1 ***Earth's Interior***

Earth 12th edition, Chapter 12

2 ***Chapter 12 – Earth's Interior***

3 **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

4 **Earth's Layered Structure**

5 **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

6 **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

7 **Seismic Waves Provide a Way to "See" into our Planet**

8 **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

9 **Possible Paths That Seismic Rays Follow Through Earth**

10 **Possible Paths That Seismic Rays Follow Through Earth**

11 **Possible Paths That Seismic Rays Follow Through Earth**

12 **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

13 **Average Velocities of P and S Waves at Each Depth**

14 **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

15 **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

16 **Determining the Depth of the Moho**

17 **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

18 **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

19 **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

20 **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

21 **P and S wave Shadow Zones**

22 **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

23 **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

24 **Earth's Core**

25 **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

26 **Earth's Temperature**

27 **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

28 **Earth's Thermal History Through Time**

29 **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

30 **Dominant Types of Heat Transfer at Various Depths**

31 **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

32 **Whole-Mantle Convection**

33 **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

34 **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

35 **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

36 **Geothermal Gradient**

37 **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

38 **Earth: Not a Sphere but an Oblate Spheroid**

39 **Gravity Anomalies**

40 **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

41 **A Seismic Tomographic Slice Showing the Structure of the Mantle**

42 **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

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

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

45 **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

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

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

48 **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

49 **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

50 ***End of Chapter 12***