Igneous Petrology

- **Igneous rocks** are assemblages of minerals (predominantly rock-forming minerals: olivines, pyroxenes, feldspars, amphiboles, micas, feldspathoids, quartz, oxides…). Minerals in abundances <1% are called accessories (apatite, zircon, sulfides…).

- Igneous rocks are **not** random assemblages of minerals

  Certain minerals are commonly associated, e.g., olivines and pyroxenes, quartz and K-feldspar, biotite and hornblende, plagioclase and all major silicates.

  Certain minerals are never associated, e.g., olivine and quartz, leucite and orthopyroxene, nepheline and quartz, sanidine and olivine…

Petrology has two aspects:

Petrography--the descriptive part of the science (modes, mineral compositions, textures, bulk composition (major & trace elements, isotopes…). [Check "Supplemental Material" on website for details on methods of characterizing igneous rocks].

Petrogenesis--the interpretive part of the science in which we try to constrain the origin of igneous rocks, i.e., where and how they are generated, how they crystallize and differentiate, etc.

Igneous Rocks

Origin: Solidified from magma (molten rock containing suspended crystals (phenocrysts/xenocrysts), and dissolved gases)

Types: Volcanic (~25%)
Plutonic (~75%)

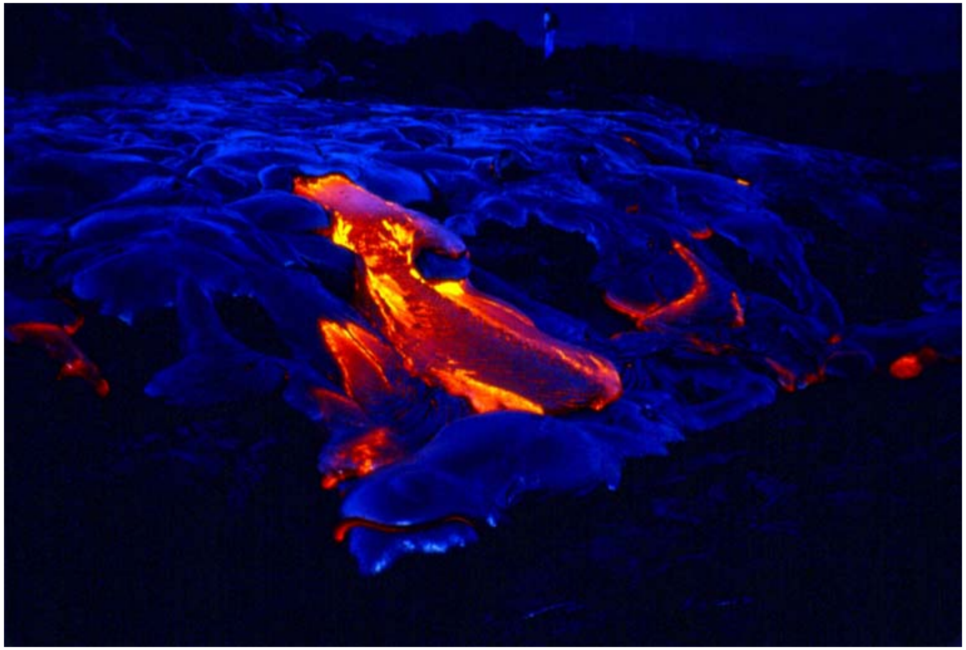
T range: ~650ºC → ~1400ºC

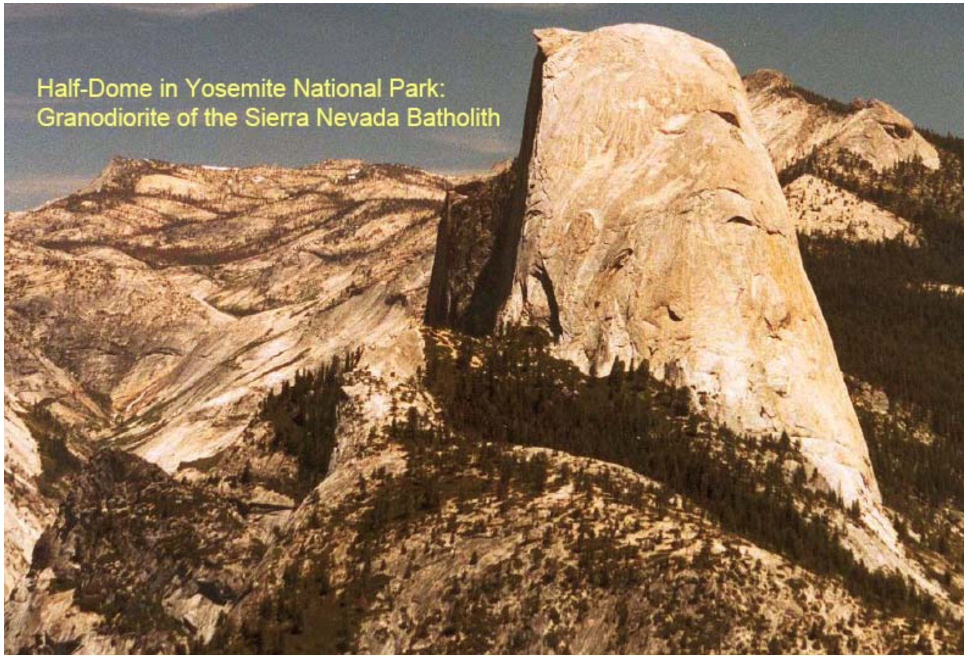
P range: 1 bar → 25 Gpa (~ 700 km)

Pressure: mostly lithostatic

Fluids: C-O-H-S system, primarily H_2O, CO_2, SO_2, …

Composition: SiO_2 ranges from 40-80 wt.%





Half-Dome in Yosemite National Park:
Granodiorite of the Sierra Nevada Batholith

Goals of igneous petrology [for additional details on each item see "Supplementary Material" on website]

Characterize of the variety of igneous rocks exposed at the earth's surface and establish relationships among them.

Attempt to identify and determine the composition and physical properties of primary/parental magmas

Understand magma diversification processes

- Melting
- Fractionation
- Assimilation
- Mixing…

Determine P, T, composition and mineralogy of magma source regions

Understand the mechanisms of segregation, transport, emplacement and eruption of magmas (magma physics)

Understand the role of magmatism in global evolution throughout earth history. We will take a global view in the remainder of today's class.

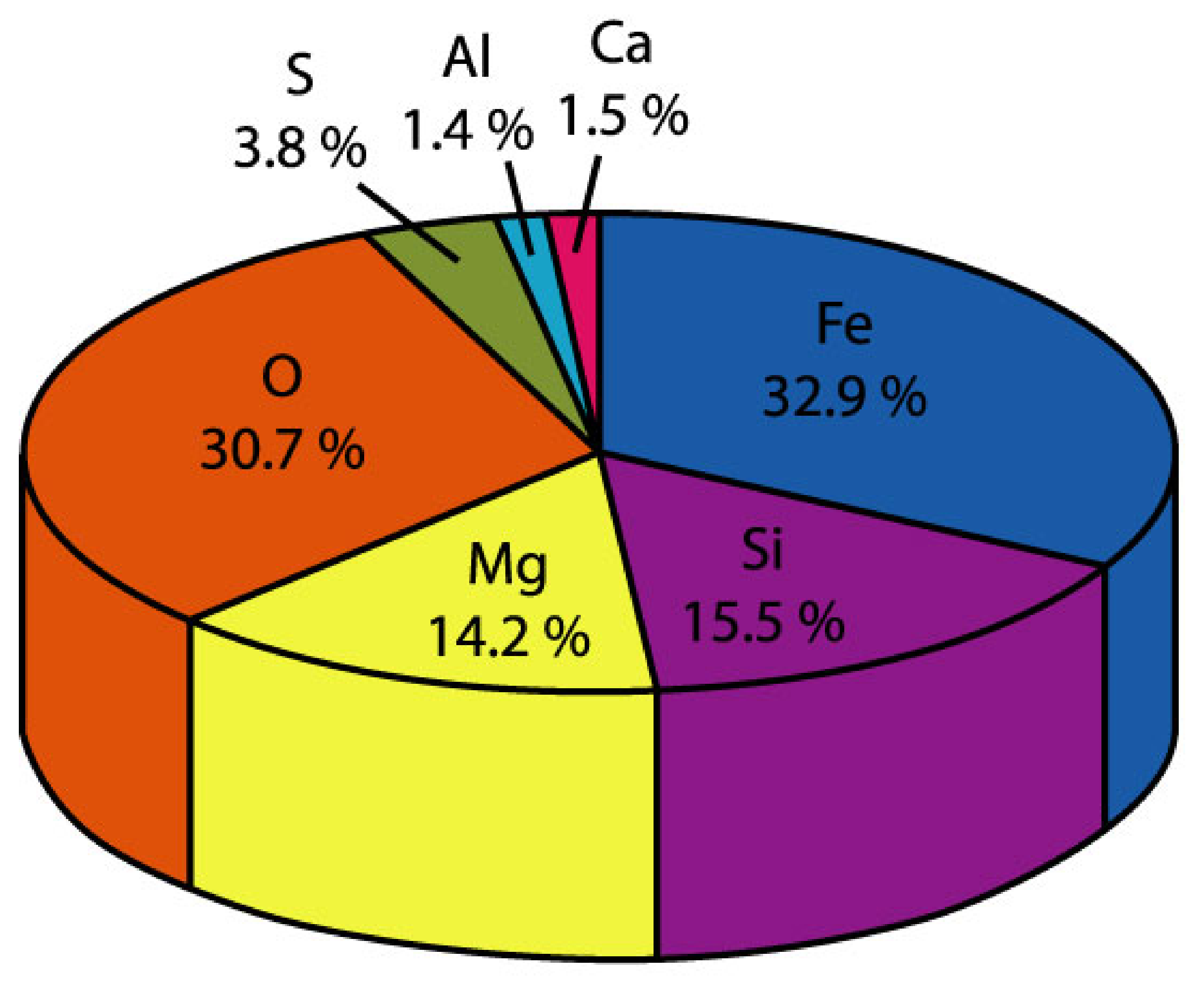


Figure 1-5. Relative atomic abundances of the seven most common elements that comprise 97% of the Earth's mass. An Introduction to Igneous and Metamorphic Petrology, by John Winter , Prentice Hall.

Earth's Interior

Mantle: Peridotite (olivine-rich rock)

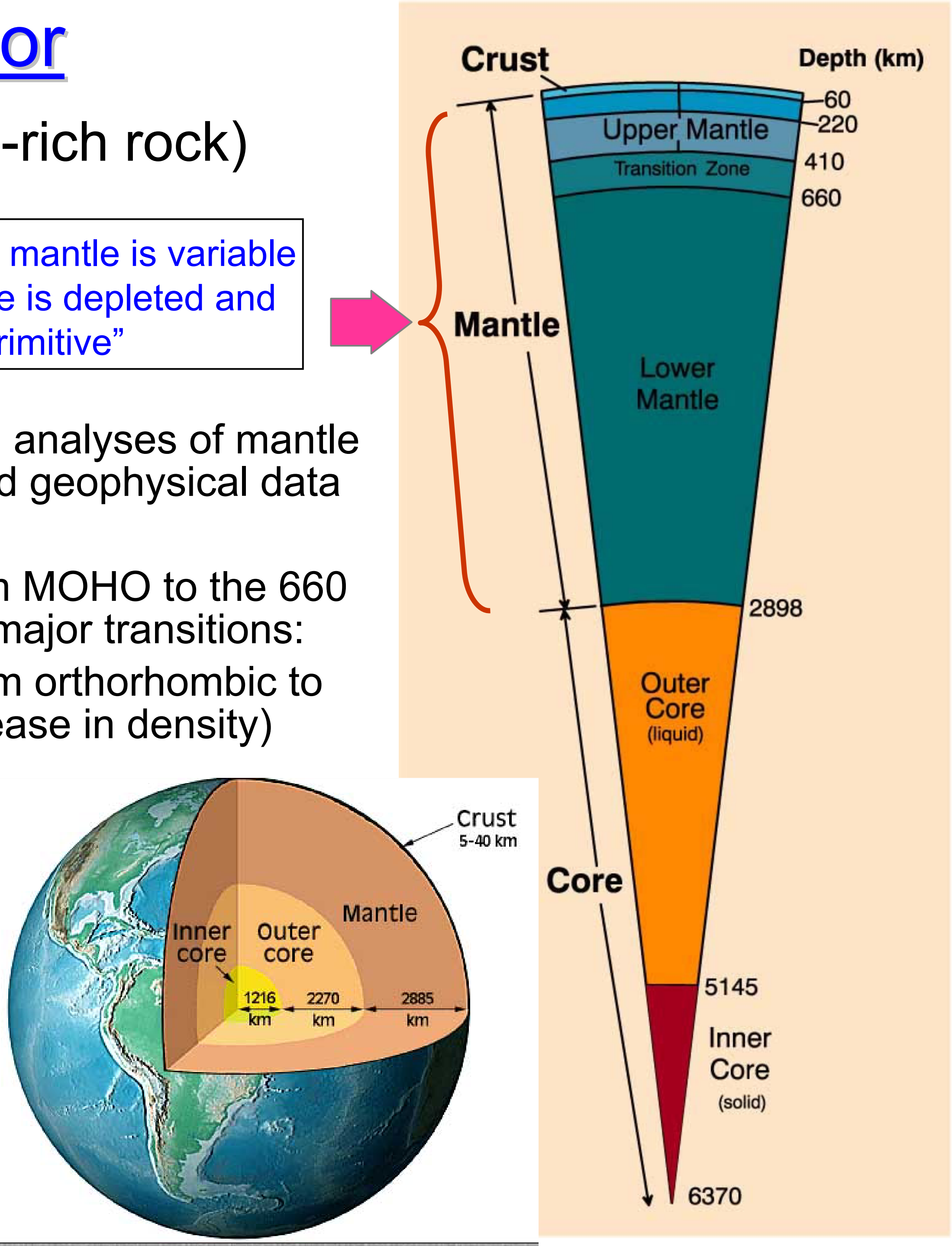
SiO_2	45.1%
Al_2O_3	3.3
FeO	8.0
MgO	38.1
CaO	3.1

Average composition: mantle is variable in comp: Upper mantle is depleted and the lower mantle is "primitive"

Average composition is based on analyses of mantle xenoliths, meteorites, density, and geophysical data

1. Upper mantle (27.5%) extends from MOHO to the 660 km discontinuity. There are two major transitions:
At 410 km (olivine transforms from orthorhombic to cubic [spinel] structure with decrease in density)

2. **Lower mantle** (55.5%) At 660 km spinel transforms to a denser structure (similar to the structure of perovskite) with Si in 6-fold coordination. Associated with magnesio-wüstite



Based on Winter (2001-Fig 1.2) An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

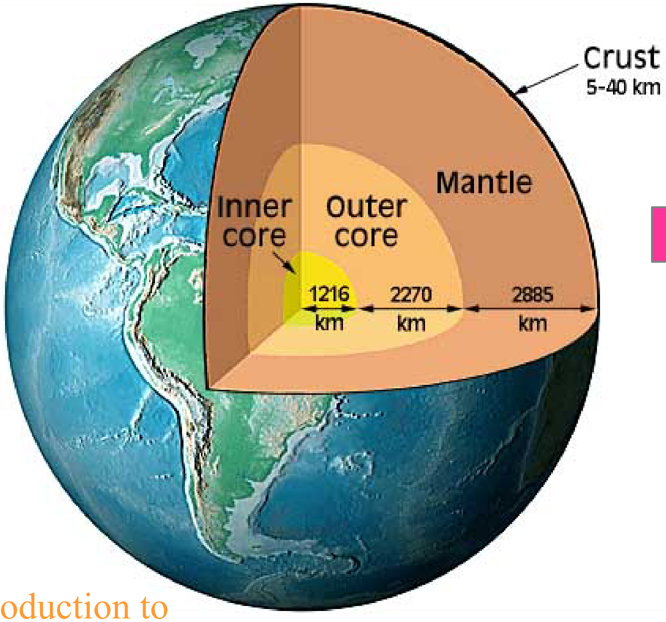
Earth’s Interior

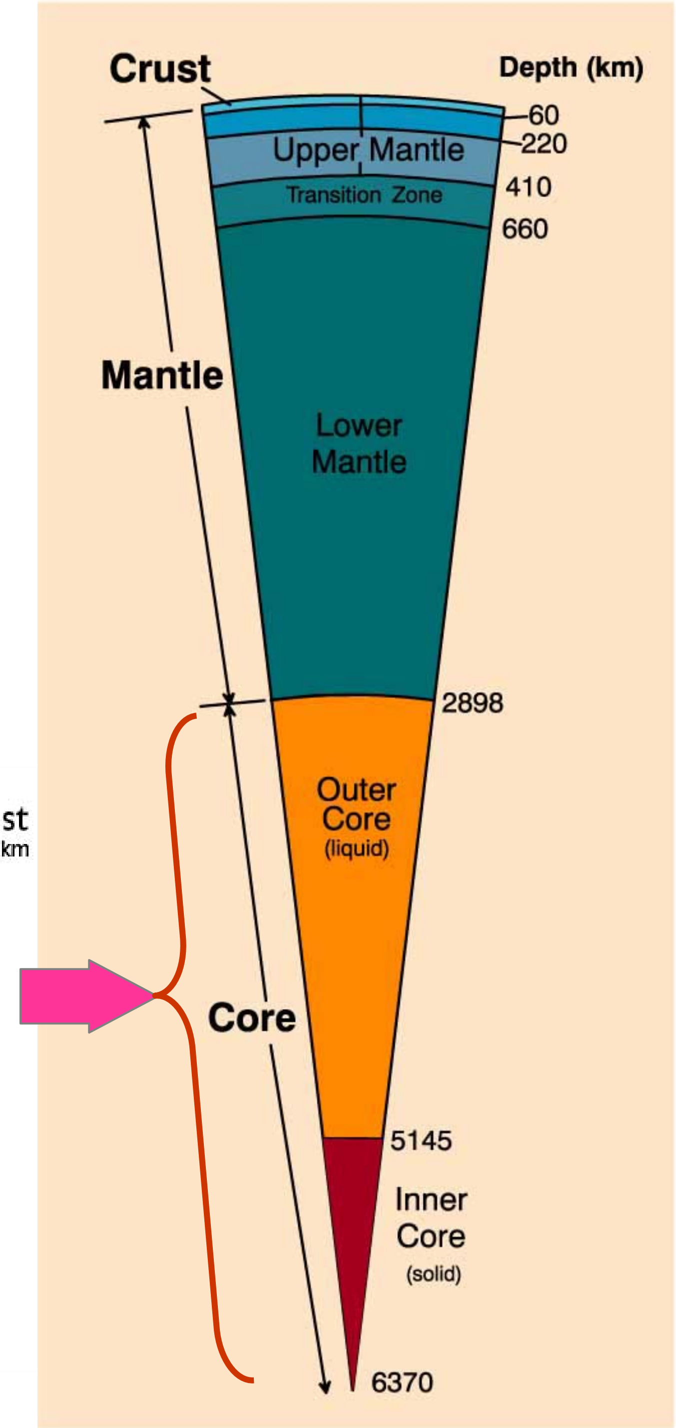
Core (16%):

- 80-85 % Fe + 5-6 % Ni “alloy” + 10-15% light elements--most likely (S + O + Si)
- Composition is based on analogy with iron meteorites, density and seismic velocity data
- Outer core Is “liquid” ,i.e., it does not transmit S waves
- Inner core is solid (pressure effect)

•Convection in the outer core is believed to be the source of the earth’s magnetic field.

•There is also a strong temperature gradient at the core/mantle boundary: may be the source of plumes.





.Based on Winter (2001) Fig 1.2 An Introduction to Igneous and Metamorphic Petrology. Prentice Hall.

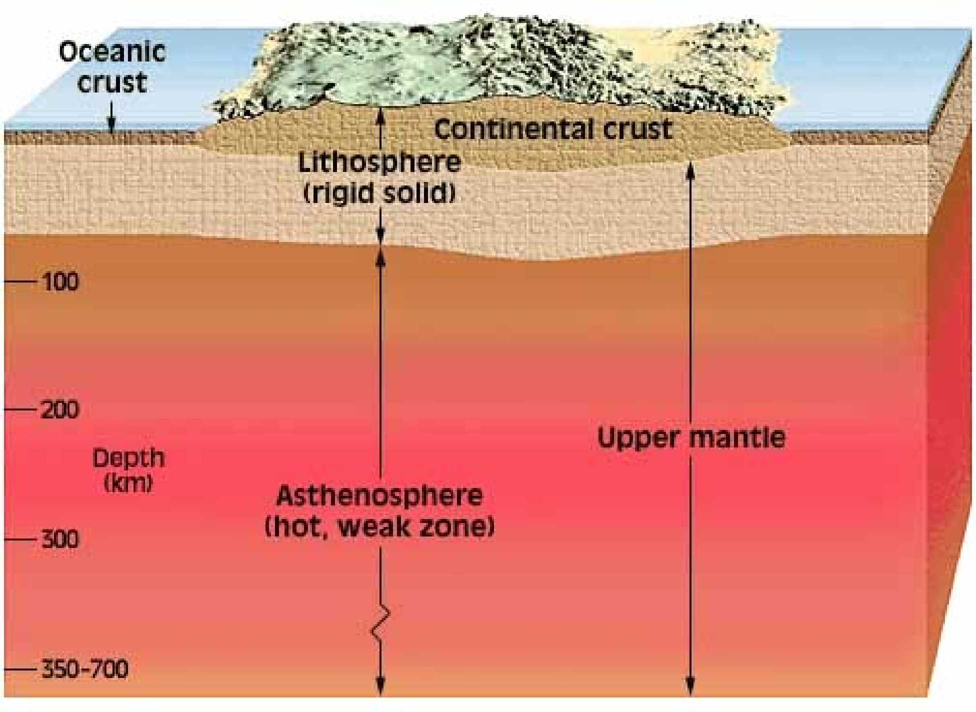
Earth's Interior (crust)

Oceanic crust (Average thickness ~7 km)

Top: Pelagic sediments (av. ~0.5 km)
Pillow lavas and sheet lavas (basalt)
Sheeted dikes (diabase)
Gabbro (isotropic)
Gabbro (layered cumulates) s-moho
Ultramafic cumulates p-moho
Bottom Ultramafic tectonite

Continental Crust (20-70 km) Average ~40 km)

- Old (up to 4 Ga)
- Heterogeneous (average composition: diorite-granodiorite)
- Cratonic core (pre-Cambrian): surrounded by progressively younger mountain belts
- Lower crust is mafic and upper crust is more silicic



Questions:

1. How do we know the depth sequence in oceanic crust?
2. If the earth is 4.567 Ga old, why is the oldest crust only 4.0 Ga?
3. Why is lower crust mafic and upper crust silicic?

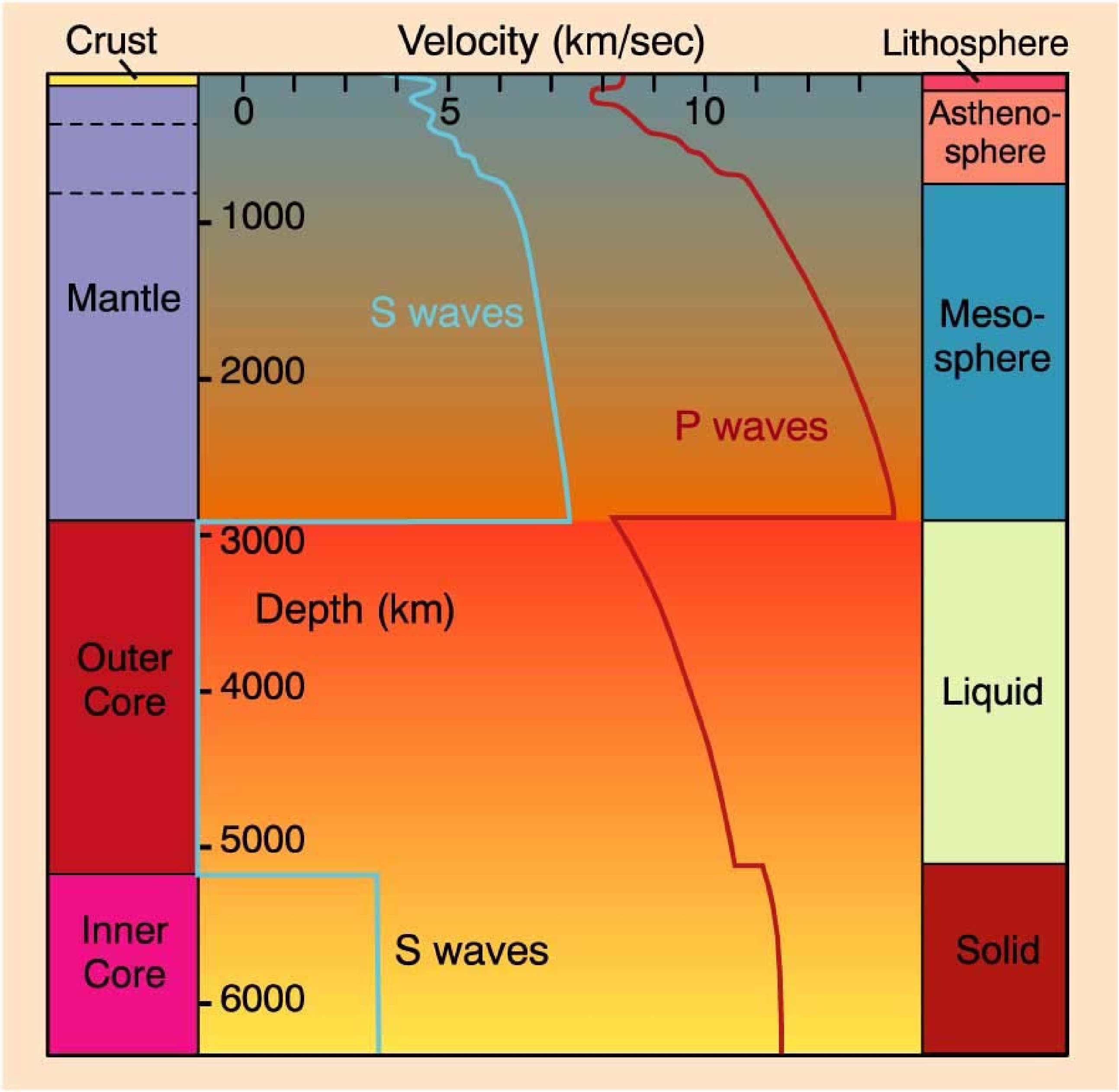
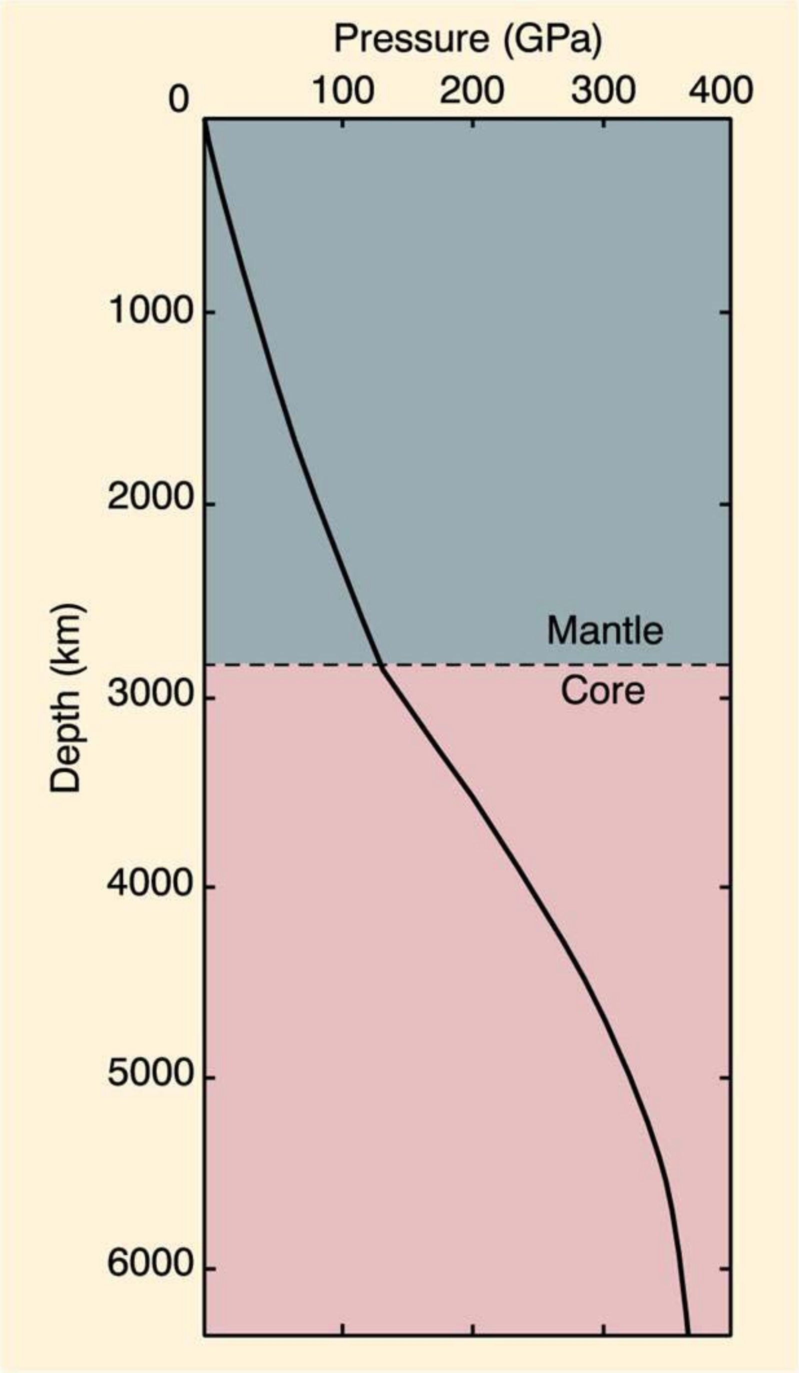


Figure 1-3. Variation in P and S wave velocities with depth. Compositional subdivisions of the Earth are on the left, rheological subdivisions on the right. After Kearey and Vine (1990), *Global Tectonics*. © Blackwell Scientific. Oxford.



Pressure as a function of depth

Pressure units: **1 Pa** = Force of 1 Newton m^{-2}
1 bar = Force of 10^6 dynes cm^{-2} = 10^5 Pa
1 Kbar = 10^2 MPa = 0.1 GPa

$dP/dZ = \rho g$ Integrate to get: $P = \rho g Z$
where P = pressure
ρ = rock density
Z = depth below surface
g = gravitational acceleration (981cm s^{-2})

At base of crust ($z = 40$ km, $\rho_C = 2.7$ g cm^{-3}):

$P = 2.7 \times 981 \times 40 \times 10^5$ dynes cm^{-2}
$= 10.6 \times 10^9$ dynes cm^{-2}
= 10,600 bars =10.6 kilobars = 1.06 GPa

At depth of 200 km in mantle ($\rho_m = 3.5$ g cm^{-3})

P = 65.5 kilobars = 6.55 GPa

Pressure gradient in mantle is nearly linear

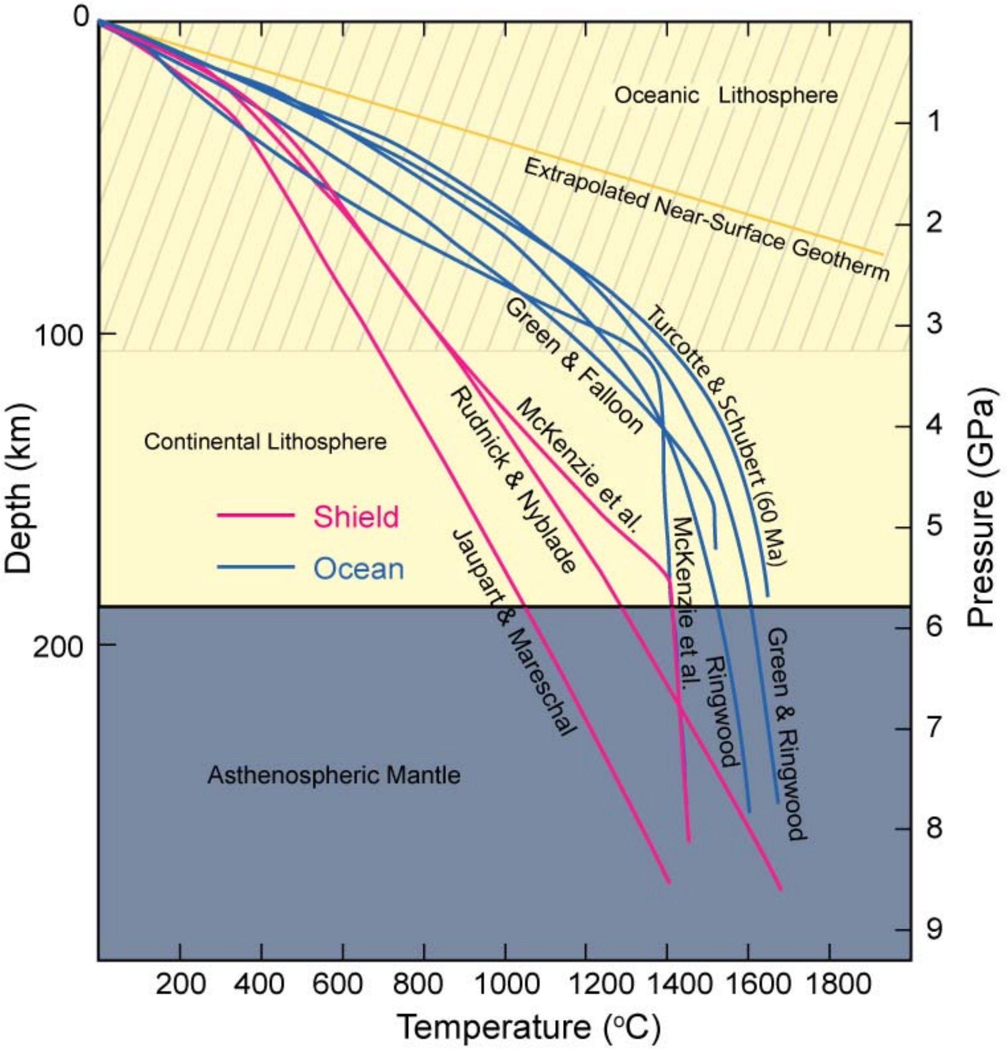
Temperature in the earth

Two main heat sources:

1. Heat from the initial accretion and differentiation of the Earth: heat from this source is still reaching the surface
2. Heat from radioactive decay, primarily decay of U,Th and K. This source is diminishing with time and is highly variable in the earth.

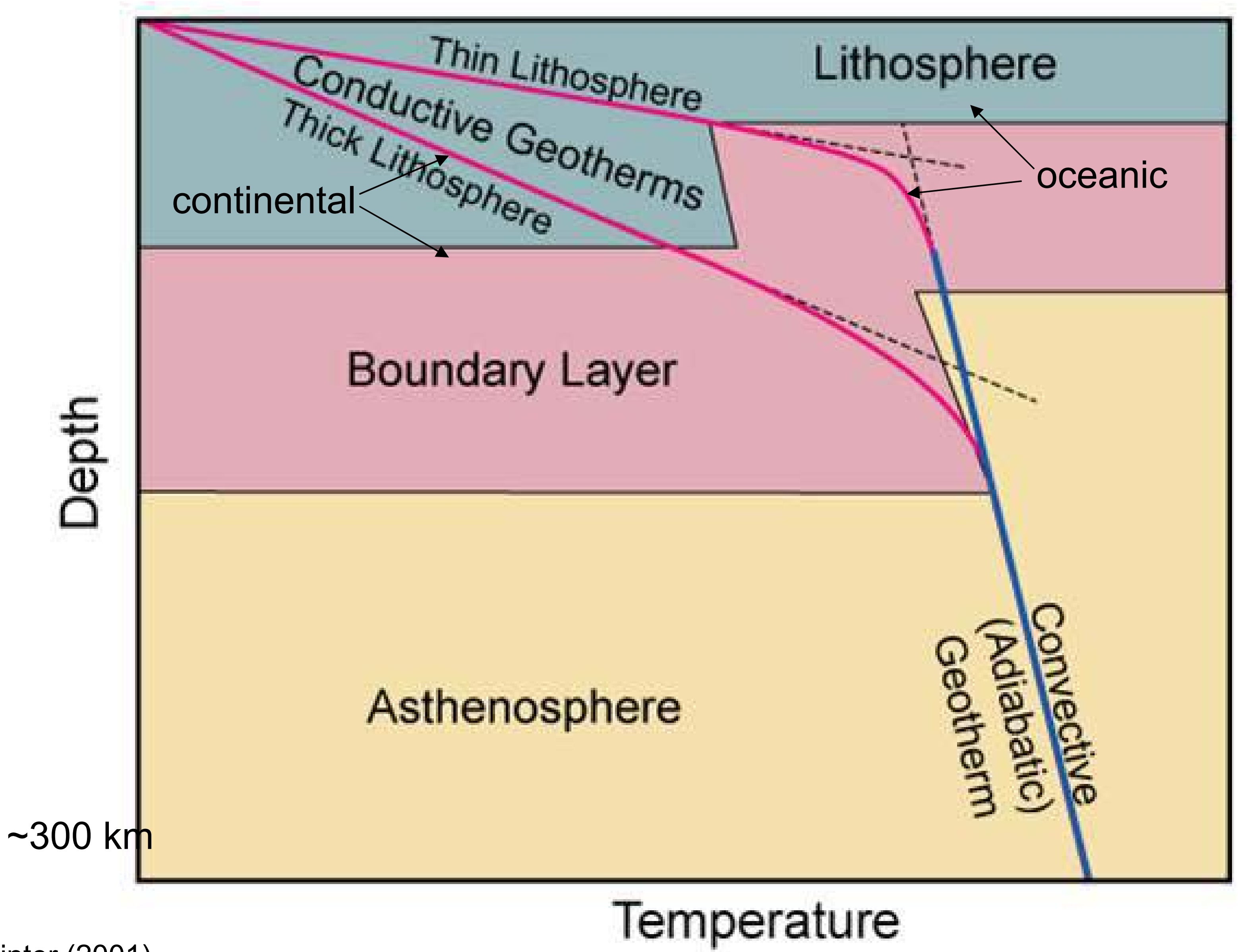
Heat is transferred via **conduction, convection and radiation**

Computed **geothermal gradients** for uppermost 300 km of earth



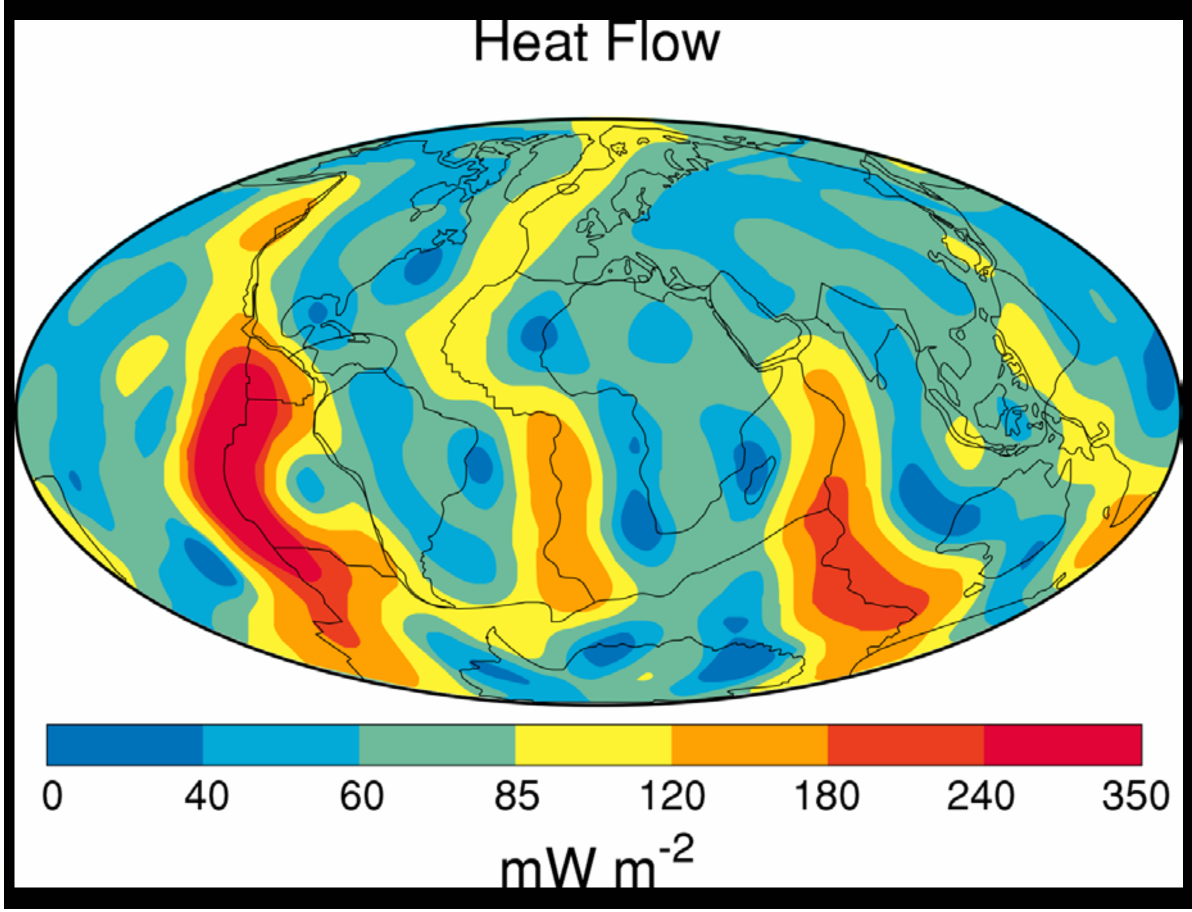
after Winter (2001)

Schematic oceanic and continental temperature gradients

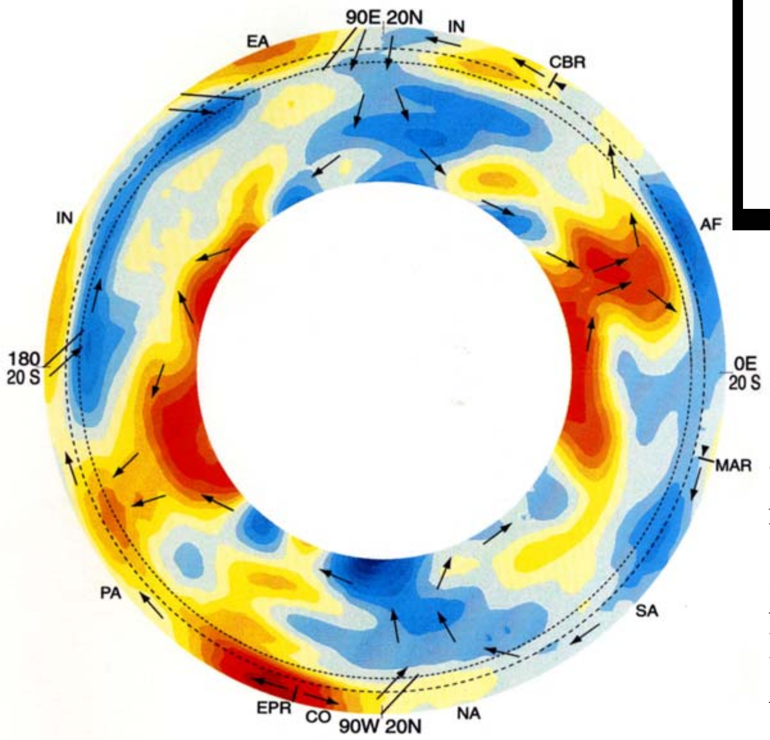


after Winter (2001)

Heat in the earth



Pattern of global heat flux variations compiled from observations at over 20,000 sites. From Pollack, Hurter and Johnson. (1993) Rev. Geophys. 31, 267-280.

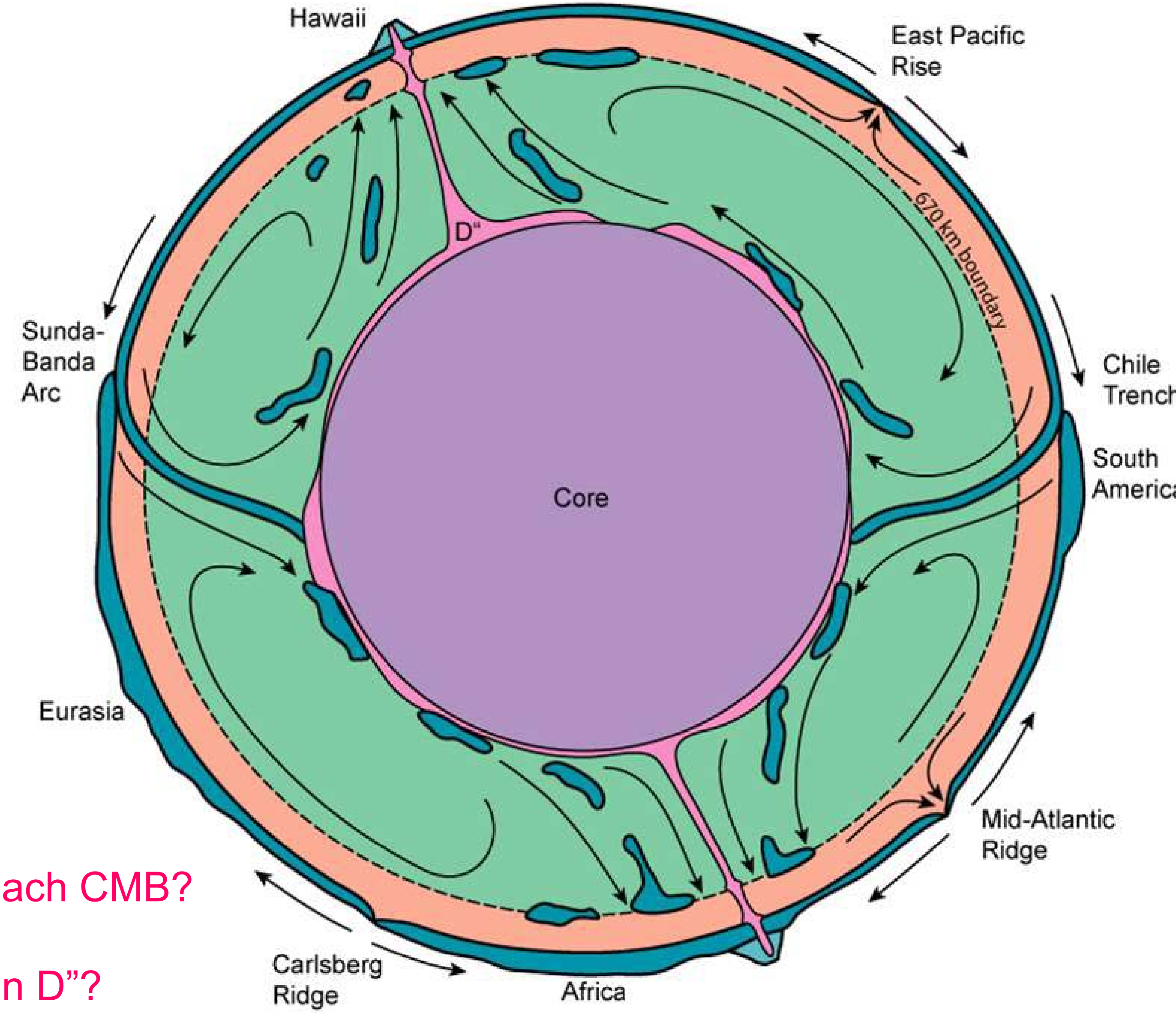


Cross-section of the mantle based on a seismic tomography model. Arrows represent plate motions and large-scale mantle flow. Subduction zones shown by dipping line segments. EPR =- East Pacific Rise, MAR = Mid-Atlantic Ridge, CBR = Carlsberg Ridge. Plates: EA = Eurasian, IN = Indian, PA = Pacific, NA = North American, SA = South American, AF = African, CO = Cocos. From Li and Romanowicz (1996). JGR, 101, 22,245.

Global schematic view of plate tectonics and mantle convection

Subducted plates are shown descending to the core--mantle boundary

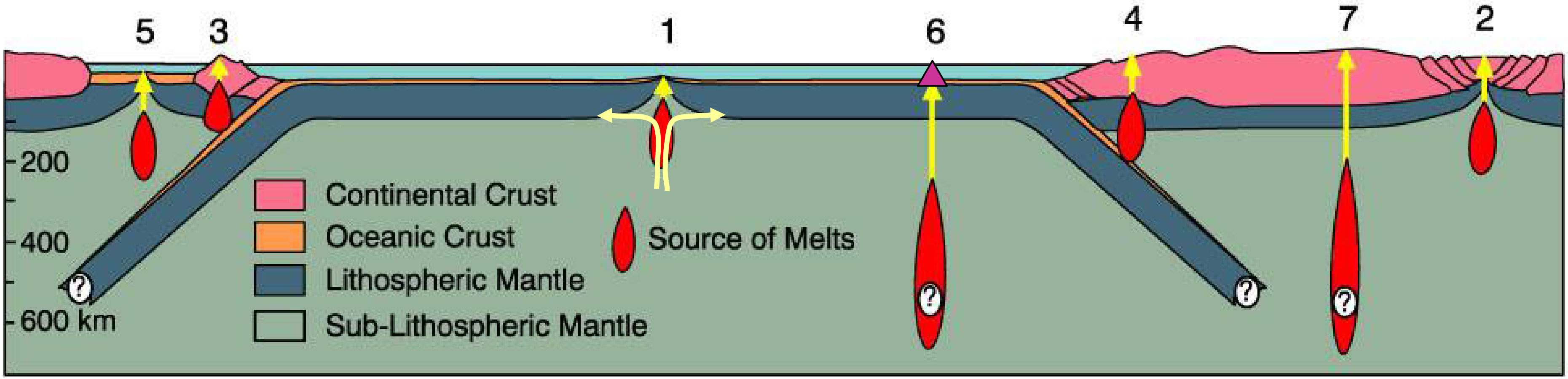
Hot spot volcanism is shown arising from thermal anomalies at the core--mantle boundary (D” layer)



Questions:

1. Do subducted slabs reach CMB?
2. What is the D” layer?
3. Do hotspots originate in D”?
4. Single layer or two layer mantle convection?

Schematic cross section through the upper part of the earth showing major magmatic environments



1. Mid-ocean ridge (divergent margin): thin crust, asthenosphere is close to earth's surface, mantle upwelling, abundant basaltic volcanism/plutonism, e.g. Juan de Fuca Ridge, East Pacific Rise, Mid-Atlantic ridge
2. Intraplate volcanic/plutonic rift system, e.g. East African rift, Rio Grande rift
3. Island arc (convergent margin): built largely on oceanic crust—composed largely of island arc basalt and andesite
4. Continental arc (convergent margin): formation of new crust, volcanism/plutonism, mountain building, regional metamorphism
5. Back arc basin: basaltic volcanism—similar to MORB
6. Ocean islands: basaltic volcanism, e.g., Hawaii, Canaries, and many others
7. Scattered intracontinental activity: may be continental hotspots, e.g., Yellowstone