The inside of the Earth

ESS 202

Earth p. 41

More pink shows less vegetation

How to attract students to geoscience

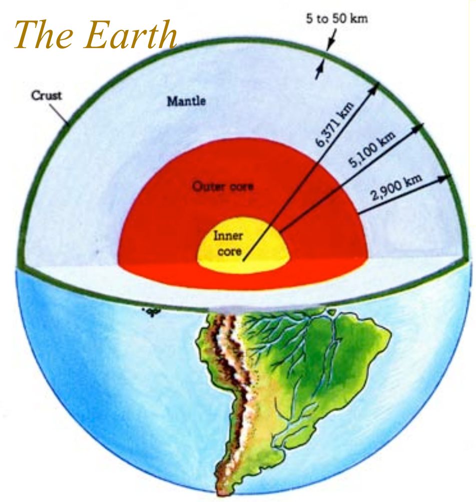
- Just finished grad student recruiting
- Eos article, March 19th, 2002
- Emphasize financial rewards
  - They don't care if it's interesting
- Don't use too many words, more pictures
- Pictures of computers
- Internet addresses
- Shave off beards! Dress well!
  - We're perceived as looking like "nerds"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

Earth: Main ingredients

- Air
- Oceans
- Crust
- Mantle
- Core

} This lecture

The Earth



Radius: 6371 km
Core radius: 3470 km
Circumference: 40,000 km

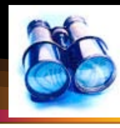
Masses

- Air 3×10^{19} kg
- Oceans 1000×10^{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?

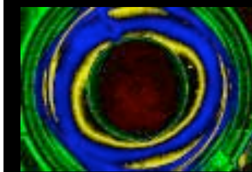
- Quantities that we want to know
  - Forces, stresses, viscosity
  - Temperature, composition
  - History
- Quantities that we can measure
  - P & S wave velocities (seismology)
  - Density (seismology and gravity)
  - Surface rock, plate motions (geodesy)

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

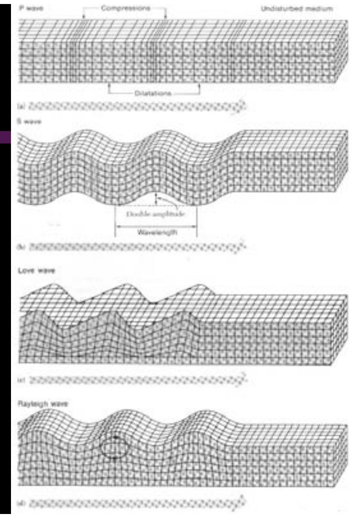


P

S

Love

Rayleigh



Bolt, 1-9

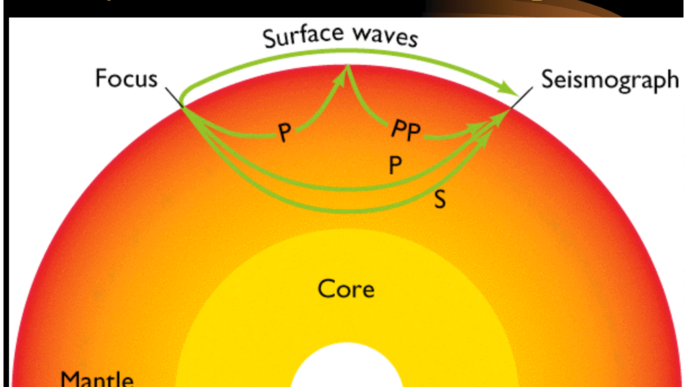
What controls size of waves?

- 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

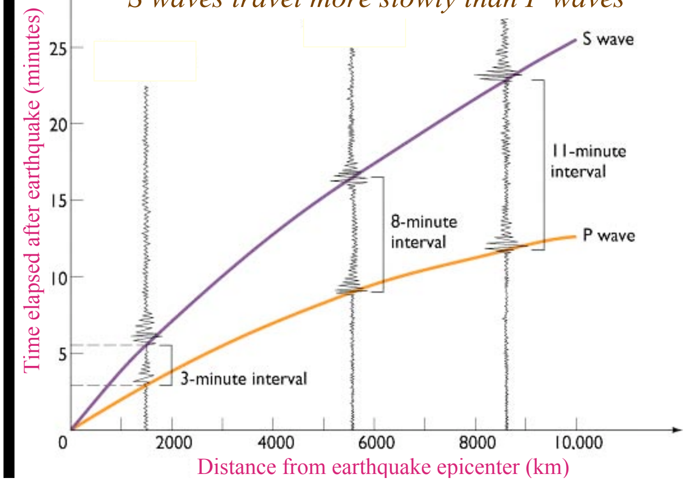
Process

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

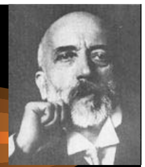
Surface waves, P, S, and PP paths



S waves travel more slowly than P waves



Crust



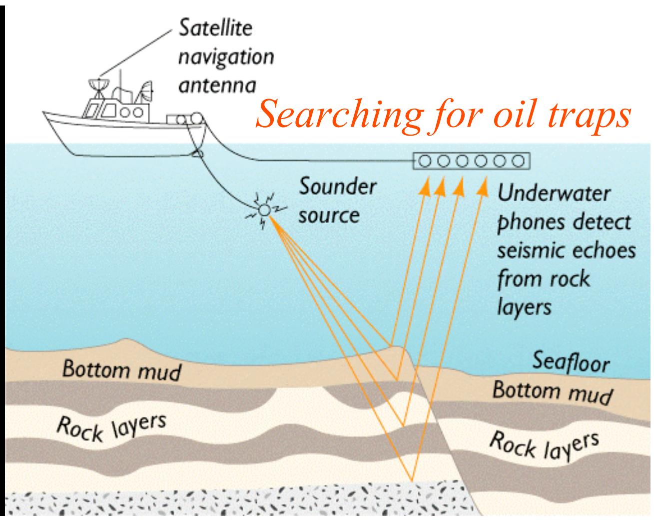
Andrija Mohorovicic 1857-1936

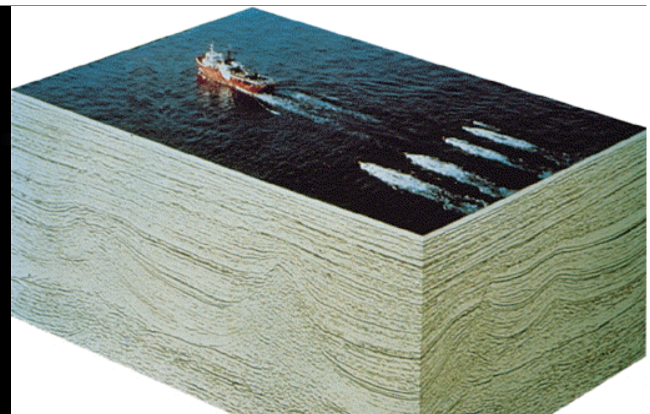
- Layer of lighter composition than mantle
  - 2.7 g/cc in crust, 3.3 g/cc in mantle
- Mohorovicic seismic discontinuity (Moho) marks boundary between crust and mantle
- Thickness mapped by seismic work
  - Crust has P velocity 6 km/s, mantle 8 km/s
  - Crust has S velocity 3.5 km/s, mantle 4.5 km/s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

Oil exploration

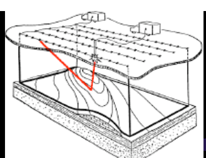
- Mapping the upper few km of the crust
- Oil and gas seep upwards
  - From buried, rotting and cooked organic stuff
- Gets trapped in pools in structures like faults and warped layers
- Looks almost entirely at sedimentary rock
  - Relatively young, not fully cooked rocks
  - Starts out laminated; sand,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

Searching for oil traps



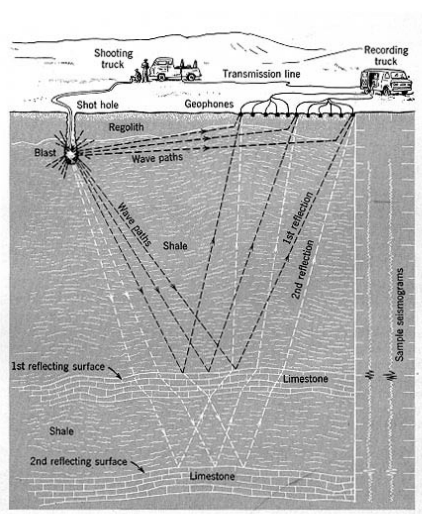


Ship makes waves with air gun and tows seismometers that detect reflected waves



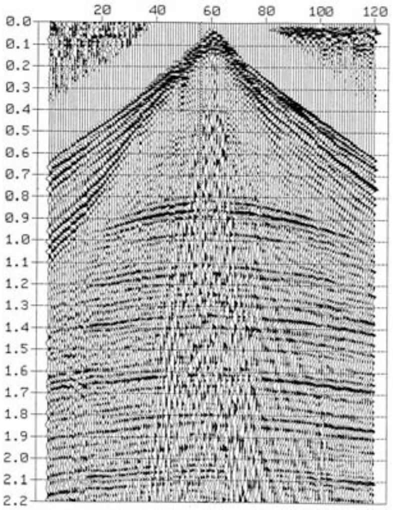
Wave propagation

- Oil people generally only use P waves
  - S waves don't travel through water
  - Don't travel as well through rock, either
- Most energy is transmitted through the water and rocks
- But a little is reflected back to make these images

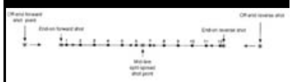


Oil exploration on land

Flint, 21-14



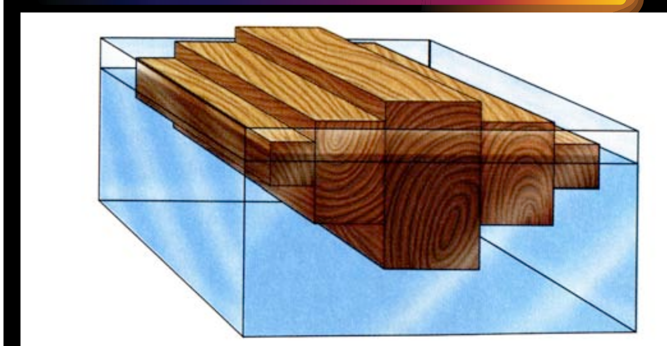
Dynamite



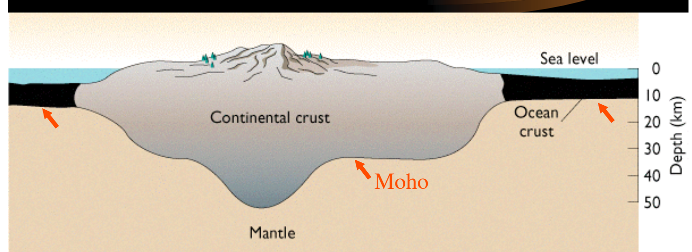
Crust, Mantle, and Core

- 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

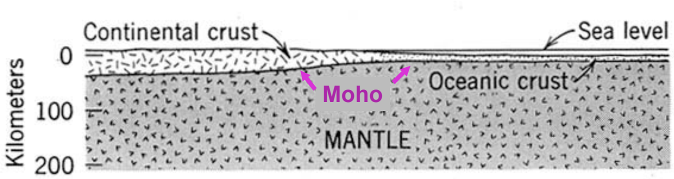


Moho is seismic jump that marks the base of the continental and oceanic crust



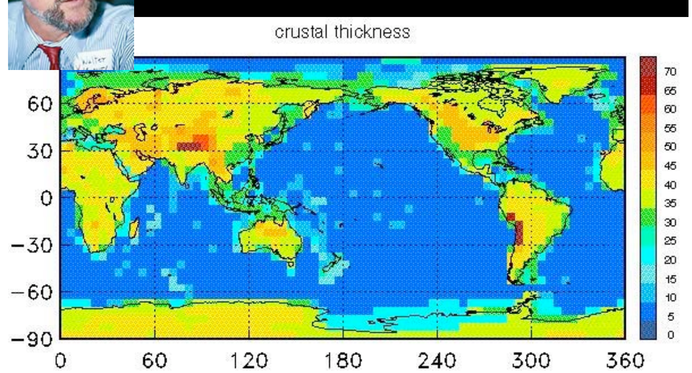
Grossly exaggerated vertical scale

Example without vertical exaggeration



Walter Mooney

Global crustal thickness

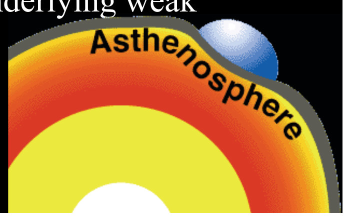


Granite- found in crust

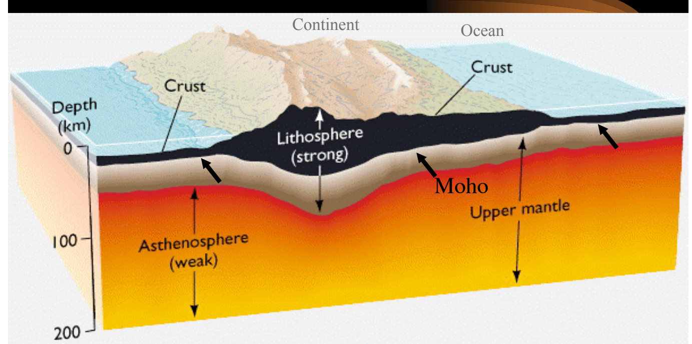
Olivine - found in mantle

Some terms

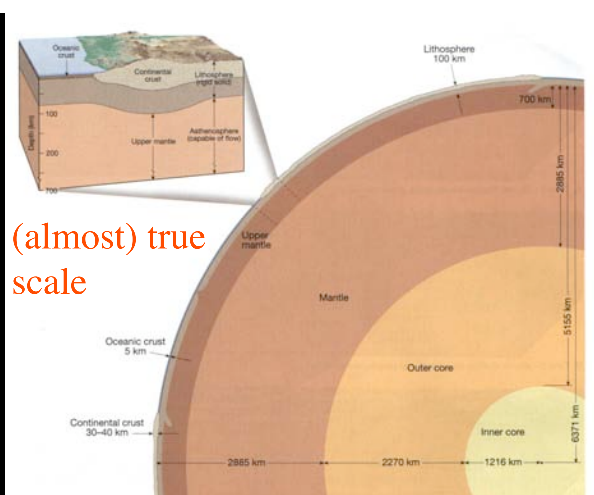
- Lithosphere - strong layer composed of crust and uppermost mantle, 30-300 km thick (actually, lively debate about thickness)
- Aesthenosphere - underlying weak layer in the mantle



Moho occurs within lithosphere.



Press 1-11

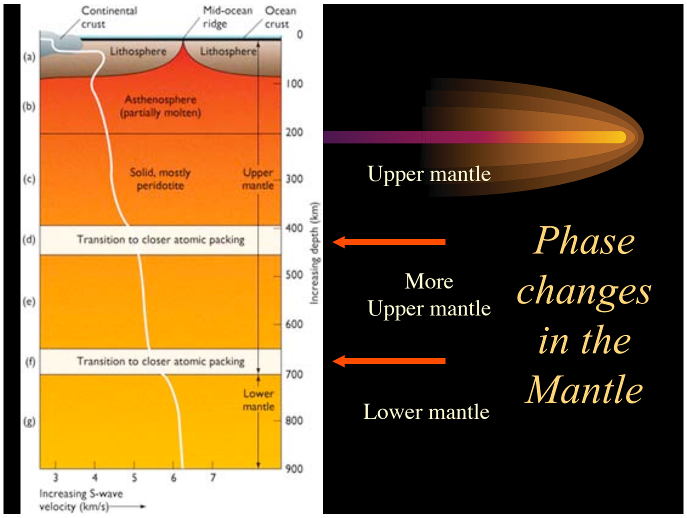


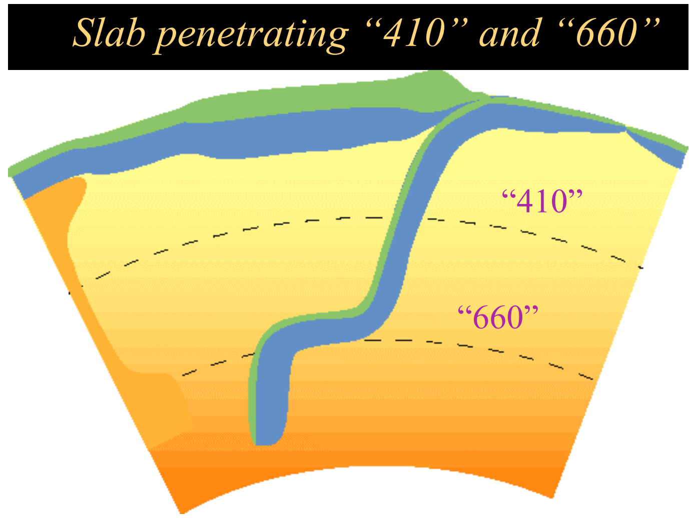
(almost) true scale

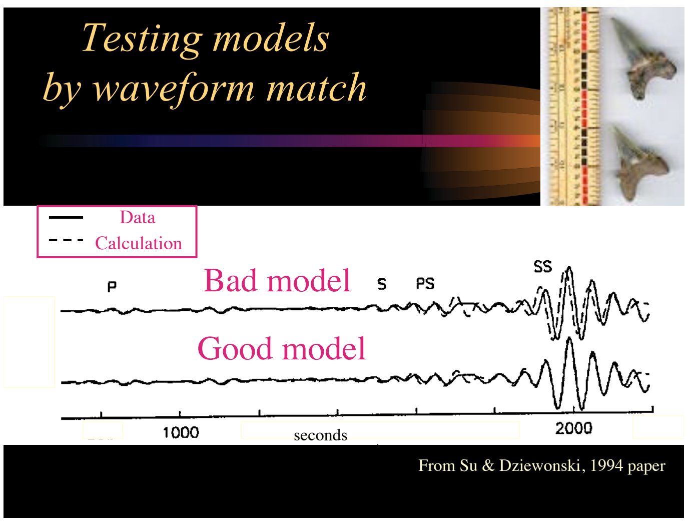
Figure 17.6 Cross-sectional view of Earth showing the internal structure.

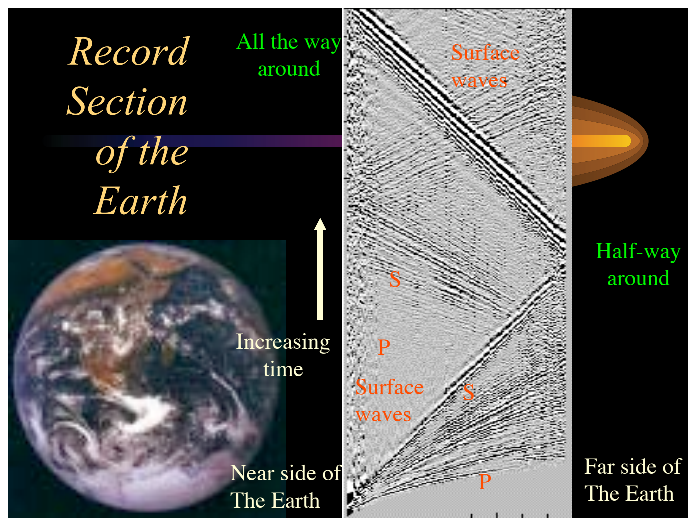
Details in the mantle

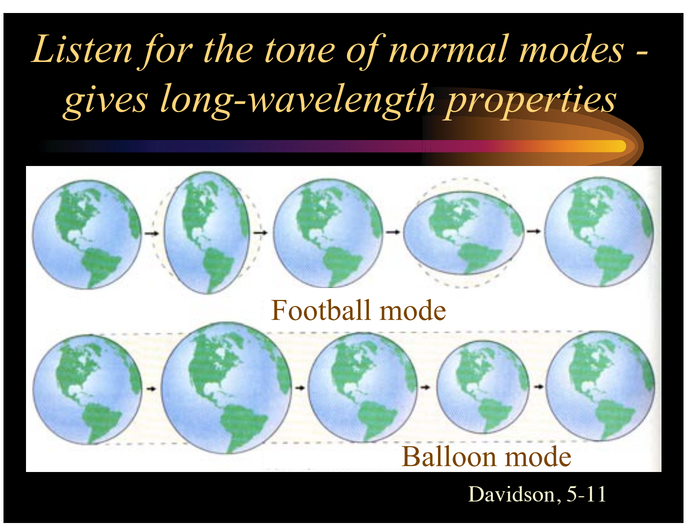
- But mantle is thought to be nearly uniform in composition
- Deeper rock is denser and stiffer due to increasing pressure, thus higher velocity
- Phase changes, 5% jumps in vel. & den.
  - Changes in molecular arrangement
  - At depths of 410 and 660 km
- 660 km depth separates upper and lower mantles

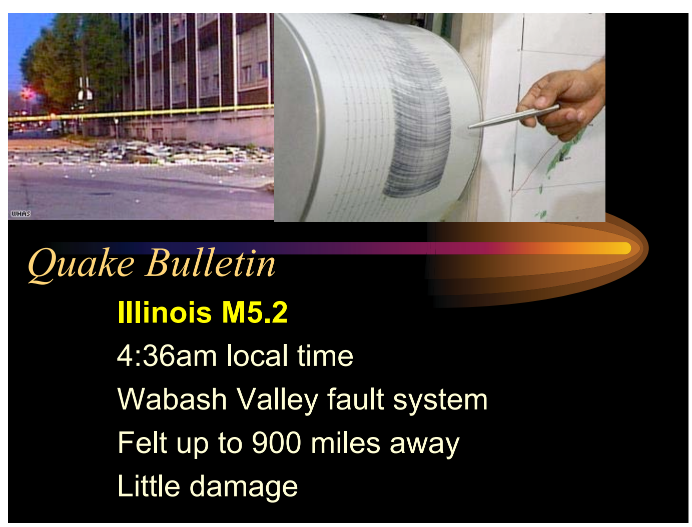

Continental crust
Mid-ocean ridge
Ocean crust
Lithosphere
Lithosphere
Asthenosphere (partially molten)
Solid, mostly peridotite
Upper mantle
Transition to closer atomic packing
Transition to closer atomic packing
Lower mantle
Increasing depth (km)
Increasing S-wave velocity (km/s)
Upper mantle
More
Upper mantle
Lower mantle
Phase changes in the Mantle

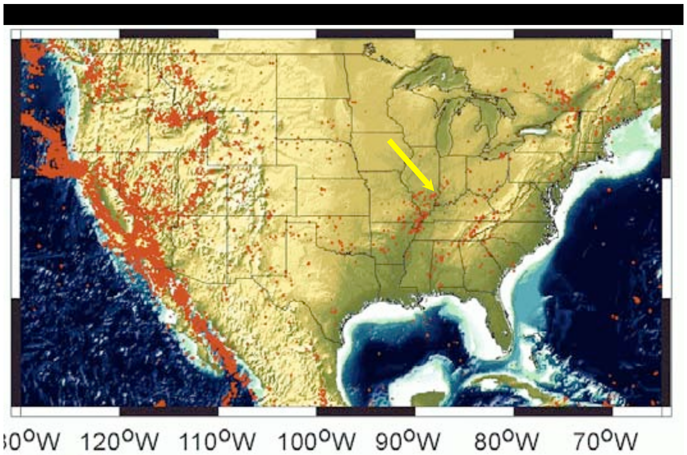

Slab penetrating "410" and "660"
"410"
"660"


Testing models by waveform match
Data
Calculation
Bad model
Good model
P
S
PS
SS
1000
seconds
2000
From Su & Dziewonski, 1994 paper


Record Section of the Earth
All the way around
Surface waves
Half-way around
S
Increasing time
P
Surface waves
S
P
Near side of The Earth
Far side of The Earth

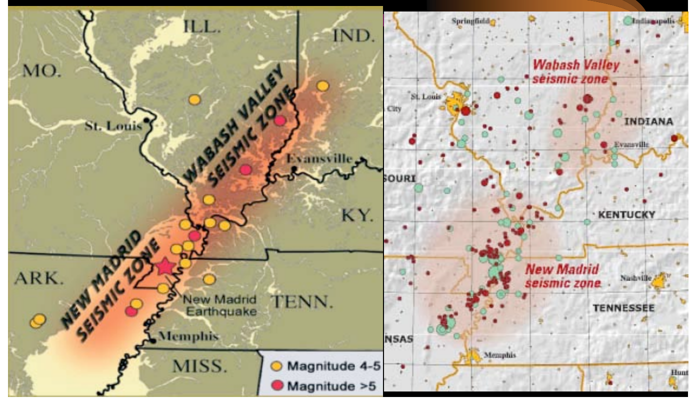

Listen for the tone of normal modes - gives long-wavelength properties
Football mode
Balloon mode
Davidson, 5-11

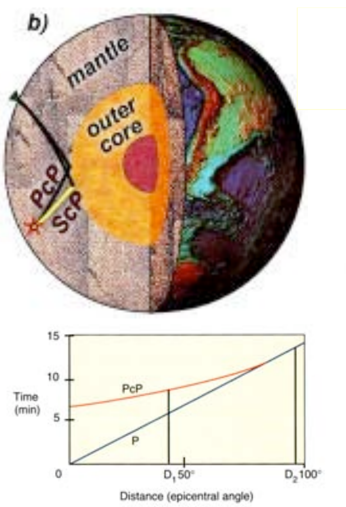

Quake Bulletin
Illinois M5.2
4:36am local time
Wabash Valley fault system
Felt up to 900 miles away
Little damage



M>3.0 earthquakes (1973-2003; data from USGS/NEIC)

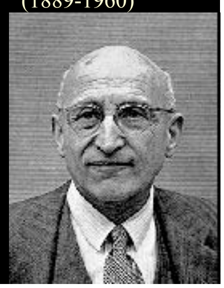
Midwest quakes



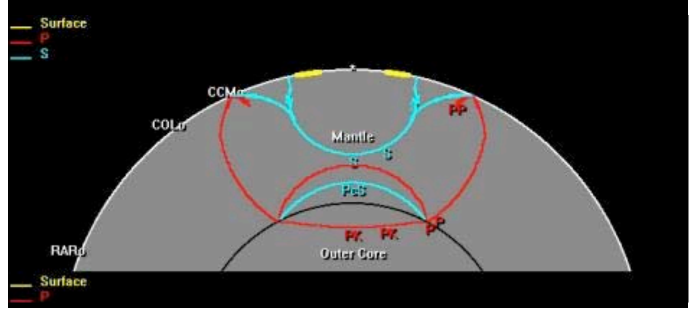


Reflection: PcP

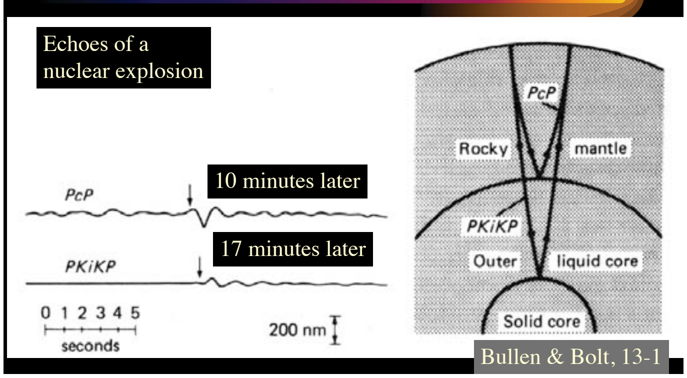
Beno Gutenberg
(1889-1960)



P&S waves in the Earth

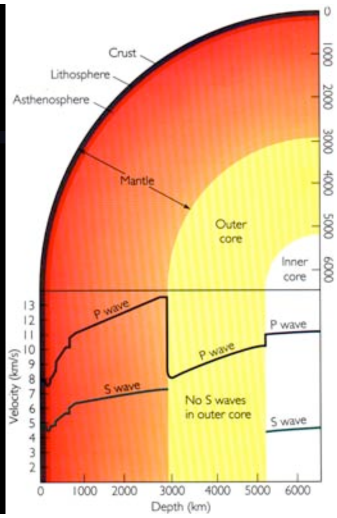


Example of core reflections

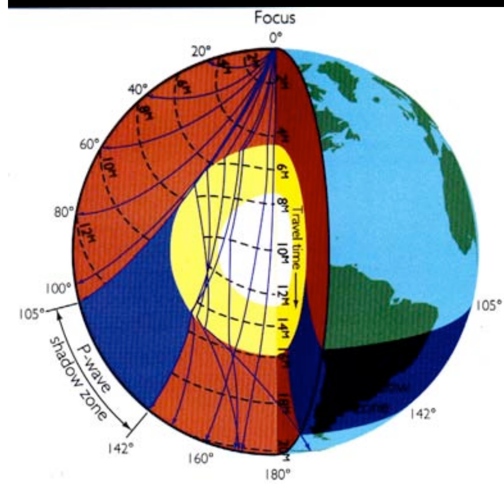


Interpreting Seismic Velocities

- Seismic wave velocity ~ $\sqrt{\dfrac{\text{Elastic stiffness}}{\text{Density}}}$
- Velocity increases with depth and so does density
  - Therefore, velocity is dominated by stiffness
- Stiffness controlled by
  - Pressure
  - Temperature
  - Composition
  - Water
  - Crystal structure

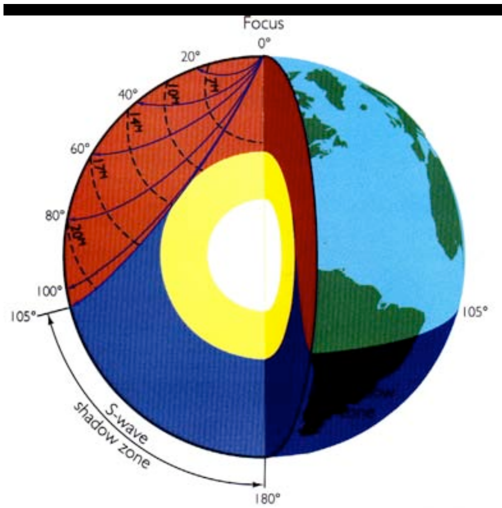


P and S wave velocity vs. depth



P wave shadow

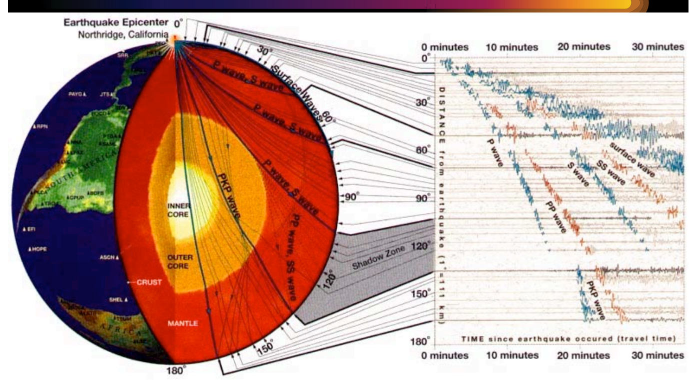
P waves bent downward (deflected) at core-mantle boundary, large velocity decrease there



S wave shadow

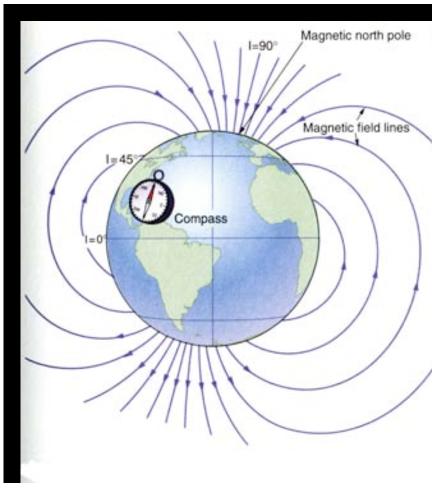
No S waves pass through outer core, therefore it is fluid!

Some real seismograms



Outer Core

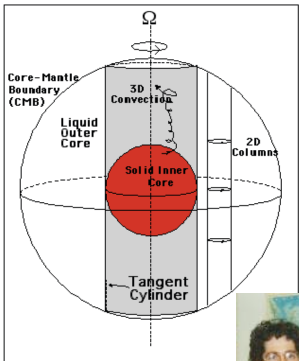
- Liquid, 84% iron + 8% sulphur + 8% oxygen?
  - Lower P velocity than mantle
  - No S waves allowed in liquid!
  - Presence inferred from P and S shadow zones
- Convection leads to magnetic field
  - In fact, magnetic field as important as inertia
    - Complicated - magnetohydrodynamic!
  - Magnetic field reverses from time to time
  - Keeps atmosphere from being blown away



Magnetic field lines

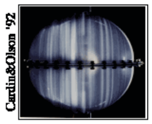
Strength of field plus reversals imply that field generated by flow in conducting fluid - molten iron core.

Convection in the Outer Core (OC)



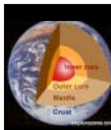
- Convection outside of tangent cylinder
  - Quasi-2D, columnar convection (Roberts '68)

Busse '70

Cardin&Olson '92


- 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)



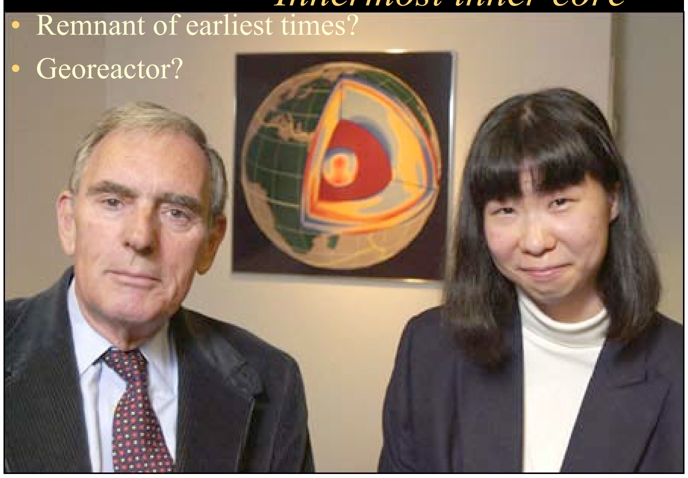
Inge Lehmann (1888-1993)

Inner core

- 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

Innermost inner core

- Remnant of earliest times?
- Georeactor?



Other things that vary with depth

- Temperature
- Gravity
- Pressure
- Density

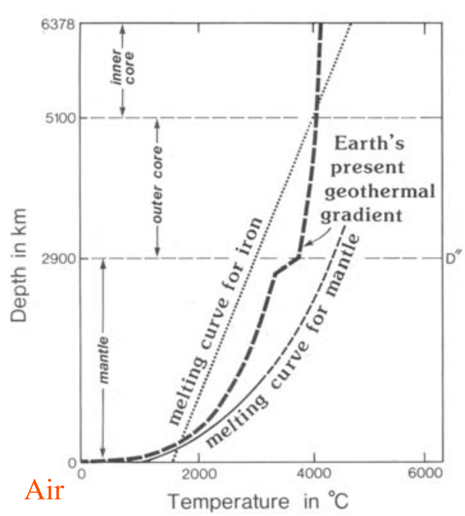
Jules Verne

Dante

Illustration for Dante's Inferno, by Donn P. Crane

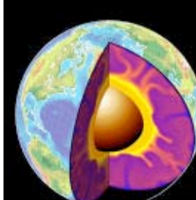
Temperature

- 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

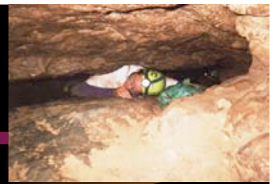


Air

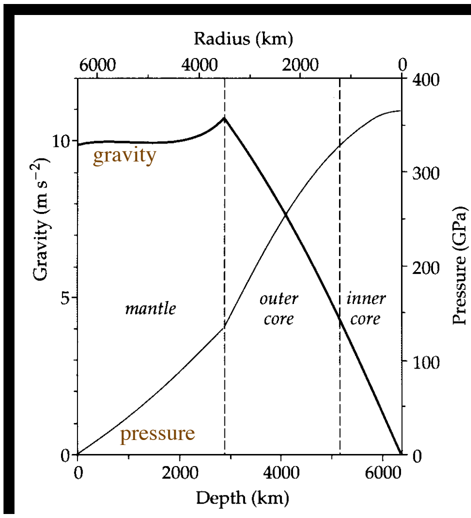
Temperature
Geotherm



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



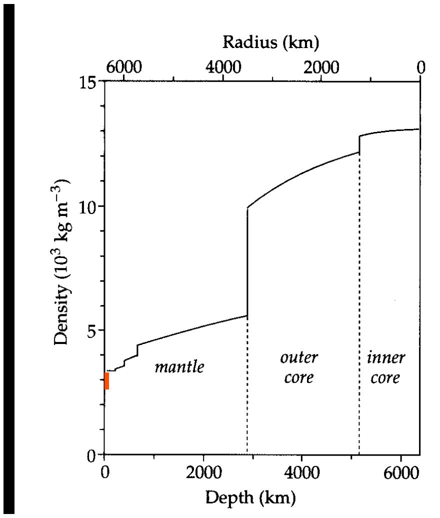
Swiss Geophysicist ETH

Gravity and Pressure vs depth

Lowrie, 3-78

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)



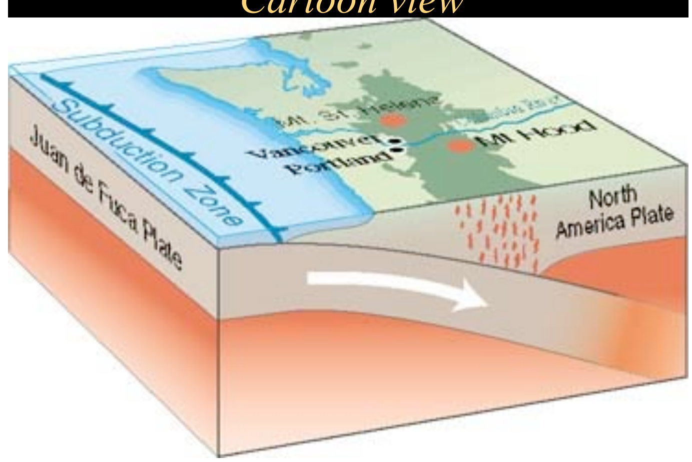
Density

Lowrie, 3-77

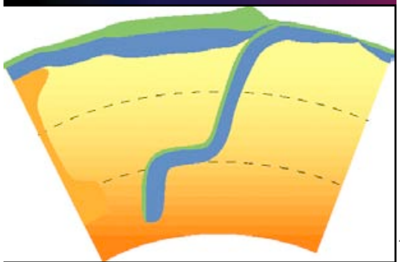
Lateral variation in the Earth

- 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

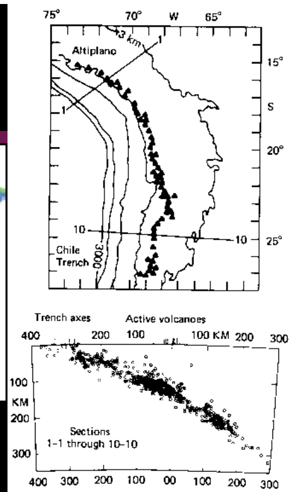
Cartoon view



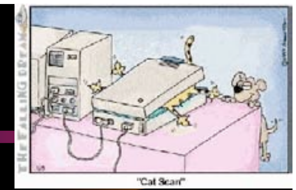
South American subduction cross-section



Wadati-Benioff zone



Seismic tomography

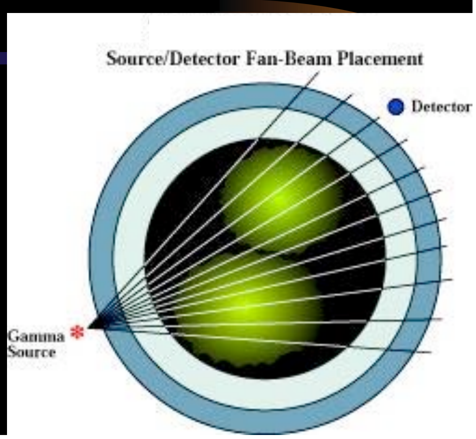


Not a "cat scan"

- 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

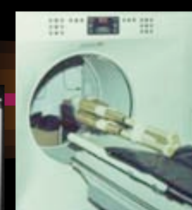
Repeat procedure for transmitters all the way around target



Medical CAT scanner

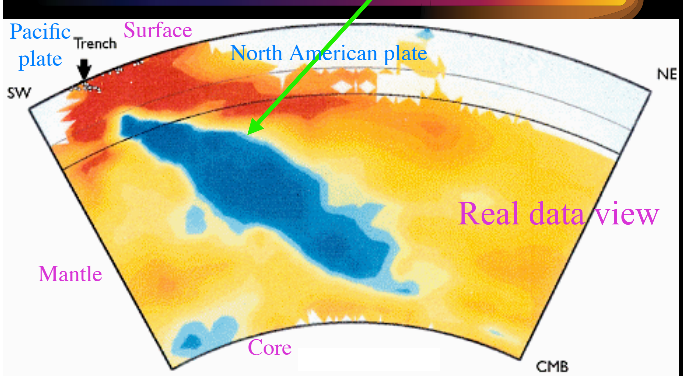
Machinery

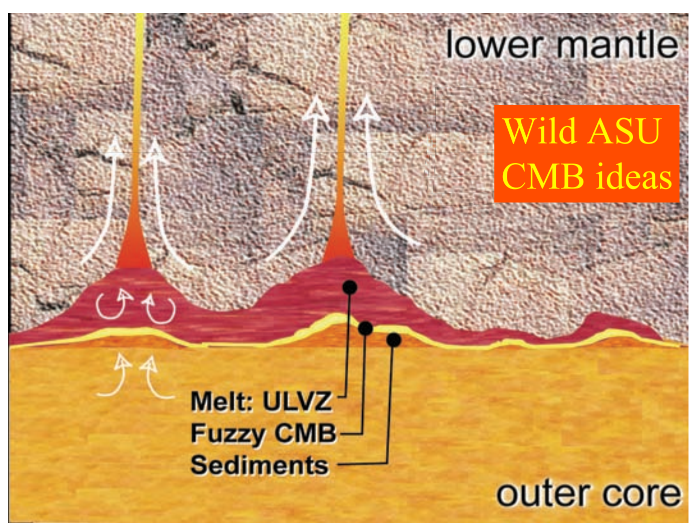
CAT scan of four baseball bat, two of which are corked

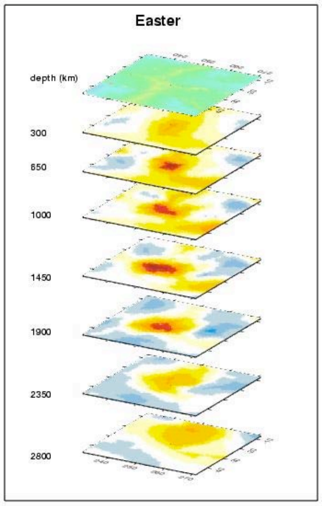


Preparing the ice man for a CAT scan

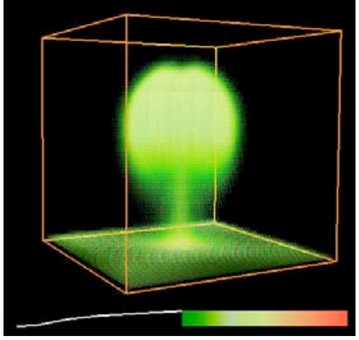
Tomography reveals the subducted Farallon plate. It is cold, so it has high seismic velocity



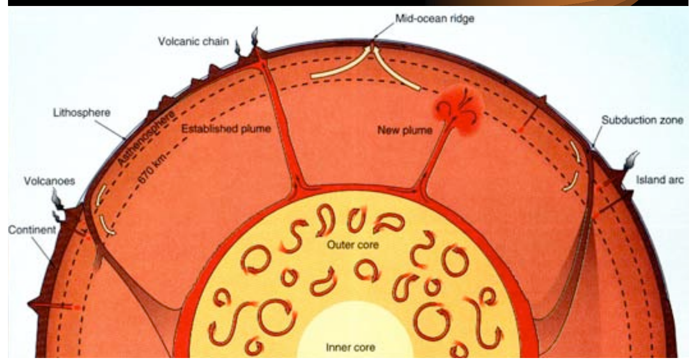




Easter Island Plume

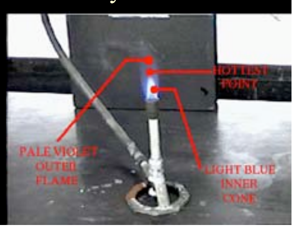


Convecting system



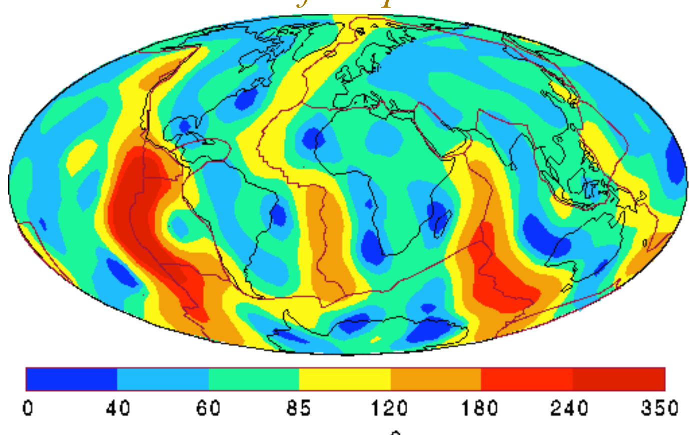
Global heat flow pattern

- 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



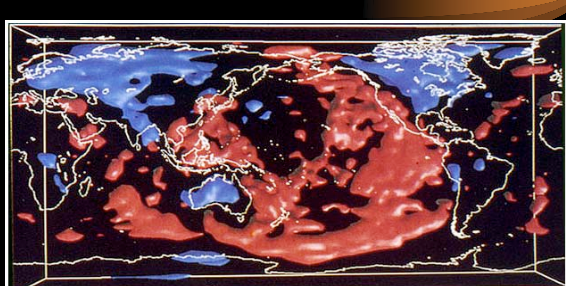
Bunsen burner

Heat flow pattern

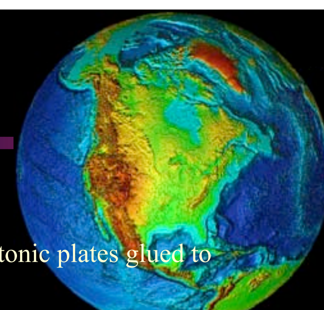


International Heat Flow Commission

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?