12.510 Introduction to Seismology
Spring 2008

BRIEF HISTORICAL SURVEY AND EXAMPLES OF MODERN RESEARCH TOPICS

Instrumentation

- Exploration (near-surface) Geophysics: geophones – easy to deploy and easy to collect data.
- Global Seismology and Teleseismics: broadband seismometers
- **G**lobal **S**eismograph **N**etwork (GSN) – expensive; mixed surface and borehole; handmade and calibrated instruments! Academic application → No industrial market → limited supply and demand.
- PASSCAL – Program using arrays of portable seismometers.

Theory

- Newton's 2nd Law of Motion: $F = ma$
- Hooke's (empirical) Law:
  1. (1D) $F = -cu$, where $c \equiv$ spring constant and $u \equiv$ displacement (extension)
  2. Alternatively, $\sigma = E\varepsilon$, where $\sigma \equiv$ stress, $\varepsilon \equiv$ strain, $E \equiv$ Young's Modulus (only 1D)
  3. Generalized Hooke's Law: $\sigma_{ij} = c_{ijkl}\varepsilon_{kl}$, where $\sigma_{ij} \equiv$ rank-2 stress tensor, $\varepsilon_{kl} \equiv$ rank-2 strain tensor, and $c_{ijkl} \equiv$ rank-4 elasticity or stiffness tensor; c_{ijkl} has as many as 21 unique elements!
  4. Full elastic equation of motion is intractable, necessitating reasonable simplifications (e.g., Poisson)
- Combine Newton's 2nd Law and Hooke's Law to develop theory of wave propagation.
- Other major contributors:
  1. Poisson – showed unbounded, isotropic media give rise to only P and S waves
  2. Navier, Cauchy
  3. Rayleigh (late 19th century) – surface waves; heterogeneous and bounded geometries give rise to wave types other than P and S.
  4. Wiechert (Göttingen) – postulated existence of core based on moment of inertia calculations.
  5. Love – surface waves (waveguides)
- Most of the seismological theory used today was developed by the foregoing contributors during the 19th century ("Victorian mathematics")

Observation Seismology

- Chinese had developed first seismometers tens of hundreds of years ago, capable of azimuthal earthquake location.
- Milne (1892) develops first 'modern' seismometer, ushering in the age of observation seismology
- **Discovery!**
  1. Mohorovicic (1909) – using the travel time data to find crust-mantle boundary (Moho)
  2. Oldham (1906) – 1st observational evidence of core; P-wave shadow zone
  3. Gutenberg (1912) – estimated depth to CMB (later developed magnitude scale, in conjunction w/ Richter)
  4. Lehmann (1936) – discovered the inner core

5. Wadati and Benioff (1920s) – determined that earthquakes occur deeper than previously assumed; discovered inclined seismicity zones "Wadati-Benioff zones".

Intermezzo: Shadow Zones

Observers noted the absence of P and S-wave arrivals at particular distances from source (>100°) and termed these regions *shadow zones*. They led to the hypothesis that the Earth possesses a liquid core (which was the only way to explain apparent wave refractions that would manifest as shadow zones observed on the surface). Lehmann postulated a solid inner core because she *did* observe weak P arrivals that had traveled through the core, which could be explained by allowing a solid reflector within. In early 1970-ies Dziewonski and Gilbert used free oscillation data to proof rigidity of inner core.

- Relics of Germanic origin in seismology nomenclature; e.g., 'K' phases, such as PKiKP, stands for "Kerne", german for 'core'.

Earth's Major Boundaries

- From observational seismology, early 20th century scientists built the first 1D or spherical models of the Earth; e.g., crust, mantle, outer core, inner core.
- Jeffries and Bullen: tabulated first wave speed models in agreement with observations
- Later on, more advanced models were introduced, such as the **P**reliminary **R**eference **E**arth **M**odel, PREM (Dziewonski & Anderson, 1981).

Intermezzo: Wave Speeds

$$\text{S-wave speed} \equiv V_S = (\mu/\rho)^{1/2}$$

$$\text{P-wave speed} \equiv V_P = [(K + 4/3\mu)/\rho]^{1/2}$$

where $\mu \equiv$ shear modulus, $K \equiv$ bulk modulus (incompressibility), and $\rho \equiv$ density.
The shear modulus in fluid is zero because fluid cannot sustain shear stress. Therefore

$$\lim_{\mu \to 0} V_S = 0$$

$$\lim_{\mu \to 0} V_P = (K/\rho)^{1/2},$$

which means that the shear speed in a fluid core must be zero, and the compressional speed must be lower than if the core material could sustain shear stresses.

- Lehman compared PKiKP and PKIKP phases and concluded inner core has a nonzero shear modulus → solid inner core.
- Mineral composition and phase transitions affect elastic properties and can explain rapid wave speed variations (with depth) observed near the surface and transition zones.

Modern Day – Some Examples

- Modern active broadband seismometers use a voltage to hold a mass in place ('feed back seismometger'). When the seismometer is subject to ground motion the voltage must vary to keep the mass in place, and these voltage variations are used as a proxy for ground motion.

- **I**ncorporated **R**esearch **I**nstitutions for **S**eismology – consortium of universities and other institutes dedicated to global seismology. Maintain an online database.
- Applications
    1. Earthquake location
    2. Volcanology
    3. Plate tectonics – seismotectonics;
    4. Earthquake risk assessment
        i. Transition from focus on earthquake *prediction* to focus on ways to *damage prevention*.
        ii. Surface waves do a lot of damage because they are large amplitude and because their frequency bandwidth overlaps the resonant frequency of many edifices, resulting in destructive sympathetic feedback oscillations.
    5. Aspherical modeling – attempts to create a more accurate Earth model that allows for more complicated (3D) geometries not incorporated in spherical (1D) Earth models.
    6. Global tomography – use as many phases as possible to increase sampling → greater accuracy and (hopefully!) lower uncertainties. Frechét derivatives and Fresnel zones.
    7. Geodynamics – help constrain and inform mantle convection, subduction processes, continental drift, etc.
- The Cutting Edge
    1. Quantify 3D variations in temperature and mineral composition → cross-disciplinary marriage of seismology and mineral physics (ex. Trampert, Deschamps, Resovsky, and Yuen, *Science*, 2004)
    2. Perovskite: Pv = (Mg, Fe)SiO_3 ; Magnesiowustite: Mw = (Mg, Fe)O
    3. Differentiate a slow/hot region from a slow/dense one, for example
    4. Bulk sound speed = $V_\phi = (K/\rho)^{1/2}$; Note: $V_\phi^2 = V_P^2 - 4/3V_S^2$. Provides useful analysis tool to constrain interpretation. V_ϕ and V_S offer comparative look at μ and K. For example, anticorrelation between μ and K can be explained by compositional variations, but not by temperature contrasts.
    5. Automation needed as datasets become larger and manually unwieldy.
    6. USArray – translate an instrument package across the States over a decade to provide a comprehensive snapshot of subsurface features.
- Exploration seismology
    1. Difference of scale and frequency w.r.t. global seismology
    2. For instance, **G**eneralized **R**adon **T**ransform (GRT)
    3. Deep Earth “Exploration” Seismology – cross-over of exploration seismology techniques (oil industry, etc.) into global seismology
    4. Multiscale resolution of structure at or near interfaces
    5. Scattering theory can help explain energy in the signal after the arrival of discernible phases
    6. May help deep earth seismology greatly improve detail at great depths