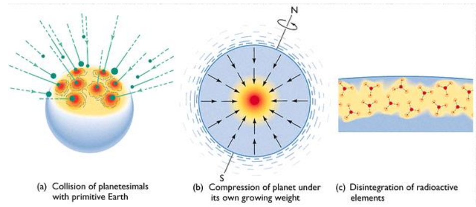
Earth's Changing Landscape Systems

Earth's Internal Energy and Structure

Earth's Internal Heat Engine



- Major processes that have contributed to Earth's internal heat:
  - Heat released by colliding particles during formation of Earth
  - Heat released during gravitational contraction of the early Earth
  - Heat emitted by radioactive decay of unstable isotopes within Earth
  - Early impact with a Mars-sized object
  - Heat released as iron crystallized to form the solid inner core

Planetesimals Aggregated into Form Larger Bodies ~4.6 B.Y. Ago

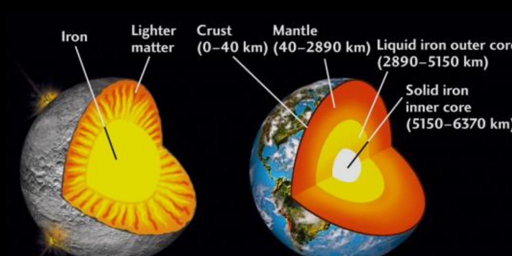
Bodies Accreted To Form Planets, Including Earth

Earth Was Hit With Large Mars-sized Body 4.5 B.Y. Ago

Collision caused extensive heating and melting of the Earth and impactor; Moon formed from material ejected into space

Global Chemical Differentiation

(began about 4.5 billion years ago)

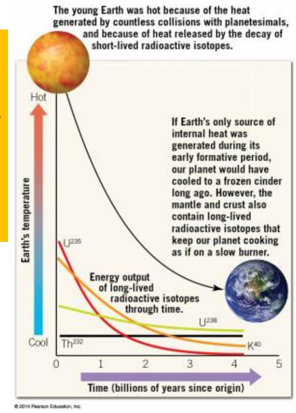


The Earth 4.5 Billion Years Ago

Initial magma ocean was hundreds of km deep

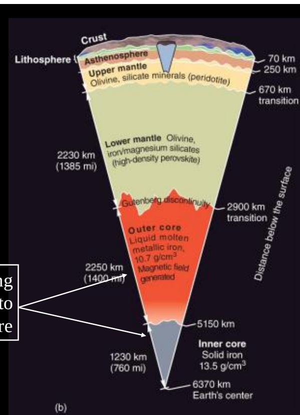
Magma ocean cooled and crystallized from the bottom-up over millions of years to form a solid mantle capped by a primitive crust of basalt and komatiite

Short-lived radioactive isotopes only had half lives of a few million years and have long since decayed



Long-lived radioactive isotopes keep planet warm today

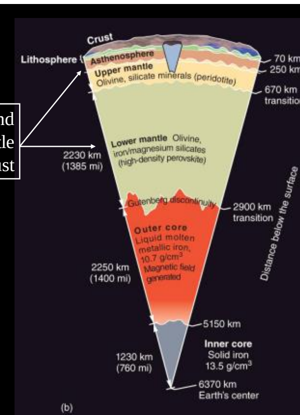
Internal Layers Of Earth Today



Iron sank during differentiation of Earth to form the outer and inner core

Internal Layers Of Earth Today

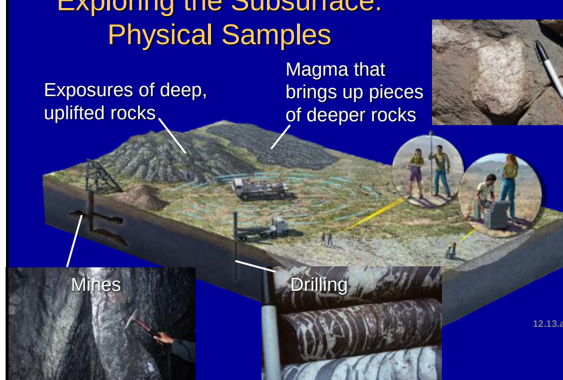
Magma ocean cooled and crystallized to form mantle and crust

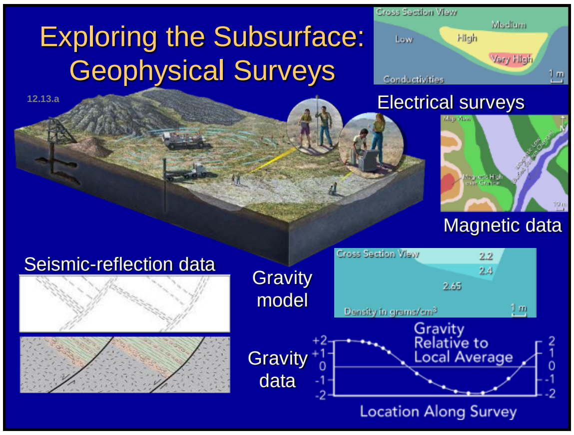


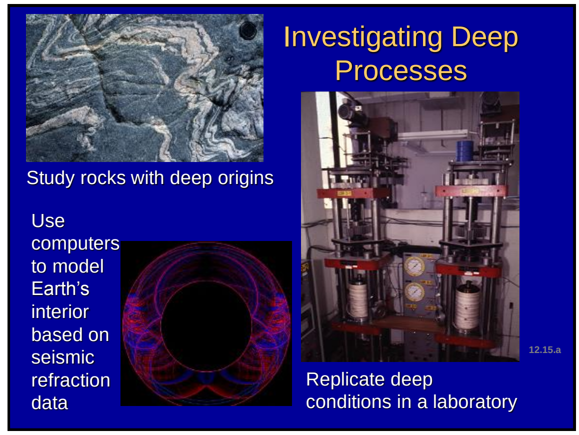
Interior of the Solid Earth

- **The study of Earth's interior is difficult:**
  - **We can drill down a few kilometers into Earth's crust**
  - **In some cases, rocks formed several kilometers beneath the surface can be sampled**
  - **Geophysical surveys can measure certain properties of deeply-buried rocks**

Exploring the Subsurface: Physical Samples

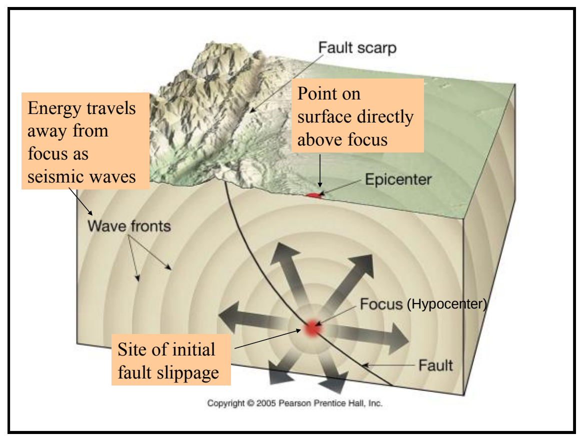






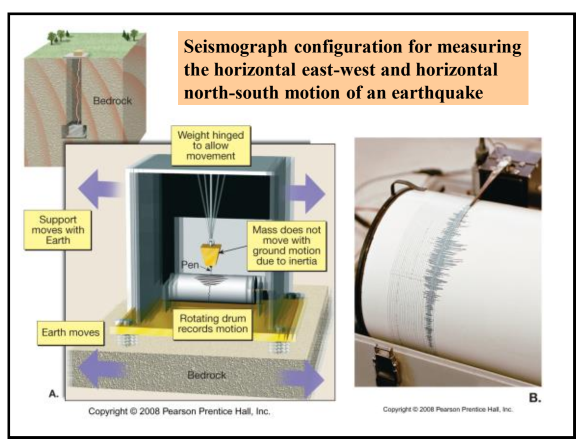
Seismic Waves

- Tectonic forces can cause the rigid crust of the Earth to deform and break along faults
- Slippage along faults releases energy as seismic waves
- Seismic waves travel through the Earth in all directions as vibrations that we recognize as earthquakes

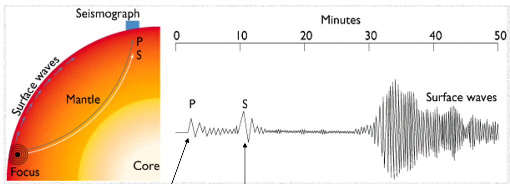


Seismographs

- Seismographs are instruments that measure the vibrations in the ground
- A typical seismic observatory measures three components of ground motion:
  - Vertical up-down motion
  - Horizontal east-west motion
  - Horizontal north-south motion



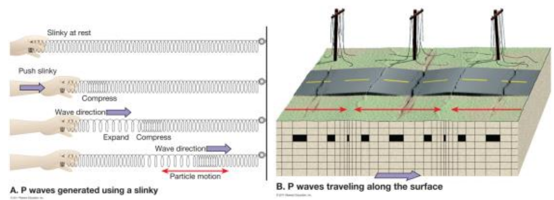
Seismic Waves Arrive at a Seismograph Station in Three Distinct Groups



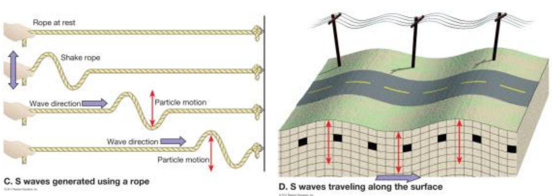
P-waves, traveling the fastest, arrives at station first

S-waves arrive at station next

Surface waves are slowest and arrive last

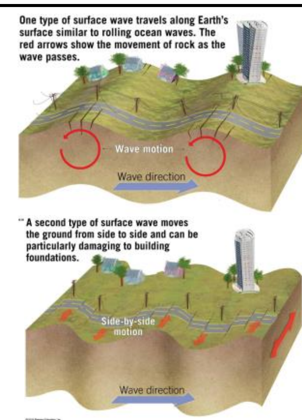


- Primary (P) waves travel through solid rock at an average velocity of ~5 km/sec
- P-waves can travel through:
  - Solids
  - Liquids
  - Gasses
- Push or pull particles of matter in the direction of their travel path



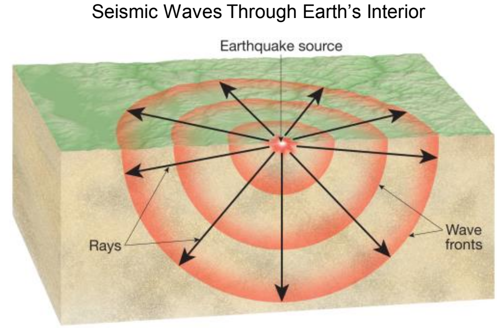
- Secondary (S) waves travel through solid rock at about half the speed of P-waves
- Also called shear waves because they push material at right angles (90º) to their path of travel
- Unlike P-waves, shear waves cannot travel through liquids or gases

- Surface waves are confined to the surface and outer layers of the Earth
- Travel at speeds slightly less than that of S-waves
- Similar to waves in the ocean
- Do most of the destruction during an earthquake

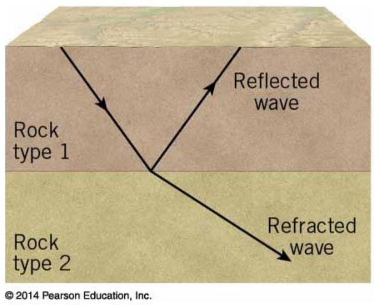


Seismic Wave Motion

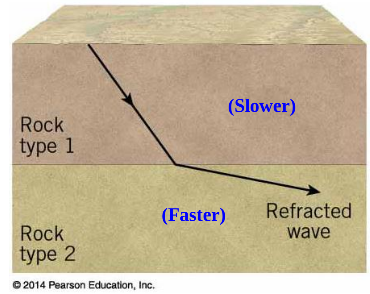
Rays Originating At The Source And Constructed Perpendicular To Wave Fronts Can Be Used To Trace Seismic Waves Through Earth's Interior



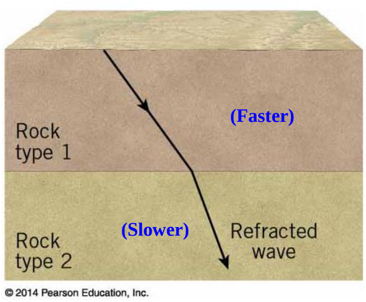
When seismic waves (rays) encounter a boundary between materials with different properties, the energy splits into reflected and refracted (bent) waves.



When the velocity of seismic waves increases when passing from one layer into another, the waves refract (bend) upward towards the boundary separating the layers

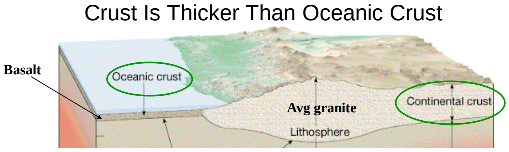


When the velocity of seismic waves decreases when passing from one layer into another, the waves refract (bend) downward away from the boundary separating the layers



Wave Reflection Refraction

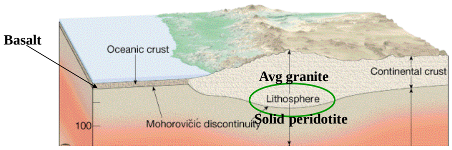
Seismic Studies Indicate That The Continental Crust Is Thicker Than Oceanic Crust



Oceanic Crust:
- Ranges from 3 to 15 km thick
- Consists primarily of basalt and gabbro

Continental Crust:
- ~40 to 65 km thick
- Average composition of granite
- Less dense (more buoyant) than oceanic crust

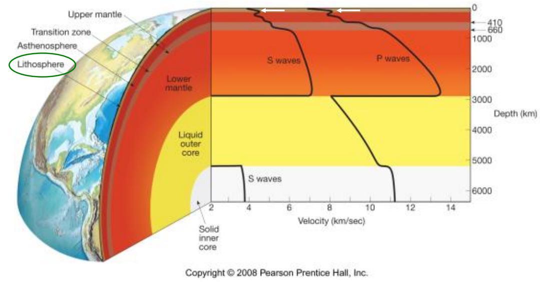
The Crust and Solid Upper Portion of the Mantle (Peridotite) Comprise the Lithosphere



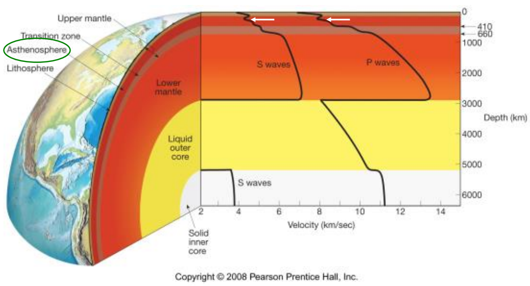
Lithosphere (sphere of rock):

- Relatively cool, rigid layer
- Averages about 100 km in thickness, but may be 250 km or more thick beneath the older portions of the continents
- Lithosphere broken into a series of plates

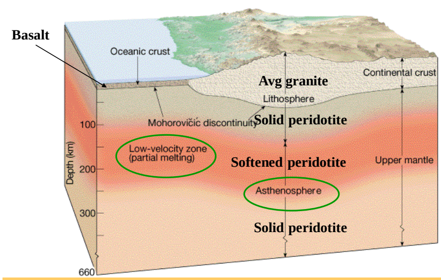
Seismic Velocities Increase With Depth Within The Lithosphere



Seismic Velocities Slow Down In Upper Asthenosphere

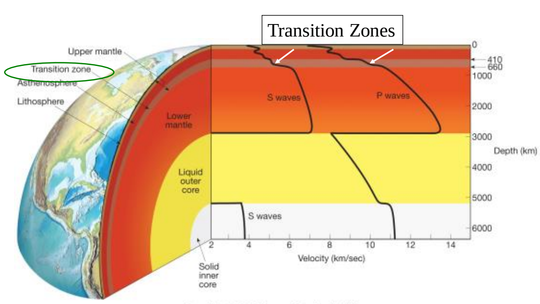


The Asthenosphere Lies Just Below The Lithosphere

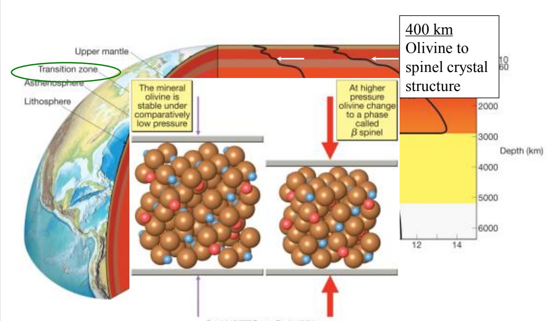


Upper asthenosphere is a weak zone of partially- melted peridotite that slows down seismic waves

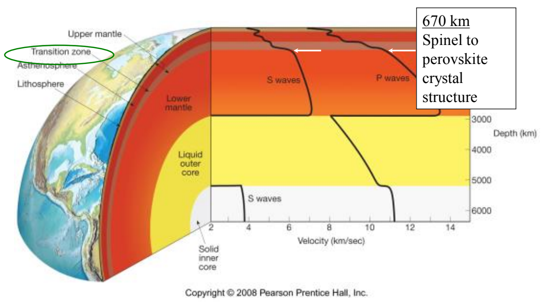
The Lower Asthenosphere IncludesTwo Transition Zones Characterized By Increases In Seismic Wave Velocities

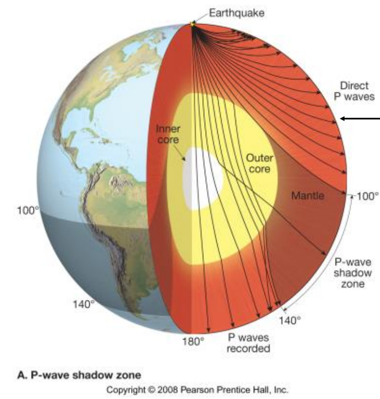


The Upper Transition Zone Marks The Change From Olivine To Spinel Crystal Structure



The Lower Transition Zone Marks The Change From Spinel To Perovskite Crystal Structure



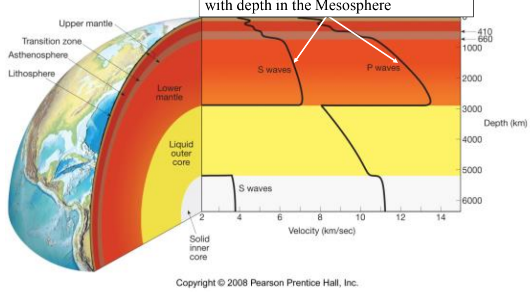


Seismic waves bend outward when traveling through the deeper mantle due to increasing velocity with depth

Increasing velocity due to increasing mantle density with depth

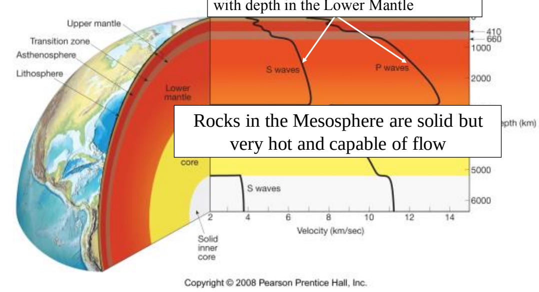
Below The 670 Km Transition Zone Lies The Mesosphere (Lower Mantle)

Velocities of P- and S-waves increase with depth in the Mesosphere

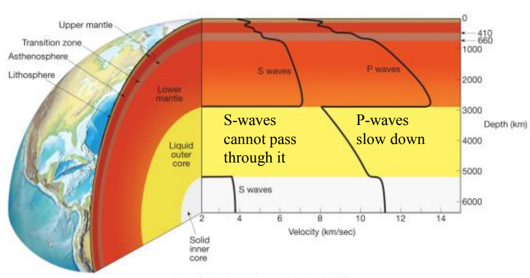


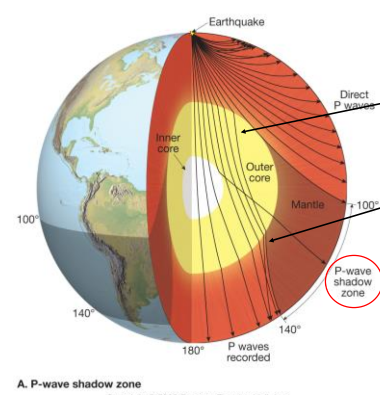
Mesosphere (Lower Mantle)

Velocities of P- and S-waves increase with depth in the Lower Mantle



Seismic Studies Suggest That The Outer Core is Composed of Liquid Iron

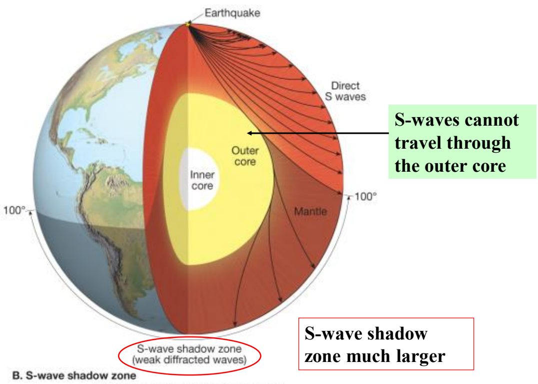




P-waves bend downward when entering the outer core due to a decrease in velocity…

…and bend again when they leave

Bending of P-waves in the outer core creates P-wave shadow zone

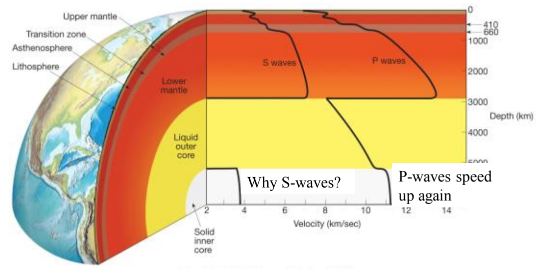


B. S-wave shadow zone

S-waves cannot travel through the outer core

S-wave shadow zone much larger

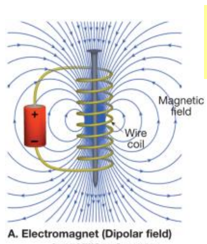
Seismic Studies Suggest That The Inner Core is Composed of Solid Iron and Nickel



Seismic Waves_Earth's Layers

The Earth's Magnetic Field

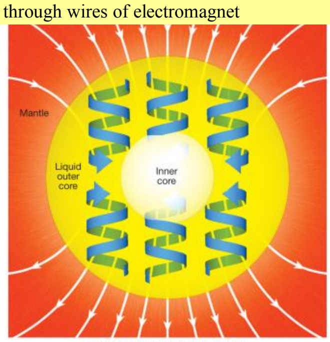
- Liquid iron in the outer core is stirred into convective motion by Earth's internal heat
- Circulation of the liquid iron produces electric currents
- These electric currents, in turn, generate the Earth's magnetic field

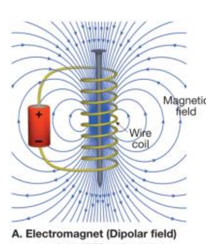


A. Electromagnet (Dipolar field)

Earth's magnetic field envisioned as an electromagnet

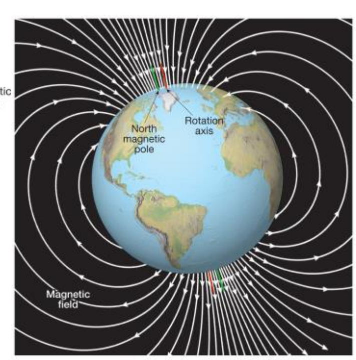
Cylinders of spiraling liquid iron in outer core behave like coil of current passing through wires of electromagnet





A. Electromagnet (Dipolar field)

Magnetic poles inclined at angle to Earth's axis of rotation



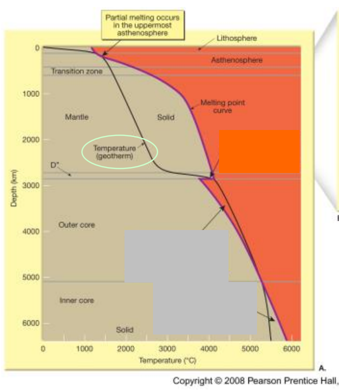
C. Earth's magnetic field (Dipolar field)

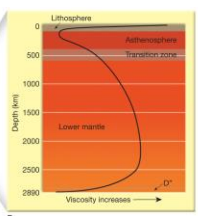
Earth's Magnetic Field

Earth' Internal Heat Engine

- Earth's temperature gradually increases with depth at a rate known as the geothermal gradient:
  - Varies considerably from place to place
  - Averages between about 20°C and 30°C per km in the crust
  - Rate of increase of heat with depth significantly less in the mantle and core

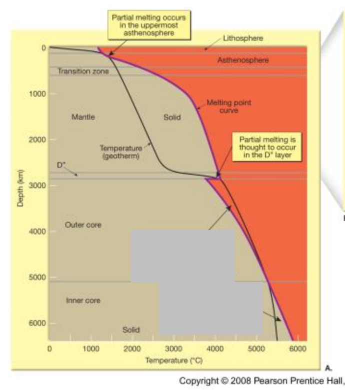
---

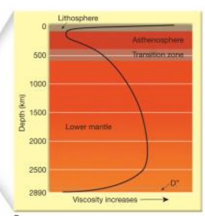




The **Geothermal Gradient** is a curve showing the increase of temperature with depth

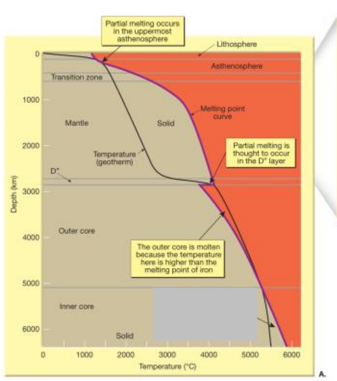
---

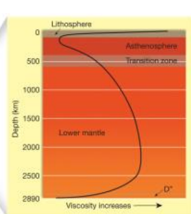




The **Geothermal Gradient** is a curve showing the increase of temperature with depth

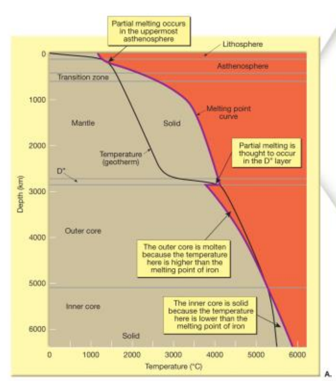
---

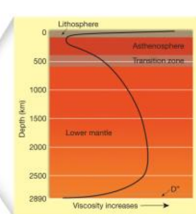




The **Geothermal Gradient** is a curve showing the increase of temperature with depth

---



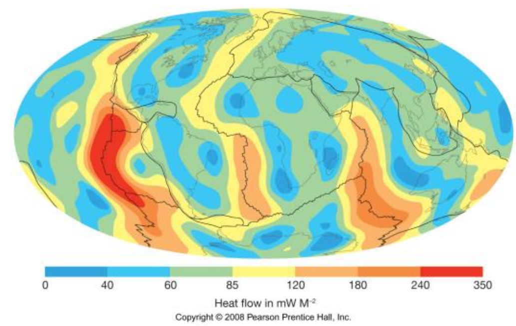


The **Geothermal Gradient** is a curve showing the increase of temperature with depth

Earth's Internal Heat Engine

- Heat continues to escape from Earth's interior today
- Movement of Earth's internal heat from the interior towards the surface is known as heat flow
- Earth's modern heat flow varies considerably from place to place:
  - High heat flow along mid-ocean ridges and other volcanically active regions
  - Lower heat flow within the interior of stable continents

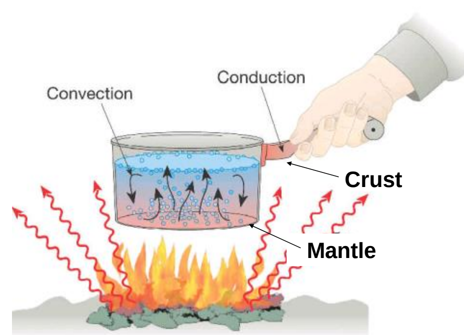
Modern Variations in Heat Flow on Earth's Surface

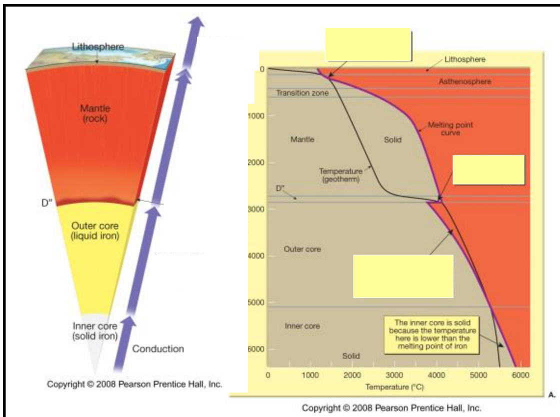


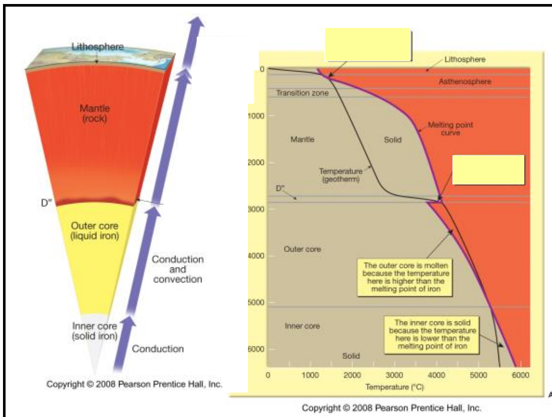
Earth' Internal Heat Engine

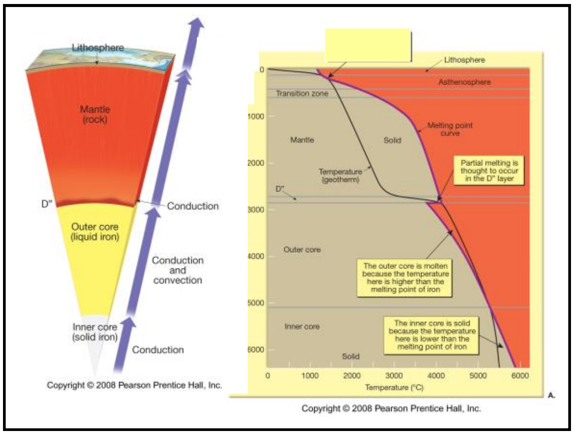
- Heat flow in the crust:
  - Process called conduction
  - Not very efficient at transferring heat
- Heat flow in the mantle:
  - There is only a modest increase in temperature with depth in the mantle
  - Mantle must have an effective method of transmitting heat from the core upward to base of the crust
  - Convection would be an effective process

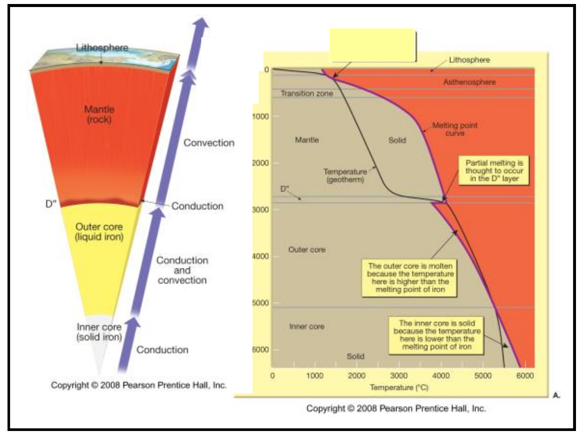
Earths Interior

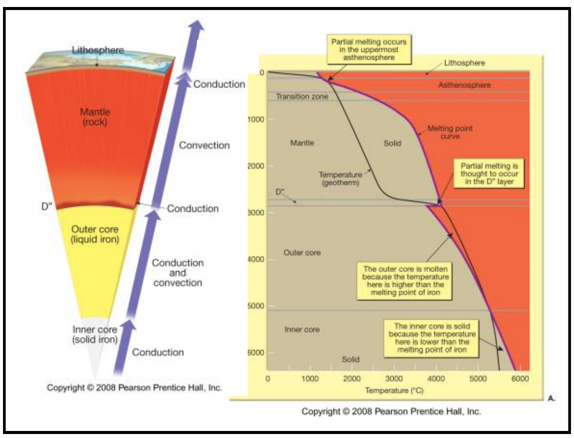


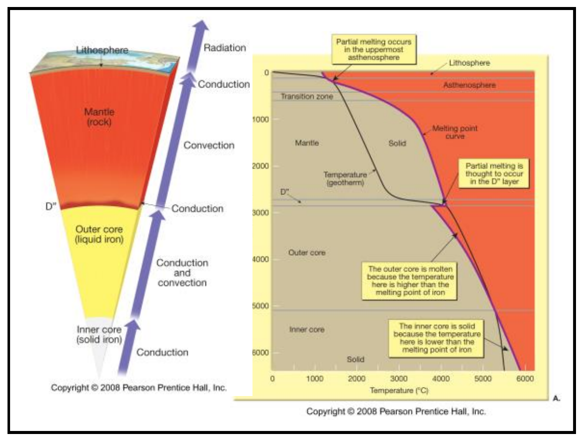








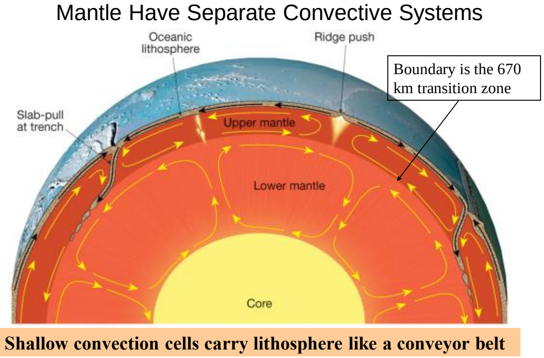




Theories of Mantle Convection

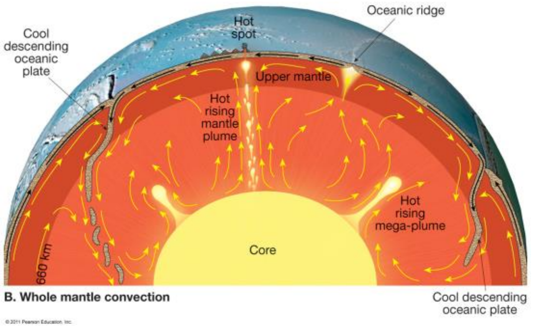
- **Two layer mantle convection:**
  - **Separate convection cells for the upper and lower mantle**
  - **Boundary between the upper and lower mantle is the 670 km transition zone**
- **Whole-mantle convection:**
  - **Upper and lower mantle part of one large convection system**
  - **Hot, rising mantle plumes originate at the core-mantle boundary**

Two-Layer Convection Model: Upper And Lower Mantle Have Separate Convective Systems



Shallow convection cells carry lithosphere like a conveyor belt

Whole-Mantle Convection Model: Upper And Lower Mantle Part Of One Convective System



Seismic Tomography

- Three dimensional model of Earth's interior based on seismic imaging
- Requires seismic records from many different earthquakes
- Identifies regions where P- and S-waves are faster or slower than average
- Velocity variations of seismic waves attributed to variable temperatures and other material properties:
  - Higher temperatures, slower velocities
  - Lower temperatures, greater velocities