Chapter 2

Plate Tectonics: A Unifying Theory

Unifying Theory

- A unifying theory is one that helps
  - explain a broad range of diverse observations
  - interpret many aspects of a science
  - on a grand scale
  - and relate many seemingly unrelated phenomena
- Plate tectonics is a unifying theory for geology.

2. Plate Tectonics

Unifying theory – plate tectonics describe movement of continental and oceanic plates and forces driving them. It explains locations of mountain chains, earthquakes, rock assemblages, and structures on sea floor.

For geology Plate Tectonics is similar in importance as the Discovery of DNA is to biology.

Plate Tectonics

- Plate tectonics helps explain
  - earthquakes
  - volcanic eruptions
  - formation of mountains
  - location of continents
  - location of ocean basins
- It influences
  - atmospheric and oceanic circulation,
  - and climate
  - geographic distribution,
  - evolution and extinction of organisms
  - distribution and formation of resources

Introduction

- Why should you know about plate tectonics?
  - Plate tectonics affects all of us, whether in relation to the destruction caused by volcanic eruptions and earthquakes, or politically and economically due to the formation and distribution of valuable natural resources.
  - Plate tectonics ties together many seemingly unrelated geologic phenomena and illustrating why Earth is a dynamic planet of interacting subsystems and cycles.

2. Plate Tectonics

Earlier related theories:
Over the past 200 years (up to late 1960s) geologists had developed many theories about the characteristics & location of Earth’s tectonic features.
Mountains, volcanoes, earthquakes, etc:
Understood
- generally how are they formed/occur,
- but not - why here, not there, relation to one and other
Early Ideas About Continental Drift

- **Alfred Wegener** and the Continental Drift Hypothesis.
  - The idea that continents have moved in the past is not new.
  - The concept of continental movement was first suggested when it was noticed that Africa and South America had coastlines which appeared to be counterparts of one another.
  - This suggested they may once have been joined and drifted apart.

- **Edward Suess**
  - Australian, late 1800s
  - noted similarities between the Late Paleozoic plant fossils
  - Glossopteris flora
  - and evidence for glaciation
  - in rock sequences of India, Australia, South Africa, South America
  - He proposed the name Gondwanaland (or Gondwana) for a supercontinent composed of these continents.

- **Frank Taylor** (American, 1910)
  - presented a hypothesis of continental drift with these features:
    - lateral movement of continents formed mountain ranges
    - a continent broke apart at the Mid-Atlantic Ridge to form the Atlantic Ocean
    - supposedly, tidal forces pulled formerly polar continents toward the equator.
    - when Earth captured the Moon about 100 million years ago.

- **Alfred Wegener** and the Continental Drift Hypothesis
  - German meteorologist
  - Credited with hypothesis “1912 continental drift.”
  - all landmasses were originally united into a supercontinent named Pangaea.

What is the Evidence for Continental Drift?

A. Continental Fit

- Wegener and others amassed a large amount of evidence in support of continental drift.
- There is a close fit between the continents off the coast at a depth of about 2000 m.
Evidence for Continental Drift

A. Jigsaw puzzle fit of continents

- Continental fit best at continental shelf

B. Similarity of Rock Sequences and Mountain Ranges

- Marine, nonmarine, and glacial rock sequences of Pennsylvanian to Jurassic age are nearly identical on all the Gondwana continents

C. Ages across oceans

D. Similarity of Rock Sequences and Mountain Ranges

- The trend of several major mountain ranges produces a continuous mountain range when the continents are positioned next to each other as they were during the formation of Pangea.

D. Correlation of Mountain ranges
Evidence for Continental Drift

E. Glacial Evidence

- Glacial tills and striations on the bedrock beneath the till provide evidence of glaciation at the same time on all the Gondwana continents, with South Africa located at the South Pole.

F. Fossil evidence (distribution of certain fossils)

- One of the strongest examples is the Mesosaurus, a freshwater reptile.

Evidence for Continental Drift

* Alexander du Toit (South African geologist, 1937)
- Proposed that a northern landmass called Laurasia consisted of present-day
  - North America
  - Greenland
  - Europe
  - and Asia (except India).
- Provided additional fossil evidence for Continental drift.

Evidence for Continental Drift

* Problems with the theory

- Wegener could not provide a convincing mechanism to demonstrate ‘how’ the continents could have moved.
- His ideas were largely ignored.

Evidence for Continental Drift

E. Correlation of Glaciation

** support of theory by others

- Alexander du Toit (South African geologist, 1937)
- Proposed that a northern landmass called Laurasia consisted of present-day
  - North America
  - Greenland
  - Europe
  - and Asia (except India).
- Provided additional fossil evidence for Continental drift.

** Also compelling evidence comes from fossils like the Glossopteris fern.
Evidence for Continental Drift
* Problems with the theory

• Most geologists did not accept the idea of moving continents
  – because no one could provide
  – a suitable mechanism to explain
  – how continents could move over Earth’s surface
• Interest in continental drift revived when
  – new evidence of Earth’s magnetic field
  – and oceanographic research
  – showed that the ocean basins were geologically young

Paleomagnetism
* Earth’s Magnetic Field

• Strength and orientation of the magnetic field varies
  – weak and horizontal at the equator
  – strong and vertical at the poles
  – inclination and strength increase from the equator to the poles

(Paleo) Magnetism
Earth’s Magnetic Field

• Similar to a giant dipole magnet
  – magnetic poles essentially coincide
  – with the geographic poles
  – and may result from different rotation
  – of outer core and mantle

Paleomagnetism

• Paleomagnetism is
  – a remanent magnetism
  – in ancient rocks
  – recording the direction of Earth’s magnetic poles
  – at the time of the rock’s formation
• Paleomagnetism in rocks
  – records the direction
  – and strength of Earth’s magnetic field
• When magma cools
  – below the Curie point temperature
  – magnetic iron-bearing minerals align
  – with Earth’s magnetic field

Paleomagnetism & Polar Wandering

• In 1950s, research revealed
  – that paleomagnetism of ancient rocks showed
  – orientations different from the present magnetic field
• Magnetic poles apparently moved.
  – Their trails were called polar wandering paths.
  – Different continents had different paths.
  – The best explanation is stationary poles and moving continents
Earth's present magnetic field is called **normal**, with magnetic north near the north geographic pole and magnetic south near the south geographic pole.

At various times in the past, Earth's magnetic field has completely **reversed**, with magnetic south near the north geographic pole and magnetic north near the south geographic pole.

The condition for which Earth's magnetic field is in this orientation is called a **magnetic reversal**.

**Paleomagnetism & Magnetic Reversals**

- Measuring paleomagnetism and dating continental lava flows lead to the realization that magnetic reversals existed and the establishment of a magnetic reversal time scale.

**Paleomagnetism**

- **Paleomagnetic studies** during the 1950's revived interest in continental drift.
  - They indicated that either the magnetic poles had wandered and each continent had its own pole (an impossibility), or the continents had moved over time. If the continents were moved into different positions relative to each other, the separate poles could be resolved into one.

**Paleomagnetism & Polar Wandering**

- How can the apparent wandering of the magnetic poles be best explained?
  - The magnetic poles have remained near their present locations at the geologic north and south pole and the continents have moved.
  - Evidence: When the continents are fitted together, the paleomagnetic data point to only one magnetic pole.

**Paleomagnetism and Seafloor Spreading**

- Earth's present magnetic field is considered **normal** - with the north and south magnetic poles located approximately at the north and south geographic poles. At various times in the geologic past, Earth's magnetic field has completely reversed.
Paleomagnetism and Seafloor Spreading

- Earth’s present magnetic field is considered normal.
- The existence of such magnetic reversals was discovered in continental lava flows by:
  - A) age dating
  - B) determining the orientation of the remnant magnetism.

Magnetic Reversals and Seafloor Spreading

- Harry Hess proposed the theory of seafloor spreading in 1962.
  - He suggested that the seafloor separates at oceanic ridges, where new crust is formed by upwelling magma.
  - As the magma cools, the newly formed oceanic crust moves laterally away from the ridge.

Continental Drift, Seafloor Spreading, and Plate Tectonics

Early explanation of motion/drift:
Wegener (1915) suggested continents drifted (floated) on oceanic crust due to sun/moon tidal forces (too weak) and he was meteorologist so mostly ignored.

Sea floor spreading (1928, Arthur Holmes, British) first to speculate that convection currents within mantle moved continents apart (little evidence or details).

Seafloor Spreading, Continental Drift and Plate Tectonics

Post-WWII (1950s)
- new techniques help map seafloor
- geological activity in mid-ocean ridges
- ring of fire
- seafloor maps

Seafloor Spreading & Mapping Ocean Basins

- Ocean mapping revealed
  - a ridge system
  - 65,000 km long,
  - the most extensive mountain range in the world
- The Mid-Atlantic Ridge
  - is the best known
  - and divides Atlantic Ocean basin
  - in two nearly equal parts
Seafloor Spreading

Theories on Seafloor spreading
No accepted theory until 60’s.
Harry Hess, submariner & professor, Princeton, showed (post-WWII) sonar & other geophysical maps of sea floor (early ’60s).

**Plate Tectonics Theories** (1960-68)
Mid-Atlantic sea floor ridge formed by upwelling crust due plate divergent motion (1962, H. Hess, Princeton Univ. & Bob Dietz, Scripps)

Seafloor Spreading or Plate Tectonics?

Plate Tectonics Theories (1960-68)

1. Mid-Atlantic sea floor ridge formed by upwelling crust due plate divergent motion (1962, H. Hess, Princeton Univ. & Bob Dietz, Scripps) – possible expanding earth

2. Ring of Fire - mapping & correlation of volcanoes & (more important) the deep sea trenches along Pacific margins (1962-64)
Plate Tectonics Evidence: Model

Convection?

Plate Tectonics Evidence: Model

Plate Tectonics: research drilling beneath sea: layers of earth

Density, Crust, Lithosphere (Crust & upper mantle, to 100km), Asthenosphere (mantle below lithosphere)

Magnetic Reversals and Seafloor Spreading

Deep-Sea Drilling and the Confirmation of Seafloor Spreading

Seafloor spreading was confirmed by the discovery of magnetic anomalies in the ocean crust that were both parallel to and symmetric around the ocean ridges.

This indicates that new oceanic crust must be formed along the spreading ridges.

Seafloor Spreading

- Harry Hess, in 1962, proposed the hypothesis of seafloor spreading
  - Continents and oceanic crust move together
  - Seafloor separates at oceanic ridges
    - where new crust forms from upwelling & cooling magma
    - the new crust moves laterally away from the ridge
  - the mechanism to drive seafloor spreading was thermal convection cells in the mantle
    - hot magma rises from mantle to form new crust
    - cold crust subducts into the mantle at oceanic trenches, where it is heated and recycled
**Confirmation of Hess’s Hypothesis**

- In addition to mid-ocean ridges,
  - ocean research revealed
  - magnetic anomalies on the sea floor
- A magnetic anomaly is a deviation
  - from the average strength
  - of Earth’s Magnetic field

**How Do Magnetic Reversals Relate to Seafloor Spreading?**

Oceanic Crust Is Young

- Seafloor spreading theory indicates that
  - oceanic crust is geologically young because
    - it forms during spreading
    - and is destroyed during subduction
- Radiometric dating confirms the youth
  - of the oceanic crust
  - and reveals that the youngest oceanic crust
    - occurs at mid-ocean ridges
    - and the oldest oceanic crust
      - is less than 180 million years old
- whereas oldest continental crust
  - is 3.96 billion years old

**Magnetic Reversals and Seafloor Spreading**

- Deep-Sea Drilling and the Confirmation of Seafloor Spreading
  - Deep-Sea Drilling and the Confirmation of Seafloor Spreading
    - Sea floor spreading is confirmed by
      - the ages of fossils in sediments overlying oceanic crust
      - radiometric dating of rocks on oceanic islands.
    - These indicate that oceanic crust is youngest at the spreading ridges and oldest at the farthest points from the ridges.

- Further evidence confirming seafloor spreading came from the Deep Sea Drilling Project are the age and thickness of the sediments overlying the oceanic crust.
Plate Tectonics: A Unifying Theory

- Overwhelming evidence in support of plate tectonics led to its rapid acceptance and elaboration since the early 1970's.
- The theory is widely accepted because it explains so many geologic phenomena, including volcanism, seismicity, mountain building, climatic changes, animal and plant distributions in the past and present, and the distributions of natural resources.
- For these reasons, it is known as a unifying theory.

Plate Tectonics Map

1.1. 12 major plates with numerous smaller plates
2. Divergent boundaries: where plates moved apart and new lithosphere is created
3. Convergent boundaries: where plates come together and plates are recycled
4. Transform boundaries: plates slide past each other

Plate Tectonics

- Plate tectonic theory is based on the simple model that
  - the lithosphere is rigid & consists of both
    - oceanic crust with upper mantle
    - continental crust with upper mantle
  - variable-sized pieces called plates
    - that move as a unit
    - that can be continental, oceanic or both
  - some regions containing continental crust
    - are up to 250 km thick
  - whereas regions containing oceanic crust
    - are up to 100 km thick max

Plate Tectonics: A Unifying Theory

- The lithosphere overlies the asthenosphere, and through some type of heat-transfer system within the asthenosphere, moves the plates.

- As the plates move over the asthenosphere, they separate mostly at oceanic ridges and collide and are subducted into Earth’s interior at oceanic trenches.
The Three Types of Plate Boundaries

- Plate tectonics has operated since at least the Proterozoic. It is important to understand how the plates move and interact with one another.

Types of Plate Boundaries

- Divergent
- Convergent
- Transform

Divergent Boundaries

- Divergent boundaries form when plates move away from one another.
- New oceanic lithosphere forms at the opening rift.
- Most divergent boundaries occur along the crests of oceanic ridges.
- They are also present under continents during the early stages of continental breakup.

Divergent Boundaries

Divergent plate boundaries
- or spreading ridges occur
- where plates are separating
- and new oceanic lithosphere is forming.

- Crust is extended
  - thinned and fractured
- The magma
  - originates from partial melting of the mantle
  - is basaltic
  - intrudes into vertical fractures to form dikes
  - some rises to the surface and is extruded as lava flows

- Ridges also have
  - high heat flow
  - and basaltic flows or pillow lavas
- Pillow lavas that formed along the Mid-Atlantic Ridge
  - with a distinctive bulbous shape resulting
  - from underwater eruptions

Divergent Boundaries

- Successive injections of magma
  - cool and solidify
  - form new oceanic crust
  - record the intensity and orientation
  - of Earth's magnetic field
- Divergent boundaries most commonly
  - occur along the crests of oceanic ridges
  - such as the Mid-Atlantic Ridge
- Ridges have
  - rugged topography resulting from displacement
  - of rocks along large fractures
  - shallow earthquakes
Divergent Boundaries

- Divergent boundaries are also present
  - under continents during the early stages
  - of continental breakup
- Beneath a continent
  - when magma wells up
  - the crust is initially
    - elevated,
    - stretched
    - and thinned

Beneath a continent
- when magma wells up
- the crust is initially
  - elevated,
  - stretched
  - and thinned

The stretching produces fractures and rift valleys.

During this stage,
- magma typically
  - intrudes into the fractures
  - and flows onto the valley floor
- Example: East African rift valleys

Narrow Sea

- As spreading proceeds, some rift valleys
  - will continue to lengthen and deepen until
  - the continental crust eventually breaks
  - a narrow linear sea is formed,
  - separating two continental blocks
- Examples:
  - Red Sea
  - Gulf of California

As a newly created narrow sea
- continues to spread,
- it may eventually become
  - an expansive ocean basin
  - such as the Atlantic Ocean basin is today,
    - separating North and South America
    - from Europe and Africa
    - by thousands of kilometers

The Three Types of Plate Boundaries

- Divergent Boundaries
  - An Example of Ancient Rifting
    - Characteristic features of ancient continental rifting include faulting, dikes, sills, lava flows, and thick sedimentary sequences within rift valleys.
    - Pillow lavas and associated deep-sea sediments are evidence of ancient spreading ridges.

Rift Valley

- The stretching produces fractures and rift valleys.
- During this stage,
  - magma typically
    - intrudes into the fractures
    - and flows onto the valley floor
- Example: East African rift valleys

Modern Divergence

- View looking down the Great Rift Valley of Africa
- Little Magadi soda lake

Ocean

- As a newly created narrow sea
  - continues to spread,
  - it may eventually become
    - an expansive ocean basin
An Example of Ancient Rifting

- What features in the rock record can geologists use to recognize ancient rifting?
  - faults
  - dikes
  - sills
  - lava flows
  - thick sedimentary sequences
  - within rift valleys
- Example:
  - Triassic age fault basins in eastern US

Ancient Rifting

- These Triassic fault basins mark the zone of rifting between North America and Africa.
- They contain thousands of meters of continental sediment and are riddled with dikes and sills.
- Palisades of Hudson River

The Three Types of Plate Boundaries

- Convergent Boundaries are places where two plates collide.
- There are three types of convergent boundaries.
  - An oceanic-oceanic boundary is where two oceanic plates collide, one oceanic plate will subduct beneath the margin of the other plate.
  - An oceanic-continental boundary is where an oceanic plate and a continental plate collide, the oceanic plate will subduct.
  - A continental-continental boundary occurs when two continents collide.

- Convergent Boundaries
  - Oceanic-Oceanic Boundaries
    - One oceanic plate is subducted beneath the other and a volcanic island arc forms on the non-subducted plate.
    - An oceanic trench forms parallel to the volcanic island arc where the subduction is taking place.
    - The volcanoes result from rising magma produced by the partial melting of the subducting plate.

- Convergent Boundaries
  - Oceanic-Continental Boundaries
    - An oceanic plate and a continental plate converge, with the denser oceanic plate being subducted under the continental plate.
    - Just as with an oceanic-oceanic boundary, a chain of volcanoes forms on the nonsubducted plate.
The Three Types of Plate Boundaries

Convergent Boundaries

- Continental - Continental Boundaries
  - Two continents converge and the ocean floor separating them is subducted, resulting in a collision between the two continents. Neither plate will subduct.
  - When the two continents collide, they are welded together to form an interior mountain chain along a zone marking the former site of subduction.

Recognizing Ancient Convergent Plate Boundaries

- Intensely deformed rocks, andesite lavas, and ophiolites are all evidence of ancient subduction zones, marking former convergent plate boundaries.

Transform Boundaries

- These are boundaries along which plates slide laterally past each other along transform faults
- These boundaries change one type of motion between plates into another type of motion.

Transform Boundaries

- Generally, no diagnostic features are left by transform faults.
- Example: San Andreas fault

Hot Spots and Mantle Plumes

What are hot spots?

- A hot spot is the location on Earth’s surface where a stationary column of magma, originating deep within the earth (possible below the mantle), has slowly risen to the surface and formed a volcano.

Hot Spots and Mantle Plumes

- Because mantle plumes apparently remain stationary within the mantle while plates move over them
- The resulting hot spots leave a trail of extinct and progressively older volcanoes that record the movement of the plate.
Plate Movement and Motion

- Determining rate and direction of plate movement
  - Hot spots enable geologists to determine absolute motion because they provide an apparently fixed reference point from which the rate and direction of plate movement can be measured.

The Driving Mechanism of Plate Tectonics

- What drives the plates?
  - Most geologists agree that some type of convective heat system is the basic process responsible for plate motion.

The Driving Mechanism of Plate Tectonics

- Gravity driven plate motion
  - Some geologists think a gravity-driven mechanism also plays a major role.
    - “Slab-pull” involves pulling the plate behind a subducting cold slab of lithosphere
    - “Ridge-push” involves gravity pushing the oceanic lithosphere away from the higher spreading ridges and toward the subduction trenches

The Driving Mechanism of Plate Tectonics

- The Supercontinent Cycle (Wilson cycle)
  - In the early 1970s J. Tuzo Wilson put forth the hypothesis of a large-scale global cycle of supercontinents.
  - Supercontinents like Pangea form, break up, and re-form in a cycle spanning approximately 500 million years.
  - The breakup forms rift valleys within the supercontinent that eventually becomes a long, linear ocean basins as the crust is depressed below sea level.
  - As the width of the narrow sea continues to expand an open ocean develops.
  - As the ocean basins close, another supercontinent forms.
Plate Tectonics and the Distribution of Natural Resources

- **Mineral Deposits**
  - Many metallic mineral deposits are related to igneous and associated hydrothermal activity, so it is not surprising that a close relationship exists between plate boundaries and the occurrence of these valuable deposits.
  - Many of the world’s major metallic ore deposits are associated with convergent and divergent plate boundaries.
  - Copper, iron, lead, zinc, gold and silver ore deposits are associated with plate boundaries.

Fig. 2.27, p. 54

Plate Tectonics and the Distribution of Life

- **Fossil evidence provided one of the first proofs for plate tectonics. Together, plate tectonics and evolution have changed the way we view our planet.**

- The world’s plants and animals occupy biotic provinces controlled mostly by:
  - Climate
  - Geographic barriers

- The location of these provinces is mostly controlled by plate movement.

Fig. 2.28, p. 56

End of Chapter 2