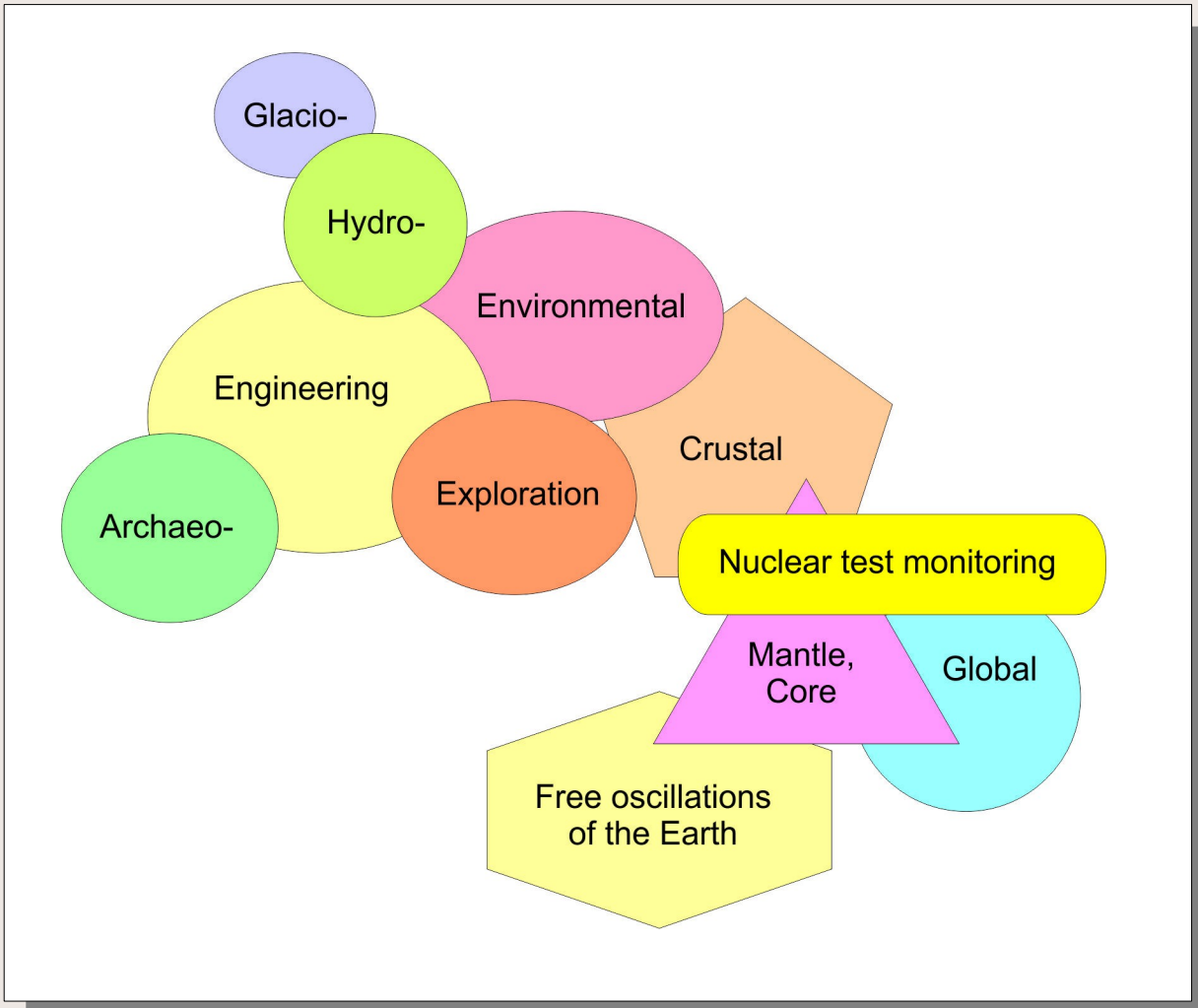
Beowulf Clusters

GPU's

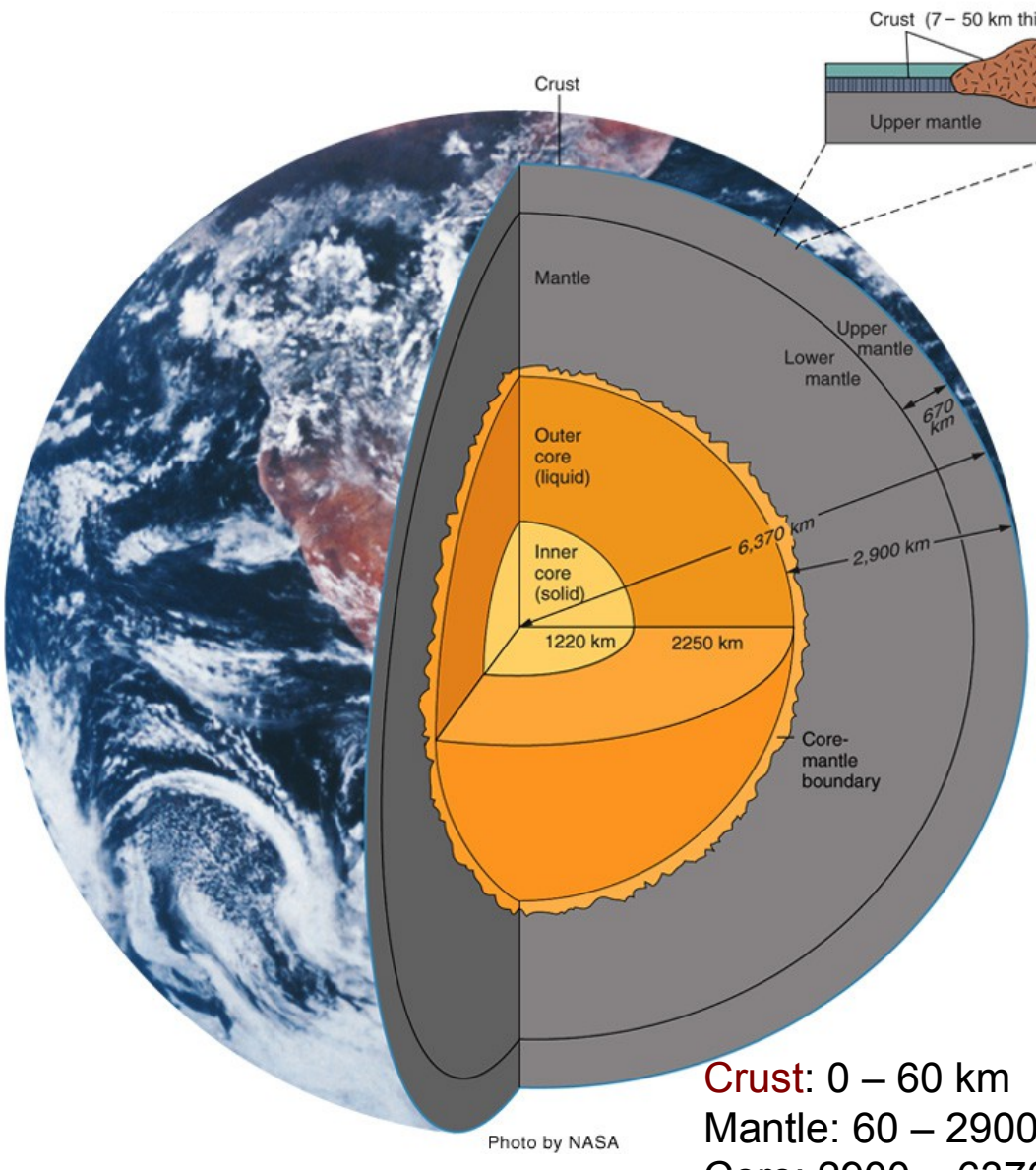
Major advances
in Geophysics and Seismology

- 1960-1980's: Regional Nuclear-Explosion seismology (U.S.S.R.);
- 1970's-90's: Continent-scale controlled-source seismic profiling
  - COCORP (USA)
  - Lithoprobe (Canada)
  - DEKORP (Germany)
- 1970's: Lunar seismology (Luna, Apollo);
- 1970-80's: Environmental and Engineering, Archeological, and Mine Geophysics;
- 2000's-present: Continent-scale migrating passive arrays (USArray, Polaris in Canada).

Seismology sub-disciplines

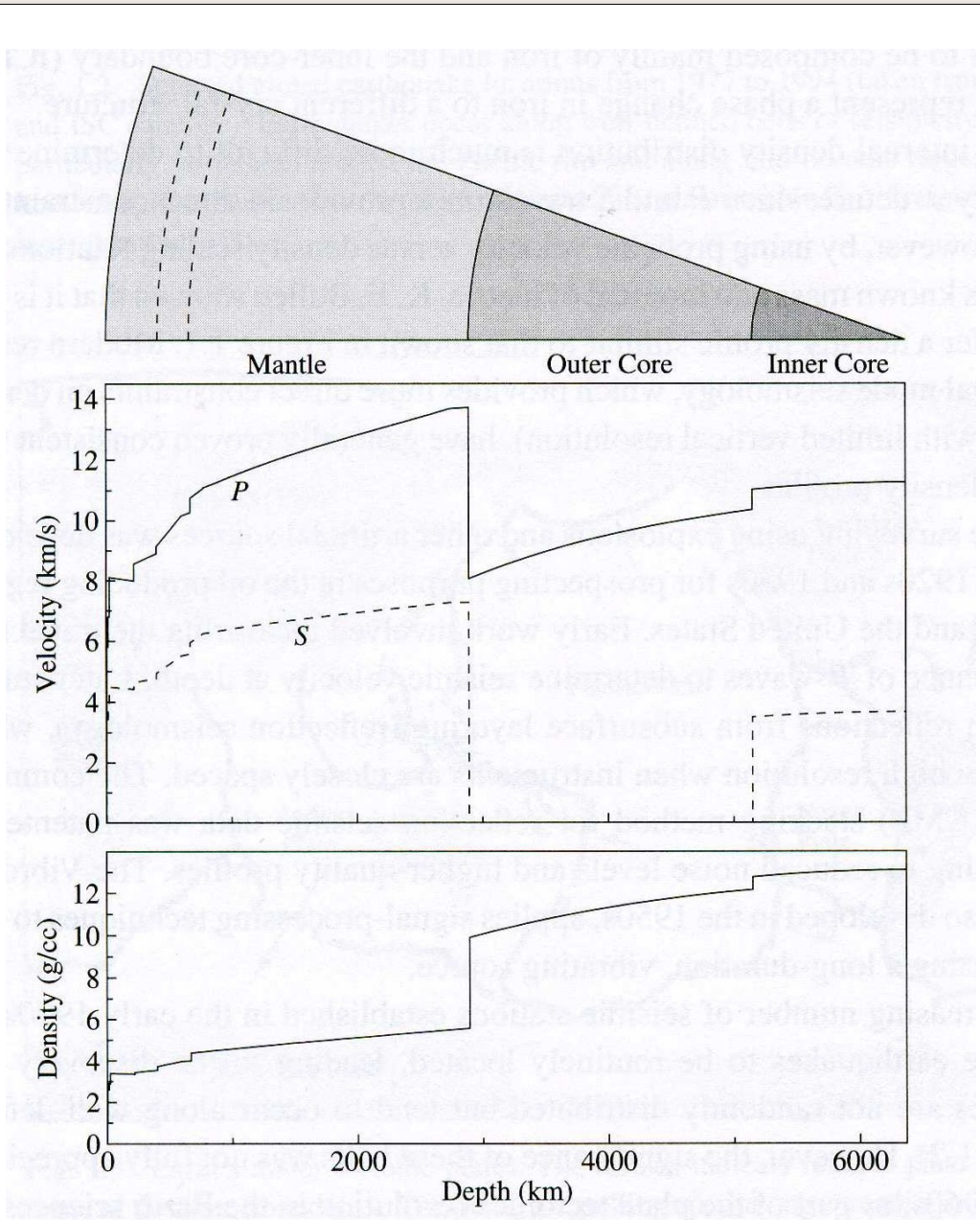


Seismology reveals:
Internal structure of the Earth

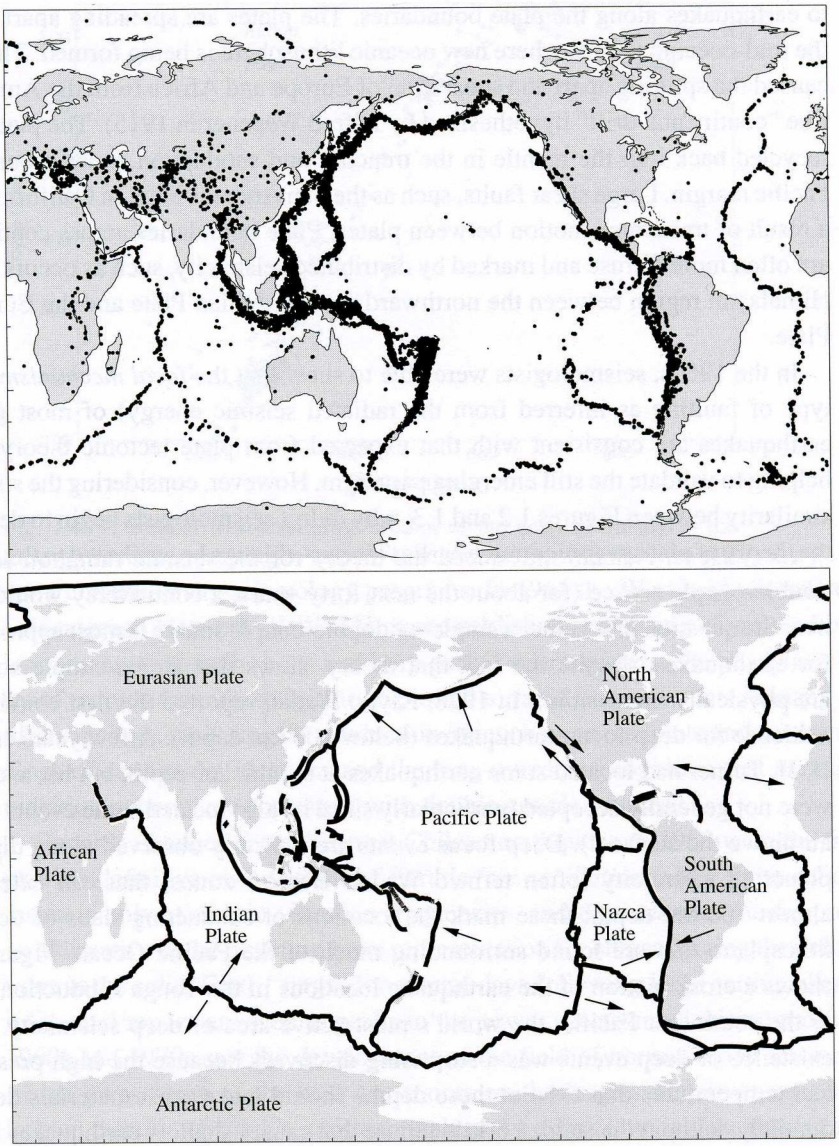


Crust: 0 – 60 km
Mantle: 60 – 2900 km
Core: 2900 – 6370 km

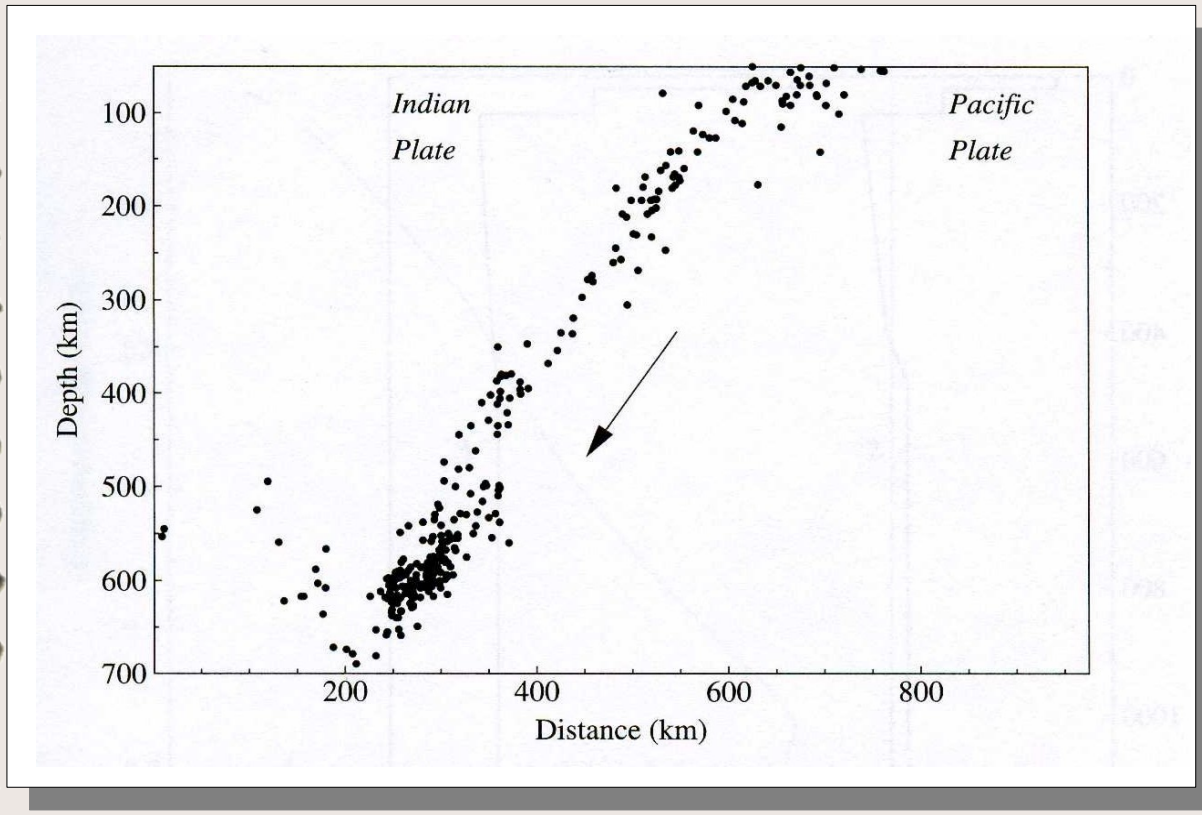
Seismology reveals: physical properties



Seismology reveals:
Tectonic plates

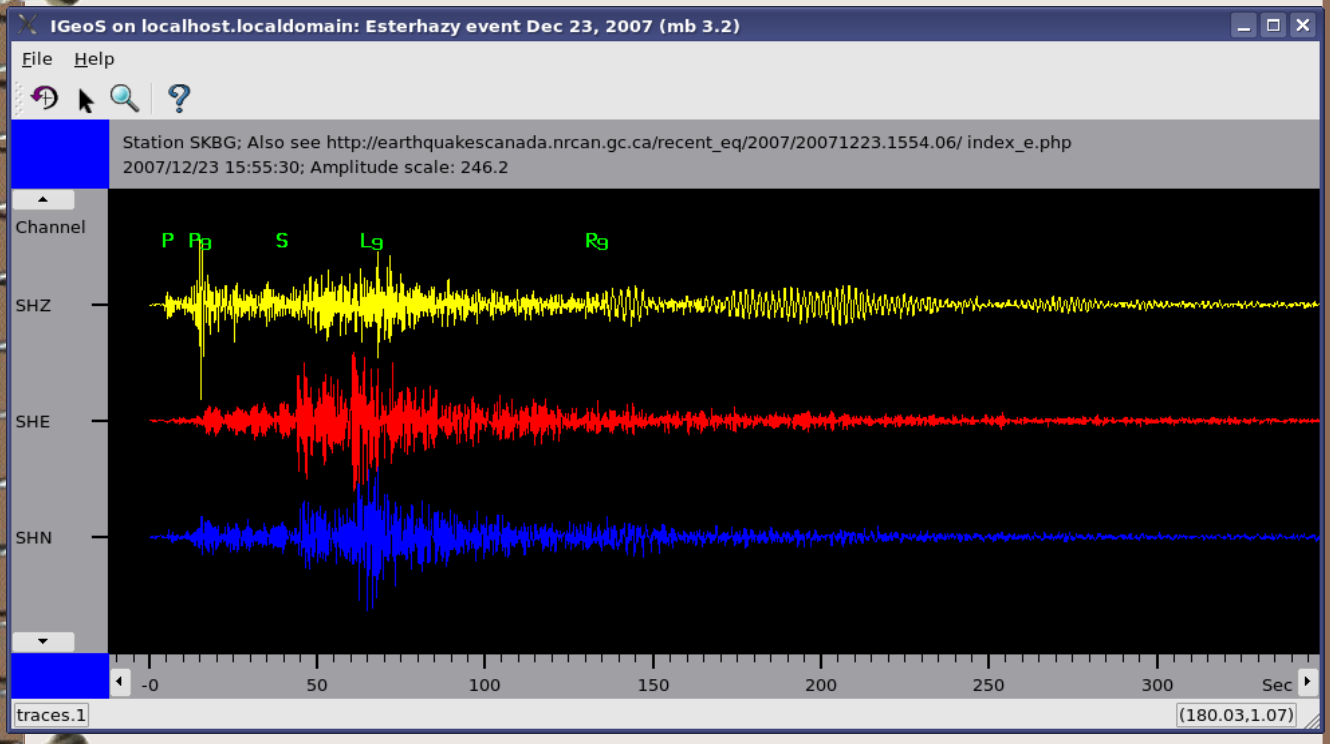


Seismology reveals:
Plate subduction



- Tonga subduction zone (~18 years of seismological observations shown here!)

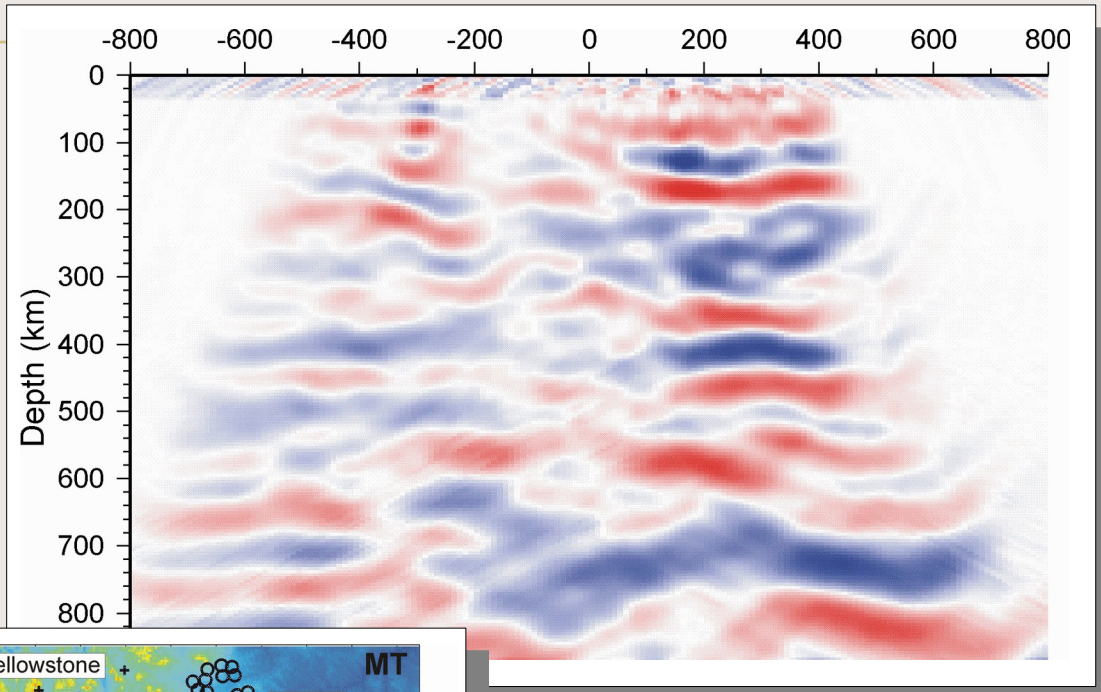
Seismic Monitoring

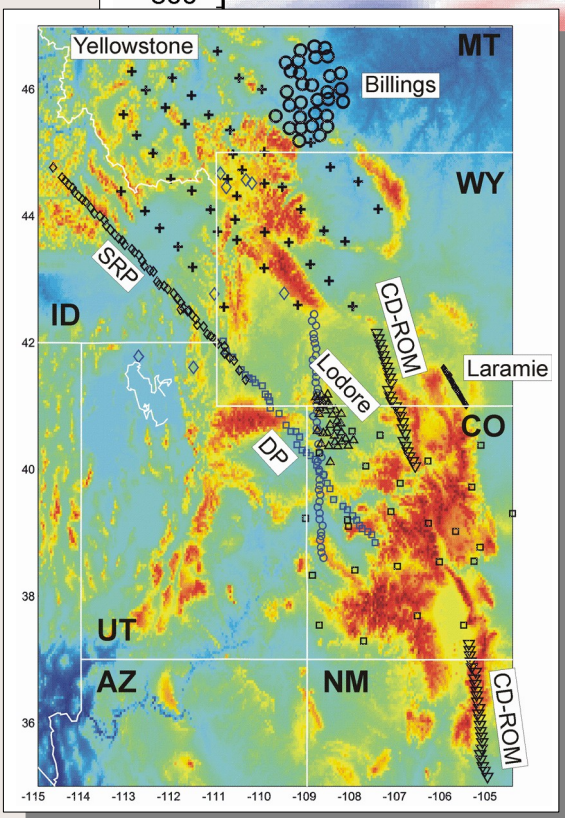


Mb 3.2 Esterhazy event on 23/12/2007
near Rocanville PCS mine

- Based on a combination of:
  - Instrumentation design and maintenance
  - Observation
  - Understanding the physics
  - Interpretation
  - Hazard mitigation

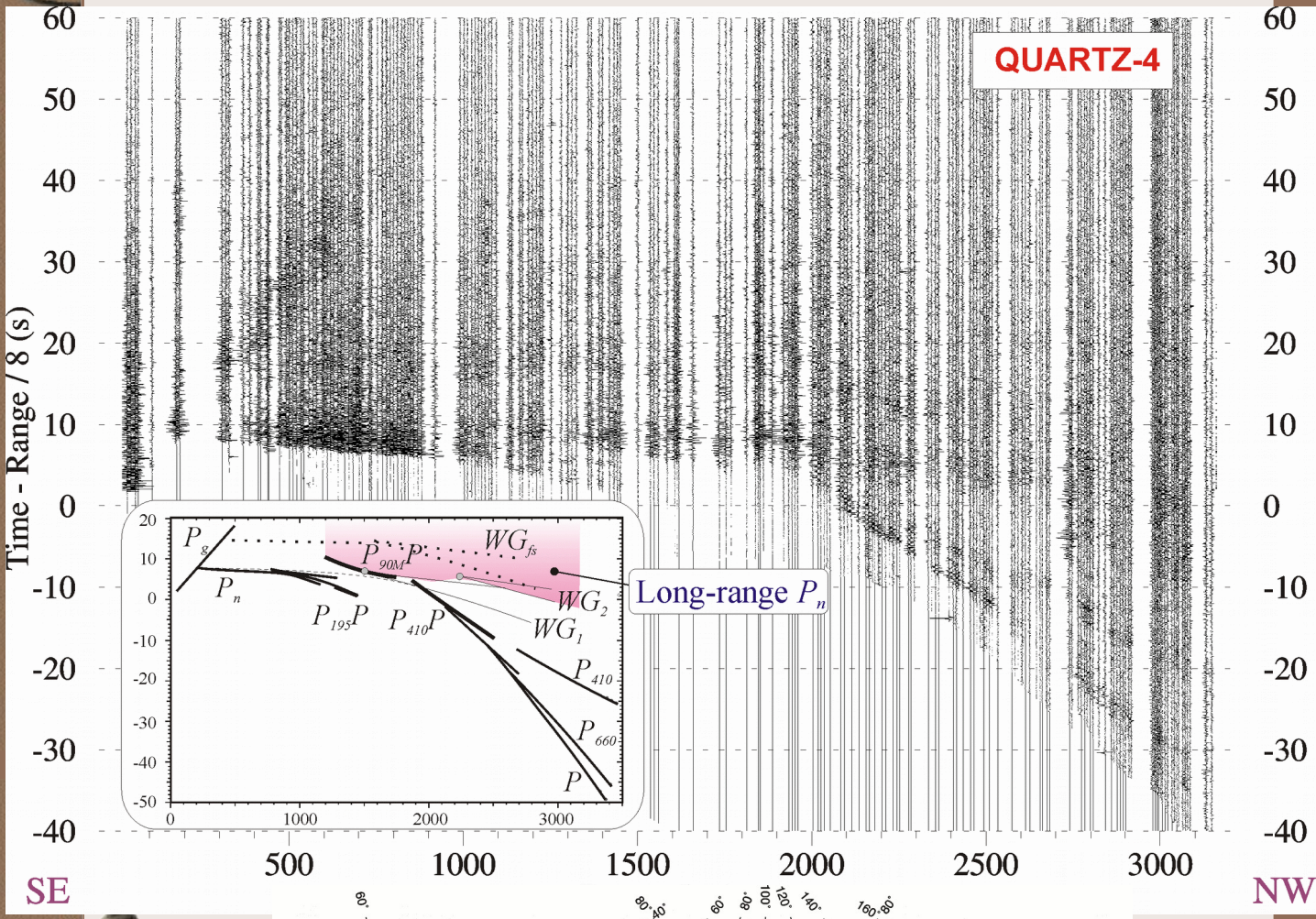
TeleSeismic Models
(from Earthquake records)

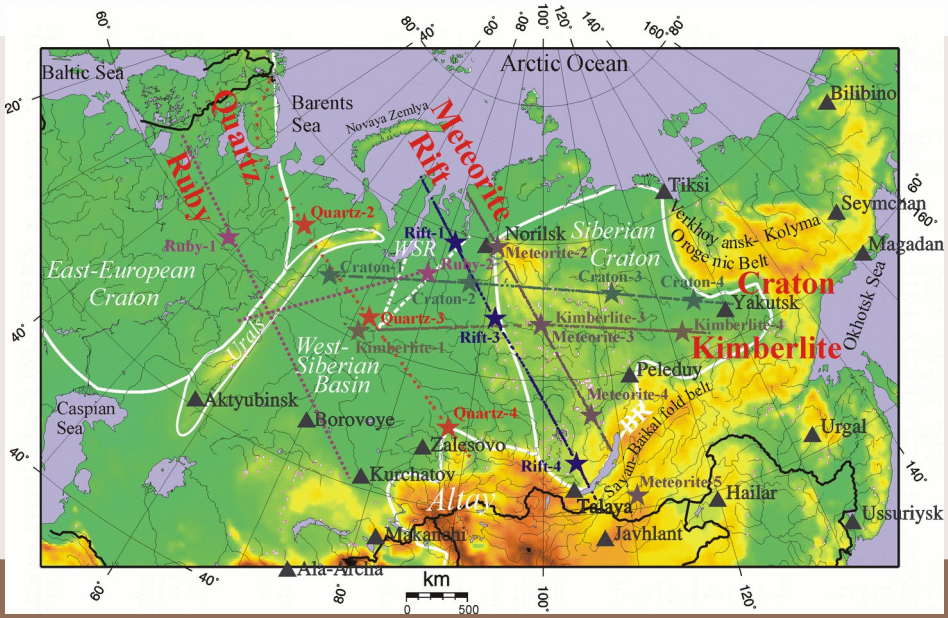




- Represent velocity variations within the Earth's mantle;
- *P*- to *S*-wave 'Converting' boundaries within the Earth's mantle.

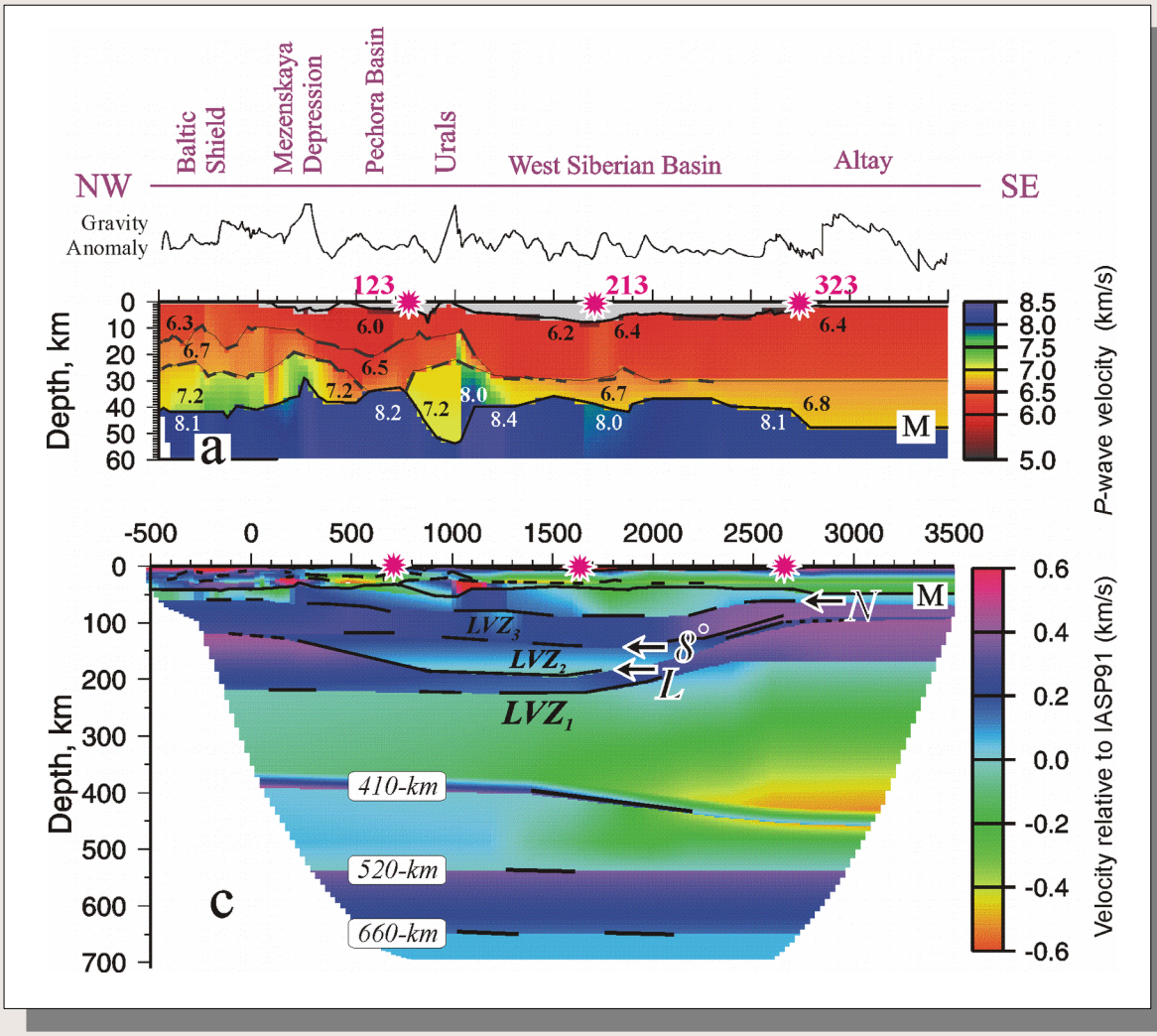
Upper-mantle seismology
(Peaceful Nuclear Explosions)





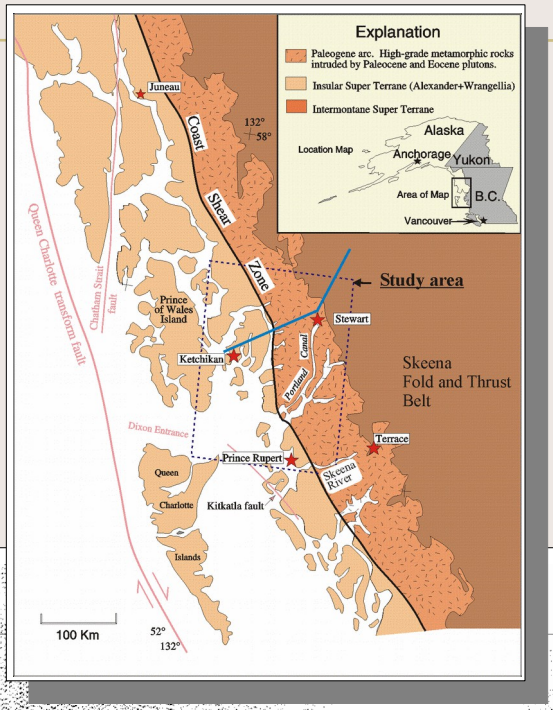
Upper-mantle structure
from Peaceful Nuclear Explosions

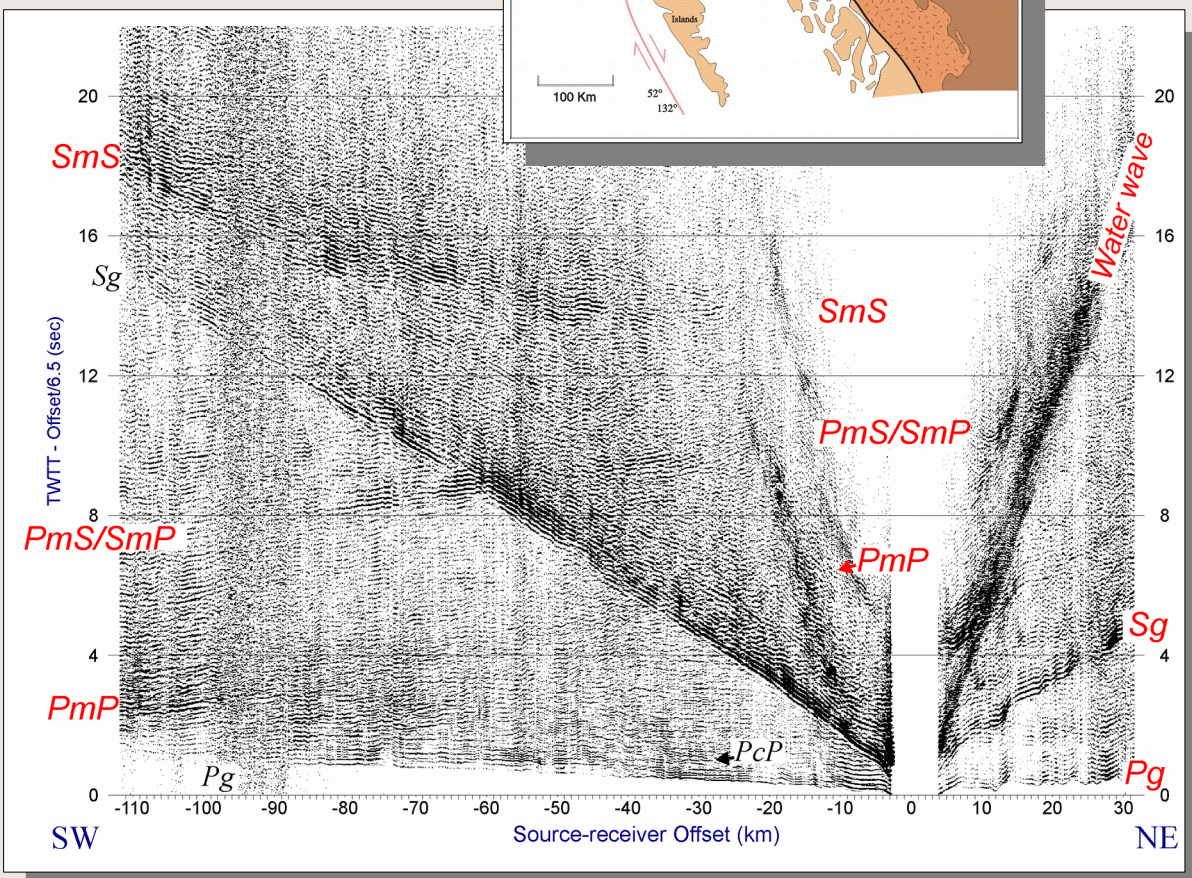
- Velocity variations;
- Reflecting boundaries;
- Attenuating zones (partial melts?) within the mantle.
- Scattering regions (?).



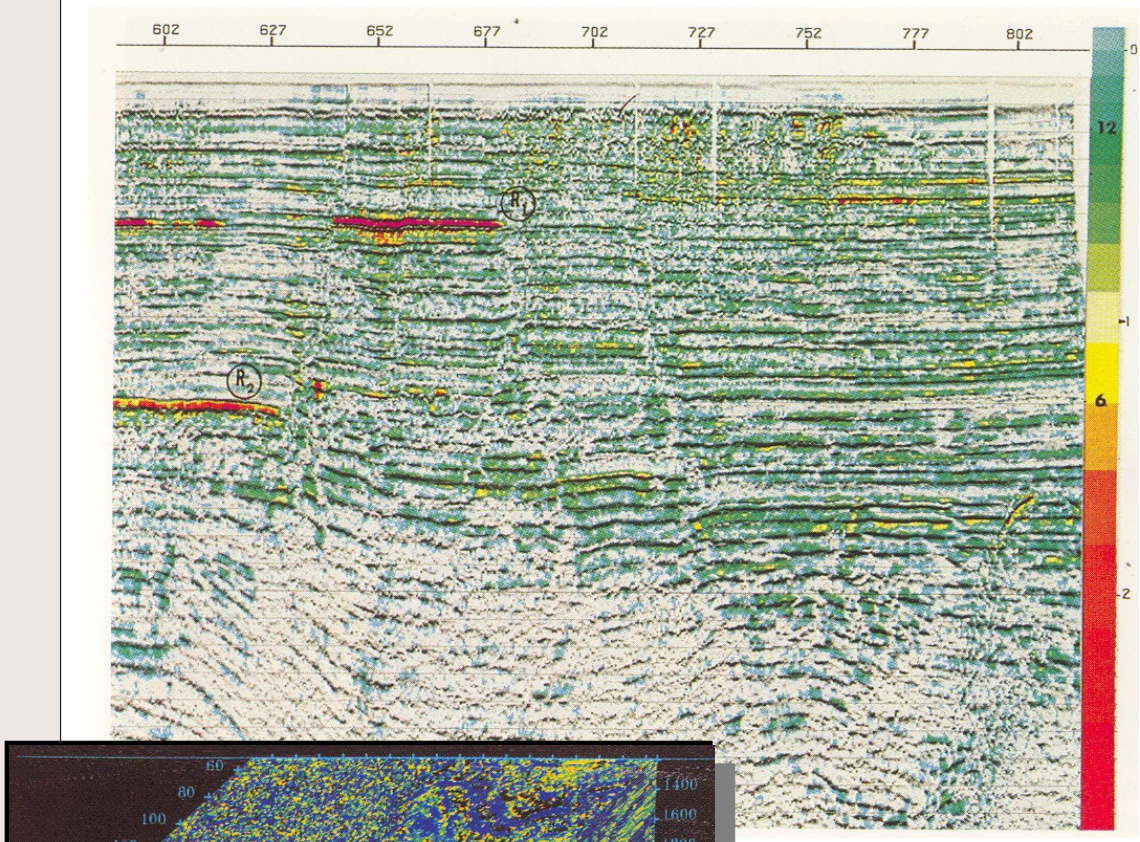
Deep crustal structure
(Reflection/Refraction seismic studies)

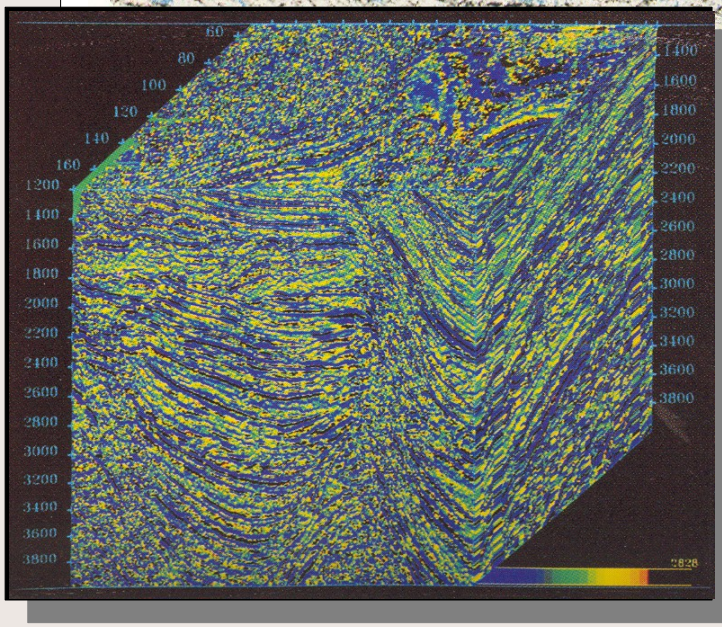
- Depth coverage to sub-Moho (~40 km);
- Good *velocity resolution;*
- Strong reflections from the *base of the crust* ("the Moho").





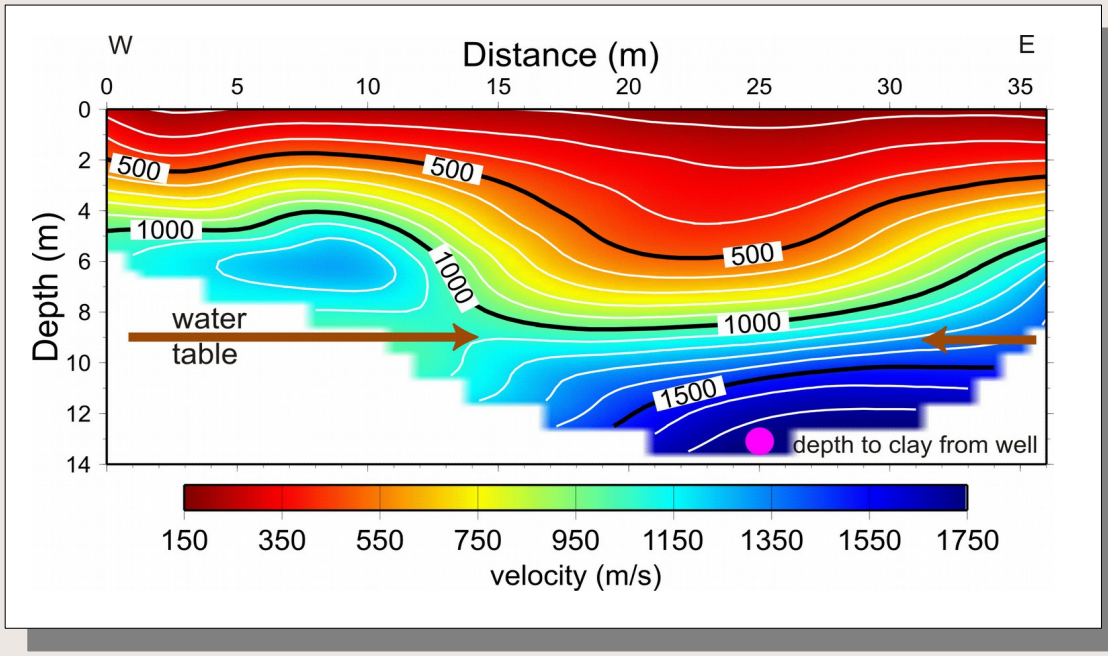
Sedimentary cover
(Exploration)

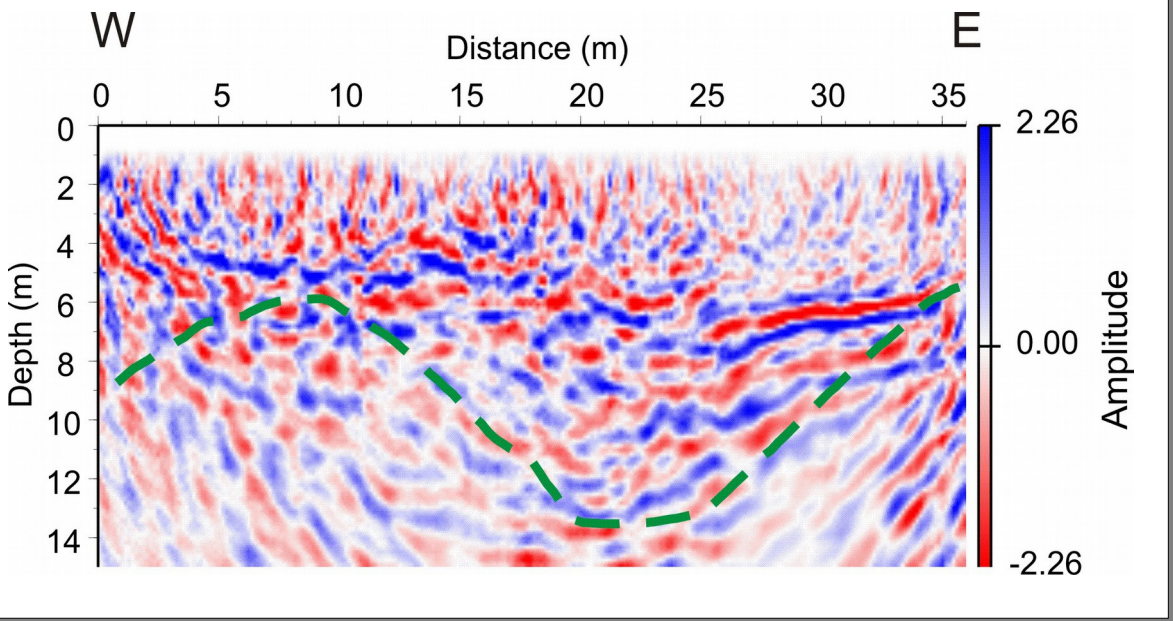




- Large volumes of data;
- Great amount of detail;
- Great accuracy;
- Complex data processing involved.

Shallow seismology





Major Organizations and Journals

- International Union of Geodesy and Geophysics (IUGG).
- International Association of Seismology and Physics of the Earth's Interior (IASPEI)
  - Mainly global (earthquake) seismology.
- Incorporated Research Institutions for Seismology (IRIS) – a U.S. University consortium
  - Collection, archiving, and dissemination of worldwide earthquake data
  - We are a foreign affiliate member
- Seismological Society of America
  - "Bulletin of the Seismological Society of America".
- Canadian Geophysical Union (CGU).
- Canadian Society of Exploration Geophysicists (CSEG)
  - "'Canadian Journal of Exploration Geophysics", "Recorder".
- American Geophysical Union (AGU)
  - "Journal of Geophysical Research, "Reviews of Geophysics".
- Society of Exploration Geophysicists (SEG)
  - 'Geophysics', 'The Leading Edge'.
- European Association of Exploration Geophysicists (EAGE)
  - "Geophysical Prospecting", "First Break"