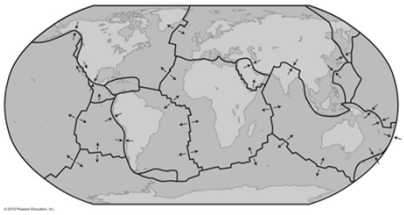
Chapter 22

Plate Tectonics



Earth Science Is an Integrated Science

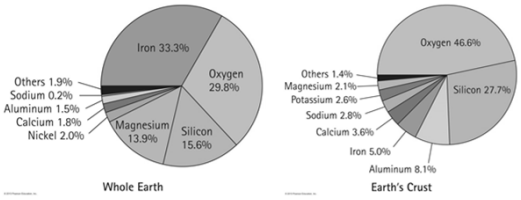
- A **system** is a collection of components that constantly affect one another.
- Systems are more than their individual parts – the way the parts work together and the emergent properties that arise from that interaction are also attributes of the system.
- Earth is a system with living and nonliving parts that interact in tremendously complex ways. This is why Earth science is an integrated science. No one science discipline is sufficient to describe all of Earth's parts, processes, and properties. Physics, chemistry, biology, and astronomy all come into play.

Differentiation

- Earth was molten when it was a young planet, due to collisions with space debris.
- Denser elements were able to sink toward Earth's center when the planet was fluid. This is the process of differentiation.
- As a result of differentiation, Earth is layered according to density and therefore also according to composition.

Differentiation

Differentiation produced different compositions in the crust vs. the entire planet.



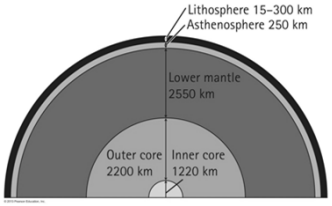
Earth Has Distinct Compositional Layers

- Earth has three basic layers: crust, mantle, and core. These layers differ in their chemical composition.
- Earth's crust is thin and cool overall but divided into basaltic oceanic crust and granitic continental crust.
- The mantle is thick and consists of hot rock rich in silicon and oxygen–like the crust, except the mantle contains more magnesium, iron, and calcium.
- The core is composed of scorching hot metal, mostly iron with some nickel.

It's Useful to View Earth in Terms of Structural Layers

- Earth consists of layers that differ by properties rather than chemical composition.
- The properties that determine Earth's layers include temperature, pressure, strength, and ability to flow.
- Earth's structural layers are: lithosphere, asthenosphere (including crust and upper mantle), lower mantle, outer core, and inner core.

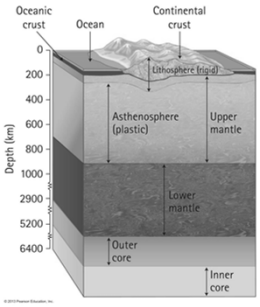
It's Useful to View Earth in Terms of Structural Layers



The structural layers not only have different compositions, they also have different thicknesses.

It's Useful to View Earth in Terms of Structural Layers

Oceanic lithosphere is thinner and denser than continental lithosphere.

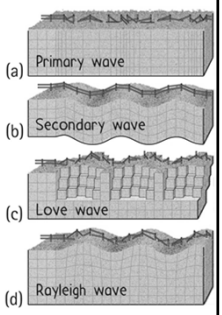


Seismology

- **Seismology** is the study of earthquakes and seismic (earthquake) waves.
- *Earthquakes* release stored elastic energy. Energy radiates outward in all directions.
- Energy travels in the form of **seismic waves**, which cause the ground to shake and vibrate.
- Analysis of seismic waves provides a detailed view of Earth's layered interior.

Seismic Waves

- Two main types of seismic waves:
  - ***Body waves*** travel through Earth's interior.
    - Primary waves (P-waves)
    - Secondary waves (S-waves)
  - ***Surface waves*** travel on Earth's surface.
    - Rayleigh waves
    - Love waves



Body Waves: *Primary Waves* (P-waves)

- Primary waves are longitudinal.
  - They compress and expand the material through which they move.
  - Compression and expansion occur parallel to the wave's direction of travel.
- Primary waves travel through any type of material – solid rock, magma, water, or air.
- Primary waves are the fastest of all seismic waves – the first to register on a seismograph.

Body Waves: *Secondary Waves* (S-waves)

- Secondary waves are transverse.
  - They vibrate rock in Earth in an up-and-down or side-to-side motion.
  - Transverse motion occurs perpendicular to a wave's direction of travel.
- Secondary waves travel through solids; they are unable to move through liquids.
- Secondary waves are slower than P-waves – the second to register on a seismograph.

Surface Waves

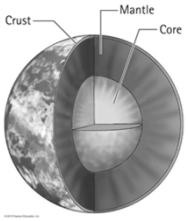
- Surface waves are the slowest seismic waves and the last to register on a seismograph.
- Surface waves are also the most destructive type of seismic waves.

Surface Waves

- Rayleigh waves have a rolling-type of motion.
  - They roll over and over in a tumbling motion, similar to ocean wave movement.
  - The tumbling motion occurs backward compared to the wave's direction of travel.
  - The ground moves up and down.
- Love waves have motion similar to S-waves.
  - Horizontal surface motion is side to side.
  - Whip-like, side-to-side motion occurs perpendicular to the wave's direction of travel.

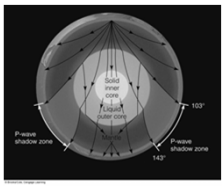
Wave Properties Reveal Earth's Interior

- The velocity of a seismic wave, whether or not it is transmitted, as well as how it reflects or refracts depend upon density and other properties.
- Wave properties can reveal density differences, compositional layers, physical state, and other characteristics of Earth's interior.



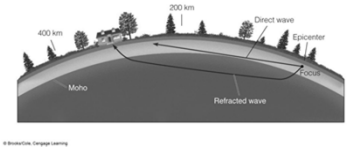
Discovery of the Core–Mantle Boundary

- Richard Oldham observed in 1906 that P-waves refract such that they are not recorded a certain distance away from the earthquake.
- He had discovered the core–mantle boundary.



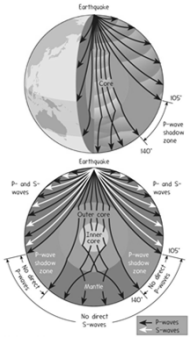
Discovery of the Crust–Mantle Boundary

- In 1909, Andrija Mohorovičić observed a sharp increase in seismic velocity at a shallow layer within Earth.
- Mohorovičić had discovered the crust–mantle boundary. Earth is composed of a thin outer crust that sits upon a layer of denser material, the mantle.



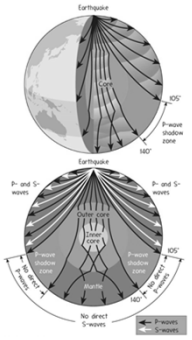
Determining the Depth of the Core–Mantle Boundary

- In 1913, Beno Guttenberg refined Oldham's work by locating the depth of the core–mantle boundary (2900 km).
- When P-waves reach this depth, they refract so strongly that the boundary casts a P-wave shadow (where no waves are detected) over part of the Earth.



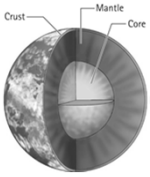
Determining the Depth of the Core–Mantle Boundary

- In 1926, Harold Jeffreys determined that S-waves do not travel through the core, therefore the core had to be liquid.
- When S-waves reach the core-mantle boundary depth, the energy is either reflected or converted into other types of energy. Hence the existence of the S-wave shadow zone.



Seismic Waves Revealed Inner Core and Outer Core

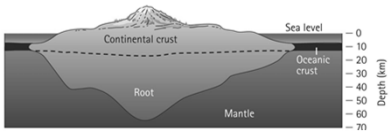
- In 1936, Inge Lehman observed that P-waves also refract at a certain depth within the core.
- At this depth, P-waves show an increase in velocity, indicating higher–density material. Lehman had discovered the inner core.
  - The core has two parts: a liquid outer core and a solid inner core.



Details of the Crust

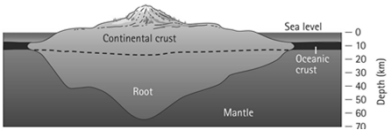
The Earth's crust has two distinct regions:

- Oceanic crust is compact and averages about 10 kilometers in thickness.
  - It is composed of dense basaltic rocks.
- Continental crust varies between 20 and 60 kilometers in thickness.
  - It is composed of less dense granitic rocks.



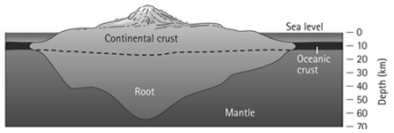
Isostasy Relates to the Vertical Position of the Crust

- The word *isostasy* is derived from the Greek roots *iso* meaning "equal" and *stasis* meaning "standing".
- Isostasy is the vertical positioning of the crust so that gravitational and buoyant forces balance one another.



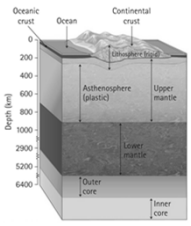
Isostasy Relates to the Vertical Position of the Crust

- Low-density crust floats on the denser underlying mantle.
- Areas of continental crust stand higher than areas of oceanic crust because continental crust is thicker and less dense than oceanic crust.
- Mountain roots respond to changes.



Details of the Mantle

- The mantle makes up 82% of Earth's volume and 65% of Earth's mass.
- The mantle is Earth's thickest layer—2900 km from top to bottom.
- Mantle rock is rich in Si and O. It also contains heavier elements, such as iron, magnesium, and calcium.
- The mantle is divided into two regions—upper mantle and lower mantle.

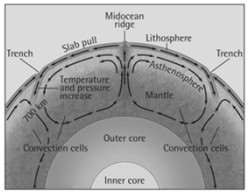


The Upper Mantle Has Two Structural Layers: *Asthenosphere* and *Lithosphere*

- The asthenosphere is found in the upper mantle. It is a solid, although it flows relatively easily over geologic time.
- The lithosphere includes the crust plus the top part of the mantle. It is a cool and rigid structural layer.
- The lithosphere rides atop the plastically flowing asthenosphere.
- Because of its brittle nature, the lithosphere is broken up into individual plates. ***Movement of lithospheric plates causes earthquakes, volcanic activity, and deformation of rock***.

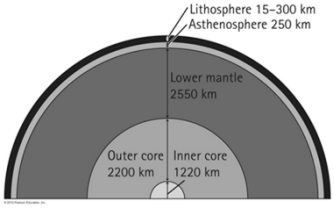
The Lower Mantle

- The lower mantle extends from a depth of 660 kilometers to the outer core.
- The lower mantle is under great pressure, making it less plastic than the upper mantle.
- Radioactive decay produces heat throughout the mantle.



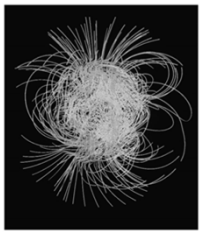
Details of the Core

- The core is composed predominantly of metallic iron.
- The core has two layers—a solid inner core and a liquid outer core.
- The inner core is solid due to great pressure.



Details of the Core

- The outer core is under less pressure and flows in a liquid phase.
- Flow in the outer core produces Earth's magnetic field, which shields us from the potentially harmful solar wind.



Continental Drift: An Idea Before Its Time

Alfred Wegener (1880–1930)

- Continental drift hypothesis:
  The world's continents are in motion and have been drifting apart into different configurations over geologic time.
- Proposed that the continents were at one time joined together to form the supercontinent of Pangaea = "universal land".

Evidence for Continental Drift

Wegener used evidence from many disciplines to support his hypothesis:

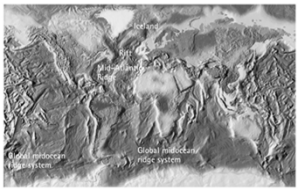
- Jigsaw fit of the continents
- Fossil evidence
- Matching rock types
- Structural similarities in mountain chains on different continents
- Paleoclimate evidence

Continental Drift: Lacking a Mechanism

- Despite evidence to support continental drift, Wegener could not explain *how* the continents moved.
- Without a suitable explanation, Wegener's ideas were dismissed.

A Mechanism for Continental Drift

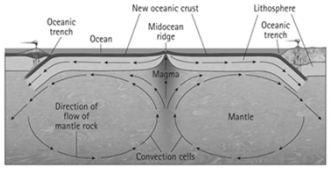
- Detailed mapping of the seafloor revealed:
  - Huge mountain ranges in the middle of ocean basins
  - Deep trenches alongside some continental margins



Seafloor Spreading

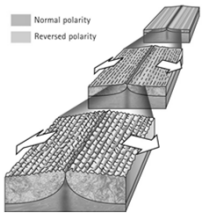
Harry Hess's hypothesis (based upon an idea from Arthur Holmes) of seafloor spreading provided the mechanism for continental drift.

- The seafloor is not permanent; it is constantly being renewed.
- Mid-ocean ridges are sites of new lithosphere formation.
- Oceanic trenches are sites of lithosphere destruction (subduction).



Seafloor Spreading Is Supported by Magnetic Studies of the Ocean Floor

- Lava erupted at the mid-ocean ridges is rich in iron.
- Magnetite crystals in lava align themselves to Earth's magnetic field.
- Earth's magnetic poles flip—the north and south poles exchange positions. This is known as magnetic reversal.



Seafloor Spreading Is Supported by Magnetic Studies of the Ocean Floor

- The seafloor holds a record of Earth's magnetic field at the time the rocks of the seafloor cooled.
- The magnetic record appears as parallel, zebra-like stripes on both sides of mid-ocean ridges.
- The age of the ocean floor and the rate of seafloor spreading could be determined.

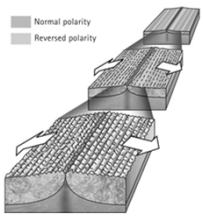


Plate Tectonics: A Modern Version of an Old Idea

Plate tectonics is the unifying theory that explains the dramatic, changing surface features of the Earth in terms of the shifting of tectonic plates.

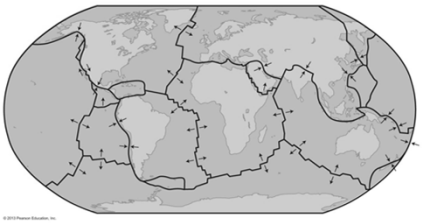
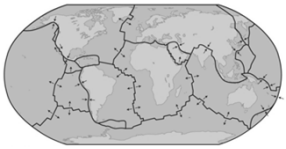


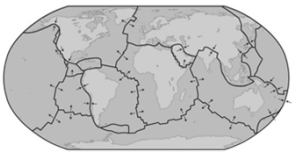
Plate Tectonics

- Earth is divided into a dozen or so major lithospheric plates as well as a few smaller ones.
- Plates are in motion and continually changing in shape and size.
- The largest plate is the Pacific Plate.
- Several plates include an entire continent plus a large area of seafloor.



Features of Tectonic Plates

- Plates are sections of Earth's strong, rigid outer layer—the lithosphere.
- Because plates are composed of lithosphere, they consist of the uppermost mantle and oceanic or continental crust.
- Plates overlie the weaker asthenosphere. They ride along with the asthenosphere as it flows.

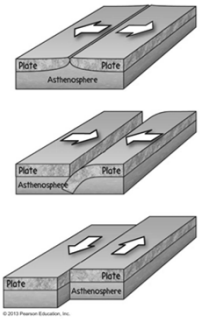


Speed of Tectonic Plates

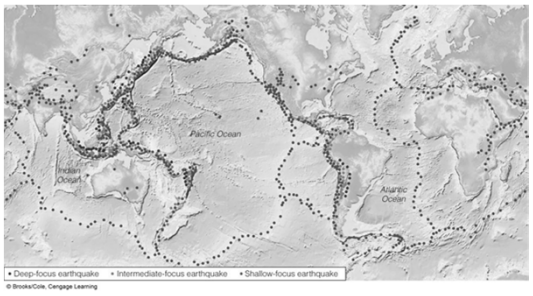
- Earth's plates move in different directions and at different speeds. The average rate varies between 1 and 15 cm per year.

Plate Boundaries

- Interactions between plates occur along plate boundaries.
- Earthquakes, volcanoes, and mountains occur along plate boundaries—and sometimes along former plate boundaries.



Most earthquakes occur along plate boundaries



Volcanoes occur along plate boundaries

Most volcanic activity is associated with subduction plate boundaries.

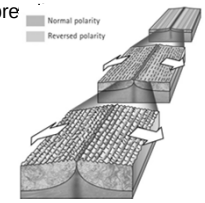
The region around the Pacific Ocean contains >60% of all volcanic activity and is called "The Ring of Fire".

Plate Tectonics: Three Types of Plate Boundaries

- Divergent plate boundaries
  - Magma generation and lithosphere formation
- Convergent plate boundaries
  - Magma generation and lithosphere destruction
- Transform–fault boundaries
  - No magma generation, no formation or destruction of lithosphere

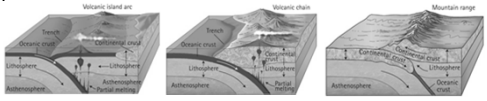
Divergent Boundary Features

- Plates move away from one another and shallow earthquakes occur.
- As plates move apart, the asthenosphere rises and partially melts to form lava. New crust is formed as lava fills in the gaps between plates.
- In the ocean, there is seafloor spre
  - Mid-ocean ridge
- On land, continents tear apart.
  - Rift valley



Convergent Boundary Features

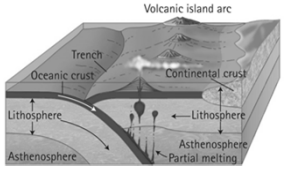
- Plates move toward each other, and shallow-to-deep focus earthquakes occur at subduction zones. *Tsunami* can be generated by subduction zones.
- *Oceanic crust is destroyed* when plates converge at a subduction zone and *continental crust is deformed* when plates collide.



Types of Convergent Boundaries

Oceanic–oceanic convergence

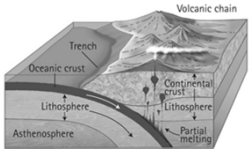
- When two oceanic plates converge, the older and denser plate descends beneath the younger / lighter plate.
- As the denser plate descends, partial melting of mantle rock generates magma and volcanoes.
- If the volcanoes emerge as islands, a *volcanic island arc* is formed (examples: Japan, Aleutian islands, Tonga islands).



Types of Convergent Boundaries

Oceanic–continental convergence

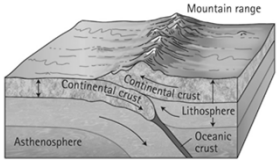
- The denser oceanic slab sinks into the asthenosphere.
- As the denser plate descends, partial melting of mantle rock generates magma.
- The mountains produced by volcanic activity from subduction of oceanic lithosphere are called *continental volcanic arcs* (Andes and Cascades).



Types of Convergent Boundaries

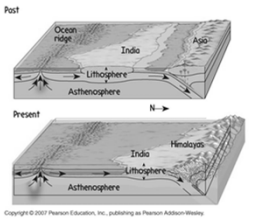
Continental–continental convergence

- Continued subduction can bring two continents together.
- The less dense, buoyant continental lithosphere does not sink, resulting in a collision between two continental blocks.
- The process produces mountains ranges (Himalayas, Alps, Appalachians).



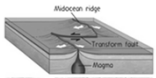
Continental–Continental Convergence

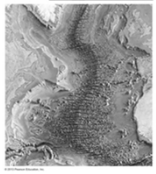
The continent-to-continent collision of India with Asia produced – and is still producing – the Himalayas.



Transform-Fault Boundaries

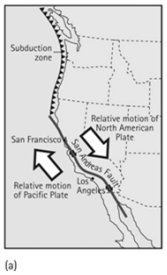
- Plates slide past one another and no new lithosphere is created or destroyed. Shallow but strong earthquakes occur.
- Most *transform faults* join two segments of a mid-ocean ridge. The transform faults are oriented perpendicular to mid-ocean ridges.





Transform-Fault Boundaries

- A few transform-fault boundaries, such as the infamous San Andreas Fault, cut through continental crust.



(a)

Life in the Trenches

- Extremophiles are organisms adapted to the extreme conditions.
- Some ocean trenches contain hydrothermal vents, which are cracks in the crust often associated with tectonic activity.
- A *food chain* can develop around a hydrothermal vent where chemosynthesis, rather than photosynthesis, provides food for the lowest-level organisms in the chain.