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.

**Reading:**

- 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'**

<table>
<thead>
<tr>
<th>Method</th>
<th>Property</th>
<th>Value Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>Density</td>
<td>Spatial variations in natural gravity field</td>
</tr>
<tr>
<td>Magnetic</td>
<td>Magnetic susceptibility</td>
<td>Spatial variations in natural magnetic field</td>
</tr>
<tr>
<td>Radioactive</td>
<td>Abundance of radionuclides</td>
<td>Gamma radiation</td>
</tr>
<tr>
<td>Heat flow</td>
<td>Thermal conductivity, radioactive heat production</td>
<td>Heat flow</td>
</tr>
<tr>
<td>Electrical</td>
<td>Electron conductivity</td>
<td>Apparent resistivity</td>
</tr>
<tr>
<td>Telluric current</td>
<td>Electrical conductivity</td>
<td>Relative apparent resistivity</td>
</tr>
<tr>
<td>Spontaneous polarization</td>
<td>Oxidation potential, ion concentrations</td>
<td>Natural electrochemical potentials</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Electronic conductivity</td>
<td>Polarization voltages</td>
</tr>
<tr>
<td>Induced polarization</td>
<td>Electrical conductivity+ magnetic susceptibility</td>
<td>Alternating electromagnetic field, phase and intensity</td>
</tr>
<tr>
<td>Seismic</td>
<td>Natural ground motion, velocity, heterogeneities</td>
<td>Ambient seismic noise, travel times, polarization</td>
</tr>
<tr>
<td>Remote sensing</td>
<td>Natural radiation</td>
<td>Refraction intensity</td>
</tr>
<tr>
<td>Borehole</td>
<td>Natural radioactivity</td>
<td>Natural voltages, natural gamma radiation</td>
</tr>
<tr>
<td></td>
<td>Electrical conductivity, seismic velocity, nuclear reactions</td>
<td>Apparent resistivity, travel times, amplitudes, induced and back-scattered radiation</td>
</tr>
</tbody>
</table>

*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.
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: $50 \cdot 10^6$
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*
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: Vibroseis method developed (Conoco) but not applied extensively until ~1970's.
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

- **1950s**: GOOD OLD DAYS: A person ("Computer") acquired, processed, and hand-interpreted seismic data in field.
- **1960s**: The Batch Processing Era
- **1970s**: Advent of INTERACTIVE INTERPRETATION: Interpretive workstations with simple post-stack processing (c. 1984)
- **1980s**: Advent of COLLABORATIVE PROCESSING: Concurrent processing and interpretation integrated at the desktop (c. 1992-93)
- **1990s**: COLLABORATIVE ACQUISITION: Multidisciplinary teams plan, acquire, process, and interpret data concurrently to identify optimal parameters (c. 1991)
- **2000**: GPU's

**Diagram Directions**
- **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

- Glacio-
- Hydro-
- Environmental
- Exploration
- Archaeo-
- Engineering
- Crustal
- Nuclear test monitoring
- Mantle, Core
- Global
- Free oscillations of the Earth
Seismology reveals: Internal structure of the Earth

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

Photo by NASA
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)
- Society of Exploration Geophysicists (SEG)
  - 'Geophysics', 'The Leading Edge'.
- European Association of Exploration Geophysicists (EAGE)
  - “Geophysical Prospecting”, “First Break”