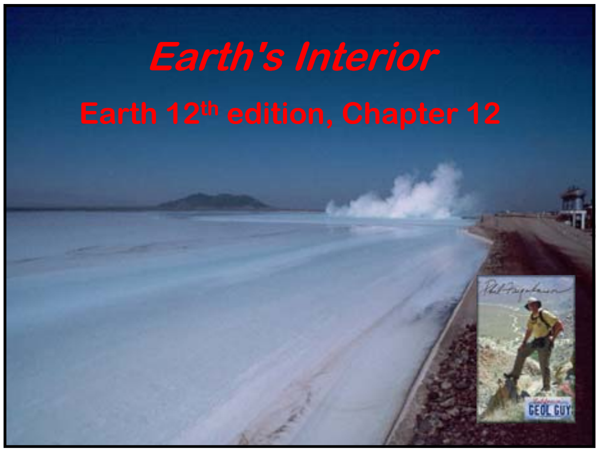
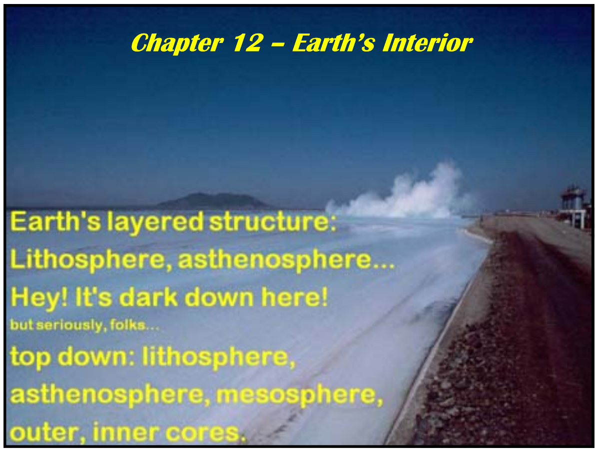


Earth's Interior

Earth 12th edition, Chapter 12



Chapter 12 – Earth's Interior

Earth's layered structure:
Lithosphere, asthenosphere...
Hey! It's dark down here!
but seriously, folks...
top down: lithosphere,
asthenosphere, mesosphere,
outer, inner cores.

Earth's Internal Structure

- Earth's three major interior layers can be further subdivided into zones
  - Gravity and chemical segregation established the three basic divisions
  - The densest material (iron) sinks to the center
  - The least dense material makes up the outer layers of the planets
  - In addition, the layers have small horizontal variations in mineral composition and temperature with depth
  - These differences indicate that the Earth's interior is very dynamic

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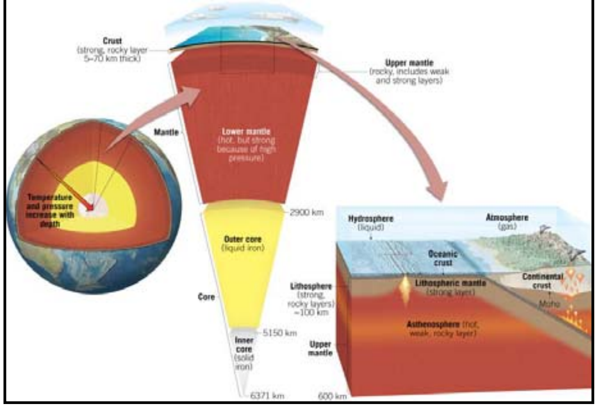
Earth's Layered Structure



Earth's Internal Structure

- Mineral and Phase Changes
  - The density of rocks increases toward the center of the planet due to gravity
    - Upper mantle rocks have a density of 3.3 g/cm^3
    - The same rocks in the lower mantle have a density of 5.6/cm^3
    - The lower mantle rocks undergo a **mineral phase change** as the minerals are compressed under higher pressures

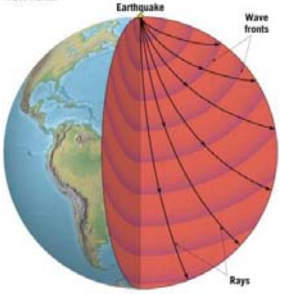
---

Probing Earth's Interior

- "Seeing" Seismic Waves
  - Most of our knowledge of Earth's interior comes from the study of earthquake waves
  - Seismic velocities
    - Travel times of P (compressional) and S (shear) waves through Earth vary depending on the properties of the materials
      - Seismic waves travel fastest in stiff (rigid) rocks
      - Seismic wave velocities also vary based on composition of the rocks

Seismic Waves Provide a Way to “See” into our Planet

When traveling through Earth, seismic waves spread out from an earthquake source (hypocenter) as circular features called *wave fronts.*

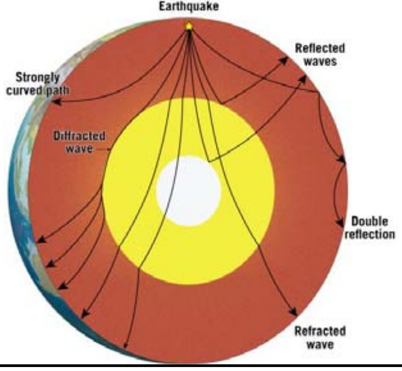


The paths taken by these waves can also be considered *seismic rays*, lines drawn perpendicular to the wave front as shown here.

Probing Earth’s Interior

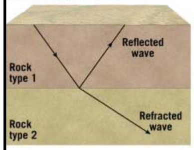
- “Seeing” Seismic Waves
  - Interactions between **seismic waves** and Earth’s layers
    - Seismic waves reflect and refract as they pass through the different layers of Earth
    - Allow us to “see” inside the Earth
  - P and S waves travel at different velocities which also depend on the properties of the materials that transmit them
    - Faster through more rigid materials
    - S-waves cannot travel through liquids

Possible Paths That Seismic Rays Follow Through Earth

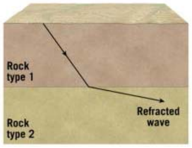


Possible Paths That Seismic Rays Follow Through Earth

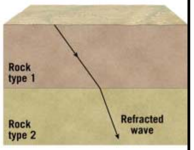
When seismic waves (rays) encounter a boundary between materials with different properties, such as air and water, the energy splits into reflected and refracted (bent) waves.



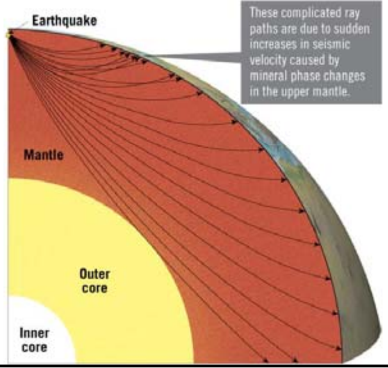
When the velocity of seismic waves increases as they pass from one layer into another, the waves refract (bend) toward the boundary separating the layers.



When the velocity of seismic waves decreases as they pass from one layer into another, the waves refract (bend) away from the boundary separating them.



Possible Paths That Seismic Rays Follow Through Earth

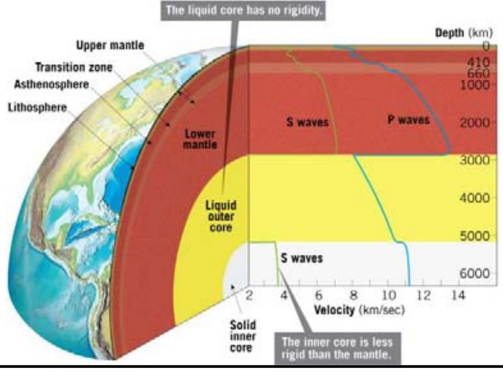


These complicated ray paths are due to sudden increases in seismic velocity caused by mineral phase changes in the upper mantle.

Earth’s Layers

- Studying seismic-wave velocities gives seismologists a layer-by-layer understanding of Earth's composition
  - When a seismic wave hits a boundary between different Earth materials some of the waves are reflected and some are refracted
  - Velocity of seismic waves increases with depth
    - By examining the behavior of a variety of rocks are the pressures corresponding to various depths, geologists have learned about the compositions of Earth's crust, mantle, and core

Average Velocities of P and S Waves at Each Depth


The liquid core has no rigidity.

The inner core is less rigid than the mantle.

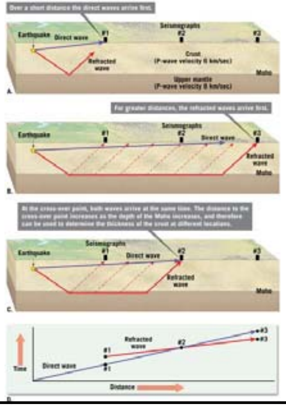
Earth’s Layers

- Earth’s Crust
  - Oceanic crust
    - Forms at mid-ocean ridges
    - Averages 7 km thick
    - Composed of basalt and gabbro
    - Average density of 3.0 g/cm^3
  - Continental crust
    - Heterogeneous structure and composition
    - Averages 40 km thick
      - Thickest (70 km) at mountains like the Himalayas
      - Thinnest (20 km) in the Basin and Range region
    - Average density of 2.7 g/cm^3

Earth’s Layers

- Discovering the boundaries: The Moho
  - The **Moho** is the boundary between the crust and the mantle
    - Discovered in 1909 through jump in velocity of P waves below the base of the continents
  - P wave velocities abruptly increase at the Moho
    - Seismic waves refract as they cross the Moho

Determining the Depth of the Moho


Over a short distance the direct waves arrive first.

For greater distances, the refracted waves arrive first.

At the cross-over point, both waves arrive at the same time. The distance to the cross-over point increases as the depth of the Moho increases, and therefore can be used to determine the thickness of the crust at different locations.

Earth’s Layers

- Earth’s Mantle
  - Over 82% of Earth's volume is in the **mantle**, which is the layer between the crust and the core
    - Nearly 2900 km thick
    - Extends from Moho to the liquid outer core
  - Solid rocky layer composed of silicate minerals rich in iron and magnesium
    - Determined based on observations of seismic waves

Earth’s Layers

- Earth’s Mantle
  - The **upper mantle** extends from the Moho to 660 km deep
    - Composed of peridotite, an iron and magnesium rich rock composed of olivine and pyroxene
    - The **lithospheric mantle** is the uppermost part of the mantle and ranges in thickness from a few km to 200 km
      - This layer plus the crust make up the rigid lithosphere
    - The **asthenosphere** is a weak layer beneath the lithospheric mantle
    - The lower portion of the upper mantle ranges between 410 and 660 km depth, called the **transition zone**
      - Due to pressure increase, olivine converts to spinel
      - Pyroxene converts to a garnet-like structure

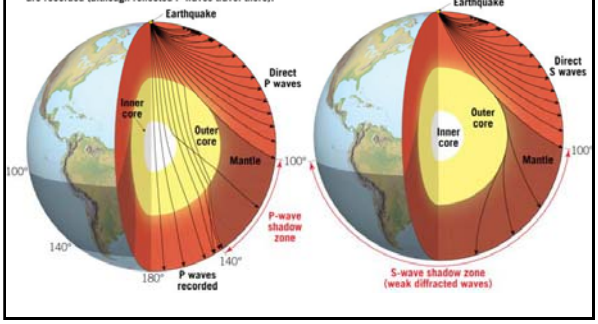
Earth’s Layers

- Earth’s Mantle
  - The **lower mantle** extends from the transition zone to the liquid core (2900 km deep)
    - Earth's largest layer, occupying 56 percent of Earth's volume
    - Olivine and pyroxene are converted into perovskite
  - The **D” layer** is the boundary between the rocky lower mantle and the liquid outer core
    - Cool regions are thought to be the remnants of subducted lithospheric plates
    - Hot regions are though to be the start of deep mantle plumes

Earth’s Layers

- Earth’s Mantle
  - Discovering boundaries: **The core-mantle boundary**
    - Beyond 100 degrees from an epicenter, P and S waves are absent or weak
    - Called a **shadow zone**
      - S waves cannot travel through liquid
      - P waves are considerably refracted through liquid

P and S wave Shadow Zones



A. The P-wave shadow zone exists because P waves interact with the low-velocity liquid iron of the outer core, which causes their rays to be refracted downward. This creates a shadow zone where no direct P waves are recorded (although reflected P waves travel there).

B. The core is an obstacle to S waves, because they cannot pass through liquids. Therefore, a large shadow zone exists for direct S waves.

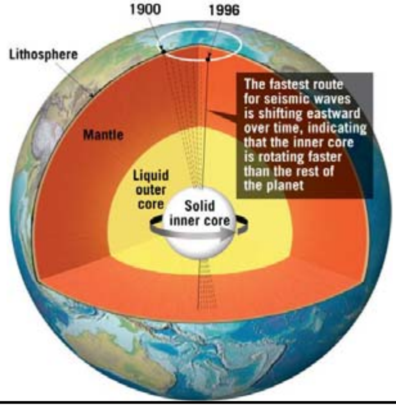
Earth’s Layers

- Earth’s Core
  - The **outer core** is liquid, based on the absence of S waves traveling through the core
    - The outer core has a density of 9.9 g/cm^3
    - Composed mostly of iron with some nickel
    - 15 percent of the outer core consists of lighter elements
    - The **core** (outer core and inner core) accounts for one-sixth of Earth’s volume but one-third of its mass because it is so dense
    - Outer core is 2270 km thick

Earth’s Layers

- Earth’s Core
  - The **inner core** is a solid, dense sphere (all other layers are *shells*)
    - Has a density of 13 g/cm^3
    - Is growing as Earth cools at the expense of the outer core
    - Rotates faster, and moves independently of, the crust and mantle
    - Has a radius of 1216 km
  - *The inner core-outer core boundary*
    - Some P waves are strongly refracted by a sudden increase in velocity at a boundary within Earth’s core

Earth’s Core

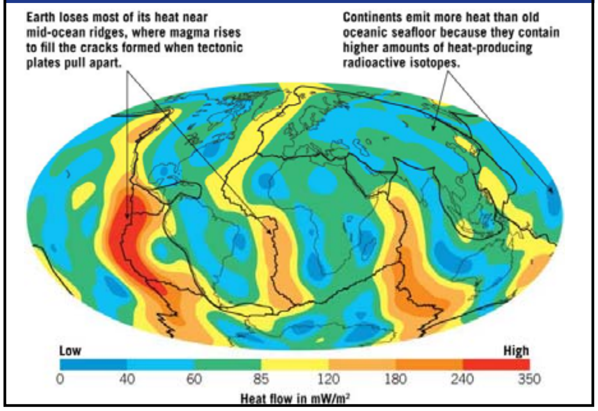


The fastest route for seismic waves is shifting eastward over time, indicating that the inner core is rotating faster than the rest of the planet

Earth’s Temperature

- Heat flow from hotter regions to colder regions
  - – Earth’s core is 5500°C
  - – Earth’s surface is 15°C
  - – Heat flows from the core to the surface
    - Rate at which Earth is cooling can be estimated by determining the rate at which heat escapes Earth’s surface
  - – Heat flow is highest near mid ocean ridges
  - – Heat flow is lowest the deep abyssal plains

Earth’s Temperature



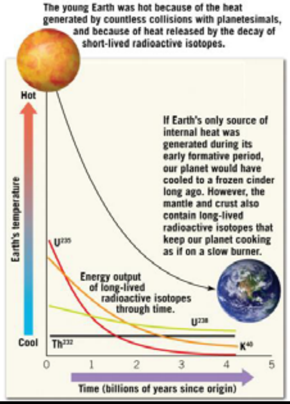
Earth loses most of its heat near mid-ocean ridges, where magma rises to fill the cracks formed when tectonic plates pull apart.

Continents emit more heat than old oceanic seafloor because they contain higher amounts of heat-producing radioactive isotopes.

Earth’s Temperature

- How Did Earth Get So Hot?
  - – Earth has experienced two thermal stages
    - First stage lasted 50 million years when temperatures increased rapidly, caused by
      - – Collision of planetesimals
      - – Decay of radioactive isotopes
      - – Asteroid collision that created the Moon
      - – Temperatures increased
    - Second stage involves the slow cooling over the next 4.5 billion years
      - – Some heat is still generated through radioactive decay in the mantle and crust

Earth’s Thermal History Through Time



The young Earth was hot because of the heat generated by countless collisions with planetesimals, and because of heat released by the decay of short-lived radioactive isotopes.

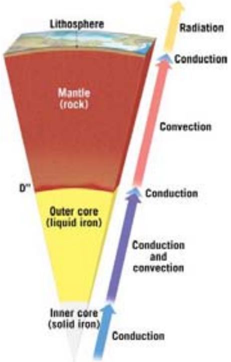
If Earth’s only source of internal heat was generated during its early formative period, our planet would have cooled to a frozen cinder long ago. However, the mantle and crust also contain long-lived radioactive isotopes that keep our planet cooking as if on a slow burner.

Energy output of long-lived radioactive isotopes through time.

Earth’s Temperature

- Heat Flow
  - – Heat travel through Earth by conduction, convection, and radiation
    - **Convection** and **conduction** occur within Earth’s interior
    - Radiation transports heat away from Earth's surface to space

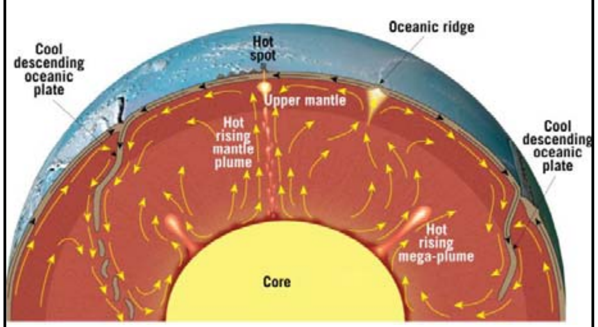
Dominant Types of Heat Transfer at Various Depths



Earth’s Temperature

- **Convection** is the transfer of heat where hot materials replace cold material (or vice versa)
  - – Primary means of heat transfer within Earth
  - – Convection cycles occur within the mantle and outer crust
    - Mantle plumes are the upward flowing arm of the cycle
  - – Similar to a pot of boiling water
  - – Material must flow in a convection cycle
    - **Viscosity** is a material's resistance to flow

Whole-Mantle Convection



Earth’s Temperature

- **Conduction** is the transfer of heat through a material
  - – Through the collision of atoms or through the flow of electrons
  - – Materials conduct heat at different rates
    - Metals are better than rocks at conducting heat
    - Diamonds are better than air at conducting heat
- Conduction is not an efficient way to move heat through most of Earth
  - – Most rocks are poor conductors of heat

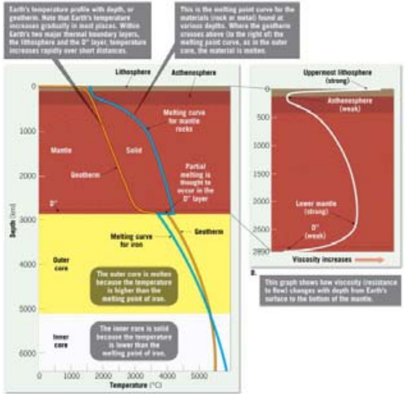
Earth’s Temperature

- Heat flow in Earth’s interior
  - – Conduction is important in the solid inner core
  - – Convection is important from the inner to the outer core
    - Top-down, thermally driven convection
    - Crystallization and sinking of iron to the inner core drives chemical convection
    - Radioactive isotopes provide additional heat to drive convection

Earth’s Temperature

- Earth’s Temperature Profile
  - – The profile of Earth's temperature at each depth is called the **geothermal gradient**
    - Varies within Earth's interior
      - – Crust is 30°C per kilometer of depth
      - – Mantle is 0.3°C per kilometer
        - » Exception is the D” layer
    - Base of the lithosphere is roughly 1400º
    - Base of the mantle is roughly 2500º
    - Temperature at Earth's center is estimated to be 5500º

Geothermal Gradient


Earth's temperature profile with depth, or geotherm. Note that Earth's temperature increases gradually in most places. Within Earth's two major thermal boundary layers, the lithosphere and the D" layer, temperature increases rapidly over short distances.

This is the melting point curve for the materials (rock or metal) found at various depths. Where the geotherm crosses above (to the right of) the melting point curve, as in the outer core, the material is molten.

The outer core is molten because the temperature is higher than the melting point of iron.

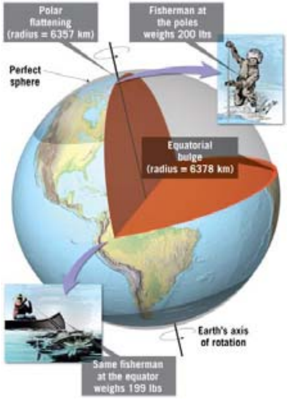
The inner core is solid because the temperature is lower than the melting point of iron.

This graph shows how viscosity (resistance to flow) changes with depth from Earth's surface to the bottom of the mantle.

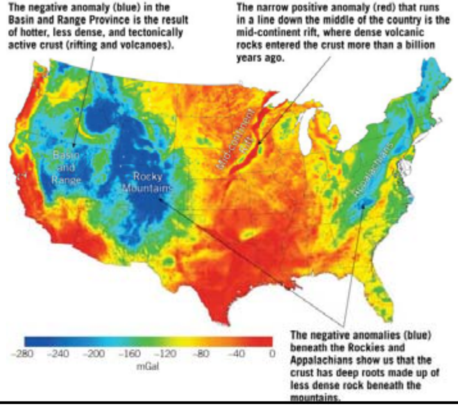
Earth’s Three-Dimensional Structure

- Earth’s Gravity
  - Changes at the surface are due to Earth’s rotation
    - Rotation causes a centrifugal force that is proportional to the distance from the axis of rotation
    - Earth’s shape is an oblate ellipsoid (bulges at the equator), resulting in weaker gravity at the equator
      - Other variations cannot be explained by Earth’s rotation:
        - » Bodies of unusually dense rock
        - » Metals, metal ores

Earth: Not a Sphere but an Oblate Spheroid



Gravity Anomalies


The negative anomaly (blue) in the Basin and Range Province is the result of hotter, less dense, and tectonically active crust (rifting and volcanoes).

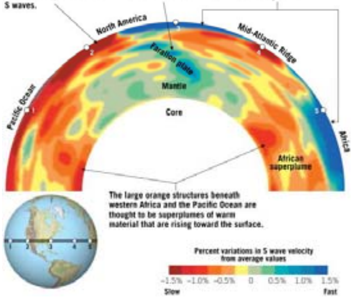
The narrow positive anomaly (red) that runs in a line down the middle of the country is the mid-continent rift, where dense volcanic rocks entered the crust more than a billion years ago.

The negative anomalies (blue) beneath the Rockies and Appalachians show us that the crust has deep roots made up of less dense rock beneath the mountains.

Earth’s Three-Dimensional Structure

- Seismic Tomography
  - **Seismic tomography** involves collecting data at many different seismic stations to “see” parts of Earth’s interior in three dimensions
  - Three-dimensional changes in composition and density are detected with gravity measurements and can be viewed using seismology
    - Identifies regions where P and S waves travel faster or slower than average
    - Variations in P and S wave velocities allow scientists to image subducting plates and mantle plumes

A Seismic Tomographic Slice Showing the Structure of the Mantle


The western United States is tectonically active, making that portion of the continent warmer and weaker (shown by the color red), which slows S waves.

The large blue structure extending far beneath North America is likely a sheet of cold, dense, ancient Pacific seafloor that is sinking toward the base of the mantle.

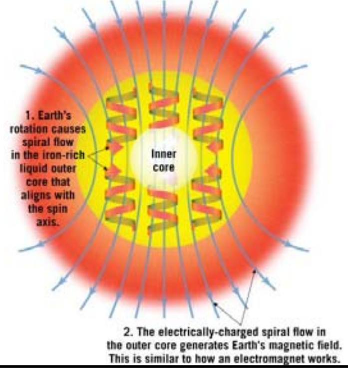
Older portions of continents, North America and Africa, are cold and strong—the blue color indicates fast S wave speeds.

The large orange structures beneath western Africa and the Pacific Ocean are thought to be superplumes of warm material that are rising toward the surface.

Earth’s Three-Dimensional Structure

- Earth’s **Magnetic Field**
  - Produced by convection of liquid iron in the outer core
  - A **geodynamo** is the magnetic field caused by spiraling columns of rising electrically charged fluid in the outer core
    - It is primarily dipolar but considerably more complex
    - Patterns of convection change rapidly enough so that the magnetic field varies noticeably over our lifetimes

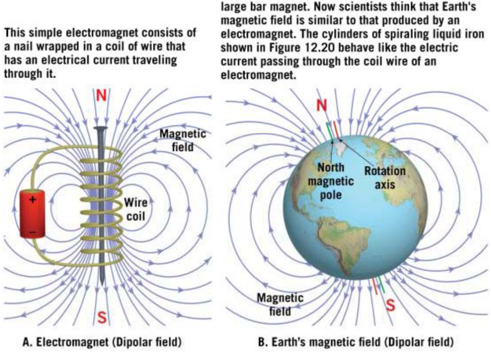
How Earth's Magnetic Field Is Generated in the Liquid, Iron-Rich Outer Core



1. Earth's rotation causes spiral flow in the iron-rich liquid outer core that aligns with the spin axis.

2. The electrically-charged spiral flow in the outer core generates Earth's magnetic field. This is similar to how an electromagnet works.

How Earth's Magnetic Field Is Generated in the Liquid, Iron-Rich Outer Core



This simple electromagnet consists of a nail wrapped in a coil of wire that has an electrical current traveling through it.

It was once thought that Earth's core acted like a large bar magnet. Now scientists think that Earth's magnetic field is similar to that produced by an electromagnet. The cylinders of spiraling liquid iron shown in Figure 12.20 behave like the electric current passing through the coil wire of an electromagnet.

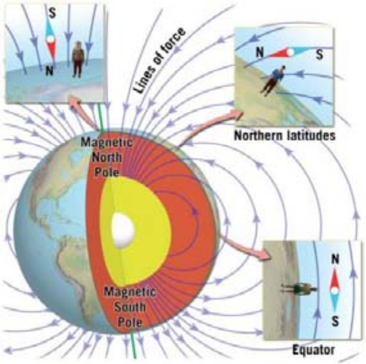
A. Electromagnet (Dipolar field)

B. Earth's magnetic field (Dipolar field)

Earth's Three-Dimensional Structure

- Earth's Magnetic Field
  - Measuring Earth's magnetic field and its changes
    - The magnetic field is measured by *declination* and *inclination*
      - Declination measures the direction of magnetic north pole with respect to the geographic north pole
      - Inclination measures the downward tilt of the magnetic lines
    - The locations of magnetic poles change significantly over time

Inclination (or Dip) of the Magnetic Field at Different Locations



Inclination (or Dip) of the Magnetic Field at Different Locations

Earth's Three-Dimensional Structure

- Magnetic Field
  - **Magnetic reversals**
    - The magnetic field randomly reverses and north and south poles swap direction
    - Reversal takes only a few thousand years, but during that time, the magnetic field, which protects Earth from solar wind, significantly decreases—to about 10% of normal
    - Evidence that convection patterns in the outer core change over relatively short time spans
    - The discovery of reversals has been extremely important to the foundation of the theory of plate tectonics

Earth’s Three-Dimensional Structure

- Magnetic Field
  - Global dynamic connections: Earth’s layers are connected by their thermally driven motions
    - Example: The break-up of Pangaea
      - Break-up of Pangaea led to an increase in subduction of sea-floor, leading to an increase in cold, suducted slabs at the core-mantle boundary
      - Cold slabs displaced hot rocks at the core–mantle boundary causing an increase in mantle plume activity
      - Cold slabs disrupted outer core convection and magnetic reversal activity

End of Chapter 12