Plate Tectonics: A Scientific Theory Unfolds
What do these terms mean?

• Tectonics – study of large-scale deformation and structures in the outer portion of the Earth.

• Plate Tectonics relates such deformation to the existence and movement of rigid “plates” over a weak or partly molten layer in the earth’s upper mantle.
Rock Response to Plate Tectonics

- **Stress** – force applied on a rock
  - **Compressive stress** – squeeze or compress an object
  - **Tensile stress** – pull or stretch an object
  - **Shearing stress** – different parts of an object move in different directions or at different rates

- **Strain** – results from stress; is the change in shape or size of an object because of the stress it experienced
Figures 3.6
Strain

• Temporary or permanent
• **Elastic deformation** – temporary strain, object recovers original size and shape once the stress is removed
  – Elastic limit – strain that becomes permanent in an object once limit of recoverable strain has been exceeded
  – **Plastic deformation** occurs in materials once elastic limit has been exceeded
  – **Brittle** deformation occurs at the limit of strength of the material, a rupture or a break occurs
Lithosphere and Asthenosphere

- Earth’s crust and upper most mantle are solid and compose the **lithosphere**
  - Stresses cause brittle and elastic deformation
- Beneath the lithosphere is a plastic layer called the **asthenosphere**
- Lithospheric plates can move over this plastic layer; plate tectonics plausible
- Boundaries of the plates are active with earthquake and some with volcanic activity
Plate Tectonics - excellent example of the scientific process in action

• Demonstrates how scientific “hypotheses” evolve as new evidence is found that supports or does not support the idea.
Alfred Wegener’s Hypothesis:

• Continental drift hypothesis
  • A supercontinent called *Pangaea* began breaking apart about 200 million years ago
However, Wegener was not the first to suspect the continents were on the move.

• 1596 – Dutch map maker Abraham Ortelius – *Thesaurus Geographicus* – Americas were, “torn away from Europe and Africa…by earthquakes and floods…the vestiges of the rupture reveal themselves, if someone brings forward a map of the world and considers carefully the coasts of the three (continents).”
Antonio Snider-Pelligrini – 1858 -geographer-
Alfred Lothar Wegener

- First proposed his hypothesis in 1915
- Published: *The Origin of Continents and Oceans*
- Known as “Continental Drift”
Continental Drift: An Idea Before Its Time

- Continental drift hypothesis
  - Continents "drifted" to present positions
Wegener’s Original Pangea
Break up of Pangaea

+ 50 Million years into the future
Evidence used in support of continental drift hypothesis

- Fit of the continents
Sir Edmund Bullard “Fit”
Depth of 1000m on continental slope

Figure 4.1
The best fit of the continents around the Atlantic Ocean was obtained by Sir Edmund Bullard and his colleagues at Cambridge University using a computer. It was found to lie on the continental slope at a depth of about 1000 m (500 fathoms).
Fossil Evidence

- Mesosaurus
Found only here!
Glossopteris. This fossil of a now-extinct plant is from Australia and is about 15 cm across.
Much Fossil Evidence Exists

- Fossil remains of Cynognathus, a Triassic land reptile approximately 3 m long, have been found in Argentina and southern Africa.
- Remains of the freshwater reptile Mesosaurus have been found in both Brazil and Africa.
- Fossils of the fern Glossopteris, found in all of the southern continents, are proof that they were once joined.
- Evidence of the Triassic land reptile Lystrosaurus have been found in Africa, Antarctica, and India.
Fossil/Rock Sequences

**Figure 4.3**
A leaf of *Glossopteris*.

**Figure 4.4**
Rock sequences similar to this are found in India, Africa, South America, Australia, and Antarctica. The rocks in each of these localities contain the fossil plant *Glossopteris*. 
Matching Rock types and Structures

Figure 19.11
Jigsaw puzzle fit and matching rock types between South America and Africa. Light-blue areas around continents are continental shelves (part of continents). Colored areas within continents are broad belts of rock that correlate in type and age from one continent to another. Arrows show direction of glacier movement as determined from striations.
Matching Mountain Ranges
Paleoclimate evidence
Paleoclimatic Evidence

Figure 5.6
Wegener’s Polar Wandering based on paleoclimatic evidence
Two Interpretations:

A. Present pole position (geographic North Pole)
   - Ancient pole
   - Ice
   - Deserts
   - Reefs

B. Ancient pole position and present pole position the same
   - Ice
   - Deserts
   - Reefs
   - Ancient pole position
   - Apparent position of ancient pole
The Great Debate!

- Objections to the continental drift hypothesis
  - Lack of a mechanism for moving continents
  - Wegener incorrectly suggested that continents broke through the ocean crust, much like ice breakers cut through ice
  - Strong opposition to the hypothesis from the scientific community
• The Fatal Flaw!
  – Geophysicists found it in defiance of the laws of physics
  – Sir Harold Jefferies – “what force could cause the continents to plow through the oceanic crust?”

![Figure 19.6]

Wegener’s concept of continental drift implied that the less dense continents drifted through oceanic crust, crumpling up mountain ranges on their leading edges as they pushed against oceanic crust.
How did Wegener explain the forces necessary for “drift”?

- gravitational attraction of equatorial bulge
- also “tidal forces of the Moon”
- Wegener died in 1930 while pursuing evidence, freezing to death on the Greenland Icecap
- So, continental drift fell into obscurity for the next 30 years
Continental drift and the scientific method

• Wegener’s hypothesis was correct in principle, but contained incorrect details

• A few scientists considered Wegener’s ideas plausible and continued the search
Rebirth of a Theory

• Ironically, the revival and eventual vindication of Wegener’s hypothesis was to come from the very field that discredited him –

• The study of geophysics

• And world War II
Paleomagnetic evidence
Paleomagnetism

Figure 19.7
Some rocks preserve a record of the earth’s magnetic field.
Renewed interest in Polar Wandering!

Figure 19.9
Paleomagnetic studies of Permian lava flows on North America indicate an apparent position for the north magnetic pole in eastern Asia.
A New View!

• **Harry Hess** - Professor of Geology, Princeton
  – During WWII, did echo soundings of Pacific between battles!
    » Resulted in the hypothesis of

**Seafloor Spreading**
What Problems with Wegener’s Model Did Seafloor Spreading explain?
The evidence accumulates

• Vine and Matthews – 1963
  – Observed reversals in the earth’s magnetic field
A Time of normal magnetism

B Time of reverse magnetism

C Time of normal magnetism
A. Period of normal magnetism

B. Period of reverse magnetism

C. Period of normal magnetism

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Research vessel towing magnetometer across ridge crest

Ridge axis

Magnetometer record showing symmetrical magnetic field across ridge

Low intensity

High intensity

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Magnetic Patterns of the Sea Floor

Figure 19.19
The age of the sea floor as determined from magnetic anomalies.
Sedimentary Evidence

*DSDP - Glomar Challenger*

1968-1983

*JOIDES Resolution*

*IODP – Chikyu*
FIGURE 2.27 Since 1968 drilling ships have gathered core samples of seafloor sediment and crustal rocks at hundreds of sites. Results from these efforts showed that the ocean floor is indeed youngest at the ridge axis. This was the first direct evidence supporting the seafloor spreading hypothesis and the broader theory of plate tectonics.
Sea floor moving over a hot spot forms an aseismic ridge as a chain of volcanoes and guyots.
FIGURE 2.29  The chain of islands and seamounts that extends from Hawaii to the Aleutian trench was generated as the Pacific plate moved over a mantle plume (hot spot). Radiometric dating of the Hawaiian Islands shows that the volcanic activity increases in age moving away from the “big island” of Hawaii.
Mantle Plumes

**Figure 19.42**
Mantle plumes rise upward through the mantle. When the large head contacts a continent, it causes uplift and the eruption of flood basalts.
Figure 19.43
Distribution of hypothesized mantle plumes, identified by volcanic activity and structural uplift within the past few million years. The hot spots near the poles are not shown.
Compiled by W. S. F. Kidd and K. E. Parker, 2011.
Earth’s major plates

• Associated with Earth's strong, rigid outer layer
  • Known as the *lithosphere*
  • Consists of uppermost mantle and overlying crust
  • Overlies a weaker region in the mantle called the *asthenosphere*
Earth’s major plates

– Seven major lithospheric plates
– Plates are in motion and continually changing in shape and size
– Largest plate is the Pacific plate
– Several plates include an entire continent plus a large area of seafloor
See any patterns?
Plates move relative to each other at a very slow but continuous rate

- Average 5 cm (2 inches) per year
- Cooler, denser slabs of oceanic lithosphere descend into the mantle
VLBI and GPS now used to measure rates directly
Plate Boundaries

• Interactions among individual plates occur along their boundaries

• Types of plate boundaries
  – *Divergent plate boundaries* (constructive margins)
  – *Convergent plate boundaries* (destructive margins)
  – *Transform fault boundaries* (conservative margins)
Divergent Plate Boundaries

• Most are located along the crests of oceanic ridges

• Oceanic ridges and seafloor spreading
  • Along well-developed divergent plate boundaries, the seafloor is elevated forming oceanic ridges
Divergent plate boundaries

- Oceanic ridges and seafloor spreading
  - Seafloor spreading occurs along the oceanic ridge system
- Spreading rates and ridge topography
  - Ridge systems exhibit topographic differences
  - These differences are controlled by spreading rates
Divergent Plate Boundary

Figure 5.10

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Divergent Plate Boundaries

• Continental rifting
  • Splits landmasses into two or more smaller segments along a continental rift
  • Examples include the East African rift valleys and the Rhine Valley in northern Europe
  • Produced by extensional forces acting on lithospheric plates
Continental Rifting
Convergent Plate Boundaries

- Older portions of oceanic plates are returned to the mantle in these destructive plate margins
  - Surface expression of the descending plate is an ocean trench
  - Also called subduction zones
  - Average angle of subduction = 45°
• Types of convergent boundaries
  • Oceanic-continental convergence
    – Denser oceanic slab sinks into the asthenosphere
    – Along the descending plate partial melting of mantle rock generates magma
    – Resulting volcanic mountain chain is called a
      \textit{continental volcanic arc} (Andes and Cascades)
• Types of convergent boundaries
  • Oceanic-oceanic convergence
    – When two oceanic slabs converge, one descends beneath the other
    – Often forms volcanoes on the ocean floor
    – If the volcanoes emerge as islands, a volcanic island arc is formed (Japan, Aleutian islands, Tonga islands)
• Types of convergent boundaries
  • Continental-continental convergence
    – Less dense, buoyant continental lithosphere does not subduct
    – Resulting collision between two continental blocks produces mountains (Himalayas, Alps, Appalachians)
Converging Margins: India - Asia Collision

Present-day Indian Ocean floor map

India-Asia collision animation
**Transform Fault Boundaries**

- Plates slide past one another and no new lithosphere is created or destroyed

- Transform faults
  - Most join two segments of a mid-ocean ridge along breaks in the oceanic crust known as *fracture zones*
A few (the San Andreas fault and the Alpine fault of New Zealand) cut through continental crust.
FIGURE 2.26 Along the San Andreas Fault, the Pacific plate is moving toward the northwest, relative to the North American plate. This aerial view shows the offset in the dry channel of Wallace Creek near Taft, California. (Photo by Michael Collier)
What Drives Plate Motions

• Researchers agree that convective flow in the mantle is the basic driving force of plate tectonics

• Forces that drive plate motion
  • Slab-pull
  • Ridge-push
  • Slab suction
Forces Driving Plate Motions

The driving force of plate motions into the asthenosphere is gravity. This phenomenon involves slabs of ocean floor that become denser as they cool,下沉, and are subducted beneath the crust. The forces that drive these motions include:

- **Ridge push**: This is a gravity-driven force that results from the elevated position of the ridge.
- **Slab pull**: This force is generated by the sinking of a cold, dense slab of lithosphere into the mantle.
- **Mantle drag**: This force resists subduction and enhances plate motion when the velocity of the asthenosphere exceeds that of the plate.

**Frictional resistance** between the overriding plate and the subducting slab also plays a role in plate motions.
What Drives Plate Motions

• Models of plate-mantle convection
  • Any model must be consistent with observed physical and chemical properties of the mantle
Layering at 660 kilometers

- Volcanic trail
- Oceanic ridge
- Descending oceanic slab
- Hot spot volcanism
- Asthenosphere
- Mesosphere
- Core
Whole-mantle convection