The inside of the Earth

How to attract students to geoscience

• Just finished grad student recruiting
• Eos article, March 19th, 2002
• Emphasize financial rewards
  – They don’t care if it’s interesting
• Don’t use too many words, more pictures
• Pictures of computers
• Internet addresses
• Shave off beards! Dress well!
  – We’re perceived as looking like “nerds”
  – And often like slobs

Earth: Main ingredients

• Air
• Oceans
• Crust
• Mantle
• Core

This lecture

Masses

• Air $3 \times 10^{19}$ kg
• Oceans $1000 \times 10^{19}$ kg
• Crust $20,000 \times 10^{19}$ kg
• Mantle $400,000 \times 10^{19}$ kg
• Core $200,000 \times 10^{19}$ kg

What’s in the Earth?

• Quantities that we want to know
  – Forces, stresses, viscosity
  – Temperature, composition
  – History
• Quantities that we can measure
  – P & S wave velocities (seismology)
  – Density (seismology and gravity)
  – Surface rock, plate motions (geodesy)
How seismology looks at the Earth

- Travel times of direct waves
  - P waves
  - S waves
  - Surface waves, both Rayleigh and Love
- Reflected waves
- Trying to match entire seismograms
- Normal modes (Earth rings like bell)
- Plus gravity, magnetism, chemistry

Waves

- P
- S
- Love
- Rayleigh

What controls size of waves?

- Magnitude
  - Bigger slip (offset) or fault area leads to bigger motions
- Distance
- Wave type
  - S larger than P because shearing motion of quake produces shear waves (S) preferentially to compressional waves (P)
  - Surface waves larger than body waves because surface waves die away more slowly with distance

Process

1. Identify many waves, each with a different path
2. Measure either their amplitude and/or time of arrival
3. Reconstruct the structure through which the waves must have traveled

Surface waves, P, S, and PP paths

- S waves travel more slowly than P waves

Focus

Seismograph

Core

Mantle

Surface waves

P

Pp

P

S
**Crust**

- Layer of lighter composition than mantle
  - 2.7 g/cc in crust, 3.3 g/cc in mantle
- Mohorovicic seismic discontinuity (Moho) marks boundary between crust and mantle
- Thickness mapped by seismic work
  - Crust has P velocity 6 km/s, mantle 8 km/s
  - Crust has S velocity 3.5 km/s, mantle 4.5 km/s
- Thinner under oceans (4 to 6 km)
- Thicker under continents (25 to 80 km)
  - Causes most of topography on Earth

**Oil exploration**

- Mapping the upper few km of the crust
- Oil and gas seep upwards
  - From buried, rotting and cooked organic stuff
- Gets trapped in pools in structures like faults and warped layers
- Looks almost entirely at sedimentary rock
  - Relatively young, not fully cooked rocks
  - Starts out laminated; sand, silt, pebbles ...
**Dynamite**

**Crust, Mantle, and Core**

- Crust is thin veneer floating on mantle
  - 4 to 80 km thick
  - Upper part of rigid plates
- Mantle is most of Earth’s mass, dense rock
  - Slowly flowing in convection
  - Several “phase changes” in upper mantle
- Core’s radius is about half of Earth’s radius
  - Outer core is liquid iron, makes magnetic field
  - Inner core is solid iron

**Isostacy:** Crust is less dense than mantle, like wood floating on water

**Moho**

Moho is seismic jump that marks the base of the continental and oceanic crust

Grossly exaggerated vertical scale

**Example without vertical exaggeration**

**Global crustal thickness**

Walter Mooney
Some terms

- **Lithosphere** - strong layer composed of crust and uppermost mantle, 30-300 km thick (actually, lively debate about thickness)
- **Aesthenosphere** - underlying weak layer in the mantle

Moho occurs within lithosphere.

Details in the mantle

- But mantle is thought to be nearly uniform in composition
- Deeper rock is denser and stiffer due to increasing pressure, thus higher velocity
- Phase changes, 5% jumps in vel. & den.
  - Changes in molecular arrangement
  - At depths of 410 and 660 km
- 660 km depth separates upper and lower mantles
Phase changes in the Mantle

Testing models by waveform match

Record Section of the Earth

Listen for the tone of normal modes - gives long-wavelength properties

Quake Bulletin

Illinois M5.2
4:36am local time
Wabash Valley fault system
Felt up to 900 miles away
Little damage
Midwest quakes

Reflection: 
PcP

Beno Gutenberg
(1889-1960)

P&S waves in the Earth

Example of core reflections

Echoes of a nuclear explosion

Interpreting Seismic Velocities

- Seismic wave velocity \( \sqrt{\frac{\text{Elastic stiffness}}{\text{Density}}} \)
- Velocity increases with depth and so does density
  - Therefore, velocity is dominated by stiffness
- Stiffness controlled by
  - Pressure
  - Temperature
  - Composition
  - Water
  - Crystal structure
P and S wave velocity vs. depth

P waves bent downward (deflected) at core-mantle boundary, large velocity decrease there.

S wave shadow

No S waves pass through outer core, therefore it is fluid!

Some real seismograms

Outer Core

- Liquid, 84% iron + 8% sulphur + 8% oxygen?
  - Lower P velocity than mantle
  - No S waves allowed in liquid!
  - Presence inferred from P and S shadow zones

- Convection leads to magnetic field
  - In fact, magnetic field as important as inertia
    - Complicated - magnetohydrodynamic!
  - Magnetic field reverses from time to time
  - Keeps atmosphere from being blown away

Magnetic field lines

Strength of field plus reversals imply that field generated by flow in conducting fluid - molten iron core.
**Convection in the Outer Core (OC)**

- Convection outside of tangent cylinder
  - Quasi-2D, columnar convection (Roberts '08)

- Inside tangent cylinder
  - 3D plumes, strongly affected by rotation
  - Possible polar upwelling and associated large-scale thermal winds

(Real science slide, Jon Aurnou, compatriot at UCLA)

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**Innermost inner core**

- Remnant of earliest times?
- Georeactor?

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**Other things that vary with depth**

- Temperature
- Gravity
- Pressure
- Density

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**Temperature**

- Increases with greater depth
  - Gets hot in mines at about 25°/km depth
- Generally near melting point inside mantle
- We know temp. at surface
  - 0° - 30° C in air, close to 0° at ocean bottom
- 0° to 1500° Celsius in crust
- 1500° to 3000° in most of mantle
- 3000° to 4000° in core

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**Inge Lehmann (1888-1993)**

- Solid, 92% iron 8% sulphur
  - hard to tell it exists, presence inferred from normal mode analysis
  - recently discovered to slowly rotate
    - About 0.2-0.3° every three years, still controversial
- Inner core grows as outer core “freezes”
  - because Earth is cooling, releases a lot of heat
  - eventually, outer core will all freeze
  - less protection from cosmic rays for us
Gravity and Pressure

- **Gravity**
  - Roughly constant through mantle
  - Diminishes to zero in the center of the Earth
- **Pressure**
  - Proportionate to weight of overlying material
  - Increases enormously with depth
  - Particularly in the iron core

Gravity and Pressure vs depth

Density

- **Density** is mass per unit volume
- Increases with depth
  - Partly just due to compression from increasing pressure
  - Partly from phase changes (small change)
  - Partly from compositional changes
    - Crust to mantle (small change)
    - Mantle to core (big change)
  - Partly from freezing (outer to inner core)

Density

Lateral variation in the Earth

- **Tomography**
  - Buzzword for finding 3-D structure
  - Similar to CAT scans, which look inside people
- **Wadati-Benioff zones**
  - Cold, subducting material is stiffer than average
  - Subduction seems to extend down to core
- **Hot spots**
  - Warm, mushier material that is rising

Cartoon view
Seismic tomography

• Like a CAT scan
  – reveals 3-D image of structure inside the Earth
• Shows where seismic waves travel faster or slower
• Colder material is stiffer (although denser)
  – Therefore has faster P and S velocities
  – But composition also affect wave speeds

How CAT scan works

Repeat procedure for transmitters all the way around target

Medical CAT scanner

Preparing the ice man for a CAT scan

Tomography reveals the subducted Farallon plate. It is cold, so it has high seismic velocity
**Global heat flow pattern**

- High at spreading ridges
  - Hot material is upwelling
- Cold on old continents
  - They have been cooling for billions of years
- Hot spots are also hot
  - but a minor feature

**Heat flow pattern**

**Mantle temperatures at 100 km depth**

**The Earth: An ongoing project**

- Connections
  - To what extent are the tectonic plates glued to the underlying mantle?
  - How variable is the composition in the mantle?
  - What action is at the core-mantle boundary?
- What do plumes really look like?
- How does the core dynamo work?
- Why is there structure in the inner core?